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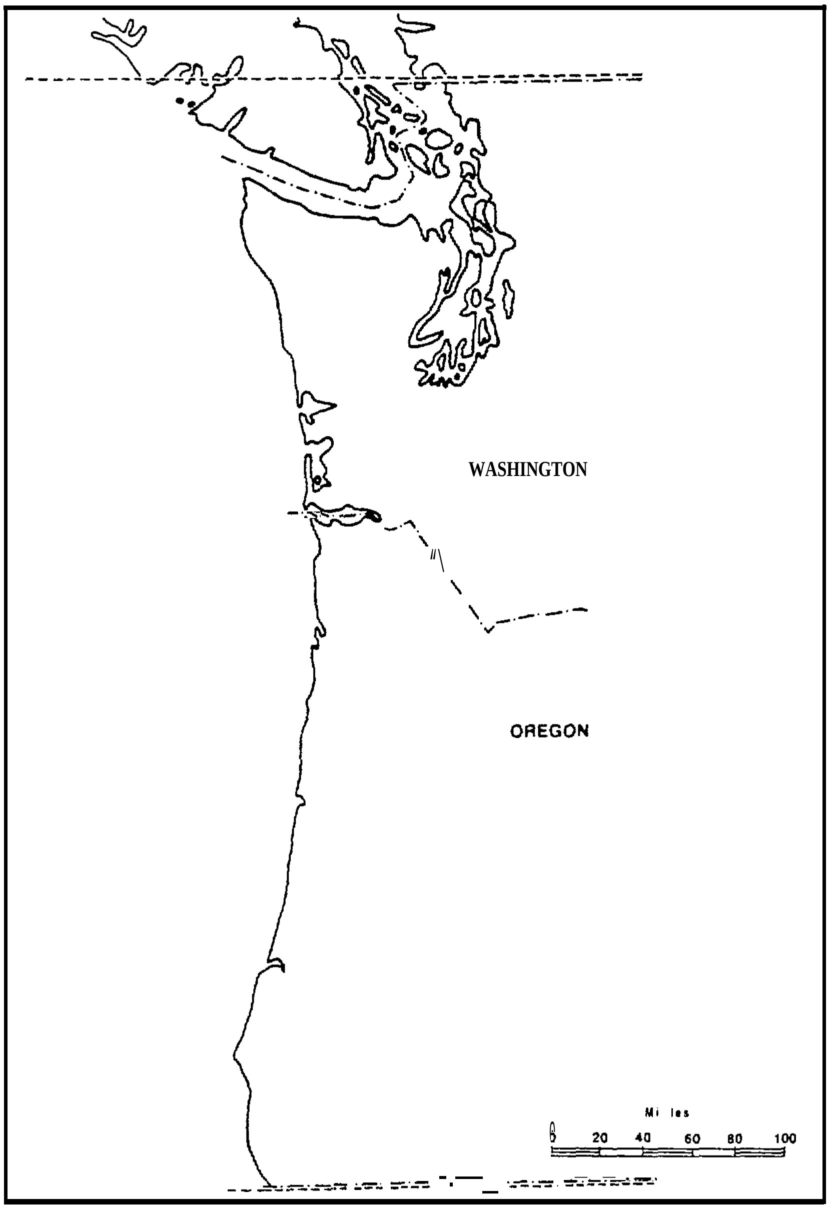
A SUMMARY OF KNOWLEDGE OF THE OREGON AND WASHINGTON COASTAL ZONE AND OFFSHORE AREAS

VOLUME I: Ch. I - III



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A SUMMARY OF KNOWLEDGE OF THE OREGON AND WASHINGTON COASTAL ZONE AND OFFSHORE AREAS

Volume I

(Chapters I-III)

by the

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Introduction

A requisite task in the effective management and regulation of the Northwest Outer Continental Shelf (OCS) is an assessment of the regional environment in all its aspects. The purpose of this study was to conduct a comprehensive literature and information survey characterizing the current disposition of natural, social and economic resource data for the Oregon, Washington and Southern British Columbia coastal zone and offshore areas. The vulnerability of recreational resources in the coastal zone to OCS development was also assessed. This study provides the primary database required to conduct a regional environmental assessment.

This investigation sought all pertinent information from published and unpublished research documents, doctoral and masters theses' material, federal and other governmental agencies, and current and proposed research projects in the study area. Compilation of the information involved integration, analysis and interpretation of the collected data, as well as documentation of gaps that exist in the current environmental data base.

The study disciplines covered in this report include the following:

- geology
- meteorology
- oceanography
- marine ecology
- terrestrial ecology
- water quality
- marine traffic and navigational hazards
- industrial and commercial activities
- petroleum industry activities
- demography and socio-economic characteristics
- land and water use characteristics
- pollution sources
- transportation systems
- recreational resources

Although the total duration of the study was ten months, the major data collection tasks were accomplished in the first four to six months. In the course of these initial tasks, information was gathered from a variety of sources. Socio-economic data was collected by the most readily available and utilized detailed characteristics for 1960, 1970, and 1975 (where available) for: states; Standard Metropolitan Statistical Areas (SMSA's); counties; and incorporated areas. Extensive environmental data was gathered from: federal sources; state, county and local government offices; academic institutions; industry; consulting groups; and other published and unpublished sources.

The marine coastal zone in Oregon and Washington extends for some 3000 miles. This shoreline area includes over two-thirds of the Northwest region's residents encompassing 22 counties and nearly 50 cities. This coastline area, its associated continental shelf and slope to the distance of 100 miles from shore, the counties adjacent to the Pacific Ocean and the Puget Sound and Columbia River estuaries and the portion of Vancouver Island, British Columbia, south of the 49th parallel comprised the project study area.

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I. GEOLOGY

Janet Cullen, Tom Pierson and
Lincoln Loehr

A. Introduction

The inland boundaries of this discussion are defined on the basis of geologic history (Table I-1). Although the strata underlying all of western Oregon, Washington and southern British Columbia were derived primarily from an Eocene eugeosyncline that extended from southern Vancouver Island into northern California and as far inland as the site of the present Cascade Mountains, subsequent convergence of the Juan de Fuca and North American plates during the Miocene Epoch and uplift of the Coast Ranges during the Pliocene have created a structural barrier which divides the inland provinces from the coastal and offshore units. Although sediments from the Cascades are incorporated into the waters of the Columbia River and Puget Sound, the Cascade Province is not included in this coastal study.

For the purposes of this report, the southern boundary of the Puget Lowland Province is defined as the limit of the Fraser Glaciation. Present landforms and their accompanying geological processes, surficial strata and soils, as well as surface response to earhquake shaking, are all a product of the Pleistocene glaciers. The remaining Puget-Willamette basin to the south is, therefore, separated from the study area by its Quaternary history.

Sediment transport, bathymetry, offshore bedrock geology, and offshore geologic processes are discussed in detail. Bathymetry of the Strait of Juan de Fuca-Puget Sound system is presented in Chapter III., Oceanography, because of its influence on currents and water properties.

The offshore geology is divided into three distinctly different regions. These are 1) the offshore region, 2) the coastal estuaries, and 3) the Strait of Juan de Fuca-Puget Sound system. The offshore region includes the continental shelf, continental slope, and the Cascadia Basin. Bathymetric features in this region include submarine canyons, deep-sea channels, and an oceanic ridge system. The geologic processes of sedimentation and sediment transport are discussed. The coastal estuaries are where the riverine and marine systems come together, and are characterized by large volumes of sediment transport and high sedimentation rates. The Strait of Juan de Fuca-Puget Sound system is treated separately because of its glacial origin and its tremendous size.

The discussion of onshore geologic structures is more detailed than the discussion of offshore geology. There are two primary reasons for this. First, very little is known -- or can be known, considering the present state-of-the-art -- about the bedrock geology of the ocean floor. There are no quarries or road cuts from which to determine stratigraphy. Very little bedrock drilling has been done on the continental shelf off Oregon and Washington; the cores contain sediments, primarily. Also, the process of bedrock coring is expensive, so the coverage is spotty. Seismic profiling can show only the structure of the rock layers. Different rock layers can be distinguished by their reflective and refractive qualities, but their individual mineral constituents cannot be "seen." Their positions in relation

Table I-1

GEOLOGIC TIME SCALE

ERA	PERIOD	EPOCH	MILLIONS YEARS† BEFORE PRESENT
CENOZOIC	Quarternary	Holocene (Recent)	0.015
		Pleistocene	1.5
	Tertiary	Pliocene	7
		Miocene	22.5
		Oligocene	37
		Eocene	55
		Paleocene	65
MESOZOIC	Cretaceus		135
	Jurassic		180
	Triassic		230
PALEOZOIC	Permian		280
	Pennsylvanian (Carboniferous)		310
	Mississippian	Many epochs recognized	340
	Devonian		400
	Silurian		430
	Ordovician		500
	Cambrian		600
PRECAMBRIAN	No subdivisions recognized worldwide		4500

†to the base of the period.

to other layers can be discerned, but their individual color, grain size, and other vital distinguishing characteristics are hidden.

The second reason stems from a basic lack of knowledge of offshore geology: an understanding of onshore geology is vital to the understanding of subsea geology in that it establishes the geologic character of the area. Cores and seismic profiles are correlated with known structures and formations. It is the landward geology that furnishes the key to interpreting submarine stratigraphy.

Concerning tectonics and seismicity, events lying outside of the study area are included because of their impact inside it. Detailed descriptions (e.g., soil properties) are confined to the coastal strip -- from the shoreline to approximately 16 km inland.

The geologic provinces discussed are: the Klamath Mountain Province, which includes the southwest corner of Oregon from the border to the Cascades (in the vicinity of the town of Bandon); the Coast Range Provinces, which include the Klamath Mountains northward to the vicinity of Aberdeen, Washington; the Olympic Mountains Province, which includes the coast of the Olympic Peninsula and the Strait of Juan de Fuca; the Puget Lowland Province, which includes the area adjacent to Puget Sound, the San Juan Islands, and where relevant, the southern portion of the Strait of Georgia and the Fraser Delta: and the southern portion of the Insular Mountains Province, which includes the area in and around Vancouver Island and the Gulf Islands (Figure I-l).

The rationale for the subdivisions is based on the needs of this study, the geologic provinces as they are commonly accepted, and the geographic parameters set by the U.S. Bureau of Land Management (BLM). Although much of the Fraser Delta is outside the boundaries set by BLM, it is geologically relevant to the Strait of Georgia and northern Puget Sound. It cannot logically be separated from them in discussions of sedimentation, slumping and other geologic hazards.

The primary sources of data were academia (Universities of Oregon, Oregon State, Washington, Portland State, and British Columbia), government agencies (federal and state agencies in Oregon, Washington and British Columbia, and county planning agencies in Oregon and Washington), and industry (consulting firms and oil companies).

Both historical and current information were used. Major texts, many individual publications and unpublished reports, and academic theses were consulted. Scientists were interviewed in person and by telephone with regard to current and proposed research, updating of historical material, and existing data gaps.

B. Results of Data Collection and Data Analysis

1. Regional Geologic Setting and History.

a. Tectonics. According to the theory of plate tectonics (sea floor spread= ing, continental drift) the crust and upper mantle of the earth are subdivided into a series of semi-independent slabs or plates, each of which is moving laterally in response to deeper seated activity within the earth.

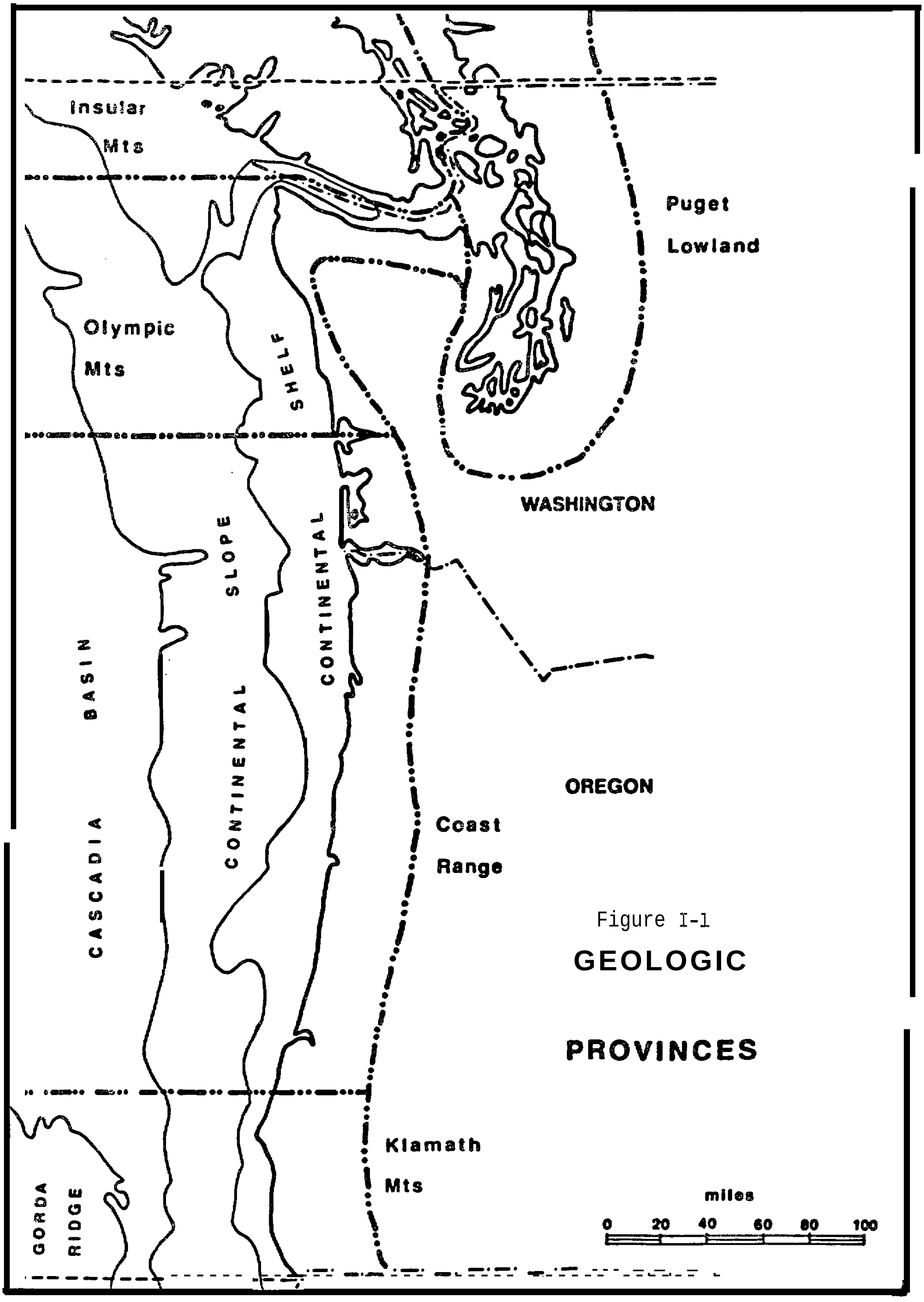


Figure I-1
GEOLOGIC
PROVINCES

The boundaries between the plates are characterized by sea floor rises in areas of divergence or spreading, trenches or related features in areas of convergence or subduction, and transform faults in zones of parallel movement.

A relatively complex border zone has developed in the northeastern Pacific Basin between the Pacific Plate on the west and the North American Plate on the east. As the Pacific Plate moves northward relative to the North American plate, a right lateral component of movement is experienced along the faults and rises separating the two plates. These areas include the Mendocino Escarpment, the Gorda Rise, the Blanco Fracture Zone, and the Juan de Fuca Rise off the Oregon coast (Figure I-2).

The Puget Sound region of western Washington lies in a north-trending structural and topographic trough between the Olympic Mountains on the west and the Cascade Range on the east. The geological structure of the basin itself is poorly known, largely due to the thick accumulation of glacial deposits that hide the underlying bedrock structure.

In recent years, several researchers have focused attention on the place of Puget Sound and adjacent regions in the emerging pattern of sea floor spreading and global tectonics. The Juan de Fuca and Gorda plates seem to be remnants of a once more extensive plate. They are now caught in the interaction between the North American and Pacific plates.

There exists abundant evidence that the oceanic crust is, or was until recently, being subducted along a line generally coinciding with the coast of North America between Vancouver Island and Cape Mendocino (Crosson, 1972) . However, the motion may be either slowed or presently inactive, since there is neither oceanic trench nor Benioff Zone along the plate margin.

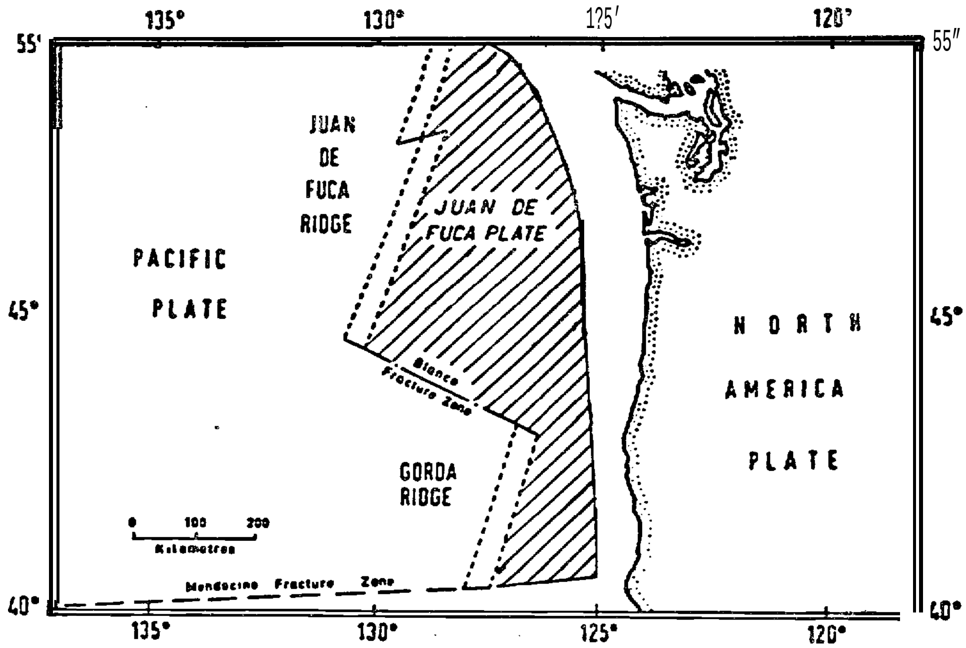
The geometric relationships of the Puget Sound depression are still unclear.

b. Physiography. The Oregon and Washington coasts are outlined by a Coast mountain range which merges with the Klamath Mountains of southern Oregon and northern California at the southern end. At the northern end, the Coast Range rises to its greatest elevation on the Olympic Peninsula of Washington in the Olympic Mountains. There are few rivers which breach it completely from east to west -- the Rogue and Umpqua in southern Oregon, the Columbia River, forming the boundary between Oregon and Washington, the Chehalis at the southern end of the Olympics, and the Strait of Juan de Fuca at the northern end of the Olympic Peninsula. In British Columbia, the geologic and topographic continuations of the Coast Range are Vancouver Island and the Queen Charlotte Islands, which together define the Insular Mountains Province.

The major physiographic features found off the coast of Oregon, Washington, and British Columbia are a continental shelf, a continental slope, a deep sea basin, and a mid-ocean-type ridge offset along the major fracture zones. The shelf slopes gradually seaward from the shoreline to a depth of about 183 m. It varies in width from less than 1.6 km off the Brooks Peninsula near the northern end of Vancouver Island to about 80 km opposite the Strait of Juan de Fuca. The average width of the shelf is

Figure 1-2

Regional Tectonics Showing the Position of the Crustal Plates and Fracture Zones Influencing Geologic Structure of the Continental Margins[§,t]



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§ After Murray and Tiffin, 1974.

t The plate boundaries are inferred.

about 40 km. The continental slope passes from the shelf edge down to the margin of the deep sea floor, with an average width of 48 km and a slope of 3 to 4 degrees.

The sea floor between the continental slope and the ridge is known as the Cascadia Basin. Its average depth is approximately 3,000 m. The surface slopes gently southward. The maximum width of the basin is about 820 km, off central Oregon. The Cascadia Basin, located between an actively eroding continent and an oceanic mountain belt, seems to be a huge sediment trap, the largest single sediment source being the Columbia River. The surface of the Basin is cut by well-defined channels bounded by natural levees. The most prominent are the Cascadia and Vancouver Channels. These join near the southern end of the Basin and run westward through a canyon in the Blanco Fracture Zone (off southern Oregon) to reach the Tuffs Abyssal Plain. Occasional turbidity currents pass down these channels, carrying fine sediment out into the Pacific Ocean.

The ocean ridge is composed of several separate ridge segments, offset along major fracture zones or transform faults. From south to north, the segments are Gorda Ridge, Juan de Fuca Ridge, and Explorer Ridge. Each is a complex region of mountains, hills, and depressions, as are the fracture zones joining them. Most of these features lie outside the immediate study area, but they are included to completely describe the general physiography of the region.

C. Bedrock Geology of the Cordilleran geosyncline. The continental margin off Oregon and Washington represents the western portion of a Tertiary depositional trough (geosyncline) that extended southward from what is now Vancouver to the Klamath Mountains. The width of the trough extended from the Cascade Mountains to near the base of the present continental slope [Figure I-3). The Cobb and Blanco Fracture Zones represent the approximate offshore boundaries on the north and south.

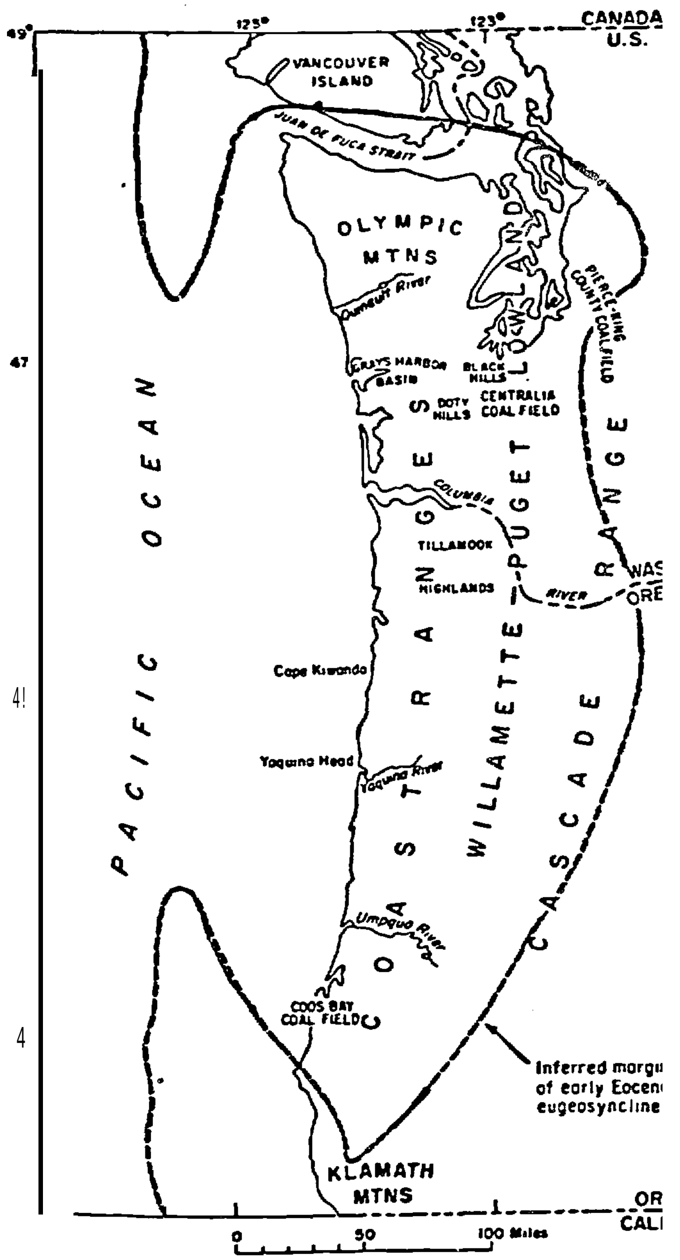
The oldest rocks in the depositional basin are early Eocene pillow lavas and breccias that erupted from numerous centers. The entire Tertiary basin sequence is thought to overlie oceanic crust, although some Cretaceous deposits may be present within the southern part of the trough.

There was a mild regional uplift of the southern part of the geosyncline during early and middle Oligocene times, with regional subsidence taking place in the northern part. In places, marine Oligocene beds overlap upper Eocene strata and rest unconformably on lower Eocene volcanic rocks. On the eastern side of the geosyncline there was vigorous pyroclastic volcanism, which, combined with large amounts of water-laid tuffs, buried the late Eocene coastal plain. Much pumice-rich material was transported to the nearshore marine environment, in some areas forming deltas. Slumping and submarine landsliding carried this detritus into deeper parts of the basin.

In early Miocene time, deposition continued essentially uninterrupted in the same basins that received upper Oligocene sediments. In the early part of the middle Miocene time older Tertiary strata were folded and faulted along northeasterly structural trends in Oregon and northwesterly trends in Washington. The coarse elastic debris that characterizes much of the sedimentary rocks of middle Miocene age was furnished by the erosion

Figure I-3

Index Map of Western Washington and Oregon Showing the Inferred Extent of the Eocene Eugeosynclineξ



ξAfter Snavely and Wagner, 1963.

of the land areas elevated during this period of deformation.

During the middle Miocene tectonic activity, shallow marine bays encroached eastward along structural downwarps. The maximum known extent of marine expansion was in the Grays Harbor basin and in a broad west-trending downwarp just south of the present Columbia River. An embayment seems to have extended along the Strait of Juan de Fuca as far east as Puget Sound. Also during the middle Miocene, basalt extruded onto the sea floor from a north-trending series of vents and fissures to build small islands.

Many of the headlands along the northern part of the Oregon Coast were centers of this local activity. The most widespread lavas, however, were the Miocene flood basalts that flowed down the Columbia River downwarp and spread northward as far as the Grays Harbor basin. These flows -- the Columbia River Basalts -- reached the marine environment and formed thick accumulations of pillow lava and breccia. Near the close of the Miocene, marked regional uplift of the Coast Ranges and intense deformation in the Olympic Mountain area further reduced the area of marine deposition.

Pliocene strata consist mainly of debris eroded from older Tertiary formations that bordered the basin. More than 900 m of shallow water marine strata rest unconformably on older rocks in the Coos Bay and Grays Harbor structural embayments. Slump structures in the Pliocene beds indicate that the deeper part of the basin still lay west of the present coastline. Downwarping and sedimentation continued in the depression along the Puget-Willamette lowland.

During late Pliocene, the Olympic Mountains and the Coast Ranges probably attained most of their present elevation. There is some evidence that uplift is still continuing along the Coast Ranges. Structurally, the Coast Range is a broad regional upwarp consisting of numerous alternating structural ridges and troughs. These folds continue offshore and appear to be still growing. The late Tertiary strata are cut by numerous shale diapirs on the Washington and the western half of the Oregon continental margin. Late Pliocene volcanism provided the platform on which the andesite cones later formed what now characterize the Cascade Range.

In summary, the depositional history of the coastal geologic provinces has been complicated by periodic submarine, subaerial, and deep-seated volcanism accompanied by several phases of tectonic uplift and subsequent erosion. In view of the limited well data and thick overburden of Holocene sediments, estimates on the nature and distribution of the offshore Tertiary strata are largely speculative and must be largely inferred from onshore structures.

The portions of the study area outside of the eugeosynclinal structure and the pretertiary history of the area are covered in the following discussion of the individual provinces.

2. Brief Geologic History of the Separate Provinces.

a. Lithology/Stratigraphy.

i. Klamath Mountain Province. The Klamath Mountains extend from northern California into southwestern Oregon. They are surrounded on three sides by other mountain ranges: the Oregon and California Coastal Ranges and the Cascades. For purposes of this study, the Klamath Mountain Province encompasses the Klamath Mountains area and its adjacent coastal area southward from Bandon, Oregon to the California border.

The preceding and following materials are taken from McKee (1972), Snavely and Wagner (1962), Loy (1976), Beaulieu and Hughes (1975), Koch (1966), Baldwin (1964) and personal communications with Ewart Baldwin and Allen Kays (1977).

The Klamath Mountains are composed of complex overlapping thrust sheets that become progressively older from west to east and contain the oldest rock in Oregon. Structure and stratigraphy define their limits, which are drawn arbitrarily at the edge of the younger strata outcropping extensively in the surrounding mountains. These are Lower Tertiary marine beds to the north, Cretaceus marine beds to the south, and nonmarine Lower Tertiary volcanic rocks to the east.

The stratigraphic record of the Cordilleran geosyncline in the Klamath Mountains is more complete and less metamorphosed than in the nearby Sierra Nevada Province of California. The overall picture is one of generally marine sedimentation, volcanism, and periods of local uplift and erosion, with much of the sediment coming from weathering of the volcanic materials. Westward, the core of the Klamaths has been highly deformed and metamorphosed.

The late Mesozoic record consists of (1) very thick sections of marine volcanic sandstone, shale, and lava of Late Jurassic age; (2) igneous intrusions, also Late Jurassic; and (3) various shallow water marine sandstones and shales of Late Jurassic and Cretaceus age.

Jurassic rocks in the Klamath Mountains Province lie largely in a north to northeast-trending belt extending from the southwestern corner of the state to the Riddle quadrangle, where they are covered by the younger volcanics of the Cascade Range.

The Otter Point Formation is a complex structural assemblage of highly varied rocks of diverse origin, that is, a melange. It corresponds to part of the Franciscan Assemblage in California (Ghent and Coleman, 1973).

Rhythmic bedding of sand and siltstones indicates a turbidity origin for parts of the Otter Point Formation (Beaulieu and Hughes, 1975). It also contains blue schist pods of older age. The Otter Point Formation is thought to represent Mesozoic sea floor and island arc rocks (Coleman, 1972) that were subducted beneath the continental curst.

Although the term has been loosely applied to several groups of coastal rocks, the Otter Point Formation is found in exposures along the South Fork of the Coquille River between Myrtle Point and Powers and in coastal and upland exposures south of Bandon, and more recently extending under the Coast Range into the Roseburg area (Baldwin, 1977). It flanks the periphery of the Klamath Mountains and extends down the Curry County coastline into California. All observable contacts with younger and older rocks are faulted. Complex structure and areal repetition of similar lithologic types make questionable any inference regarding the original thickness of this formation or the distribution of its different rock types. However, field relations and laboratory studies suggest that the Otter Point and Lower Cretaceous are unconformable (Koch, 1966).

The late Mesozoic (Middle Cretaceus) strata are represented by the Hornbrook Formation -- 600 m of arkosic sandstone, siltstone, and conglomerate, found in the Medford-Ashland area and northern California. These sediments were laid down in a shallow water marine environment.

Late Cretaceus beds, younger than the Hornbrook Formation, are present at Cape Sebastian (Dott, 1971). The basal beds are medium grained, massively bedded sandstone and minor amounts of conglomerate. The upper part of the section is thin bedded, dark gray siltstone. Both the sandstone and siltstone units have been traced to Pistol River and to Mack Arch, where they terminate against border faults.

Most of the Tertiary strata of the Klamath Mountains are present along the coastal margin. It is known that the Eocene geosyncline referred to in the introduction received large amounts of volcanics during the early part of the epoch. In middle Eocene time, major uplift south of the geosyncline resulted in the deposition in that ancient basin of great quantities of arkosic, volcanic, and lithic detritus derived from the Klamath metamorphic, igneous, and sedimentary terra. It is thought that this is one of the major sources of material for the Tyee Formation of the Coast Range Province.

Where sediment-bearing streams from these source areas reached the coast, large deltas and submarine fans were constructed. Periodic slumping of large amounts of unconsolidated delta material caused the sands and silts to be transported, probably by turbidity currents, into the deeper parts of the geosyncline. Near the close of the Middle Miocene, the southern part of the geosyncline was filled with turbidity current deposits. During this time, coal-bearing beds and nearshore bar-type sands were laid down in the southern part of the basin. By the end of the Pliocene, the Klamath source area apparently was eroded to a region of moderate relief, furnishing less debris to the marine environment.

The southern part of the Tyee Formation (see discussion of Coast Range Provinces below) is present only in a narrow syncline south of the Middle Fork of the Coquille River. It crops out in Bone Mountain, Eden Ridge and terminates at Bald Knob, overlooking the Rogue River at Illahee. Coal is interbedded with the massive sandstone. Thin members of conglomerate are present in the basal part of the formation.

Pliocene formations at Cape Blanco will be described in the discussion of the Coast Range. Somewhat similar beds abut the Klamath Mountains near the California line. These are the Wimer beds. They contain a few marine fossils and some leaves, indicating an interfingering of near shore and nonmarine sediments. They are generally considered to be Mio-Pliocene. The Klamath Mountains were evidently peneplaned during the Miocene and Pliocene.

The Cenozoic record is thin. Cenozoic rocks near the Klamaths are excluded from the province by definition. Within the range there are stream gravels and sands, some of which date to the Miocene. Apparently they were deposited at a time when the range was lower with less erosion. The uplift of the Klamath Mountains in the past few millions of years has elevated many of these older gravels, preserving some remnants. Recent uplift is also shown by raised, wave-cut benches and terraces along the Pacific shore. A few of the higher peaks in the Klamaths underwent Pleistocene glaciation. These glaciers were small and located mostly on the relatively sheltered north- and east-facing slopes. Little is known of them, and there are no glaciers in the area today.

Quaternary geology of the Klamath Mountain Province is discussed in Section 3.1., Surficial Geology.

ii. Coast Range Provinces. The Coast Range in Oregon extends from roughly the Middle Fork of the Coquille River northward to the Columbia. It is succeeded on the north by the Washington Coast range, which, in turn, becomes the Olympic Mountains.

The following material is taken primarily from McKee (1972), Baldwin (1964), Schlicker, *et* aZ. (1972, 1973), and Schlicker and Deacon (1974).

The summits of the Coast Range passes lie east of the axis of the range because of more active erosion by the shorter, steeper coastal streams, the steeper overall gradient, and the higher rainfall on the western slope. A wave-cut terrace forms a narrow coastal plain along the western edge of the Range between headlands of resistant rock. Remnants of even high wave-cut terraces are present up to 490 m. Drowning of river mouths by rising sea level formed bays and the larger coastal lakes.

The seaward side of the Coast Range contains younger and less continuous Oligo-Miocene formations. These generally w-rap around the north end of the range along the Columbia, and extend a lesser distance southward along the east slope. Marine Pliocene rock, unknown on shore, is present in Stonewall Bank west of Newport. The Eocene sediments are exposed in a narrow syncline which extends as far south as the mouth of the Illinois River. Although this syncline is largely within the Klamath Highlands, it is usually included with a discussion of the southern Coast Range.

Nearly all of the rocks in the southern end of the Coast Range are Eocene sedentary and volcanic rock. Younger marine Teritary and Quaternary formations are present only near Coos Bay and Cape Blanco.

In the south, the Eocene Umpqua Formation is generally equivalent to the Siletz River Volcanics, but contains a larger percentage of sedimentary rock. The central part of the Coast Range is occupied by the massive Tyee Formation, which is intruded by dikes and sills. The coal bearing Coaledo Formation overlies the Tyee in the Coos Bay basin, and in turn is overlain by later Tertiary sedimentary formations in the same basin. Late Eocene volcanics at Heceta Head and Cape Perpetua are generally equivalent to the Coaledo.

Early Oligocene seas may have partially covered the Coast Range, but there is evidence that land took shape as the Oligocene progressed, so that the late Oligocene and early Miocene embayment reached around only the north end of the Coast Range into the northern Willamette Valley. Oligocene stratigraphy in the Coast Range is dominated by marine shales containing a very high proportion of volcanic ash. This was probably derived from vents in the ancestral Cascades and carried to the sea by winds and streams. Compared to the Eocene, the Oligocene was fairly stable, with little offshore volcanic activity, folding, or vaulting. It was a time of slow accumulation of fine-grained tuffaceous sediment, with coarser sands and gravels deposited near shore.

By the middle of the Miocene most of the Coast Range region had merged from the Pacific. Subsidence, rather than uplift, had until then characterized the continental margin. Widespread emplacement of gabbroic sills, as much as 300 m thick, accompanied the uplift.

As the shoreline of the geosyncline withdrew to the western edge of the Coast Range and uplift continued, the older Cenozoic formations were shaped by erosion and the present river valleys were cut. This revealed the dikes and sills and stripped their cover, so nearly all the central Coast Range peaks are made up of the remaining intrusive rock.

Very little is known of the pre-Tertiary history of the Oregon Coast Range and very little of the Washington Range prior to the Quatternary. The earliest formations in the Coast Range date back to the early Eocene, at which time the Coast Range and much of the adjacent Willamette Valley lay in the geosyncline. The oldest unit consists of layers of pillow basalt, breccia, and sedimentary rock. It was probably formed as an island arc complex, later telescoped against the continent and uplifted by crustal movements near the close of the Eocene. It outcrops near Tillamook, along the Siletz River, near Coos Bay, and at Roseburg. The visible strata of the Washington Coast Range are almost all of Pleistocene age, with a few exceptions that are discussed near the end of this section.

The Umpqua Formation of Early to Middle Eocene age makes up much of the southern part of the Coast Range. One of the thickest sections is exposed along the North Fork of the Umpqua River. On the southeast side of the arch near Glide there are several thousand meters of sandstone and siltstone dipping gently eastward beneath the Cascades.

The Umpqua can be divided into three parts. The lower part consists of submarine basalt flows, siltstone, sandstone, and local conglomerates. The base is seldom exposed. Instead the lower part is usually in fault contact with pre-Tertiary rocks and the basalt correlates with the Siletz River Volcanics. The lower beds and flows were severely faulted and folded, in some places are now lying vertically or overturned.

The middle unit was deposited by the advancing sea that reoccupied the southern part of the Coast Range. Beds are characterized by thick conglomerates at the base that give way to sandstone and siltstone.

The top unit was laid down upon truncated beds of both of the older units, but the unconformity is not as pronounced as the one preceding the middle unit. Fossiliferous sedimentary rock resting with angular unconformity on the lower Umpqua basalt is assigned to the upper and middle units. All three units are unconformably overlain by the Tyee Formation.

The Siletz River Volcanics is the oldest formation exposed in the Coast Range. Early Eocene age has been assigned. The formation has not been found south of Alsea, and the area between Alsea and Drain is covered by the Tyee sandstone. Although the volcanics thin toward the margins of the geosyncline, geological and geophysical data suggest that the sequence is probably more than 3000 m thick in most parts of the Coast Range. These basaltic flows are estimated to have the largest volume of any volcanic unit in the Pacific Northwest -- more than 2S0,000 km^3.

The middle Eocene saw a general cessation of volcanism in Oregon, but renewed uplift of the Klamath Mountains produced an influx of sand. The sediments piled temporarily on river deltas before being swept by currents along the basin floor and out to the sea bottom. These currents produced graded beds.

Volcanism was renewed in the late Eocene, but not as extensively as earlier. Coal formed in swamps along the margin of the basin.

The Middle Eocene Tyee Formation is the most widespread indurated formation underlying the area. It extends from near the coast to the eastern boundary of the study area. The formation is composed of massive, rhythmically bedded sandstone and siltstone and is more than 1500 m thick. It is extensively faulted in the areas where it has been mapped. The Tyee is particularly widespread in the central part of the Coast Range.

The Yamhill Formation is Middle to Late Eocene. It is exposed along the south slope of the Yamhill Valley and southward to the Luckiamute River, where it appears to interfinger with beds of the Tyee. The Yamhill directly overlies the Siletz River Volcanics in the Mill Creek and Rickreall Creek areas, a position usually occupied by the Tyee. Thus the Yamhill is either equivalent to the Tyee or is unconformable upon the volcanics.

The Yamhill consists of several thousand meters of indurated, massive to thin-bedded clayey siltstone. Some minor interbeds of arkosic, basaltic, and glauconitic sandstone are also present. The Yamhill is conformable upon the Tyee and unconformably overlain by the Nestucca Formation.

The Late Eocene Coaledo Formation is the coal bearing formation in the Coos Bay area. The Coaledo encompasses most of the beds of Late Eocene age. It is divided into three members. The lower

Coaledo member crops out along the beach from Cape Arago to the lighthouse. It is composed predominantly of blue-grey medium to coarse-grained nodular sandstone, with some grit and intercalated fine-grained sand shale beds. The sandstone is tuffaceous, with many of the pebbles in the conglomerate being lenses of fine-grained basalt.

The middle member is exposed between the lighthouse and Yokam Point (Mussel Reef]. It is a medium-grey tuffaceous shale and siltstone with some sandy lenses. Several beds of well indurated light colored tuff are present.

The upper Coaledo makes up Yokam Point and extends to the west side of Bastendorff Beach near the mouth of Miner Creek. It is a medium to fine-grained gray, tuffaceous sandstone that contains carbonaceous sandstone, sandy shales, carbonaceous shales, and coal. The measured thickness of the coastal section is 400 m, with one coal bed. The principal coal bed of the member is the Newport-Beaver Hill bed, from which most of the coal has been mined.

The Bastendorff Formation is apparently conformable upon the Coaledo. The best exposures are along the coast and good exposures are present at Eastside across the bay from Coos Bay and near Beaver Hill on the Coos Bay-Coquille highway. The section is 700 m thick at Bastendorff Beach. The beds are composed of a thin-bedded medium- to dark-gray shale streaked by lighter colored thin tuffaceous beds. The formation is easily eroded by wave action, accounting for the very broad beach. It is dated as Late Eocene to Early Oligocene.

The Nestucca Formation, of Late Eocene age, consists of 240 to 1500 m of indurated thin-bedded tuffaceous clayey siltstone, with subordinate amounts of ash and interbedded arkosic, basaltic, and glauconitic sandstone. Small sandstone dikes and sills are common in the upper part of the section. The Nestucca rests unconformably on the Yamhill Formation. Exposures of the Nestucca Formation are located at Lincoln City, in the Toledo area, and south of Yaquina Bay. It was previously mapped as part of the "lower Toledo" formation in the south coastal area.

Late Eocene volcanic rock of basaltic composition forms the headlands south of Yachats and at Cascade Head. The total area of these units is approximately 80 km2. These are the Yachats and Cascade Head Basalts. They are 700 m thick at Cape Perpetua, and consist of basaltic flows, breccia, and lapilli tuff. Flows are generally 3 to 6 m thick and appear to have been subaerially extruded. Dike rocks are generally basaltic but range to dacites locally. At Cascade Head, the volcanics consist mainly of fine-grained to glassy basaltic breccias and lapilli tuffs with intercalated siltstone.

Intrusive rocks occur in numerous, widely scattered places throughout the area. They are most abundant between Cape Perpetua and Heceta Head and easterly in the uplands, where they intrude the Yachats Basalt. They intrude the Tyee Formation as well. They range in thickness from a meter to several hundred meters and extend to a length of several kilometers in some outcrops. Late Eocene basaltic dikes in the Waldport, Marys Peak, and Alsea quadrangles are similar to those along the coast. It is possible that volcanism continued into the oldest

Oligocene.

The Siltstone of Alsea is a massive, fine-grained indurated sedimentary rock of Oligocene age in the Newport and Waldport areas. It used to be included in the "upper Toledo" formation. The unit is well-exposed at Alsea Bay and forms a 2 km wide bank that extends northward past Toledo to the mouth of the Siletz River. It is 450 m thick at Yaquina Bay, where it is predominantly a massive, tuffaceous siltstone with subordinate fine-grained sandstone. Concretions are abundant. The siltstone passes laterally and downsection into firmly cemented, thick-bedded basaltic sandstones that grade down into poorly sorted basaltic conglomerates forming the base of the Oligocene section near Yachats. The Siltstone of Alsea overlies the Nestucca Formation and late Eocene volcanic rocks.

The Yaquina Formation conformably overlies the Siltstone of Alsea and is conformably overlain by the Nye Mudstone. It consists of deltaic sedimentary rock up to 600 m thick. It is exposed in a 2 to 8 km wide band from Siletz Bay southward through the uplands immediately west of Toledo to the coastal parts of the Waldport quadrangle south of Waldport. To the north and south it passes laterally into fine-grained sediments of the Alsea siltstone and Nye Mudstone.

The Yaquina Formation exhibits a diverse lithology. It is composed of micaceous, tuffaceous, arkosic sandstone that is hard but locally friable and massive to well bedded and cross bedded, pebbly sandstone, conglomerate, massive tuffaceous siltstone, and coal deposits. The lithology, together with thickness patterns and fossil types, indicates that the Yaquina was laid down as a large delta. Late Oligocene age has been assigned to most of the unit, but the upper part is Early Miocene.

Large dark-colored bodies of rock were intruded into the Eocene strata during Late Oliogocene time, as in the Late Eocene. The softer Eocene sediments have been eroded so that these Late Oligocene intrusives now form most of the higher peaks. Only slight changes took place in the depositional environment in western Washington during Late Oligocene time. Farther south along the present site of the Oregon Coast Range the widespread emplacement of gabbroic sills was accompanied by broad uplift. Late Oligocene marine deposition was restricted generally to the west flank of the uplift, with the exception of a marine embayment that extended into the northern part of the present Willamette Valley. Westward-flowing streams constructed deltas. The crossbedded sandstone of the Yaquina Formation is typical of these deposits.

The Nye Mudstone disconformably overlies the Yaquina Formation and unconformably underlies the Middle Miocene Astoria beds. Thus, an Early Miocene age is assigned to the Nye Formation. The unit is exposed along the sea cliffs and coastal creeks of the southern Yaquina quadrangle and extends 13 km north of Yaquina Bay, where it is onlapped by the Astoria Formation inland from Cape Foulweather. The Nye Mudstone is exposed for 8 km along the Siletz River inland from Depoe Bay. The thickness ranges from 150 m north of the Bay to 1340 m at Yaquina Bay.

The unit consists of indurated, massive to indistinctly bedded clayey siltstone, rich in organic matter. Thin, calcareous lenses and interbeds of sandstone are common in the lower section, and large concretions are common in the upper part.

The Astoria Formation consists of a variety of nearshore marine sandstones and siltstones of Middle Miocene age, overlying the Nye Formation and underlying the Middle Miocene rocks of Depoe Bay. It is composed largely of hard, massive, fine to medium-grained, micaceous, arkosic sandstone and interbedded carbonaceous siltstone. The Astoria Formation is approximately 600 m thick where the total section is exposed near Depoe Bay. An outcrop at Beverly Beach is 150 m thick.

The ancestral Columbia River, which then ran along a west-trending downwarp across western Oregon, transported large quantities of sand and silt to the marine environment. These deposits have a higher percentage of heavy minerals than are present in the upper Eocene and Oligocene rocks. Pyroclastic materials from the ancestral Cascade volcanoes also are included in the detritus. Overturned folds in slump structures, which are present in many parts of the Astoria Formation, indicate that the deepest part of the geosyncline lies near the present coast line.

The Tunnel Point Sandstone is of Middle Oligocene age. It overlies the Bastendorff shale with apparent conformity and is unconformably overlain by the Empire Formation. The base of the unit on the west side of Tunnel Point contains a massive concretionary bed composed of quartz and feldspar with an admixture of tuffaceous material and glauconite. The sandstone is interbedded with brittle shale near the top. A thin bed of tuff is also present. About 2S0 m of sandstone is exposed at Tunnel Point, but no other outcrops are known. Farther inland, the Tunnel Point Sandstone is overlapped by the Empire Formation and Pleistocene deposits.

The Depoe Bay Basalt is a Middle Miocene unit exposed about 2 km north and south of Depoe Bay, covering an area of about 2.5 km^2. It consists of about 23 m of submarine basalt that contains many pillows in a palagonitized basaltic glass matrix. To the south, the pillows pass laterally into a subaerial flow of columnar fine-grained basalt. Numerous dikes and sills in the vicinity attest to the local origin of the unit.

Volcanics of similar age and lithology are found to the north at Capes Lookout and Meares and Tillamook Head. They are all petrochemically equivalent to the Yakima Basalt in eastern Oregon.

The Sandstone of Whale Cove is a thick-bedded, semi-friable sandstone overlying the Depoe Bay Basalt. The unit is restricted to the sea cliffs in the Depoe Bay and Whale Cove area, where it is covered by a thin layer of marine terrace sand. The Sandstone of Whale Cove is 60 to 90 m thick. It consists of massive to thick-bedded, medium- to fine-grained arkosic sandstone and thin-bedded, carbonaceous, very fine-grained sand- and siltstone. Deposition in a shallow-water environment is indicated. The unit is unconformably overlain by terrace sands and Cape Foulweather Basalt and lies with slight unconformity upon the Depoe Bay Basalt.

The Cape Foulweather Basalt forms the headlands at Cape Foulweather and overlies the Whale Cove sandstone at Depoe Bay and Government Point. Its total extent is approximately 8 square km. It contains mostly basaltic breccias and water laid fragmental rocks. Pillow lavas and massive flows are subordinate. Most of the unit is of subaerial extrusion. The numerous feeder dikes surrounding Cape Foulweather are lithologically similar to some of the basalts at Cape Lookout and Ecola State Park. The unit unconformably overlaps the Whale Cove sandstone, the Depoe Bay Basalt, and the Astoria Formation. It is apparently no older than Middle Miocene.

Not all of the Middle Miocene basaltic magma reached the surface. Swarms of intrusive in the Cape Foulweather and Yaquina quadrangles are probably of the same origin as the Cape Foulweather and Depoe Bay basalts. Farther south, at Seal Rocks, Middle Miocene basaltic sills intrude the Yaquina Formation to form small rocky headlands.

The Empire Formation is situated in the center of the South Slough Syncline along the west side of the Coos Bay area. It is composed of as much as 900 m of massive, poorly-bedded sandstone with minor interbeds of siltstone and at least one prominent fossiliferous conglomerate lens that crops out at Fossil Point. Other outcrops are at Coos Head and between South Slough and Pigeon Point. Relatively large blocks of fossil-bearing sandstone are incorporated within the conglomerate. The beds at Fossil Point contain many more fossils than the rest of the formation. A lower and middle Pliocene age has been assigned to the Empire Formation.

Miocene and Pliocene beds (the "Empire Beds") at Cape Blanco are made up of tuffaceous indurated sandstone with fossil-bearing concretions. Some of these may be of Miocene Age. The "Empire Beds" are overlain unconformably by the Port Orford Formation, a sequence of much less indurated beds with an approximate thickness of 60 m. The base is concealed and the top has been removed by erosion. There are conglomerates at the north end, but most of the formation is composed of a massive, poorly consolidated sandstone of quite uniform lithology. The "Empire Beds" and the Port Orford Formation have been described as the "Cape Blanco Beds" by earlier geologists. The age is probably Middle to Late Pliocene. The Port Orford Formation has a slight eastward dip, indicating recent deformation along this part of the coast.

Pliocene sedimentary rocks known as the Troutdale Formation are found along the Columbia River from the St. Helens area to the mouth. It is composed mainly of quartzite pebbles in partially indurated conglomerates. The formation indicates that the Columbia has flowed along this general path since the early part of the Pliocene, perhaps 1 onger. On the coast, the Troutdale Formation is restricted to a relatively small exposure of unsorted gravel in south-central Astoria.

Little is known about bedrock geology of the southern Washington coast. Until very recently, the only definitive study has been Weaver's 1916 paper, Post-Eocene Formations of Western Washington and his 1937 book, Tertiary Stratigraphy of Western Washington. The

Raymond and South Bend quadrangles were mapped in 1967 by Holly C. Wagner of the U.S. Geological Survey (USGS). Ray Wells of the Menlo Park office of the USGS and Sandra Leo of the University of Washington Dept. of Geology are currently working in this area.

Virtually nothing is known of the pre-Tertiary stratigraphy of this particular area. During the early Eocene, the volcanic rocks of the Umpqua and Siletz Formations in Oregon formed the Crescent and Metchosin volcanic series in the Olympics and Coast Ranges of western Washington in the Late Oligocene. Only slight changes took place in the depositional environment. The sedimentary basin largely disappeared by the Miocene. This was probably due to filling in by sediments and to regional uplift. Early Miocene marine deposition occurred on the continental shelf and in a few shallow embayments, most notably those along the lower reaches of the present Columbia River and in the Grays Harbor area. Columbia River Basalt flows of Miocene age are found in the Washington Coast Range from the Willapa Hills to the Columbia. In southwestern Washington, the best exposures are along the north shore of the lower Columbia, with some poorly exposed outcrops in the Willapa Hills.

According to Weaver (1916, p. 19-23):

"Marine deposits of Tertiary age form a considerable part of the formations exposed at the surface in western Washington. They have been folded and eroded, and in some areas, are deeply buried beneath sand and gravel of glacial and fluviatile origin. ..outcrops are usually found in the form of low cliffs along the banks of rivers and creeks or along the sea cliffs of the Sound or ocean. ..Marine deposits of Pliocene age with the exception of a very small area of the Olympic Peninsula are unknown within the state. The uppermost division or upper Miocene is separated from the lower four divisions by a well-marked unconformity. The pre-Pleistocene formations of the southwestern portion of the state are somewhat obscured by clays, sands and gravels of fluviatile origin. In many areas the Tertiary rocks themselves have been so deeply weathered that very little information can be obtained concerning their lithological character and structure...

"The Oligocene and Miocene deposits of western Washington exist in three separate areas. The largest and most representative area occupies the northern half of the Puget Sound basin and the north border of the Olympic Peninsula. A second area embraces the western portion of the Chehalis and Willapa River valleys in the southwestern part of the state. A third area constitutes a belt ranging from [eight to twenty-four kilometers] in width and trending east and west along the north shore of Columbia River.. .

"From the southern margin of the Olympic Mountains.. .Oligocene and Miocene formations extend southerly to the middle of Pacific county . ..They have been cut by the Columbia River and their southern extension forms a part of the well-known series of outcrops occurring at Astoria, Oregon. No marine deposits of Oligocene or Miocene age are known to occur with the Cascade Mountains or within the great basin area of eastern Washington. . .

"Thick lavas, known as the Metchosin Volcanics, are found in the extreme western part of Washington and on Vancouver Island and gradually diminish toward the east in the Wildcat Hills of Kitsap County. The Teanaway basalt exposed in the eastern flanks of the Cascade Mountains in Central Washington may represent the time equivalent of the Metchosin volcanics.

The following paragraphs are also from Weaver (1937):

"The Metchosin volcanics are exposed from the western part of Grays Harbor southwesterly through Willapa Harbor into Pacific County, and thence continue in a general southeasterly direction into the northern part of Wahkiakum County and the southwestern part of Lewis County. This area of lavas varies in width from [nine to sixteen kilometers] forms the divide between the drainage passing directly into Shoalwater Bay and Columbia River and that which flows northerly into Willapa Harbor and the south fork of Chehalis River...In the area from the city of South Bend, upon Willapa Harbor, northwesterly to Grays Harbor excellent exposures of the lava sequence may be observed. About [two kilometers] west of the city of Redmond, these rocks are exposed in high rugged cliffs along the northern bank of the Willapa River. . .

"About [nine and one-half kilometers] northwest of South Bend on the north shore of Willapa Harbor and near the mouth of Smith Creek there occur high cliffs composed of agglomerates and basaltic lavas.

"The thick series of massive sandstones, shales, interstratified sandstones, intercalated layers of carbonaceous shales and coal seams exposed in Western Washington in the western foothills of the Cascade Mountains from the Canadian boundary south to Columbia River have been described as the Puget Group. . . This group consists of a sequence of sandstones and shales the various members of which vary in lithology from one locality to another rendering it impossible to correlate the details of any sequence at one locality with the stratigraphic columns at other adjacent places. The exposures are not continuous in their north and south extent but are covered by varying thicknesses of sands, gravels, and clays of glacial origin. The exposures are best represented in the sea-coast cliffs or in the canyons which have been carved downwards through the mantle of glacial deposits into the underlying sandstones and shales. Because of the occurrence of commercial deposits of coal interbedded with these sediments, they have been studied in far more detail than the other Tertiary formations in western Washington. . .

"All the sediments. . . within the Puget Group are of continental origin, and represent accumulation upon a floor slightly above sea level which formerly existed on the site of the western foothils of the Cascade Mountains, and the eastern part of the Puget Sound trough. The basal strata of the Puget Group have been recognized at the surface in very few localities. They may be seen in Skagit County in the vicinity of McMurray and southeast of the City of Arlington. . .

"It is difficult to place the Puget Group in its exact position within the Eocene of the Pacific Coast...It is probable that the lowest strata was deposited during the middle and late Eocene and possibly to a small extent in the very earliest part of the Oligocene epoch. . .

"Oligocene sedimentary formations with a thickness of over [1500 meters] are exposed in the canyons of the Satsop, Wynoochee, Wishkah, and Humptulips rivers, all of which flow in a general southerly direction across the southern flanks of the Olympic Mountains. . . They rest unconformably upon the Metchosin volcanics. ..The eastern border of these Oligocene formations is limited by the uplift of the Black Hills in southern Mason and northern Thurston counties. The basal contact between the Eocene and Oligocene may be followed southerly to Chehalis River. . .

"It is probable that the southern limb of the North River syncline continues beneath Grays Harbor and northwesterly to the vicinity of Pacific Beach, although no exposures of rock are available.

"The Oligocene in the southern limb of the South Bend anticline occupies an area about [thirteen kilometers] in width and [forty"eight kilometers] in length which progressively narrows toward the east. The lithology differs from that farther north and consists of medium-grained brownish-gray massive and well-stratified sandstones together with subordinate amounts of clay shales the thickness of which aggregates more than [1800 meters]. The strata on the western side of Grays River, as far as the shore of Willapa Bay, are well exposed in the canyons of the rivers and creeks as well as in the numerous railway and highway excavations. . .

"The Miocene Astoria Formation lies within an elongate horseshoe like area of a westerly plunging syncline situated on the north side of Chehalis River with the open end pointed toward the west and the nose between the towns of Elms and McCleary. The exposures in the northern flanks of the syncline form an area of approximately [five kilometers] in width and [thirty-eight kilometers] in length. ..the southern limb occurs on the south side of Chehalis River east of the town of Montesano but crosses to the northeast of Aberdeen. ..where it is intersected by the lower portions of Wishkah, Wynoochee, and Hoquiam rivers. The exposures in both limbs are concealed on the western side of Hoquiam River as far as the ocean. . .

"The Astoria sandstones south of the city of Elms which form the southern limb of the Grays Harbor syncline gradually flatten and in the vicinity of Independence Creed are developed into a synclinal flexure, termed the Independence syncline, which plunges to the north. ..These sandstones rest upon the sandy shales of the Blakely formation of the upper Oligocene and in apparent conformity. . .

"The Montesano formation of lower Pliocene age is involved within the axial portion of the fold in the Grays Harbor area north and south of the city of Aberdeen. These formations are separated by unconformities of varying degrees of magnitude. ..The formation lies within two synclinal troughs in the Grays Harbor area of Western Washington. . . The sandstones of the Montesano formation occupy the axial portion of this trough and form an area varying from [eight to thirteen kilometers] in width and nearly [forty-eight kilometers] in length. These beds are exposed in the cliffs and river banks of the Wishkah, Wynoochee, and

Satsop rivers. . .

"The second trough lying both north and south of the eastern end of Grays Harbor contains exposures of the Montesano formation on the lower portions of the Wishkah and Hoquiam Rivers in the vicinities of the cities of Aberdeen and Hoquiam, and in the hills south of the city of Cosmopolis. This broad fold plunges westerly beneath the silts and sands of Grays Harbor and the Pleistocene terrace deposits north of Hoquiam and the lower portion of the valley of Humptulips River. . .

"The thickness of the Montesano strata on the south side of Grays Harbor is approximately [s20 meters] and on the north side there may be a maximum of [670 meters]. The thickness increases progressively west of Aberdeen and Hoquiam due to the general plunge of the synclinal trough and the corresponding existence of higher members of the formation. The basal beds are generally conglomerates and associated pebbly sandstones which may be observed in the road and railway cuts south of Cosmopolis. The formation as a whole consists of sandstones of varying degrees of coarseness and with characteristic cross-bedding. Occasional layers of shale occur. . .

"It is probable that the Montesano formation was deposited during an interval extending from the late Miocene up into the early and middle Pliocene since the strata from which these fossil plants were obtained lie within the lower portion of the Montesano formation..."

Quaternary geology of the Coast Range Provinces is discussed in Section 3., Surficial Geology.

iii. The Olympic Mountain Province. For purposes of this report, the Olympic Mountain Province begins at Grays Harbor and borders the Olympic Peninsula to the Clallam/Jefferson County line. It covers the Strait of Juan de Fuca to the general vicinity of the international border and the submarine edge of Vancouver Island. This line is not sharply defined, since stratigraphy and structure are not defined by international boundaries. Some of the inland geology of the Olympic Mountains is herein discussed in general. Detailed information is limited to those formations that outcrop in the study area. Olympic landforms are discussed in detail in Section 3., Surficial Geology. The tectonics and structure are also examined in the appropriate sections.

The following material is taken from McKee (1972), Danner (1955), Rau (1973, 1975), Snavely and Wagner (1962), Tabor (1975), Brown, Gower and Snavely (1960), and Gower [1960).

The Olympic Peninsula resulted from the collision of Tertiary geosynclinal deposits and volcanics on the Juan de Fuca plate with the leading edge of the North American plate, followed by uplift and glaciation.

A narrow coastal plain borders the peninsula on the northeastern and southwestern sides, from which the mountains rise abruptly in the northeast and much more gradually in the southwest. Rivers derived from glaciers and snowfields radiate out from the mountains in all directions.

The dome-shaped rise of the Olympics trends northwest-southeast across the peninsula. Beginning in the northwest at Cape Flattery as a series of hills rising to elevations of over 300 m, the mountains gradually gain in elevation for a distance of 100 km to the southeast, reaching their highest point at Mt. Olympus. They continue along the same trend for approximately 40 km, dropping to sea level along Hood Canal. The mountains are narrowest where they rise from the sea at Tatoosh Island off Cape Flattery and they widen to the southeast. The highest and widest peaks are in the east central part of the peninsula.

Superimposed on the northwest-southeast trend is a belt of relatively higher peaks and ridges formed by the outcrop of a group of hard, resistant lava flows uplifted around the main mountain area. This belt begins near Cape Flattery in the northwest and continues around the borders of the mountains to just south of Lake Quinault. This is the Crescent (Metchosin) Formation, which consists of ancient lavas from the floor and borders of the Eocene geosyncline that were rafted to, and crumpled by, their collision with the continental plate.

A major problem in the Olympic Mountains has been interpreting the rocks in the core of the range. They occur beneath the Crescent Formation. The rocks consist of dark sandstones and siltstones and altered submarine basalts. They have been markedly folded, fractured, and slightly metamorphosed. This assemblage, once known as the Soleduck Formation, was long assumed to be older than the Crescent and possibly of Mesozoic age. However, mapping of the core rocks by the U.S. Geological Survey (USGS), the Washington State Dept. of Natural Resources, and university graduate students has clarified several of the problems. Except for the ancient rocks at Point of Arches, no rocks older than those of the Eocene basaltic horseshoe and some minor sandstones and shales underlying it have been found in the core (Tabor, 1975). It has been shown that the "Soleduck Formation" -- referred to (along with the Hoh Rocks) as the "argillite-graywacke sequence" (Brown, Gower and Snavely, 1960) -- is probably Tertiary in age rather than Mesozoic. Moreover, the rocks of the core appear to have been emplaced beneath the Crescent Formation along major thrust faults. This sequence appears to have been the sediments deposited in the Eocene geosyncline that collided with the continental crust.

In the Eocene, subsidence followed erosion with encroachment of the sea to a few kilmoeters east of the present site of Seattle. This epoch began with intense volcanic activity. Fissures poured immense quantities of basalt onto the sea floor. The greatest accumulation took place in the eastern part of the present Olympic Peninsula -- at least 1500 m thick. The upper flows seldom show the pillow structure of the lower flows, indicating subaerial extrusion. In other areas, submarine lavas alternated with deposition of sandstone, shale, and conglomerate.

Oligocene rocks in the Coast Ranges are primarily marine shales containing a high proportion of volcanic ash. This ash was probably derived from volcanic vents in the ancestral Cascades. Locally fossil-bearing sandstone and conglomerate are interbedded with the shale. Compared to the Eocene Epoch, the Oligocene was fairly stable, with little offshore volcanic activity. It was, for the most part, a time of relatively slow accumulation of fine-grained tuffaceous sediment, with coarser sands and gravels deposited nearshore.

The sedimentary basin was being filled during the Miocene, while regional uplift was occurring. Early Miocene marine deposition occurred on the continental shelf and in a few shallow embayments inshore, in addition to deep water deposition of coarse gravel (Stewart, 1977].

Within the Puget Sound basin and along the northern portion of the Olympic Peninsula, Miocene sediments are more or less covered by deposits of glacial drift. Late in the Miocene, uplift renewed. Between 12 and 30 million years ago, spanning the Miocene Epoch, the major part of the subduction and continental underthrusting took place. The thick mass of sedimentary rock that had been derived from the continent was jammed against and under the edge of the basalt, which was in turn jammed against the continent (Figure I-4).

When movement on the sea floor began to diminish in the upper Pliocene and lower Pleistocene, the sedimentary rock began to rise. The spreading ocean crust had acted to drive the rocks beneath the continent, but, when movement ceased, the lighter rocks rose. This late episode, accompanied by faulting and folding, raised the Olympic Mountains.

The Late Cenozoic stratigraphic record of the Coast Ranges, including the Olympics, is not extensive. Near the coast, the Pliocene Montesano and Quinault Formations consist of shallow-water marine and non-marine sandstone, siltstones, and conglomerates. These strata suggest that the Pliocene shoreline was not far removed from its present position. In many places Quaternary deposits rest unconformably on Tertiary rocks. However, contact relations are not fully known between what is believed to be the oldest gently dipping Pleistocene deposits and the moderately dipping and faulted Quinault Formation. In places, the two units may well be conformable (Rau, 1973). Quaternary history of the Olympic Mountain Province is discussed in the section on Surficial Geology.

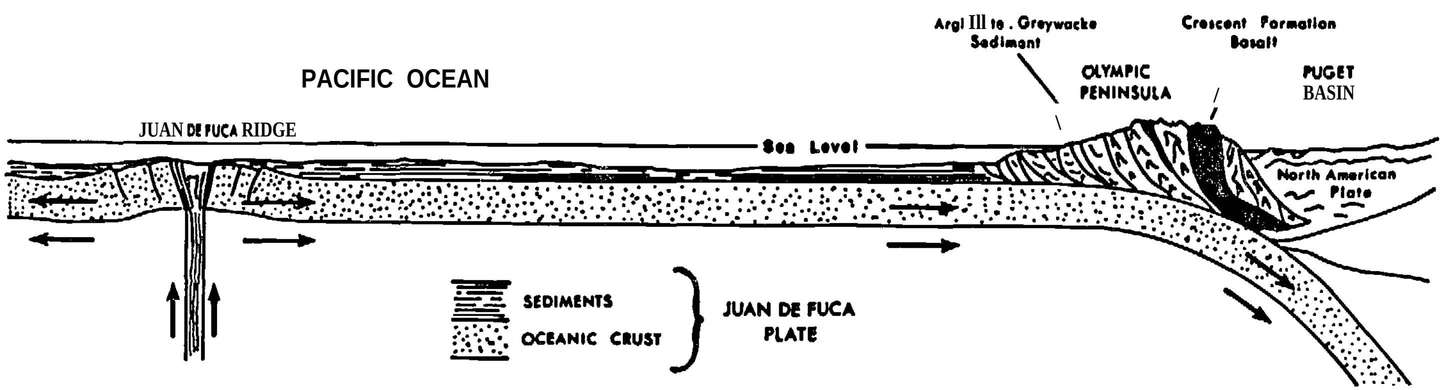
The <u>argillite-graywacke sequence</u> (Brown, Gower and Snavely, 1960) constitutes the oldest rocks known in most areas of the province. Good exposures of the argillite-graywacke sequence occur east of Bigler Mountain and along Rainey Creek. Nearly half of the area underlain by the sequence is covered by glacial outwash and alluvium in the valleys of Soleduck River and Bear Creek.

The sequence is in most places intensely sheared, faulted and folded, and the base is nowhere exposed and no accurate measurement of its thickness is possible. However, it is estimated to be more than 2750 m thick.

The graywacke varies from very fine to very coarse-grained, but fine-grained graywacke is most common. It is usually very thin- to thin-bedded, but very thick beds do exist. Basaltic rocks consisting of pillow lava, flow breccia, and massive flows are interbedded with the argillite and graywacke in a few places. These crop out in an

Figure I-4

A Generalized Diagrammatic Section Showing How the Structurally Complex Rocks of the Olympic Mountains and the Coastal Area May Have Been Formed[§,†]



[§] Adapted from Rau, 1973 and Tabor, 1975.

[†] Sediments (argillite-greywacke sequence) and basaltic volcanics from the ocean floor (Crescent Formation) have been carried eastward on a thick oceanic crust of volcanic rock. Where the heavier rocks of the Juan de Fuca plate met the lighter rocks of the North American plate, most of the former were subducted beneath the continent. However, some of the materials were not subducted but were underthrust by the continental rocks, "skimmed off", foreshortened, piled up, and accreted to the edge of the North American plate.

approximately one kilometer wide belt south of the Soleduck River, an estimated 1800 to 2100 m below the top of the sequence. The basalt is most commonly fine-grained. Most of the volcanic rocks are interbedded with grayish-red argillite and siliceous argillaceous limestone.

Argillite and graywacke, with associated volcanic rocks and minor amounts of quartzose or feldspathic micaceous sandstone, crop out in the area south of Lake Crescent, Barnes Creek, and Hughes Creek. Angular fragments of siltstone are scattered through the rock. A similar but thicker sandstone unit is exposed in the canyon of the North Fork of the Soleduck River. Although part of the argillite-graywacke sequence may be as old as Cretaceus, it is overlain by and locally interfingers with the Crescent Formation, which has been dated as Eocene. Thus, a tentative Eocene date has been assigned.

The oldest rocks known along the southern coast of the Olympic province are largely volcanic breccias with a few interbeds of marine siltstones. These rocks form most of Point Grenville and the nearby offshore stacks. Microfossils contained in the interbeds of marine siltstone indicate that these rocks were formed during the middle Eocene. The volcanics are submarine lava flows, in places incorporated with existing sediments or mud. Highly broken, rhythmically bedded siltstones and sandstones outcrop immediately to the north of the main volcanic body of Point Grenville. Microfossils indicate that these were deposited during the late Eocene. These rocks are distinctly younger than the nearly middle Eocene siltstone interbeds. Local relations between these two rock units are not clearly shown because of limited exposures and structural complications.

Tectonically melanged materials are well exposed in the cliffs of the Hogsback area. Here, the harder rocks consist of conglomerates, sandstones, siltstones, and altered volcanics. The softer, finer grained materials of the matrix are mostly clays and badly broken siltstone.

The two major Tertiary units, the moderately folded and faulted Pliocene Quinault Formation and the older intensely folded and faulted unit are separated by a profound and widespread unconformity. Structural relations clearly indicate that major tectonism took place prior to the deposition of the Quinault in the Pliocene and sometime following the middle Miocene. Much of the bedrock south of the Queets River, east of the ClearWater River, and in the Hoh River valley is masked by thick deposits of drift. The extent of each Tertiary unit has not been fully determined in these areas.

Destruction Island, about six kilometers offshore, is the largest island off the coast of Oregon and Washington, and the first one north of the Farallons. It is the westernmost major bedrock outcrop exposed above sea level in the area and is thought to be representative of offshore bedrock in the area. The foundation of the island and surrounding low-tide reefs is very similiar to the bedrock exposed in the Brown Point-Starfish Point area. Most strata are massive to thick-bedded graywacke sandstone and represent typical turbidite deposition of the rock assemblage referred to by Rau (1973) as the Hoh Rock Assemblage.

Overlying the argillite and graywacke sequence are 1500 to 2750 m of predominantly volcanic rocks assigned to the Crescent Formation. The Crescent Formation forms the high, rugged, northwest trending ridges that include Deadman's Hill, Snider Peak, and North Point. The volcanic rocks of the Crescent form a belt 3 to 5 km wide, extending from near Mount Muller southeastward to Round Mountain. This outcrop belt runs along the south limb of the Clallam syncline. On the north limb of the syncline the Crescent Formation is best exposed along the Strait of Juan de Fuca at Crescent Bay eastward to the west edge of Freshwater Bay. The thickness is difficult to estimate because of local accumulations of lava and the scarcity of structural data. Near the east end of Lake Crescent the formation is more than 3000 m thick.

The Crescent formation consists of pillow basalt, massive diabasic basalt, flow breccia, tuff breccia, and tuff, most of which is of submarine origin. Beds of basaltic conglomerate and sandstone, and well-indurated massive tuffaceous siltstone and argillite are interbedded with the volcanic rocks. These rocks grade into each other and interfinger with other varieties of extrusive and pyroclastic rocks in the Crescent Formation.

The contact between the Crescent and the underlying argillite-graywacke sequence can be seen in the valleys of Rainey Creek, where they are interbedded in a zone about 30 m thick.

On the basis of age and lithologic character, the Crescent Formation correlates in part with the Metchosin Formation of Vancouver Island, the Siletz River Volcanics of Oregon, and the volcanic rocks of the Umpqua Formation in Oregon.

The Crescent is overlain in most places by the Aldwell Formation. The Aldwell consists mainly of laminated to thin-bedded, well-indurated siltstone, with thin beds of fine-grained graywacke present in varying proportions. Massive lenses of unsorted pebbles, cobbles, and basalt boulders occur throughout the siltstone. Their nature suggests that they may have been formed by landslides or mudflows in a marine environment. All the elastics are hard and firmly compacted. Pillow lava, basalt breccia, and waterlaid lapilli tuff occur in places near the base of the formation. These are similar to the volcanics of the Crescent.

East of the Deep Creek Guard Station the formation is as much as 75 m thick. To the west, near Beaver Lake, it appears to be more than 240 m thick. The formation is exposed in the defile between the East Twin River and the Elwha River. The formation has not been recognized north of the axis of the Clallam syncline, but some of the basaltic sandstone at Tongue Point on Crescent Bay may be equivalent in age to part of the Aldwell Formation. The age of the Aldwell Formation has been established as middle to late Eocene. It correlates with the McIntosh Formation of southwestern Washington and the Yamhill Formation of southwestern Oregon.

Basal strata of the Lyre Formation rest unconformably upon and, in places, interfinger with beds in the upper part of the Aldwell Formation. The resistant rocks of the Lyre Formation crop out in a series of westerly-trending ridges north of Boundary Creek, Lake Sutherland, and Indian Creek. This formation does not crop out in the north limb of the Clallam syncline due to overlap by younger sedimentary rocks. A sequence of sandstone and conglomerate that resembles the Lyre outcrops in the Morse Creek area. These rocks may represent an eastward extension of the Lyre, but they may also be a downfaulted block of the lower part of the Twin River formation.

The Lyre Formation consists of well-indurated relatively coarse-grained elastic rocks, which include an upper conglomerate member and a lower sandstone member. These members interfinger and sometimes only one is present. The combined thickness of both members does not exceed 460 m. The Lyre Formation is considered to be late Eocene, correlating with the upper part of the McIntosh Formation and the Northcraft Formation of southwestern Washington.

The Twin River Formation consists of more than 5200 m of marine elastic sedimentary rocks, which may be divided into three sections: a lower section consisting mainly of bedded sandstone and siltstone, a middle section in which massive siltstone is predominant., and an upper section consisting of massive mudstone with minor amounts of thin-bedded sandstone. A conglomerate lentil occurs in the middle member in some local areas.

The lower member is composed of platy to massive fine- to medium-grained sandstone and bedded siltstone that intergrade and interfinger. These rocks are moderately resistant and form a westward-trending range of hills bordering the coastal plain of the Strait of Juan de Fuca. They are exposed on the north side of the Clallam syncline south and west of Crescent Bay.

The middle member crops out on both limbs of the Clallam syncline, but is best exposed along the Strait of Juan de Fuca from the mouth of Field Creek to a point past the mouth of Whiskey Creek. South of the axis of the syncline, it crops out in a belt roughly parallel to the south boundary of the coastal plain of the Strait of Juan de Fuca. Near the Lyre River it is roughly 600 m thick. The most common rock types are massive siltstone and clayey mudstone. In places, these are poorly sorted and contain minor amounts of sand and pebbles of volcanic rocks . A lentil of pebble and cobble conglomerate outcrops about 3 km west of the Elwha River. It may represent reworked material from the Lyre Formation. At its base is a sedimentary breccia of angular volcanic debris that apparently represents material eroded from the Crescent Formation.

The upper member of the Twin River Formation is composed mainly of massive, semi-indurated mudstone and sandy siltstone. In places it contains beds of fine-grained calcareous sandstone. It crops out in a belt westward from Freshwater Bay and at scattered locations along streams in the coastal plain east of the Elwha. East of the Elwha it is largely concealed by glacial drift. The thickest known section is about 900 m thick and is located between the mouth of Murdock Creek and the mouth of the East Twin River, in sea cliffs and wave-cut platforms . Beds of massive calcareous sandstone occur in the upper member.

Many exposures contain broken shell material and fragments of teredo-bored wood. The age of the Twin River Formation is late Eocene to early Miocene.

The Clallam Formation underlies most of the area north of Last Creek between Pillar Point and Slip Point. It is well-exposed in sea cliffs and wave-cut benches along the Strait of Juan de Fuca, but much of the coastal section is so highly deformed that an accurate measurement of its thickness has not been made. It is composed of poorly sorted, medium-grained, lithic sandstone. Carbonaceous flakes and thin stringers of coal are common. Some of the sandstone is pebbly and thin lenses of pebble conglomerate are common. At the base of -the formation, the conglomerate locally contains angular to subrounded pebbles and cobbles of siltstone. A few sandstone beds are laminated with argillaceous or carbonaceous material. The Clallam Formation is correlated with the Astoria Formation of southwest Washington, to which the age of middle Miocene has been assigned.

The lithology of the Quinsult Formation varies widely. Massive to well-bedded siltstone are common, as are massive to well-bedded sandstones. The former are well-exposed along the coast south of Taholah and in cliffs south of Duck Creek. The latter beds can be seen in the cliffs of the Cape Elizabeth area and northward for about 2 km.

Although the formation or its equivalent is believed to be widespread on the Continental Shelf, its known extent onshore is limited to coastal outcrops which occur mostly between the mouth of the Queets River and Point Grenville. Outcrops are also known inland south of Raft River and inland from Taholah. Melange rocks are frequently found between major outcrops of the Quinault, associated for the most part with faults along which major displacement is thought to have taken place. Some of these are interpreted to be piercement structures where the older melange rocks are believed to have moved into the Quinault Formation (Rau and Wagner, 1974).

The Quinault rests with major angular unconformity on Rau's (1973) “Hoh Rock Assemblage”. Fossils indicate a Pliocene age for the formation. However, the lowermost part may be upper Miocene. Data from offshore wells indicate that late Miocene strata are present between the older rocks of middle Miocene age and Pliocene strata.

The Strait of Juan de Fuca is the principal marine re-entrant connecting the inland waters of western Washington and British Columbia with the Pacific Ocean. It is bounded by Vancouver Island on the north and the Olympic Peninsula on the south; by northern Puget Sound on the east and the Pacific Ocean on the west. For the most part, the bottom topography is strikingly linear and is apparently unrelated to the topography and drainage pattern of the adjacent land masses (Mayers and Bennett, 1973). There is a northeast-southwest striking anticline beneath the junction of the Strait and Juan de Fuca canyon, immediately to the northwest of the Olympic Peninsula. Erosion of the anticline has produced this partially filled canyon. The lithographic nature of the contorted, semi-consolidated, and consolidated material lining the walls of the canyon has not been fully determined. The monolithic nature of the deeper material suggests that the regional "bedrock" is texturally homogeneous and unstratified -- perhaps a volcanic lava bed.

Eocene volcanics appear to underlie most of the strait. The volcanic sequence is believed to be thickest near the mouth. The basalts are underlaid and overlain by relatively non-magnetic sedimentary rocks. In the central sector of the strait, the basalts are intruded by a more magnetic, north-dipping rock mass believed to be a submarine extension of the Sooke gabbroic intrusive of southern Vancouver Island (Mayers and Bennett, 1973). West of the mouth of the strait, the basalts have apparently been displaced along the Leech River Fault. The Tertiary and Mesozoic rocks have subsequently been unconformably eroded and covered by a layer of undeformed, interbedded glacial and marine sediment.

Offshore bedrock lithology and structure must be inferred from the inland stratigraphy, since there is little or no definitive information on units as a whole. Core samples taken indicate that the lithology is basically the same as the corresponding land sections, as do seismic surveys. Weldon Rau of the Washington State Dept. of Natural Resources is constructing a map of the inferred bedrock geology of the shelf and slope off the Olympic Peninsula, particularly extending the thrust-faulted structures and major units beneath the sea. floor. The project is to be completed by the end of 1977.

Quaternary geology of the Olympic Mountains Province is discussed in Section 3., Surficial Geology.

iv. <u>Puget Lowland Province</u>. The Puget Lowland is an elongated north-south oriented structural trough that has been modified by Pleistocene glaciation. Channels were carved in the bedrock surface during at least four major advances of a continental ice sheet southward from Canada. The Province is bounded by the Cascade Mountains on the east, the Olympic Mountains and east end of the Strait of Juan de Fuca on the west, the southern extent of glaciation on the south, and -- for the purposes of this study -- the San Juan Islands and extreme south end of the Strait of Georgia on the north. The overall structure of the lowland is a broad, young downwarp between the Cascades and the Coast Range.

The geology of the Puget Lowland Province is primarily Quaternary glacial and post-glacial geology. During the last major advance of the glaciers, the area was inundated by ice to a depth of as much as 1.6 km. The present topography was formed largely by movement of glaciers within the structural trough. Toward the end of the last glaciation, the lowland area was flooded by the sea, and it has risen as the weight of the ice was removed during the last glacial retreat.

Except for a few outcrops that relate closely to the Tertiary bedrock exposures in the adjoining Cascade and Coast Range Provinces, the bedrock of the lowland basin is buried beneath deposits of glacial materials up to 600 m thick. For this reason, pre-Quaternary stratigraphy is largely inferred from the adjacent structures.

"(In) detail, the structure is much more complex, consisting of numerous mid-Cenozoic folds and faults that trend transverse to the regional downwarp. Hills within the lowland consist most commonly of relatively resistant volcanic rock. In Washington, these volcanics are correlated with the Eocene basalts of the Olympics and the Willapa Hills. Along the eastern side of the lowland, they are correlated with (subaerial) andesitic and basaltic flows in the Cascades. Sedimentary formations interbedded with the flows locally contain fossils that permit both dating and interpretation of the depositional environment" (McKee, 1972).

Although the Puget Lowland was a part of the great Eocene eugeosyncline, late Tertiary orogeny has separated it structurally from the coastal and offshore geological province. The convergence of the Juan de Fuca and North American plates and subsequent uplift of the Olympic Mountains has isolated the Puget Lowland from its Eocene counterpart on the continental shelf and slope. The detailed pre-Tertiary stratigraphy of the Puget Lowland is therefore a less relevant consideration for offshore bedrock geology than that of the Coast Range and Olympic Provinces. The following discussion of-pre-Quaternary history is general. The material is taken primarily from Snavely and Wagner (1963], Oceanographic Commission of Washington (1975), McKee (1972), and Rogers (1970).

The Tertiary rocks of western Washington were laid down on a basement consisting of sedimentary, intrusive, and extrusive rocks that have been metamorphosed in varying degrees and range in age from early Paleozoic to late Jurassic. There are also cretaceous deposits consisting of sandstones, shales, and conglomerates. All of these older strata show a complicated tectonic history. In the general area of interest of this study, pre-Tertiary rocks occur only in the San Juan Islands, along the west flank of the Cascade Mountains from North Bend northward, and in the interior of the Olympic Mountains. With these exceptions, no pre-Tertiary rocks are known to be exposed at the surface, or to have been penetrated by drilling within the Puget Lowland or its immediate borders (Rogers, 1970). The significance of the pre-Tertiary rocks to this investigation lies chiefly in that they presumably form the floor upon which the Tertiary eugeosynclinal rocks were deposited. Their structures and lithologic variations have at least influenced later structural developments in the Lowland, but their discovery has yet to be made.

During the early Eocene, the northeast part of the geosyncline was bordered by a broad, low-lying, swampy coastal plain. Large streams meandered across this plain carrying arkosic debris from pre-Tertiary highlands in northern Washington. These continental deposits are represented in parts of the Puget, Chuckanut, and Swauk Formations. Marine equivalents of these sandstone beds are probably present downdip from the outcrop area of the Puget Formation. Farther south, along the eastern margin of the geosyncline, it is likely that nearshore marine sands were deposited. If so, they are buried beneath the Cascades.

During middle Eocene time more than 1S00 m of nonmarine coal-bearing arkosic sands were deposited on a subsiding low alluvial plain bordering the northeastern part of the geosyncline. These sands intertongued locally with marine silt in the central part of the basin. Downwarping of the alluvial plain apparently equalled deposition, and most of the coarser elastics were confined to the continental environment. Within this sequence occur the principal coal fields of Western Washington that extend from the Roslyn field east of the Cascades to the Pierce and King County coal fields along the western side of the range.

At the beginning of the late Eocene, areas of local uplift and active volcanism divided the geosyncline into several separate basins and reduced the area of marine deposition. Intermittent, rapid downwarping of the basins produced interfingering of nearshore marine and nonmarine coal-bearing strata in a coastal belt 48 to 64 km wide. A relatively uniform thickness of the coal beds over broad areas in King County and the Centralia coal districts indicates that coal swamps tended to be widespread on the low-lying coastal plain. Volcanic activity along the eastern margin of the geosyncline contributed large quantities of pyroclastic and epiclastic debris to these deposits. Ash beds up to one-third meter thick are interbedded with the coal in one bed in the Centralia coal district. In both Centralia and King County, 900 to 1070 m of coal-bearing strata were deposited after late Eocene volcanic rock deposition came to an end in these areas.

In early and middle Oligocene, mild regional uplift took place in the southern part of the geosyncline, and regional subsidence occurred in the northern part. The Puget Sound basin Oligocene and Miocene area is thus effectively separated from that of southwestern Washington by uplifted basalts and sedimentary rocks of the Eocene. In places, marine Oligocene beds overlap upper Eocene strata and rest unconformably on lower Eocene volcanics. At the same time, vigorous pyroclastic volcanic action adjacent to the eastern margin of the geosyncline brought about a marked change in the type of sediments that were being deposited in the marine basins. Large quantities of pumice-laden detritus were transported to the nearshore marine environment.

In most parts of the geosyncline, ash was rapidly and periodically deposited. Typical Oligocene rocks consist of massive tuffaceous siltstone and fine-grained sandstone with intercalated beds of pumiceous lapilli tuff and glauconite.

Adjacent to the eastern margin of the geosyncline, thick deposits of' water-laid andesitic and dacitic tuffs with interbedded lava and ash flows eventually buried the late Eocene coastal plain and brought the widespread coal-forming environment to an end. The extensive accumulation of volcanic material along the northern part of the present Cascade Range also cut off the streams that had carried arkosic detritus to the northern part of the basin.

In the early part of the Miocene, deposition continued essentially uninterrupted. Middle Miocene, however, brought extensive folding and faulting along northwest trends in Washington as the Juan de Fuca plate continued to force material from the western portion of the eugeosyncline against the North American plate. Erosion of the land areas elevated by this period of deformation furnished the coarse elastic debris that characterizes much of the sedimentary rock of middle

Miocene. Shallow marine bays encroached eastward along structural downwarps during this tectonic activity. Along the Strait of Juan de Fuca, an embayment may have extended as far east as Puget Sound, but no middle Miocene rocks have been found in the Lowland to confirm this possibility (Snavely and Wagner, 1962).

In late Miocene, large shallow lakes existed in local structural basins along the Puget-Willamette lowland. Sedimentation in these basins equalled downwarping -- 300 m of claustrine clay, fluvial sand, and volcanic mudflow deposits were laid down. Thick beds of partially carbonized wood are common. These strata are in large part composed of pumice-rich pyroclastics derived from the venting of granodiorite plutons along the site of the present Washington Cascades. Hornblende andesite flows were also extruded locally. Near the close of the Miocene, considerable regional uplift of the Coast Ranges and deformation in the Olympic Mountains occurred, which further reduced the area of marine deposition in western Washington.

The downwarping and sedimentation of the depression along the Puget-Willamette lowland continued throughout most of the Pliocene. During Late Pliocene, the Olympics and Coast Ranges probably reached the greater part of their present elevations, completing the isolation of the Puget Lowland from the sea coast. On the west, late Pliocene volcanic action provided the platform on which the andesitic cones were later constructed that now characterize the Cascades.

Detailed geologic maps for Admiralty Inlet, in Puget Sound, are unavailable (Oceanographic Commission of Washington, 197S). The U.S. Geological Survey is currently conducting detailed mapping in the area, but work is not yet complete enough for general publication. The general geologic conditions, however, are indicated by various state of Washington geologic maps; based on reconnaissance in the area. Essentially, Tertiary sedimentary bedrock underlies the west side of the Admiralty Inlet channel and the adjacent islands. It slopes downward to the east beneath the channel and Whidbey Island, where the bedrock surface is believed overlain by several hundred meters of unconsolidated glacial deposits.

The approximate thicknesses of unconsolidated deposits over bedrock are discussed in the section on offshore geology. There are large areas for which little or not information is available on which to base thickness contours. Barnes and Creager (Oceanographic Commission of Washington, 1975) of the University of Washington Department of Oceanography have pointed out that the sill at the entrance to the Inlet is likely underlain directly by bedrock:

"Marine sandstone of early Eocene age is reportedly exposed in the lower bluffs and beach area in approximately the south half of Marrowstone Island. In the area of Nodule and Liplip Points, the beds strike east-west to east-northeast and dip about 10 to 20 degrees south . Farther south on the east shoreline of the Quimper Peninsula near Basalt Point, pillow basalts of the Crescent formation are exposed along the bluffs. Available maps indicated bedrock is not exposed in the shoreline areas farther to the north including Port Townsend nor along the entire west shoreline of Whidbey Island.

Apparently, in those areas unconsolidated glacial deposits similar to that which overlie the bedrock on the west shore of Admiralty Inlet extend below sea level. ..Subbottom profiles obtained in a single traverse lengthwise along Admiralty Inlet performed by the University's Department of Oceanography do not yield conclusive evidence of the bottom conditions, including the possible presence of bedrock.

"Sounding charts prepared by a lead line survey in 1942 and 1943 indicate somewhat more irregular bottom conditions in the Admiralty Head sill area and this contrasts with an apparent more even bottom surface south of the sill. Based on this information, it is tentatively concluded that bedrock is at or within a meter of the bottom in the sill area between Point Wilson and Admiralty Head, along the east shore of Marrowstone Island and southward in the area of Basalt Point. Somewhat greater thicknesses of unconsolidated sediments likely overlie bedrock near the northern end of Marrowstone Island and possibly in Oak Bay near the south end of that Island."

More than eighty percent of the San Juan Island Group's total area is contained in the three largest islands -- Orcas, San Juan, and Lopez. Orcas is nearly cut in-half by East Sound. 'Lopez Island is covered largely by Pleistocene glacial deposits, with the only extensive bedrock outcrops being at the south end. San Juan Island has good exposures of bedrock on its northern and western shores. All the smaller islands also have bedrock exposed in varying amounts. Many rocks and reefs lie barely submerged, in contrast to the Strait of Juan de Fuca and the open waters of Puget Sound.

The geologic history resembles that of the Cascades: pre-Tertiary basement rock, a late Paleozoic and early Mesozoic eugeosynclinal sequence, Cretaceus thrust faults, and Lower Tertiary sandstones and shales. There are no significant intrusions of Cretaceus or Tertiary age.

The oldest rocks in the San Juans are a series of gneisses and granitic rocks, called the Turtleback Complex. They crop out on several of the islands, but are most prominent in the Turtleback Range on the western half of Orcas Island. 'These beds were deposited on top of crystalline rocks. Conglomerate beds at the base of the Paleozoic section locally contain pebbles apparently derived from the Turtleback gneisses. Radiometric dating of zircon crystals from Turtleback granitics shows a Devonian or older age (McKee, 1972). The Turtleback compares well with the Yellow Aster Complex of the North Cascades, which is pre-Middle Devonian and perhaps as old as Precambrian. The units both consist primarily of quartz diorite and diorite, containing only minor amounts of older schists and gneisses. Metamorphosis occurred prior to the deposition of Middle Devonian strata.

The Chilliwack Formation rests unconformably on the Turtleback Complex. It is composed of 2300 m of andesitic breccia and tuff, graywacke sandstone, shale, chert, and limestone -- mostly of marine origin. San Juan, Orcas, and Shaw Islands contain outcrops of the unit. It is dated as Permian through Devonian.

No strata of Late Permian to Late Triassic have been found in western Washington. This gap in the stratigraphic record indicates uplift above sea level during at least the latter part of this interval. Triassic deformation was apparently not severe, since the older Chilliwack strata are not appreciably more deformed than are Mesozoic strata lying above the unconformity. Marine sedimentation resumed late in the Triassic Period and continued intermittently into the Cretaceus.

The principal formations of Middle Mesozoic age in the San Juan Islands are the Hare, Constitution, Deer Point, and Speiden Formations. The Haro Formation underlies Davison Head at the northern top of San Juan Island and contains the only certain Triassic fossils in all of western Washington. It consists of 425 m of conglomerates, sandstones, and siltstones with abundant volcanic rock fragments, along with several very thin beds of limestone and chert. The limestone contains shells of the distinctive Late Triassic clam, *Halobia*, and fragments of a few other organisms. Its stratigraphic relationship to the Constitution Formation is uncertain.

The Constitution Formation covers much of the eastern half of Orcas Island and much of the central part of San Juan Island. It consists of 900 m of fine-grained, non fossil-bearing sandstones and siltstones and rests unconformably on Permian beds. It is overlain on southeastern Orcas Island by the Deer Point Formation, also 900 m thick, which consists of a series of sandstones and shales with many volcanic fragments. Deer Point beds are also well-exposed at the south end of Lopez Island. They are non-fossiliferous. If the two formations are contemporaneous, the Constitution must then be older than Late-Jurassic.

The Speiden Formation on Speiden Island is equivalent to the upper part of the Nooksack group of the Cascades. It consists of approximately 300 m of conglomerate with minor amounts of marine fossil-bearing sandstone, siltstone, and silty limestone. Sedimentary rocks similar to the Speiden are interbedded with volcanic strata on Lummi, Eliza, Samish, and Fidalgo Islands.

A Late Cretaceus age has been assigned to the Nanaimo Formation, which underlies most of the Gulf Islands to the north of the San Juans, as well as Stuart, Johns, Waldron, Pates, and Matia Islands of the San Juan group. Nanaimo strata also crop out along the north shore of Orcas Island.

The Nanaimo sediments are of arkosic composition. They were formed in a shallow marine trough that developed late in the Cretaceus on the deformed, truncated remains of the Cordilleran Geosyncline. The beds on Sucia Island have been bent into open folds trending northwest to southeast. The harder layers of sandstone and conglomerate, which are most resistant, form prominent ridges that project offshore as submerged reefs.

Cretaceus thrust faulting also occurred in the San Juans. The Turtleback, Chilliwack, and Constitution Formations have been sliced by low angle thrusts on Orcas Island.

The Chuckanut Formation, found in the North Cascades, Lummi Island, and possibly on Sucia Island, consists of non-marine arkosic sandstone, siltstone and conglomerate, with abundant leaf fossils. The unit is 4600 m thick in the Cascades. No definite age has been agreed upon for the Chuckanut, but an Early Tertiary age seems likely on the basis of fossils.

Early Tertiary has also been tentatively assigned to the Cypress Island Serpentine, an unusual mass of serpentine and ultrabasic rocks found on Cypress and Fidalgo Islands. Tertiary units younger than the Chuckanut have not been found in the San Juan Islands. It is likely that the region has been eroding throughout much of the Cenozoic Era. Erosion was assisted by the Pleistocene glaciers, which also deposited gravels and other material on the islands.

Quarternary geology of the Puget Sound Lowland Province, including the San Juan Islands, is discussed in Section 3., Surficial Geology.

v. Insular Mountain Province. The portion of the Insular Mountain Province inside the study area is that part of Vancouver Island south of the 49th parallel, the adjacent Gulf Islands, and the surrounding offshore region to the limits of the study area. The following material is taken primarily from McKee (1972) and Muller (1975, 1976, and [1977?1).

Vancouver Island is the main component of the Insular Belt, the westernmost major tectonic subdivision of the Canadian Cordillera. The stratigraphy and structure of southern Vancouver Island is quite complex. It unites a variety of Paleozoic, Mesozoic and Tertiary volcanic, intrusive, sedimentary and metamorphic rocks. The entire assemblage was deformed and faulted more than once, the most severe deformation occurring in early Tertiary time. The result is a geological collection of similar-appearing, mainly basic, crystalline rocks and graywacke-argillite sequences, almost totally lacking in distinct marker-beds or sediments of known age. Muller (1975) regards it as a key area that , with sufficient study, will yield important data on the history of the Pacific Margin.

The age of the oldest rocks in western British Columbia, a shear-folded graywacke-argillite sequence found on the southwest part of Saltspring Island and north of Maple Bay on Vancouver Island, is unknown. They are tentatively dated at 460 million years b.p., which puts them into Ordovician (Cameron, 1977). However, they may be pre-Cambrian.

The graywacke-argillite sequence is intruded by the early Paleozoic granitics known as Tyee Intrusions. They are quartz-feldspar porphyrins, common with many conspicuous glassy quartz eyes. Along Burgoyne Bay on Saltspring Island the porphyry is massive and unsheared and grades into medium-grained light colored quartz monzonite. Similar, generally much-altered, granitic rocks are exposed on the south coast of Saltspring Island east of Fulford Harbor (Muller, [1977?3].

The Sicker Group comprises all other known Paleozoic rocks of

Vancouver Island. Some stratigraphers include the Saltspring Island graywacke-argillite sequence with the Sicker Group. It is divided into a lower volcanic formation, a middle graywacke-argillite formation, and an upper limestone formation. The group is exposed in narrow, fault-bounded uplifts. The largest, the Home Lake-Cowichan Lake uplift, is the farthest to the south, the Buttle Lake uplift occupies the center, and some smaller outcrop areas occur to the northwest in the Nimpkish region.

The volcanic rocks are mainly massive, dark-colored, tuffs, volcanic breccias, and massive to amygdaloidal lavas. Well banded siliceous tuffs form the transition zone to the Sicker sediments. The volcanics have been partly altered to chlorite-sericite schist, probably as a result of deformation in the fault zones. They are locally intruded by the Tyee Intrusions where they overlie the ancient basement rocks. The age of the Sicker volcanics is early Permian or older, possibly pre-Devonian (Muller, 1976).

The Sicker sediments overlie the Sicker volcanics, but are not well-exposed , and time has not permitted the study of the part sections in detail. There is a lower unit, 180 m thick, of thin-bedded cherty tuff and an upper unit of interbedded gray crinoidal limestone and black chert. It grades laterally into chert without limestone. In the Victoria map-area, the bulk of the Sicker sediments consists of a turbiditic, very well bedded, graywacke-argillite sequence. Ribbon chert and banded tuff are also common. A Middle Pennsylvanian age has been tentatively assigned (Muller, [1977?3).

The Sicker limestone, or Buttle Lake Formation, is the youngest part of the Sicker Group. It is exposed in many places along the margins of the uplifts where Paleozoic rocks are overlain by the Karmutsen Formation.

"The Sicker Group formations may be a continuous succession, but the possibility of an unconformity between the broadly folded Buttle Lake limestone and the commonly tightly folded graywacke-argillite sequence cannot yet be excluded. Furthermore, as parts of it are invaded by Devonian or older Tyee Intrusions whereas other parts are Pennsylvanian, the group may represent several tectonic units of which the oldest one would appear to be pre-Devonian. That question remains to be solved by further structural and isotopic investigation.

"Sicker Group rocks are the apparent remnant of a mid-Paleozoic volcanic arc, built on oceanic crust or perhaps on the continental edge" (Muller, [1977?1).

The limestone with its fauna indicates that the time interval closed with stable, fairly shallow water conditions. Locally, conglomerates occur at the top of the Sicker Group at Buttle Lake. No other rocks remain to record the rest of the Permian and Early Triassic, so these were probably times of mild uplift and restricted erosion.

Starting in Middle Triassic time, great outpouring of submarine basalt occurred on what is now Vancouver Island. This lava pile, the Karmutsen Formation, is more than 3 km thick and may have once had a total volume of 410,000 km^3. The formation is composed of a lower member (about 2600 m thick) of pillow lava, a middle member (about 800 m thick) of pillow breccia and aquagene tuff, and an upper member (about 2900 m thick) of massive flows with interbedded pillow lava, breccia, and sedimentary layers. Except in contact zones with granitic intrusions, the volcanics exhibit low-grade metamorphism. The several thousand meter thick Quatsino and Parson Bay formations, that elsewhere on Vancouver Island separate Karmutsen and Bonanza volcanics, are missing in the Victoria map-area. Because the volcanics were formed on a rifting oceanic crust they are probably underlain by the Sicker Group in only some areas -- elsewhere they would have constituted new ocean floor (Muller, [1977?1). Eruptions everywhere stopped nearly synchronously early in the late Triassic.

As soon as the eruptions ceased, the organic and inorganic precipitation of lime began to form the Upper Triassic Quatsino Formation. The Quatsino consists of limestone, mainly massive to thick-bedded calcilutite, varying from 24 to 480 m in thickness and containing ammonites and other fossils. The succeeding Parson Bay Formation is in diachronous contact with Quatsino and in places lies directly on Karmusten volcanics. It is composed of interbedded calcareous black argillite, calcareous graywacke, and sandy to shaly limestone. The formation is between 300 and 600 m thick.

The Sutton Limestone, found near Cowichan Lake, is uncommon and its stratigraphic relationships with Quatsino limestone cannot readily be established. Farther north, Sutton limestone locally forms the top of the Parson Bay Formation (which overlies Quatsino limestone), but it seems to be a lateral equivalent of Quatsino limestone in the Cape Flattery map-area. The Sutton limestone is detrital and has many shell fragments (Muller, 1976).

The Wark Diorite and Colquitz Gneiss are intimately related units confined to the area between the Leech River and the San Juan faults. They occur in alternating northwest-trending belts and have indistinct contacts with one another. Wark Diorite is hornblende diorite and hornblende quartz-diorite, with some minor biotite locally. It varies from fine to coarse grained. It was likely formed by recrystallization of basic volcanic rocks, probably mainly Paleozoic Sicker volcanics and Karmutsen basalts. The Colquitz Gneiss is gneissic quartz diorite and grandiorite with minor hornblende and biotite. The gneiss may well be derived from stratified graywackes, tuffs and cherts that form the bulk of Sicker sediments. The age is probably Paleozoic for the parent rocks and early Mesozoic for the metamorphism which created the Wark and Colquitz (Muller, 1975).

Meanwhile, in the southern part of the area volcanism began again, but this time with explosive eruptions of porphyritic andesite agglomerates and tuffs instead of quiet effusions. Complete volcanic structures, 1800 m thick or more, were built in some areas. In other areas, considerable quantities of marine volcanic sandstones and argillites interfinger. These Bonanza Volcanics underlie large parts of the area south of Cowichan Lake Fault and, although accurate measurements are lacking, their thickness is believed to exceed that of the Karmutsen Formation. Like the Karmutsen, they have been identified only by lithology. They underlie a large area north of the San Juan Fault and smaller areas near Shawnigan Lake and on Saanich Peninsula. The most typical lithologies are massive andesitic to dacitic tuffs and flows, commonly with feldspar and hornblende phenocrysts in a feldspathic matrix. In general they are similar to the Sicker volcanics, but less metamorphosed. They are quite distinct in appearance from the Karmutsen volcanics. Their age is early Jurassic.

The general non-deposit environment of the Paleozoic Era persisted through the first half of the Mesozoic. It then gave way to the cataclysmic events that destroyed the Cordilleral Geosyncline. During the Jurrasic, the West-Coast Complex and Island Intrusions were formed. They are exposed in a large area between the Cowichan Lake and San Juan faults and likely underlie all other formations in the remainder of that block (Muller, 1976). The Island Intrusions (Saanich granodiorite) occur in small batholiths, one on Koksilah Ridge and one occupying the greatest part of Saanieh Peninsula and extending across Saanich Inlet to Mill Bay. Extensive sills of dacite porphyry on both sides are also included in the Island Intrusions, as are intrusions south of Ladysmith and north of Cowichan River.

The West' coast rocks are various types of agmatite, composed of dark amphibolite and diorite and lighter quartz diorite. They were probably derived from basic volcanic rocks and minor sediments by magmatization. The resulting granitic fractions migrated to form the Island Intrusions. Contacts of the two crystalline formations with one another and with the older formations are poorly defined, as are contacts with sediments. Some small islands in Barkley Sound consist of highly folded contact metamorphic bedded sediments of assumed Triassic age (Muller, 1975 and 1976).

The Leech River Formation occupies the belt between the San Juan and Leech River faults. It consists of shearfolded graywacke and argillite. Metamorphic grade increases from slate and phyllite near the San Juan fault to garnet-bearing, quartz-biotite schist near the Leech River fault. Like the Pacific Rim Complex farther north, they are probably a tectonized "assemblage of slope and trench sediments and their metamorphic equivalents, formed in a late Jurassic to Cretaceous trench off the continental margin. They are equivalent in age and facies to the Franciscan Terrance of California although the metamorphic facies is apparently different. It was postulated that the volcanic arc, paired to this trench, is the Coast Plutonic complex and that Upper Jurassic and Cretaceus elastic sediments of the Insular Belt were deposited in the arc-trench gap" (Muller, [1977?]).

The Nanaimo Group sediments underlie most of the Gulf Islands, part of the coastal area between Ladysmith and Crofton, and a large area around Duncan, with extensions into the Cowichan and Chemainus River valleys. The Nanaimo Group accumulated in a trough situated between the coast plutonic belt, which was then an active volcanic arc, and the Insular Belt, during the late Cretaceus. They are mostly fossil-bearing marine sandstones, shales, and conglomerates containing much quartz and feldspar. Coal beds have formed from the coastal swamp 'materials. The-group is well exposed in the Gulf Islands and along the side of Vancouver Island from Saltspring Island to Campbell River (McKee, 1972).

The Tertiary history of British Columbia is imperfectly known, but bears a great deal of resemblance to that of Oregon and Washington. Eocene basic volcanic and intrusive rocks, known as the Metchosin Volcanics, underlie the entire area south of the Leech River fault. The lithology of pillow basalt, aquagene breccia, and basaltic lavas is strikingly similar to that of the Karmutsen volcanics. Unlike the Karmutsen, this formation contains some bedded cherts and tuffs. Definite dating of the rocks as lower Eocene, based on fossils, makes the rocks equivalent to the Crescent Volcanics of the Olympic Peninsula.

Along part of the coast, the Metchosin, is overlain by a narrow strip of sandstone and conglomerate called the Sooke Formation. It is of Miocene to Pliocene age. Muller ({1977?]) divides the Sooke into the "Sooke Intrusions" and the "Sooke Bay Formation'". The latter occurs in depressions on the erosion surface of the Metchosin Volcanics and Sooke Intrusions. It is probably less than 210 m thick and does not extend north of the Leech River fault. It contains fossils indicating Miocene age, but the microflora may indicate early Pliocene age as well. The formation is fluvial to deltaic in origin.

The Sooke Intrusions are partly coarse-grained gabbro with minor anorthosite. They apparently underlie the Eocene volcanics. The Metchosin Volcanics and Sooke Intrusions could be interpreted as the upper and lower parts of the new oceanic crust formed in Early Tertiary time (Muller, [1977?]). Small plutons intrude various pre-Tertiary rocks of the Insular Belt in many places and form sills in flat-lying Upper Cretaceus sediments.

The Carmanah and Escalante Formations are Tertiary elastic sediments that overlie bevelled Island Mountain rocks in a narrow strip of land along the west coast. They are also exposed on most of the continental shelf west of Vancouver Island, The Escalante Formation is Eocene basal conglomerate. The overlying Carmanah Formation is mainly siltstone and sandstone. The two together are nearly 1525 m thick. The beds overlie the Leech River Formation with clear angular unconformity. They were deposited on the upper part of the coastal shelf area. Many beds, however, are sedimentary melanges that were redeposited by massive slumping. The two formations may have extended much farther eastward, but were removed by Late Tertiary and Pleistocene erosion (Muller, [1977?]).

Quaternary geology of the Insular Mountains Province is discussed in Section 3., Surficial Geology.

b. Structure and Tectonics.

i. Introduction. The basic theory of plate tectonics and the general tectonic history of this area have been previously discussed. This section outlines the basic structure of the area as interpreted from geophysical investigations and then discusses tectonic processes as they have been and are active in the region.

ii. Basic Structure of the Area as Interpreted from Geophysical Investigations -- Offshore. Various investigations have been made of the oceanic structures between the Mendocino Escarpment of northern California and the Dixon Entrance off British Columbia. These have included bathymetric surveys, sediments and rock analyses, magnetic and gravity surveys, heat-flow measurements, seismic refraction surveys, seismic reflection profiles, locations of recent earthquake epicenters and determinations of earthquake source motions.

Gravity maps have been published for the entire region. The maps have essentially zero-average free-air anomalies over the entire region and its major structural features, indicating that both the region as a whole and its major provinces are in isostatic equilibrium (Dehlinger, *et al.*, 1971]. Dehlinger (1969) discussed the relation of gravity with topography and concluded that many of the local anomalies on the gravity maps are due to the effects of bottom topography. There is no significant correlation between gravity and bottom topography for large-scale structures, a poor correlation for intermediate-sized structures, and a fair correlation for small structures. Since gravity anomalies result from geologic variations, a good correlation between gravity and geology is assumed.

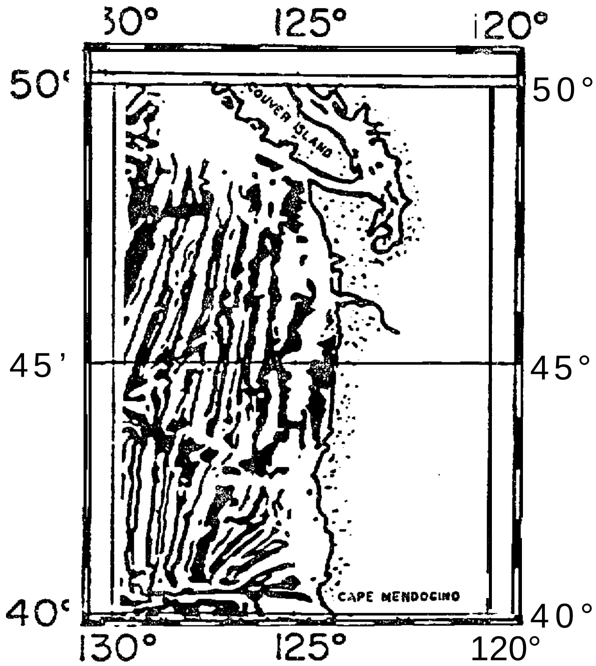
Dehlinger, et al. (1967) have proposed that a thick, low-density, mantle section lies beneath a thin crust in the Gorda Ridge. Their ideas are based on their own gravity data and seismic-refraction studies done in 1963. In those studies seismic refraction lines were shot along both sides of the Mendocino Escarpment. The mantle is at normal depth on the south side and has a high seismic velocity. Gravity data for the Gorda Ridge include a -30 to -40mgal anomaly for the central trough across the ridge, +30 to +40 regal anomalies for the flanking crests, with the average anomaly across the ridge being approximately +20 regal (Dehlinger, *et al.*, 1971).

There is less information for the central and northern parts of Gorda Ridge. Escanaba Trough is apparently offset slightly to the east, then changes from a north-south trend toward the northeast. It was suggested by McManus (1967) that a northwest-trending fracture zone might cross the ridge at this point. Vine and Wilson (1965) postulated that, on the basis of north-trending magnetic lineations, Gorda and Juan de Fuca Ridges are axes along which sea floor spreading occurs, along with reversal in the earth's paleomagnetic field.

Large offsets, such as Wilson and others have attributed to transform faulting, occur in the magnetic anomalies (Figure I-5). Tobin and Sykes (1968) have confirmed that such fault motions are the likely mechanisms, especially along the Blanco Fracture Zone. The fanning out of magnetic anomalies between Gorda Ridge and the continental slope may indicate a differential spreading rate and possible crustal distortions. In addition, there are many oblique lineations in offsets of the magnetic patterns. Although these may represent faults, there are few current earthquakes that can be associated with them. Dehlinger, *et*

Figure I-3

Total Magnetic-field Anomaly Map off Washington and Oregon[§]



[§] After Raff and Mason, 1961; Couch, 1969; Emilia, *et al.*, 1968: and Dehlinger, *et al.*, 1971.

al. (1971) feel that these lineations are boundaries between independently moving blocks.

Many aspects of oceanic magnetic patterns have yet to be explained. The large, positive anomaly over the median valley of Gorda Ridge is one of them. The true structural implications of magnetic anomalies cannot be understood fully until the nature of the anomalies themselves are better understood.

High heat-flow values are related to the Mendocino Escarpment east of Gorda Ridge, to Gorda Ridge itself, and to the Gorda Basin. North of Mendocino Escarpment to latitude 55°N, the average of 41 heat-flow stations is 2.44 μ cal/cm^{2}sec (Dehlinger, *et al.*, 1971), approximately 90% higher than the average for basins and 60% higher than the average for the ridges (Figure I-6).

The Cape Blanco Fracture Zone is characterized by a generally negative free-air anomaly that is most negative near Cascadia Gap, where water depths are greater than the surrounding areas (Figure I-7).

The continental slope along most of the Oregon coast is straight and steep. A large anomaly contrast, typical of a mantle dipping beneath the continent, occurs along the slope. Positive anomalies are small, except where basaltic headlands such as Cape Blanco protrude seaward. On the shelf, there are elongated negative anomalies, with values to -60 regal. They are produced by sediment-filled basins like those off the coast of Washington. Numerous local anomalies are caused by tectonic activity, particularly flows of Tertiary basalt (Dehlinger, *et al.*, 1971).

Heceta and Coquille Banks are characterized by positive anomalies, suggesting a slight mass excess beneath them. The area around Nehalem Bank, however, shows a negative anomaly, implying a fairly thick, low-density sedimentary section (Dehlinger, Couch and Gemperle, 1968).

Most reflection profiles of the continental margin off Oregon show one or more unconformities. The greatest amounts of discordance are in the vicinity of the submarine banks and near the present coastline. There are at least two prominent angular unconformities on the Oregon continental shelf: Pliocene-Pleistocene and middle to late Miocene (Kulm and Fowler, 1974). The youngest is present beneath most of the shelf.

Coquille Bank is underlain by a north-south trending, asymmetrical, doubly-plunging anticline that is cut on the western limb by a normal fault along the seaward edge of the bank (Kulm and Fowler, 1974).

A series of interconnected shallow synclines is found between the shore and the outer banks of central and northern Oregon and southern Washington. The largest is off Cascade Head. Along the seaward limb, the sediments have ponded behind and overlapped a series of subsurface folds. The most recent development of these synclines involves Pleistocene sediments that unconformably overlie older units. Large negative free-air anomalies are associated with these synclines. From the gravity data and reflection profiles it appears that much thicker and

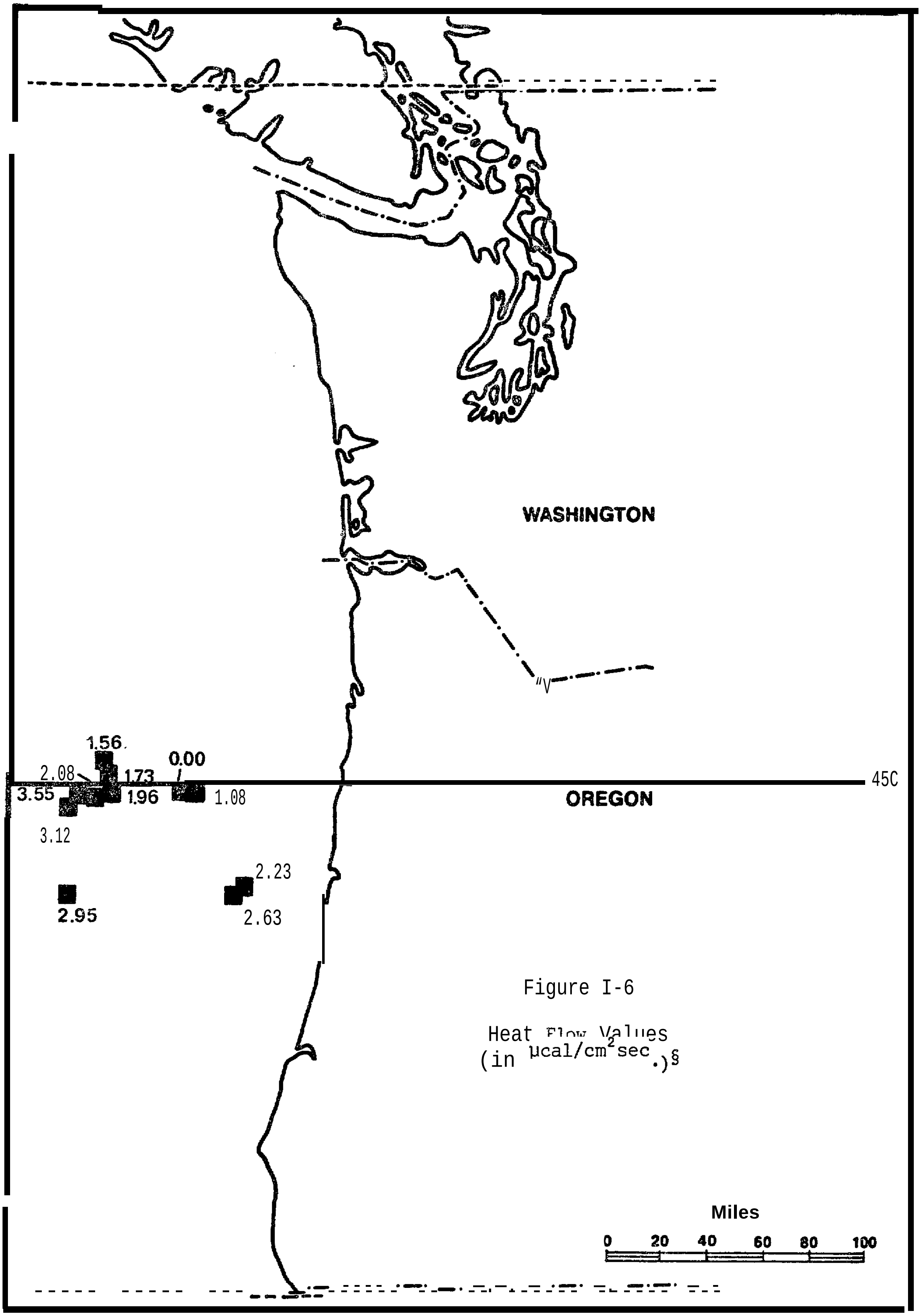


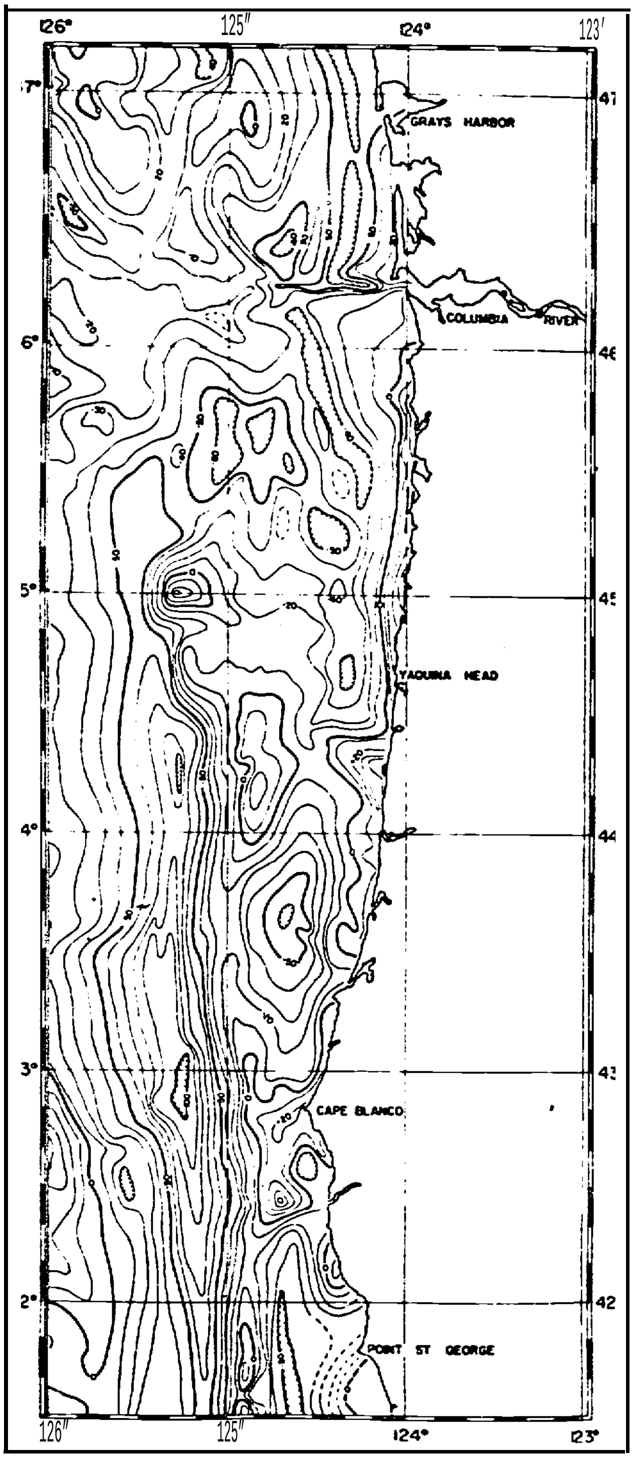
Figure I-6

Heat Flow Values (in µcal/cm²sec.)§

§Dehlinger, *et al.*, 1971.

Figure I-7

Free-air Gravity Map and Magnetic Source Depths for Oregon Shelf and Slope[§]



§Kulm and Fowler, 1974.

older sedimentary basins lie beneath the shallow Pleistocene basins.

West of Tillamook Head, an acoustic basement, marked by large positive magnetic anomalies, dips seaward beneath the inner part of the continental shelf. Snavely and Wagner (1963) believe it to be the seaward extension of the Miocene volcanic rocks found offshore.

From central Vancouver Island to the Columbia River the continental slope is more gentle. Free-air anomalies are so gentle, i.e., broad and of low relief, that the slope is difficult to locate on a gravity map. Negative anomalies on the shelf are elongated, with values to -70 mgal -- larger than those on both sides of the slope. These are thought to mark sediment-filled basins above a gently dipping mantle surface (Dehlinger, *et al.*, 1971).

The Juan de Fuca Ridge is outside the study area proper, but it appears to be a spreading ridge that exercises tectonic control over much of the northwest coast. The topography of the ridge is so low that Dehlinger, *et al.* (1971) describes it as being more a magnetic anomaly than a topographic ridge. Two elements dominate the topography of the Juan de Fuca Ridge region: low, narrow, elongate hills and furrows that are best developed parallel to the crest of the ridge, and large seamounts rising to very near the water surface.

Magnetic profiles of the area have convinced many researchers that the Juan de Fuca is a mid-ocean type ridge whose eastern flank lies under the continent. Dehlinger, *et al.* (1971) believes that high heat-flow in Cascadia Basin is due to the blanketing effect of the sedimentary strata in the basin, which are being deposited on the eastern flank of the ridge as oceanic crust created by volcanic Processes at the ridge crest. This sediment prevents the rapid transfer of heat from newly created crust to the overlying ocean by blocking normal hydrothermal circulation by sealing fissures in the basement rocks along which hydraulic circulation would occur.

Refraction measurements across Juan de Fuca Ridge, the adjacent abyssal plains, and the continental margin (Shor, *et* aZ., 1968) show that the ridge exhibits the thin crust overlying a low-velocity mantle that is characteristic of ocean ridges. The crust under the Cascadia Basin and Continental margin is also thinner than normal (Dehlinger, *et al.*, 1971).

Although the majority of investigators interpret the magnetic anomalies of Juan de Fuca Ridge as indicative of an active, spreading ocean ridge, others have questioned such an hypothesis on the grounds that' the ridge has few earthquake epicenters (Tobin and Sykes, 1968), has undisturbed turbidite layers (Hamilton and Menard, 1968), and shows two undisturbed magnetic lineations that extend from the Cascadia Basin across the continental rise and slope to the shelf edge (Emilia, Berg and Bales, 1968). These investigators argue that the ridge has been quiescent since Middle Tertiary time. Alternate explanations have been given for the magnetic anomalies, including remnant magnetization and localized heating of the basaltic crust.

The northern limit of Juan de Fuca Ridge is not well defined topographically or magnetically. The crest is disrupted at about 47° 30'N, where it merges with a trend of sea mounts.

Additional information on the tectonic significance of the Juan de Fuca Ridge and adjacent fracture zones is presented in part iii. of this discussion, concerned with tectonics and seismicity.

The shelf presents glaciated topography north of the trough that crosses it at the Strait of Juan de Fuca. From here northward, the shelf could have been modified by any number of agents including glaciation, isostatic rebound, eustatic sea-level fluctuations, and diastrophism.

During 1975, a marine gravity and magnetic survey was carried out from CSS 'Parizeau' by the Earth Physics Branch and the Geological Survey of Canada, in conjunction with the Canadian Hydrographic Service. It was done as part of the Natural Resource charting program (Tiffin and Currie, 1976), in cooperation with the U.S. Geological Survey, It covered the area from the coast out to 122°W and between 48° and 49°N Lat.

The resulting magnetic and gravity maps are available from the Geological Survey of Canada and from the Earth Physics Branch, Gravity Division, as a part of the Natural Resource Map Series.

The contrast between the oceanic and continental areas is the dominant feature of both the Bouguer gravity and magnetic maps.

"The zone intermediate between them (approximately the continental slope) is shown on the Bouguer anomaly map. ..by the steep gradient from +10 to +100 regal, interpretable in general terms as reflecting the rise in the Mohon from continent to ocean. On the Free-Air anomaly map... at least south of 49030', the same line of division is paralleled by a gravity ridge, ranging from -30 to +10 regal, again explicable as part of the edge effect produced at the continent/ocean boundary.

"On the magnetic map... the two areas present a striking contrast with strong, north to northeast trending linear anomalies over the oceanic area and lower relief or northwest trending anomalies over the continental shelf. The linear anomalies in the oceanic area are a continuation of the series of ocean crust magnetic anomalies created at the Juan de Fuca Ridge and first mapped by Raff and Mason (1961). The greater detail of the present survey clearly demonstrates their continuity beneath the continental slope. . .

"On the continental shelf, the most outstanding features are the extended, northwesterly trending anomalies parallel to the coast of Vancouver Island from Cape Flattery to Estevan Point. The geographic coincidence of the negative Bouguer and Free-Air gravity anomalies with the positive magnetic anomaly, the Prometheus anomaly (Shouldice, 1971), is not perfect but significantly close. Preliminary interpretations (Riddihough, 1976 and Tiffin and Curry, 1976) suggest that the gravity anomalies arise from an elongate basin of up to 5 km of sediments (the Tofino Basin) and the Prometheus magnetic high from volcanic rocks within the basin. A Shell Canada test well, drilled on the anomaly, reached volcanics at [178S ml and drilled through [550 ml of volcanics before being abandoned. The anomaly lies along the same trend as the volcanics of the Crescent Formation on the nearby Olympic Peninsula and has a similar magnetic character. Those volcanics are Eocene in age, correlative with the Metchosin volcanics on Vancouver Island (MacLeod, *et al.*, [1977?]) and are interpreted to be of oceanic ridge and seamount origin. If the volcanics associated with the Prometheus magnetic anomaly are Eocene, the history of the continental shelf off southern Vancouver is probably similar to that of the Olympic Peninsula" (Tiffin and Riddihough, 1976).

It is not easy to interpret or understand the structural design of the Tofino Basin off Vancouver Island, but Shell Canada seismic studies show the complexity of the area. Some structures involve the volcanic basement rock, others do not. Most are faulted, some are not. Some are broad and simple, others highly complex. There is a wide variation in the age of the Tertiary rocks involved and in the age of structural growth and faulting. Two basic mechanisms are considered -- simple compressional folding, with detachment from the basement, probably accompanied by underthrusting; and flowage of overpressured shales into the cores of the structures over varying periods of time (Shouldice, 1971). Paleontological data from some wells in the basin show typical melange structure. The Tofino Basin shows significant differences in depositional history and environment, pressure regimes, and structural style from the Queen Charlotte Basin to the north.

According to Tiffin and Riddihough ([1977?]), both gravity and magnetic anomalies decrease and fade away to near 49°15'N. The "edge effect" ridge of the free air anomaly map also terminates near 49°30'N, and preliminary gravity interpretation of a profile across the continental slope and shelf north of this suggests that the complete shelf and slope area may be constructed of low density sediments. A strong magnetic "high" extends southeastward from the Brooks Peninsula, parallel to the coast over the area of the Kyuquot Uplift (Tiffin, Cameron and Murray, 1972), and seems to be associated with a gravity "high" over the same area. The anomalies may be geologically related to basic rocks in the core of the uplift, similar to those exposed on Brooks Peninsula (Muller, 1975).

iii. <u>Basic Structure of the Area as Interpreted from Geophysical Investigations -- Onshore (including inland waters)</u>. The study area in the northern Klamath Mountains is characterized by northeasterly trending compressive structures, including thrust faults, by block faulting, and by widespread distribution of the pervasively sheared Otter Point Formation. These structures result from tectonic events of the late Mesozoic and early Tertiary time rather than from any current seismicity. The present uplift does not seem to be concentrated along major faults, but is more likely related to deepseated isostatic processes (Beaulieu and Hughes, 1975).

The Western Coast Range is marked by gentle north-south folds and scattered faults that probably have been quiescent since the Eocene Epoch

An area of crustal weakness centered at Coos Bay, the Coos Bay Synclinorium, contains numerous small synclines and anticlines into which many Tertiary sedimentary formations have been deposited (see former discussion on Stratigraphy). Structures are more intense than in most other Coast Range areas, with dips approaching the vertical in some places. Major downwarps include the South Slough Syncline and the syncline beneath Isthmus Slough, which are separated by the Westport Arch (Beaulieu and Hughes, 1975).

The coastal area of Lane County, Oregon, lies on the west flank of the Coast Range geosyncline, which is a complex north-trending structure with strong northeast trending anticlines and synclines developed in the Tyee Formation. Structural relationships in the Yachats Basalt are not clear. The predominant strike of the unit appears to be northwest. Many of the major streams appear to be controlled by faults whose presence is verified by radar imagery. The northwest-trending series of dikes in the Tyee Formation suggests emplacement along weakened fault zones. Structural deformation is reflected in the uplifted alluvial terraces on the north side of the Suislaw River, which may represent elevation of the land or a high standing sea during the Pleistocene. No structural deformation is evident in the younger units (Schlicker and Deacon, 1974).

Lincoln County is also located on the west flank of the Coast Range geosyncline. The Siletz River Volcanics form the core of the northeast-trending anticlinal highs in the northeastern part of the county, with younger formations flanking the high to the west and northwest, south and east. Post-Tyee rocks crop out in the western part of the county. There are northwest and northeast-trending normal faults throughout the county, some with large vertical displacements and others with large horizontal displacement. All the bedrock units are faulted, but none since the late Pliocene. Holocene uplift is indicated by elevated marine terraces and entrenched river channels (Schlicker, *et* aZ., 1973).

The coastal area of Tillamook County ia also a part of the Coast Range geanticline. The older rocks are situated along the crest of the range, while the younger ones are along the coast on the west flanks of the upwarp and at the northern end of the geanticline. The beds trend northeasterly along the coast and east-west in the north. Major faulting is suggested along the mountain front from the Wilson River to Garibaldi. Apparent facies changes in the Eocene units, displaced volcanic rock, and onlapping of the Astoria Formation over the older units, all add to the complexity of the area. Faults are also indicated in the Wilson River area, the Nestucca Bay area, the Cape Meares area, and the Cape Lookout area, among others.

The major structural development occurred in the late Miocene and none of the faults shows more recent development. The presence of Pliocene fluvial sediments at 76 m above sea level is evidence of post-Pliocene uplift, which appears to be continuing (Beaulieu, Hughes and Mathiot, 1974).

As of 1966, over 8000 gravity measurements had been taken in

Oregon by oil companies, government agencies, and universities. Woolard and Rose prepared a map in 1963 (Figure 1-8) that shows isolated highs along the coast, indicating basalt flows; a steep gradient about 80 km east of the coast, indicating major structural features such as faulting; and a generally decreasing field to the southeast, interpreted by Thiruvathukal and Berg (1966) as variations in regional geology, such as increasing thickness of the crust. Bromery and Snavely (1964) agree with these conclusions. Their map of the northwest Oregon coast is the most available for the state and generally coincides with Woolard and Rose's. Bromery and Snavely (1964) also found good agreement between magnetic anomalies and the gravity and bedrock studies.

The major fold in the northern Olympic Peninsula is the Clallam Syncline, a symmetric structure of post-lower Miocene age. It trends roughly N80W and may be truncated at its western end. The dips along the south limb of the syncline are steeper than those along the north. The Clallam syncline may extend northwest across the Strait of Juan de Fuca as far as 48°20'N and 12°10'W (Mayers and Bennett, 1973). This structure is a symmetric syncline which folds Tertiary strata. Though apparently offset between 124°10′ and 123 45'W, the alignment of the axis of this syncline is approximately parallel to the axes of the folding observed on the continental shelf immediately to the west and northwest of the Strait (Tiffin, Cameron and Murray, 1972). Like the deformation reported on the continental slope off Washington by Silver [1972), it approximately parallels the adjacent coastline.

The largest fracture zone on the northern Olympic Peninsula is the Calawah River fault zone, a wide alignment of sheared and brecciated rocks striking approximately parallel to the strait. It is believed to be a left-lateral strike slip fault of late Eocene origin (Gower, 1960).

According to Rau (1973], the extremely distorted condition of some of the Hoh melange rocks (see Section 2a. on Stratigraphy) may be the result of having been squeezed into and/or through overlying strata of younger formations. The local occurrence of these piercement structures is supported by continuous seismic profiles over the continental shelf, which show well-defined structures that can be interpreted as piercement structures (Grim and Bennett, 1969 and Tiffin, Cameron and Murray, 1972].

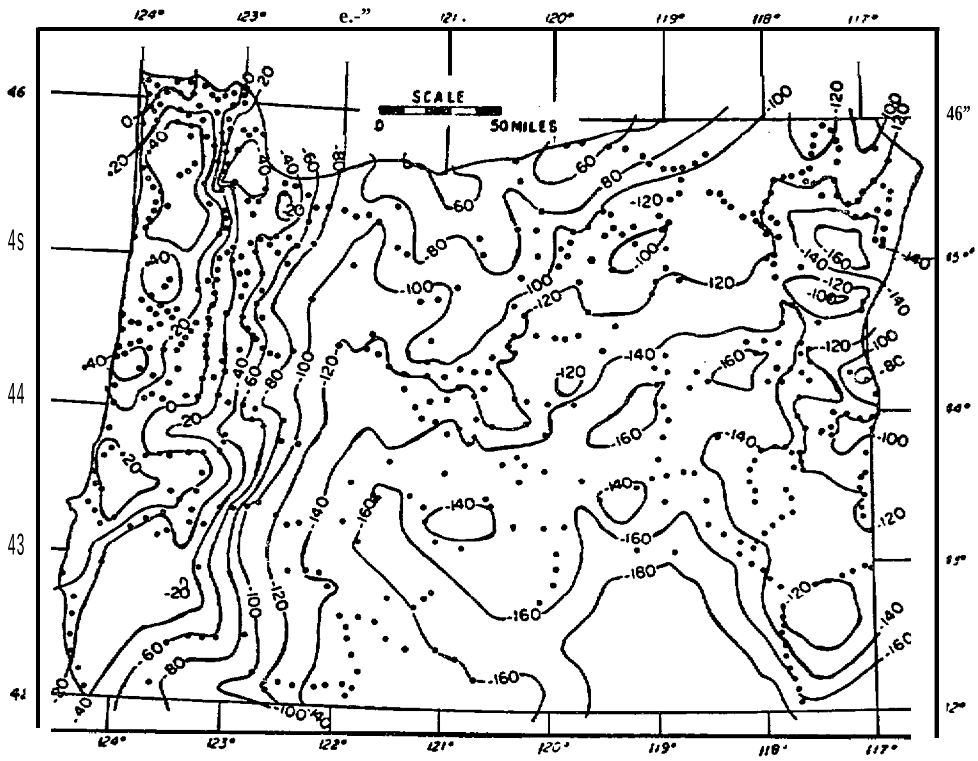
It is still not known why the Crescent Formation and the arcuate belts of rocks in the Olympic core are arranged in a horseshoe pattern. Taber (1975) believes that the "horseshoe" appears to bend into an inside corner formed by the older geologic terraces of Vancouver Island and the Cascade Range, but there is little geologic evidence to support such an assumption.

The following material is taken from Stacey, *et al.* (1969) and Stacey and Steele (1970]:

The Eocene volcanics of the Metchosin formation on southern Vancouver Island appear to be part of the Tertiary geosyncline which extended from the Strait along the Pacific coast of Washington and Oregon.

Figure I-8

Bouguer Anomaly Gravity Map of Oregon[§]



§Thiruvathukal and Berg, 1966.

The area of strongest magnetic anomalies, which lies northeast of a line from Sombrio Point on Vancouver Island to Low Point on the Washington side of the Strait, probably corresponds to the outcrop of the Metchosin Sooke intrusive. The northern limit of the geosyncline can probably be related to the east-west San Juan and Leech River faults on Vancouver Island, but between the faults the graywackes and siltstones of the Leech River formation have presented a problem to geologists and estimates of the age of this formation range from Pennsylvanian (Muller, 1967) to late Jurassic (Sutherland Brown, 1966) .

The extreme linearity of the Vancouver Island side of Juan de Fuca has prompted geologists to draw in a fault along the Strait and the steep gravity gradient between Vancouver Island and the Olympic Mountains has tended to substantiate this supposition (Walcott, 1967 and Couch, 1969). However, the structure may have developed prior to or contemporaneous with the volcanic activity at the beginning of the Tertiary period and thus may be obscured by later lavas and sediments.

Magnetic measurements show that the Leech River fault continues across the Strait at least as far as a point 7 km north of Cape Flattery. West of the Leech River fault there are few magnetic measurements but it appears that the San Juan fault could continue westward in the same way as the Leech River fault. The area of comparatively featureless magnetic field thus enclosed would correspond to the Leech River formation slates and graywackes.

The Bouguer anomaly field is dominated by the gradient between the Sooke high over southern Vancouver Island and the Olympic low in northwest Washington. The average gradient between the Sooke high where the Bouguer anomaly values are between 60 and 65 regal, and the Olympic Mountains where the Bouguer anomaly is -60 to -70 regal, is approximately 2 regal/km. Across Juan de Fuca Strait this gradient attains 4 regal/km from the comparatively heavy basaltic and gabbroic rocks of the Metchosin formation and the Sooke intrusive (average density between 2.8 and 2.9 g/cm^3) to the later and less dense sediments (average density 2.4 to 2.5 g/cm^3) [Walcott, 1967) farther south. This effect can also be seen in the deflection of the isogals west of Sooke.

At the western end of the Strait, between Cape Flattery and Port San Juan, the Bouguer anomaly values are lower and this has been related to the outcrop of the graywackes and siltstones of the Leech River formation between Leech River and San Juan faults.

In the Insular Belt, folding is less important than faulting both in governing the present distribution of rocks and in fundamental tectonics. Folds are gentle in general. Compressed and overturned folds appear limited to special adjustments between fault blocks, between massive panels of volcanic rocks, or are adjacent to intrusive plutons [Sutherland Brown, 1976).

The major structures of southern Vancouver Island consist of two large east-west faults, the Leech River and San Juan faults. The former is a high-angle, northward dipping, reverse fault of Oligocene age. It separates the Leech River Formation for the Metchosin volcanics on the south and extends diagonally across southern Vancouver Island. It is also thought to have some right-lateral displacement (Mayers and Bennett, 1973).

9

North of, and parallel to, the Leech River fault is the San Juan fault, a northward dipping normal fault estimated to be of Oligocene age (Sutherland Brown, 1966). North of the San Juan fault, the geology is typical of northern Vancouver Island, but the origin and age of the graywackes and siltstones of the Leech River Formation between the faults have proved difficult to determine (Sutherland Brown, 1966 and Muller, 1967).

On the southeast side of Vancouver Island are a number of Tertiary gabbroic intrusive. Brown and Hanna (1971) have shown from modelling studies of the regional total magnetic field that it is likely at least one similar intrusive body underlies the strait immediately to the south . Milne (1963) and Rasmussen (1967) have reported that the area of this proposed intrusive is characterized by anomalous seismicity.

In general, the structure of the Nanaimo basin is relatively simple and is dominated by open folding. There is, however, a progressive increase in the tightness and complexity of the structures southward. The Trincomali anticline is the largest and most persistent structure within the area. It extends from Thetis Island southeastward for 40 kilometers to the north end of Saturna Island and then passes along the strike into a faulted fold structure which continues another seven kilometers across Saturna Island to Narvaez Bay. Only on Thetis, Kuper, part of the north share of Saltspring and Saturna Islands, is the crest of the fold, or its fault equivalent, exposed on land. For the remaining 70% of its length, the axis lies below the waters of Trincomali and Navy channels (Henderson and Vigras, 1962).

By combining the magnetic and gravity results, delineation of the gross features of the geology of the Strait of Georgia has been attempted and it appears that the transition from typical Vancouver Island geology to that of the Coast Mountains is complex. Tiffin, Cameron and Murray (1972) have concluded from continuous seismic profiling data that sediments of Tertiary age underlie the glacial debris off the mainland coast. They suggest they are equivalent to the Tertiary sediments seen in the vicinity of Vancouver to the southeast of the profile.

The featureless gravity field and the lack of magnetic data over the southern end of the profile make it very difficult to determine the nature of the rocks below the Nanaimo group sediments. On Vancouver Island beyond the southern end of the profile, the sediments overlie rocks of the Vancouver and Sicker groups and it has been tentatively assumed that these units extend northward below the Nanaimo group as far as the center of the Strait of Georgia. At this point, the magnetic values begin to increase rapidly to the north, indicating that the magnetic basement is approaching the surface in this direction. This basement is assumed to be the Coast Mountains complex because the increase in the magnetic field values occurs throughout the area toward the mainland. The line of this gradient follows the topographic feature marking the northern margin of the Malaspina - Ballenas basin that, as has already been suggested, may be a fault or simply the transition from Vancouver Island rocks to those of the Coast Mountains complex. The decrease in the magnetic values close to the mainland may be related to the gravity minimum in the same area, or it may reflect a change within the magnetic basement rocks (Stacey and Steele, 1970).

The Puget Sound lowland lies in a north-trending structural and topographic trough. Geological structure is poorly known due to the thick accumulation of glacial deposits that cover the underlying bedrock structure. Subsurface data is further limited by the scarcity of deep exploratory wells and by nearly all water-wells being in shallow Pleistocene or Holocene sediments. Older interpretations imply that the Puget Lowland is basically a simple downwarp, complicated mainly by the bedrock topography and older structure of the downwarped floor, and additionally modified by glaciation. However, Rogers (1970) and others suggest that the Lowland may be the site of late Tertiary sedimentary accumulation and continuing tectonism. A regional structural interpretation was made by Rogers (1970), using general geomorphic analysis of topography, surface and subsurface geology, regional gravity data, geomagnetic data, and broad aspects of area seismicity. He describes a structural geometry that consists of structurally high mountain units descending sharply to a step-like foothills belt. He concluded that the entire floor of the Puget Lowland may be composed of a mosaic of fault-bounded blocks (Figure I-9).

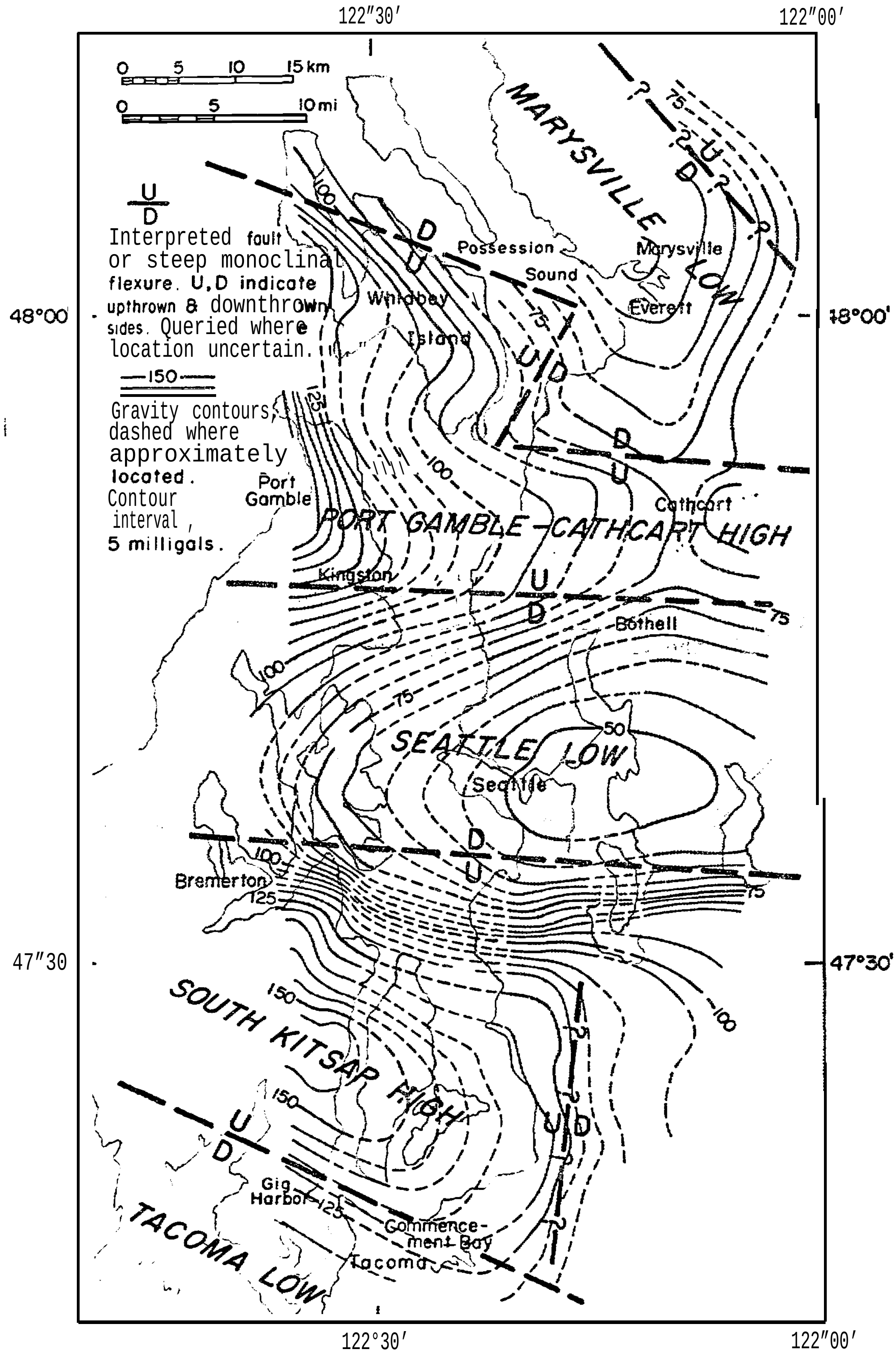
Gravity, magnetic, and seismic refraction investigations have also been carried out by Heiskanen (1951), who noted large negative gravity anomalies in the vicinity of Seattle; Stuart (1961), and Danes, *et al.* (1965), who reported regional gravity'measurements and noted large gradients in the central basin. Kaarsberg (1967), who reported significant magnetic anomalies generally correlated with gravity; and White and Savage (1965), who interpreted crustal structure to the north (Vancouver Island) to be complicated and thick, with a significant thinning toward Puget Sound. Rogers (1970) reported that a series of alternating relatively high and relatively low major gravity features is the most significant overall aspect of the gravity field study of the area.

Rogers (1970) noted that the most outstanding feature of the geomagnetic field in the area is the large positive anomalies occurring over the South Kitsap gravity high in each of the Puget Sound and Kitsap Peninsula profiles. The north flank of this anomaly, adjacent to the Seattle gravity low, is characterized by very steep magnetic gradients and local magnetic relief as much as 900 gammas. The south flank of the broadly positive anomaly passes southward into a large broadly negative anomaly. This latter anomaly appears to correspond generally with the Tacoma gravity low of Danes, *et* aZ. (1965). Kaarsberg (1967), Rogers (1970) and others have reported good correlation between gravity values and total magnetic intensity profiles for the Puget Lowland.

iv. <u>Tectonics and Seismicity.</u> Tectonic activity in the study area was first discussed by Gutenberg and Richter (1941, 1954). The results of bathymetric surveys led Menard (1964) and Hurley (1960) to construct physiographic diagrams of the area, showing the overall complexity of

Figure I-9

Map Showing Structural Interpretation on Bouguer Gravity§



§ After Rogers, 1970.

the shape of the ocean floor for the first time. Gibson (1960), Hurley (1960), and McManus (1964, 1965) constructed bathymetric maps showing the gross topographic features of the seamounts and fracture zones off Washington and Oregon. On the basis of magnetic lineations, Vine and Wilson (1965) and Vine (1966) proposed that sea-floor spreading is occurring outward from the Gorda and the Juan de Fuca ridges. Wilson (1965) proposed that the offset between the ridges along the Blanco fracture zone was the result of motion on a transform fault. Tobin and Sykes (1968) and Bolt, Lomnitz and McEvilly (1968) studied earthquake source motions and agreed with Wilson. Their studies showed that earthquakes along the fault occurred between the two ridges.

Dehlinger, *et al.* (1971) believed that the intrusions that form the ridges have been occurring during most of Cenozoic time, possibly longer. Since the ridges and the area in general are essentially in isostatic equilibrium, and since earthquakes occur along definite zones, it follows that the ridges are still active today, and that stresses are alleviated as they develop. Local compression is evidenced in the sediments along the shelf and slope of central and southern Oregon, but regional east-west compression does not appear to be present. The local compression could result from local diapirism along the edge of the steep slope in that region. The compression is considered to represent adjustments to dominantly vertical forces rather than to regional east-west shortening of the crust (Dehlinger, *et* aZ., (1971).

Tobin and Sykes (1968) found epicenters located along Gorda Ridge, the Mendocino' Escarpment east of Gorda Ridge, along the Blanco fault between the Juan de Fuca and Gorda ridges, within the Gorda Basin, along the continental margin, and along the Queen Charlotte Island fault. Few, if any, occur along Juan de Fuca Ridge, the Mendocino Escarpment west of Gorda Ridge, or in other parts of the area.

Fault-plane solutions for Gorda Basin, Gorda Escarpment, Cascadia Basin and Western Oregon all indicate right lateral motions for southeasterly strikes. Along the Gorda Ridge, normal faulting was observed for a plane parallel to the ridge. This is similar to the motions reported along the axis of the Mid-Atlantic Ridge (Tobin and Sykes, 1968) . Along the Blanco fracture zone, most solutions are consistent with a right lateral motion along a 'southeasterly strike.

In the Puget Sound and Georgia Strait regions, normal faulting fits the data for a southeasterly plane, a northeasterly plane, or a high-angle reverse fault along a southeasterly plane. These results are consistent with large faults that are known to strike southeasterly in the area (Danes, *et al.*, 1965 and Algermissen and Harding, 1965] .

In the Portland area, first motion studies are consistent with right lateral displacements along southeasterly fault planes. Such displacements are consistent with recent faulting observed from surface geology.

Tobin and Sykes (1968) have interpreted source motions between Cape Mendocino and Dixon entrance as consistent with sea-floor spreading and associated transform faulting. They interpret the Blanco fault as a dextral transform fault that connects two spreading ridges (Gorda and Juan de Fuca). They also interpret both the Mendocino Escarpment east of Gorda Ridge and the Gorda Escarpment to be the seaward extension of the San Andreas fault. Bolt, Lomnitz and McEvilly, (1968) do not agree entirely that the escarpments represent the seaward extension of the fault. They believe that "some motion is transferred by transcurrent faulting from the San Andreas fault (on land) across the Gorda Basin to the Blanco transform-fault systems." The numerous shocks in the Gorda Basin, the anomalous mantle structure there, and the local magnetic patterns support this conclusion.

Two of the principal questions in the study and interpretation of Northwest tectonism are whether subduction and underthrusting are actively occurring along the boundary between the Juan de Fuca and the North American plates and, if so, what is the nature of that activity. Crosson (1972) has concluded, with Atwater (1970), that the Juan de Fuca and Gorda plates are remnants of a once more extensive plate. They are now trapped in interaction between the American and Pacific plates. A zone of lithosphere consumption must exist somewhere along the continental margin between Vancouver Island and Cape Mendocino. However, the absence of an oceanic trench and Benioff zone along the margin indicates that motion may be either slowed or stopped. However, the lack of activity is caused by a reduced rate of underthrusting plus the fact that the plate is perhaps above normal temperatures because of its proximity to the ridge (Atwater, 1970).

The spatial distribution of small earthquakes in the Puget Sound area indicates that there is deformation over a broad volume of the crust in contrast to motion along well-defined faults. Crosson (1972) also found "the clear thrust component in the composite focal mechanism solutions suggests that the region is deforming in response to active north-south compression," and that the small earthquake seismicity of the region is "remarkably different" from that observed along the major fault systems in California (Crosson, 1972).

It is clear, at any rate, that the tectonics of the region are dominated by the active translation of the Pacific plate with respect to the American plate along the San Andreas and Queen Charlotte systems. -The region seems to be in a transition phase, as shown by the distortion of magnetic anomaly patterns and the occurrence of earthquakes in the Gorda plate (Bolt, Lomnitz and McEvilly, 1968).

Kulm and Fowler (1974) believe that the Pleistocene abyssal plain and fan deposits of the Cascadia Basin are being thrust beneath the earlier Cenozoic rocks that underlie the continental shelf. According to their studies, these abyssal deposits have been uplifted more than 1 km and incorporated into the lower and middle continental slope. Those that are not exposed are covered with late Quaternary deposits. "The stratigraphic position of these. ..deposits. ..and their age relationships strongly suggest imbricate thrusting of thick slices of sand turbidites typical of submarine fans, which alternate with silt turbidites characteristics of abyssal plains" (Kulm and Fowler, 1974). They interpret this to mean that thrusting is producing rapid-uplift of the lower continental slope at a rate averaging 1000 meters per million years, with the rate for older, compacted deposits on the outer shelf reduced by a factor of ten. Barnard (1973) concludes that folding and thrusting of the outermost ridge at the base of the continental slope is presently occurring at the rate of 0.7 cm per year.

Evidence from parts of the Oregon continental margin indicate that the ridges are uplifted and folded Pliocene or Pleistocene age sediments, suggesting rapid subduction (Byrne, Fowler and Maloney, 1966). However, Kulm, *et aZ.* (1971) cite the North Pacific magnetic anomaly pattern produced by the spreading ridge as the best evidence for subduction, and that the Alaska continental margin is a more typical subduction zone than that of Oregon.

Mayers and Bennett (1973) conclude with Crosson (1972), Silver (1971], and others that only residual underthrusting is still taking place -- at least beneath the Strait of Juan de Fuca. Tiffin and Riddihough (1977) suggest that subduction must have certainly occurred within the last ten million years. "If underthrusting of the oceanic crust is occurring, the younger oceanic rocks must be subducting below the shallower and older volcanics of the Prometheus anomaly. The plane of underthrusting must lie to the west of the Prometheus anomaly marking the westward edge of the continental magnetics" (Tiffin and Riddihough, [1977?]).

Riddihough and Hyndman (1976) have reviewed the evidence for subduction at the continental margin of British Columbia, and have concluded that, although the pattern is complex and changing south of 50°N, convergence has continued to the present day. They point out that it is of critical importance to realize that the very slow sinking rate, combined with the young and very thin oceanic plate, renders the usual subduction phenomena absent or not readily detectable.

The regional tectonic record indicates that five orogenies have made major contributions to the sub-bottom structural geology of the Strait of Juan de Fuca and the adjacent Olympic-Insular provinces: the large eroded anticline beneath the Strait of Juan de Fuca and adjacent canyon junction may date from the Jurassic-Cretaceous; the southward-dipping extension of the Calawah Fault Zone and the Sooke Intrusive date from the middle Eocene epoch; the Leech River and San Juan faults from the upper Oligocene; the folding and faulting of the Olympic Peninsula from the middle and late Eocene; and the Clallam Syncline, the Pys River fault and its companion fault are assigned to the Miocene and Pliocene. It is not known if the five episodes of tectonism coincided with periods of increased stress or were times when the accumulated stress was released by failure (Mayers and Bennett, 1973).

A recent study of earthquake activity in the Puget Sound region for the period June 18, 1970 - July 3, 1971 indicates that most of the regional seismicity is crustal (Crosson, 1972). However, the Puget Sound region is the only zone in the contiguous United States where large subcrustal earthquakes are known to occur.

The 1949 and 1965 earthquakes are the largest Puget Sound-region earthquakes in the recent historical record and these were 70 and 59 km in focal depth, respectively. Based on the observations that these two deep earthquakes were characterized by an extremely low level of aftershock activity, and noting that the 1939 and 1946 earthquakes also exhibited low aftershock activity, Algermissen and Harding (1965) concluded that the 1939 and 1946 shocks were also subcrustal. Such a lack of aftershock activity is characteristic of subcrustal earthquakes. The physical basis for the lack of aftershock activity for subcrustal earthquakes appears to be related to the small source dimensions of deep earthquakes and to the high hydrostatic pressure that exists at these depths, which has the effect of quickly arresting any rupture process (Wyss and Molnar, 1972).

Geological and geophysical studies have been undertaken over the years to define the active and potentially active faults of the Puget Sound region. Since the bulk of major seismic activity within the study area takes place in this region, the major faults postulated by the researchers are briefly discussed. It should be pointed out that, while each investigator has compiled geological and/or geophysical evidence for his case, none of the faults has been shown conclusively to be the source of an historic earthquake. There is wide disagreement among investigators and not all authorities will accept all the faults as being accurately conceived.

Bradford and Waters (1934) postulated a major north-south fault structure along the face of the Cascades from North Bend to Sultan, and possibly as far as the Canadian border. This Mt. Si fault -- thought to be the dividing line between the Cascades and the Puget Lowland -- was thought to be the locus of the 1932 Tolt River earthquake (Bradford and Waters, 1934) and the 1945 North Bend earthquake (U.S. Geological Survey, 1975].

Danes, *et al.* (1965) postulated an active fault along Hood Canal, separating the Puget Sound depression from the Olympic Peninsula. The Hood Canal fault is assumed to have a 4000 meter throw and may have been the locus of several earthquakes (U.S. Geological Survey, 1975].

Rogers (1970) inferred five areas of faulting (or boundaries of large monoclinal flexures). The South Whidbey-Possession Sound-Everett fault is broken into three segments separating the Marysville low from the Port Gamble-Cathcart high. It was identified by mapping that showed an abrupt steepening of gradients. The Kingston-Bothell fault and the Seattle-Bremerton fault define the limits of the Seattle low, an east-west-trending, 26 km-wide, trenchlike feature, which is one-of the largest isostatic gravity anomalies in the United States or Canada. Rogers postulated a possible fault of large displacement, with the west side upthrown and with a north-south trend along the Duwamish-Puyallup valley, citing geologic evidence as well as magnetic relief and steep gravity gradients along the east side of the south Kitsap gravity high. On the south margin of the south Kitsap block is the Tacoma-Gig Harbor fault, evidence for which includes steep gravity and magnetic gradients, temporal changes in ground level across the area, and seismic profiling of bottom sediments in Commencement Bay (Tacoma harbor), which indicates faulting since the most recent glaciation. Three of the four largest historic earthquakes located in the south part of the Puget Sound Basin have occurred on or very near the postulated structures (Rogers, 1970).

Carson (1973) discovered the Saddle Mountain fault, about 14 km north of Shelton in north-central Mason County, halfway between Hood Canal and Lake Cushman. Movement has taken place since the deglaciation of the southern Puget Lowland, about 13,000 years ago, but probably prior to the 19th century. It strikes north to northeast. The 1 to 2 km scarp exposure shows a throw of up to 6 m. It is a reverse fault with some strike-slip movement.

Carson and Wilson (1974) have also reported the Saddle Mountain East fault, a reverse fault north-northwest of Hoodsport that apparently moved 1200 years ago. It appears to offset the pre-Vashon Dow Mountain fault (28,000-23,000 b.p.). Another probable late Quaternary fault reported by Carson and Wilson (1974) is the Cushman Rift located on Dow Mountain east of Lake Cushman. It is a linear valley approximately 2 km long, 30 to 90 m deep, and 60 to 90 m wide. It may have moved since the beginning of the Fraser glaciation (18,000 year b.p.).

Crosson and Frank (1975) have examined an apparent fault zone trending slightly west of northwest along the south side of Mt. Rainier, which may have been the locus of the earthquake shocks of July 18, 1973 and April 20, 1974.

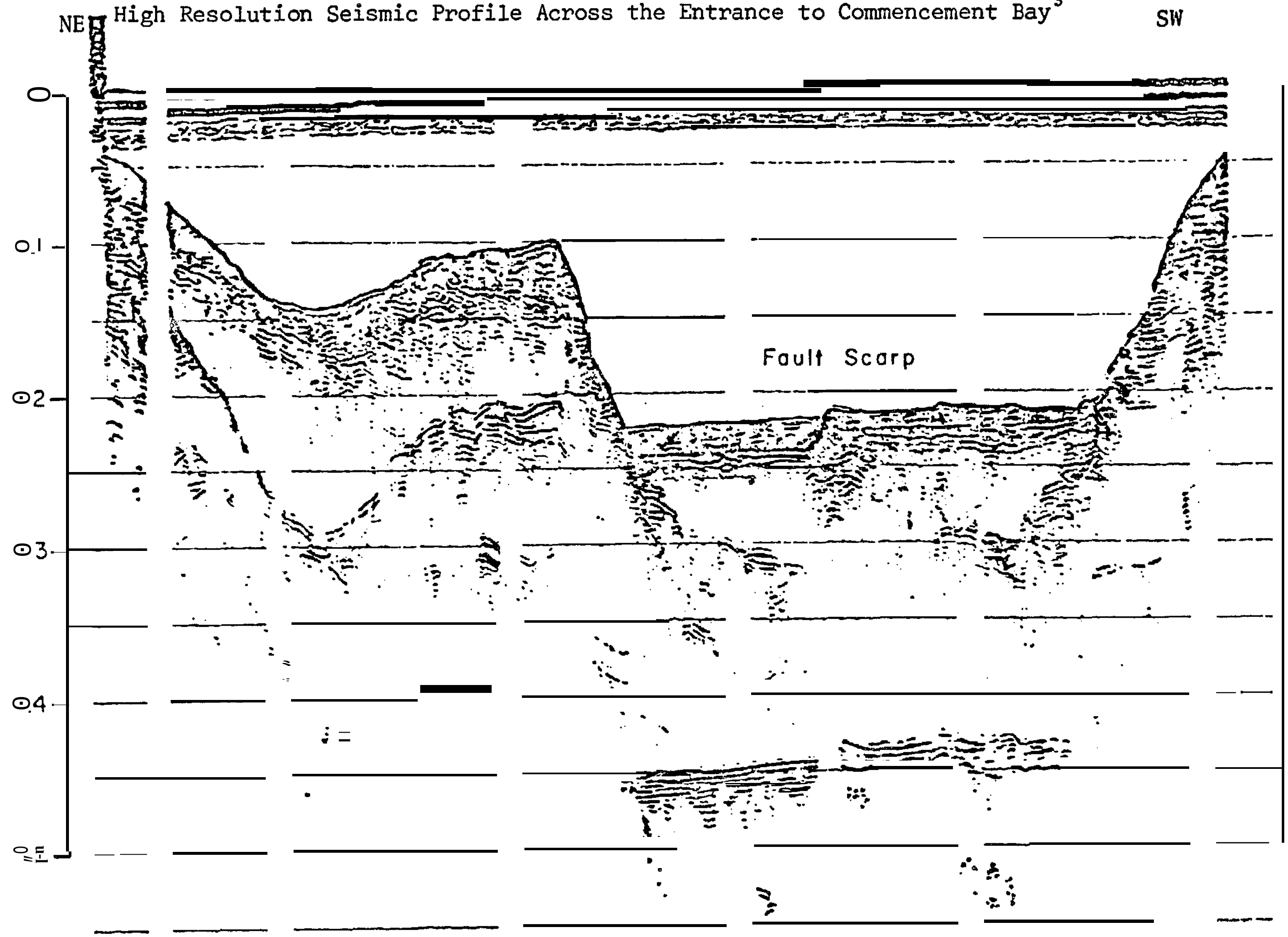
Sylwester, *et al.* (1971) conducted a detailed seismic profiling study of Commencement Bay and adjacent areas in an attempt to identify one or more active faults suggested by earlier investigators. A small scarp trending NW-SE with a relief of as much as 5 meters was traced almost continuously from Commencement Bay to Vashon Island (Figure I-lo) . This scarp indicated that the northeastern side has moved downward in relation to the southwestern side, in contradiction to the earlier model proposed by Danes, *et* aZ. (1965), and Rogers (1970).

Park Snavely, geologist with the U.S. Geological Survey at Menlo Park, California, reports Pleistocene age faulting in the Morse Creek area near Port Angeles. The fault strikes east-west, dips southward and has thrust Tertiary bedrock over Alpine glacial deposits.

Creager, quoted in the Oceanographic Commission of Washington report on Admiralty Inlet (1975), raises the possibility that a fault of unknown age and capability is located beneath Admiralty Inlet in the vicinity of Nodule Point to Bush Point. These findings were disputed by other geologists, who felt the structure was insufficient to make a final judgment either way and that future study is needed.

Bottom profiling and gravity studies of the Nisqually Delta beween Olympia and Tacoma were conducted by a joint team from the Geology and Oceanography departments of the University of Washington in the fall of 1970. Large slump blocks and a scarp were found. The scarp is associated with a magnetic anomaly and is coincident with the epicentral area of the 1949 earthquake. The gravity study indicates the presence of a steep gravity gradient on the eastern edge of the Nisqually River Valley near Interstate 5, which suggests the presence of major block faulting in the Nisqually River Basin. Regional gravity data for the

Figure I-10
High Resolution Seismic Profile Across the Entrance to Commencement Bay[§]



[§]Sylwester, *et al.*, 1971.

Seattle and Tacoma basins (Danes, *et al.* , 1965) indicate a pattern of block faulting consistent with these results. If such faulting is present it may act as a structural control of the location of the delta (University of Washington, Dept. of Geological Sciences, 1970).

Recently, Dr. Eric Cheney of the University of Washington has postulated the existence of two faults (and the extension of another) in the area of the proposed Skagit nuclear plants near Sedro Woolley. In his testimony before the Nuclear Regulatory Commission (Cheney, 1976 and 1977a) (and the (former) state Thermal Power Plant Siting Evaluation Council) and a paper submitted to the Geological Society of America (Cheney, 1977b), Cheney offers evidence for the existence of the Bellingham Bay-Lake Chaplain fault zone, a major tectonic structure extending from above the Canadian border southeast 54 km beyond the Skagit River. This fault zone is thought to be the southern and landward part of a larger fault system in the Strait of Georgia and could be as much as 360 km long. The fault appears to cut mid-Tertiary rocks and therefore may be active or at least potentially active. On a plate tectonic scale, the Bellingham Bay-Lake Chaplain fault system has the same strike as the Queen Charlotte and San Andreas faults, and may mark the northwestern border between the Cascade Mountains and Puget Lowland Provinces.

The westerly trending Devilfs Mountain fault, is 13 to 27 km long. Geological evidence, Cheney believes, suggests that this fault may be the offset eastern portion of the Leech River fault. The age and distribution of Pleistocene sediments in the Puget Lowland and the seismic reflection records of oil companies near Whidbey Island seem to indicate that the latest major displacement along the Leech River fault near Whidbey Island was 22,000 to 18,000 years b.p.

Cheney suggests that consideration of the geological, gravimetric, and earthquake data yields evidence of a northeasterly fault, perhaps as much as 38 km long, crossing the Skagit River Valley at Hamilton and within 5 to 6 km of the nuclear plant site. This inferred northeasterly fault is termed the Hamilton fault. Geologists for the Bechtel Company of San Francisco, which did the siting studies for the Skagit Plant, do not agree with Cheney on the earthquake potential for the faults which he proposed (Adair, 1975).

There exists a real need for definition of active and potentially active faults onshore and offshore. There are other possibly active faults in the study area. Research is being done in Canada by the Dominion Observatory in Victoria and the Geological Survey of Canada. In Oregon, research is being done on faults in the Portland area by the Department of Geology and Mineral Industries and by geologists from Portland State University. Names of resource persons at the above agencies are included in the reference list at the end of this chapter.

The Puget Sound region was chosen for an overview of possible faulting because it is the region from which damaging earthquakes in the study area are apparently most likely to emanate (with the possible exception of offshore earthquakes from the Blanco Fracture Zone).

Oregon is similar to Washington in having a history of earthquakes with no major destruction. All of Oregon's coastal counties have reported earthquakes. Couch and Lowell (1971) compute that the Coast Range of Oregon will have one 5.0 magnitude earthquake each decade. Lincoln County has had seven quakes during a seventy-year period ending in 1967. Four of these were centered at Newport [maximum intensity IV).

The most intense earthquakes on record for the Klamath Mountain Province originated in the Mendocino Escarpment within 320 km of the coast of California. Although this observation is consistent with the general tectonic model of the region, more data are needed for a complete assessment of potential seismic activity, and investigations continue. Silver (1971) recently defined a large subsea fault off the coast of Oregon with a displacement of 70 km. He interprets activity along the fault as ending approximately 500,000 years ago.

Couch and Lowell (1971) have summarized information on seismic energy release in the entire Coast Range physiographic province of western Oregon. They report the seismic energy release for a 100-year period (1870-1970) as 6.4×10^{16} ergs per year, which they computed as approximately equivalent to one magnitude 5.0 earthquake (W) each decade. This compares with 2.6x1017 ergs per year for the same period at Portland, and an approximate earthquake level of one magnitude 4.8 (W) earthquake each year or one magnitude 5.2 (W-VI) each decade.

Couch and Deacon (1972) have attempted to evaluate the maximum level of seismicity to be expected in the U.S. Bonneville Power Administration (BPA) service area (Oregon, Washington, Idaho, and western Montana). These studies indicate that for the Newport area, a maximum intensity of VII to IX could be produced from a distant earthquake epicenter near Port Orford. These studies also indicate that distant earthquakes, such as in the Gorda Basin off the southwest Oregon coast, could produce intensities of between VI and VII.

Local records of the 1873 quake, felt with an intensity of VIII in Port Orford, are not available for Coos or Douglas Counties. An earthquake of magnitude 7.2 and calculated intensity X occurred 64 km off the coast of Cape Mendocino in 1922 and was felt with an intensity of V in Coos Bay, but caused no damage (Beaulieu and Hughes, 1975).

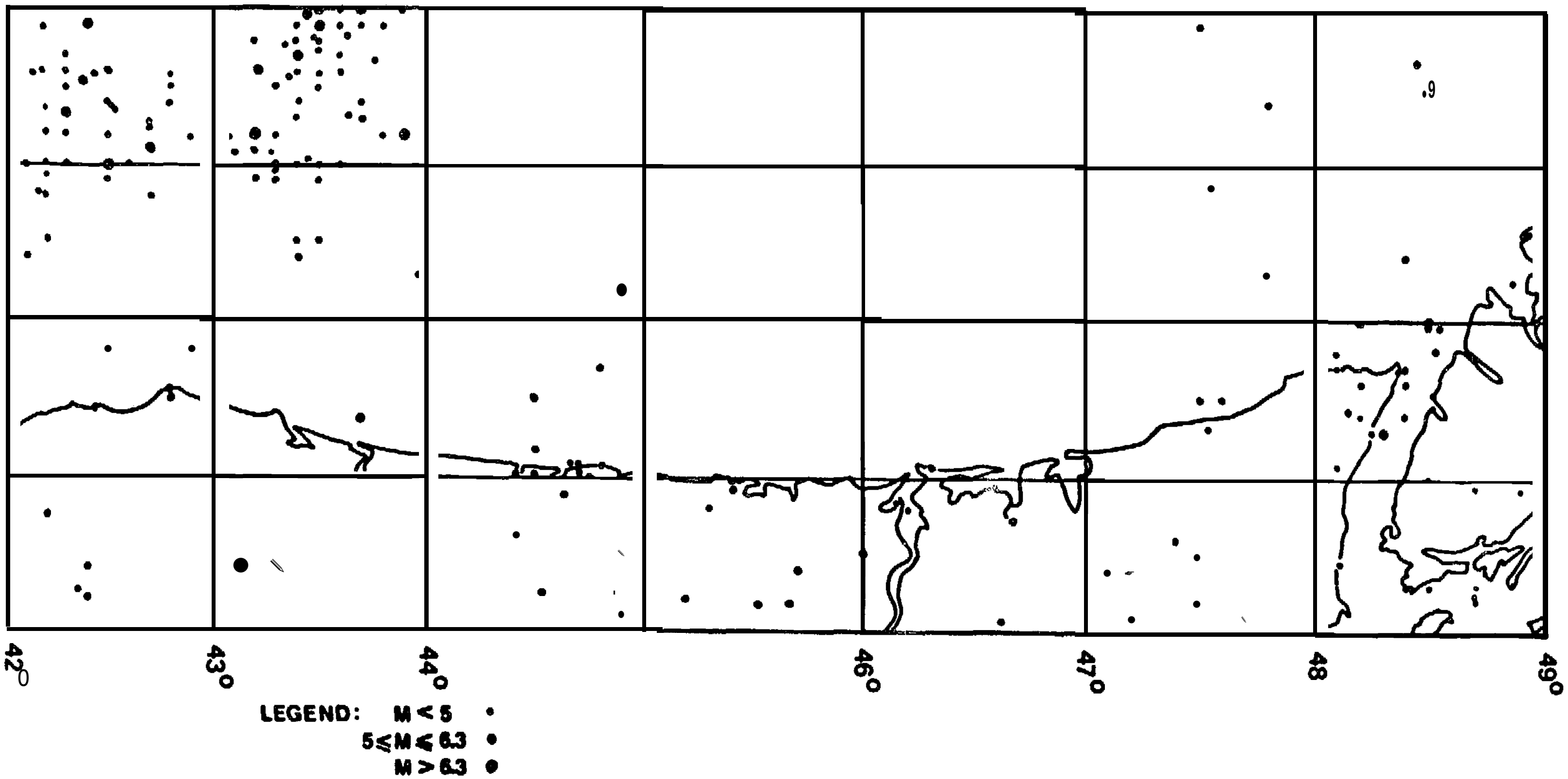
A record of historic earthquakes along the coast of the Pacific Northwest has been prepared by Couch, Victor and Keeling [1974) and is reproduced as it applies to the study area in Figure 1-11 and Tables I-2 and I-3.

Crosson (1974) has published a compilation of earthquake hypocenters in western Washington form July 1970 through December 1972. It lists all seismic events ranging down from M 1.0 and smaller recorded on the University of Washingtonts multistation seismograph telemetry network.

Rasmussen, Millard and Smith (1974) have compiled an earthquake hazard evaluation of the Puget Sound Region based on historical seismicity and soils data. They have computed return rates against intensity function for various intensities, using attenuation curves

Figure 1-11

Coastal and Offshore Earthquakes of the
Pacific Northwest 1853 to 1973§†



§Couch, Victor and Keeling, 1974.
†Adapted for 42°N Latitude and 123° to 127°W Longitude.

Reference Key to Tables I-2, I-3, I-4

Earthquakes with Epicenters in the Study Area

BERG	Berg, J. W. and C. D. Baker. Oregon Earthquakes, 1841 through 1958. Bulletin Seismological Society of America, v. 53(1): 95-108, 1963.
BERK	Seismographic Station. Department of Geology and Geophysics. University of California, Berkeley. Archival Data.
BRBUL	Bulletin of Seismographic Stations. University of California, Berkeley. 42, Jan. 1, 1972 - June 30, 1972.
BSSA	Bulletin of Seismological Society of America, Seismological Notes. 1924, 14(3):274; 1934, 24(2):127, 135, 136; 1935, 25(1):105; 1936, 26:394; 1938, 28:341; 1949, 39(4):314; 1950, 40(4):306; 1955, 45(3) :251; 1957, 47(2):167; 1962, 52(4) :971; 1972, 62(3): 876.
CGSxxx GUTE PDE	NOAA Earthquake hypocenter data tape for period 1961-1970. (Number following CGS indicates the PDE number) CGSxxx replaced by NOSxxx recently).
DOM	McMechan, G. A. Division of Seismology, Department of Energy, Mines and Resources, Victoria Geophysical Observatory, Victoria, B.C. 1973. (Archival Data]
Osu	Seismographic Station Bulletin. School of Oceanography, Oregon State University, Corvallis, Ore. July, 1963 - March, 1965.
RAS 1	Rasmussen, N. H. Seismology report on Washington, Idaho, Northern California and the Hanford Area, Washington to Douglas United Nuclear, Inc. Richland, Washington. May 3, 1966.
RAS2	Rasmussen, N. H. Washington State earthquakes 1840 through 1965. Bulletin of Seismological Society of America, v. 57(3): 463-476, 1967.
RAS3	Rasmussen, N. H. Unpublished additions to Washington State earthquake list, June, 1966 to February, 1971.
SYKES	Tobin, D. G. and L. Sykes. Seismicity and Tectonics of Northeast Pacific. Journal of geophysical research, v. 73, 1968.
TOWN	Townley, S. D. and M. W. Allen. Descriptive catalog of earthquakes of Pacific Coast of the U.S. 1769 to 1928. Bulletin of Seismological Society of America, v. 29(l), 1939.
WASH	Seismographic Station Bulletin. University of Washington, Publications in Seismology, 1950-1963.
USEQS	U.S. Dept. of Commerce. United States Earthquakes. U.S. Coast and Geodetic Survey. 4 v. 1928-1969.

Table I-2

Earthquakes Felt in the Study Area That Have Uncertain or Unknown Epicenters[§]

DATE	EPICENTER (UNCERTAIN)	FELT LOCATION AND INTENSITY	REFERENCE[†]
1891, Nov. 29		VII#-Port Townsend* VI#-Pysht II#-Tacoma* Point Wilson Lighthouse, Admiralty Head Lighthouse Point No Point Lighthouse, (clocks stopped) F - Seattle (Wash)	TOWN
1909, Jan. 11	"...Strait of Juan de Fuca or along or off the south end of Vancouver Island..."	VI-VII# Shock felt approximately 200 miles north and south of Strait of Juan de Fuca; Dungeness*, Port Angeles*, Crescent, Neah Bay (violent) (Wash)	TOWN
1920, Jan. 24		VI-VII#(?) Clallam Bay, Forks, Bellingham* Anacortes* (strongest) IV#-Blaine* F - Marietta*, Tatoosh (Wash)	TOWN
1926, Dec. 4	Strait of Juan de Fuca (probably)	V-IV#-Anacortes*, Mount Vernon* VI#-Bellingham*, Everett*, Friday Harbor*, Port Angeles*, Port Townsend* III#(?)-Clallam, Ediz Hook* II#-Concrete*, Coupeville*, Mariette* (Wash)	USEQS
1927, Mar, 27	Off southern Wash. coast (probably)	Northhead-Raymond* (Felt by many) F - Ilwaco, South Bend* (Wash)	TOWN
1934, May 5		V-Puget Sound Area IV-Neah Bay I-III-Forks, Hoquiam, Quinault (Wash)	USEQS

Table I-2 (cont.)

DATE	EPICENTER (UNCERTAIN)	FELT LOCATION AND INTENSITY	REFERENCE†
1937, Dec. 14		Dallas*, Fall City*, 3 miles southeast of Sheridan*, Tillamook (house shook) (Ore)	USEQS
1938, July 23		Oregon and S.W. part of Pacific County, Wash. Astoria, Ore. (moderate shock)	USEQS
1940, May 25		Waldport (objects moved) F - Toledo, Depoe Bay, Nashville*	USEQS
1940, Oct. 27		V-Puget Sound area* I-III-Clallam Bay (Wash)	USEQS
19s0, June 2		F - Salmon River Country*, Forks*, Sawyers*, Blue Lake	BSSA
1951, Feb. 23	Oregon Coast foreshock of 44.5°N, 129.5°W		WASH
1953, July 21	Off Oregon Coast		WASH
1955, July 5	200 miles off Oregon Coast		WASH
1955, Sept. 21	Near Oregon Coast		WASH
1957, Nov. 17	Probably off Oregon Coast		WASH
1963, Aug. 1	"about 450 km NW OF Corvallis, (Ore)		Osu
1963, Aug. 16	"about 120 km NW of Corvallis, (Ore)		OSU

LEGEND All listed intensities refer to the Modified Mercalli Scale of 1931 unless otherwise noted.

- The Rossi-Forel Scale of Intensities

* - Locations outside area of compilation

F - Felt

§Couch, Victor and Keeling, 1974.

†Reference lists the source of data by a letter code which corresponds to the listing on page I-65.

Table I-3

Earthquakes Outside the Study Area Which Were Felt in or Affected the Area[5]

DATE	EPICENTER LOCATION INTENSITY OR MAGNITUDE	FELT LOCATION AND INTENSITY	Reference
1892, Feb. 3	Portland, Oregon	Oregon: Astoria (houses shook) Yaquina Head Lighthouse (light)	TOWN
1946, Feb. 15	47.3°N, 122.9°W VII	Washington: IV-Clallam Bay, Forks, Ilwaco North Head, Ocean Park, Sekiu Oregon: V-Bay City IV-Astoria I-III-Gold Beach, Rockaway, Seaside	USEQS
1946, June 23	49.9°N, 125.3°W 7-7.25 (msg.]	Washington: VI-Quinault, Moclips, Sekiu, Tatoosh Island Oregon: V-Astoria, Tillamook IV-Rockaway Beach	USEQS
1949, Apr. 13	47.1°N, 122.7°W VIII	Washington: VIII-Hoquiam VII-Grayland VI-Bay Center, Clallam Bay, Pacific Beach, Quinault V-Ilwaco, Moclips, Neah Bay, Ocean Park Oysterville, Sekiu IV-Clearwater, Forks (1 1/4 miles east of), Lake Crescent Oregon: VI-Bay City, Depoe Bay, Florence, Manhatten Beach, Newport, Oceanside, Siletz, Tillamook, Toledo, Twin Rocks, Waldport V-Agate Beach, Kernville, Neskowin, North Bend, Pacific City	USEQS

Table I-3 (cont.)

DATE	EPICENTER LOCATION INTENSITY OR MAGNITUDE	FELT LOCATION AND INTENSITY	REFERENCE†
1949, Apr. 13	47.1°N, 122.7°W VIII	Oregon: IV-Fairview, Otter Rock, Otis, Tidewater I-III-Eastside, Powers, Rose Lodge, Siltcoos	USEQS
1954, May 15	47.4°N, 122.4°W VI	Washington: I-III-Hoquiam	USEQS
1961, NoV. 7	45.7°N, 122.9°W VI	Oregon: V-Tillamook IV-Garibaldi, Netart, Pacific City I-III-Beaver, Cannon Beach, Fairview, Nehalem, Neskowin, Rockaway	USEQS
1962, Nov. 6	45.6°N, 122.7°W	Washington: V-Ocean Park IV-Chinook, Long Beach I-III-Ilwaco Oregon: VI-Fairview, Seaside, Tillamook V-Astoria, Bay City, Cannon Beach, Garibaldi, Manhatten Beach, Neskowin, Netarts, Pacific City, Rockaway, Waldport, Warrenton IV-Hammond, Hebo, Hernville, Nehalem, Newport, Rose Lodge, Toledo I-III-Mapleton, Oceanside, Seal Rock	USEQS
1964, July 14	48.9°N, 122.5°W VI	Canada: I-III-British Columbia, Lake Cowichan area (Vancouver Island)	USEQS
1965, Apr. 29	47.4°N, 122.3°W VII, 6.5 (msg.)	Washington: VI-Amanda Park, Bay Center, Beaver, Clallam Bay, Copalis Beach, Copalis Crossing, Long Beach, Pacific Beach, Sekiu, Tokeland	USEQS

Table I-3 (cont.)

DATE	EPICENTER LOCATION INTENSITY OR MAGNITUDE	FELT LOCATION AND INTENSITY	REFERENCE†
1965, Apr. 29	47.4°N, 122.3°W VII, 6.5 (msg.)	Washington: V-Chinook, Humptulips, La Push, Moclips, Neah Bay, Heilton, Ocean City, Ocean Park IV-Forks, Sappho, Westport I-III-ClearWater Oregon: VI-Astoria, Seaside, Hammond IV-Coos Bay, Depoe Bay, Gardiner, Gerhart, Mapleton, Nehalem, Pacific City, Tillamook, West Lake I-III-Coquille, Florence, Toledo, Waldport, Winchester Bay, Yachats	USEQS

§Couch, Victor and Keeling, 1974.
†Reference lists the source of data by a letter code which corresponds to the listing on page I-65.

for estimation of earthquake hazards. They have concluded that "any earthquake with a depth less than approximately 40 km will not reach a magnitude greater than about 6.5, while earthquakes with a depth greater than 40 km could obtain a maximum magnitude of nearly 7.5." For a further discussion of potential seismic hazards in the study area, see Section B.6., Environmental Constraints to Development.

The U.S. Geological Survey (1975) has also compiled a study of expected earthquake magnitude and intensities for the Puget Sound region, based on methods developed by Sims (1975) and Stepp (1971). Sims' method is based on counting and dating of alternating layers of fine and coarse glaciolacustrine sediments near Hood Canal. In one 1800 year long section he found 14 zones that he interpreted as indicating earthquake-induced deformation.

Magnitude-intensity relationships and attenuation curves were also plotted (Figures 1-12 and 1-13). Soils and structural data were added to the seismic data to produce an estimate of loss of life and property in the six county area surrounding Puget Sound in the "worst case" earthquakes projected for the region. (See B.6. on Environmental Constraints.) A list of earthquakes affecting the Puget Sound-northwest Washington area for 1859 to 1973 (U.S. Geological Survey, 1975) is included in Table I-4. Rasmussen (1967) has published a list of Washington earthquakes for 1841-1965, and has compiled unpublished lists for each year since then. Figure 1-14 is from Rasmussen, Millard and Smith (1974).

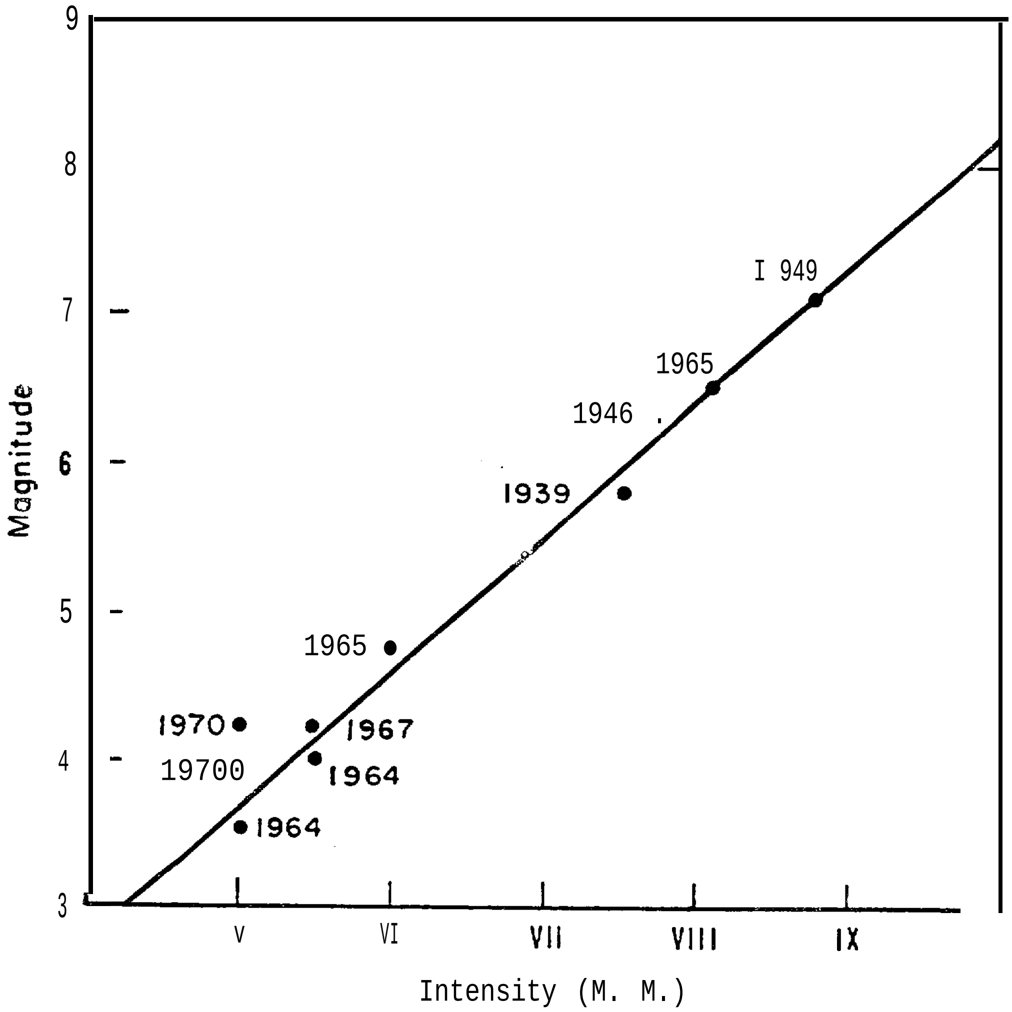
The worst historic earthquake in the northwestern Washington area was the shock of April 13, 1949, which had a magnitude of 7.1 and a focal depth of 70 km. The epicenter was between Tacoma and Olympia in the general area of the Nisqually Delta. The second was the shock of April 29, 1965, which centered between Seattle and Tacoma, with a magnitude of 6.5 and a focal depth of 59 km. A strong earthquake in 1872, the epicenter of which is still a matter of debate among researchers, was felt as far north as Eugene, Oregon and throughout British Columbia. The Skagit Valley Herald of June 6, 1973 (Jordan, 1973) speaks of a violent earthquake -- actually a series of earthquake shocks -- that, in the recollection of the pioneers, struck the Skagit Valley in May of 1871. This quake is not recorded in the usual earthquake lists, and while 1871 could have been mistaken for 1872 in the pioneers' memories, it is difficult to mistake December (the time of the 1872 quake) for May.

An attempt was made by Vance (1971) to relocate several well-recorded older events using refined techniques. The epicenters were moved an average of 35 km. Although depth control was poor for the older solutions, many of which were from three-station observations, Vance still had very little data on which to make conclusions. Although Vancets epicentral locations may have greater accuracy than the originals, the actual difference is not great enough to be significant (Crosson, 1977).

Additional northwest earthquake data have been accumulated by the several consultants for nuclear power plant siting projects, and are

Figure I-12

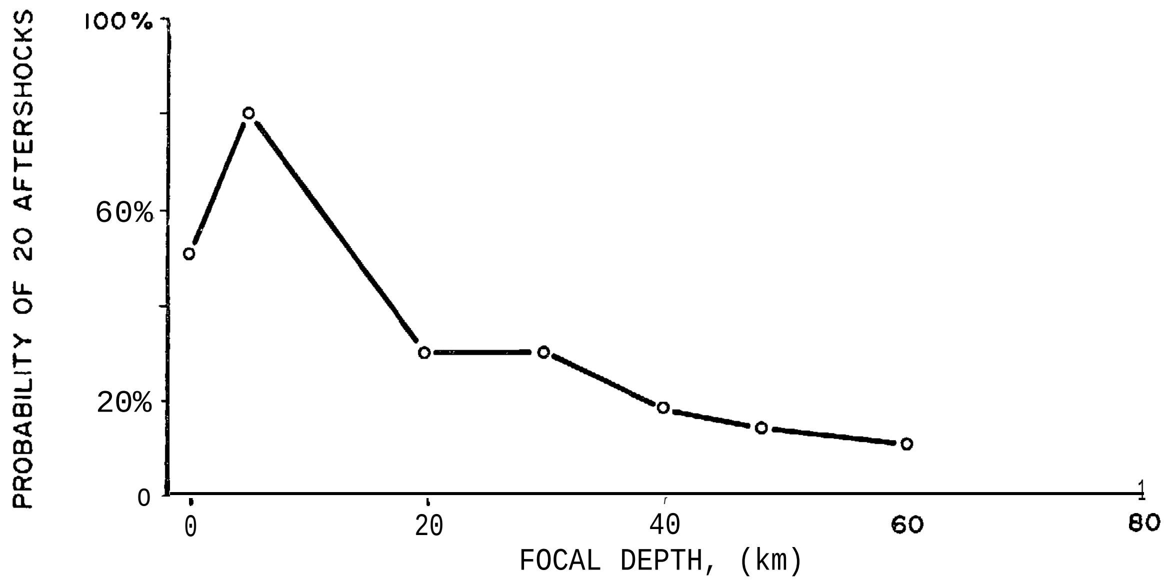
Plot of Magnitude vs. Intensity for Largest Known Puget Sound Earthquakes[§]



[§]U.S. Geological Survey, 1975.

Figure X-13

Probability of a Magnitude 6.0 or Larger
Earthquake Being Followed by 20 or More
Aftershocks of Magnitude 3.0 or Larger,[§†]
as a Function of Main Shock Focal Depth



[§]U.S. Geological Survey, 197S.

[t]Curve is empirically derived from earthquakes which have occurred in and near Japan.

Table I-4

Earthquakes with Epicenters in the Study Area §†

PACIFIC NORTHWEST OFFSHORE EARTHQUAKES

YEAR	DATE	TIME	LAT	LONG	LOCATION	M	OB	MC	INT	DEP	DUR	REF
1856	1226		48	123	Pt. Townsend, Wn			2.3	2			RAS2
1860	0507		48	123	Pt. Townsend, Wn			2.3	2			RAS2
1869	0627	0400	46 12	123 48	Astoria				F			RAS3
1873	1123	0505	42 48	124 30	Port Orford, Or			6.3	8			BERG
1880	0822	0822	47 30	123 30	NW Washington, Wn			2.3	2			RAS2
1885	1009	16	47	123	Olympia, Wn			4.3	5			RAS2
1885	1209	0940	48 07	123 27	Port Angeles, Wn			2,3	2			RAS2
1885	1218	0830	48 24	124 42	Tatoosh Is, Wn				3			TOWN
1885	1219	0830	48 22	124 41	Tatoosh Is, Wn			3.0	3			RAS2
1891	0921	1300	48 00	123 30	Wn			4.3	5			RAS2
1891	1129	2321	48 07	123 27	Port Angeles, Wn			5.0	6			RAS2
1892	0417	2250	47	123	Olympia, Wn			5.0	6			RAS2
1895	0416	0802	48	123	Pt. Townsend, Wn			5.0	6			RAS2
1896	0109	0556	48 41	123 14	Turn Pt. Lth. Wn			2.3	2			RAS2
1896	0207	0555	48 18	124 18	Strt Juandee Wn			5.0	6			RAS2
1896	0402	1117	45 12	123 12	McMinnville, Or			5.0	6			BERG
1896	0605	0620	42 48	124 33	Cape Blanco, Or			3.7	4			BERG
1897	0126	2245	44 48	124 05	Newport, Or			3.7	4			BERG
1897	1207	0430	45 32	123 10	Forrest Grove, Or			3.0	3			BERG
1902	0615	0400	44 42	124 06	Newport				4			BERG
1902	0615	0400	44 45	124 00	Newport, Or			3.7	4			BERG
1901	0615	0900	44 42	124 03	Newport, Or			3.7	4			BERG
1902	1202	1000	42 12	123 45	Kerby, Or			3.0	3			BERG
1902	1205	0930	42 24	123 24	Grants Pass, Or							BERG
1904	0317	0421	47 30	124 00			6.0					DOM
1910	0805	01.5136	42 00	127 00			6.8		F			BERK
1913	0316	02	43 20	123 20	Roseburg, Or			3*7	4			BERG
1914	0905	0935	47	123	Olympia, Wn			4.3	5			RAS2
1915	0211	0307	47 32	124 19	Queets River, Wn			3.0	3			RAS2
1916	0104		44 40	124 06	Newport, Or			2.3	2			BERG
1916	0104	1840	44 40	124 06	Newport, Or			3.7	4			BERG

Table I-4 (cont.)

PACIFIC NORTHWEST OFFSHORE EARTHQUAKES

YEAR	DATE	TIME	LAT	LONG	LOCATION	M	OB	MC	INT	DEP	DUR	REF
1918	1206	0845	49 18	123 00	Vancouver, B.C.			4.3	5			RAS2
1919	1010	010720	48 18	124 18			5.5					DOM
1924	0224	054510	44 00	127 00			5.8					DOM
1925	0801	2005	48 07	123 27	Port Angeles, Wn			3.7	4			RAS2
1925	1126	2140	48 30	123 18	Haro Strait, Wn			3.0	3			RAS2
1926	0917	221436	49 00	124 00			5.5					DOM
1927	0518	215652	49 00	124 00			5.0					DOM
1928	0209	1105	48 30	125 00			3.7					DOM
1928	0904		44 42	124 06			3.0					DOM
1928	0904		44 38	123 54	Newport, Or.			3.7	4			BERG
1930	0708	2030	45 01	123 15	Perrydale, Or			3.0	3			BERG
1930	0719	0238	45 00	123 12	Perrydale, Or			5.0	6			BERG
1931	1001	1100	42 54	124 48	Sea Report							BERG
1931	1231	1525	47 30	123 00	Eldon, Wn			5.0	6			RAS2
1932	0106	223S	48 06	124 05	Pysht, Wa			2.3	2			RAS1
1934	0505	0406	48	123	Discovery Bay, Wn			4.3	5			RAS2
1934	1103	1450	48	123	Discovery Bay, Wn			4.3	5			RAS2
1935	0724	1514	47 13	123 06	Shelton, Wn			2.3	2			RAS2
1936	0508		43 07	123 24	Roseburg, Or							BERG
1937	1110	071923	43 00	127 00			5.8					DOM
1937	1214	09	44 52	123 15	Dallas, Or			3.7	4			BERG
1938	0528	101406	43 00	125 36			6.0					DOM
1938	0723	0250	46 10	123 50	Astoria, Or			3.7	4			BERG
1938	0803	133236	43 54	126 12			5.6					DOM
1939	0214	13	45 25	123 55	Tillamook, Or			3.7	4			BERG
1939	1113	074554	47 12	123 00	Shelton, Wn			5.7	7			RAS2
1940	0525	1602	44 25	124 02	Waldport, Or			3.7	4			BERG
1940	1027	222918	47 12	123 24					5			CGS
1941	0609	061724	42 42	126 06			5.3					DOM
1941	0609	084354	42 30	125 00			5.0					DOM
1941	1020	0605	44 30	124 02	Seal Rock, Or			3.0	3			BERG
1942	0131	0654	48 30	123 00	San Juan Is, Wn			2.3	2			RAS2
1942	0513	0052	44 32	123 15	Corvallis, Or			4.3	5			BERG

Table I-4 (cont.)

PACIFIC NORTHWEST OFFSHORE EARTHQUAKES

YEAR	DATE	TIME	LAT	LONG	LOCATION	M	OB	MC	INT	DEP	DUR	REF
1942	1006	025818	43 40	126 48			4.7					DOM
1942	1127	105548	42 12	126 00			4.9					DOM
1944	0305	09	44 55	123 30	Dallas, Or			3.0	3			BERG
1944	0305	1300	45 00	123 25	Dallas, Or			4.3	5			BERG
1944	0331	2215	47	123	Olympia, Wn			4.3	5			RAS2
1944	0721	122S00	42 30	127 00			4.0					DOM
1944	0916	224442	42 30	127 00			4.3					DOM
1944	1207	0448	47 00	123 54	Hoquiam			5.0	6			RAS3
1944	1221	051906	42 00	125 00			4.7					DOM
1944	1230	220306	43 42	127 00			5.8					DOM
1945	0411	112257	42 00	126 00			5.0					DOM
1945	0615	232502	48 48	123 00	Strt Georgia, Wn			4*3	5			RAS2
1948	0110	004550	42 00	127 00			5.3					BERK
1948	0213	2100	46 38	123 04	Adna, Wn			3.7	4			RAS2
1948	0301	0630	45 40	123 10	Buxton, Or			3.7	4			BERG
1948	0525	151307	44 00	127 00								GUTE
1948	0525	153202	43 30	127 00			5.8					DOM
1949	0325	045648	42 00	126 30			6.2		F			BERK
1949	0328	194316	42 00	126 00			5.8					DOM
1949	0330	202828	49 00	127 30			4.8					DOM
1949	0401	164545	43 30	126 00			4.9					DOM
1949	0601	082315	47 30	124 30			4.0					DOM
1949	0824	060714	43 30	127 00			5.5					DOM
1950	0127	104720	42 00	125 05			4.7					BERK
1950	0414	110346	48 00	123 00					6			CGS
1950	0425	223807	43 30	127 30			4.5					DOM
1950	0619	183013	44 00	127 00			4.2					DOM
1950	0824	174534	42 30	126 00			5,6					DOM
1950	0831	184743	42 00	125 00			4.2					DOM
1950	1216	104901	43 30	127 00			4.5					BERK
19s1	0214	005148	44 00	127 00								BERK
1951	0823	075407	48 30	124 58			3.0					DOM
1951	0922	101657	48 00	127 00			4.5					DOM

Table I-4 (cont.)

PACIFIC NORTHWEST OFFSHORE EARTHQUAKES

YEAR	DATE	TIME	LAT	LONG	LOCATION	M	OB	MC	INT	DEP	DUR	REF
1951	1008	041035	40 17	124 48	Alton		5.8		7			BERK
1951	1013	194506	43 30	127 00			4.5					DOM
1951	1226	063146	43 30	127 00			4.3					DOM
1952	0129	234545	43 30	127 00			4.2					DOM
1952	0220	190707	48 42	123 12	San Juan Is, Wn			3.7	4			RAS2
1952	0222	093931	48 36	123 06	San Juan Is, Wn			4.3	5			RAS2
1952	0302	001154	49 12	124 00			3.0					DOM
1952	0314	145936	48 36	123 06	San Juan Is, Wn			3.7	4			RAS2
1952	0411	094834	48 24	124 24	Vancouver Is, B.C.			2.3	2			RAS2
1952	0820	152450	43 00	127 00			6.5					DOM
1952	0821	094448	43 00	127 00			4.0					DOM
1952	0821	190830	43 30	127 00			4.1					DOM
1952	1007	070336	42 00	127 00			5.4					DOM
1952	1007	073032	42 00	127 00			4.5					DOM
1952	1119	122800	48 32	124 49			3.0					DOM
1952	1120	213100	48 54	123 56			3.0					DOM
1953	0108	052604	47 30	124 30			3.6					BERK
1953	0322	201557	48 52	125 15			3.0					DOM
1953	0410	1107	47 00	124 00	Grays Harbor, Wn			3.7	4			RAS2
1953	0705	135507	48 15	124 18			3.0					DOM
1954	0103	094833	43 00	125 00								BERK
1954	0103	111452	43 00	125 00								BERK
1954	0107	213947	42 30	125 S4			3.5					BERK
1954	0404	124229	48 31	124 32			3.0					DOM
1954	0522	124700	48 12	124 36			3.0					DOM
19s4	0705	011300	48 00	127 00			3.8					BERK
1954	1005	130100	49 00	126 00			3.0					DOM
1954	1111	221512	46 41	123 44	Raymond, Wn			3.0	3			RAS2
1954	1111	2230	46 41	123 44	Raymond, Wn			2.3	2			RAS2
1954	1202	090448	43 24	126 42								SYKES
1954	1203	084602	44 00	127 00			4.4					DOM
1955	0111	102008	47 49	124 01					5			CGS

Table I-4 (cont.)

PACIFIC NORTHWEST OFFSHORE EARTHQUAKES

YEAR	DATE	TIME	LAT	LONG	LOCATION	M	OB	MC	INT	DEP	DUR	REF
1955	0111	102008	48 00	123 36	Pt. Angeles, Wn			4.3	5			RAS2
1955	0224	100050	47 54	123 00	Quilcene, Wn			3.0	3			RAS2
1955	0516	030127	47 48	125 18			3.0					DOM
1955	0729	133409	48 12	124 24								WASH
1955	0911	005246	48 24	124 36	Juan de Fuca, Wn			4.3	5			RAS2
1955	0921	091801	42 30	126 24								SYKES
1955	1003	112408	49 00	127 00			3.5					DOM
1955	1027	180937	48 09	124 26			3.0					DOM
1956	0408	222912	48 24	123 18	Juan de Fuca, Wn			3.7	4			RAS2
1956	0706	022155	42 00	127 00			4.9					BERK
1956	0706	081310	42 18	126 30			3*5					BERK
1956	0708	020128	42 12	126 22			3.9					BERK
1956	0715	015509	44 00	127 30			4.7					DOM
1956	0812	212230	47 54	127 30			3.4					DOM
1956	1019	071527	42 30	126 11			4.2					BERK
1956	1018	091141	42 30	126 11								BERK
1956	1019	235831	42 30	126 35			4.7					BERK
1956	1110	180918	42 30	126 35			3.0					BERK
1956	1123	025140	42 48	126 24			3.2					BERK
1956	1126	000046	47 06	123 24	McCleary, Wn			2.3	2			RAS2
1957	0322	2400	44 25	123 38	Alsea, Or			3*O	3			BERG
1957	0529	093557	47 30	123 12	Olympic N P, Wn			3.7	4			RAS2
1957	0914	032053	48 42	123 S7			3.4					DOM
1957	1003	190355	47 30	127 00			3.0					DOM
1957	1117	060029	45 18	123 48	Beaver, Or			5.0	6			BERG
1957	1229	21S658	42 00	126 24			3.7					BERK
1958	0122	125931	44 30	124 11			3.0					BERK
1958	0605	110504	42 48	126 30								BERK
1958	0710	190418	47 33	125 52			3.0					DOM
1958	1003	000850	47 36	124 30			3.0					DOM
1958	1007	050752	46 42	124 00	Bay Center, Wn			S.0	6			RAS2
1958	1007	160941	44 00	127 30								BERK

Table I-4 (cont.)

PACIFIC NORTHWEST OFFSHORE EARTHQUAKES

YEAR	DATE	TIME	LAT	LONG	LOCATION	M	OB	MC	INT	DEP	DUR	REF
1959	0220	005355	42 42	125 48			3.4					BERK
1959	0320	154147	43 48	126 11			4.4					BERK
1959	0723	081512	44 30	124 30			4.3					DOM
19s9	0802	093552	47 48	126 24			3*O					DOM
1959	0808	190659	43 30	126 30			4.8					DOM
1959	0813	190659	43 30	126 30								CGS
1959	0818	051330	42 00	127 00			4.3					DOM
1959	0821	002817	44 48	124 41			4.6					BERK
1959	0928	015032	42 02	126 41			4.1					BERK
1959	1027	061217	42 23	126 32			5.1					BERK
1959	1119	23S345	42 24	126 54			5.1					BERK
1959	1212	062417	48 42	123 18	San Juan Is, Wn			4.3	5			RAS2
1960	0514	125622	48 24	125 24			3.0					DOM
1960	0910	150634	47 42	123 06	Olympic NP, Wn			5.0	6			RAS2
1960	1108	113627	44 54	125 11			5.0		F			BERK
1960	1222	114106	43 18	126 12			4.1					DOM
1961	0206	051923	47 30	126 54			3.3					DOM
1961	0508	235856	43 30	125 30								BERK
1961	0508	235927	43 42	124 22								BERK
1961	0823	175947	42 24	123 12						10		BRK
1961	1030	014452	42 30	126 36						33		CGS-B
1961	1030	021632	42 18	126 42						36		CGS-B
1962	0117	192726	48 33	124 58			3.3					DOM
1962	0619	015814	49 00	127 36			3.1					DOM
1962	0627	051148	43 00	126 24						33		CGS-B
1962	0811	1653	46 00	123 30	Vesper, Or			5.0	6			RAS2
1962	0821	02S738	42 18	126 36						40		CGS-B
1963	0307	235325	44 54	123 30			4.6		5	33		CGS-B
1.963	0702	123434	42 54	126 11			4.1					BERK
1963	0704	055049	43 42	126 24			4.4			33		CGS-B
1963	0822	092703	42 00	126 24			4.6					BERK
1963	0916	171534	43 12	126 48			4.7					CGS-B

Table I-4 (cont.)

PACIFIC NORTHWEST OFFSHORE EARTHQUAKES

YEAR	DATE	TIME	LAT	LONG	LOCATION	M	OB	MC	INT	DEP	DUR	REF
1963	0922	223623	42 00	126 30			4.3			33		CGS-B
1963	1005	042254	43 42	127 06			4.2			16		CGS-B
1963	1010	031.515	47 36	127 06			3*9					DOM
1963	1218	100651	43 42	126 54			4.2					DOM
1963	1227	023621	45 42	123 24			4.5		6	33		CGS-B
1964	0101	042213	43 42	126 18			3.7			33		CGS-B
1964	0128	045649	43 18	125 54			4*5					BERK
1964	0212	161430	43 18	126 00			4.1			33		CGS-B
1964	0214	120722	43 36	126 00			4.5			33		CGS-B
1964	0331	021107	43 36	126 36			4.5			33		CGS-B
1964	0423	082701	43 18	126 30			4.3			33		CGS-B
1964	0508	100416	43 24	126 36			4.3			33		CGS-B
1964	0509	10041643	24	126 35			4.3					BERK
1964	0704	134129	43 36	126 42			4.7			33		CGS-B
1964	0721	032708	42 12	125 30						33		CGS-B
1964	0727	184050	42 18	126 00			3.8					BERK
1964	0806	104628	43 24	126 42			5.3			33		CGS-B
1964	0813	063541	42 00	126 05			3*9					BERK
1964	0813	085040	42 00	126 00			3.7					BERK
1964	1001	110048	43 30	126 54			6.0		F			BERK
1964	1007	172625	43 30	126 00			4.5			23		CGS-B
1964	1106	121429	43 30	126 35			4.6					BERK
1964	1212	041907	48 30	126 00			3.3					DOM
1965	0310	200915	43 24	125 24			4.0			33		CGS-B
1965	0326	185846	43 12	126 12			5.0			33		CGS-B
1965	0327	090358	43 48	126 54			3.9			33		CGS-B
1965	0327	202514	43 30	125 54			3.8			33		CGS-B
1965	0430	031443	43 36	127 00			4.6			33		CGS-B
1965	0617	112252	43 06	126 05			4.5					BERK
1965	0620	172355	42 48	126 24			4.6					BERK
1965	0620	180430	42 48	126 35			4.7					BERK
1965	0620	191759	43 12	126 06			4.2			33		CGS-B

Table I-4 (cont.)

PACIFIC NORTHWEST OFFSHORE EARTHQUAKES

YEAR	DATE	TIME	LAT	LONG	LOCATION	M	OB	MC	INT	DEP	DUR	REF
1965	0624	105445	43 36	126 54			4.1			33		CGS- B
1965	0725	083443	42 06	126 (.90			4.6			33		CGS-B
196s	0831	112622	43 18	126 00			4.2			33		CGS-B
1965	0904	094210	42 06	12.5 24			4.1			33		CGS -B
1965	1014	06005	43 24	126 18			4.2			34		CGS-B
1965	1124	051516	43 24	125 30			3.9			32		CGS- B
1966	0309	130602	43 24	126 00			4.3			11		CGS-B
1966	0712	024959	42 06	125 00			4.0			33		CGS-B
1966	0806	204022	48 30	124 00			3.1					DOM
1966	0810	113231	48 06	124 48			3.3					DOM
1966	0811	114602	48 06	124 42			3.4					DOM
1966	0817	143950	48 12	125 00			3.8					DOM
1966	0817	144003	48 00	123 36			3.5			33		CGS-B
1966	1014	180218	48 54	127 00			4.1					DOM
1966	1120	154726	42 12	125 48			4.5			33		CGS-B
1966	1230	105504	42 30	124 48			4.3			33		CGS-B
1967	0103	201336	45 35	126 01			4.4					DOM
1967	0203	015705	43 17	126 05			4.1			33		CGS-B
1967	0416	150427	43 25	126 25			4.2			33		CGS-B
1967	0416	161854	43 22	126 34			4.3			33		CGS-B
1967	0518	020938	43 38	126 19			4.0			33		CGS-B
1967	0522	025931	43 38	126 50			4,4			12		CGS-B
1967	0813	164422	43 30	126 54			5.0			33		CGSPDE
1967	1007	150704	43 24	126 54			4.4			33		CGSPDE
1967	1025	192233	43 24	126 42			4.4			33		CGSPDE
1967	1113	174412	43 24	126 48			4.2			33		CGSPDE
1967	1213	101249	43 12	125 $4			4.3			33		CGSPDE
1967	1218	132316	42 36	126 00			4*4			33		CGSPDE
1967	1227	140403	41 36	126 41			3.6					BERK
1968	0119	202337	43 24	126 36			4.6			33		CGSPDE
1968	0130	012107	43 30	126 30			4.1			22		CGSPDE
1968	0313	116032	43 30	126 30			4.0			33		CGSPDE

Table I-4 (cont.)

PACIFIC NORTHWEST OFFSHORE EARTHQUAKES

YEAR	DATE	TIME	LAT	LONG	LOCATION	M OB	MC	INT	DEP	DUR	REF
1968	0321	123146	42 18	126 12		4.6			33		CGSPDE
1968	0508	175455	43 54	127 00		4.3			33		CGSPDE
1968	0509	030301	43 27	126 58		5.2			33		CGSPDE
1968	0626	043524	42 12	125 56		4.1			33		CGSPDE
1968	0915	112736	43 58	125 17		3.9			33		CGS 77
1968	1019	163516	42 10	125 49		4.3			33		CGS 85
1968	1221	195642	43 05	126 11		4.6			33		CGS102
1968	1223	123948	43 18	125 58		4.4			33		CGS103
1968	1225	094245	43 30	126 44		3.9			33		CGS103
1969	0206	110341	43 27	126 02		4.3			33		CGS 11
1969	0214	083336	48 56	123 05		4.2		5	33		CGS 11
1969	0707	052716	43 46	126 40		4.2			33		CGS 44
1969	0813	161216	48 29	126 28		4.6			33		CGS 53
1969	1001	171111	48 31	126 29		4.7					DOM
1970	0131	113125	42 08	126 35		4.7					BERK
1970	0222	152243	43 29	126 49		4.5			33		CGS 15
1970	0514	033554	42 31	126 23		4.7			33		CGS 42
1970	0514	081847	42 26	126 35		4.1			33		CGS 42
1970	0528	173832	48 27	126 40		4.9					ROM
1970	0911	031706	42 11	126 36		4.6			33		CGS 64
1971	0114	082936	47 24	123 36	Quinault, Wn	3.8		3	40		RAS3
1971	0225	155056	43 13	126 37		5.0			33		NOS 19
1971	0517	091143	42 32	126 22		4.9			33		NOS 45
1971	0520	075243	42 18	126 53		4.7			33		NOS 45
1971	0520	080108	42 18	126 20		5.0			33		NOS 45

Table 1-4 (cont.)

PACIFIC NORTHWEST OFFSHORE EARTHQUAKES

YEAR	DATE	TIME	LAT	LONG	LOCATION	M OB	MC	INT	DEP	DUR	REF
1972	0103	041458	42 12	126 12	NW Cres. C	3.6					BRBUL
1972	0323	212540	42 42	126 14		4.9			33		ERL 19
1972	0324	025025	42 42	126 16		4.8			33		ERL 20
1972	0409	011010	42 42	126 17		4.7			33		ERL 23
1973	0525	113625	43 .?1	126 46		4.2			33		ERL 40

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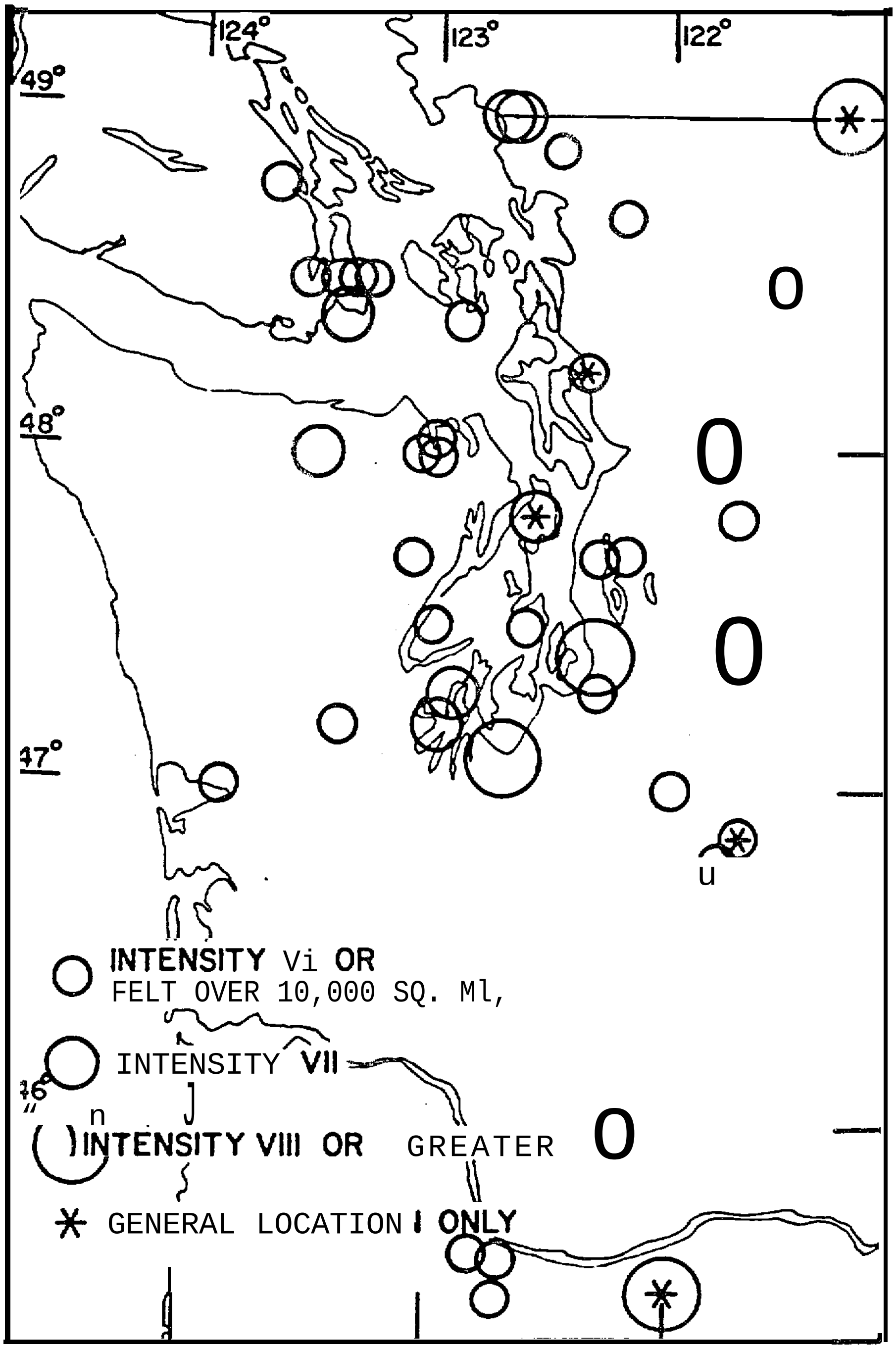
§ Couch, Victor and Keeling, 1974.

† The column entitled MOB indicates the observed body wave magnitude of the earthquake and the column entitled MC indicates a computed magnitude for the event using the relation $M = 1 + 2/3\ I_o$ where I_o is the maximum observed intensity. The column entitled INT lists the highest intensity observed at the LOCATION. The column headed DEP lists the focal depth of the earthquakes. Occasionally the reviewing geophysicist constrains the focal depth to 33km to achieve a satisfactory solution for the epicenter hence the value 33 in this column implies an unknown but probably shallow focal depth. The column headed DUR lists the duration or length of the coda of the earthquake. The column entitled REF lists the source of the data by a letter code which corresponds to the listing on page I-65.

Figure 1-14

All Earthquakes Felt Over 10,000 Sq. Mi.[§†] of Intensity VI and Greater, 1841-1974



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§ Rasmussen, Millard and Smith, 1974.
† One sq. mi. = 2.59 km^2.

part of the public hearing records of the Nuclear Regulatory Commission (formerly AEC) and of the environmental impact statements. Studies for the Satsop plant in western Washington near Grays Harbor were done by Woodward-Clyde (then Woodward-Lundgren) of San Francisco, and for the Skagit plants by Bechtel, Inc. of San Francisco, already mentioned.

Western Canada experienced 24 earthquakes of M 6.5 or greater between 1872 and 1972 (Whitham and Milne, 1972). None, however, centered within the study area (Rogers, 1977). The strongest of the quakes to affect the study area was the 1872 quake, which has been assigned a tentative magnitude of 7.5. The second strongest occurred in June, 1946 and centered in the Strait of Georgia between Powell River and Courtenay. The magnitude was 7.3 and heavy damage occurred in the epicentral region. The bottom of Deep Bay in the Strait of Georgia was reported by the Canadian Hydrographic Department to have sunk 3 to 26 m. A 3 m vertical ground shift occurred on Read Island. Ground settlements of up to 30 m were noted at other points. South of the international boundary, in the State of Washington, some chimneys fell at East Sound and a concrete mill was damaged at Port Angeles. It was felt strongly at Olympia, Seattle, Tacoma, Raymond, and Bellingham. Seattle, where tall buildings sustained damage at upper levels, was the hardest hit in the Puget Sound area.

The focal depth was virtually "zero", for this was a surface quake with ground rupture along the fault (Riddihough, 1977). The actual rupture was not found and was assumed to have been covered by the debris of the landslide that it induced. Research is still being done to try to locate traces of the fault scarp.

It should be noted that both of these earthquakes were stronger than any centered in the Puget Sound region in historical times.

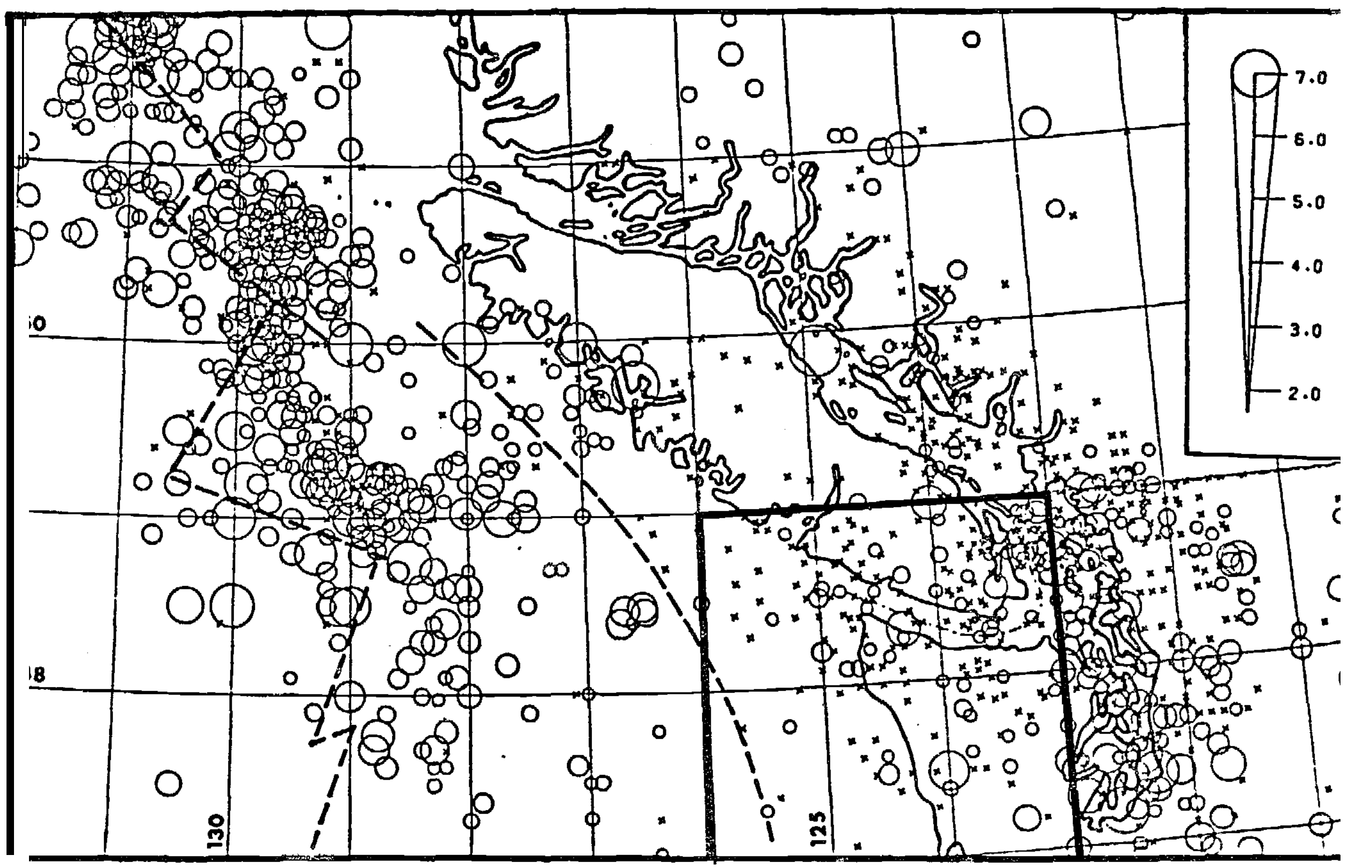
Another quake that centered outside the study area and was felt strongly inside it was the "Nootka Island" earthquake of December, 1918, which centered at 49.8N, 126.5W. Its estimated magnitude was 7.0.

While the Puget Sound region is nearer to the Oregon-Washington OCS, and its earthquakes may have more damaging effects due to the proximity of the epicenter, southwestern British Columbia and the offshore area adjacent to it have produced some powerful earthquakes, the repetition of which could have a significant effect on U.S. installations. (See Section B.6. on Environmental Constraints.)

Offshore seismicity generally follows the Queen Charlotte fault and the ridge systems. Epicenters, however, are rather imprecisely located on specific ridges or transforms (Riddihough and Hyndman, 1976). Within the American plate, Rogers (1977) has analyzed the first motions of a number of larger earthquakes and concludes that the region can be divided into two distinct areas. North of 49°, in central Vancouver Island, the earthquakes are shallow and consistent with strike-slip faulting in response to north-south compression. South of 49°N, in the Gulf Islands-Puget Sound area, a high concentration of predominantly shallow earthquakes has been recorded (Figure 1-15). Riddihough and Hyndman (1976) conclude that, based on what

Figure 1-15

Compilation of Earthquake Epicenters
from Seismological Series[§]



[§]Milne, *et al.*, 1976.

would be expected from the rate and type of subduction they have postulated, the maximum depth of earthquakes expected for the southern portion of the area is 70 km and is 30 km for the area north of 49°.

3. Surficial Geology.

a. Introduction. Surficial geology includes the study of sediments or volcanic rocks "recently" deposited on the earth's surface and the study of geologic processes acting on the earth's surface today. Understanding of surficial geologic deposits and processes is critical to the recognition and evaluation of most geologic hazards, and to land-use planning.

Although surficial geology is oriented toward ongoing processes, it is necessary to have some perspective on "recent" geologic history -- events of the last two to three million years that are responsible for the deposits, soils, and landforms seen today. This epoch of the earth's history is termed the Quaternary Period, and it has been traditionally thought of as the period of the "ice ages", although it is now recognized that cold climates and glaciers were not confined to the Quaternary (Flint, 1971).

It is evident now that extensive glaciers had formed in the polar regions before the end of Miocene time (about 10 million years ago). Since then, the earth has been subjected to a large number of climatic oscillations. During the colder periods, ice sheets advanced out of the polar and alpine regions (Figure I-16). The shift in mean annual temperature between interglacial and glacial periods does not appear to have been great -- about 3° to 6°C in low elevation and maritime areas and increasing to about 12°C or more in continental regions (Flint, 1971).

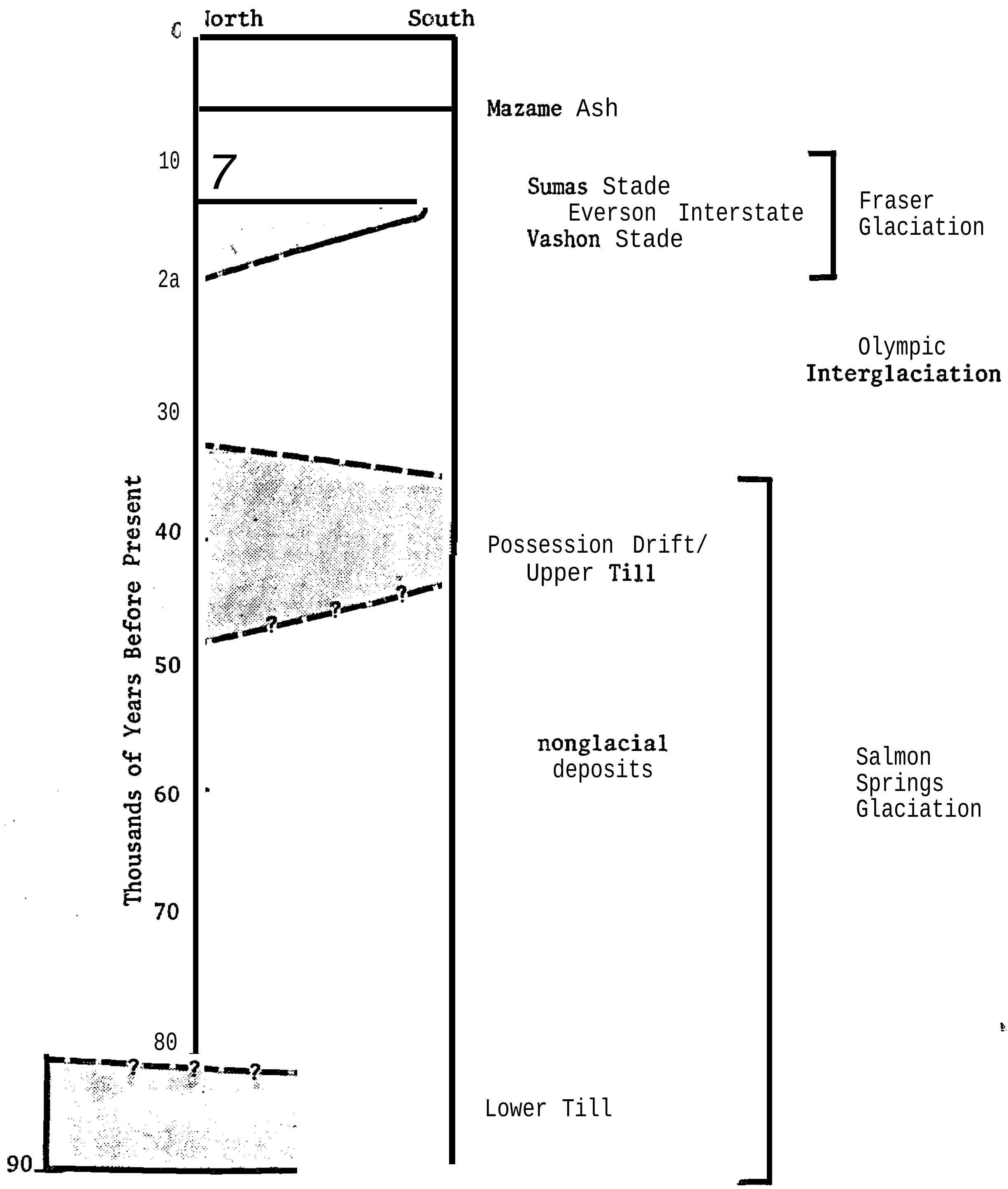
In the study area, geologic processes continued operating throughout this period much as they do today. However, glacier ice did cover the Puget Lowland, Vancouver Island, and much of the Olympic Peninsula, drastically altering the landscape in these areas. Sea level fell as global water supplies went into making glacier ice during the glaciation. World-wide sea level has fluctuated from as much as 90 to 120 m below present sea level to about 18 to 21 m above it. Such fluctuations are in part responsible for elevated marine terraces along the Oregon-Washington coast (Palmer, 1967a).

b. Landforms and Associated Geologic Units. In coastal Oregon and Washington, various kinds of processes acting on different rock types and unconsolidated materials over that last few million years have resulted in a number of different landform types. With the exception of glaciers, these processes are still acting upon and modifying the land surface.

The following discussions of landforms include a description of the landform, the general description of the landform in the coastal zone, and an overview of engineering properties and geologic hazards associated with the surficial unit. Hazardous present-day geologic processes, such as floods and landslides, will be discussed later in this section (Section 3.d., Surficial Geologic Processes) and in Section 6a., Geologic Hazards. Landform characteristics are summarized in Table I-5. More detailed discussions of the landforms may be found in the indicated references. Beaches, seacliffs, dune land, marine terraces, flood plains (including stream terraces and tidal flats), glacial drift plains, and uplands are mapped on Figure 1-17.

Figure I-15

Summary of Late Pleistocene Glacial Events in Western Washington[§]



[§]After Flint, 1971.

Table I-5

Summary of Landform Characteristics

Landform	Surficial Geologic Units	Origin	Soil	Hazards and Suitability Characteristics
Beaches	Horizonally bedded fine- to medium-grained sand, sometimes mixed the gravel	Deposition by wave action	Sand	Ocean flooding, wave erosion, poor foundation strength, caving of excavations, minimal waste disposal
Sea Cliffs	None (erosional feature)	Wave erosion	None	Landslides, rockfall
Dune Land	Fine-grained sand with indistinct cross-bedding	Wind deposition	From unweathered sand to loamy sand with surficial humus	Wind erosion and deposition, ocean and ground-water flooding, potential for ground-water pollution, restricted waste disposal
Lakes and Marshes	Horizontally bedded sand, silt, and clay, rich in organic material; peat	Deposition by streams; entrapment of wind-blown sediments, vegetation growth and decay	Silty to clayey loams; muck; peat	Compressible soils, settling, liquefaction, flooding, high ground water
Tidal Flats	Horizontally bedded sand, silt, clay, and organic material	Ocean and river sediment winnowed by tidal action	Silty clay; loam; peat	Ocean flooding, liquefaction, settling, caving of excavations
Marine Terraces	Compact, horizontally bedded, deeply weathered sand and silt; pan development locally	Wave erosion followed by deposition, then uplift relative to sea level	Silt loam, silty clay loam, sandy loam, sand, silt	Ocean erosion, stream erosion, poor drainage locally

Table I-5 (cont.)

Landform	Surficial Geologic Units	Origin	Soil	Hazards and Suitability Characteristics
Floodplains	Sand, silt, clay, and gravel depending upon environment and source; mostly cross-bedded	Streams sediments deposited in channel and on floodplain surface as overbank deposits	Sandy loam, silty loam, silty clay loam, sometimes gravelly	Flooding, pending, settling, siltation, high ground water, caving of excavations
Stream Terraces	Sand, silt, clay, and gravel, depending upon environment and source; mostly cross-bedded	Older floodplain deposits left elevated above present floodplain after down-cutting of stream	More weathered than floodplain soils - silt loam, silty clay loam	Pending, high water table, stream-bank erosion
Glacial Drift Plains	Till, cross-bedded sands and gravels, horizontally bedded silt and clay	Deposition by glacier ice or by melt-water streams and lakes with glacier	Highly variable	Landslides, flooding, pending, high ground water, volcanic mudflows
Uplands	Thin, poorly developed soils overlying bedrock on moderate to steep slopes	Highlands being actively eroded by streams, ground water and mass wasting processes	Generally thin and immature; texture depends on underlying bedrock	Landslides, flash floods, forest fire

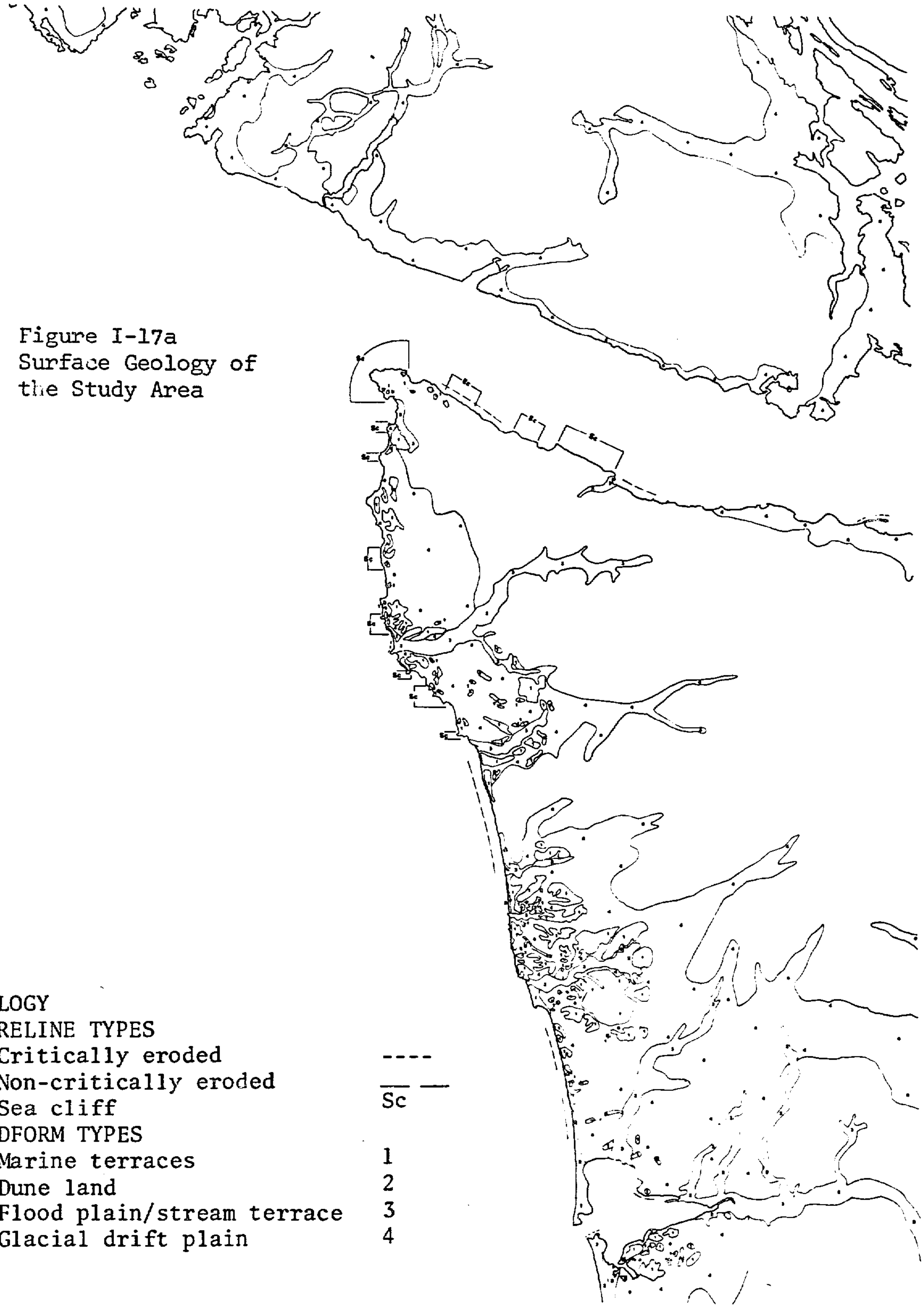


Figure I-17a
Surface Geology of
the Study Area

GEOLOGY

SHORELINE TYPES

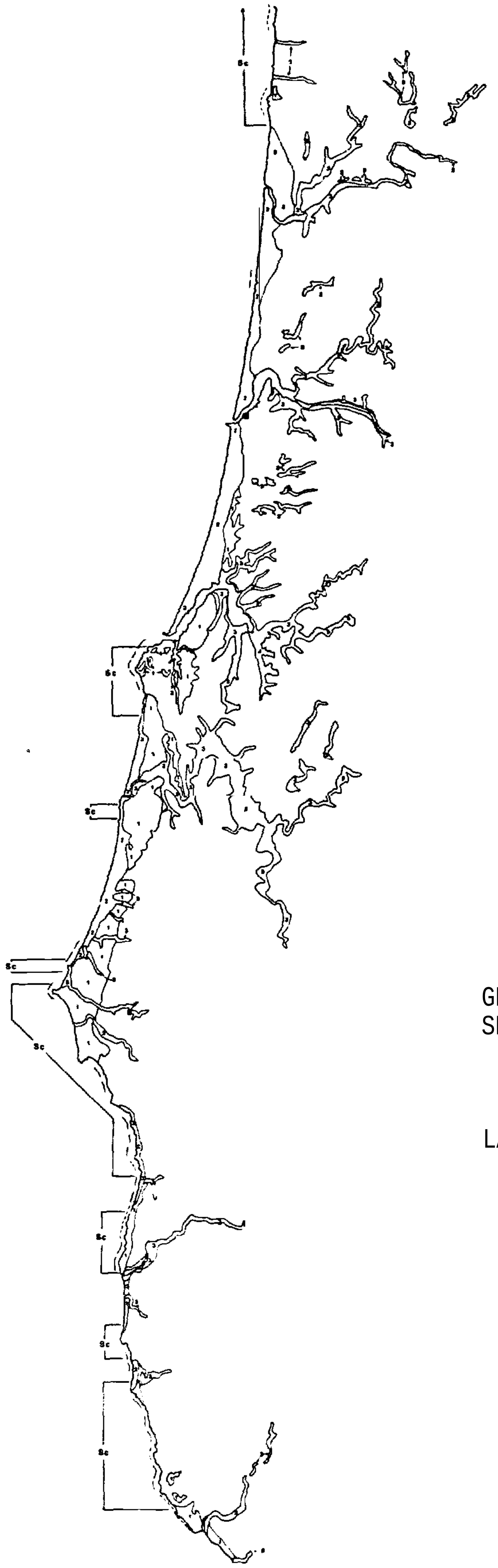
Critically eroded	----
Non-critically eroded	— —
Sea cliff	Sc

LANDFORM TYPES

Marine terraces	1
Dune land	2
Flood plain/stream terrace	3
Glacial drift plain	4

Figure I-17b

Figure I-17c



GEOLOGY

SHORELINE TYPES

Critically eroded	----
Non-critically eroded	— —
Sea cliff	Sc

LANDFORM TYPES

Marine terraces	1
Dune land	2
Flood plain/stream terrace	3
Glacial drift plain	4

Figure I-17d

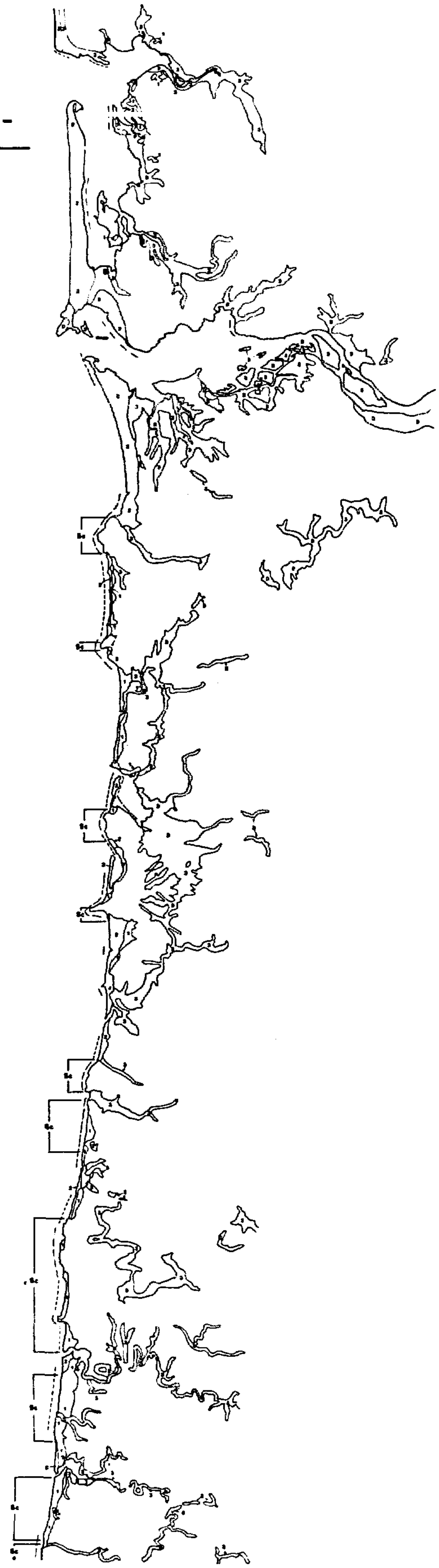
GEOLOGY

SHORELINE TYPES

Critically eroded	----
Non-critically eroded	— —
Sea cliff	Sc

LANDFORM TYPES

Marine terraces	1
Dune land	2
Flood plain/stream terrace	3
Glacial drift plain	4



i. Beaches. The Oregon and Washington coasts are quite diverse in the kinds of beaches present and their distribution. U.S. Army Corps of Engineers, North Pacific Division (1971), U.S. Soil Conservation Service and Oregon Coastal Conservation and Development Commission (1975), Lund (1971, 1972a, 1972b, 1973a, 1973b, 1974, 1975), Rau (1973), Dicken (1961), and Bauer (1974, 1975) provide a detailed physical description of the coastline. From the California border to Cape Blanco, the shoreline is rugged, characterized by cliffs and small bays. Coarse sands and gravels make up the narrow bay-head beaches. North of Cape Blanco to Coos Bay the beaches are narrow and sandy. From Coos Bay to the mouth of the Siuslaw River is a 85 km continuous stretch of broad, sandy beaches. The remaining Oregon coast, from the Siuslaw to the Columbia River, is composed of numerous short sandy beaches, broken by headlands, bays, and estuaries.

From the Columbia River north to the Quinault River the shoreline is predominantly flat, straight, sandy beaches abutted by dunes and gently sloping uplands. Rocky bluffs and cliffs dominate the coast from the Quinault River to Cape Flattery. Narrow, sandy to cobble beaches are irregularly interspersed along this stretch. Beaches along the Strait of Juan de Fuca, from Cape Flattery to Point Wilson, are typically narrow, backed up by steep bluffs of glacial drift. Exceptions to this are the large sand spits Ediz Hook and Dungeness Spit. The shoreline of Puget Sound and the Strait of Georgia is irregular, with narrow beaches composed of very fine sand to gravel. Beaches are frequently interrupted by rocky points and high, steep bluffs .

Beaches are formed by wave action and are therefore susceptible to frequent wave attack. Additional hazards include ocean flooding, tsunamis, possible liquefaction during moderate to strong earthquakes, differential settling, and caving of excavations. Beaches are transient, ever-changing landforms that result from the gross equilibrium between erosion and deposition. They are not suitable for development (Sorensen and Mitchell, 1975; Beaulieu and Hughes, 1975).

ii. Sea Cliffs. Sea cliffs are steep erosional faces that border the ocean without an intermediate beach. (For this report, the term sea cliff is not applied to the wave-cut edges of marine terraces or to steep bluffs of glacial drift -- both of which are faced by narrow beaches.)

Sea cliffs are frequently associated with rocky protrusions subjected to active wave erosion and thereby oversteepened, promoting rock fall and landslides. The eroded material, however, is removed so rapidly by wave action that beaches do not form. These types of sea cliffs are common along the Pacific Ocean coasts of Oregon and Washington. The other form of "sea cliff", originally eroded by glaciers, is common in the San Juan and Gulf Islands and on southern Vancouver Island.

Distribution of sea cliffs in the coastal zone of Oregon, Washington and southern Vancouver Island is irregular. Large-scale topographic maps (U.S. Geological Survey 7½ minutes series or the equivalent) or aerial photographs should be consulted for questions about specific areas.

Headlands undergo active erosion from rockfall and landslides, but the rate of retreat is usually quite slow. Therefore, building on headlands is usually not hazardous if structures are located back far enough from the edge of cliffs. Glacially eroded cliffs are usually stable.

iii. Dune Land. Dune land includes all areas underlain by semi-consolidated or unconsolidated windblown sand. Sand in dunes has an extremely narrow range in particle size. Almost all grains are between 1/8 and 1/2 mm in diameter (Cooper, 1958). Most grains are fragments of either quartz or feldspar; heavier minerals are left behind on the beaches where they may be concentrated locally as "black sands". Active dune landforms include traverse, oblique, and parabola dunes, active dune hummocks, and active foredunes (U.S. Soil Conservation Service and Oregon Coastal Conservation and Development Commission, 1975) . These forms are shown diagrammatically in Figure I-18. Cooper (1958) has noted that dunes can advance at rates ofup to nearly 3 m per year. At many places along the Oregon coast, dunes are advancing into forest. Detailed descriptions of dune features and characteristics may be found in Cooper (1958) and U.S. Soil Conservation Service and Oregon Coastal Conservation and Development Commission (1975) .

Dune land occurs along 62 percent of the ocean-facing shoreline in Oregon and along 17 percent in Washington. Sand dunes are not found along the shore of the Strait of Juan de Fuca, Strait of Georgia, or Puget Sound.

Active dune areas exist in a state of dynamic equilibrium, balancing the effects of wind, vegetation cover, and sand supply (Cooper, 1958) . Changes in any of these through development can initiate responses in either wind erosion or deposition. These relationships are examined more closely in Section 3.d.viii. , Wind Erosion and Deposition. Foredune areas are also subject to catastrophic wave erosion during storms (Beaulieu and Hughes, 1975; U.S. Soil Conservation Service and Oregon Coastal Conservation and Development Commission, 1975).

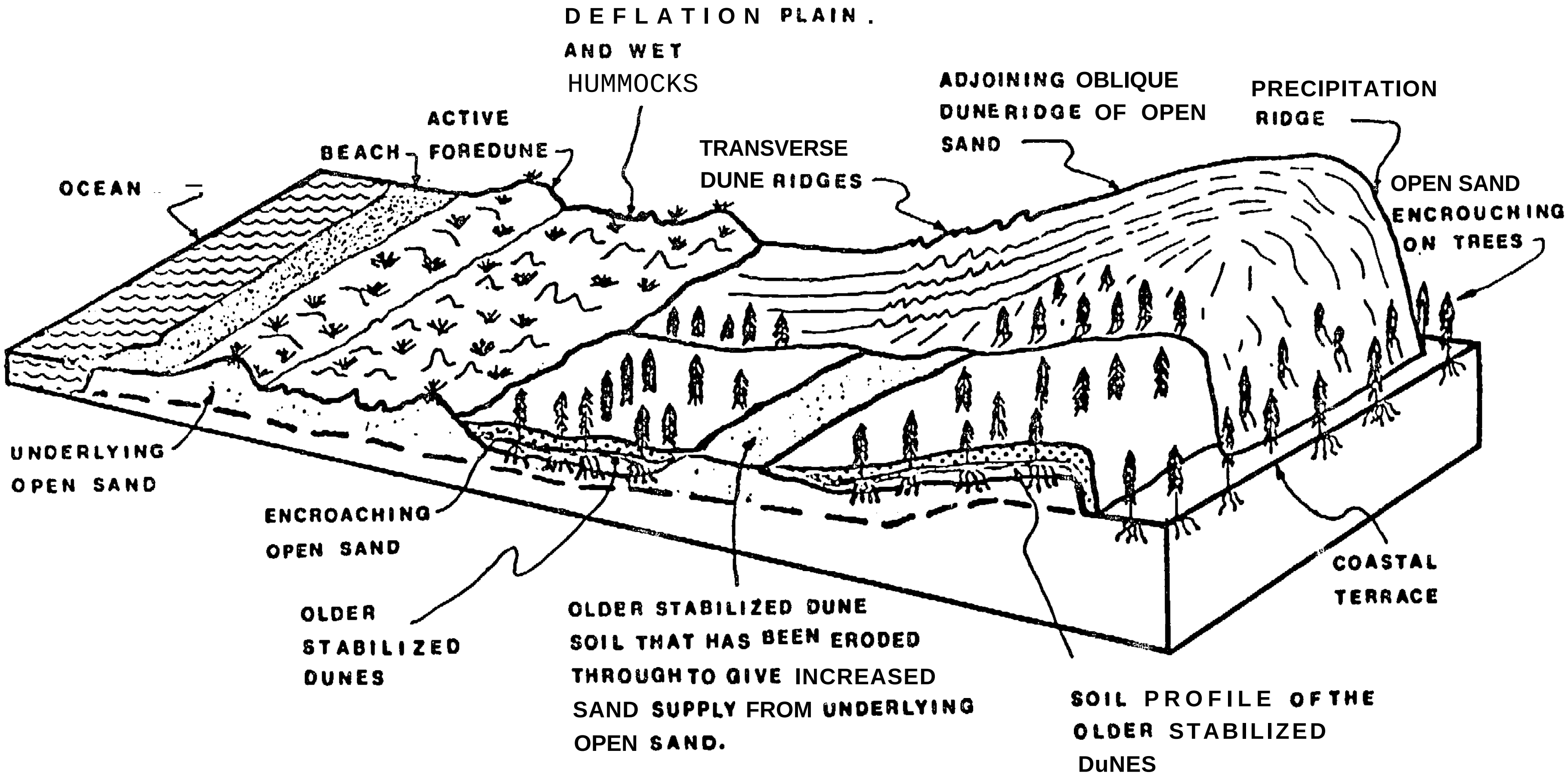
Infiltration rates and permeabilities are generally very high in dune areas, except in areas where high water tables have caused impermeable pans of iron-cemented sand to develop at shallow depths. Because of this, ground-water potential is excellent in dune areas, but so is the potential for ground-water pollution. Use of septic tanks and other such waste disposal practices can be safe only under strictly controlled conditions (Beaulieu and Hughes, 1975).

Foundation strength in sand dune areas is variable, owing to peat deposits that are frequently encountered in the subsurface. In areas of high water table, liquefaction may be induced by earthquakes or wide fluctuations in the water table. Localized quicksand conditions are sometimes encountered between dunes when ground water reaches the surface. Open excavations are subject to collapse and often promote wind erosion (Beaulieu and Hughes, 1975).

iv. Lakes and Marshes. Lakes and marshes are inland bodies of standing

Figure 1-18

Diagrammatic Sketch of Features Typical of Dune Land Along the Pacific Ocean Coast[§]



[§]/U.S. Soil Conservation Service and Oregon Coastal Conservation and Development Commission, 1975.

water and are differentiated on the basis of water depth and the' amount of vegetation growing in them. Most of the lakes and marshes along the Oregon and southern Washington coasts are situated immediately inland from beaches and dune lands. They are formed by the natural impoundment of streams through dune growth or represent the intersection of local depressions by the water table (Beaulieu, Hughes and Mathiot, 1974).

Along the Washington coast north of Grays Harbor and around Puget Sound, most lakes and marshes have a glacial origin, either directly or indirectly. They form where glacially scoured or dammed depressions intersect the water table and where impervious glacial sediments create a perched water table that intersects depressions in the ground surface. Marshes are also associated with tidal flats.

The surficial geologic units deposited in these lakes and marshes are water-rich silts and clays with varying amount of partially decayed organic matter or peat. Shifting streams and dune migration may bury these deposits under other surficial units. Consequently, the subsurface distribution of lake and marsh deposits may be much larger than the surface distribution, and can only be verified by digging or drilling. Areas of present-day marsh and peat development are recognized by abundant vegetation, low-lying and saturated ground, and sinuous drainage patterns (Beaulieu and Hughes, 1975).

Geologic patterns associated with lake and marsh deposits are high ground water, flooding, and caving of deep excavations. Peat is spongy and fibrous, with a high water content. When subjected to loads it compresses and expels the water, often causing uneven settlement of structures and roads. Under heavy loads it may spread laterally (Schlicker and Deacon, 1974; Beaulieu and Hughes, 197S).

v. Tidal Flats. Tidal-flat sediments are often buried beneath sand dunes and alluvium (flood plain deposits). Their thickness may vary from a meter to over 60 m. Flats may be bare or covered with marsh vegetation

Tidal flats can be found in each of the numerous estuaries along the Oregon and Washington coasts, including Puget Sound, near the mouths of major rivers, and in some spit-protected bays, such as at Dungeness Spit (Walters, [n.d.]; Beaulieu and Hughes, 1975; Schlicker and Deacon, 1974; Schlicker, *et al.*, 1972; University of Washington, Dept. of Geological Sciences, 1970).

Tidal flat sediments are constantly saturated and frequently reworked by tidal action. Hazards include possible liquefactions during earthquakes, caving of excavations, and exposure to tsunamis, tidal flooding, and storm surge. Peat and compressive clays are frequently found in the subsurface, offering poor foundation support. Because of constant saturation conditions, septic tanks and other such forms of waste disposal are probably unacceptable.

vi. Marine Terraces. Marine terraces are flat, wave-cut platforms along the coast that have been brought to their present positions by a combination of fluctuating sea level (eustatic change) and tectonic uplift of the land. The bedrock platforms are usually veneered by a combination of various unconsolidated sedimentary units, including beach deposits (sand and gravel), landslide and other mass-wasting deposits (colluvium), and fine grained, wind-blown sand. Terrace surfaces usually slope gently seaward because of the accumulated deposits (see Figure 1-19). Total thickness of these surficial geologic units may vary from just a meter to over 30 m. Elevations of marine terraces along the Washington-Oregon coast may vary from a meter to over 460 m above sea level (Palmer, 1967a; Palmer, 1967b; Beaulieu and Hughes, 1975).

Marine terraces can be found intermittently all along the Pacific Ocean coast of Oregon and Washington. They usually occur as fairly small terrace remnants, but in the Cape Blanco area of southern Oregon the terraces are well developed and extensive. Terraces are not found along the shore of the Strait of Juan de Fuca or in Puget Sound. Detailed descriptions and locations of terraces may be found in Palmer (1967a).

Gently sloping surfaces on marine terraces inhibit erosion and promote deep weathering of the deposits. Soils (Figure I-20) can vary from silt loam and silty clay loam on the older finer grained deposits to sandy loam, sand, and silt on the more recent wind-blown deposits. Iron-cemented pans (hard, impermeable layers) are often encountered in the soil horizons or deeper. Geologic hazards are generally greatest near the edges of the terrace deposits, where wave erosion, stream-bank erosion, and caving of deep excavations may occur. Drainage on marine terraces is generally good, although iron-cemented pans may cause bogs to form locally. Permeability depends on the nature of the material, and it can vary with depth and from site to site. Waste-water disposal must therefore depend on the nature of the surficial unit, local groundwater conditions, and the kind of waste-disposal technique proposed (Beaulieu and Hughes, 1975).

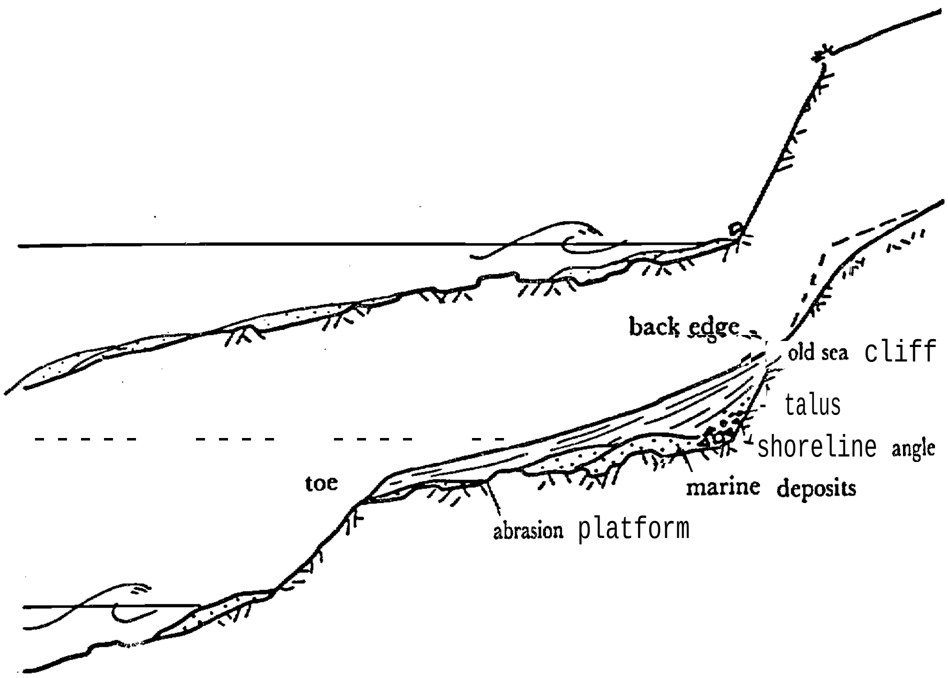
vii. Flood Plains. Flood plains are broad, flat, low-lying areas adjacent to streams and rivers that are subjected to flooding (under natural conditions) once every one to two years on the average. They are depositional features (Leopold, Wolman and Miller, 1964; Morisawa, 1968). Flood plain sediments of major rivers in the study area are predominantly sand and silt, with surficial layers of silt and clay. Small, steeper steams have flood plains composed of mostly sand and gravel (Schlicker and Deacon, 1974; Schlicker, *et* aZ., 1972; Schlicker, *et al.*, 1973; Beaulieu and Hughes, 1975; University of Washington, Dept. of Geological Sciences, 1970).

Flood plains of varying size may be found along nearly all streams that empty into salt water in the study area. In southern Oregon, where recent or present-day tectonic uplift appears to have been more vigorous than elsewhere, streams are downcutting more rapidly and flood plains tend to be much narrower than they are further north (Leopold, Wolman and Miller, 1964; Janda, 1970).

Soils developed on floodplain deposits tend to be complex, the combined results of floodplain deposition, weathering, and plant growth.

Figure I-19

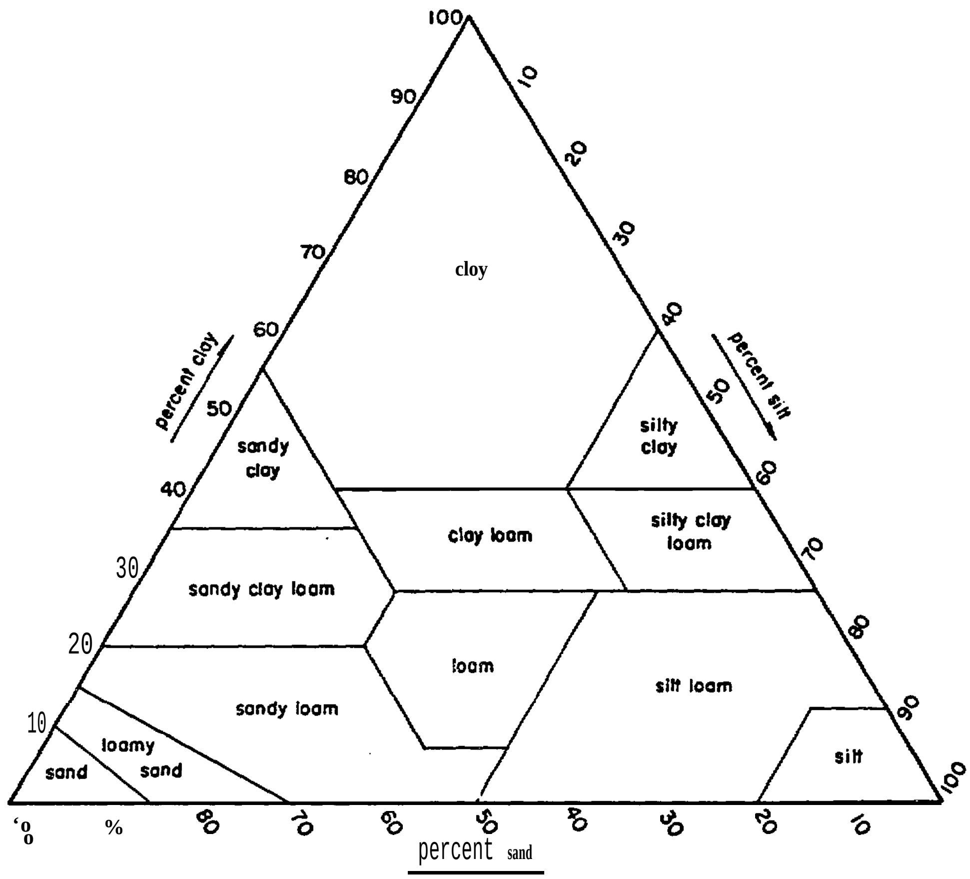
Diagrammatic Cross Section of a Marine Terrace During Formation Through Wave Erosion (Upper Profile) and After Modification by Marine Deposition, Uplift, and Mass Movement[§]



[§]After Palmer, 1967a.

Figure 1-20

Diagram Indicating How Soils Are Named on the Basis of Texture§



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§ Beaulieu and Hughes, 1975.

On larger flood plains, soil textures are generally silt loams, silty clay loams, or silts, with varying organic contents. Interbeds of peat and alluvium with abruptly changed grain size are common. The main hazards are flooding and high ground water. Other problems include siltation and settling of ground under structures. Alluvium is easily excavated, but prone to caving, especially in saturated areas. Infiltration and drainage depend on the local soil type, topography, and position of the water table. The water table is generally close to the ground surface the year-round and ground water production is good. Because of the high water table, septic tanks and other similar forms of waste disposal are not recommended (Beaulieu and Hughes, 1975).

viii. Stream Terraces. Stream terraces are remnants of old flood plains that are left behind after a stream cuts downward and forms a new floodplain at a lower elevation (Figure 1-21). Changes in stream and/ or sediment discharge, lowering of sea level, and tectonic uplift of the land can all promote downcutting and terrace formation (Leopold, Wolman and Miller, 1964; Morisawa, 1968).

Terrace deposits within the study area consist of the same type of material found in flood plains -- mostly gravel, sand, or silt at depth, mantled by silt or clay at the surface. The nature of the sediments depends on the type of bedrock available for erosion and the ability of the stream to transport the eroded sediments. Thickness of these deposits can vary from a few to many tens of meters (Schlicker and Deacon, 1974; Beaulieu and Hughes, 1975].

The flat surfaces of stream terraces most commonly have silt loam and silty clay loam soils developed in them. Drainage is usually moderate to poor because of the fine grained sediments at the surface, but terraces have less of a problem with high ground water than flood plains (Schlicker, *et al.*, 1973; Beaulieu and Hughes, 1975).

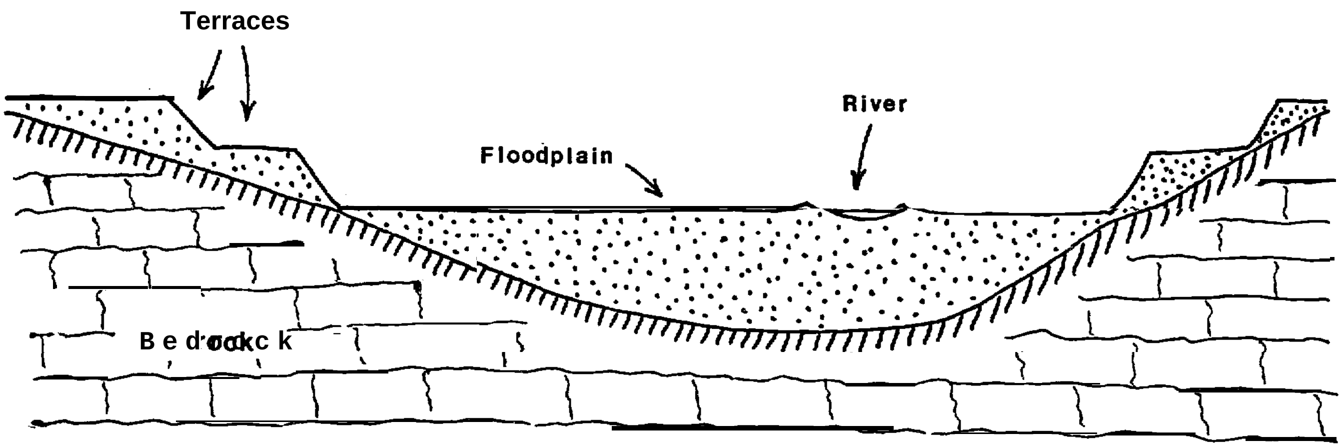
Geologic hazards include pending, stream-bank erosion along the edges, and high ground water. Where deposits are thin, characteristics of the underlying bedrock become a critical factor. Terrace deposits are well suited to development because they are flat, stable landforms with minimal hazards over large areas (Beaulieu and Hughes, 1975).

ix. Glacial Drift Plains. The Puget Lowland, the north coast of the Olympic Peninsula, and most of southern Vancouver Island were covered by glacier ice that flowed southward and westward out of the Fraser Lowland in Canada on at least four separate occasions during the Pleistocene Period (Crandell, 1965). These episodes of ice advance (glaciation) are termed, from oldest to youngest, the Orting, Stuck, Salmon Springs, and Fraser Glaciation. The periods of intervening warmer climate are referred to as the Alderton, Puyallup, and Olympic Interglaciations (see Figure 1-16) (Crandell, 1965). At least four separate alpine glaciation (ice advance out of the Cascade, Olympic, and Insular Mountains) are also known to have occurred, corresponding roughly with the advances of continental ice, but out of synchronization.

Ages of the older glaciation are not certain. The Orting and Stuck are thought to be early and/or middle Pleistocene. The Salmon

Figure 1-21

Diagrammatic Cross Section of a River Valley Showing Relative Positions of River, Floodplain and River Terraces[§]



[§]After Morisawa, 1968.

Springs appears to have an early Wisconsin age (ending roughly 35,000 years ago), and the main advance of the Fraser Glaciation is well established as a late Wisconsin event (from about 20,000 to 13,500 years ago for the central Puget lowland) (Flint, 1971).

Continental glacier ice reached beyond Olympia in the Puget Lowland (known as the Puget Lobe) and extended from the Olympics to the Cascades (see Figure I-22). It has been estimated that ice stood close to 1100 m thick over what is now Seattle and almost 2 km thick near the Canadian border (McKee, 1972). Another tongue of ice flowed westward out of the Strait of Juan de Fuca. Because the Fraser Glaciation was the most recent, its deposits conceal the earlier sediments, except in the southeastern and southwestern parts of the Puget Lowland (Crandell, 1965).

The glaciers left behind a complex stratigraphy. Although the erosion caused by the last advance is responsible for much of the landscape we see today, the lithologic nature of the glacial sediments is more important to the land-use planner and developer. In general, these glacial deposits include silts and clays deposited in ice-dammed lakes, beds of sand and gravel left by meltwater streams, and layers of till (unsorted, unstratified sediment that is carried, deposited, and sometimes overridden by the glacier). Between these glacial units are interglacial sequences of alluvial sands and gravels, local lakebed and peat deposits, and occasional volcanic mudflows that moved westward into the lowlands from the Cascades (Easterbrook, 1962; Mullineaux, Waldron and Rubin, 1965; Crandell, 1965).

Stratigraphic relationships vary considerably from place to place in the glaciated lowlands. Figures I-23 and I-24 demonstrate some of this variation. However, a generalized sequence of impermeable silt and clay beds overlain by outwash sand and gravel and finally capped by till is characteristic of the upper section of much of the Puget Lowland (Figure I-25) (Mullineaux, Waldron and Rubin, 1965; Tubbs, 1975). On the north side of the Olympic Peninsula, much thicker beds of outwash sand and gravel are exposed in the wave-cut bluffs. Continuing west and then south to the Quillayute River one encounters a sequence of glacial drift deposited by the Juan de Fuca Lobe. Surficial deposits south of the Quillayute River one encounters a sequence of glacial drift deposited by the Olympic Mountains alpine glaciers and meltwater streams, partially reworked by wave action during higher stands of sea level (Moore, 1965; Carson, 1970). On Vancouver Island, the generalized sequence includes two sets of glacial deposits and a thick intervening succession of non-glacial deposits capped by varied late-glacial and post-glacial marine and fluvial deposits (Fyles, 1963).

Geologic hazards associated with glacial drift vary with topography and sediment type, but may include landsliding (usually on slopes greater than 15% and near the edges of wave-cut bluffs), stream flooding, and pending and high ground water.

x. Uplands. Uplands is a general term referring to the regions of moderately to stepply sloping terrain that lie inland from beaches, dune land, glacial drift plains, marine terraces, and the lakes and marshes of the coastal areas, and upslope from the bottomlands of

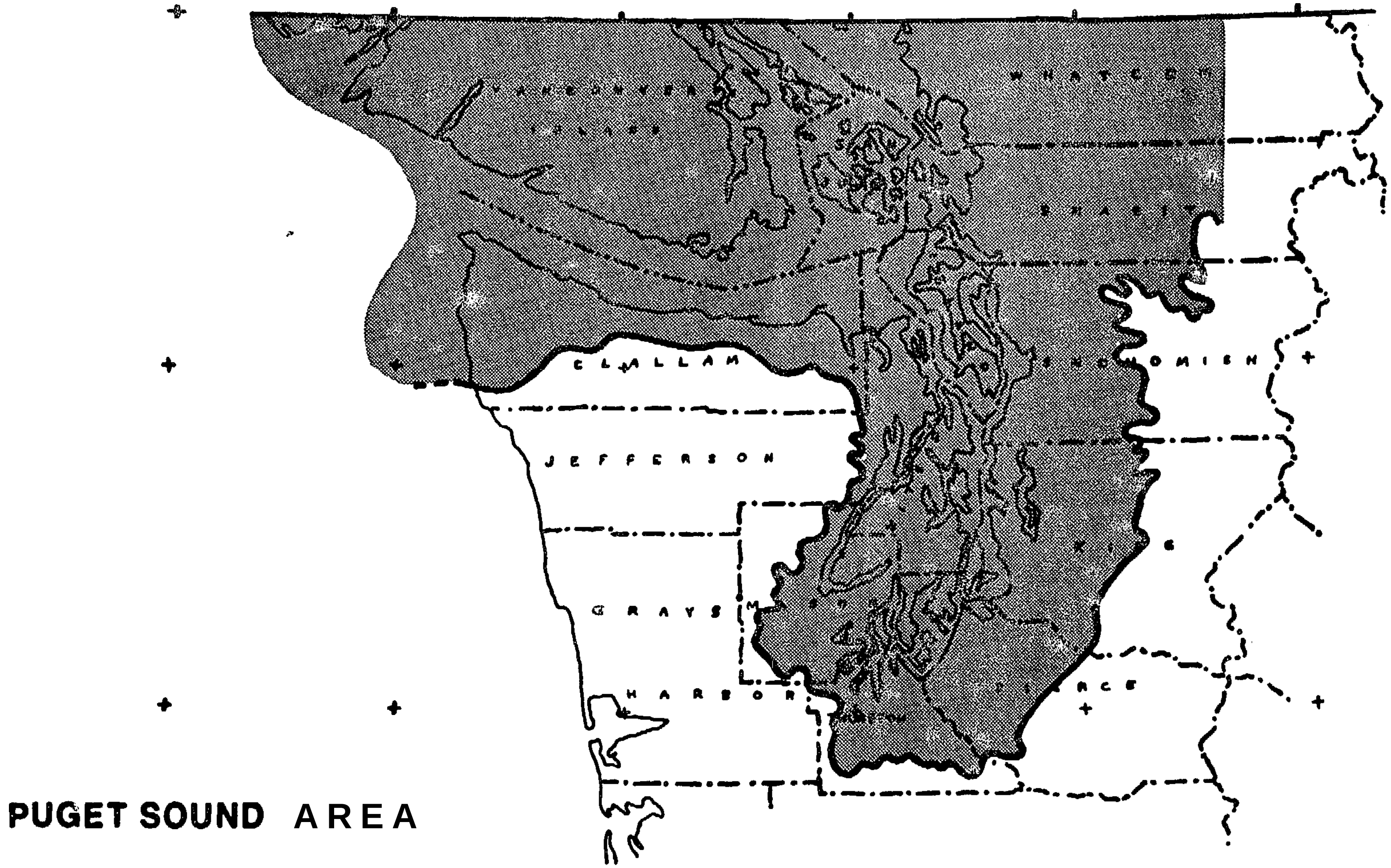
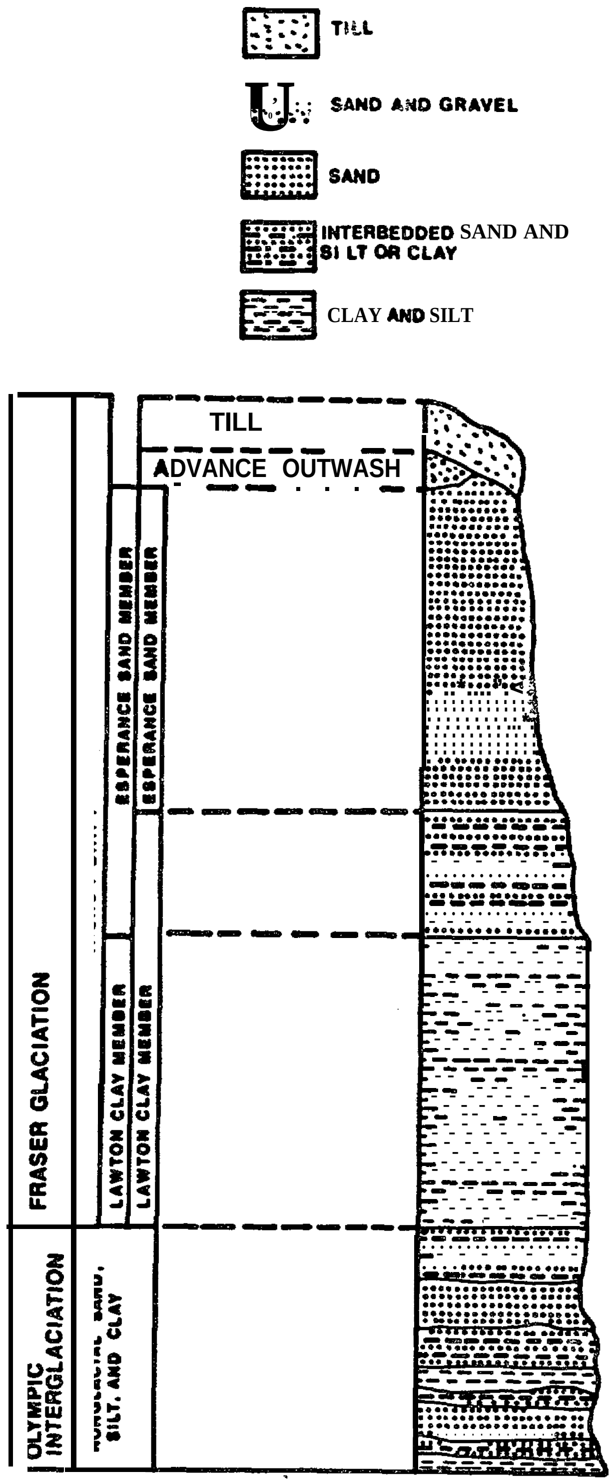


Figure I-22

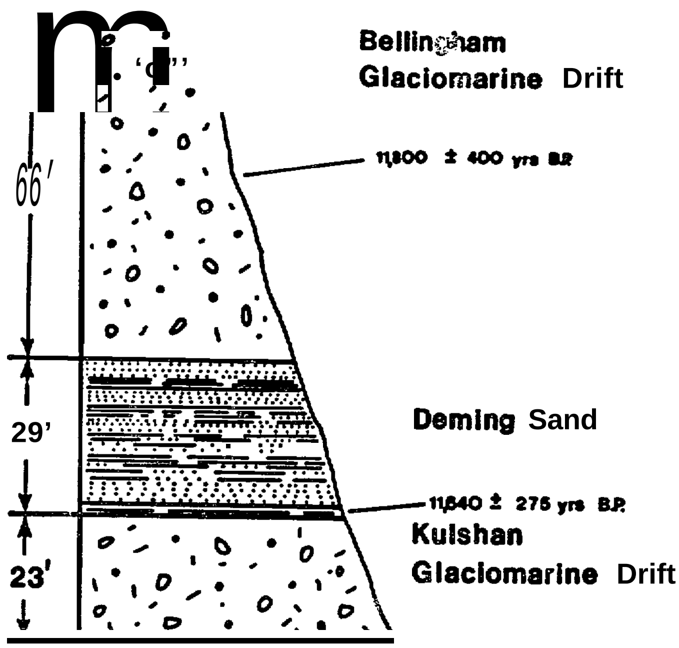
Maximum Extent of Continental Glacier Ice
During the Last (Fraser) Glaciation[5]

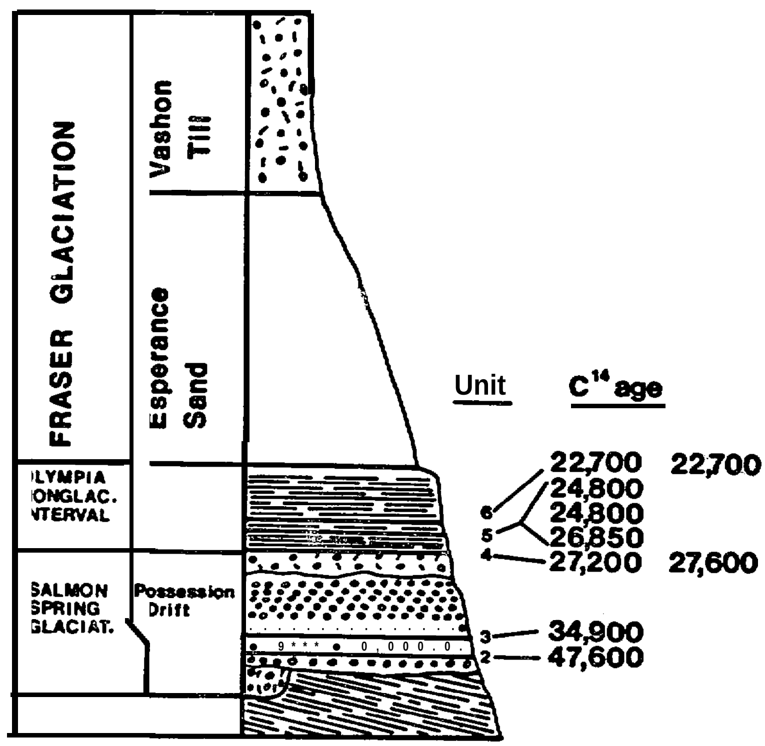
[5]McKee, 197?.

Figure I-23
Stratigraphic Relationships at Three Different
Locations in the Puget Lowlands§



STRATIGRAPHY OF LATE OLYMPIA INTERGLACIAL
AND FRASER GLACIAL SEDIMENTS IN SEATTLE

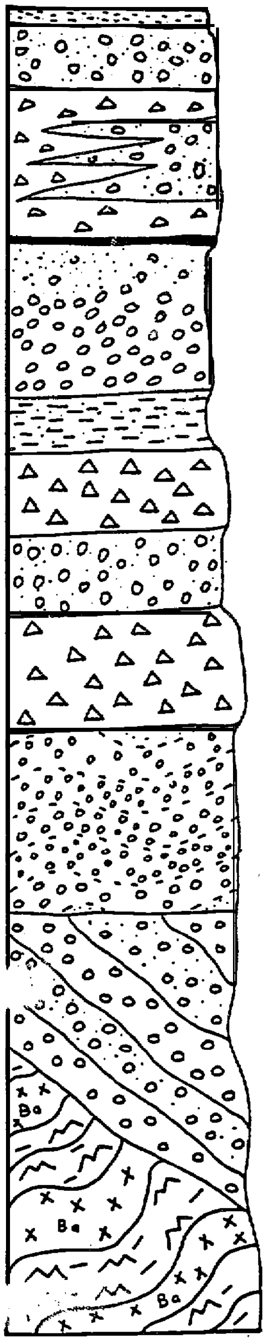




§Tubbs, 1975.
†Hanson and Easterbrook, 1974.

Figure I-24

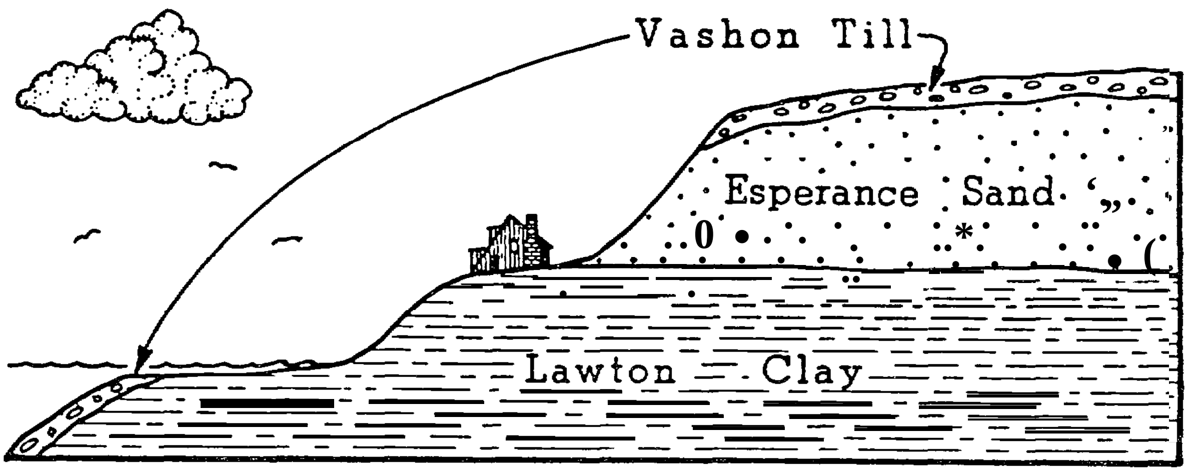
Generalized Stratigraphic Section - Southwest Olympic Peninsula§



§Moore, 1965.

Figure I-25

Generalized Glacial Stratigraphy
of the Seattle Area



streams. Except for sea cliffs, headlands along the coast are considered uplands for this report. Uplands are subject to continuous weathering and erosion, primarily through the action of ground water, streams and mass wasting (landslides, rock fall, and soil creep).

Soils in upland areas are generally poorly developed, relatively thin and, in steep terrain, unstable. Because of this, the engineering properties of the bedrock should be considered if development is planned. Geologic hazards are significant and include landslides (slumps, debris flows, rock fall), flash floods, and forest fires. Drainage is generally good, but, because impervious bedrock is so close to the surface, ground water potential is poor. Due to the thin soils and rapid runoff, pollution problems could arise where septic tanks and other similar forms of waste disposal are practiced (Beaulieu and Hughes, 1975).

c. Soils.

i. Definition. Definitions of soil vary widely. For this report, soil is the unconsolidated mineral and organic material at the earth's surface, weathered in place over a period of time and differing from its parent material in both chemical and physical properties. This definition is more restrictive than that used by many agronomists, who limit their definition to that material capable of supporting plant growth, and it is more restrictive than the definition employed by many engineers, who consider soil to be all unconsolidated material overlying bedrock. It is a definition consistent with the methods of sampling (limited to the upper 1.5 to 2 m) used by the U.S. Soil Conservation Service and it emphasizes the unique characteristics of the weathered zone (Beaulieu and Hughes, 1975).

Weathering processes include the chemical, biological and physical breakdown of minerals, chemical reconstitution into mineral forms, and leaching of dissolved minerals out of the system. Any particular soil is a unique result of the parent material, topographic setting, climate, biological activity, and time. Because chemical and physical conditions vary vertically in soil, horizons of different texture and compositions develop (Beaulieu and Hughes, 197S; Brady, 1974).

The upper, or A, horizon is the zone of leaching and clay removal. It is the zone of maximum mixing and organic activity. Iron oxide, carbonates, and other soluble ions are removed from this horizon. The middle (B) horizon is the zone of accumulation for suspended material and iron oxide, which gives it a characteristic reddish or orange color. The lower (C) horizon is the transition zone to the underlying parent material (either bedrock or unweathered surficial deposits). Consequently, it is composed of partially weathered and decomposed rock and mineral fragments. In some environments, such as flood plains, dune land, and tidal flats, deposition is sometimes uninterrupted and weathering does not have a chance to modify the sediments to form a soil at the surface (Beaulieu and Hughes, 1975; Brady, 1974).

ii. Systems of Soils Classification. Soils are mapped and classified in different ways, depending on the planned utilization of the land. Traditionally, most soils mapping has been aimed at agricultural uses.

The recently adopted Seventh Approximation System of Soils Classification (Comprehensive Soil Survey System] (Table I-6) is used by agencies of the U.S. Dept. of Agriculture, including the U.S. Soil Conservation Service -- the agency responsible for most of the published soil surveys in the United States. Other major classification systems are the Unified Soils Classification (Table I-7), used by the U.S. Army Corps of Engineers, and the AASHO (American Association of State Highway Officials) System (Table I-8), utilized by the U.S. Bureau of Reclamation and other government agencies. Comparison of the particle size boundaries employed by these three systems is given in Table 1-9. Another system specifically aimed at forest management practices and associated slope stability problems was recently developed at the Siuslaw National Forest for upland terrain in that jurisdiction of the central part of the Oregon coastal zone (Badura, Legard and Meyer, 1974].

iii. Soils of the Coastal Zone. It is impractical to describe all the mapped soil units within the study area for this report. Table I-10 refers the reader to more detailed reports of soil conditions. Soil groups in this region are described in a very generalized way. Table I-11 provides definitions of soil terminology.

Soils in the Klamath Mountains region (Inceptisols and Alfisols) are described as dominantly light-colored, medium to slightly acid, loamy, and commonly stony and shallow. Soils of the Pacific coastal lowlands, including dune land, marine terraces, and flood plains, generally fall into the categories of Spodosols, Inceptisols, and Entisols. These soils are strongly acid, and usually dark and deep. Poorly drained silty and clayey soils are common in flood plains and estuaries. Sandy Spodosols, commonly with iron-cemented subsoils (pans) occur on lower marine terraces. Entisols are found on younger sand dunes. Soils of the upland areas of the Coast Range Province are predominantly Inceptisols, Alfisols, and Ultisols. They vary from dark, loamy or clayey soils to shallow, stony and sandy soils. Deeper, reddish, clayey Ultisols are found on flatter, more stable slopes (Badura, Legard and Meyer, 1974; Loy, *et al.*, 1976).

In Washington State, soils along the coast are Inceptisols, Spodosols, and Alfisols, except in dune areas and flood plains. They are deep, strongly acid, predominantly silt loam to silty clay soils developed on glacial drift, sandstone, and shale. Soils in the Olympic Mountains are Inceptisols, Mollisols, Ultisols, and Alfisols -- medium acid to extremely acid, sandy and silty loam soils developed on glacial drift, shale, and basalt. In the Puget Lowland and the coastal strip north of the Olympic Mountains soils are predominantly Inceptisols, Mollisols, and Spodosols. These are moderately deep to deep, imperfectly drained to somewhat excessively drained, sandy, sandy loam, and silt loam soils formed on glacial drift. This classification also includes most of the soils of the San Juan Islands (Chapin, 1968).

d. Surficial Geologic Processes.

i. Stream Flooding. Floods occur when stream channels can no longer contain all the water in them, resulting in bank overflow and inundation of lowlands. Under natural conditions, streams can be expected to overtop their banks every one to two years on the average

Table I-6

Names of Soil Orders in the Comprehensive Soil Classification System and Approximate Equivalents in the Old System[§]

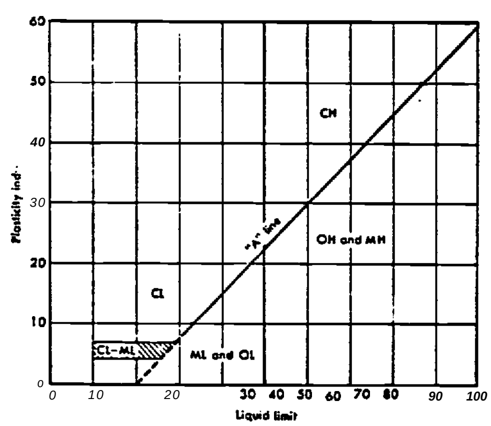
Name	Approximate Equivalents in the Old System
Entisol	Azonal, some Low-Humic Gley soils
Vertisol	Grumusols
Inceptisol	Ando, Sol Brun Acide, some Brown Forest, Low-Humic Gley, and Humic Gley soils
Aridisol	Desert, Reddish Desert, Sierozem, Solonchak, some Brown and Reddish Brown soils and associated Solonetz
Mollisol	Chesnut, Chernozem, Brunizem (Prairie), Rendzinas, some Brown, Brown Forest, and associated Solonetz and Humic Gley soils
Spodosol	Podzols, Brown Podzolic soils, and Groundwater Podzols
Alfisol	Gray-Brown Podzolic Gray Wooded, and Non-Calcic Brown soils, Degraded Chernozems and associated Planosols and some Half-Bog soils
Ultisol	Red-Yellow Podzolic soils, Reddish-Brown Latertic soils of the U.S., and associated Planosols and Half-Bog soils
Oxisol	Laterite soils, Latosols,
Histosol	Bog soils

[§]Brady, 1974.

Table I-7

Unified Soil Classification System[§]

Major divisions			Group symbols	Typical names	Laboratory classification criteria	
Coarse-grained soils (More than half of material is larger than No. 200 sieve size)	Gravels (More than half of coarse fraction is larger than No. 4 sieve size)	Clean gravels (Little or no fines)	GW	Well-graded gravels, gravel-sand mixtures, little or no fines	Determine percentages of sand and gravel from grain-size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size), coarse-grained soils are classified as follows: Less than 5 per cent ... GW, GP, SW, SP; More than 12 per cent ... GM, GC, SM, SC; 5 to 12 per cent ... Borderline cases requiring dual symbols**	$C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ between 1 and 3
			GP	Poorly graded gravels, gravel-sand mixtures, little or no fines		Not meeting all gradation requirements for GW
		Gravels with fines (Appreciable amount of fines)	GM* d / u	Silty gravels, gravel-sand-silt mixtures		Atterburg limits below "A" line or P.I. less than 4 — Above "A" line with P.I. between 4 and 7 are borderline cases requiring use of dual symbols
			GC	Clayey gravels, gravel-sand-clay mixtures		Atterburg limits above "A" line with P.I. greater than 7
	Sands (More than half of coarse fraction is smaller than No. 4 sieve size)	Clean sands (Little or no fines)	SW	Well-graded sands, gravelly sands, little or no fines		$C_u = \frac{D_{60}}{D_{10}}$ greater than 6; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ between 1 and 3
			SP	Poorly graded sands, gravelly sands, little or no fines		Not meeting all gradation requirements for SW
		Sands with fines (Appreciable amount of fines)	SM* d / u	Silty sands, sand-silt mixtures		Atterburg limits below "A" line or P.I. less than 4 — Limits plotting in hatched zone with P.I. between 4 and 7 are borderline cases requiring use of dual symbols.
			SC	Clayey sands, sand-clay mixtures		Atterburg limits above "A" line with P.I. greater than 7
Fine-grained soils (More than half of material is smaller than No. 200 sieve)	Silts and clays (Liquid limit less than 50)		ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity	Plasticity Chart (see below)	
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays		
			OL	Organic silts and organic silty clays of low plasticity		
	Silts and clays (Liquid limit greater than 50)		MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts		
			CH	Inorganic clays of high plasticity, fat clays		
			OH	Organic clays of medium to high plasticity, organic silts		
	Highly organic soils		Pt	Peat and other highly organic soils		



Plasticity Chart

LEGEND * Division of GM and SM groups into d and u are for roads and airfields only. Subdivision is based on Atterburg limits; suffix d used when L.L. is 28 or less and the P.I. is 6 or less; the suffix u used when L.L. is greater than 28.

** Borderline classification, usef for soil possessing characteristics of two groups, are designated by combinations of group symbols. For example, GW-GC, well graded gravel-sand mixture with clay binder.

§ Beaulieu and Hughes, 1975.

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Table I-8

American Association of State Highway Officials (AASHO) Soils Classification[§]

General classification			Group symbols	Grain size (sieve)	Atterburg limits for fraction passing No. 40: Liquid limit	Plasticity index*	
Granular materials Less than 35% is smaller than No 200 sieve	Stone fragments gravel and sand	A-1	A-I-a	50% max. passes No. 10 3W4 mox. posses No. 40 15% max. passes No. 200		Less then 6	Good to excellent subgrade
			A-1 -6	50% mox. passes No. 40 25%max. posses No .200			
	Fine sand	A-3	A.3	50% min. posses No. 40 10% max. passes No .200		N.P.	
	Silty or clayey gravel and sand	A .2	A-2-4	35% max. passes No. 200	Less than 40	Less than 10	
			A-2-5		Greater than 40	Less than 10	
			A-2-6		Less than 40	Greater than 10	
			A-2-7		Greater than 40	Greater than 10	
More than 35% is smalle than No 200 sieve	Silty soils	A-4	A-4	Greater than 35% passes No. 200	Less than 40	Less than 10	Poo to fai subgrade
		A-5	A-5		Greater than 40	Less than 10	
	Clayey soils	A-6	A-6		Less than 40	Greater than 10	
		A-7	A-7-5 and A-7-6		Greater than 40	Greater than 10	

*The difference between liquid limit and plastic limit; the range of water content through which the soil behaves plasticly.

§. From Beaulieu and Hughes, 1975.

Table I-9

Comparison of Three Systems of Soil Particle-Size Classification§

System	Classes (fine to coarse)
American Association of State Highway Officials - soil classification	Colloids · Clay · Silt · Fine sand · Coarse sand · Fine gravel · Medium gravel · Coarse gravel · Boulders
U.S. Department of Agriculture - soil classification	Clay · Silt · Very fine sand · Fine sand · Medium sand · Coarse sand · Very coarse sand · Fine gravel · Coarse gravel · Cobbles
Unified soil classification U.S. Army Corps of Engineers Bureau of Reclamation, Dept. of Interior	Fines (silt or clay) · Fine sand · Medium sand · Coarse sand · Fine gravel · Coarse gravel · Cobbles
Sieve sizes - U.S. standard	270 · 200 · 140 · 60 · 40 · 20 · o · 4 · 1/2" · 3/4" · 3"
Particle size - millimeters	.001 · .002 · .003 · .004 · .006 · .008 · .01 · .02 · .03 · .04 · .06 · .08 · .1 · .2 · .3 · .4 · .6 · .8 · .0 · 2.0 · 3.0 · 4.0 · 0 · m.0 · 10 · 20 · 30 · 40 · 60 · 80

§Beaulieu and Hughes, 1975.

Table 1-10

Soil Condition Data Available for the Coastal Counties of Washington and Oregon

COUNTY	SOILS	GROUND WATER	SURFICIAL NAPPING	HAZARDS
CURRY	Beaulieu and Hughes, 1976 Buzzard and Bowesby, 1970	Beaulieu and Hughes, 1976	Beaulieu isnd Hughes, 1976 Lund, 1975	Beaulieu and Hughes, 1976 U.S. Federal Insurance Administration (in progress)
COOS	Beaulieu ond Hughes, 197s	Beaulieu and Hughes, 197.5 Brown and Newcomb, 1963 U.S. Geological Survey (in progress)	Beaulieu and Hughes, 1975 Baldwin and Beaulieu, 1973	Beaulieu and Hughes, 1975 U.S. Federal Insurance Administration (in progress)
DOUGLAS	Beaulieu and Hughes, 197s Pomerening and Simonson, 1976	Beaulieu and Hughes, 197S	Beaulieu and Hughes, 1975	Beaulieu and Hughes, 197S U.S. Army Corps of Engineers, Portland District, 1966 U.S. Federal Insurance Administration (in progress)
LANE	Schlicker and Deacon, 1974	Schlicker and Deacon, 1974 Hampton, 1963	Lund, 1971 Schlicker and Deacon, 1974 Feiereisen (in progress)	Schlicker and Deacon, 1974 U.S. Federal Insurance Administration (in progress)
LINCOLN	Schlicker, et aZ., 1973 Corliss, 1973	Schlicker, *et al.*, 1973 Frank and Laener (in progress) U.S. Geological Survey (in progress)	Lund, 1972b, 1974 Schlicker, *et al.*, 1973	Schlicker, *et al.*, 1973. Komar and Rea, 1976 Stembridge, 197S U.S. Federal Insurance Administration (in progress)
TILLAMOOK	Schlicker, *et al.*, 1972	Schlicker, *et al.*, 1972	Lund, 1972a Schlicker, et aZ., 1972	Schlicker, *et al.*, 1972 Terich and Komar, 1973 Komar (in progress) U.S. Federal Insurance Administration (in progress]
CLATSOP	Schlicker, et *al.*, 1972	Schlicker, *et al.*, 1972 Frank, 1970	Lund, 1972 a Niem, 197S Schlicker, *et* al., 1972 Carter (in progress)	Schlicker, *et al.*, 1972 Carter (in progress) U.S. Federal Insurance Administration (in progress]
WAHKIAKUM	Pringle, et *al.*, (in progress)	nothing available -- mostly surface-water utilization in this count y	Wolf and McKee, 1968	U.S. Federal Insurance Administration (in progress)
PACIFIC	Pringle, *et al.*, (in progress)	U.S. Geological Survey (in progress)	Wolfe and McKee, 1968	Pacific Co. Regional Planning Comm., 1974 U.S. Federal insurance Administration (in progress)
GRAYS HARBOR	Pringle, et aZ., (in progress)	Eddy, 1966	Moore, 1965 Rau, 1973, 197S Eddy, 1966 Carson, 1970	U.S. Federal Insurance Administration (in progress)

Table I-10 (cont.)

COUNTY	SOILS	GROUND WATER	SURFICIAL MAPPING	HAZARDS
MASON	Fowler, Parbin and Roberts, 1960	Molenaar and Noble, 1970	Molenaar and Noble, 1970	Smith (in progress) Gryta (in progress) Wilson (in progress) U.S. Federal Insurance Administration (in progress)
JEFFERSON	McCreary, 1975		Rau, 1973	Gryta (in progress) Carson, et *al.* S (in progress) U.S. Federal Insurance Administration (in progress)
CLALLOW	Smith, Olsen end FOX, 19s1	Noble, 1960	Noble, 1960 Brown, Gower and Snavely, 1960 Horn (in progress) Horn and Othberg (in progress) Othberg (in progress)	U.S. Army Corps of Engineers, 1971 Watters, U.S. Federal Insurance Administration (in progress)
THURSTON	Glassey, *et al.*, 19S8	Noble and Wallace, 1966 Wallace and Molenaar, 1961	Noble and Wallace, 1966 Wallace end Molenaar, 1961	Artim, 1976a, 1976b, 1976c U.S. Federal Insurance Administration (in progress)
PIERCE	Anderson, Ness and Anderson, 195s	Griffin, et *al.*, 1962 Walters and Kimmel, 1968	Walters and Kimmel, 1968 Smith, 1972 Fiksdal (in progress)	Smith, 1976a, 1976b U.S. Federal Insurance Administration (in progress)
KING	Poulson, 19S2 Snyder, Gale and Pringle, 1973	Liesch, Price and Walters, 1963 Luzier, 1969	Liesch, Price and Walters, 1963 Livingston, 1963 Mullineaux, Waldron and Rubin, 1965	Miller, 1973 Tubbs, 1974a, 1974b, 1975 U.S. Federal Insurance Administration (in progress)
KITSAP	Wildermuth and Perkins, 1939	Garling, et *al.*, 196S	Garling, et *al.*, 196S Deeter (in progress)	Bauer, 1975a U.S. Federal Insurance Administration (in progress)
ISLAND	Ness and Richins, 1958	Anderson, 1968 U.S. Soil Conservation Service, 1969	Easterbrook, 1968 Thorsen (in progress)	Thorsen (in progress) U.S. Federal Insurance Administration (in progress)
SNOHOMISH	Anderson, et al., 1947	Eddy, 1971 Grimstad, 1971 Newcombe, 1952	Grimstad, 1971 Smith, 1976a, 1976b	U.S. Army Corps of Engineers, 1967 U.S. Federal Insurance Administration (in progress)
SKAGIT	Ness, Buchanan and Richins, 1960	Grimstad, 1971	Grimstad, 1971	U.S. Army Corps of Engineers, 1965 Cheney (in progress) Artim (in progress) U.S. Federal Insurance Administration (in progress)

Table 1-10 (cont.)

COUNTY	SOILS	GROUND WATER	SURFICIAL NAPPING	HAZARDS
SAN JUAN	Schlots, *et al.*, 1962	Russell, 1975	Russell, 1975	Bauer, 1975a U.S. Federal Insurance Administration ({n progress)
WHATCOM	Poulson and Flannery, 19S3		Dames and Moore, 1976 Bayrock, 1976 Esterbrook, 1976	Bauer, 1975a, 197519, 1974 Whatcom Co. Planning Comm., 1972 Byrne, 1976 U.S. Federal Insurance Administration (in progress)
VANCOUVER ISLAND AND GULF ISLANDS	Day, Furstad and Laird, 1959	Fyles, 1963 Halstead, 1965 Foweraker, ongoing	Halstead and Treichel, 1966 Clapp, 1913, 1914 Halstead, 196S Halstead and Fulton, 1972	

Table 1-11

Definitions of Soil Orders[§]

Entisols:	These are recent soils that have not developed genetic horizons or have only begun to develop them.
Vertisols:	These are mineral soils that contain a high percentage of swelling-type clay minerals. They expand when wetted, and shrink and crack when dried. This behavior is often a problem for foundations and roads.
Inceptisols:	Inceptisols are weakly developed, immmature soils that show more profile development than Entisols, but less than in other soils. Clays and iron oxides have not yet accumulated markedly in the B-horizon.
Aridisols:	These soils are found principally in dry climates, and are characterized by horizons of accumulated soluble salts such as calcium carbonate and gypsum and by a light-colored surface horizon low in organic matter.
Mollisols:	Mollisols are easily worked soils suitable for agriculture and characterized by a thick dark surface horizon. Mollisols dominate in grassland areas.
Spodosols:	Spodosols usually form under forests in humid, temperate (to cold) climates. They are characterized by an accumulation of organic matter and aluminum oxides in a one subsurface horizon, which overlies a light-colored highly leached horizon.
Alfisols:	Alfisols appear to be more highly weathered than Inceptisols, but not as weathered as Spodosols. They also tend to form under forests (deciduous) and have gray to brown surface horizons overlying a zone of accumulation of bases and clay minerals.
Ultisols:	These are highly weathered reddish or yellowish soils containing accumulated clays and free iron oxides. They often form under forests.
Oxisols:	Oxisols are the most highly weathered soils in the classification system. Hydrous oxides or iron and aluminum predominate in the subsurface "oxic" horizon. Some quartz and clay minerals are usually also present, but the other original minerals have been leached out of the soil. These soils are common in warm, humid climates.
Histosols:	These are the organic soils (bog soils) that have developed in a water-saturated environment where organic material has been prevented from decaying by the lack of oxygen that typifies these environments. They contain at least 20% organic matter if clay content is low, and at least 30% organics-if clay content exceeds 50%.

[§]Brady, 1974.

(Leopold, Wolman and Miller, 1964). Because flood plains have been desirable locations for homes and for other forms of human activity, floods often result in deaths and serious economic losses.

Various means of predicting the occurrence and severity of floods do exist. The best methods are based on past flood records. Sophisticated mathematical models for predicting areas subject to flooding at various frequencies have been developed and flood maps published by the U.S. Army Corps of Engineers, U.S. Soil Conservation Service, and U.S. Geological Survey for major rivers in the study area. Offices of these agencies and county and other local planning agencies should be consulted as to the status of flood-zone mapping in their areas. An overview of flood plain management in Oregon and Washington can be obtained from the University of Oregon, Bureau of Governmental Research and Service (1971) and Washington Dept. of Ecology (1976].

Flood-hazard boundary maps (generalized) and flood-hazard studies for urbanized areas (detailed) are presently being prepared for all coastal counties in Washington and Oregon under the direction of the Federal Insurance Administration (Flood Insurance Studies). Coverage by these studies will eventually include all coastal areas subjected to flood hazard, both from stream and ocean flooding. Reports and maps are being prepared by the U.S. Army Corps of Engineers, U.S. Geological Survey, U.S. Soil Conservation Service, and private consultants (Federal Insurance Administration on-going studies). Flood information can also be obtained from the U.S. Geological Survey Water Supply Papers, which contain streamflow records from all parts of the United States. For small watersheds, useful flood data can be obtained from the Soil and Water Conservation Research Division of the Agricultural Research Service (U.S. Dept. of Agriculture). Some hydrologic data is also available from the U.S. Forest Service, although this information is usually not published (Dunne and Leopold, [1977?]).

For areas where there is little or no recorded data, flood-prone terrain can be deduced from topography, landforms, soils, vegetation cover, and other natural features. Deduction methods of this type are summarized in Dunne and Leopold ([1977?]).

a) Causes. Flooding results from heavy rainfall, when the storage capacity of the soil is exceeded and runoff moves quickly from hillslopes to the stream channels. Steep upland areas worsen the situation because they provide a steep hydraulic gradient for the runoff and relatively little storage capacity. Flash floods occurring in upland areas can cause catastrophic erosion and deposition.

At lower elevations, high water from many tributary creeks converges on the main channels, excess water overtops the stream banks, and flood waters flow out on the flood plains. Commonly, ocean flooding (high tides, storm surge) make flooding near the channel mouth much worse than it would otherwise be (Beaulieu and Hughes, 1975) . Artificial channel fill, construction in the floodway (part of the flood plain that conveys the fast-moving water), and even flood prevention measures can aggravate stream flooding. In this last instance, channelization and diking can seriously worsen flooding downstream from the modified section of channel by moving the flood waters downstream faster than they would normally flow, causing a higher flood peak to form downstream (Keller, 1976).

b) Distribution. Flooding is a geologic hazard along all major stream in the study area, unless flood-control measures have already been taken. Federal, state, county and local agencies can be consulted to assess the hazard in any particular area, and methods exist for calculating flood risk where data are not available (Dunne and Leopold, [1977?]).

ii. Ocean Flooding. Ocean flooding is the inundation of lowland areas by salt water due to storm surge, tidal flooding, or tsunamis (seismic sea waves). The highest levels affected by any of these processes varies from place to place along the coast and is a function of coast orientation and shallow-water configuration (Bascom, 1964). In rare instances, one or more of these processes may be superimposed on another, causing higher water levels than would otherwise be expected. Beaches, marshes, coastal lowlands (including flood plains) and low-lying dune land are all subject to ocean flooding.

a) Tidal Flooding. Causes of tides, controlling factors, and expected magnitudes at different locations along the Washington-Oregon coast, are treated in detail in Chapter III., Oceanography.

b) Storm Surge. Storm surge is the rise of sea level above predicted tide levels caused by low barometric pressure and wind. Local factors influencing the magnitude of storm surge include bottom gradient, shore slope, position of the coast relative to storm center, and harbor configuration (Bascom, 1964). A more detailed discussion of factors contributing to storm surge is found in Chapter III., Oceanography.

Ocean flooding caused by the combined effects of high tides and storm surges is common in winter, and results in considerable lowland flooding along the Pacific coast. The rise in sea level hinders stream drainage, further contributing to inland flooding. Because elevated base level (level of prevailing seas) rather than siltation causes this type of flooding, dredging and channel modification can not alleviate the flood problem in the lower reaches of coastal streams.

Storm surges allow waves to pass unbroken over coastal bars to break directly on beach and dune areas (Beaulieu and Hughes, 1975) .

c) Tsunamis. Tsunamis are high velocity, long period waves generated at sea by large shocks or impulses, such as earthquakes, underwater volcanic eruptions, huge landslides into water, or nuclear explosions. Tsunamis are difficult to detect at sea, having wave lengths of hundreds of kilometers and wave heights seldom exceeding one-third meter or so. Wave velocity is a function of water depth, but in parts of the Pacific velocities can exceed 720 km/hr. (Bascom, 1964; Beaulieu and Hughes, 1975).

As tsunamis move into shallow water approaching a coast, the height of these waves increase dramatically. Waves over 30 m high have been recorded (Beaulieu and Hughes, 197S). As a result of the 1964 "Good Friday" earthquake in Alaska, tsunamis ranging in height from about 1 to 5 m above mean high water were recorded in Oregon (Beaulieu and Hughes, 1975). The height of a tsunami at any given location depends on 1) the magnitude of the disturbance generating the tsunami, 2) attenuation with distance, 3) bathymetry, and 4) run-up. Tsunamis are discussed in detail in Chapter III., Oceanography.

Potential effects of tsunamis include flooding of tidelands and peripheral marshes and lowlands, damage to moorings, vessels, and structures built near the water, and injury or drowning of people on beaches, in isolated coves, and on low-lying terrain. The 1964 tsunami occurred late at night, but still caused four drownings and $700,000 damage in Oregon (Beaulieu and Hughes, 1975).

Tsunamis are a major hazard along the Pacific coast.

iii. High Ground Water and Pending. When the water table is close enough to the ground surface to cause problems, it is termed high ground water. Position of the water table can be determined from wells and surficial and soil features such as marshy ground, presence of reeds, marsh grass and horse tails (*Equisetum* sp.), depressions, high organic content of the soil, and blue-gray color and sometimes orange mottling of the soil. Pending is the local surface accumulation of runoff caused by depressions in the topography and low permeability of the underlying soil or bedrock.

High ground water and ponding can lead to 1) flooding of basements, underpasses, and other subsurface structures, 2) flotation or damage to buoyant structures such as pipelines, tanks, swimming pools, newly installed septic tanks, and basements, 3] differential settling of large to moderate-sized structures, and 4) complications in installation of underground facilities, including the danger of caving under excavation. Other problems include damage to roads and structures caused by "shrink-swell" behavior of clay- rich soils, liquefaction during earthquakes, and pollution of ground and surface water from septic systems and landfills (Beaulieu and Hughes, 1975).

A summary of all types of flooding that occur within the study area is presented in Table 1-12.

iv. Mass Movements. Mass movement is the downslope movement of rock and soil material in response to gravity. A number of different types of mass movement are recognized on the basis of nature of movement, rate of movement, type of material, and water content of the material. The various kinds of movement are diagrammatically shown in Figure I-26 and their characteristics are summarized in Table I-13. Landslide and rockfall terrain can usually be identified from aerial photos and on-site inspection. Soil creep is a very common and widespread form of mass movement, but it is difficult to recognize or evaluate without instrumenting the hill slope.

Mass movement occurs when shear stress on an earth mass (downslope component of gravitational force) exceeds the shear strength of

Table 1-12

Types of Flooding[s]

TYPE	VARIETY	DISTRIBUTION	CAUSES	IMPACT
STREAM FLOODING	Flash Flood	Interior uplands with slopes of 50% of greater and moderate to high relief.	Steep slopes, low infiltration capacities due to shallow soils, heavy rainfall.	Channel scour and streambank erosion; minimal bank overflow due to lack of floodplain.
	Lowland Stream Flood	Floodplains of streams and other wetland areas	Heavy rainfall, sometimes combined with effects of channel obstruction and ocean flooding.	Wide variety of structura and water damage, siltation of cropland, safety and health hazards, disruption of transportation,
OCEAN FLOODING	Tidal Flooding	Low-lying coastal areas including beaches and marsh. Highest tide varies with local conditions.	Daily and seasonal tidal variations	Salt-water inundation, aggravates stream flood-ing, covers mature high marsh.
	Storm Surge	Same as tidal flooding but additive to it.	Wind and low atmosphere pressure elevate local sea level; waves additional	Same as tidal flooding but additive to it; also includes severe wave erosion in places
	Tsunami (seismic sea wave)	Same as other ocean flooding but can inundate greater areas; amplitudes of 4.6 m possible; dissipation in estuaries; amplification at headlands.	Large magnitude earthquakes with epicenters under water or along coasts; large landslides into sea.	Loss of life to unwary beach combers, clammers, and residents at low elevations along coast; damage to moorings and other low-elevation structures; salt-water inundation

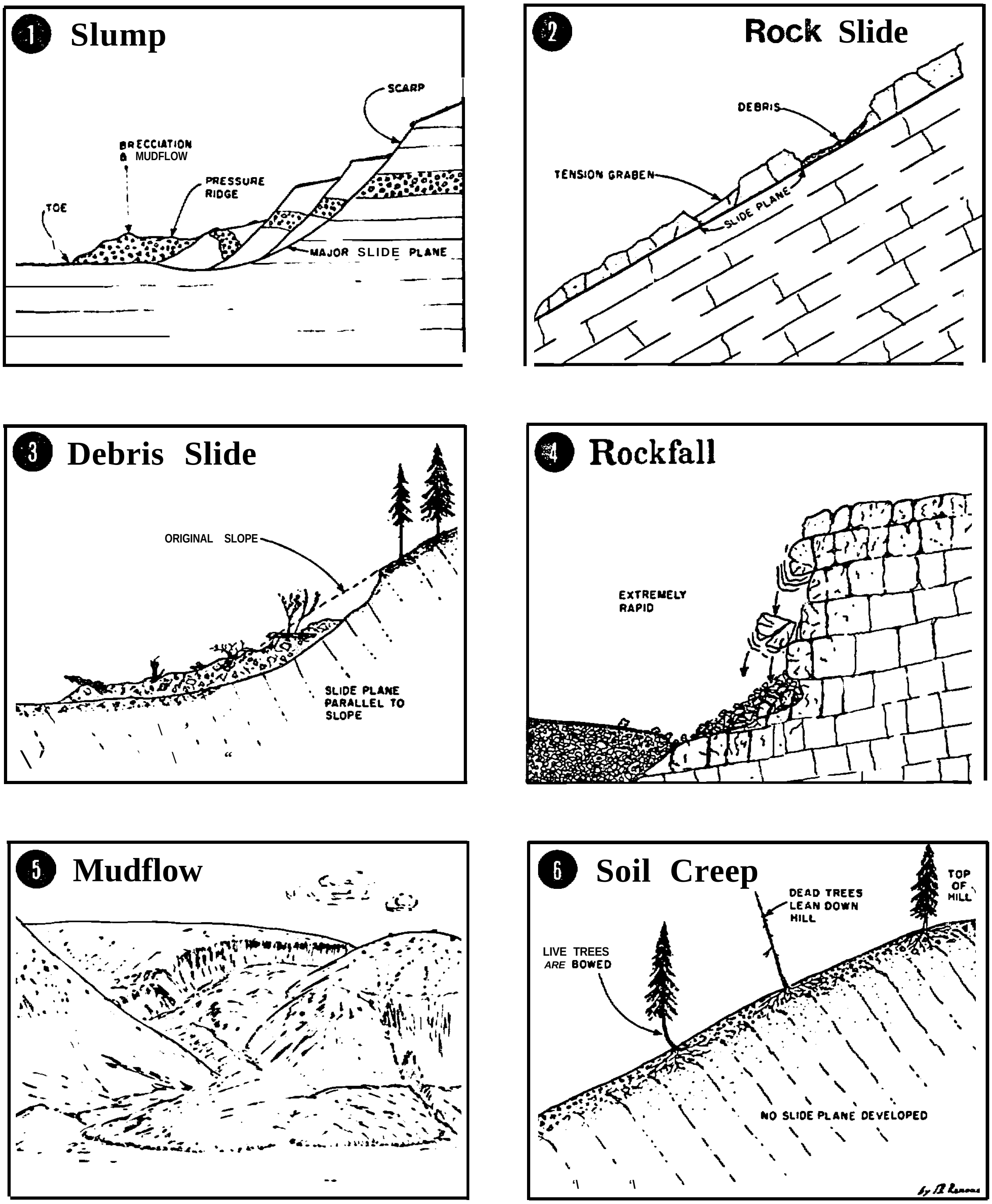
Table 1-12 (cont.)

TYPE	VARIETY	DISTRIBUTION	CAUSES	IMPACT
GROUND WATER FLOODING	Pending	Floodplains, behind levees, wetlands, topographic depressions, interdune areas	Low infiltration rates in topographic depressions	Flotation, caving, compressible soils, flooding, waste disposal malfunctions
	High Ground Water	Same as pending, also includes areas of ground-water discharge	Intersection of ground surface with water table or perched water table	Same as pending; also includes settling, unfavorable shrink-swell of soil, liquefaction during earthquakes

§After Beaulieu and Hughes, 1975.

Figure I-26

Types of Mass Movement[9]



§Schlicker and Deacon, 1974.

Table 1-13

Characteristics of Various Types of Mass Movement

(PE	MOVEMENT	MATERIAL	WATER CONTENT	TOPOGRAPHY	ADDITIONAL CHARACTERISTICS
Rockfall	Extremely rapid	Blocks and boulders of bedrock	Low	Very steep to vertical upland slopes and sea cliffs	Look for vertical slopes with jointed bedrock surface, unvegetated talus, and other signs of recent activity.
Rockslide	Usually very rapid	Blocks of bedrock, perhaps with over-lying soil	Low to moderate	Steep upland slopes	Either weak bedding planes or well-jointed, faulted, or fractured bedrock (same as for rockfall)
slump	Slow to rapid; rotational move-ment or curved failure plane.	Weak bedrock unconsoli-dated units, or soil	Moderate to high	Moderate to steep slopes; predominant in areas with deep soils	Movement can be inter-mittent, continuing over many years
Mudflow/ debris flow	Moderate to very rapid -- as viscous slurry	Rock and soil in varying propor-tions	High	Steep upland slopes (generally steeper than 40°)	Do catastrophic erosion in upper parts of water-sheds; often deposited behind log jams; usually start as small slumps or debris slides, and pick up additional material as they move.
Debris slide	Moderate to very rapid	Rock and soil in varying propor-tions	Moderate to high	Steep upland slopes (generally steeper than 40°)	Failure plane parallel to slope; do not contain enough water to flow.

Table 1-13 (cont.)

TYPE		MOVEMENT	MATERIAL	WATER CONTENT	TOPOGRAPHY	ADDITIONAL CHARACTERISTICS
LANDSLIDES	Earth-flow (not shown)	Slow	Rock and soil in varying proportions	Moderate to high	Moderate slopes	Can have same style of movement as any of the preceding three, but slow rate of movement puts it in another class; high clay content typical.
	Soil Creep	Very slow	Soil	Low to high -- velocity is a function of water content	Moderate to steep slopes	Movement is continous, slow (mm/yr), and usually involves only about upper few meters of soil. Not generally considered a hazard.

the material (upslope resisting force) (Carson and Kirkby, 1972). Slope failure may result from either an increase in shear stress or a decrease in shear strength. Shear stress can be increased by steepening the slope [through tectonic tilting, undercutting by stream or wave erosion, placing fill on the upper part of the slope, or excavating the toe of a slope) and by earthquakes, which can cause a momentary acceleration that can be additive to the acceleration of gravity. Shear strength can be decreased by 1) pore-water pressures building up between the mineral grains in a soil or in cracks in bedrock, which exert a buoyant force on the mass, reducing the friction that helps hold it in place, 2) reducing the cohesion and internal friction of the material through weathering (i.e., dissolving the "cement" that helps hold the mass in place or breaking down large particles that exert a stabilizing effect by interlocking, and 3) clearcutting of forest and destruction of roots that help bind the soil and hold it in place.

Landslides are most prevalent in upland areas, along wave- and stream-cut banks and bluffs, along the edges of marine terraces, and in certain critical areas in glacial drift plains (Beaulieu and Hughes, 1975; Swanston and Swanson, 1976; Tubbs, 1975). Rockfalls and rockslides occur along steep slopes where bedrock is exposed, such as along sea cliffs and artificial cuts.

In upland areas, landslide occurrence and frequency is controlled by the geology, hydrology, and vegetation. Areas underlain by weak, clay-rich bedrock are usually mantled by thick soils. Here, mass movement is predominantly earthflow, slump, and creep. Such terrain occurs extensively in the Klamath Mountains and in much of the Coast Range Province. Upland areas underlain by more competent bedrock types are more commonly subject to debris slides and debris flows (Swanston and Swanson, 1976).

Over much of the Puget Lowland, slopes are susceptible to debris slides and slumps. Here, the occurrence of landslides is predominantly controlled by the glacial stratigraphy. Slopes steeper than 15%, where the contact between an impervious clay or till and an overlying permeable sand is exposed, are particularly susceptible. Ground water builds up as a saturated zone (perched water table) above the clay, increasing the pore-water pressure in the sand, and reducing the shear strength of this geologic unit -- often to the point of failure [Miller, 1973; Tubbs, 1974a, 1974b, 1975).

V. Stream Erosion and Deposition. Stream erosion is defined here to include erosion by running water on hillslopes, erosion in regular stream channels, and scouring by flash floods. Deposition occurs when the transporting water loses the capacity to carry the material because of changes in stream parameters -- velocity, discharge, width, depth, slope and channel roughness. Sediment load is then dropped, as in the inner parts of meander bends, behind obstacles, and on flood plains (Beaulieu and Hughes, 1975). The distribution, causes, rates, and impacts of stream erosion are briefly summarized in Table I-14.

a) Causes. Hillslope erosion (sheetwash, rill erosion, and gully

Table I-14

ummary of Stream Erosion and ition§

TYPE	MATERIAL AND LANDFORM	PROCESS	FACTORS AND CAUSES	RATE	IMPACT
Channel scour and deposition by flash floods	Upland streams with little or no flood plain and scoured in bedrock, in particular the hard Tertiary sandstone of the interior uplands	Erosion	High precipitation, impermeable bedrock, steep slopes and stream gradients, moderate to high relief	Sufficient to remove all available soil and boulder cover	Scouring to bedrock, removal of vegetation, road destruction, clogging of culverts, and damage to manmade structures
		Deposition	Reduction of carrying capacity of the stream generally through abruptly reduced gradient at base of slope	Extremely rapid	Buries roads and clogs culverts, blocks channels, buries property
Slope gullying and downslope deposition; also rills and sheetwash	Moderate to steep upland slopes and long gentle slopes of the uplands, terraces, and other coastal areas	Erosion	Favored by silty to sandy soil of low cohesion, steep and/or long slopes, lack of surface protection	Slow to very rapid depending on slope, and soil properties	Removal of soil, reduction of productivity and infiltration capacity, increases runoff, damage landscaping
		Deposition	Reduction of gradient at base or lower concave part of eroding slope	Variable depending upon local factors	Siltation of crops and lawns, clogs storm sewers, damage to landscaping

Table I-14 (cont.)

TYPE	MATERIAL AND LANDFORM	PROCESS	FACTORS AND CAUSES	RATE	IMPACT
Stream-bank erosion and channel deposition	Unconsolidated flood-plain material of the coastal lowlands and dune sand where crossed by streams from the interior	Erosion	Hydraulic friction and meandering, discharge greater than stream mean	Slow under natural conditions; rapid near improper stream use	Undercut structures, destroys farmlands, alters channel characteristics
		Deposition	Local changes in stream regimen including natural and man-made obstructions, reduction in discharge, increased load upstream, etc.	Variable depending on local conditions and upstream conditions	Hinders navigation, redirects currents toward other banks, promotes marsh development in estuaries

§Beaulieu and Hughes, 1975.

erosion) is caused by water running downhill over the ground surface. This happens only when rainfall intensity (or storm drain discharge, etc.) exceeds the infiltration capacity of the soil or when the ground becomes completely saturated and there is nowhere else for the water to flow but over the surface (Dunne and Leopold, [1977?]). The amount of erosion caused by this process depends on the nature of the soil, the amount of vegetation cover, slope gradient, slope length, and rainfall intensity. Sandy and fine sandy soils are the most susceptible to erosion. Vegetation adds organic matter to the soil, which generally increases the permeability and allows more water to soak in. Friction provided by grass and other small plants also can slow the running water to the point where it is no longer capable of eroding (Beaulieu and Hughes, 1975; Dunne and Leopold, [1977?]).

Erosion within stream channels is in part due to the tendency of all streams to meander. The meander patterns concentrate most of the force of the current against the outside banks of the meander bends (see Figure I-27) (Leopold, Wolman and Miller, 1964; Morisawa, 1968) . This causes bank erosion on the outside of the bends and permits deposition of "point bars" on the inside of bends where the current eddies. This mechanism causes the positions of meandering channels to shift within their floodplains over time. In fact this is the major mechanism of floodplain formation (Leopold, Wolmar and Miller, 1964).

Erosion from flash floods is caused by the high velocity with which flood waters flow down the steep upland channels. Material deposited previously in these channels by soil creep, small landslides, and normal stream flow (e.g., sand, gravel, boulders, trees) is picked up by the torrent, increasing the erosion potential of the flood.

b) Distribution. Undisturbed terrain in the study area is normally heavily vegetated. Consequently, hillslope erosion is minimal under natural conditions. However, in areas of building and road construction, logging, and heavy trampling by people or livestock, vegetation is removed and the soil is often packed, decreasing its ability to soak up rain water. In these areas, hillslope erosion can be very significant (Keller, 1962; Wolman and Schick, 1967).

Stream-bank erosion is a natural and continuing process that occurs throughout the study area where floodplains have developed.

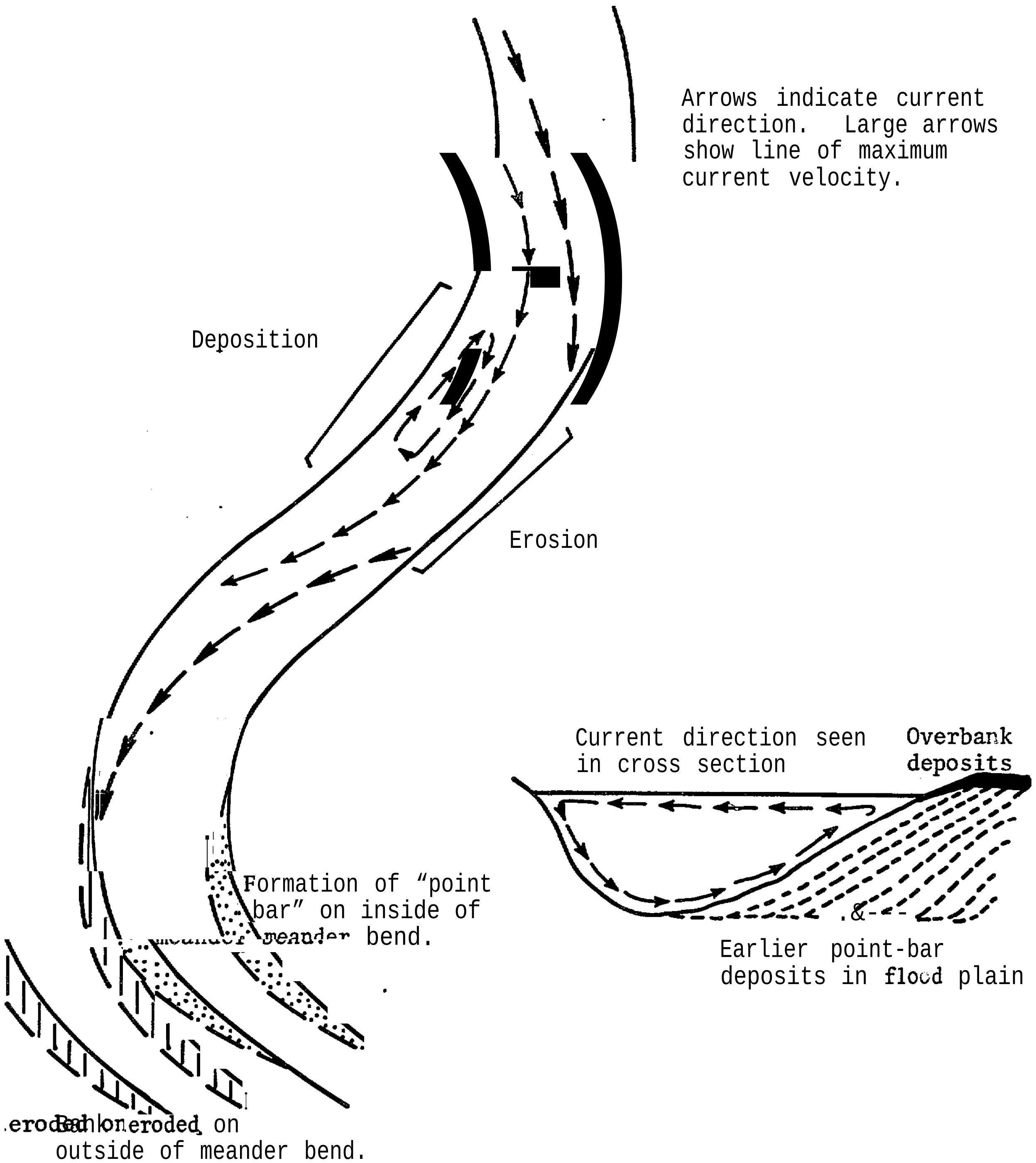
Flash floods are restricted to the steep topography of upland areas.

c) Impact. Hillslope erosion removes valuable top soil from the ground and deposits it where it is not wanted -- in storm sewers, drains, on lawns, and in streams -- as well as depositing "new" soil in lowland areas.

Stream-bank erosion undercuts homes and roads built too near to the outside edge of meander bends and can initiate landslides. There is, however, no net loss of land in the floodplain, because the

Figure I-27

Meandering Reach of Stream Channel Showing
Zones of Bank Erosion and Deposition



§After Morisawa, 1968.

erosion is balanced by the accretion of new banks at point bars.

Erosion and deposition of sediment in watersheds is a natural process and is a necessary part of the overall geomorphic process. Excessive sedimentation, however, usually brought on by man's activities, can damage fresh-water habitats, increase the cost of water treatment, cause excessive wear in pumps and sprinklers, and cause siltation in estuaries and rivers (Beaulieu and Hughes, 1975).

vi. Coastal Erosion and Deposition. Erosion of coasts is accomplished primarily through the action of waves as they break against the shore and release large amounts of energy. Abrasion, cavitation, compressed air in cracks in rocks, and solution are contributing mechanisms. Deposition of sediments is accomplished by currents along the bottom associated with waves and tides. Patterns in erosion and deposition are controlled by tectonic uplift, sea-level changes, distribution of rivers supplying sediment to the coast, bedrock hardness, structure and sediment grain size. In addition to these natural controlling factors, man-made coastal engineering structures often affect the coastal erosion and sediment transport system (summarized in Table 1-1S). A more detailed discussion of sediment transport and deposition along coasts can be found in Section B.4., Offshore Geology.

a) Headland Erosion. Headlands are subjected to much more of the energy of breaking waves than other features along the coast. This is because the shallow-water bottom topography refracts incoming waves, focusing them on the headlands (Bascom, 1964). However, headlands on the Pacific coast are composed of resistant bedrock so that rates of headland retreat are relatively slow and depend on the kind of bedrock. Retreat rates here can average from less than 2 cm per year to several cm per year (Beaulieu and Hughes, 197S). The same process operates in the calmer inland waters, but with less energy expenditure.

vii. Beach Erosion and Deposition. The formation of a beach requires a source of sediment, either from rivers that dump their sediment load along the coast or from erosion of the coast itself. The beach material, usually sand, is transported parallel to the coast by longshore drift, filling in embayments along the way with sand.

In addition to sediment transport parallel to the coast line, there is also seasonal onshore-offshore movement of sand from beaches to offshore bars in the winter, and back again in the summer (Bascom, 1964). Differences in average size of incoming waves in winter and summer are responsible for this movement and consequent change in beach profiles (see Figure I-28). Summer beaches with wide berms act as a buffer between the waves and the bluffs, cliffs, or other land forms. But during the winter months the berm is moved offshore and storm waves can break directly on the land behind the beach. Consequently, during the months of December and January Pacific shorelines experience most of their sea cliff and property erosion (Komar, *et al.*, 1976).

Another kind of erosion and deposition associated with beaches is caused by shifts in channels of rivers that traverse beaches to get to the sea. Major shifts can sometimes occur over a very short period

Table 1-15

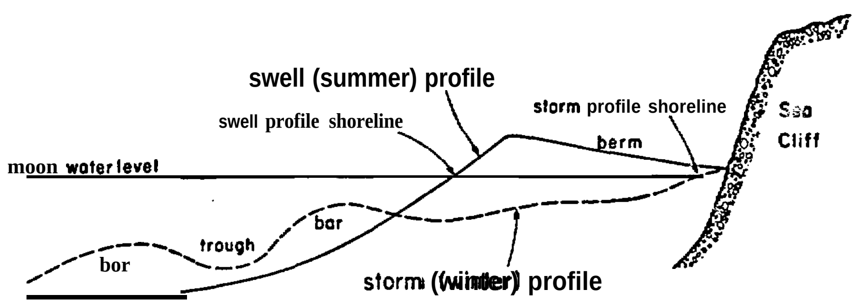
Engineering Treatments for Reductioncof
Coastal Erosion and Their Impacts[y]

TREATMENT	PURPOSE	COST	IMPACT AND OTHER LIMITATIONS
Beach nourishment	Mitigate erosion losses on beaches by storms or other short-term activity	Relatively low	Impact on borrow area; requires on-going program if applied to areas with long-term threats of erosion
Dune stabilization	Reduce flooding or catastrophic shore regression; **also,** to minimize wind erosion	Relatively low	May starve inland dune areas leading to deflation and reduction of esthetic **appeal**
Breakwater	Protect shore areas from wave erosion	Moderate	Not suitable in deep water; promotes local deposition behind the structure and may lead to downdrift beach starvation
Jetty	Stabilize inlets and channel and mitigate large-scale erosion; promote large-scale deposition	High	Induces large-scale erosion **or** deposition of adjacent beach areas; benefits must outweight costs
Sea walls, revetments, and bulkheads	Protect high-value structures on cliffs or dunes	Variable with design	Unattractive, limited beach access; must be designed to prevent undercutting or flanking; access to suitable construction material often a limiting factor
Groins	Maintain or increase sand supply on beach at a particular site	Moderate to high	Promotes downdrift erosion if too long; not suited to beach areas with steep gradients
Relocate	Save structure from probable undercutting	Variable	Space availability; moving skill required

[§] Beaulieu and Hughes, 1975.

Figure I-28

Seasonal Beach Profiles[§†]



[§]After Komar, et *al.*, 1976.

[†]Solid line shows the profile characteristic of summer swell waves, characterized by a wide berm above mean sea level, and dashed line shows the profile characteristic of winter storm waves, where sand has been removed from the berm and shifted offshore to form a series of bars.

9

of time, even during individual storms. Figure I-29 illustrates the shifts in the Copalis River that occurred in only 73-year period.

Areas undergoing significant coastal erosion were indicated on Figure 1-18. However, a number of specific cases are worth mentioning.

In Oregon, significant erosion problems are recognized near the mouths of the Necanicum and Siuslaw Rivers, at Tillamook Bay (the Bayocean Peninsula), on the east side of the sand spit separating Nehalem Bay from the ocean, at Siletz Spit, at Clatsop Beach (just south of the Columbia River south jetty) and along the south side of the Columbia River estuary, upstream from Hammond.

In Washington, severe erosion has occurred at Cape Shoalwater and Toke Point at the entrance to Willapa Bay, and at Point Chehalis (Grays Harbor). The rocky shoreline of the northern Washington coast is relatively stable, with only isolated areas undergoing significant erosion. The shoreline along the Strait of Juan de Fuca is also relatively stable, except at Ediz Hook, where erosion is serious. In the protected waters of Puget Sound, erosion problems are local and minor. One particular serious problem is the shoreline erosion at Titlow Beach, near Tacoma.

Considerable deposition of sand has recently occurred just south of the Columbia River mouth in the Clatsop Plains area. Sand has accumulated here in a series of parallel dune ridges, resulting in a significant oceanward movement of the beach. This coastal deposition is attributed to jetty construction at the mouth of the Columbia (U.S. Soil Conservation Service, 1975).

viii. Wind Erosion and Deposition. Erosion and deposition by wind is only a problem in the duneland areas along the Pacific coast of Oregon and Washington. Here, wind transport of sand is favored by the abundant supply of sand, the absence of protective vegetation over large areas, and the persistence of moderate to strong winds over much of the year. The physical characteristics of dune areas are described under landforms .

In recent years, the presence of European beach grass has tended to stabilize the coastal dune fields in many places, especially on the foredunes. However, individual dunes can and do advance relatively rapidly. Between 1945 and 1957 dunes west of Eel Lake, Oregon advanced at rates between 0.6 and 1.8 m/yr (Cooper, 1958). One small inland dune on the Banden Spit in southern Oregon advanced over 9 m in 15 years (Dicken, 1961). Near Florence, Oregon rates of advance of 1.8 to 5.3 m have been observed (Beaulieu and Hughes, 1975). Advancing dunes of this sort can easily bury roads, buildings, and other structures.

Blockage of the wind in dune areas, either by natural or man-made structure, will cause sand to be deposited in the lee of the structure. This can cause problems of sand deposition in locations where it is not wanted, such as on parking lots, roads, and lawns. It can even partially bury structures.

Figure I-29

Shifts in Channel Position of Mouth of Copalis River in 73 Years[8]

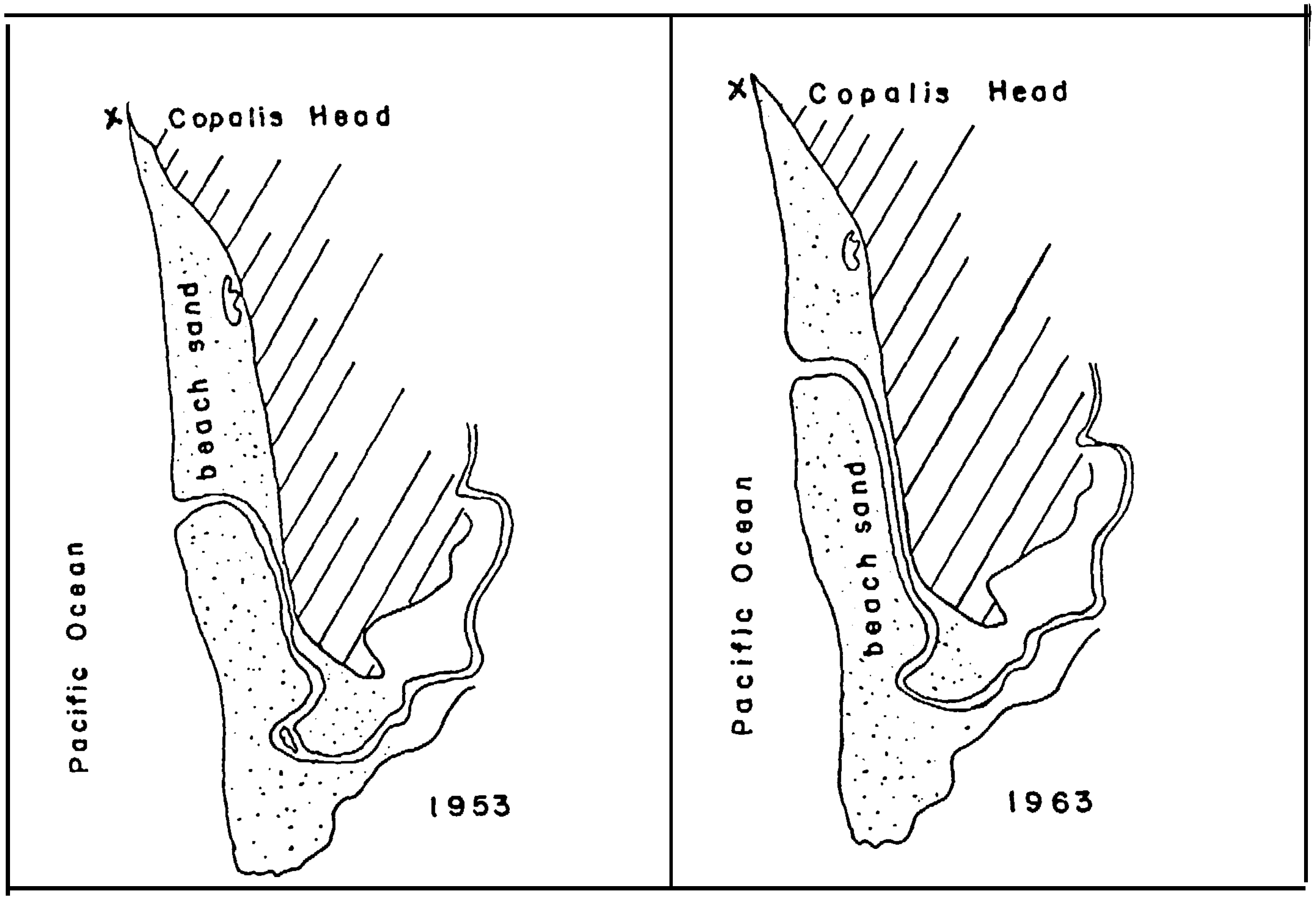
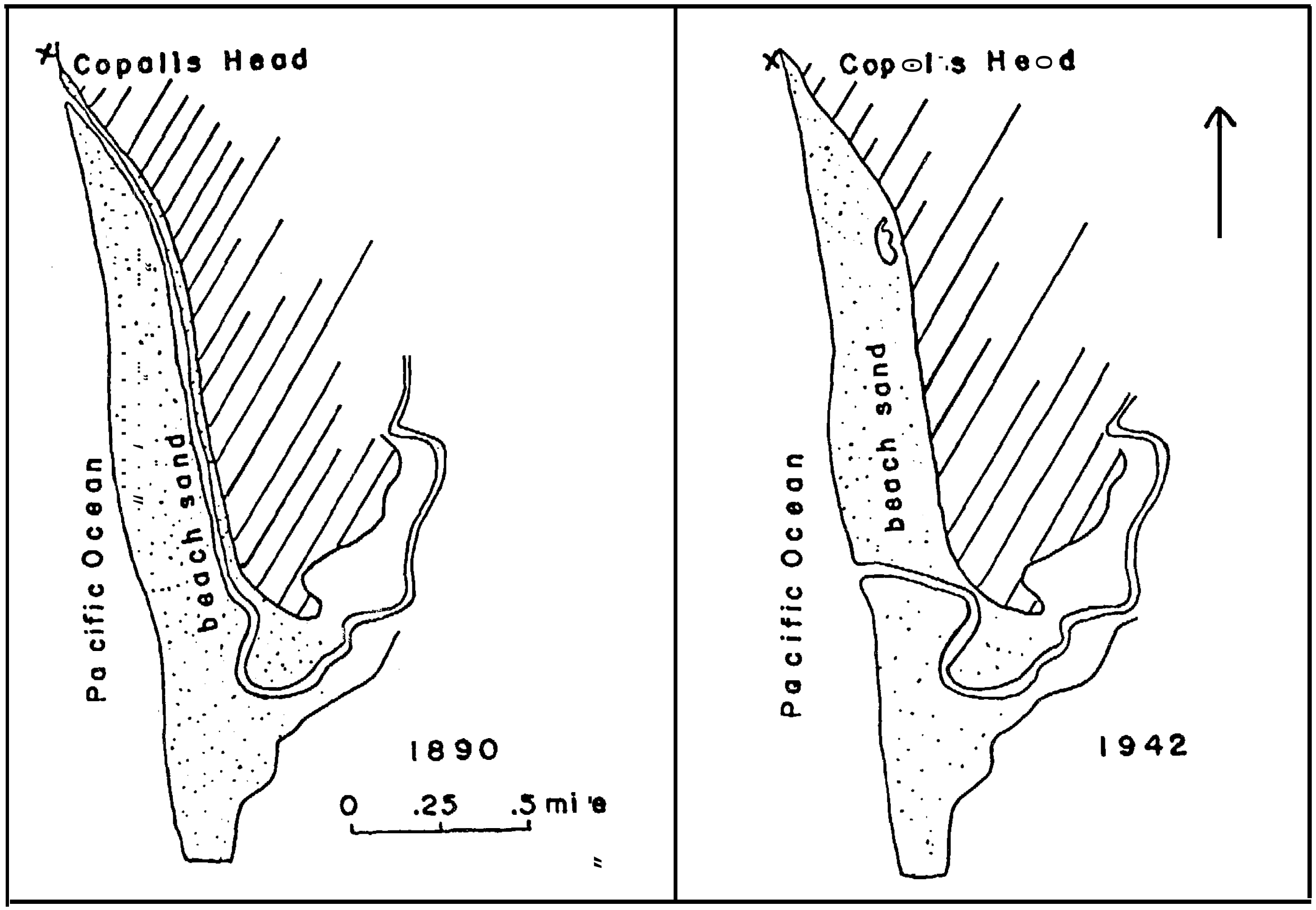


Figure I-29 (cont.)



§Moore, 1965.

4. Offshore Geology. Offshore submarine geology may be considered a western extension of Coast range geology. Geological oceanography is the study of geological processes in the ocean.[1]

a. Bathymetry and Geomorphology. McManus (1965 and 1967) describes the physiographic provinces of the Cobb and Gorda rises and the Blanco Fracture zone in detail. He also names and briefly describes the major bathymetric features near the coast (McManus, 1964]. Griggs and Kulm (1970) describe the physiography of Cascadia Channel. Barnard (1973) describes in detail the upper and lower continental slope regions off Washington and the various canyon-valley systems that exist. Kulm and Fowler (1974) discuss the irregular width of the shelf and submarine banks and the abundant benches and linear ridges in the slope off Oregon. They suggest strong structural control of the morphology exists.

The bathymetry of the northeast Pacific is presented in Figure 1-30 and the physiographic provinces as defined by McManus (1967) are presented in Figure 1-31.

The continental shelf within the study area is narrow to the south (15 km off Cape Blanco, Oregon] and wider to the north (75 km off Cape Flattery, Washington). Heceta Bank and Stonewall Bank widen the shelf to 50 to 70 km off central Oregon. The shelf and slope are cut by submarine canyons from the Columbia River north. Large canyons are conspicuously absent off Oregon. La Perouse and Swiftsure Banks are located off the southwest coast of Vancouver Island. The average depth of the shelf break is about 180 m, but may be shallower where the heads of canyons cut into the shelf.

The continental slope is also narrow off Oregon (40 km off of Cape Blanco). It widens to about 100 km off Washington and narrows again to - about 60 km off southern Vancouver Island. Figure I-32 shows a typical cross section of the slope off Washington. This province is very complex, consisting of an upper slope, extending from the shelf break to a depth of about 1,500 m; a lower slope of borderland, composed of several north to northwest trending, anticlinal ridges; and the numerous submarine canyons that divide the slope into segments (Barnard, 1973). Between the borderland ridges, low gradient areas represent sediment-filled basins (Dehlinger, et *al.*, 1971).

The morphology of the lower continental slope, which is directly related to its structure, has a strong influence on the distribution of sediment and the dispersal patterns of turbidity currents in transit to Cascadia Basin. As ridges were successively formed at the western edge of the lower slope, the" valleys east of the ridges began to fill with available sediment. As the older basins near the base of the upper slope or those closer to the major sediment dispersal routes became filled, deposition probably shifted gradually to the younger, more isolated basins

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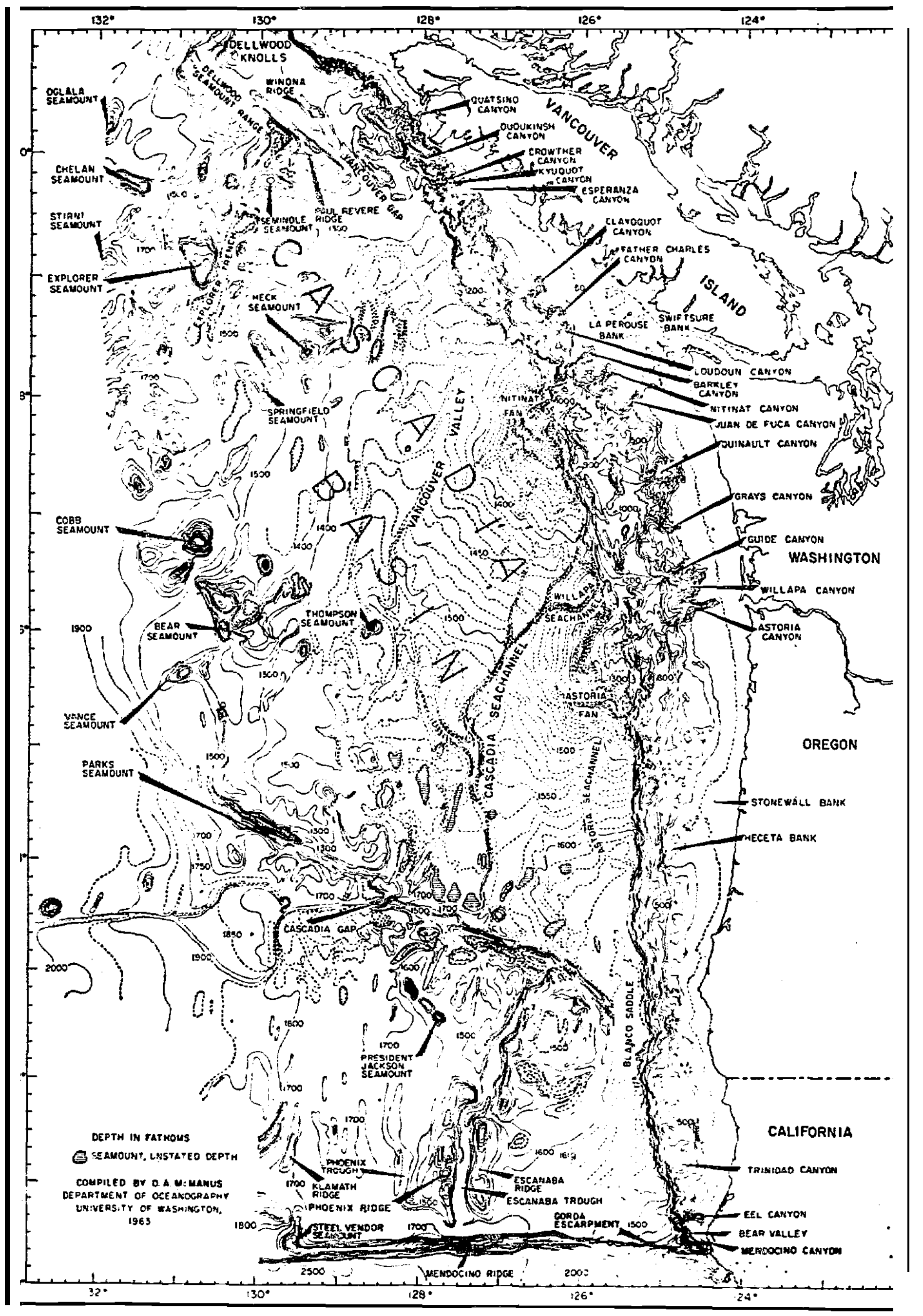
[1]Mark Holmes of the University of Washington is preparing a chart summarzing geological and geophysical data to date for the Washington continental shelf and margin. The chart will employ a mercator projection at a scale of 1:1,000,000. Bathymetry, magnetics, and gravity will be illustrated as well as bottom sampling stations and sample seismic profiles.

Figure I-3o

Bathymetry of the Sea Floor Off the Coast of the Northwestern United States[§]



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§From McManus, 1965.

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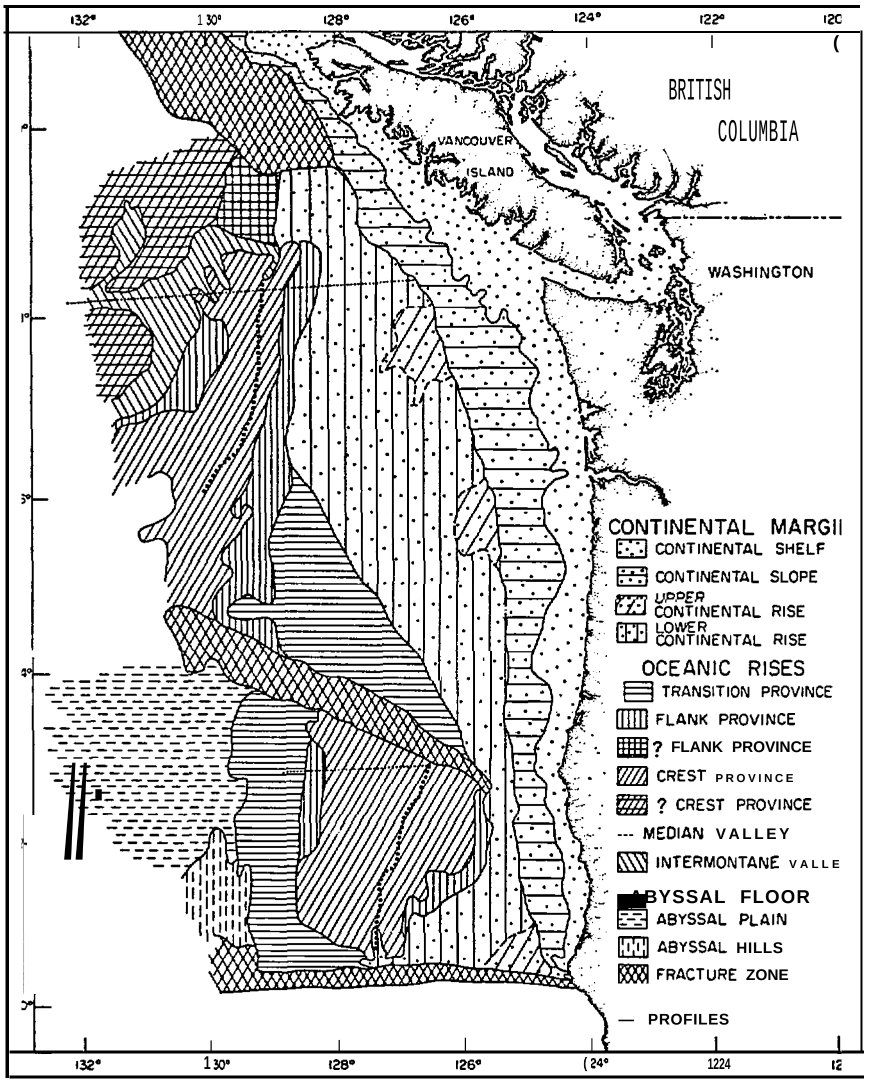
Figure 1-31

Physiographic Provinces on Gorda and Cobb Rises,
Northeast Pacific Ocean[§†]

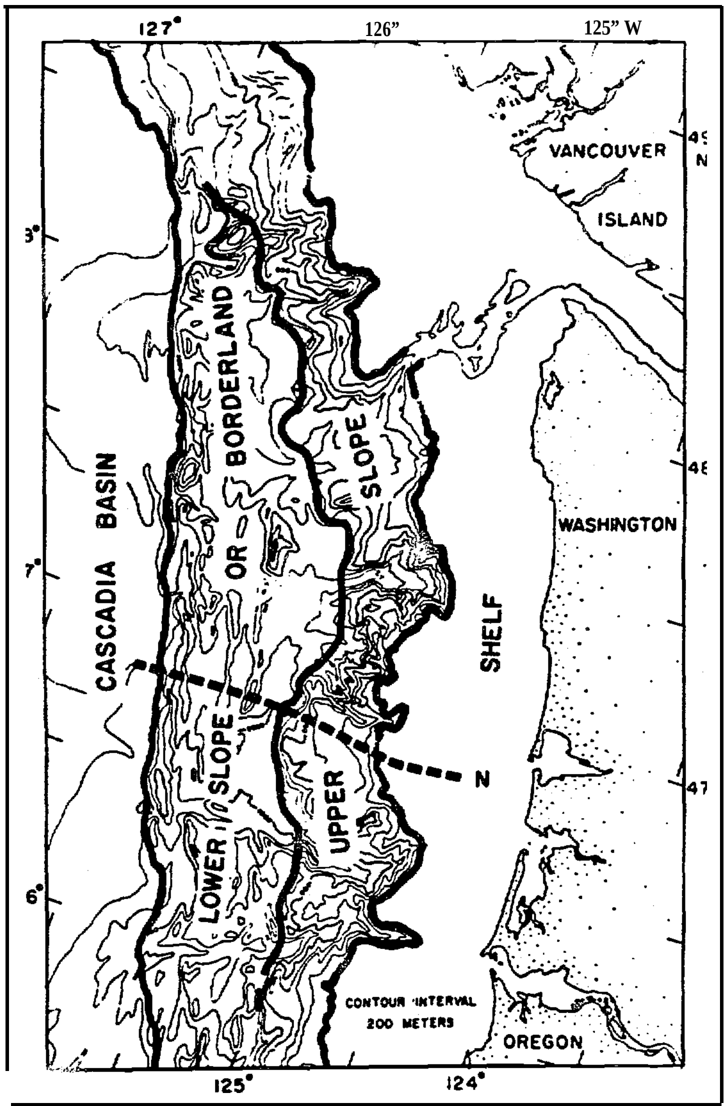


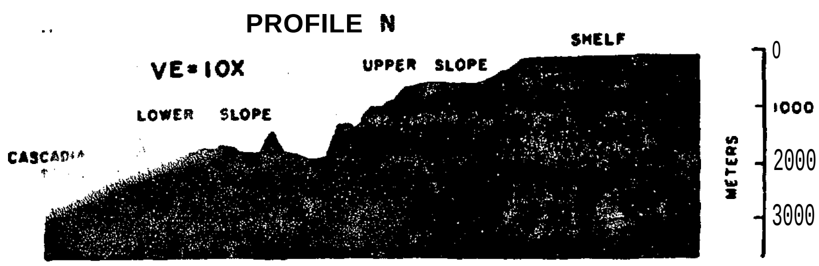
§ McManus, 1967.

† Northern part of Cobb and southwestern part of Gorda Rise are poorly surveyed. Median valley is poorly developed on Cobb Rise but may extend southward to Blanco Fracture Zone.

Figure I-32

Bathymetric Chart Showing Physiographic Provinces and a Typical Cross Section§





§From Barnard, 1973.

to the west.

"The Blanco fracture zone is short and narrow compared to other fracture zones in the eastern Pacific. It angles west-northwest away from the continental slope off Cape Blanco. It divides and offsets the Cobb and Gorda rises, with the Gorda Rise being to the south and very near (30 km) to the continental slope. The Cobb Rise (also called the Juan de Fuca Rise) is to the north and at its northeastern corner comes to within 75 km of the continental slope (McManus, 1967). Both rises have characteristic crest, flank and transition provinces and median valleys. Cobb Seamount lies on the west flank of the Cobb Rise beyond the coverage of Figure 1-30. Between the rises and the continental slope lies the Cascadia Basin, shown as the lower continental rise province in Figure I-31. The Cascadia Channel, with a relief of 20 to 300 m and an average width of 2 to 4 km, runs through the Cascadia Basin, crosses the Blanco fracture zone at Cascadia Gap, and continues some distance along the bottom of the north Pacific. It is one of the longest channels identified in the world oceans (Griggs and Kulm, 1970) .

Figure I-33 presents the bathymetry of the study area using an oblique profile technique. The varying shelf width, the complex continental slope region off Washington, and the Blanco fracture zone stand out. The rift valley of the Gorda Rise is evident to the south. The Juan de Fuca Canyon is apparent as an extension from the Strait of Juan de Fuca, and the Cascadia Basin is evident by its low relief.

b. Bedrock and Sediment Structure. The continental margin off Oregon and Washington represents the western part of a Tertiary depositional trough that trended north-south from what is now Vancouver to the Klamath Mountains. The width of the trough extended from the Cascade Mountains to near the base of the present continental slope. The geologic history of this depositional trough was discussed earlier in Section 2a.

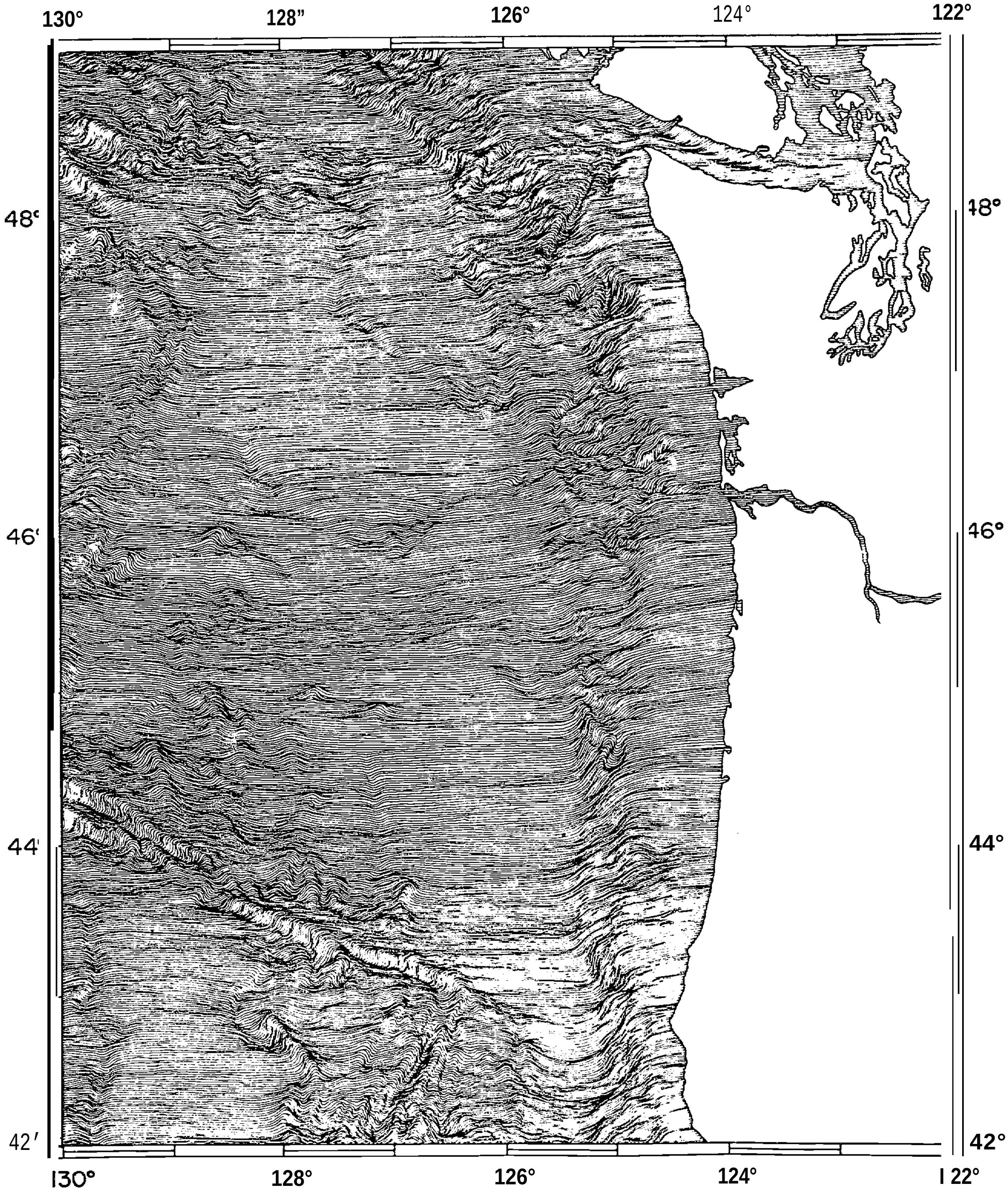
The theory of plate tectonics as interpreted for the Pacific Northwest was also presented earlier in Section 2.b. The bedrock and sediment structure of the continental slope and shelf are a result of the interaction of the Juan de Fuca and the North American plates.

Seismic reflection surveys have been-conducted on the Washington continental shelf by Bennett (1969) and in Cascadia Basin by Carson (1971). Tiffin, Cameron and Murray (1972) summarized the tectonics and depositional history of the continental margin off Vancouver Island. Barnard (1973) conducted seismic reflection surveys on the continental slope of Washington and analyzed the faults and structures in detail. Seismic reflection surveys off the coast of Oregon are reported by Kulm and Fowler (1974). Couch (1969) examined the gravity data and constructed hypothetical crustal sections between Washington and the Juan de Fuca Ridge (part of the Cobb Rise). Descriptions of the magnetic anomaly pattern found in the area have been included in studies by Raff and Mason (1961), Couch (1969), and Emilia, Berg and Bales (1968). Other geophysical investigations in the northeast Pacific have been summarized by Dehlinger (1971).

Selected seismic profiles from Kulm and Fowler (1974), Barnard (1973), and Tiffin, Cameron and Murray (1972) are presented in Figures I-35 and I-36, with track locations for these profiles shown in Figure I-34.

Figure I-33

Oblique Profile Presentation of Regional Bathymetry§



§After McGary, 1971.

Figure 1-34

Location Map of Profiles

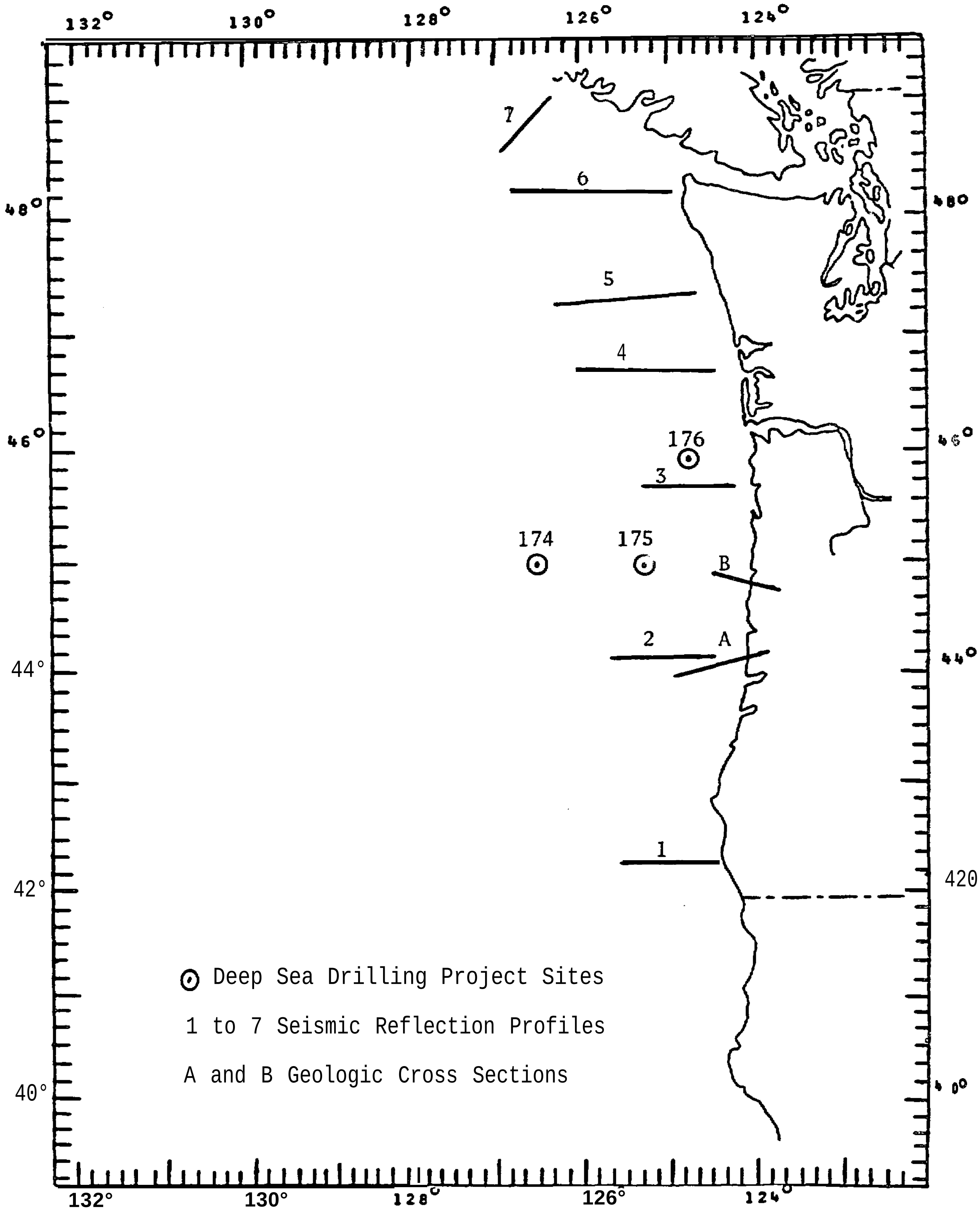
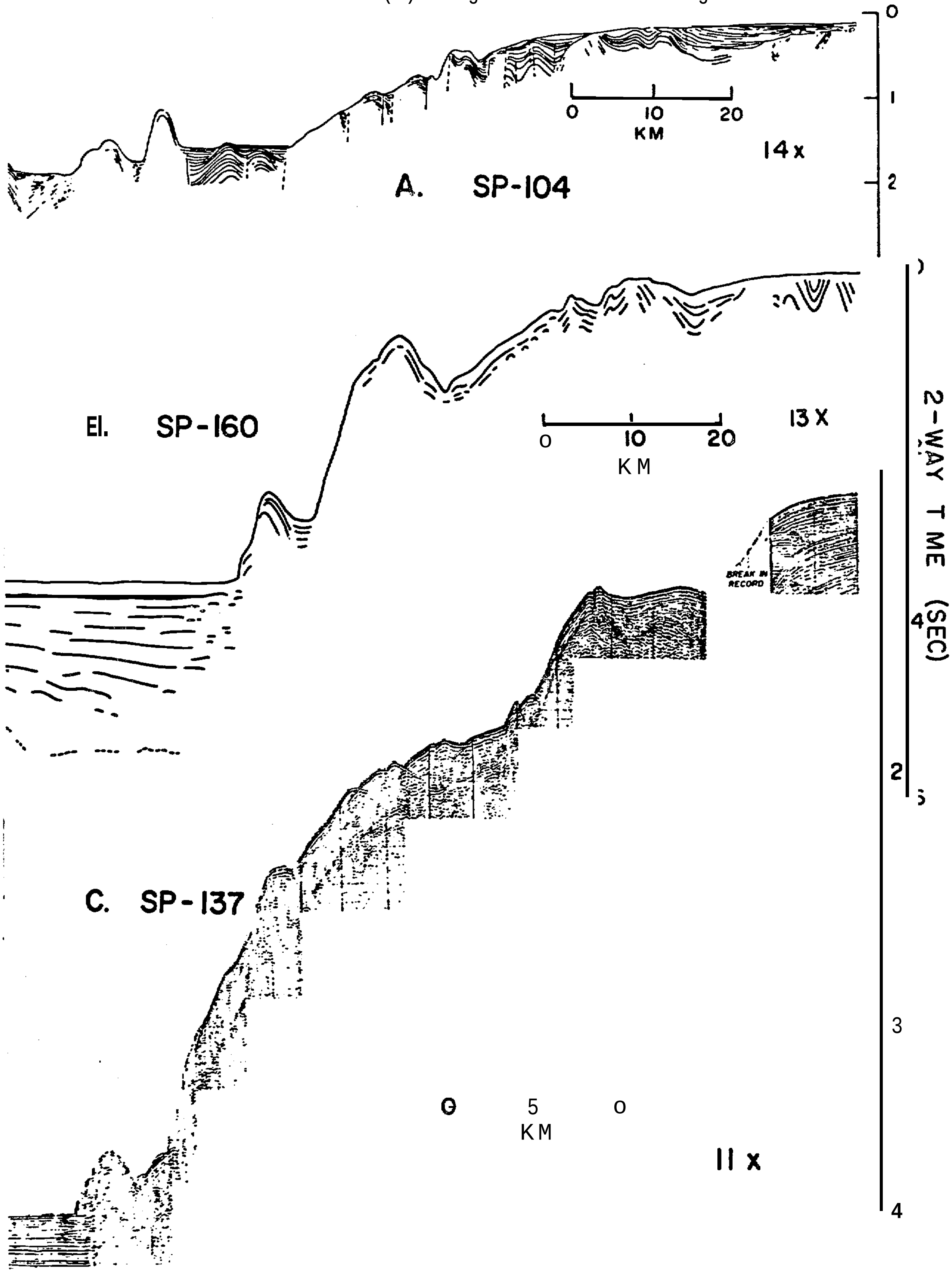


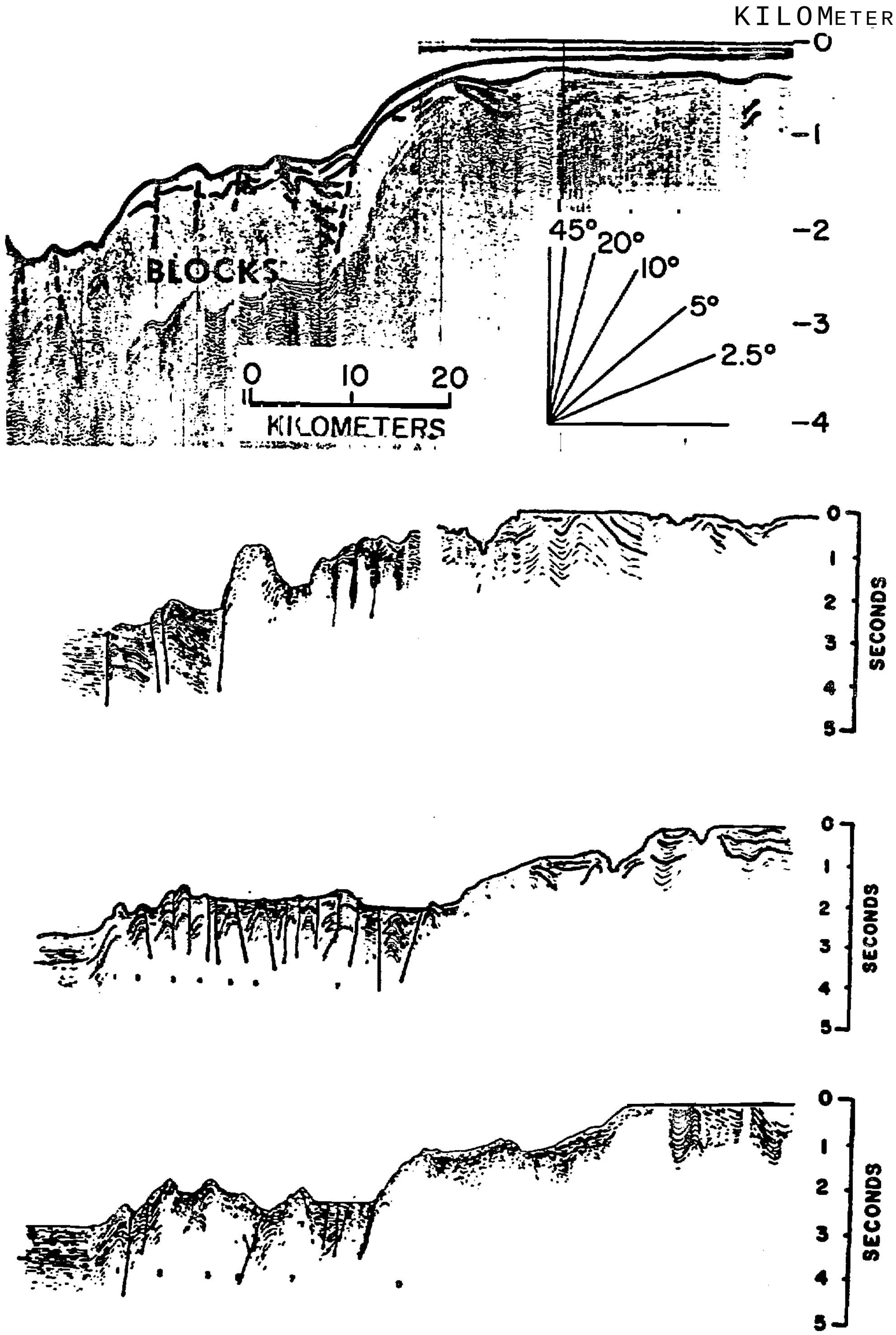
Figure I-35
Seismic Reflection Profiles for southern (l), central (2) and northern (3) Oregon Continental Margin[§]



§ After Kulm and Fowler, 1974.

Figure 1-36

Seismic Reflection Profiles for southern (4), central (5) and northern (6) Washington[§] and for Southern Vancouver Island (7)[†] Continental Margins



[§]After Barnard, 1973.
[†]After Tiffin, *et al.*, 1972.

Profiles 1 and 2 in Figure I-35 illustrate the widening of the shelf and slope from southern Oregon to central Oregon. In Profile 3, the slope starts to widen and two separate provinces are distinguishable (upper and lower slope). In Profiles 4 and 5, off southern and central Washington, the upper and lower slope provinces are most pronounced. The north to northwest trending anticlinal ridges previously mentioned are seen in the lower slope provinces of Profiles 3, 4 and 5. Buried anticlinal ridges are also evident in the flat deposition basins in Profiles 3 and 5. Profile 6, across the northern Washington shelf and slope, shows a very irregular slope with the upper and lower slope provinces from the south beginning to merge. Profile 7 is across the southern continental shelf and slope off Vancouver Island and illustrates a marginal plateau on the slope, deformed by faulting and folding where stratified sediments terminate abruptly against acoustically reflective blocks (Tiffin, Cameron and Murray, 1972). The shelf structure off Vancouver Island is relatively uniform, but becomes more deformed to the south. Note that the horizontal scales and vertical scales are not the same for all profiles.

Because of the scarcity of offshore stratigraphic data insofar as bedrock is concerned, it is generally accepted that offshore structure and lithology are continuations of that found in the shoreward unit. Where the lithologic character of the offshore unit is disrupted by faulting, shearing, or intrusion, the resultant change is discernible by geophysical investigation. Most offshore core samples are of geologically recent sediments rather than older bedrock. Those core studies of bedrock that have been done are too scattered to present any coherent picture of large-scale lithologic composition of offshore units. In addition, the Geological Survey of Canada (Cameron, 1976) recommends that because of the nature of the projects, often done under time constraints that preclude intensive analyses, great caution should be used in applying local results to larger areas. Thus, the lack of knowledge of bedrock stratigraphy of the continental slope and shelf represents a significant data gap.

Extension offshore of onshore formations, coupled with seismic survey analysis and any supporting drill cores, allows for some interpretation of offshore bedrock structure.

Dredging in the area of Stonewall Bank, situated approximately 35 km off Yaquina and Alsea Bays has yielded fossils dating from the Pliocene to the Holocene. Heceta Bank, which lies approximately 6S km west of the mouth of the Siuslaw River, rises to within 100 m of the surface. It lies offshore from a prominent basaltic headland but no samples of basalt have been dredged from it.

The Pliocene formations at Cape Blanco, and Coos Bay, abundant loose Pliocene fossiliferous boulders on the beach at Brandon, and reported Pliocene strata at Stonewall Bank suggest the presence of a widespread sheet of Pliocene sedimentary rock along the coast. In places it probably rests on thickened seaward sections of Miocene rocks and in others laps against older formations.

The Miocene strata of Cape Blanco, Coos Bay, Newport, Cape Kiwanda, and Astoria are probably widespread seaward (Baldwin, 1964).

The older Tertiary formations of the Coast Range may extend westward beneath the shelf and slope and probably vary in depth and thickness. Unconformities probably exist in this section much as they do in the Coast Range. Older formations present may be in synclinal basins or depressed fault blocks, and probably only the younger Mio-Pliocene strata are widespread.

During the Pleistocene stages of glaciation and deglaciation, sea level rose and fell irrespective of movements of the land itself. Movements of sea level accompanying glaciation are relatively fast, whereas the land tends to rise or sink very slowly. Evidence points to a gradual rise of the Oregon coast during the Pleistocene. During the last glacial stage Stonewall Bank would have been a prominent headland or island and Heceta Bank would probably have formed a peninsula or lower headland (Baldwin, 1964).

Geologic cross sections along the continental shelf of Oregon are presented in Figure I-37. Section B in Figure I-37 ties in to a test well drilled by an offshore exploratory rig. Weldon Rau of the Washington Department of Natural Resources is constructing a map of the inferred bedrock geology of the shelf and slope off the Olympic Peninsula, particularly extending the thrust-faulted structures and major units beneath the sea floor. The project is to be completed by the end of 1977.

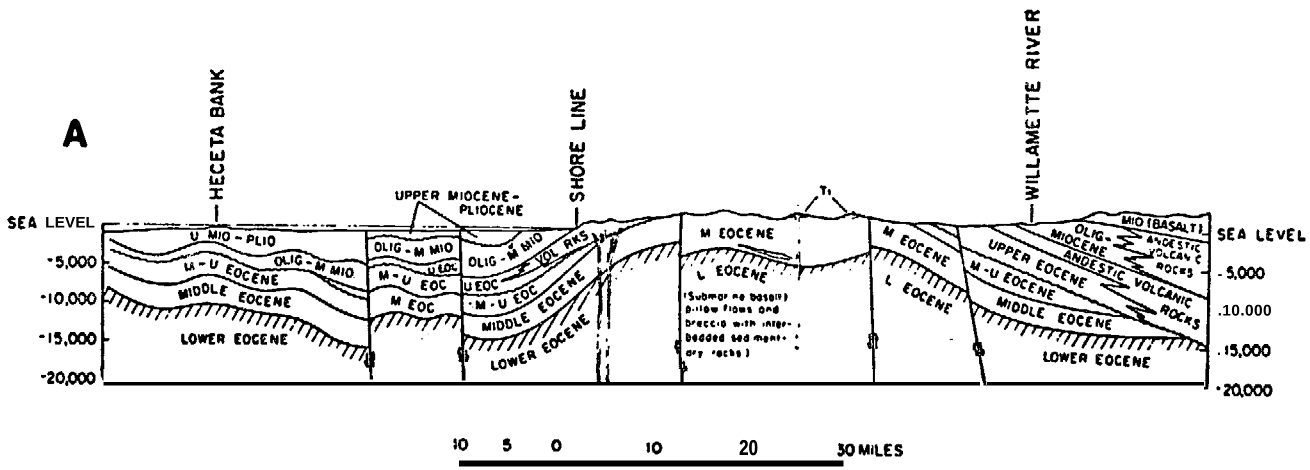
The oldest rocks in the OCS off Oregon and Washington are early Eocene volcanics that form the effective basement, or subsurface boundary. The entire Tertiary basin sequence is thought to overlie oceanic crust, although late Cretaceus deposits exposed along the southern margin may be present within the trough as well. Within the basin, the middle to late Tertiary section generally consists of a marine sandstone and siltstone sequence up to 7500 m thick, with occasional interbedded volcanic and non-marine rocks. Drilling offshore central Oregon has penetrated over 3500 m of rock dating from late Eocene to recent (Figure I-37).

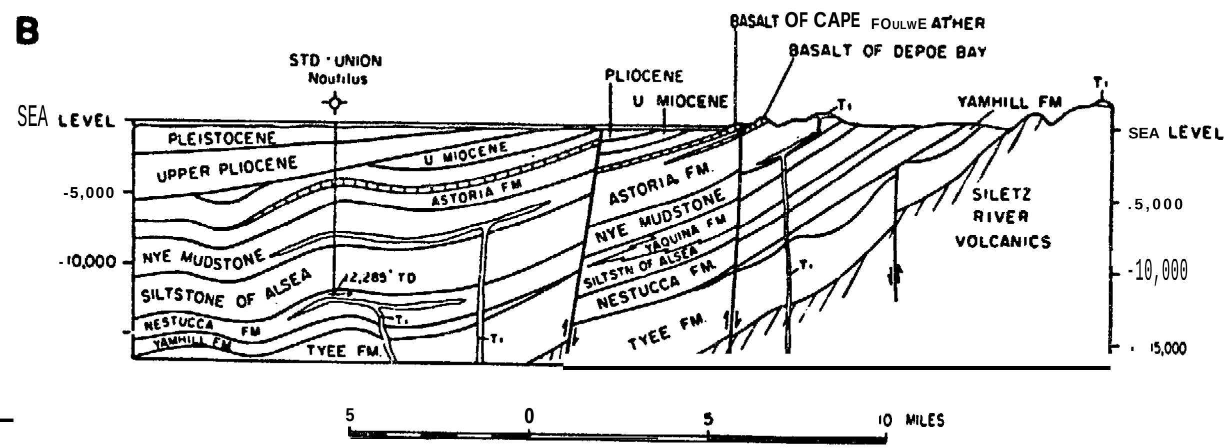
Shouldice (1971) discussed the western Canadian continental shelf structure, based primarily on released Shell Canada geological and geophysical data. The maximum thickness of Tertiary sediments is 4500 m although, for the southern Tofino Basin (the northern part of the study area), the maximum thickness was on the order of 2500 m. The data for the shelf of the Tofino Basin indicate that the structures are large, the dips are moderate and deformation has not been extreme. A heavy cover of Pleistocene sediments hampers structural interpretation.

Structurally, the Coast Range is broad anticlinorium that consists of numerous alternating structural ridges and troughs. These folds continue offshore where some of the ridges appear to be actively growing, involve Quaternary strata, and form bathymetric highs. The later Tertiary strata are cut by numerous shale diapirs on the Washington and western half of the Oregon continental margins.

The shelf is essentially a terrace cut by wave action. The depth to which the shelf extends is a result of sea level changes associated primarily with glaciation. Structural geologic formations on land and on the shelf have been subject to erosion, whereas erosion on the slope is generally associated with submarine canyons. Barnard (1973) mapped the axis of the north to northwest trending anticlinal ridges and thrust faults on the lower

Figure I-37
Geologic Cross Sections From (A) Williamette Valley to Hecata Bank
and (B) Central Oregon Coast to Edge of Continental Shelf[§†]





§ After Braislin, Hastings and Snavely, 1970.

† See Figure III-75 for locations of sections A and B.

continental slope off Washington.

Surficial geologic mapping of the submarine geology is not as indicative of structure as for land geology, due to the blanketing of sediment and the comparative lack of data.

C. Sediments and Sediment Transport. A generalized distribution of sediments in the region is shown in Figure I-38.

Sediments of the continental shelf are derived from two principal sources, rivers and erosion of coastal terrace deposits. Scheidegger, Kulm and Runge (1971) used a heavy mineral analysis of the rivers of Oregon and northern California to outline four major sources of sediments on the Oregon continental shelf. These sources include the Columbia River Basin, the Oregon Coast Range, the Klamath-Siskiyou Mountains, and terrace deposits along the central Oregon coast. Dispersal patterns of sand-size sediments show that the dominant direction of littoral transport has been to the north at least during the past 18,000 years. Sands were transported 270 km to the north on the continental shelf during the end of the Late Wisconsin regression and the beginning of the Early Holocene transgression. The observed dispersal patterns of heavy minerals may be indicative of more efficient littoral processes during the last major sea level lowering. Reduction of sand supply to the littoral zone and natural obstacles (such as erosion-resistant headlands) to the littoral transport of sand have apparently limited the northward transport of sand during the past 3,000 years.

The Columbia River is the largest single source of sediment for the Washington and northern Oregon coast. Royse (1964) noted that the Columbia River is the major source of sand along the southern Washington coast beaches. Terrace deposits of Oregon are actively eroding and are thought to contribute annually about 590,000 cubic meters of sediment to the continental shelf.

Evidence suggests that much of the inner-shelf sand is probably a relict transgressive sheet that was deposited during the last rise in sea level. Most of the deposition of the modern sand on the shelf has been confined to the inner portion of the inner shelf. Finer-grained sediments have been deposited on the outer shelf and upper slope (Runge, 1966).

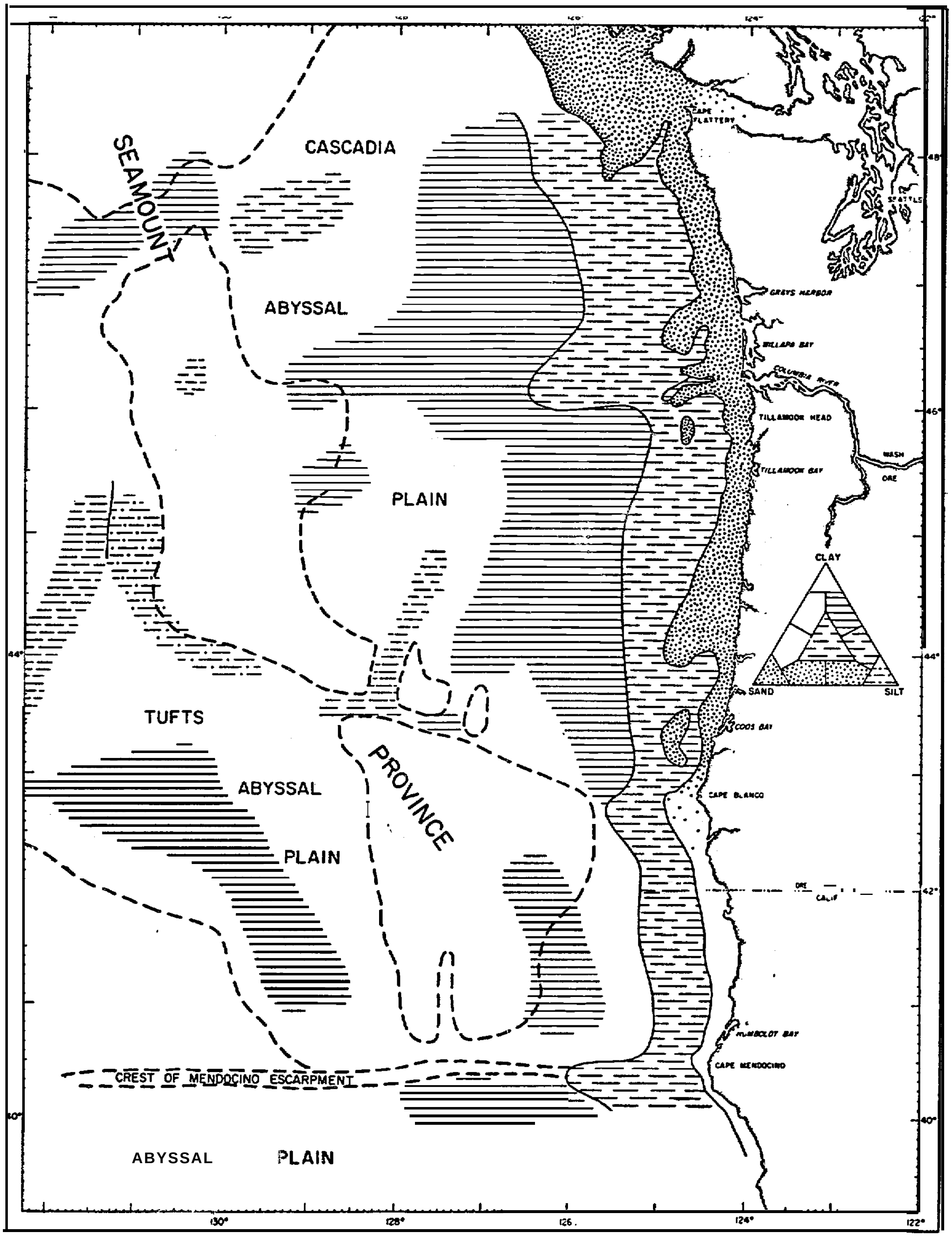
Sediments on the inner portion of the Oregon continental shelf consist of clean, well-sorted, detrital sand. This sand has a medium diameter of 2.53Φ [0.173 mm). Deposits with median diameters in the coarse sand and gravel classes occur at depths of 20 to 40 fathoms and probably represent ancient beach or fluviatile deposits formed during lower stands of sea level.

The grain size distribution of sediment on the Washington continental shelf is relatively simple. Fine sand (mean grain diameter of 0.090 to 0.180 mm) occurs in a band nearly parallel to the shoreline at depths generally less than 90 m. Sand is also irregularly distributed along the continental shelf edge. Such occurrences are especially noticeable north and south of Astoria Canyon and between Guide and Grays Canyon (see Figure 1-31).

The outer shelf and upper slope are covered by poorly sorted sediments

Figure I-38

Distribution of Sediments Along the Oregon-Washington Coast in Adjacent Offshore Areas§



§Gross, McManus and Creager, 1963.

with median diameters in the fine sand to fine silt classes (mean grain diameter 0.020 to 0.045 mm) (Runge, 1966). Recent studies have indicated that sand probably underlies the silt in most areas (Byrne, 1973).

Sediment data for the Washington shelf and upper slope were compiled by Roberts (1974) into area charts showing the percent composition of gravel, sand, silt, and clay based on over 5,000 samples.

Submarine canyons serve as passageways for conveying shelf sediments by turbidity currents to the Cascadia Basin and beyond. At times of low sea level and glaciation, the canyons were more active than today in this offshore transport of sediment. The activity of many of the canyons has waned, and the turbidites of today are finer-grained than before.

Barnard (1973) studied sediment cores from the lower continental slope of Washington along with seismic studies. He mapped sediment thicknesses for the lower slope, performed stratigraphic correlations between samples, and evaluated Turbidite deposits.

The most common bottom sediment type found in the Cascadia Basin is silty clay. Radiolarian tests account for coarsening of particle size in many of the areas of clayey silt (Gross, McManus and Creager, 1963).

Gross (1965 and 1967) found the distribution of calcium carbonate in the sediments ranged from less than 5% on the shelf, slope and eastern Cascadia Basin, to between 5 and 30% in the western Cascadia Basin, and greater than 30% in the crest province off the Cobb Rise. The organic carbon in the surface sediment was essentially the inverse of the calcium carbonate, with a high of greater than 2% on the Washington and northern Oregon slope, decreasing to less than 0.5% on the oceanic rises. The. organic carbon in the sediment on the shelf was quite low, generally less than 1% except to the southwest of the Columbia River.

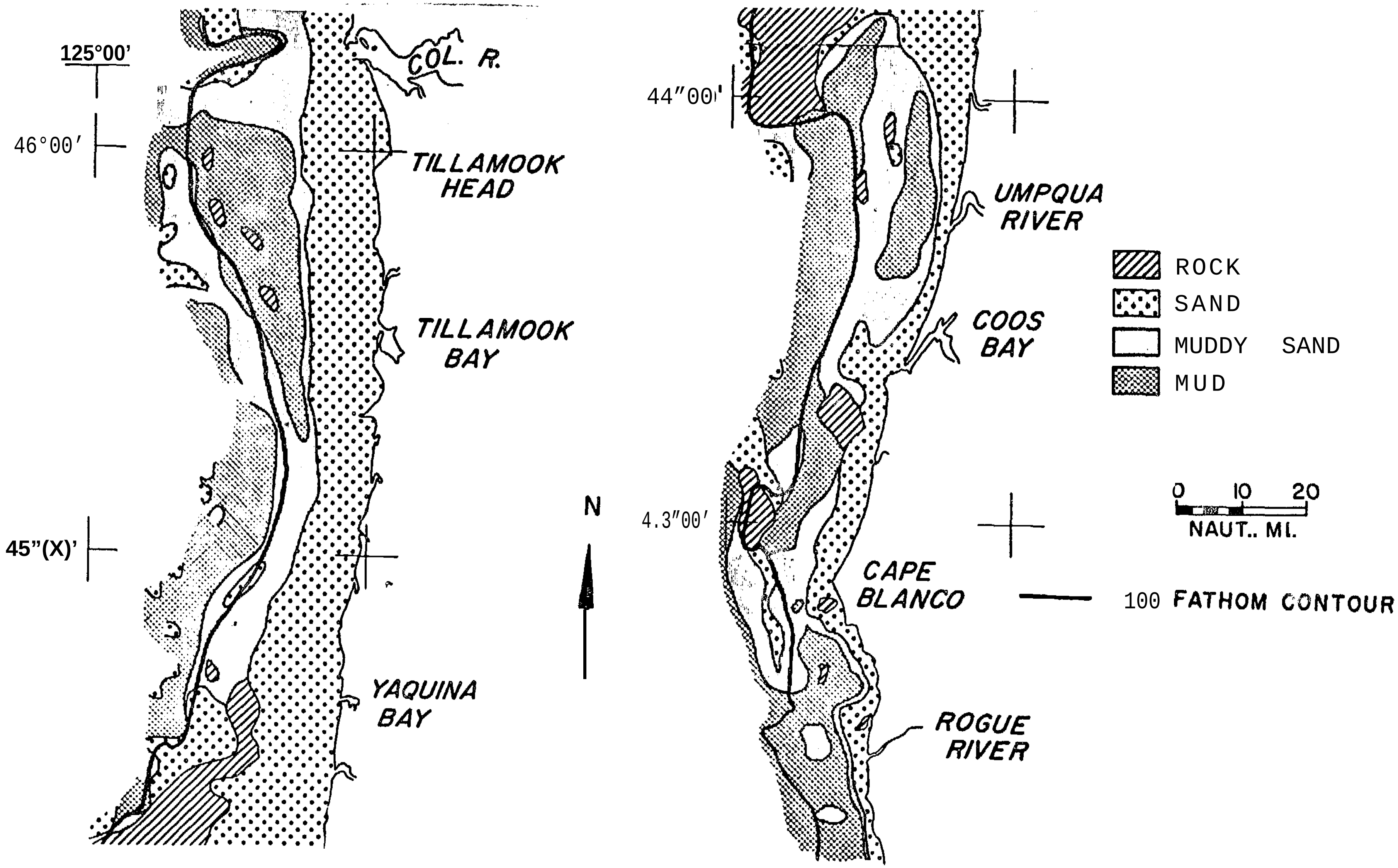
Figure I-39 presents the shelf and upper slope sediment distribution for the Oregon coast. Figure 1-40 presents the shelf sediment distribution for the Washington coast. The 180 m contour approximates the shelf edge.

Kulm, *et aZ.* (1968) noted that several well-defined heavy mineral concentrations occur in the surface sediments on the continental shelf off southern Oregon. The heavy mineral percentages range from 1% to more than 40% of the total sand friction. The most extensive and most prominent heavy mineral zones occur in the vicinity of the Rogue River, below Cape Blanco. This large surface concentration is 37 km long and extends 19 km north and 19 km south of the river mouth and apparently extends from the shoreline out to 90 m. Magnetic intensity studies off southern Oregon indicate several narrow, steep sided, strong, positive anomalies. Some of these correlate to surficial heavy mineral placer sediments. Some buried heavy mineral assemblages probably also exist (see Section 5.b.i., Metallic Minerals).

Spigai (1967) examined the heavy mineralogy of beach sands along the entire Oregon coast.

Ballard (1964) studied the distribution of heavy and magnetic minerals for beach areas from 46°N to 47°N (south of the Columbia River to north of Grays Harbor). He concluded: 1) the high percentage of heavy minerals in the vicinity of the Columbia River rapidly decreases in both directions along

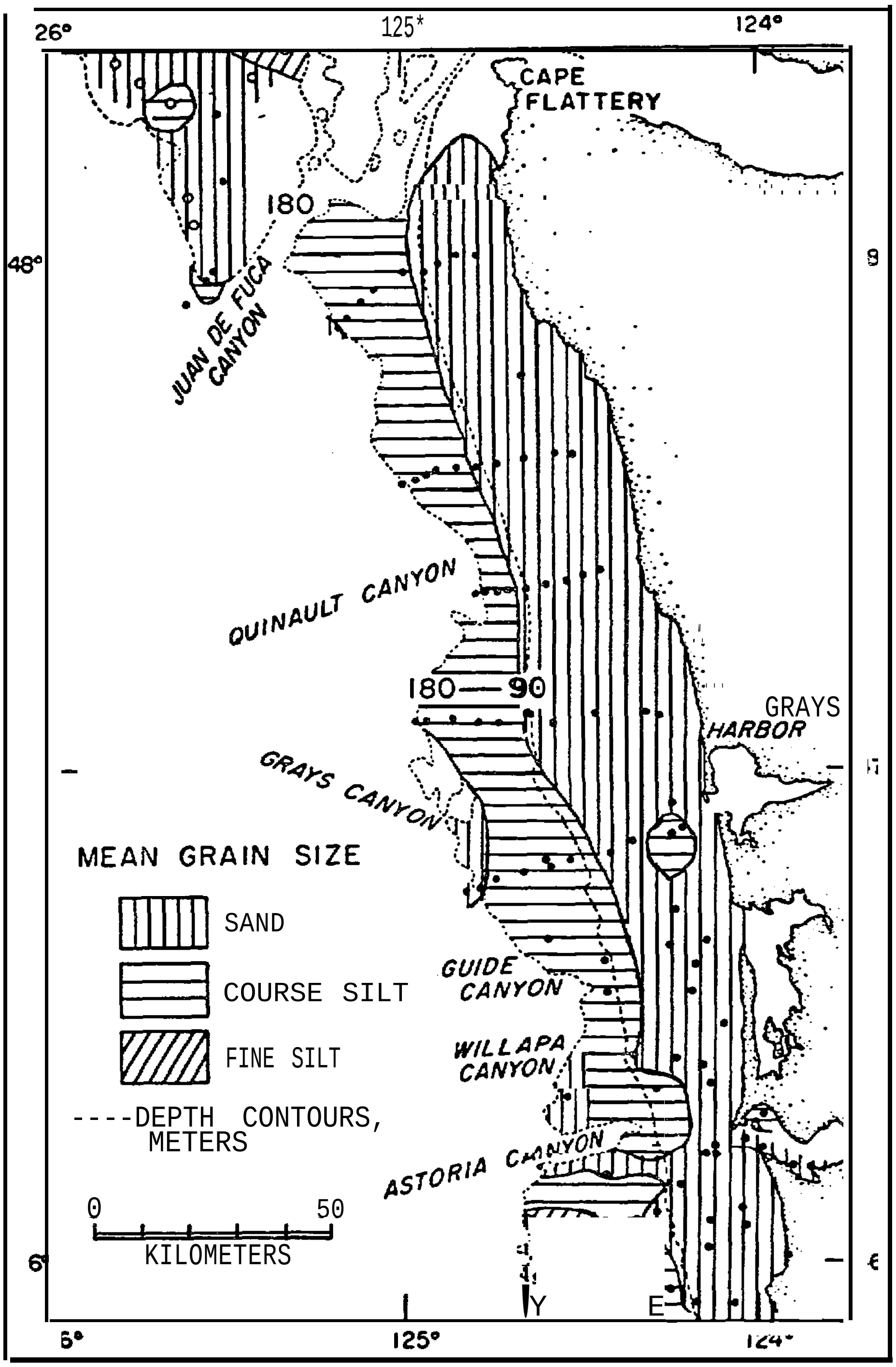
Figure 1-39
Shelf and Upper Slope Sediment Distribution for the Oregon Coast§



§Byrne, 1973.

Figure I-40

Sediment Distribution on the Continental Shelf
off Northwestern United States and
Southern Vancouver Island[§]



[§]Gross, McManus and Ling, 1967.

the coast; and 2) preferential transport (controlled by size, shape and density) may result in localized increases of certain minerals.

White (1967) studied the mineralogy and geochemistry of sediments on the shelf between approximately 46°N and 47°N (the area off the Columbia River). He determined three areas of characteristic sediment distribution exist: Group A, the area near the discharge outlet of the Columbia River; Group B, the main shelf area to a depth of about 90 m; and Group C, the shelf area deeper than 90 m. White found that, within each, the mineralogical, chemical and petrologic parameters are characteristic. He also determined that the association of boron and glauconite alone may delineate these three areas. The folloiwng discussion is extracted from White's thesis:

"The Group A Environment. The lower content of boron and the abundance of Ba, Sr, Cr and Ni in the Group A samples are important in the delineation of this environment. The boron content for Group A averages 30 ppm, which is characteristic of fresh water sediments.

"Ba, Cr, Ni and Sr show relatively large differences in contents between the shelf sediment average and the Columbia River sediment average. Ba and Sr are more abundant in the river sediments, whereas Cr and Ni are higher in content by 6 ppm in Group B, these four trace elements have their highest content in the Group A samples.

"The average Cr and Ni in the estuary and shelf sediments is 190 and 100 ppm, respectively, four times greater than in Columbia River sediments. There is a source of Cr and Ni in southern Oregon (Baldwin, 1964; Ramp, 1953, 1961), and this appears to be substantiated by the high amount of these elements in samples south of the Columbia River entrance.

"It seems possible that the Cr and Ni can be entering the Columbia River estuary from the continental shelf. As the sediments leave the estuary, Cr and Ni become indicators of the Columbia River sediments. In this manner, Cr and Ni have somewhat the same distribution of boron, Ba and Sr.

"The major element oxide compositions for the samples of Group A are diagnostic in the delineation of the Group A environment. SiO_2, MnO and CaO have relatively big% percentages in the Group A samples.

"The Group B Environment. The remaining trace elements, with the exception of boron, are the most abundant in the Group B samples. Boron is highest in the Group C samples. Each of these trace elements has an abundance in the shelf sediments equal to or just above the average for the Columbia River sediments. Most of these elements may have a Columbia River source. However these elements apparently are most abundant in the Group B samples relative to Group A because of the greater influence of the marine environment and the role of other sediment variables.

"A high boron content is characteristic for the Group B samples. The average content is 60 ppm and this is typical of a marine environment. The area of Group B sediments has higher salinity waters, and an increase in the amounts of glauconite and/or illite. All factors would lead to increased boron availability and uptake into the sediments.

"The trace elements of the Group B samples could be brought to the continental shelf by the Columbia River, but upon reaching the marine environment some are concentrated by absorption and possibly by biologic processes. Others, present in distinct minerals, are distributed and concentrated by oceanographic processes.

"For the Group B samples, Al_2O_3, CaO, TiO_2 and MnO have the highest percentages. The Al_2O_3 content shows the increasingly argillaceous nature of the sediments for this shelf area. Other sources contributing to the Al_2O_3 content are the feldspars and lithic fragments.

"For the Group B samples it is apparent that the argillaceous nature of the sediments, biologic processes, the mineral composition and distribution processes all indicate a specific environment in which the sediments have a characteristic trace element and major oxide composition.

'The Group C Environment. The Group C environment on the continental shelf has the most distinctive and diagnostic characteristics. Group C represents a marine environment, but rather than an active marine environment, its particular characteristics seem to make it a relict environment. The abundance of all the trace elements are below the continental shelf sediment average except for boron. The average boron content is 22o ppm, which is four times higher than the content for Group N.

"Bathymetric characteristics> the occurrence of glauconite, the distribution of the heavy minerals and the major chemical oxides are evidence of a specific chemical and physical environment for this shelf area. The discontinuous distribution of the trace elements confirms this. If this area was participating in normal shelf sedimentation and oceanographic processes, the trace element content should perhaps be more typical of the Group B samples.

"The Group C environment is outlined by the 5% glauconite and 100 ppm boron contour. This would then delineate the Group C area as seaward of the 146 m contour (outer shelf) from 45°55'N to 46°20'N. This area has the following characteristics: the bathymetry is variable with shoals or banks which may be exposures of Tertiary sedimentary rocks; glauconite is present; and all sediment variables appear to have a discontinuous distribution in this area. The presence of glauconite, its chemistry, chemical mode of origin, and mineralogical makeup would require low SiO_2, Al_2O_3, CaO, TiO_2, Na_2O, MnO, and high K_2O, Fe_2O_3 and MgO.

"In view of the data presented, there appears to be no doubt that the area outlined by the Group C samples or the 100 ppm boron contour represent a relict environment. The environment is restricted chemically and physically. Active authigenic mineral processes are present, but the area is not within the realm of the active depositional or marine conditions on the continental shelf."

Duncan and Kulm (1970) studied the mineralogy of sandy sediments deposited during the late Pleistocene and Holocene in southern Cascadia Basin and the adjoining Blanco Fracture zone and determined systematic regional and temporal trends.

The light-mineral constituents of these sands are lithic, arkosic, or volcanic in composition. They are mainly derived from extrusive and intrusive basic igneous rocks. Four deep-sea heavy-mineral Provinces [A, B, C, and D) are distinguishable in the area investigated. Province A iies in the Blanco Fracture Zone-Gorda Ridge transition area. Textural and mineralogical compositions of these deposits suggest local submarine volcanism. The volcanism may be associated with sea-floor spreading along the young crustal zone of Gorda Ridge. Province B is restricted to the late Pleistocene sediments of western Cascadia Abyssal Plain and Vancouver Valley. The most probable sediment source is Vancouver Island and vicinity. Sandy sediments from the island no longer reach the deep-sea environments because they are presently being trapped behind the sills of the glacially-scoured inlets of the island.

Province C includes the late Pleistocene and Holocene deposits in southeastern Cascadia Basin and Cascadia Channel. The sediments were derived from the Columbia River drainage. During Holocene time, the supply of coarse-grained detritals from the Columbia River diminished as sea level rose, and locally derived sediments from the metamorphic terrain of the Klamath Mountains were deposited at the base of the continental slope off southern Oregon and northern California (Province D), overriding the influence of the Columbia River sedimentation.

Sediment transport is a phenomenon that operates under many different mechanisms. Breaking waves drive a littoral drift along the shore. Sea level changes coupled with littoral drift have historically moved and sorted sediments over different parts of the shelf and are responsible for relict sand deposits near the edge of the shelf. Currents carry suspended sediments great distances before they settle out. Strong bottom currents associated with large waves stir the bottom sediments on the shelf, suspending them near the bottom for short periods of time, and making them susceptible to transport by regional and tidal circulation patterns. Sediments transported to the heads of canyons gradually build up to a point where they are unstable and, perhaps with the help of seismic activity, proceed down the canyons in density-driven turbidity currents, reaching out into Cascadia Basin and beyond.

The following discussion on sediment transport mechanisms is extracted from Kulm, *et al.* (1975):

"The nature and distribution of sedimentary facies on the Oregon continental shelf are controlled by several factors: (1) river discharge and sediment input, (2) estuarine circulation system, (3) wave dimensions and direction, (4) subsurface and bottom currents, (5) density stratification of the water column, and (6) reworking by benthic organisms. Most of these factors were probably operating during the Holocene transgression of the sea which deposited a basal sand facies over the shelf. As sea level approached its present position, mud (silt and clay) began to accumulate slowly on the mid- and out-shelf. Through the reworking by benthic organisms, this mud was mixed into the underlying basal sand creating a mixed mud and sand facies. A mud facies developed in the vicinity of the Columbia, Umpqua, and Rogue Rivers where the rate of mud deposition exceed the reworking activity. The drowned mouths of coastal estuaries produce a sediment trap for fluvial and marine sand and the silts and clays that come in contact with the intruding salt wedge. The grain size modes of the modern shelf sediments suggest that the very fine sand (0.062 to 0.125 mm) and finer material are presently transported in suspension through estuaries with a high fresh-water discharge and a large sediment input. This material diffuses through the turbulent surf zone and emerges as three distinct turbid layers on the continental shelf: (1) a surface layer at the seasonal thermocline, (2) a mid-water layer at the permanent pycnocline, and (3) a bottom turbid layer.

"During the winter, long-period surface waves from the southwest stir the bottom to water depths of 200 m and, when combined with bottom currents associated with internal and surface tides and northward flowing subsurface currents, provide the mechanism to transport very fine sand across the 45 km wide shelf off the Columbia River. This stirring process resuspend previously deposited bottom sediments which are then carried to the lower continental slope in low-density flows. The bulk of the silt and clay, as well as the biogenic debris in the water column, probably bypasses the shelf in the surface and mid-water layers and is deposited on the lower continental slope. Summer waves have shorter periods and are from the northwest, with bottom stirring occurring only to depths of 90 m on the average. These conditions favor deposition of silts and clays on the mid- and outer-shelf. While the fluvial sediment supply from small, coastal rivers is substantially decreased at this time, the discharge from the Columbia River reaches a maximum during the onset of these moderate wave conditions.

"The sand facies, particularly on the inner shelf, consist of relict sand and gravel or mixtures of these relict deposits and modern sands. The modern sand facies is a transient feature in some areas of the shelf; its presence is largely controlled by the resuspension processes and sediment input on the continental shelf."

Numerous approaches have been used in computing longshore sediment drift. Ballard (1964) used hindcast wave statistics to compute longshore components of wave energy for points south and north of the Columbia River (Table 1-16). From this and other analyses he concluded there was a net-northerly transport of sediment alongshore. P. D. Komar of Oregon State University has done considerable work in the mechanics of sand transport on beaches and has evaluated erosion problems at Siletz Spit, Oregon (Komar, *et* aZ., 1973).

Onshore and offshore motion of sediment follows a seasonal pattern. Large winter waves move sediment offshore forming protective bars that they then expend their energy against. Summer waves in turn bring sand ashore from the bar and build up the beaches. The winter condition is sometimes referred to as the "storm profile" and the summer condition as the "swell profile". In general, from late December through January the beaches have the least amount of sand. It is during these months that the coast experiences nearly all of its sea-cliff and other property erosion. Komar, *et al.* (1976) correlated inferred wave breaker heights with beach erosion on the Oregon coast.

Sediment transport on the shelf is controlled by bottom currents. At times of significant wave activity larger amounts of sediment will be suspended and transported. Inman and Quinn (1952) used 10 cm/sec as the threshold for motion of fine sand under waves. Net regional bottom currents are to the north. Sternberg and McManus (1972) assumed that threshold velocity is 40 cm/sec for steady or quasi-steady flows 3 m above the bottom. Using contemporary data of Hopkins (1971a) the following conclusions were

Table 1-16

Longshore Component of Wave Energy Flux for a Point South (S) and a Point North (N) of the Columbia River as a Result of Seas and Swells§†

MONTH/DIRECTION			NNW	NW	WNW	W	WSW	SW	SSW	S	TOTAL
JAN	(SWELL)	N	0.000	..6.003	-21.250	13.397	33.453	160230	16.067	0.680	52.573
		S	0.000	-1.991	-12.959	-11.307	170774	12.902	15.260	0.692	200371
	(SEA)	N	0.000	-60979	-160606	4.378	5.496	30.020	40.758	55.398	174*048
		S	0.000	-2.281	-8.907	-3.939	1.688	21.925	44.187	55.940	135.077
FEB	(SWELL)	N	-0.990	-9.750	-25,043	14.216	12.117	16.094	26.349	8.737	41.731
		S	-0.185	-3.446	-15.857	-11.277	5.943	12.081	24.751	99117	210127
	(SEA)	N	-0.438	-14.631	-13.053	5.904	9.919	12.487	36.428	29.053	65.668
		S	-0.038	-4.845	-110067	-5.494	3.235	9*995	35.361	37.451	64..S97
MAR	(SWELL)	N	-0*191	-49737	-18.182	30.359	7.853	6.245	14.500	3*591	39*438
		S	-0.037	-1.558	-11.836	-24.673	3.618	5.324	16.473	4.366	-8.323
	(SEA)	N	-2.154	-3.932	-5.678	8.883	9.899	19.902	15.784	26.454	690156
		S	-0.170	-1.126	-7.427	-7.920	3.316	16.505	20.071	36.961	60.211
APR	(SWELL)	N	0.000	-110416	-190405	6.667	26.408	00385	10417	0.260	4.235
		S	0.000	-3.842	-12.470	-5.716	140094	0.318	1.813	0.295	-5*509
	(SEA)	N	-6.107	-28.810	-3,525	2.120	170409	6.265	5.240	2*539	-4.868
		S	-0.422	-90061	-4.403	-2.084	5.391	3.929	7*854	8.003	9.207
MAY	(SWELL)	N	0.000	-6.012	-179797	79598	3.640	0.410	3.342	0.041	-8.779
		S	0.000	-0.936	-110551	-6.438	1.624	0.368	2.568	0.420	-136945
	(SEA)	N	-15.172	-40.092	-0.712	10266	0.465	2.a39	2.018	5.537	-43.852
		S	-1.455	-12.898	-3.206	-1.256	0.080	1.934	3.292	7*375	-6.134
JUN	(SWELL)	N	0.000	-7.869	-11,519	9.807	2.331	3.036	00000	0.000	-4.214
		S	0.000	-2.654	-7.863	-8.291	10021	2.708	0*000	0.000	-155079
	(SEA)	N	-4,692	-240161	-1.260	30416	1.927	59094	2.452	10361	-15.862
		S	-0.324	-7.626	-3.205	-3.334	00471	4.277	3.821	4.746	-1.175

Table 1-16 (cont.)

MONTH/DIRECTION			NNw	Nw	WNw	w	WSw	Sw	Ssw	5	TOTAL
JUL	(SWELL)	N	0*000	" -18.274	-12.337	2.083	2.478	2.601	10013	0.010	-22.425
		S	0*000	-6.121	-8.492	-107S4	1.103	2.371	1●149	0*106	'11.638
	(SEA)	N	-13. 183	-61.519	-09360	1.198	1.218	3.990	2.111	0.790	-65. 775
		S	-1.229	-19.649	-I .893	-1.191	0.179	. 2.560	2.910	1.481	-16 .831
AUG	(SWELL)	N	-0.281	-9.257	-190391	7.055	3.890	0.244	0.034	0.000	-17.706
		S	-0*029	-2 *993	-14.528	-6.082	. 1.463	0.118	09055	00000	-21 ●999
	(SEA)	N	-8.316	-18*232	-0.177	1.639	0.616	1 .325	0.294	1.658	-21 .192
		S	-00533	-5*276	-10120	-1 ●623	09000	1.020	0.820	1.742	-4.970
SEP	(SWELL)	N	-59156	-1.426	-30,679	10.631	0.428	4*747	0.000	0.946	-20*512
		S	-0.801	-0.465	-18.626	-8.869	0.231	3*347	0*000	1*032	-24.150
	(SEA)	N	-8.442	-11s464	..3.457	-20193	0,637	2.428	120414	6.453	0.762
		S	-0.620	-3*331	-4.592	-2.050	0.080	18666	149714	14.219	20.086
OCT	(SWELL)	N	0.000	-13.858	-48.527	12.080	6 ●996	10.786	3.042	4 ●053	-25.428
		s	00000	-4.598	-27 ●906	-10*373	" 3.527	8.313	1.272	3.052	'26.714
	(SEA)	N	-3.870	-18*474	-1.448	3.410	6.291	33.716	140776	13.294	47.696
		s	-0.303	-6.076	-2.737	-3.232	1 ●432	24.648	18.241	18.942	50.915
NO V	(SWELL)	N	-0.560	-10*754	-69,045	16.916	6'.156	1 ●059	3*009	1 ●683	-500797
		S	-0.038	-3.396	-42.607	-219853	3 ●244	0.971	3.323	1 ●5s1	-5 8.461
	(SEA)	N	-0.714	-150377	-4.438	2.546	11●529	11.483	219494	13.110	39.631
		S	-0.043	-5.009	-4.838	-2.405	4 ●569	8.153	26.201	17*557	4401135
DEC	(SWELL)	N	0*000	-49584	-36.408	26.228	21 ●749	9 .885	7.102	79147	31*119
		S	0.000	" -1.494	-22.303	-21.121	11.720	9,111	7.916	5.420	-10*79 I
	(SEA)	N	0*000	-5.867	-10.746	9.328	18.047	28.363	44.683	37.099	12.091
		S	09000	-0.961	-109847	-8.435	6.618	23.322	52.31 I	37.457	99.465
YEAR	(SWELLI	N	-0 .394	-8.405	-28.91 1	14.064	11.244	6.450	6.393	2*519	3.021
		S	-0.064	-2 ●000	-18.055	-110682	5*734	5.239	6.181	2.489	-12.930
	(SEA)	N	-5.460	-6.722	-4.937	3.826	5.999	13.041	16.292	15.189	39.997
		S	-0.479	-6.905	-5.246	-3.554	1 ●933	9.889	18.896	19.496	37.450

§ Ballard, 1964.

† (Foot lbs/foot of beach/unit of time) X (10)

‡ - = Flux toward the south

reached by Sternberg and McManus (1971):

1. The stronger bottom currents on the central continental shelf off the Washington coast are the result of meteorological conditions, most specifically wind stress associated with storm conditions rather than wave surge;

2. Measured current speeds at 3 m off the sea floor frequently exceed 40 cm/sec during the winter months and may exceed 80 cm/sec during severe storms;

3. Current direction vectors show a high variability throughout the year; however, when averaged over monthly and annual periods, bottom velocities exceeding 40 cm/sec exhibit a net directional response, dominantly northward on the continental shelf of Washington;

4. The observed direction variability of the higher speed classes could account for significant sediment dispersal across the continental shelf; however, moving sediment would also experience a net northward migration as a result of the net transport of bottom water;

5. If approximately six major storms sweep the Washington shelf per year, then a sedimentary particle might be displaced as much as 35 km northward and 12 km westward per storm, or the maximum annual displacement of a sedimentary particle eroded from the bottom would be approximately 220 km in a northwesterly direction.

Komar, *et al.* (1976) photographed ripple marks believed to be produced by surface waves in 204 m of water. In evaluating the significance of waves on sediment transport, Komar concludes that winter storm conditions off the coast generate waves that should commonly produce bottom orbital velocities capable of rippling the sediments to water depths of 150 to over 200 m. Summer waves produce ripples at depths of up to 50 to 100 m.

Gross and Nelson (1966) interpreted sediment movement on the shelf from the distribution and concentrations of radionuclides from the Columbia River. Changes in the relative concentrations of zinc-65 and cobalt-60 and in the ratio of the activity of zinc-65 and cobalt-60 suggested that radioactive sediment moves northward 12 to 30 km per year along the shelf and 2.5 to 10 km per year westward away from the coast. This study was based on data collected from 1961 to 1963 and gave a first guess on the rates of sediment-movement in this region.

Findings of Harlett and Kulm (1973] indicated that suspended material concentrates near the surface (at the seasonal thermocline), at mid-depth (the permanent pycnocline), and at the bottom. Seaward transport at the upper two surfaces provides a mechanism by which terrigenous sediment and biogenous material bypasses the outer continental shelf. Most of this material is silt, clay, or biogenic debris. This results in the low values for organic carbon on the shelf and the high values on the slope as discussed previously. The bottom turbid layer moves sediment to the shelf edge and down to the lower continental slope in low density currents.

Barnard (1973) reviews the slope sediment dispersal routes for the late Cenozoic based on turbidites in sediment cores. The submarine canyons were all actively transporting sediment during the last glacial stade (period of glacial advance), and as the sea level rose and sediment supply diminished, the canyons became less active. The following is extracted from Barnard and describes the late postglacial dispersal routes from 6,7S0 years before the present to the present:

"By about 6,750 years B.P. sea level had risen to within about 5 to 10 m of its present level. Astoria, Grays Harbor and Juan de Fuca canyons were filling up with hemipelagic mud and some sand/silt turbidite layers. However, Willapa Canyon remained active until about 5,000 B.P. when it too began to fill up at rates of about 25 $mg/cm^2/year$. All these canyons presently appear to be filling up with fine grained material, which is probably derived primarily from the Columbia River. In contrast to the above canyons, Quinault Canyon apparently acts as a funnel for a large amount of material that is moving northward along the shelf. This material accumulates in the head of the canyon for about 500 years before it is flushed down the canyon as a large turbidity current that flows down lower Quinault Canyon, out of lower Willapa Canyon and into Cascadia Basin."

Harlett and Kulm (1972) measured currents in Cascadia deep-sea channel of up to 10 cm/sec and suggested that these currents provided a mechanism for transporting suspended materials from the continental margin to the deep ocean basins.

d. Estuarine Geology. The deposition of sediment is common to all estuaries. Although the origin and types of the estuarine sediments may vary from one area to another, in general all are supplied by four primary sources: surface water runoff, the ocean, shore erosion (by wind and water], and biological activity (including organic waste).

Sedimentation is a continuing geologic process that interferes with shipping activities. In order to maintain existing shipping charnels and dock spaces in the major estuaries, maintenance dredging is periodically undertaken. If any facilities are to be expanded, additional dredging is often needed.

Dredging produces certain physical effects including: 1) alteration of the circulation patterns; 2) increase in the distance of salt water intrusion; 3) destruction of benthic organisms (by either direct dredging, or by being smothered in settling sediment); 4) increase in turbidity; S) decrease in oxygen concentration, and 6) redistribution of any toxic substances that may have been in the sediment.

Because of the problems relating to dredging, the characteristics of sediments are studied prior to commencing dredging operations so as to dispose of the spoils with minimal impact. Characteristics that may be analyzed include:

1. Volatile solids -- A measurement of the amount of organic material present in bottom sediments. Organics may include detritus, biological wastes, dead organisms, wood chips or any biotic debris;

2. Biochemical oxygen demand (BOD) -- A measure of the oxygen necessary to satisfy the requirements of microbes for the aerobic

decomposition of organic matter. The amount of oxygen consumed in the test can be used as a direct measure of biodegradable organic matter;

3. Chemical oxygen demand (COD) -- A measure of the oxygen necessary to satisfy the oxidation requirements for inorganic matter released;

4. Initial dissolved oxygen demand (IDOD) -- The amount of dissolved oxygen that is consumed during the first 15 minutes following re-suspension in seawater. This provides an indication of the oxygen that will be used from surrounding waters when dredged sediments are resuspended during dredging and disposal operations. Almost all of the IDOD will consist of COD.

The following site-specific information is presented for each of the major estuaries in the study area.

i. Coos Bay Estuary. Littoral drift is to the south in the summer and to the north in the winter with a net transport to the south (Bourke, Glenne and Adams, 1971). Since the completion of the south jetty, entrapment of sand has occurred between this jetty and Yoakim Point located approximately 1.5 km to its south (Percy, *et al.*, 1974). Shoaling occurs at the entrance bar as a result of littoral drift, at the interface of fresh and salt water where tributaries enter the Bay, and in areas of the Bay where the velocity of incoming, sediment-laden waters is reduced (usually between kilometers 21.76 and 23.20) (U.S. Army Corps of Engineers, Portland District, 1975a).

South Slough of Coos Bay is relatively uncontaminated and un-dredged, while Isthmus Slough is heavily industrialized and frequently dredged.

Sediments transported to the estuary from its drainage basin average about 72,000 metric tons annually (Percy, et aZ., 1974).

Slotta, et aZ. (1973) proposed a sediment classification system based upon the sulfur-iron cycle in estuarine sediments. In developing their system, test sediments were taken from known sites of active sulfate reduction in the Coos Bay estuary. They determined that the formation of pyrite (FeS_2) in estuaries is an important mechanism in the removal of iron and sulfides. Slotta, et aZ. (1973) also examined some physical and biological impacts of dredging in estuaries, using Coos Bay as their main study area.

ii. Umpqua River Estuary. Net transport of material along the coast near Umpqua Bay appears to be to the south (Percy, et aZ., 1974) although it has also been reported as nearly balanced (U.S. Army Corps of Engineers, Portland District, 1976). Movement of sand sediments around the north jetty and into the estuary, during high tide, has been observed by the use of aerial photographs (James, 1970). Sediments transported to the estuary from its drainage basin are estimated at 431,000 cubic meters annually.

Analysis of dredge samples, taken at numerous points within the estuary from November 1970 to August 1971 show the following:

1) organic contents ranging from 0.91% to 3.2% (both samples taken in August 1971 -- the first from the east side between kilometers 8.53 and 8.85 and the second from the west side at Buoy #9; 2) void ratios ranging from 0.772 (November 1970 at km 128 to 160 at Barrets upper dike) to 0.0967 (August 1971 from the west side at Buoy #9); and 3) mean grain size that of fine sand.

Sediment deposition probably is greatest during the winter months when the estuary is two-layered to partly mixed and sediment contributions from river inflows are greatest. During this period, the river deposits primarily sand-sized sediments. The majority of the sands carried into the Umpqua estuary by the river are probably deposited upstream of Double Cover Point. Silt- and clay-sized sediments are held in suspension by the turbulent water and are either flushed out to the ocean or are carried by eddying currents into less turbulent areas where they can settle out.

The quantity of sediments transported into the estuary during the summer is probably very small in comparison to that transported during the winter.

Marine sands also intrude into the estuary. The upstream limit of the marine sand intrusion in the Umpqua is probably the area below Double Cover Point.

iii. Yaquina Bay Estuary. Kulm and Byrne (1966) analyzed the texture and mineralogy of Yaquina Bay sediments and evaluated their response to hydrographic conditions.

The following discussion of sediments in Yaquina Bay is extracted from the U.S. Army Corps of Engineers, Portland District (1975b), which in turn drew heavily upon the work of Kulm and Byrne (1966).

With regard to soil sediments, three depositional realms occur within the Yaquina estuary. These realms have been termed marine, fluviatile, and transitional marine-fluviatile.

From the mouth of the estuary to about McLean Point, sediments are similar to the sediments of adjacent dunes, the coastal beaches, and the near-shore shelf material near the mouth of the estuary. They consist of well-sorted, subangular to subrounded, fine to medium sands.

Although the marine realm terminates in the vicinity of McLean Point (where the first appearance of micas marks the seaward extent of fluviatile dominance), marine sands are transported by tidal currents during the high flow regime (i.e., when the estuary is a partly-mixed system) up the navigation channel as far inland as Oneatta Point. This marks the upstream extremity of marine influence on the bottom sedimentation. These sands move into the estuary and upstream beyond the marine realm primarily as bed load -- which is defined as material not vertically supported by the flow and which moves along the bottom by sliding and rolling. During the low flow regime, marine sediments apparently do not intrude into the estuary beyond McLean Point. Dune sands blown into the estuary are included in the marine intrusion of sediments. The actual yearly amount of marine sand moving into the estuary is virtually impossible to determine. However, maintenance dredging records from 1959 through 1967 indicate that quantities ranging from about 49,000 to 282,000 cubic meters of sand annually have been removed from the entrance and inner channels (i.e., up to about the Highway 101 bridge). The average yearly dredge quantity for the 1959-67 period is on the order of 165,000 cubic meters.

Marine sands deposited in the estuary originate from adjacent coastal dunes, beaches and the near-shore ocean shelf. Littoral drift moves beach and shelf sand southward in the spring, summer and early fall (during low flow conditions in the estuary) and northward during late fall and winter (high flow conditions). Net littoral drift is to the north. Southward littoral transport is restricted, probably because of deflection of the current by Yaquina Head and/or the submarine Yaquina and South Reefs. The south jetty obstructs the northern littoral drift, and sand accumulates on the south side of the south jetty. As the northward longshore currents pass the south side of the jetty, some eddying and minor erosion may occur on the north side of the north jetty. An average annual accretion of 209 cubic meters of sand for the 70-year period (1896-1961) was estimated for the south shore. Since the 1971 extension of the south jetty, the accretion rate may have increased.

Sediments consist of poorly sorted angular to subangular, medium and coarse sands and silty sands. They are, as a whole, considerably coarser grained and more angular than the sands in the marine realm.

The river transports these sediments into the estuary from upstream in the form of bed load and suspended or wash load. Silt- and clay-size particles are generally included in the suspended load whereas the coarser material, such as the sand, makes up the bed load. During high-river discharge, the finer sands are probably also included in the suspended load. Sediments deposited into the Bay each year by the river and its tributaries total an estimated 27,000 metric tons. During low-flow, the major portion of the river sands appear to be deposited above Oneatta Point; during high-flow, some sand is carried farther downstream into the Bay.

Coarse-sand-size and gravel-size fragments of sandstone are common in the channel above Toledo. Between Toledo and Oneatta Point, siltstone and shale fragments are prevalent.

A transition realm occurs in the river channel and two tidal flats (Sallys Bend and South Beach) between the fluviatile and marine realms (i.e., between about McLean and Oneatta Points). Types of sediments in this realm vary widely and consist of an intermingling of marine sediments which intrude into the area during the high flow regime and the fluviatile sediments which are transported into the area throughout the year.

In the channel, and in the area of the South Beach tidal flat, bottom sediments consist primarily of poorly- to well-sorted, angular to subangular fine to medium sands. On the basis of the particle roundness, the sands of the South Beach tidal flat appear to have a marine origin. This suggests that complex currents develop within the Bay which tend to direct some of the inland migrating marine sand during the high flow regime against the southerly side of the Bay.

Windborne sands from the nearby dunes also probably contribute to the marine sediments in the South Beach tidal flat area. As discussed previously, the sands in the channel are primarily of marine origin, although between Coquille Point and Oneatta Point the concentration of marine sands is reduced significantly as a result of mixing with the river-transported sands.

Flanking both sides of the channel from about River Kilometer 10 to King Slough on the south and about McLean Point on the north, the bottom sediments are silty sand -- the silt content indicating low-velocity flow which permits some silt and clay fines to settle out of suspension. Similarly, due to current patterns, the remaining fine suspended sediments carried into the estuary from the river drainage basin stay in suspension until they are either flushed out to the ocean or until they are carried into the quiet, shallow water such as King Slough and the northerly, shoreward portion of Sallys Bend tidal flat. There, they can also settle out or be deposited at low tide. Apparently due to the channel characteristics, the finer grained sediments (of silt and clay size) also tend to accumulate near shore on both sides of the estuary at Oneatta Point.

Chemical analysis of Yaquina Bay bottom sediments is presented in Table 1-17.

iv. Siletz Bay Estuary. Littoral drift in the area varies, but is believed to be to the north (Percy, *et aZ.*, 1974). In the past, the Siletz spit has been both breached and topped by ocean waves and new temporary inlets have formed because of the spit's low profile and the severity of storms and high tides to which it has been subjected.

The sand that originally occupied these inlets is spread out over the ocean bottom at the outfall of the Siletz River, forming a delta or sandbar. In time, these inlets could become permanent, thus cutting off portions of the spit from the mainland and changing the course or configuration of the estuary. The formation of barrier islands might also result. Barrier islands, beaches, and sandbars are relatively short-lived features of the sea environment and their existence is subject to the interaction of tides, wind, sand supply and offshore currents.

The seaward side of the Siletz Bay spit, locally known as Salishan Spit, is being severely eroded. During the winter and spring of 1973, high tides eroded the spit as much as 23 meters, with the loss of one house and the need for considerable expense to protect others. While properly designed seawalls and riprap might stabilize the spit, interference with the supply of coastal sand could cause problems at other areas along the coast. A further indication of erosion on the seaward side of the spit is the location of existing riprap, now west of the line between dune and beach.

The inner margin of the spit is also being eroded by tidal forces and the flow of the Siletz River, and a breakthrough is always a possibility. Because the sand dunes are highly erodible and the threat of high storm waves always exists, the stability of the spit is considered marginal.

Table 1-17

Analysis of Yaquina Bay Bottom Sediments[§]

Parameter (dry weight)	Sample 1	2	3	4	5
Volatile Solids (%)	17.1	7.0	2.6	13.7	21.8
COD (g/kg)	111	58	20	160	268
Initial Oxygen Demand (g/kg)	0.95	0.79	0.08	2.75	1.92
Oxidation - Reduction Potential (rev)	-0.14	-0.09	+0.41	+0.11	+0.09
Sulfides (g/kg)	1.74	1.03	0.03	0.11	0.10
Total Phosphorus (g/kg)	1.53	0.66	0.24	1.27	1.19
Kjeldahl Nitrogen (g/kg)	0.72	1.41	0.11	-	-
Grease and Oil (g/kg)	2.08	1.62	0.17	-	-

Note: Samples 1, 2, and 3 were taken on February 27, 1969 and Samples 4 and 5 on May 1, 1969.

Sample No.	Location
1	Yaquina Bay
2	Weiser Point
3	Toledo
4	Mouth of Depot Slough
5	Depot Slough at Toledo

§After O'Neal and Sceva, 1971.

Siletz Spit is also subject to erosion by wind. Where protective vegetation has been disturbed by development or use, trough blowouts are developing. While vegetation does protect dunes against wind erosion, it is of little value during severe storms.

The cost of stabilizing and maintaining the dune and spit artificially may outweigh the value of the private property in jeopardy. Further, a recent study at Oregon State University concludes that the long-term effectiveness of attempts to riprap against erosion is uncertain (Komar and Rea, 1976).

The deposition of sediment is a problem common to all estuaries, and is a major problem in the Siletz. Although the origin and types of the estuarine sediments may vary from one area to another, in general all are supplied by four primary sources: surface water runoff, the ocean, shore erosion (by wind and water), and biological activity (including organic waste].

Most sediment enters the Siletz estuary with the fresh water flow. The bedload material is primarily sand-size or larger and is transported along the bottom. The suspended load consists of silts and fine clays held in suspension by the turbulence of the water. The particle sizes and volumes of the transported material depend on the magnitude of the river flow and the composition of streambeds in the drainage basin. In order for this material to be transported, the current must maintain a minimum entrainment velocity.

Relatively little research has been conducted on sedimentation in Siletz Bay, but some observations have been made. An estimated 67,000 metric tons of sediment are transported into the Siletz estuary by the basin's river system annually (Rauw, 1974), so the amount of riverborne sediment carried into the estuary depends on the fresh water flow which, in turn, depends on precipitation in the drainage basin. Thus, the Siletz River transports a greater sediment load downstream during the rainy period, between October and March. Sedimentation and shoaling are occurring in many areas of the estuary, most noticeably in the southern portion of the bay where several large sandbars have formed. There are also delta deposits near the mouths of Drift Creek and Schooner Creek, and in Millport Slough west of the dike.

Since no large sand dunes are found in the immediate vicinity of Siletz Bay, it is felt that windborne particles constitute no more than a minor portion of the estuary's sediments. Undoubtedly, some sediment is blown into the lower reaches of the estuary by onshore winds from the sandspit south of the mouth of the Siletz River. Erosion of the spit due to wave action and circulation patterns has become so severe that there is reason to fear the spit will soon be breached (Komar, et aZ., 1973).

There is some concern that the lower reaches of the Siletz estuary may be filling in. Sandbars are forming in the northern portion of the bay, and marine sediments are accumulating in the mouth and lower reaches of the estuary.

Sedimentation from upstream logging practices is possibly a major threat to the. long-term viability of the Siletz estuary. If not controlled, it may accelerate the conversion of tideflats to marsh, smother marine life and further prevent recreational use of the estuary. The Siletz estuary is one of the worst sedimented on the Oregon coast according to the Oregon Division of State Lands, it is already 65% tidelands, which is very high compared to other Oregon estuaries (Percy, *et al.*, 1974).

v. Columbia River Estuary. The following discussion is extracted from U.S. Army Corps of Engineers, Portland District reports (1974a and 1974b) :

"The bottom sediments that accumulate in the main channel of the Columbia River are typified by a clean, fine sand that was found during boring tests at approximately River [Kilometer 177]. Ten percent of the sand was finer than 0.1 millimeters in diameter. Other bottom sampling in waters adjacent to the main channel yielded samples containing at least 50 percent sand, up to 93 percent sand and 7 percent silt and clay. These samples were taken in the estuary near Astoria, Oregon.

"Suspended sediments transported by the Columbia River are primarily lithogenous particles, generally inorganic crystalline material, that are ultimately derived from erosive weathering of rocks. suspended sediment is primarily of a silt and clay composition with the load increasing as the water moves downstream. Coarse sediments tend to bounce and flow along the bottom of the river and are responsible for scouring effects. At Vancouver, Washington, the estimated particle size composition of the total sediment discharge for 1963 (6.2 million metric tons) was 35 percent sand, 50 percent silt and 15 percent clay. The biogenous particles, living and non-living organic materials, are composed of phytoplankton (90 percent diatoms) and organic detritus. Organic detritus includes wood fibers and plant, animal and textile (cotton and wool) materials.

"In the lower Columbia River the average suspended sediment concentration is 100 mg/l. The average concentration at Vancouver, Washington in 1967 was 78 mg/l. Concentrations recorded during 1962-63 were generally lower, ranging from 1 to 50 mg/l. A concentration of 570 mg/l was recorded in a February 1963 storm and about 4,000 mg/l in the December 1964 flood.

"While the suspended sediment concentration is not high, the large flow volume in the-Columbia River transports a large volume of sediment. An estimated average annual sediment load transported by the lower Columbia River (October 1962 to September 1963) yielded the following:

7.6 million metric tons (carried past Vancouver, Washington)
1.0 million metric tons [contributed by Willamette River)
.5 million metric tons (contributed by other tributaries)
9.1 million metric tons approximately equal to 5 million cubic meters.

"In the reach of the estuary affected by salt water intrusion (approximately up to River [Kilometer 37],) suspended sediment transport is affected significantly by a turbidity maximum that develops in response to the estuarine circulation pattern. In turn, the estuarine circulation pattern intensifies, abates and translates back and forth with the tides and with the season. About 30 percent of the fine sediment transported into the estuary by the river may be retained for extended periods.

"A sampling of suspended sediments in the estuary (River [Kilometer 8.4 to 29.31) taken 1.5 m above the bed in September 1969, Yielded a particle composition of four percent sand, 20.5 percent clay and 75.5 percent silt. A similar sampling taken in May 1970 yielded a particle composition of 5.3 percent sand, 34.1 percent clay and 60.6 percent silt.

"During the September 1969 sampling, a net upstream (landward) transport of 6700 metric tons of sediment occurred, whereas, in the May 1970 sampling, a net downstream (seaward) transport of 45,000 metric tons occurred.

"The previous figures do not include the substantial transport of sediments along the bottom. In this reach of the estuary, sediment movement along the bottom is highly influenced by the estuarine circulation pattern and tends to be landward in deep channels and seaward in the shallow areas. Coarse sediment tends to be trapped in the estuary due to landward transport of sediments along the bottom.

"The over-all effect is a net transport of bed material to the sea resulting in the formation of sandbars and sill across the mouth of the river. In 1974, an estimated 1.S million cubic meters of material will have to be dredged at the mouth of the Columbia River and another 0.8 million between the mouth and River [Kilometer 37].

"Included in the suspended load of the lower Columbia River are the finer organic and inorganic particles that cause turbidity. Along the project reach, the river has a mean annual turbidity of approximately 10 to 15 Jackson Turbidity Units (JTU's)[see Ch. VI., p. VI-24]."

Net-littoral drift at the mouth of the Columbia River was studied by Ballard (1964). Unlike the other coastal estuaries, the high river flow of the Columbia moves considerable material out to the ocean. Waves and current action carry this material along the shelf or beaches, and prevent a delta from forming. The estuary is not a large sediment trap in this sense.

Sedimentation occurs seaward of the jetties at the Columbia River mouth, forming the Columbia River Bar. This bar causes waves to peak and sometimes break, making passage hazardous for vessels. Numerous shipwrecks have occurred here.

Chemical analysis of sediments 18 km from the river mouth are presented in Table 1-18. Size analysis of five samples within the estuary and numerous samples at the mouth are presented by Roberts (1974a).

vi. Willapa Bay Estuary. Andrews (1965) performed detailed sediment sampling, and physical and chemical properties analyses for Willapa Bay. Seventy-eight locations were sampled.

Table I-18

Columbia River Estuary Sediment Quality§

	SEDIMENT	ANALYSIS		
SAMPLE NUMBER†	1427	1428	1429	SAMPLES TAKEN: 1969 EPA Standards
Particle Size Dist.				
Gravel (+6 Mesh)	0%	1%	0%	No Standard Established
Sand	70%	51%	93%	" " "
Silt and Clay (-200 Mesh)	30%	48%	7%	" " "
Chemical Characteristics (Cone. % Dry wt.)				
Volatile Solids	4*5	4.8	2.2	6.0%
Chemical Oxygen Demand (COD)	38.0	27.0	20.0	5.0%
Initial Oxygen Demand (IDOD)	0.45	0.49	0.26	No Standard Established
Oxygen - Reduction Potential	-0.13	-0.11	+0.01	" " "
Sulfides	0.13	0.25	0.04	" " "
Total Phosphorus	0.78	0.84	0.74	" " "
Kjeldhal Nitrogen	0.84	1.180‡	0.490	0.10
Oil and Grease	0.61	1.010	0.310	0.15

§ U.S. Army Corps of Engineers, Portland District, 1974.
† Grab samples 18 km from river mouth
‡ Exceeds EPA Tentative Criteria

Of particular interest in this estuary is the rapid rate of erosion of Cape Shoalwater. The amount of sediment supplied to Willapa . Bay and to the offshore region by this erosion and by sediment transport along Long Beach results in a tidal delta off the mouth of Willapa Bay.

The following observations are from Andrews (1965):

"Sediment eroded from Cape Shoalwater, at the entrance to Willapa Bay, is carried out to the offshore tidal delta and into the bay to form shoals and spits. As the cape recedes northward, the entrance charnel migrates with it, and a large shoal area has developed between the channel and Leadbetter Point. An important littoral drift to the north is indicated at the bay entrance.

"The channel through the offshore tidal delta migrates to the south, shoals, reforms to the north and again migrates southward in cycles of 10 to 20 years, indicating an offshore littoral drift to the south.

"Sediments of the tidal flats in Willapa Bay range from thick deposits of silt- and clay-size material at the south end of the bay and adjacent to the river mouths to eroding sand flats on the north side of the bay entrance. The fine sediment deposition is a result of the interaction of river silting and tidal currents.

"Nahcotta Channel is constantly being scoured clean of deposited sediment by strong bottom currents. Well-sorted fine sand with low organic carbon content and few macroscopic marine organims is characteristic of this channel.

"Channel sedimentation does occur in the Willapa River Channel and in Stanley Channel near the confluence with Nahcotta Channel. This sediment is generally river-derived.

"Heavy minerals in Willapa Bay form two suites, one originating from high-rank metamorphic rocks and the other from basic igneous rocks. These minerals are probably derived from the Willapa Bay and Columbia River drainage basins as well as reworked local sediments. At the present time, sediment eroded from Cape Shoalwater is probably the most important source of fine sand to the bay.

"Two types of organic matter appear to be present in Willapa Bay based on the ratio of organic carbon to organic nitrogen (C/N). One type associated with the fine-grained tidal flat sediment, had an average C/N of 13.8; the other type, associated with the coarser channel sediment, had an average C/N of 6.1.

&

"Foraminifera in Willapa Bay may be classified in terms of brackish-water, marine and mixed brackish-water and marine suites. The distribution of these suites of Foraminifera is closely related to the sedimentary environments of the bay.

"The tidal flat adjacent to Long Beach Peninsula represents a relict of the growing spit; the layer of finer-grained sediment over fine sand represents a deposition of river-derived material subsequent to growth of the spit past the given location."

The dredging program carried out by the Army Corps of Engineers has been made necessary by continued sedimentation in the navigation channels of Willapa Bay, in the Willapa River, and in the outer bar channel at the entrance to the bay. Although the Corps has maintained the navigation channels, much of the rest of the bay has been filling in over a period of years. The sediment entering the bay originates from the rivers of the drainage basin, ocean beaches, and the bay shore.

The dunes on the north end of the Long Beach Peninsula are another contributor of sediment to the bay. Much of the dune area is unvegetated and the loose sand is exposed to wind erosion. The sediments in the intertidal and shallow subtidal areas in the lee of the peninsula are coarse sand, which Andrews (1965) suggests were transported by wind.

The shores of Willapa Bay, which themselves are built up of sediment deposits, contribute through wave erosion to the sedimentation in the bay. Where the sloughs curve, the banks usually have an accreting side and an eroding side. The currents scour sediment away from the eroding banks and deposit it downstream on accreting banks.

The ebb and flow of the currents would not appear to result in any net change in sediment distribution. However, incoming currents and outgoing currents often use separate channels and often have different velocities. As the channels migrate through erosion and accretion, the sediment distribution changes.

Log storage and handling, both in the water and on the shoreline, have contributed organic material to the sediment. This material consumes oxygen from the surrounding water and influences the species of invertebrates that are able to live in the bottom.

The material carried into the bay by the Columbia River plume also shows signs of man's activities. Radionuclides from the Hanford Atomic Works have appeared in Willapa Bay as phosphorus-32, zinc-65, and chromium-51. The zinc-65 is present not only in the sediment, but also has appeared in the marine life. This problem caused concern over the effect it might have on the .marketability of oysters, but the State Shellfish Laboratory reports that the level of radioactive zinc has declined in recent years since its source was cut off at Hanford.

Samples of sediments in the channels requiring maintenance dredging at Willapa were collected by the Army Corps of Engineers on 15 May 1974 (U.S. Army Corps of Engineers, Seattle District, 1976b). Results of chemical and physical analysis are presented in Table I-19. These results indicate that concentrations of potential toxic materials including heavy metals and sulfides are present at levels which naturally occur in finely divided Pacific Northwest marine sediments. Of most significance is the oxygen consumption demand of the sediments and the small particle size which can cause high turbidity.

The chemical oxygen demand (COD) ranged from 6.7 to 15.1% and

Table 1-19

Results of Analysis of Sediment Samples Collected in Willapa Bay Channels to be Dredged[§†]

Characteristic	(Tokeland) S1	S2	(Bay Center) S3	S4	S5	(West of Raymond) S6	S7	S8	S9	S10	S11	S12	S13
Total Solids (%)	56.2	52.7	63.8	43.3	35.8	58.2	36.0	36.3	34.9	39.6	40.3	45.2	49.8
Volatile Solids (%)	5,7	6.1	4.5	9.0	10.1	7.8	11.9	10.8	10.9	10.6	9.3	7.8	7.0
IDOD (mg/kg)	360	390	315	540	465	255	675	615	385	660	570	495	540
Chemical Oxygen Demand (%)	6.7	7.6	11.0	10.0	1s.1	7.4	9.1	11.0	16.5	15.5	13.4	10..5	10.4
Kjeldahl Nitrogen (%)	0.12	0.13	0.07	0.10	0.20	0.08	0.23	0.23	0.24	0.20	0.19	0.16	0.14
Oil and Grease (%)	0.06	0.13	0.08	0.13	0.11	0.14	0.06	0.06	0.07	0.29	0.24	0.11	0.11
Mercury (mg/kg)	Less than 0.0001												
Lead (mg/kg)	10.0	10.0	10.0	40.0	20.0	20.0	20.0	10.0	20.0	10.0	10.0	10.0	10.0
Zinc (mg/kg)	60.0	60.0	50.0	70.0	90.0	60.0	60.0	60.0	60.0	70.0	80.0	80.0	80.0
Cadmium (mg/kg)	Less than 0.0001												
Copper (mg/kg)	20.0	30.0	20.0	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	20.0	20.0
Chromium (mg/kg)	10.0	10.0	10.0	20.0	20.0	10.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Nickel (mg/kg)	20.0	10.0	10.0	20.0	20.0	20.0	20.0	20.0	20.0	10.0	10.0	20.0	20.0
Sulfide as S (mg/kg)	70.0	80.0	540.0	40.0	310.0	90.0	220.0	250.0	540.0	1050.0	270.0	90.0	640.
Total Phosphorous (mg/kg)	560.0	550.0	450.0	550.0	610.0	430.0	610.0	390.0	630.0	690.0	570.0	600.0	240.0
Density (kg/m^3)	1025	886	987	815	731	937	769	790	785	798	777	827	848
Turbidity after settling (JTU):													
1 hour	150	150	240	140	130	400	550	500	650	160	330	480	210
6 hours	80	80	100	130	120	110	260	270	260	70	160	140	75
24 hours	20	15	30	40	50	40	120	75	50	25	70	60	25

§U.S. Army Corps of Engineers, Seattle District, 1976b.

†All samples were collected on 15 May 1974 using a Peterson grab sampler. Sample locations are labeled S1, S2, etc.

averaged 12.0% at Bay Center, 7.2% at Tokeland, 11.9% in the river channel and 10.5% in the inner bay channel. In the same samples, the initial dissolved oxygen demand (IDOD) averaged 566 grams/cubic meter (g/m^3) at Bay Center, 556 g/m^3 to Tokeland, 693 g/m^3 in the river channel and 676 g/m3 in the inner bay channel. The IDOD measurement refers to the amount of dissolved oxygen that is consumed during the first 15 minutes following resuspension in seawater and provides an indication of the oxygen which will be used from surrounding waters when dredged sediments are resuspended during dredging and disposal operations. These oxygen consumption values are relatively high, apparently due to the presence of deposited wood wastes in channel areas (U.S. Army Corps of Engineers, Seattle District, 1976).

vii. Grays Harbor Estuary. Numerous studies have been conducted on the coast near Grays Harbor on the movement of littoral drift and a number of theories exist as to the direction and volume of movement. These studies include sediment analysis, aerial reconnaissance, evaluation of historical changes, hydraulic modeling, etc.

Wave energy studies indicate that net transport of material by the littoral drift should be to the north (due to the region's prevailing southwesterly winds and coastline alinement). Clearly, short-term seasonal variations, local topographic features, and variations in the sediment supply cause reversals that may be either short or long term.

The mineralogic and geomorphic studies show that the sand accreting west of the Point Chehalis Groins is derived largely from Halfmoon Bay to the west. Also apparent is the fact that the sediment source for the outer harbor channel shoaling and Damon Point Shoals is the sediment accreted north of the North Jetty, in that it bypasses the jetty by land, sea, and air.

Grain size analysis indicates that sediments become finer grained toward the head of the estuary. Analysis of samples taken throughout the estuary show that sand [whether marine or fluvial) is the predominant sediment size with silts and muddy silts predominant nearer to the Humptulips and Chehalis Rivers.

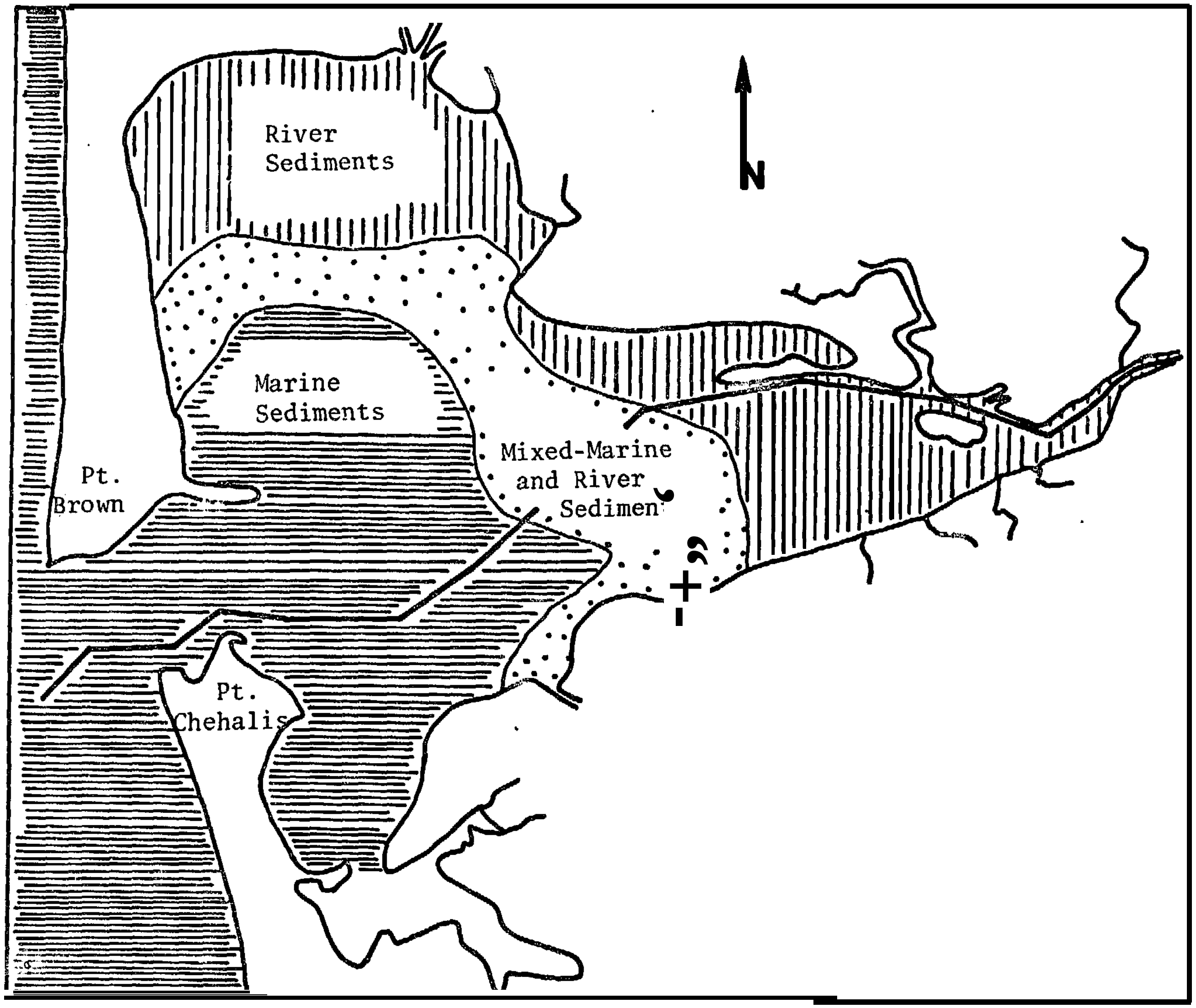
Figure 1-41 presents the generalized distribution of sediments by origin for Grays Harbor.

The average annual suspended-sediment discharge from the Chehalis River Basin was about 490,000 metric tons, with a range from 245,000 to 626,000 metric tons. About 74% of this suspended-sediment discharge was derived from the Satsop and Wynoochee River drainage basin. This is expected to diminish due to the damming of the Wynoochee River in 1973 (U.S. Army Corps of Engineers, Seattle District, 1974).

Model studies have been conducted to evaluate the changes and shoaling that would result from a large port expansion requiring dredging a deeper channel (U.S. Army Corps of Engineers, Seattle District, 1976a) .

Data taken and analyzed in 1974 and 1975 by the Department of Ecology for heavy metals and pesticide concentrations showed both

Figure I-41
Grays , Washington General Sediment Distribution[§]



[§] U.S. Army Corps of Engineers, 1974c.

water and sediment samples with significant amounts of these potential toxicants. In some samples, the concentration of certain pesticides exceeded concentrations reported harmful to various marine organisms. There is a considerable increase of metals concentrations found in sediments toward the inner harbor. Of the heavy metals measured, zinc and copper were predominant, followed by nickel, chromium and lead. Table 1-20 presents the analysis of sediment samples taken near Hoquiam in 1974.

e. Marine Geology of the Strait of Juan de Fuca-Puget Sound System.

i. Geologic History. Puget Sound, the Strait of Georgia, and the Strait of Juan de Fuca owe their great depths and shape to glaciation. The glacial history of the region has already been discussed.

Much of the Puget Sound basin consists of glacial till, and as such is a poor source for sand for beach formation within Puget Sound. The last glaciation ended about 10,000 years ago, and beach formations in the inland waters are very recent. The combination of 1) source material very low in sand-size particles (i.e., the glacial till), 2) the comparative sheltering from wind and waves (compared to the open coast), 3) the steep sides of the straits, basins and inlets and 4) the short time that nature has had to work the bluffs and sediments, leads to a region that has many kilometers of coastline, and very few kilometers of beaches. In Puget Sound, 85% of the shoreline consists of bluffs, with no passable beaches at high tide. The remaining 15% is evenly divided between river estuaries and beaches, and both have been subjected to considerable population pressures and developments.

A feature common to glaciated basins is a sill, representing a terminal morraine where the glacier either stopped advancing or where it may have been receding relatively slowly. Chapter III., Oceanography discusses the importance of sill formations in the circulation and mixing of water masses in the inland waters of Washington and British Columbia.

ii. Bathymetry/Geomorpho logy. The general geographical and bathymetric features are discussed in the introduction section for the inland waters in Chapter 111., Oceanography, due to the influence of bathymetry on the circulation patterns which affects the distribution of physical and chemical properties.

Delta formations occur where rivers enter the inland waters. In the open ocean regions, the estuaries act as sediment traps, and the finer particles entering the ocean region are transported by wave action. The waves are not nearly as significant in the inland waters, where the river energy dominates, transporting sediments into the basins and forming deltas. The largest in the region is the Fraser delta, On which most of the city of Vancouver is built, however, this delta is to the north of the 49th parallel and out of the study area. The next largest is the Skagit delta in Whidbey Basin. Other deltas include the Stillaguamish, the Snohomish, both in Whidbey Basin; the Nisqually in southern Puget Sound; the Skokomish, Hamma Hamma, Duckabush and Dosewallips on Hood Canal; the industrialized deltas of the Puyallup

Table 1-20

Analysis of Sediment Samples Taken Near Hoquiam in 1974[§]

	Gross Features - Per Cent							Metals - mg/kg (ppm)													
	Moisture	TVS		COD		Kjeldahl-N		Cadmium		Chromium		Copper		Lead		Mercury		Nickel		Zinc	
		Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Pile Dolphin 50 ft West Of Port Oock	67.7	3.9	10.1	3.8	11.6	0.09	0.29	0.4	1.3	21	66	19	60	0.16	0.S1	0.01	0.03	13	40	50	93
Port Slip No. I	S3.7	3.S	7.S	3.0	6.4	0.07	0.16	0.4	1.0	2s	54	2s	54	0.1S	0.32	0.02	0.04	19	40	38	82
Off East End of Test Barge so ft	59.9	3.8	9.4	4.0	9.9	0.11	0.27	0.7	1.7	23	58	26	64	0.21	0.53	0.02	0.0S	13	32	37	92
Off West End of Test Barge 50 ft	S2.3	3.S	8.3	3.S	8.3	0.08	0.19	0.4	1.1	2S	60	22	53	0.32	0.7S	0.02	0.0S	17	39	34	81
Rennie Island at Station 2A	S8.6	3.8	9.1	3.5	8.4	0.08	0.10	<0.4	<1.0	14	34	16	39	0.26	0.62	0.02	0.0S	<3	<6	19	46

§Herrman, 1975.
‘Analyses expressed on wet weight and dry weight basis.

and the Duwamish, in the main basin of Puget Sound; the Nooksack delta in North Sound (Bellingham Bay); and the Elwha delta on the Washington side of the Strait of Juan de Fuca.

Many smaller delta formations occur at the heads of the many inlets and are deposits from small tributaries.

iii. Bedrock and Sediment Structures. Structure can be viewed as an extension of onshore formations. Mayers and Bennett (1973) interpreted the structure underlying the Strait of Juan de Fuca from seismic profiles. Sylwester, *et al.* (1971) used seismic profiling in the southern part of the main basin of Puget Sound to study active fault zones. Subbottom structure has been analyzed for Admiralty Inlet by Harding-Lawson Associates (Oceanographic Commission of Washington, 1975) and by Creager, *et al.* (1975). Seismic profiling in Saanich Inlet, B.C. has been reported by Lister [1967). Sediment thickness over the bedrock in the Admiralty Inlet appears to be 1 to 5 m.

Further structural analysis for Puget Sound is planned by Creager and others as part of a class cruise training program at the University of Washington as stated in the Compendium of Current Environmental Studies in Puget Sound and Northwest Estuarine Waters (Schott and Pizzo, 1975).

iv. Sediment Data. The primary sources of sediment are the rivers and the eroding bluffs. Glacial till consists largely of clay-size particles and cobbles (very few sand sized particles). As the bluffs feed sediment to the beaches, the fine fraction (clay and silt) is carried offshore in suspension and deposits in the basins, In Puget Sound, the basin sediments are largely clay and silt, with some sand and gravel appearing near the major rivers. Concentrations of gravel and sand are high over the entrance sills, where the currents scour away the finer fractions. In the Strait of Juan de Fuca, the sediments consist of gravel and sand in high energy zones near Cape Flattery and in the western half of the Strait, and on the Victoria to Green Point sill.

Marine sediment data of the inland waters of Washington state for the Strait of Juan de Fuca, Puget Sound, San Juan Island Passages, North Sound and Saanich Inlet are compiled and presented graphically and tabularly by Roberts (1974b). Over 2,000 marine surface sediment samples are presented from the University of Washington and the Institute of Oceanography, University of British Columbia.

Surficial bottom sample distributions for Puget Sound and the eastern Strait of Juan de Fuca are also illustrated in the Puget Sound literature survey, volume 2 (University of Washington, Dept. of Oceanography, 1953-54).

Schell (1976) reported sedimentation rates in Puget Sound, the Strait of Juan de Fuca, Bellingham Bay, off of Cape Flattery, and 16 km off the Washington coast, based on lead-210 dating of cores. The largest sedimentation rates were observed near the sewer outfall off West Point in Puget Sound. Rates 16 km of the coast were 0.4 mm/yr, while rates in Puget Sound ranged from 1.0 to 10 mm/yr. Sedimentation rates from Schell are presented in Table 1-21.

Table I-21

Sedimentation Rates in Puget Sound Obtained from Lead-210 Dating[§]

Core #	Depth (meters)	Location	Sedimentation rate mm/year
41058	187	1.9 km N.W. of Pt Williams	10.2
410s9	157	1.9 km S. of Alki Pt.	3.4-4.2
41054	196	1.9 km N. of Blake Island	9.4
41055	183	1.9 kmN. of Blake Island	5.7-7.3
C-278 41159	200	18.5 km of Wash. coast	0.4
C-254 41157	102	Colvos Passage	1.0
6-15 cm		N. end of Vashon Island	
C-302 41162	283	Jefferson Head	2.0
4-11 cm			
C-299 41160	250	2.4 km S.W. of Alki Pt.	3.0
14-34 cm			
C-259 41158	160	Commencement Bay	4.8
17-27			
C-301 41161	252	West Point (near sewer outfall]	very large
C-223	146	JDF-1 (Juan de Fuca Strait)	0.8-1.3
C-241	119	Fraser River	2
C-237	210	Cape Flattery	5.2-6.4
C-252	28	Bellingham Bay	5.7
11-30			
1-s cm			
Sedimentation rates as reported by Crecelius et al.			mm/year
Quartermaster Harbor			2.2
East Passage			20.0
Fox Island			
North Seattle			10.0

§Schell, 1976.

Harman and Sylwester (1976), of Shoreline Community College, have plotted the distribution of microbiogenic sediments in Puget Sound and discussed their use in evaluating estuaries of the central Puget Sound. Four hundred grab samples were obtained. The basic microbiogenic components of the sediment (diatoms, foraminifera and ostracods) were identified and the basic distribution patterns utilizing floral and faunal groupings was determined. The use of microbiogenic sediments in evaluating glacial or man influenced sediments was assessed, and the findings were presented at the Fourth Technical Conference on Estuaries of the Pacific Northwest (Oregon State University Engineering Experiment Station, 1974). Their findings are summarized as follows:

"In Central Puget Sound, centric or disc shaped diatoms such as *Coscinodiscus* species dominated the deeper portions of estuaries. Angular shaped diatoms such as *Biddulphia* and *Ischmia* species are more frequently found in higher salinity waters or current swept rocky and gravelly areas. Rod and chain diatoms, such as *Milosiranae,* were common in low salinity waters, especially on mud flats and eastern portions of Puget Sound. Pennate diatoms characterize river beds or inner portions of tidal flats. Differences between foraminiferal fauna reflected the influence of substrate and salinity differences. In current swept passages a greater diversity of species in the microfauna existed. Mudflats contain predominately *Trochamina inflata* and *Miliammina fusca* while sandy tidal flats were dominated by *Trochimina pacifica.* Estuaries with lower salinities were more frequented by *Elphidium selseyense* while *Elphidiella hannai* were typically more seaward. In the main Puget Sound basin *Eggerella advena* and *Legenammina atlantica* were dominant but appeared to be excluded from the more distant estuaries of Sinclair Inlet, Dyes Inlet and Liberty Bay. Wood fragments appeared to be controlled by advection and water stratification, since their concentrations were low in deeper waters despite their near proximity. Off the old and new sewer outfall at METRO (Municipality of Metropolitan Seattle) tideflat, species *Trochamina inflata,* was found in deep water (30 fathoms) suggesting possible influence of either the old or new sewer outfall. Both polluted and glacial sediment should have lower E. *selseyense,* pennate diatoms and *Milosiranae* should dominate glacial sediments while arenacous foraminiferal faunas will be found dominating polluted sediment in Central Puget Sound."

5. Resources.

a. Oil and Gas. The Oregon and Washington coastal areas are 17th on a list of 17 "industry preferences" according to the U.S. Bureau of Land Management (1974) . Although there are some areas that appear, from a geological standpoint, at least, to show promise (Rau, 1970; Schlicker, *et al.*, 1973; Rau and Wagner, 1974; Beaulieu and Hughes, 197S), little drilling has been done, and most of that unsuccessfully.

The tectonics of the West Coast have been explored earlier in this chapter [Section 2.b.). Thompson (1976) feels that an encouraging tectonic framework for hydrocarbon resources is the divergent, Atlantic-type rifts where the crust is actively spreading. The convergent, Pacific-type margins can also be favorable if they-include the features-of rapid, deep burial, and subsequent uplift by thrust-faulting adjacent to deep oceanic trenches. Colliding continents, the final stage of convergence, results in extreme structural contrasts, including contrasts of oil potential. Nowhere in his paper does Thompson mention the Pacific Northwest as to possible oil-producing capability based on tectonic factors.

*Q

According to Braislin, Hastings, and Snavely (1970) only "about 560 wells" have been drilled during the 20th century. Few have been drilled since 1970, so a figure of approximately 600 total would suffice. Only since 1960 has exploration been done on the continental margin in the area. Although oil and gas in commerical quantities have not been found, the geologic environment appears to be favorable.

The first known test for oil in western Washington was drilled between 1900 and 1902 near Stanwood Station or Machias in Snohomish County. In Oregon, the initial test for oil was drilled about 1902 near the town of Newberg, Yamhill County (Braislin, Hastings and Snavely, 1970).

Many of the first wells drilled in western Washington were in the vicinity of seeps or in areas where gas shows were found in water wells. Although commercially significant quantities of oil and gas have not been produced in either state, documented shows of hydrocarbons have been common in exploratory drilling in Washington. In Oregon, confirmed reports of petroleum are few.

The early 1930's was a particularly active period, and most wells were drilled by independents and small operators. Few were based on sound geological principles. Commercial drilling after World War II revealed promising shows of gas and high-gravity oil in the Ocean City area, but commercial production could not be established because of the low permeability of the reservoir rocks (Braislin, Hastings, and Snavely, 1970.

The Coos Bay Synclinorium (see Section 2.b. on Structure) is promising from the standpoint of rock type, thickness, structure, and geologic history. At least 3000 m of folded siltstones and sandstones may underlie the region. Phillips Petroleum Company drilled on the Westport Arch south of Coos Bay, between South Slough and Isthmus Slough, but encountered submarine basalt at a depth of 700 m. The electric logs indicated the presence of a 3 m gas sand at 317 m, but no tests were made. Another well drilled 5.6 km to the southwest in 1963 by E. M. Warren and Associates penetrated over 1830 m of Coaledo Formation (see Section 2a. on Stratigraphy). Several gas and oil shows were found in the Warren well, but the rock was too fine grained to produce commercial amounts of petroleum (Beaulieu and Hughes, 1975) .

Upper Coaledo is exposed along the crest of a narrow anticline between Isthmus Slough and Catching Slough. Although more section is available here than in the anticline to the west, no drilling has been done on this structure. Faulting and gentle plunging to the south provide closure in this direction. The structure extends 11.2 km and has a width of 1.6 to 3 km.

The geologic history of the continental shelf is similar to that of the mainland. Offshore bedrock units have been tentatively correlated to bedrock units exposed onshore. Major structures include the Coquille Bank (see Section 2.b. on Structure), the southern part of the Heceta Bank, and a large linear basin between Bandon and Cape Blanco that is filled with a thick Miocene to Pliocene section. Generally, the late Tertiary section

*

is thicker and more extensive on the shelf than onshore, a feature which contributes to the attractiveness of the shelf in terms of oil potential.

The West Shore Oil Company drilled the first oil and gas well in Coos County in 1919 near the town of Bandon. No production was reported in the well, nor has significant production been reported in 10 other wildcat wells drilled during the following 40 years in the County. Coast Oil Company, however, encountered strong gas shows in 2 of its holes drilled 4 km southwest of Coquille along Fat Elk Creek. A hole near Bandon drilled by Pacific Petroleum Company in 1941 reportedly yielded enough gas to fire the engine boiler (Beaulieu and Hughes, 197'5).

Only four of the eleven tracts offered for lease in the "Bandon Block" in 1964 were leased. A good gas show was encountered at 1650 m in a 18 m sandstone, but the bed was too tight to yield commercial amounts.

Approximately 2850 km^2 of shelf lands offshore from Coos County remain unexplored for oil and gas. Prospects are considered to be good for the area, and it is considered to be one of the best for petroleum exploration in western Oregon. Similar potential is interpreted for the southern part of the Heceta Bank off the coast of Douglas County. No exploratory wells have been drilled onshore in western Douglas County (Beaulieu and Hughes, 1975) .

Only one significant well has been drilled onshore in western Lane County in search of petroleum. This was located on the west flank of the Coast Range anticline near Mapleton. The firm attempted to drill through the volcanic sequence, but gave up at a depth of about 3930 m after penetrating more than 1830 m of basalt. Traces of hydrocarbons were found in the Umpqua shale at 1620 to 1623 m. No flow tests were made during the drilling and the hole was abandoned as a dry test. A small amount of oil was reported in cavities in a basalt dike that cut Eocene sediments.

Three holes were drilled on the continental shelf offshore from Lane County in 1966. The well on Heceta Bank bottomed in upper Eocene marine sediment at 3747 m.

Prospects for commercial deposits of oil and gas offshore from Lane County are good. Reportedly, nearly all the drillings off the Oregon coast obtained shows of hydrocarbons.

Onshore prospects in Lane County are less favorable, but some areas may still hold promise. Along the coastal areas, hydrocarbon deposits may exist in middle and lower Eocene marine sediments (Schlicker and Deacon, 1974).

Oil and gas exploration in Lincoln County to 1973 was limited to three shallow wildcats drilled onshore and two deep tests drilled on the bordering continental shelf. Tertiary marine sedimentary rocks probably extend to a depth of 3050 m in the onshore area of Lincoln County and reach a depth in excess of 4575 m offshore (Braislin, Hastings and Snavely, 1970). Folding and faulting of the sedimentary rocks in Tertiary time have provided the necessary structural elements for entrapment of hydrocarbons. Gas shows have been fairly common in water wells and in the few oil drillings in the coastal region of Oregon.

A total of 16 oil companies took part in oil and gas exploration along the Oregon coast from 1961 to 1969. Eleven of these companies joined forces to drill 8 test wells, one located as far as 48 km offshore. No discoveries were made. It has been reported from several sources, however, that the companies were discouraged by the thick shale sections encountered and lack of sand beds in the 8 holes.

Since the oil companies very likely drilled seismic highs offshore, some of the drilling may have been in shale piercement domes (diapirs).

Snavely and Wagner (1963) describe the Yaquina Formation as originating as a broad submarine fan from a shoreline 6.5 to 8 km north of Yaquina Bay. This delta formed a constructional high upon which the Nye Mudstone and the Astoria Formation onlapped. Large deltas are known to be good oil and gas producing prospects, as many oil fields have been found in such a depositional environment. The continental shelf bordering Lincoln County and the central Newport embayment appear to offer the best prospects for commercial production in western Oregon (Schlicker, *et* aZ., 1973).

Possibilities for finding petroleum onshore in Lincoln County are probably less than for finding it offshore. There are, nevertheless, some areas onshore that could bear more investigation and possibly warrant drilling a deep hole if closures could be found (Schlicker, et *al.*, 1973).

Coastal Clatsop and Tillamook Counties are for the most part underlain by marine sedimentary rocks and have potential for oil and gas production. Eocene lavas and interbedded sediments having little petroleum potential are exposed in the southern portion of the study area, and younger marine sedimentary rock overlapping the lavas is estimated to be 1525 m in the Tillamook embayment and 3050 m in the Columbia River downwarp (Braislin, Hastings and Snavely, 1970).

Structural elements required for entrapment of hydrocarbons appear to be present in the study area, but dense vegetation, deep weathering, and landsliding have prevented detailed geologic interpretation.

Structural conditions favorable to accumulations of petroleum could be provided by combinations of folding, faulting, unconformities, and facies changes involving shale to sandstone. Folding of rock units during the last 35 million years has provided the opportunity for' fluids to migrate and for any oil or gas, if present, to separate from associated salt water either at the crests or folds or behind fault barriers.

Reconnaissance mapping and information from deep wells show that thick sections of siltstone and shale were deposited in the Clatsop and Tillamook region during the Tertiary period. Seismic information indicates that numerous folds associated with major faulting are present offshore.

No significant surface seeps of oil or asphalt are known in northwestern Oregon and only traces of oil and gas have been found thus far in test drillings. Permeable rocks suitable as reservoir beds have not been encountered in any of the deep wells in Clatsop and Tillamook Counties, including the offshore wells and those drilled-in Washington just north of the Columbia River.

Subcommercial production of high gravity, paraffin-base oil was discovered near Grays Harbor, Washington in 1958. The reservoir rock was a badly sheared shale with thin sandstone interbeds of early Miocene-late Oligocene age.

More detailed mapping is needed to determine if reservoir beds are exposed in the project area and to examine structural and stratigraphic features more closely. Information on subsurface strata may be obtained by seismic surveys since very little deep drilling has been done in Clatsop and Tillamook counties (Schlicker, et *al.*, 1973).

Reichold Energy Corporation drilled four exploratory wells in western Oregon searching for gas in 1975. All of them were plugged and abandoned (Pfeiffer, 1976).

Oil was first reported in Washington as early as 1881 along the beach of the western side of the Olympic Peninsula, where there are outcrops of sandy shale having a kerosene odor (called "smell muds"). At some places a small amount of 40-47-gravity, paraffin-base oil seeps from the outcrop, Small amounts of gas may be noted bubbling up from the bottom of streams and swamps on the Peninsula. No commercial production has resulted from any of the wells drilled.

In western Whatcom County, about 8 km northwest of Bellingham in the southern part of the Strait of Georgia embayment, gas in sufficient quantity for domestic use is obtained from glacial sand lenses in Pleistocene sediments at depths less than 155 m, and commonly at about 52 m [Livingston, 1974) . The gas has a high methane-nitrogen content. More than 90 wells have been drilled in western Whatcom County, most of which were shallow wells, only 3 having been drilled deeper than 1525 m, 5 deeper than 610 m, and 20 deeper than 305 m. Only 6 wells recorded oil shows, but most of the wells had good gas shows for domestic production (Rau and Wagner, 1974).

"The post-middle Eocene strata of the Pysht quadrangle are more than [6100 m] in thickness. Most of them consist of fine-grained marine sedimentary rocks that are potential source beds for petroleum. Organic remains are sparse in the Aldwell Formation and in the fine-grained rocks of the lower part of the Twin River formation and as a result, they are of doubtful potential as source rocks. Most of the upper and middle members of the Twin River formation, however, contain sufficient organic remains to be possible petroleum source beds.

"The porosity and permeability of most of the rocks in the Pysht quadrangle are too low to be suitable reservoir rocks. However, some of the sandstone beds in the middle and upper members of the Twin River formation and in the Clallam formation are porous and permeable enough to be considered as reservoir rocks. Some sandstone beds in the undifferentiated sedimentary rocks south of the Calawah River fault zone also appear porous but no qualitative data is available. The Crescent formation is brecciated and fractured and under proper structural and stratigraphic conditions could be a reservoir for petroleum.

"There are no well-defined structural traps for petroleum in the Pysht Quadrangle (Gower, 1960).

"Although no oil seeps have been found in the Port Angeles-Lake Crescent area, a strong petroleum odor is noted in rocks of the Twin River formation in the canyon of the Lyre River and a few slicks of oil have been seen in the river in areas underlain by the Aldwell formation.

"Many of the rocks in the Port Angeles-Lake Crescent area are coarse grained but few are porous or permeable enough in surface exposure to be potential reservoir rocks. Beds of permeable, porous, sandstone occur in the middle and upper members of the Twin River formation. Most of these sandstone beds are less than [3 m] thick and many contain thin beds of siltstone which may reduce their value as potential reservoir rocks. Sandstone beds in the Lyre formation and in the lower member of the Twin River formation are essentially impervious (less than 1.4 millidarcies) and nonporous (less than 10 percent) at the surface; however, they may have some potential value as fractured reservoir rocks where they are faulted or tightly folded at depth; moreover, primary porosity may be decreased in the exposed rocks where leaching and redeposition of soluble constituents have occurred during weathering.

"Surface studies of the geology in the Port Angeles-Lake Crescent area have not definitely established the presence of traps for the accumulation of oil and gas; however, these studies have suggested several areas in which traps may exist. Two small anticlines are probably worthy of further study, either by geophysical methods or by stratigraphic test drilling. The Mount Pleasant anticline, an eastward plunging fold without any visible closure at the surface, may contain fault or stratigraphic traps at depth between Morse Creek and the eastern boundary of the mapped area. Traps, if present, would probably be formed against rocks of middle or early late Eocene age, which form the core of the anticline and which may be unconformably overlain by younger rocks. Structural relations along the Swamp Creek anticline are largely concealed by glacial drift, but they suggest that this fold may be a trap for oil and gas.

"Potential stratigraphic traps for oil and gas may be present around the flanks of the structural high which forms Striped Peak. Volcanic rocks exposed at Striped Peak and in the surrounding upland area are onlapped on the west, south, and east by younger sedimentary rocks but onlap is greatest near the eastern end of the structural high where rocks of the upper member of the Twin River formation rest upon volcanic rocks of middle Eocene age. Stratigraphic traps in this area may be formed in strata of the Twin River formation by its transgressive overlap of the volcanic basement rocks" (Brown, Gower, and Snavely, 1960).

The Quinault Formation (see Section 2a. on Stratigraphy) is a very favorable potential oil and gas reservoir. Offshore geological investigations suggest that strata both structurally and stratigraphically comparable to the Quinault underlie much of the continental shelf off the Washington coast. A number of wells have been drilled off the coast. Paleontologic evidence from a few of these verifies a correlation of these beds with the Quinault. Evidence suggests that the unit is rather widespread, mainly on the shelf and extending at least 32 km to sea and at least 64 km along the coastline. In general, the foraminiferal sequence of the measured sections of the Quinault Formation compare in a broad way with that known in the Repetto-Pico sequence of the Los Angeles area (Rau, 1970).

In addition to the Olympic Peninsula, seeps have been noted at two localities adjacent to Willapa Bay in southwesternmost Washington, in the vicinity of Bellingham in Whatcom County, near Wenatchee in southern Chelan County, and near the Columbia River in southern Skamania County. These areas containing oil seeps were, of course, among the first to be prospected. Many anticlinal structures suitable for oil accumulation have been mapped in Washington, and many tested by drilling have had promising shows of oil and gas. Many similar structures are probably present but are hidden beneath the thick cover of sand and gravel deposited in Pleistocene time, obscured by the dense vegetation, buried under the great basalt flows of the Columbia Basin, or concealed beneath the Pacific Ocean on the Continental Shelf (Rau and Wagner, 1974).

The most successful petroleum-related operation in Washington state has been the exploration and development of an underground gas-storage reservoir operation located in Lewis County, a few kilometers south of Chehalis. The first test wells were drilled in 1962 and, to 1974, some 60 wells have been drilled.

Reservoir rocks are sandstones of the late Eocene Skookumchuck Formation and the structure has been described as a complexly faulted dome. Presently, this unit has 492.9 million m^3 (17.6 billion cubic feet) of gas in storage, and the estimated growth is about 61.6 million m^3 (2.2 billion cubic feet) per year. Its future potential is hoped to be about 840 million m^3 (30 billion cubic feet) of gas. Gas for this unit comes largely from Canada and is stored during off-peak times to be distributed throughout the Pacific Northwest during periods of peak demand (Rau and Wagner, 1974).

Other areas with potential for underground gas storage are those generally considered favorable for oil and gas production. Perhaps outstanding among these areas is the eastern part of the Puget basin where thick beds on non-marine sandstone are known to exist and structures have been mapped. A few test wells for oil and gas production have been drilled in some of these structures and, although reservoir rocks were encountered, no commercial production resulted.

Structures in southwest Washington, both near the Centralia-Chehalis area and to the west in the Grays Harbor basin, should also hold definite promise for gas storage potential. Three exploratory gas wells were drilled during 1975, two in Grays Harbor and one in Jefferson County. The Jefferson County well tested gas at a subcommercial rate before it was plugged and abandoned. No shows were reported in the Grays Harbor well (Pfeiffer, 1976). Nevertheless, beds have been encountered in drilling operations for gas and oil production in the Grays Harbor basin that could definitely serve as reservoirs for gas storage (Rau and Wagner, 1974).

Tertiary and Oligocene marine sedimentary rocks, similar in age and lithology to oil-bearing strata in Alaska and California, have been found off Vancouver Island. The downthrown sides of post-Miocene faults in the basin extending from the north shoreline of the Strait of Juan de Fuca to the Olympic Peninsula, offer excellent prospects for exploration (Farley and Harding, [n.d.]).

The only significant hydrocarbon shows in the southern part of the Tofino Basin are shallow gas sands in the “Pluto” and “Prometheus” holes, two of the six wildcat wells drilled there by Shell (Shouldice, 1971). Only six wells in total have been drilled in the study area of British

Columbia since 1967, and all have been abandoned (Young, 1976).

b. Minerals.

i. Metallic. Gold mining was originally the mainstay of the southern Oregon economy but is now responsible for only a small part of the state's mineral industry. Gold prospecting, originally on the inland streams, moved onto the ocean beaches, just as the gold and black sands washed down from the Klamath Mountains. Gold was found in beach sands in Curry and Coos Counties. Ancient elevated beach terraces contain black sand beds, silver, gold, and platinum. Some were worked commercially before World War II. Sporadic attempts have been made since, but commercial production has never been achieved.

In 1894, the Washington beaches were also the scene of a brief gold rush. Almost all of the Olympic coastline was prospected, but the area between the Quillayute River and Cape Flattery was found to be the most productive. The gold was found in scattered patches of sand resting on bedrock. Some of the sand is noticeably pink in color because of a concentration of tiny grains of pink garnet, known locally as "ruby sand." Among the other minerals in the sand are zircon, magnetite, ilmenite, chromite, and platinum. The individual particles of these minerals are very small. The origin of these minerals is thought to be the glacial depostis (Danner, 195S).

Black sand deposits are concentrates of heavy minerals in wave- and current-deposited sediments on marine terraces, on beaches, and on submerged Holocene shorelines out to sea. The deposits have a complex origin involving erosion from inland areas, deposition in Tertiary sedimentary units, and Quarternary erosion and redeposition. Deposits closely associated with present-day streams probably have not undergone a second cycle of erosion and deposition.

Minerals in black sands deposits contain iron, chromium, and minor amounts of gold, titanium, zirconium, platinum, and garnet. Reserves are not accurately defined and are now under investigation. Offshore research reveals a deposit of black sand about 11 km from the coast midway between the Coquille River and Cape Arago. The deposit is approximately 4.8 km long and 1.6 km wide and is situated at a depth of 18 to 36 m. Maximum percentage of heavy minerals in recovered samples is 17 percent. The deposit is smaller and lower in grade than other submerged black-sand deposits off the coast of Curry County.

Onshore deposits are concentrated on the marine terraces in the Bandon area. One estimate places the reserves of chromite ore in concentrations greater than 5% at 1,944,000 metric tons (Beaulieu and Hughes, 1975).

Cinnabar and molybdenite are also present in small, low-grade deposits along the southern Oregon coast (Loy, *et* aZ., 1976).

At present, Oregon's major production of metals takes place in the nickel deposits at Riddle in Douglas County. Oregon is the only domestic producer of primary nickel. Concentration of the nickel is in the form of garnierite. Fifteen more years of production are estimated (Loy, *et al.* , 1976).

Washington has no significant deposits of metallic minerals within the study area, except for the beach placers and ruby sands along the Olympic coast.

Copper, lead, zinc, and some iron are mined commercially from seven mines within the study area of Vancouver Island {Sutherland Brown, 1976).

ii. Non-metallic. Coal is found in many parts of Oregon, but none of it is mined at present. The principal fields are at Eden Ridge and at Coos Bay (Loy, *et al.*, 1976).

Coal in the Coos Bay area was commercially mined from 1854 to the close of World War 11. The seams are most abundant in the upper member of the Coaledo Formation but also occur in the lower and middle members.

The coal has an average heating value of slightly less than 10,000 BTU per pound and contains 17% moisture, 8% ash, and 1% or less of sulfur. It is subbituminous in grade. Additional tests are desirable at the present time to evaluate the coal in terms of present technology.

A total of approximately one billion metric tons of coal (not all economically recoverable) may be present in the Coos Bay area. This is equivalent to a 102 cm seam underlying the total extent of the Coaledo Formation. However, all grades of coal at all depths and in all thicknesses of seams are considered in the calculation, and much of the coal perhaps can never be mined. Minable coal under present economic and technologic conditions is considerably less and totals about 60 million metric tons.

The coal reserves of Coos County are not suited to large-scale coal gasification under present technology. An average-sized plant producing 250 billion BTU's per day would exhaust the entire reserve in 5 years, assuming 50% recovery. Smaller plants keyed to local industry may be feasible, however, in view of escalating energy costs nationwide (Beaulieu and Hughes, 1975).

Thin, steeply-inclined seams of subbituminous coal are present on the south side of Neahkahnie Mountain. The seams vary in thickness from approximately 30 to 60 cm and are interbedded with clays. Under present conditions the coal deposits are not of economic quality.

Most of the commercially significant coal in Washington state is found in a discontinuous belt of Tertiary rocks, which lies on the eastern and southern edges of the Puget Sound Lowland.

The coal fields in the extreme northwestern part of the state are found almost entirely within arkosic sandstones of the Chuckanut Formation. As mentioned before, exploration efforts until now have been concentrated in the Glacier area. More recently, though, reconnaissance work and detailed geologic mapping have revealed other coal sequences of possible commercial importance in other areas of Whatcom County (VonHeeder, 1975).

Thin stringers of coal and carbonaceous material are evident in many of the rocks of the Port Angeles-Lake Crescent area, but no commercial deposits of coal have been found. Three coal beds were reported in a drill hole near the east end of Freshwater Bay in 1905. These coal beds are not known to crop out, but from this description they apparently were found in rocks of the Twin River formation (Brown, Gower and Snavely, 1960).

The Clallam formation was prospected for coal as early as 1863. The first published report on the coal of this area described a 55 cm thick coal bed in a mine about 6.S km west of Pillar Point and a 56 cm thick coal bed about 1 to 2 km (presumably east) from Clallam Bay.

The Fuca mine (in sec. 25, T. 32 N., R. 12 W) coal bed ranged in thickness from 46 to 76 cm and averaged about S6 cm. At several places in the Fuca mine, lenses of coal 1.5 to 15 cm long and as much as 61 cm thick were found several centimeters below the main coal bed.

Because of small landslides and dense vegetation, none of the old coal localities described by earlier works can be found (Gower, 1960).

A 1961 survey of known coal reserves in Washington state indicates at least 2,494 million metric tons of measured coal. With the increased emphasis on energy self-sufficiency, the State Department of Natural Resources has hired a full-time geologist who is engaged in the utilization and promotion of coal on state-owned land (VonHeeder, 1975).

Borax was once mined commercially in what is now Boardman State Park in Curry County, but there is not production at present (Loy, *et al.*, 1976).

Sand, gravel, jettystone, and other construction materials are mined from quarries and streambeds in virtually every county in the study area, more in some specific localities than others.

A small limestone lens is located immediately west of the confluence of the Coos and Millicoma Rivers east of Coos Bay. Analyses of calcite content average about 80%. Total reserves are estimated at about 72,560 metric tons. The deposit overlies Roseburg basalt and represents a reef deposit, more of which may be discovered with exposures of the Roseburg formation. Limestone deposits of this type are generally small in western Oregon. The limestone is medium grade, best suited for fertilizer, although some has been used locally for mortar (Beaulieu and Hughes, 1975).

Peat is mined in Snohomish, King, Pierce, Kitsap, and Thurston Counties in Washington and most of the coastal counties of Oregon.

Clay of alluvial origin is found in Coos County, and is used for brick and tile. Relatively high-quality deposits of clay are situated south of Seaside in Clatsop County. These are suitable for pottery and structural wares. Tillamook clays are used for brick and tile (Schlicker, *et* al., 1973).

Nepheline syenite, a somewhat rare type of igneous rock, occurs in Lincoln County at Table Mountain and at Blodgett Peak. The Table

Mountain rock is 92 m thick, covers about 2.6 km^2, and has little overburden. It is estimated to contain 635 million metric tons of recoverable syenite.

Syenites in other parts of the nation have been used as a flux in making glass, but the Oregon material is not suitable for this purpose because of the iron content, which produces a dirty-brown discoloration. The syenite could be used in the manufacture of rock wool. Lincoln Countyts nepheline syenite has been used successfully for jetty rock. Because of its natural grey color, the syenite could also be used for roofing granules (Schlicker, *et* aZ., 1973).

Coastal Washington has a good supply of almost all these non-metallic minerals, but future production probably depends on economic factors and constraints posed by environmental legislation and local zoning ordinances (Moen, 1975).

c. Ground Water. Ground water is the subsurface water that occurs in the zone of saturation (zone where all voids in the rock material are filled with water). The top of this zone is called the water table; it conforms roughly to the land surface topography and may vary from zero at valley streams to a few hundred meters or more below ridge tops. Impervious rock determines the bottom of the saturated zone. The amount of ground water present (measured by level of water table) fluctuates in response to discharge and recharge of the aquifer (the geologic unit that is holding the water), usually a function of seasonal changes in rainfall. However, excessive pumping of ground water from wells can lower the water table and in extreme cases can damage the aquifer through subsidence and compaction.

Between the water table and the ground surface is the zone of aeration. Water is present here but it is held tightly in place by surface tension and fills only some of the available pore space.

i. Types of Aquifers. Ground water depends on the type of material making up the aquifer, since porosity and permeability are highly variable properties. Principal types of aquifers in the study area are:

Sedimentary Rocks -- Ground water in tertiary sedimentary rock units occurs mainly in fractures, joints, and along bedding planes. Intergranular pore spaces are too small. Porosity and permeability are low, and these units have, in general, a low ground water potential;

Volcanic Rocks -- Aquifers in volcanic rocks are generally limited to fractures, brecciated zones, and sedimentary interbeds. While porosity is usually higher than in sedimentary units, the permeability is usually quite low -- there is poor communication between the pore spaces. Ground water potential is variable;

Unconsolidated Geologic Units -- Aquifers in unconsolidated material are usually much more porous and permeable than either of the previous two types. Ground water potential is usually good, provided that the water does not drain too rapidly from them.

ii. Distribution. Ground water yields and quality vary tremendously from location to location within the study area. The reader may consuit federal and state ground water investigations for any area of particular interest. Ground water reports usually cover individual counties or still smaller areas.

d. Geothermal. Geothermal sources in Oregon are apparently all in the interior, primarily east of the Cascades. Very little of Washington's geothermal potential is located within the study area. Sites in Anacortes and Westport have been studied. The heat-flow at the Anacortes site is 0.9μcal/cm^2, with a geothermal gradient of 12.1°C/km. The rock is pre-Mesozoic quartz diorite. The heat-flow at the Westport site is also 0.9μcal/cm^2, with a geothermal gradient of 26.5°C/km, in Pleistocene sediments (Blackwell, 1974).

All the observed heat-flow values in this area are low. However, because of the structural complexities of the Anacortes area, it is entirely possible that the Turtleback rocks (see Section 2a. on Stratigraphy) are sitting on top of an oceanic crustal section similar to that beneath the other heat-flow measurements.

"If so, again the reduced heat flow would be approximately 0.8μcal/cm^{2}sec. Heat flow measurements are not available for the area of the Olympic National Park. ..Unless the heat flow there is much higher than it is in the surrounding terrain, it would appear that the hot springs there (Olympic and Sol Duc Hot Springs) must be-due to deep circulation rather than to a shallow source of magnetic heat...

"Offshore the heat flow rapidly increases so that along the Juan de Fuca Rise, several hundred kilometers offshore, heat-flow values are extremely high, up to 7 to 10 peal/cm2sec. These high values of heat flow are interpreted to be due to the formation of new crustal material along the rise. It is possible that with advances in technology the vast amount of heat in the high temperature crustal material offshore might be utilized in the future" (Dehlinger, *et* al., 1971).

On the basis of the present data, the possibilities for developing economic geothermal reservoirs between the western foothills of the Cascades to the Pacific are apparently small. The only type of resource that might be present would be moderate-temperate water at fairly great depths, as the maximum gradient in the area would appear to be about 30°C/km (Blackwell, 1974).

Potential for geothermal power development in Canada is confined to the Cordillera (Souther, 1976), outside of the study area.

6. Environmental Constraints to Development.

a. Geologic Hazards.

i. Introduction. Various geologic processes and in-situ geologic conditions may interfere with safe and economically feasible land and resource development in the coastal zone. Such processes and conditions are usually referred to as geologic hazards. These have already been discussed to some degree (see Section 2.b. on Tectonics; 3.b. on Landforms and Associated Geologic Units; and 3.d. on Surficial Geologic Processes). This section summarizes and evaluates these geologic hazards in the coastal zone and suggests what the effects might be on OCS development.

ii. Stream Flooding. Flash flooding is restricted to steeply sloping upland areas with relatively thin soils and high relief. The chances of flash floods occurring depend on the statistical return period of large rainstorms. Flash floods cause extensive stream-channel scouring and can damage or destroy roads, bridges, buildings, and other structures.

Lowland stream flooding is common on floodplains of undisturbed streams. Impacts are structural damage, water damage, siltation, and health hazards. Problems can be overcome through proper site selection, adequate engineering, or flood-prevention construction such as dikes, levees and flood-control dams.

iii. Ocean Flooding. Tidal flooding occurs twice daily and affects tidal flats and marsh and low-lying beaches to as much as 1.8 m above mean sea level on the open coast and up to 2.4 or 2.7 m in Puget Sound. It aggravates stream flooding in coastal areas and should be integrated into all flooding models.

Storm surges, caused by low atmospheric pressure and wind, may add another 1.2 or 1.5 m above the predicted tide level (Beaulieu and Hughes, 1975).

Tsunamis are generally small and infrequent, but amplitudes as high as 4.6 m have been recorded (Beaulieu and Hughes, 1975). Tsunamis may be concentrated and thereby have higher amplitudes along headlands.

iv. High Ground Water and Pending. High ground water and pending are common in lowland areas and in depressed areas with low infiltration rates. Interdune areas and flood plains are likely problem areas. Engineering difficulties include flotation, failure of waste disposal systems, caving of excavations, low bearing strength, and unfavorable "shrink-swell" soil properties.

v. Mass Movement. Debris flows, slumps, and earth flows can be serious hazards to development in upland areas. Rockfalls, slumps, and debris slides can be serious problems along coastal bluffs, sea cliffs, and marine terraces. Soil creep is not usually a problem for structures with proper foundations, since it is very slow and occurs only in the upper meter of the soil profile.

Landslides are usually small features, affecting areas less than one-half hectare in area, and they are numerous throughout much of the study area. Internal instability of soil and rock masses is often not manifested at the ground surface and only on-site studies can determine hazardous areas before a landslide occurs. For these reasons landslides have not been mapped for large parts of the study area.

A number of detailed studies showing areas of known landslide hazard do exist. OCS onshore facilities situated on or near sloping terrain could be seriously affected by landslides. Any development plans for areas where a hazard is expected should include on-site studies to assess the risk and develop engineering solutions.

vi. Stream Erosion and Deposition. Stream erosion includes stream-bank erosion, channel scour, sheet-wash and rill erosion, and gullying. Associated problems include damage to structures located too closely to eroding stream banks, loss of top soil, clogging of sewers and drains, deterioration of water quality.

Recommendations include proper siting of structures and proper construction practices. One important aspect is to prevent silt and clay-laden surface runoff from discharging into streams; siltation ponds can help alleviate this problem. Minimizing the length of time construction sites have bare soil exposed can also help.

Construction of onshore OCS facilities could adversely affect the local environment with these problems unless preventive steps are taken.

vii. Coastal Erosion and Deposition. Coastal erosion of rock headlands usually averages several centimeters per year or less, but may exceed 3 m or more per year locally, depending on rock type and structure (Beaulieu and Hughes, 1975). Engineering methods of preventing erosion may or may not be economically feasible; if not, adequate setbacks are recommended.

Coastal bluffs and edges of marine terraces are constantly receding -- their steep profiles are evidence of this. Rates of bluff retreat are highly variable, and may vary from several centimeters per year to several meters, even along the same bluff. Bluff stability can be improved by protecting the base of the slope from wave attack with sea walls or rip-rap, Maintenance of good drainage of the material making up the bluff will further enhance the stability. Adequate setback along bluffs and terraces is highly recommended. Coastal areas that have experienced intense erosion in historical time are scattered throughout the study area.

viii. Wind Erosion and Deposition. Dune areas along the Oregon and southern Washington coasts are highly susceptible to this hazard. These areas owe their existence to the balanced interplay between erosion and deposition, and interference in one area can affect another. For example, stabilization of foredunes with European beach grass has led to increased erosion and expansion of deflation plains.

Migratory dunes can bury roads and structures and block streams. Blowing sand can damage paint and structure surfaces.

Recommendations include protection of sensitive dune vegetation and limiting development to low-risk areas.

Construction of OCS onshore facilities could adversely affect the local environment unless proper steps are taken in site selection and construction.

ix. Earthquakes. Table I-22 shows basic information about earthquakes as hazardous events. The great majority of earthquakes in the study area are apparently due to the first two causes shown in the table,

Table S-22

Earthquakes as Hazardous Events§

Causes	Normal tectonic movements Compression or rebound of earth's crust in response to ice or water loading/unloading Volcanic activity Underground nuclear explosions Deliberate injection of fluid into faulted areas
Locations	Immediate vicinity of the moving fault, rebound/compression area, volcano, explosion or injection Waves spread through earth and across surface to a distance determined by energy release, geologic structure and surface conditions (fill, etc.)
Times of Occurrence (Predictable)	Following filling or emptying of large reservoirs Volcanic eruptions Planned nuclear explosions Planned injection experiments

(Non-Predictable)	Any time--(a miniscule number of quakes have been predicted correctly to date) Preceding volcanic eruptions (when no other warning signs are present)
Primary Hazards	Ground shaking, ground rupture, ground subsidence, soil liquefaction
Secondary Hazards	Landslides, rockfalls and avalanches, tsunamis, seiches, fires, falling debris Failure of critical structures such as dams, nuclear plants, and chemical tanks, causing flooding and pollution of water and/or air
Control of Causes	None for tectonic and volcanic For man-caused quakes, reversing or refraining from earthquake-causing activity
Control of Effects	Engineering standards and building codes Restriction of uses of land in quake-prone areas Structural reinforcement and removal of parapets Evacuation from areas threatened by secondary effects (direct effects on persons)

§After Cullen, 1976.

although the proportions have not been -- and today probably cannot be -- assessed. Nor does it matter, because the effects on manmade structures are the same.

Volcanic earthquakes are highly localized events, due to their shallow focal depths. As a result, they may be quite severe in the immediate vicinity of the volcano, but be unnoticed a few tens of kilometers away. Therefore since the nearest volcanoes are well away from the study area, the volcanic earthquake hazard to OCS facilities is apparently nil.

Underground nuclear explosions, because of their relatively shallow depth, act in much the same way as volcanic earthquakes. Underground nuclear explosions as a tool for mineral recovery processes have been explored. It is not possible to say at this time if any are planned near the study area.

Deliberate or accidental injection of fluid into faulted areas is known to cause earthquakes. Injection of high pressure steam into petroleum reservoirs to recover additional oil, or any similar technique, should be used with caution in any area where there is danger of causing fault movement.

The distance at which earthquake waves are felt is a function of magnitude, focal depth, bedrock structure and stratigraphy, and overburden. Magnitude (the energy released by the rupture) is determined by the length of the fault rupture. In general, the shallower the focus, the greater the intensity (the amount of ground shaking at any given location]. However, deeper focus quakes tend to be felt over a larger area.

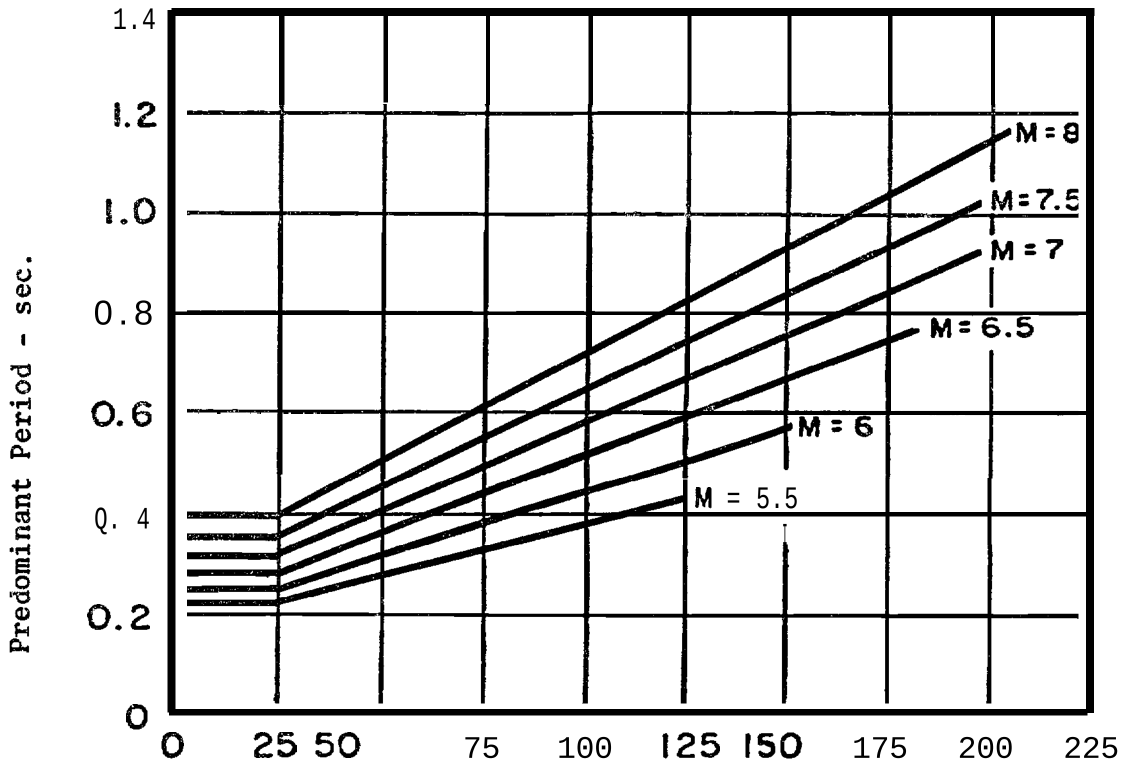
The impact (intensity) of an earthquake is directly related to ground acceleration and to the specific response of the ground to that acceleration. Housner (1965) has shown that, for earthquakes of magnitude 8.0, accelerations greater than 0.10g (1 g equals the acceleration of gravity) are unlikely at distances greater than 128 km. (See Figures I-42 and I-43). Thus, for all quakes originating in the vicinity of Cape Mendocino, for example, it is unlikely that any will produce ground accelerations greater than 0.10g in the southern part of the study area.

Ground response is a function of several factors, including the nature of the bedrock, the nature of the soil, the slope of the ground, and the water content of unconsolidated geologic units. There are several types of ground-water response. Elastic response occurs in material in which there is no damping and in which component particles maintain the same position relative to one another during the quake. Elastic response is almost universal during small quakes and is most common in consolidated bedrock and dry semi-consolidated surficial units (terrace deposits) during moderate earthquakes.

Where competent bedrock units occupy precarious positions on hillsides and are detached in moderate to strong quakes, the response is said to be brittle. Brittle response is possible in the steeply sloping sandstone terrain of the interior and along the headlands

Figure I-42

Predominant Periods for Maximum Acceleration in Rock[§]

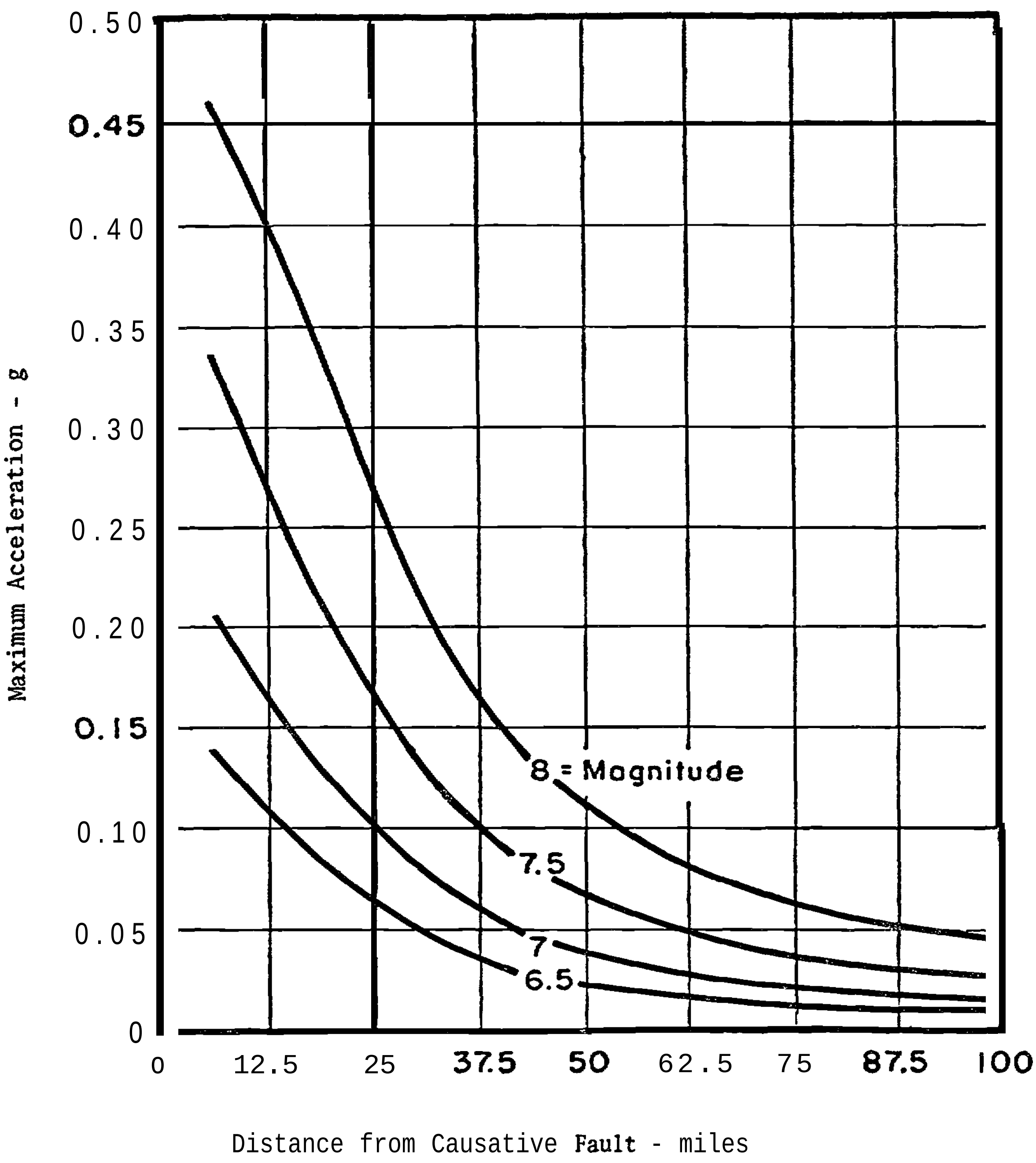


Distance from Causative Fault - miles

[§]Byrne, 1976.

Figure I-43

Relationship Between Peak Bedrock Acceleration, Earthquake Magnitude and Fault Distance§



§Byrne, 1976.

(see Section 3.d. on Mass Movement).

Clay-rich soils and weathered bedrock with appreciable immobile water on moderate to steep slopes may deform plastically in response to seismic activity to produce slow to rapid earthflow. Such response is termed viscous response and may occur in the clay and silty clays overlying weathered finer-grained Tertiary bedrock units, such as the middle Coaledo Formation (see Section 2a. on Stratigraphy).

Fine-grained granular soils with high water content may undergo a total loss of strength, after repeated application of forces, to give fluid response, or liquefaction. Basically, liquefaction occurs when seismic shaking causes a reorientation of sediment grain into a more compact arrangement. During the time of reorientation, the load normally borne by grain contacts is transferred to the pore water, reducing the shear strength tremendously and resulting in viscous behavior. Saturated clay-free sediments such as silt, sand, and gravel are most apt to undergo liquefaction (Figure I-44).

Liquefaction is largely site-dependent. While some areas have been singled out as particularly hazardous, there are many areas in which the degree of hazard is in dispute between geologists and soils engineers. The Puget Lowland is one of these. Site specific soils tests are required to determine liquefaction potential. Shallow bedrock and adjacent "islands" of till or other stable soils may render an otherwise hazardous area less hazardous.

It is impossible to assess liquefaction potential on a regional or large-areal basis without site studies covering all or most of the area in question.

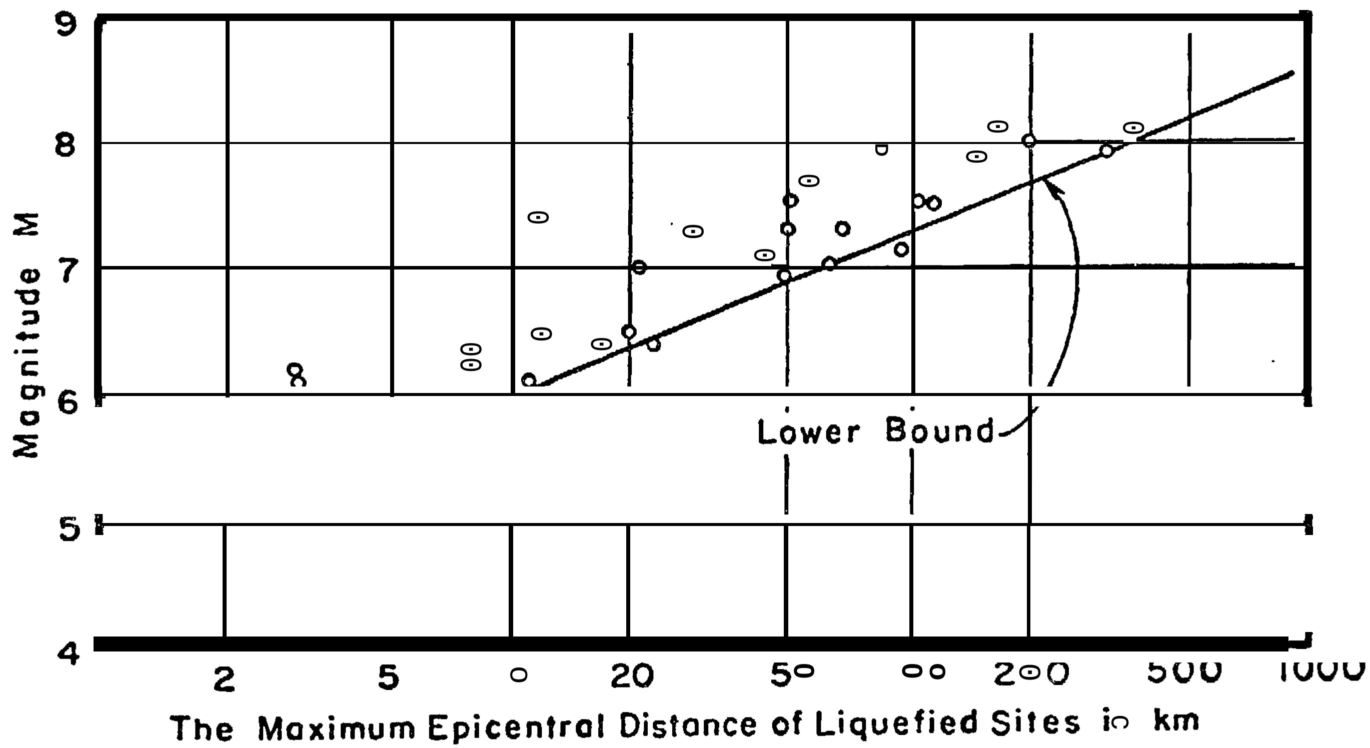
In the lowlands, loss of structural support through liquefaction may occur in areas of fill, alluvium, tidal flats, marsh, and sand. Sand mobilized at depth may emerge at the surface as rises or ridges. Of particular concern are the urban areas of Coos Bay, North Bend, and Reedsport lying in fill material over estuarine sediments. On moderately steep to very steep slopes of the uplands, debris flows and earthflows may develop in saturated granular soils during the wet winter months or on the poorly drained part of ancient landslides (Beaulieu and Hughes, 1975).

Because subsidence is usually uneven, structures on such ground may settle differentially, resulting in extensive damage. In areas of moderate to high relief, with existing landslides or unstable slopes and saturated ground conditions (such as many areas of western Lane County during winter months), an earthquake could trigger numerous landslides. In addition, ground response in saturated lowland soils could result in liquefaction or downslope flow, even on gentle slopes (Schlicker and Deacon, 1974).

Several studies since 1965 have attempted to assess seismic risk for the Puget Sound region. Some of these have concentrated on return intervals (frequency with which serious earthquakes can be expected to strike), some on maximum probable and credible magnitudes, and still others on expected areas of high intensity and extent of damage. The

Figure I-44

Relationship Between the Earthquake Magnitude, M and the Maximum Epicentral Distance of Some Liquified Sites§



§ Byrne, 1976.

most recent study is that which the U.S. Geological Survey (Brown, Gower and Snavely, 1960) recently completed for the Federal Disaster Assistance Administration (FDAA), which simulated two probable quakes and postulated expected damage to essential public service delivery systems. All Puget Sound earthquake information given below is taken from that source, unless otherwise noted.

Return rates for earthquakes, like the 50 or 100 year flood determinations, are purely statistical devices. Damaging shocks in Puget Sound have come as close together as a few months and as widely separated as 19 years. The last quake to cause serious damage as of spring 1977, was the one of 1965.

The U.S. Geological Survey postulates for planning purposes what might be called in floodplain parlance, a "standard project earthquake" of M 7.5, with maximum intensities to IX, originating at either the epicenter of the 1949 quake of several kilometers north of the 1965 event. This is considered to be the maximum credible event for the Puget Sound region, based on what is known of regional structure and historic seismicity.

An earthquake gives no warning, and risk is in large measure determined by the time of year, day of the week, and time of day. Obviously, the chance of serious damage is greater, for example, during the winter when a landslide hazard is present, on a work or school day when public buildings are occupied, or near 4:30 p.m. on a weekday in downtown Seattle. The latter was determined by the U.S. Geological Survey researchers as the time of highest risk of injury and loss of life. The death toll is estimated to be as high as 2170 for a quake centering near Seattle and 2030 for the Olympia epicenter, with a ratio of four serious injuries [requiring hospitalization) to every death.

Prediction of earthquakes by geophysical means is more complicated in the Pacific Northwest than in California, and no major projects have yet been undertaken.

The vast majority of Puget Sound quakes produce no surficial fault ruptures due to the depth of glacial overburden in the basin. The damage to structures is caused by ground shaking, compaction, and landslides. The same is true for the Washington, Oregon, and Vancouver Island coastlines.

Earthquake damage in the Puget Sound region has been heaviest in areas of alluvial and manmade fill, especially in the industrial areas near the Sound. Landslide-prone areas where development has occurred have also suffered damage. To date, neither tsunamis nor seiches (standing wave oscillations) have been serious hazards in the Puget Sound area. Some potentially liquefiable soils are present, but are not thought by the authors of the U.S. Geological Survey report (1975) to be extensive (Cullen, 1976). However, others in the field of soils engineering have asked for further studies (Sherif, 1972-76).

A particular liquefaction hazard exists on the Fraser Delta, which is underlain by soil types that have proven liquefiable in other areas of the world (Byrne, 1976). Although the delta is outside the study area, slumping from the delta front in response to earthquake-triggered liquefaction could cause excess turbidity in the portion of the Strait of Georgia inside the study area. Turbidity currents, however, would apparently move northward out of the study area (Tiffin, 1976). Large waves that might be generated by large-scale slumping from the delta could possibly cause damage on the eastern side of Vancouver Island and in the San Juan Islands.

During its recorded history (since 1841), the Puget Sound Basin has experienced some sixty-seven earthquakes greater than Modified Mercalli Intensity V: that is, severe enough to begin to cause breakage of glass and crack plaster. Some of these centered inside the study area and some outside, but all caused damage within. The largest earthquake known to have centered within the area was the shock of April 13, 1949, which had a Richter magnitude of 7.1 and reached Mercalli intensities of VIII (sufficient to cause heavy damage or partial collapse of poorly-built structures, as well as chimneys and smokestacks). It was felt over 388,000 km^2 and did $12.5 million damage. Seven persons were killed.

The frequency of damaging earthquakes is evident. Since 1859 there has been ten shocks of intensity VII (enough to cause moderate to heavy damage) or greater and which actually caused damage in the Puget Sound region. These occurred in a period of less than one hundred years, some as close together as four months, some as far apart as nineteen years (Cullen, 1976).

Damage due to earthquakes is closely related to the size of the construction, the nature of the frame and floor suspension, and the presence or absence of facing. Generally, small wood frame buildings of three stories or less are the most resistant to earthquake damage. Earthquake resistance is progressively less for larger buildings with ". frames of steel, reinforced concrete, wood, unreinforced concrete, and brick. Constructions of unreinforced adobe, hollow concrete block, and hollow clay tiles are the least resistant and may collapse in moderate shakes (Mercalli VII). Facings of unreinforced masonry, brick, or concrete block are relatively susceptible to damage.

Recent investigations show that for very thick soils (a few hundred meters) wave lengths of seismic waves approximate the natural wave lengths of buildings greater than 10 stories in height.

Damaging resonance can result where the natural period of vibration of a building is similar to that of the ground on which it rests. For thinner deposits of 30 to 100 meters in thickness, similar to that of much of the Oregon estuaries, fundamental periods of vibration are similar to those of buildings five to nine stories high (Beaulieu, Hughes and Mathiot, 1974). Although these figures are preliminary and general, they illustrate the varying responses of different types of constructions to seismic input in different geologic settings.

The earthquake hazard on the Oregon coast, north of the Klamath Mountains, is thought to be low. However, the Oregon and Washington coasts have experienced tsunamis. Although a local "tsunami" in Puget Sound or Hood Canal is a possibility, none have occurred and no research has been done to determine their likelihood. A more likely possibility is a large, landslide-induced wave.

Any of the secondary hazards in Table I-22 (page 1-196) damage onshore facilities. Little research has been done on the effects of seafloor groundshaking on drilling structures (see Data Gaps).

x. Volcanic Hazards. There are no volcanoes in the study area. The nearest active volcanoes (those having erupted within historic time) are Mount Rainier and Mount Baker. Both have shown anomalous activity within the past ten years. Either could erupt at any time (Crandell and Mullineaux, 1974). The more likely hazard is a large mudflow, which could happen without an eruption (Cullen, 1974). Mount Rainier has a long history of mudflows. Mount Baker's current steam activity could loose debris from the edge of Sherman Crater at any time [Frank, 1977?). A large mudflow down the Puyallup River Valley could reach Puget Sound at Commencement Bay (Cullen, [1977?]) A large mudflow down the Nisqually Valley, could, if it over-topped or destroyed Alder Dam, reach Puget Sound at the Nisqually Delta (Cullen, 1974). A very large mudflow from Mt. Baker could reach the Sound by way of the Skagit River (Crandell, 1976). It is also possible that a large mudflow from Mt. St. Helens could cause flooding in the Columbia River as far as Portland, raising water levels above seasonal normals from Portland to the mouth (Crandell and Mullineaux, 1974). In no case, however, could the amount of suspended matter or debris be sufficient to cause damage within the inland waterways. The hazard to OCS development is apparently nil. Due to prevailing wind patterns, the chance that ash from any of the Cascade volcanoes would be blown west is very small.

xi. Ground Subsidence. Ground subsidence is usually caused by withdrawal of fluids or by collapse of mine tunnels. The hazard to OCS development and facilities from the latter is apparently negligible. Due to rapid ground water recharge in the "rainbelt", in no Part of the study area has sufficient groundwater been withdrawn to cause subsidence (Artim, 1976a]. Large scale withdrawal of oil and gas could, however, lead to subsidence.

b. Structural Constraints. Constraints imposed by terrain and structure are involved in the development of onshore mineral resources. The contorted, faulted, and folded strata in which most of Washington's and some of Oregon's coal fields lie makes economical recovery difficult to impossible. Considerable ingenuity and use of the most modern mining techniques are required in most areas.

Water requirements also place restrictions on development. In a typical coal gasification plant, projected water needs vary from 441 to 1890 liters per second (1/s) (7,000 to 30,000 gallons per minute (g-pm)) depending upon water quality and the extent of recycling. This compares with a present rate of groundwater production in the dunes of 189 1/s (3,000 gpm) (see Section 4.c. on Groundwater), and minimum streamflows of 330 1/s (5,400 gpm) on the South Fork and 369 1/s (5,850 gpm) on the North Fork of the Coquille. Average flows during low months are 905 and 1555 1/s (4,360 and 24,680 gpm), respectively (Beaulieu and Hughes, 1975).

A characteristic of the beaches in relation to their economic importance is that they are transitory, and may vary in volume and distribution with the seasons and weather. A heavy storm may pile up sand from offshore beds on the beach, and another storm under different conditions may return the sand to the ocean. Thus the difficulty of estimating the volume and mineral content of sand on beaches is evident.

c. Gee-legal Constraints. The Shorelines Management Act in Washington, the Land Conservation Development Commission in Oregon, and federal Coastal Zones acts have established certain constraints to development of earth resources. In addition, local zoning ordinances often forbid certain kinds of resource development. Canadian federal and provincial governments have placed moratoria on certain kinds of offshore development. Other geo-legal constraints could arise through the influence of anti-oil pollution groups and potential interagency jurisdictional conflicts.

C. Data Gaps

1. Lithography/Stratigraphy , Structure and Tectonics.

The seafloor off the coasts of Oregon, Washington and British Columbia and the beds of the inland waterways have not received sufficient study to determine the structure, stratigraphy or actual seismicity of these areas. Seismic profiling, core studies which extend beyond surficial sediments into deep bedrock, and additional seismic monitoring are needed. Strong motion instruments (accelerographs) need to be placed on the seafloor to measure the response of sediments to earthquake shaking.

The effects of storm wave conditions, gravity, and earthquake shaking on oversteepened submarine slopes and delta fronts need to be studied in more detail. Finally, more detailed knowledge is needed of seafloor and subbottom mineral resources.

On land, studies of lake bed sediments, such as those previously cited in the section on Puget Sound area seismicity, would add to the short historical record of Pacific Northwest seismicity. Detailed geological studies, such as those being done for nuclear plant sites, would probably reveal more potentially-active faults in the study area.

2. Surficial Geology and Geological Hazards.

Data gaps for surficial geology of the study area are virtually non-existent in Oregon, moderate in Washington and extensive on Vancouver Island. Large lowland areas north and west of the Olympic Mountains have not yet been mapped in detail. Mapping on Vancouver Island has been mostly reconnaissance in detail, and the complex glacial history of the island has yet to be worked out in detail.

Gaps are minimal for soils coverage. The degree of detail may vary location to location, but all areas are covered.

Detailed information on ground water is generally good but spotty, and is often limited to small geographic areas. A few Washington counties (e.g., Wahkiakum, Jefferson, and Whatcom) have no known studies relating to ground water. Southern Vancouver Island has few detailed studies.

Evaluation of geologic hazards in Oregon is systematic and comprehensive. In Washington, much information is available but is scattered among many sources. An effort is currently underway to summarize hazards for the Washington coastal zone by the State Dept. of Ecology (Ruef, 1976). No studies for Vancouver Island are known.

3. Data Interpretation.

The problem with data interpretation is primarily composed of three elements. The first is that data is carried in the minds of a number of researchers, unpublished and unwritten but for the sketchiest notes. This has been suggested by some Canadian scientists to be a very serious problem, for should a lone researcher die, valuable knowledge might be irretrievably lost.

The second element is that of a surfeit of riches from satellite data. The ERTS-LANDSAT program is generating an immense data base which is outstripping the resources needed to interpret it.

The third element is the lack of communication and coordination among agencies and researchers at all levels. Valuable data in one state (or provincial) agency may be unknown to an agency in a neighboring state. Comprehensive indexes and guides to recent and current research are not available, resulting in unnecessary duplication of research time and money.

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II. Climatology

Mary M. McGarry and Steven Payne

A. Introduction

This chapter describes the climate of the Washington and Oregon coastal areas, Strait of Georgia, Strait of Juan de Fuca, San Juan Island vicinity, Puget Sound, and the immediately adjoining areas. For this discussion, the study area is divided into two main climate subdivisions: the open coast and the inland waters. Local effects cause some variations within each subdivision in climatological parameters, such as temperature or prevailing wind direction, but these variations are small relative to differences between the climates of the two subdivisions.

Almost all the climatological data that are available come from land-based observations. However, the over-land climate can be extrapolated out over the water on a limited basis. Figure II-1 shows the land-based observation stations that exist in the study area.

The general parameters of concern include climatic means and the variability and extremes of weather. Climatic means are a concise way of describing the climate of the study area but can only be used as a general forecast of future weather. They are useful for such activities as designing equipment, planning transportation routes, and for determining the location for onshore and offshore facilities. A general forecast, such as can be made using climatic means, is usually not specific or accurate enough to be used for day-to-day planning when weather is a critical factor.

Weather is a highly variable phenomenon in this study area. Wide variations from climatological means can be expected, aside from the familiar changes from day to day and from one season to another. For instance, a summer season that has much more rain than the average amount from past summers can be followed by an unusually dry autumn. Another variation might be an unusually warm summer one year and a summer whose temperatures are very near the climatic mean the next year. Another type of variation, a trend, exhibits itself over a period of many years -- 30 years or more, for instance. A trend may occur, for example, in the form of successively warmer summer seasons or successively dryer years. However, it is generally not possible to extrapolate such trends into the future to forecast weather since the causes of the trends are often unknown.

Extremes of weather are important to note in a review of the climatology of the study areas. They indicate what may occur, although they should be considered to be at best relative extremes. Even at a station of long-standing, such as Seattle-Tacoma Airport, a number of new records are set each year.

This description of climate is based upon previous analyses by other authors and researchers. Figures and tables are presented to supplement the text. The primary sources were academic institutions, government agencies, and private sources such as research organizations and industry.

The University of Washington, Washington State University and Oregon State University provided information in the form of reports with analyzed

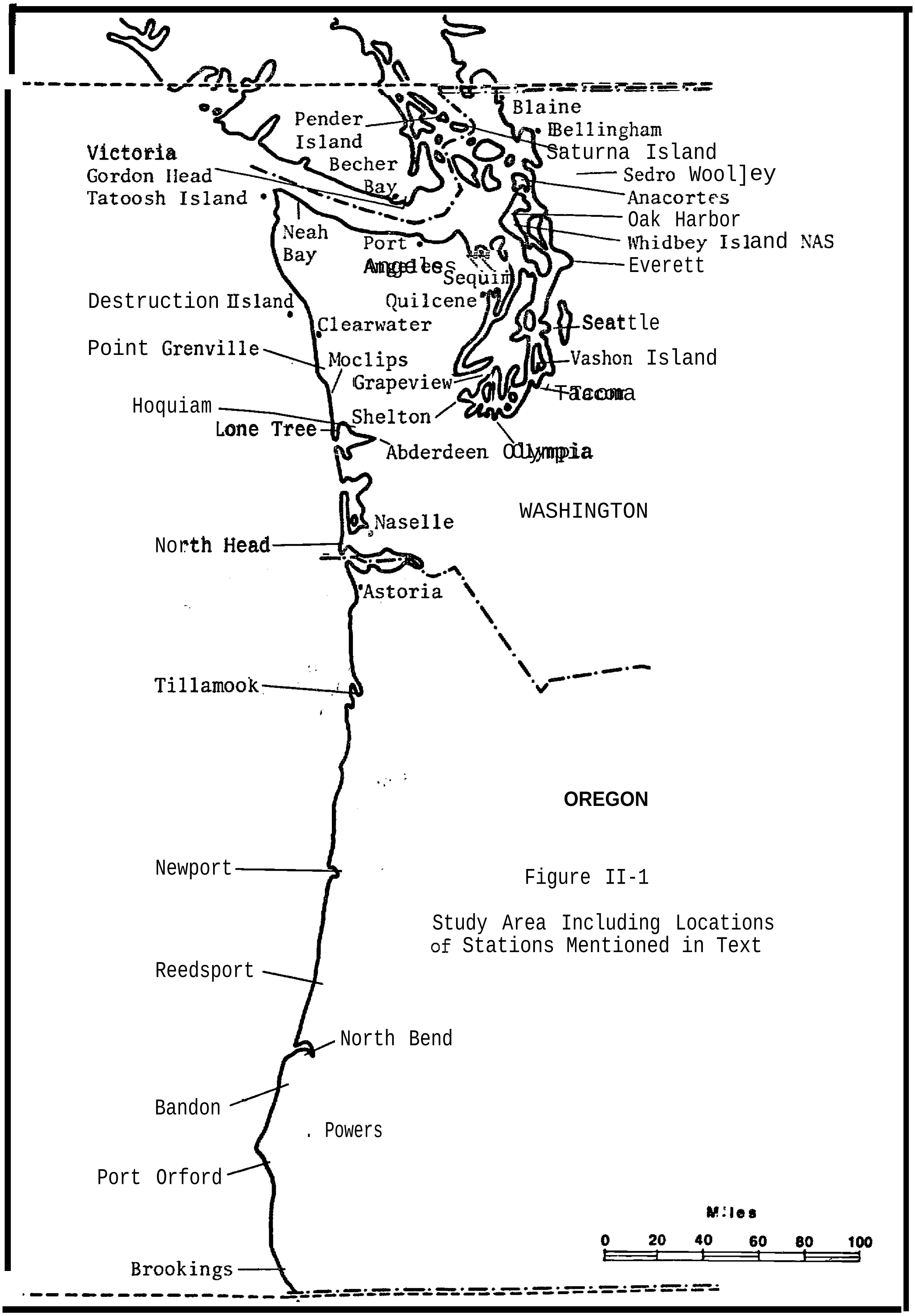


Figure II-1

Study Area Including Locations of Stations Mentioned in Text data. Most of these were prepared and funded by government agencies and public utilities.

A number of government agencies collect meteorological data on an ongoing basis and were able to provide much useful information. The National Weather Service and the Environmental Data ServiceTs National Climatic Center in Ashville, North Carolina, were the principal sources. The U.S. Navy and the U.S. Army Corps of Engineers also provided some resources. The Department of the Environment, Canada, was helpful with data for Vancouver Island and the Strait of Georgia.

Some information was available through industry publications, such as the Oil and Gas Journal, and professional society publications, such as the Bulletin of the American Meteorological Society.

By far the most useful available data was found in the series of booklets on Washington climate that was prepared by the Cooperative Extension Service of Washington State University and the State Climatologist. These, along with climatological summaries from the Climatology of the United States and local climatological summaries prepared by agencies of the Department of Commerce, gave means, extremes, and frequencies of temperature, wind, precipitation, and other meteorological factors.

The U.S. Coast Pilot 7 gives detailed descriptions of winds over water and other climatological information as well. This publication of the National Ocean Survey (NOAA) is oriented mainly toward shipping and boating interests.

The best data available for Canadian areas came from the Department of the Environment, Canada. A weather forecaster's handbook and a boating guide gave detailed weather information for small areas. Pertinent technical journal articles were also consulted.

B. Results of Data Collection and Analysis

1. Description of Climate.

a. General Climatic Features. The climate of the study area is predominately mid-latitude, west-coast-marine type. Most air masses that pass through Washington and Oregon have their source regions over the Pacific Ocean. This maritime type has a moderating influence on the weather in both winter and summer -- a warming effect in winter and a cooling effect in summer. The Cascade Mountain Range forms a barrier protecting the area from the cold, winter and warm, summer continental air mass to the east.

Two semi-permanent pressure patterns, the Aleutian Low and the North Pacific High, are the major large-scale features which control the climate of Washington and Oregon. The Aleutian Low, rather than being a single low pressure area, consists of a series of migratory low pressure centers which pass through the Aleutian Low region. The region lies over southwest Alaska and the Aleutian Islands and is characterized by prevailing pressures typically less than 1002.5 millibars (National Ocean Survey, 1973). Winds blow in a generally counter-clockwise direction around the Low, and the Low is an area where frontal storms form when warm, moist air from the south central Pacific meets the cold polar air mass.

The North Pacific High is a large region of high pressure (an anti-cyclone) located off the west coast of the United States. The air flows around the North Pacific High in a clockwise fashion, and the weather in the High is generally fair.

i. General Climatic Features - Open Coast. The climate of the Washington and Oregon coastal zone is mild, with small seasonal and daily variations in temperature. Winds are generally from the west, but the direction changes somewhat from summer to winter. The amount of precipitation at various locations depends upon elevation, -- the higher elevations generally receiving more precipitation than lower elevations.

ii. General Climatic Features - Inland Waters. The climate of the Inland Waters is also considered mild, with small seasonal and daily variations in temperature. Due to the channeling effect of the Olympic and Cascade Mountains, winds are generally either from the north or the south. Precipitation amounts depend heavily upon location due to terrain. For example, certain areas close to the east side of the Olympic Mountains receive considerably less precipitation than places further to the east. This is explained in more detail in the section on precipitation.

b. Winter Pattern. The Aleutian Low dominates the winter weather in the Pacific Northwest. During the fall, the North Pacific High contracts to its winter position off the coast of California, and the Aleutian Low expands southward to extend over the Gulf of Alaska and the Bering Sea. The counterclockwise flow of air around the Low brings prevailing winds from the west and southwest.

Frontal storms which form in the Aleutian Low region move eastward into British Columbia, Washington, and Oregon. They bring the precipitation and cloudiness typical of a Pacific Northwest winter. Most precipitation during the rainy season (October to March) is associated with these winter s terms.

i. Winter pattern - Open Coast. Winds are generally from the west or southwest and temperatures are mild. Occasionally, winds from the north and northeast bring cold, dry polar air into the area. Unusually cold temperatures prevail in such a situation, but the cold spells usually last only a few days.

ii. Winter Pattern - Inland Waters. In the Inland Waters, winds are generally from the south. The Olympic Mountains protect the area from the most severe winds of frontal storms. Temperatures are usually mild. Infrequently, winds from the north bring cold, dry air from the interior of British Columbia. This results in clear skies and cold temperatures which typically last only a few days.

c. Summer Pattern. As summer approaches, the North Pacific High expands northward to its summer position while the Aleutian Low contracts northward. During summer, the High prevails over most of the eastern Pacific Ocean north of 20°N latitude almost to Alaska and from the western United States coastal area to 160°E longitude The highest pressure is located at the latitude of San Francisco near 150 W longitude (National Ocean Survey, 1973). Clockwise circulation around the High brings a prevailing air flow from the northwest to Washington and Oregon.

Any storms in the northern Pacific Ocean are usually steered north of Washington. This means that summer is a time of little precipitation and generally fair weather.

i. Summer Pattern - Open Coast. Winds are mostly from the northwest, and speeds are usually lower than in winter. However, the heating of the land during the summer day and the resulting land-sea breeze effect modify the prevailing flow. This is discussed in more detail in the section on winds. Summer temperatures are generally mild. The highest temperatures are recorded when winds from the northeast and east bring warm air from the interior of the continent.

ii. Summer Pattern - Inland Waters. Winds at the surface are generally light during summer and come more often from the north and northwest than in winter. As along the Open Coast, the prevailing flow is modified by land-sea breeze circulations. Temperatures are mild except when winds from the east bring warm continental air to the region.

2. Temperature and Humidity.

a. Seasonal Means. Temperatures in the area are relatively mild due to the moderating influence of the Pacific Ocean. Prevailing winds from the Pacific bring the moist marine air onshore. The temperature of this air is almost the same as the ocean surface temperature, and the change of ocean temperature is small during a day or a season. Therefore, the daily and seasonal variation in air temperature is smaller than it would be if the ocean were not an influence.

Relative humidity is a measure of the water vapor content of the air. It is expressed as the ratio (in percent) of the amount of water vapor in the air to the maximum amount of water vapor that ‘the air can hold at a particular temperature. Since warmer air can contain more water vapor than cooler air can, relative humidity depends upon the temperature of the air.

The relative humidity of the area is fairly high due to the influx of moist marine air and the range of relative humidity fluctuations is small throughout the day. The highest humidity generally occurs in the hours after midnight, corresponding with the lowest temperatures of the day. The lowest humidity is usually observed in the afternoon when highest temperatures occur. Table II-1 shows mean values of relative humidity at four times of the day for several locations.

A quantity that is often computed using weather observations is “heating degree days.” Heating degree days are used to estimate heating requirements for buildings. The number of heating degree days for a given day and a given location is determined by: taking an average of the highest and lowest temperatures of the day (in °F) for the location; if the average temperature is less than the base temperature (usually 65°F), the average is subtracted from the base temperature to give the number of heating degree days for the given day. If the average is greater than or equal to the base temperature, then the number of heating days is zero.

Total heating degree days for the season July through June is 5000 to

Table II-1
Mean of Relative Humidity (in percent)
at 4 and 10 AM and PM PST§

Time of Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
OPEN COAST													
Astoria (1953 - 1965)													
4 AM	87	88	88	89	90	90	91	93	93	91	90	89	90
10 AM	84	83	77	74	73	76	75	77	76	82	83	86	79
4 PM	78	76	69	70	69	71	69	71	70	74	78	81	73
10 PM	87	87	86	85	85	86	87	90	90	90	88	88	87
Tatoosh Island (1917 - 1965)													
4 AM	84	85	86	87	89	92	94	96	92	90	86	86	89
10 AM	82	81	80	80	82	86	89	90	87	85	83	83	84
4 PM	82	80	79	79	81	84	87	90	86	85	84	83	83
10 PM	82	82	82	83	86	89	92	94	90	87	83	83	86
INLAND WATERS													
Port Angeles (Ediz Hook) (1948 - 1952)													
4 AM	82	84	84	82	85	88	89	92	89	88	86	86	86
10 AM	78	77	76	72	75	77	79	81	78	80	80	81	78
4 PM	77	77	75	71	74	75	76	79	78	81	81	81	77
10 PM	82	84	83	82	84	84	86	89	88	88	85	84	8S
Seattle-Tacoma (1954 - 1959)													
4 AM	86	87	86	89	87	89	89	90	91	91	89	88	89
10 AM	84	82	75	70	66	70	69	71	75	83	84	87	76
4 PM	80	74	64	56	50	58	50	53	60	72	79	83	6S
10 PM	86	83	81	76	74	78	73	77	81	87	87	86	81

§Phillips, 1968, and Phillips and Donaldson, 1972.

6000 over most of the lowlands and increases to 7000 or more in the higher elevations of the Olympic and Cascade Mountains. Monthly and annual mean totals for several stations are shown in Table II-2.

i. Seasonal Means - Open Coast. Winter temperatures are usually mild due to the prevailing onshore flow of marine air. On the average, maximum temperatures along the Washington coast range from 3°C to 7°C and minimums from -2°C to 2°C, producing a daily range of 5°C. Preceding a cold front, winds from the south bring in warmer air, and temperatures can rise to near 10°C.

Average temperatures are somewhat higher for locations farther south. Along the Oregon coast, maximum temperatures rise to the lower teens and minimum to near 5°C.

During the warm summer months, afternoon temperatures are in the upper teens. Nighttime temperatures are near 10°C. The daily range in temperature, about 16°C, is larger than the range in the winter season due to lighter winds and to the greater influx of solar radiation. Figure II-2 shows the mean maximum and minimum temperatures for three locations.

The air along the coast has a high relative humidity because the air from over the ocean is nearly saturated (approaching 100% relative humidity) with water vapor (National Ocean Survey, 1976).

ii. Seasonal Means - Inland Waters. During the winter, temperatures are mild and the diurnal temperature range is about 6°C (U.S. Weather Bureau, 1964). Afternoon temperatures are generally near 4°C and at night low temperatures are near freezing (Phillips, 1968).

Relative humidity is high most of the time. The daily range in relative humidity in the Inland Waters is from about 75% in the afternoon to about 90% at night.

During summer, the arrival of air -- due to the sea breeze -- from the relatively cool water surface limits the maximum temperature for the day. Afternoon temperatures are in the upper teens to the lower 20's. Temperatures in the upper 20's are considered warm (U.S. Weather Bureau, 1964). At night lows are in the lower teens. The daily range in temperature is about 11°C (Phillips, 1966). See Figure II-3 for mean maximum and minimum temperatures for two stations.

In summer the daily range of relative humidity is larger than the winter range because of the larger range in temperature. Relative humidity on an average summer day varies from 90% at night to 50% during the day.

b. Extremes. Coldest, driest weather usually occurs when high pressure develops over the Pacific Northwest and cold air from the interior of the continent moves into the area west of the Cascades. This usually results in clear skies, afternoon temperatures between -7°C and -1°C, and night temperatures from -12°C to -7°C. These low temperatures usually do not last more than a few days.

Table II-2

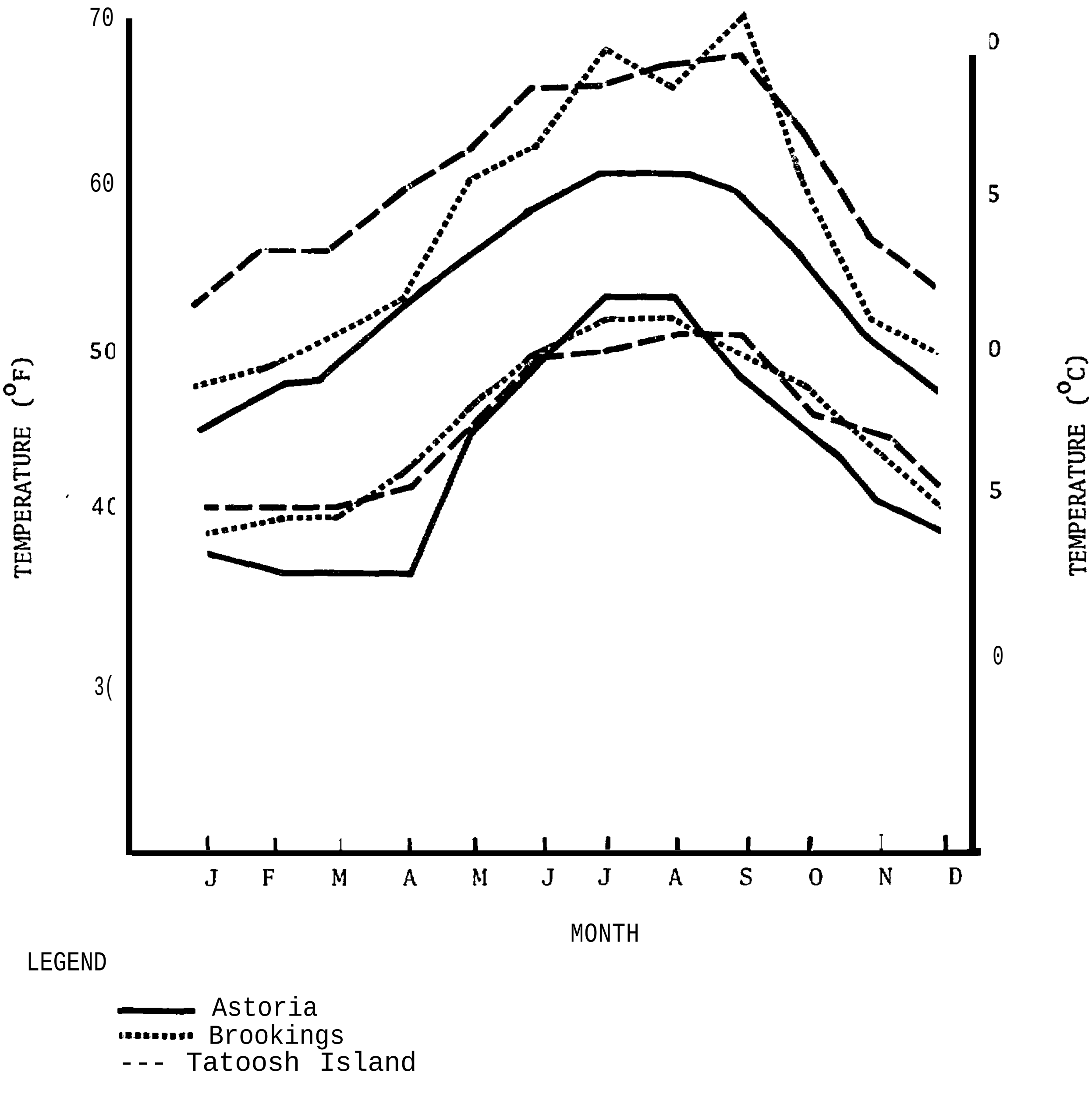
Average Monthly and Annual Heating Degree Days[§]

Station	July	Aug	Sept	Ott	Nov	Dec	Jan	Feb	Mar	Apr	May	June	Annual
OPEN COAST													
Astoria	99	65	230	388	525	810	768	623	S26	545	313	196	5088
Brookings	202	189	171	28S	396	512	558	468	S05	432	338	225	4281
Grayland 2S	206	190	227	367	550	660	710	586	623	495	401	276	5291
Hoquiam FAA	143	114	177	356	569	692	733	594	626	490	366	225	5085
Long Beach 3NNE	202	194	247	372	555	672	711	581	629	503	400	266	5332
Newport	226	220	252	356	483	608	654	552	571	477	391	279	5069
North Head	227	210	239	34S	497	626	700	593	603	484	395	286	520S
Point Grenville	258	250	281	400	564	684	719	606	670	541	445	325	5743
Tatoosh Island	295	279	306	406	534	639	713	613	645	525	431	333	5719
INLAND WATERS													
Anacortes	105	99	189	381	585	698	784	641	611	432	295	171	4991
Bellingham 2N	140	140	249	462	657	787	874	714	682	510	366	216	5797
Blaine 1E	105	115	243	462	669	794	877	722	679	498	332	180	5676
Bremerton	65	70	180	405	640	775	850	675	650	4S0	285	150	5195
Everett	105	109	213	409	618	738	818	672	632	462	319	183	5278
Friday Harbor	140	125	240	455	610	720	770	675	630	480	365	230	5440
Grapeview	53	47	147	375	594	713	791	652	617	429	264	135	4817
Port Angeles	195	195	267	462	639	744	818	692	694	534	403	279	5922
Port Townsend	127	118	213	415	597	713	794	658	636	468	329	207	5275
Quilcene 2SW	81	84	195	437	672	806	874	706	667	471	310	177	5480
Seattle-Tacoma	74	81	186	406	633	750	828	678	657	474	310	174	5251
Sequim	152	133	228	446	642	769	840	697	688	516	369	234	5714
Tacoma	66	62	177	375	579	719	797	636	595	435	282	143	4866
Vashon	80	80	185	405	595	735	825	665	630	455	315	170	5140

[§] Phillips, 1966; Phillips, 1968, and Phillips and Donaldson, 1972.

Figure II-2

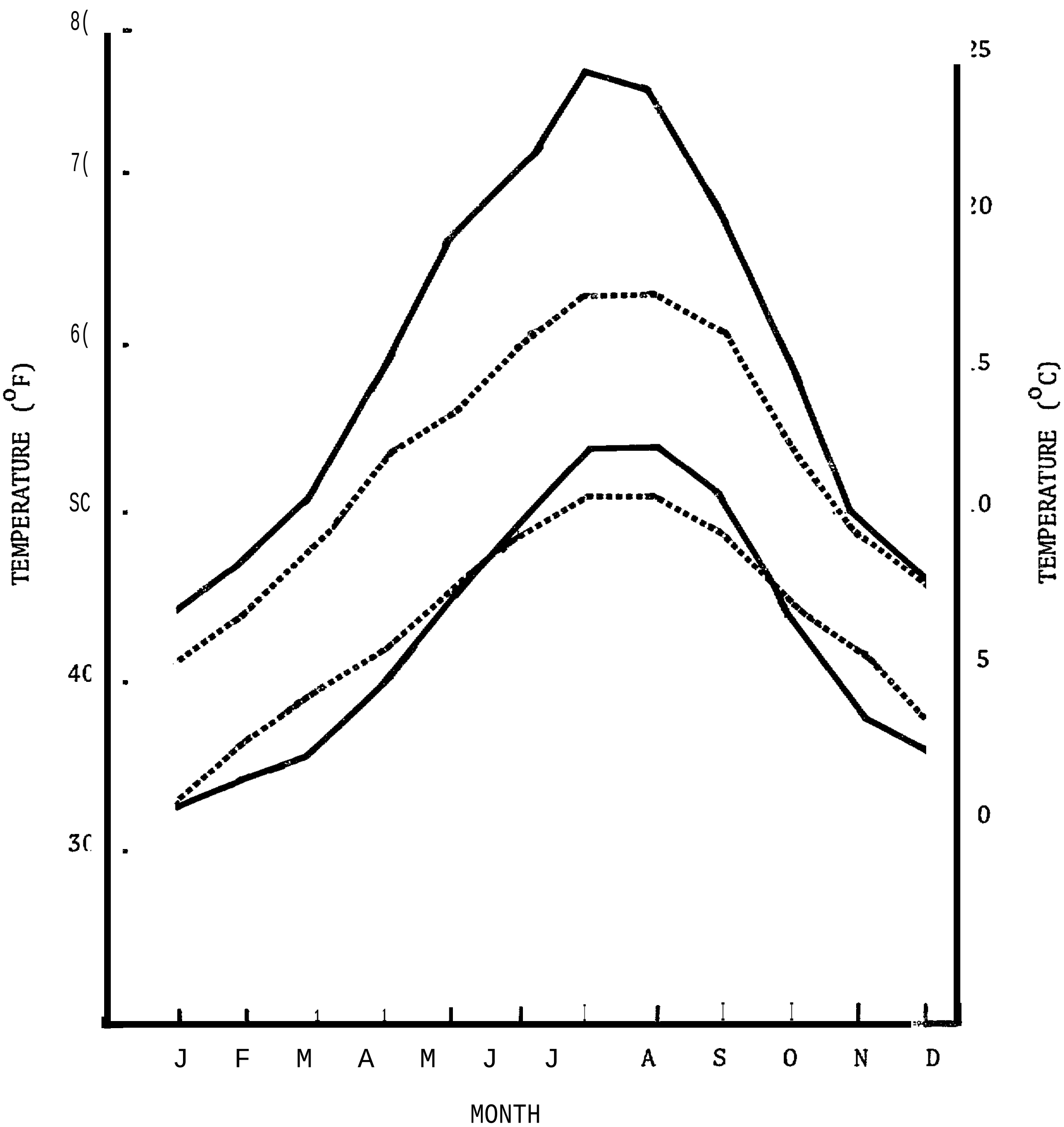
Average Maximum and Minimum Temperatures
for Selected Open Coast Stations



§Phillips and Donaldson, 1972, and U.S. Environmental Data Service, 1968.

Figure II-3

Average Maximum and Minimum Temperatures
for Selected Inland Waters§



LEGEND
.... Port Angeles (Ediz)
— Seattle-Tacoma

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§Phillips, 1966, and Phillips, 1968.

Warmest weather in summer occurs when northerly or easterly winds bring warm, dry air from the interior. Again, these spells are short-lived and seldom last longer than four days (Phillips, 1966). The warm spell ends when cool, moist air from the ocean moves into the region.

i. Extremes - Open Coast. Coldest weather occurs when winds are from the northeast. Also, cold air sometimes funnels down the Columbia River basin from the interior of Western Washington, resulting in cold temperatures in the area around Astoria (U.S. Environmental Data Service, 1930-76).

Tatoosh Island, on the average, has only eight days of below freezing temperatures each year. The record low for this station is -10°C in December (National Ocean Survey, 1973).

Astoria has an average of two days each winter when the high temperature is below freezing. During an average January, the coldest month, the temperature will drop below freezing on ten nights. The record low is -14°C set in December, 1972 (U.S. Environmental Data Service, 1930-76).

An average winter in Brookings has temperatures below 0°C on seven nights but on no day has the temperature remained below freezing. The record for this station is -8°C set in December, 1972 (U.S. Environmental Data Service, 1930-76).

During the summer, afternoon temperatures exceed 27°C only a few times each year. Aberdeen, on the average, records 27°C on eight to twelve days and 30°C on three to six days (Phillips and Donaldson, 1972). North Bend, Oregon, has a record high of 38°C, but temperatures go above 32°C only once in every three years.

Figure II-4 shows record high and low temperatures for three stations.

ii. Extremes - Inland Waters. Below -18°C readings are taken at a number of stations each winter. During cold spells, daytime temperatures at Port Angeles are near -4°C and nighttime lows are near -8°C (U.S. Weather Bureau, 1964). This is typical for low-lying areas.

The record low at Whidbey Island Naval Air Station was -18*C in January, 1950 (Halladay, 1970). At the Olympia Airport, the record was -19 C (Phillips, 1964).

During the summer, maximum temperatures of 30°C and 32°C occur on a few days each year. 38°C or higher has been recorded on one or more occasions in most localities (Phillips, 1968).

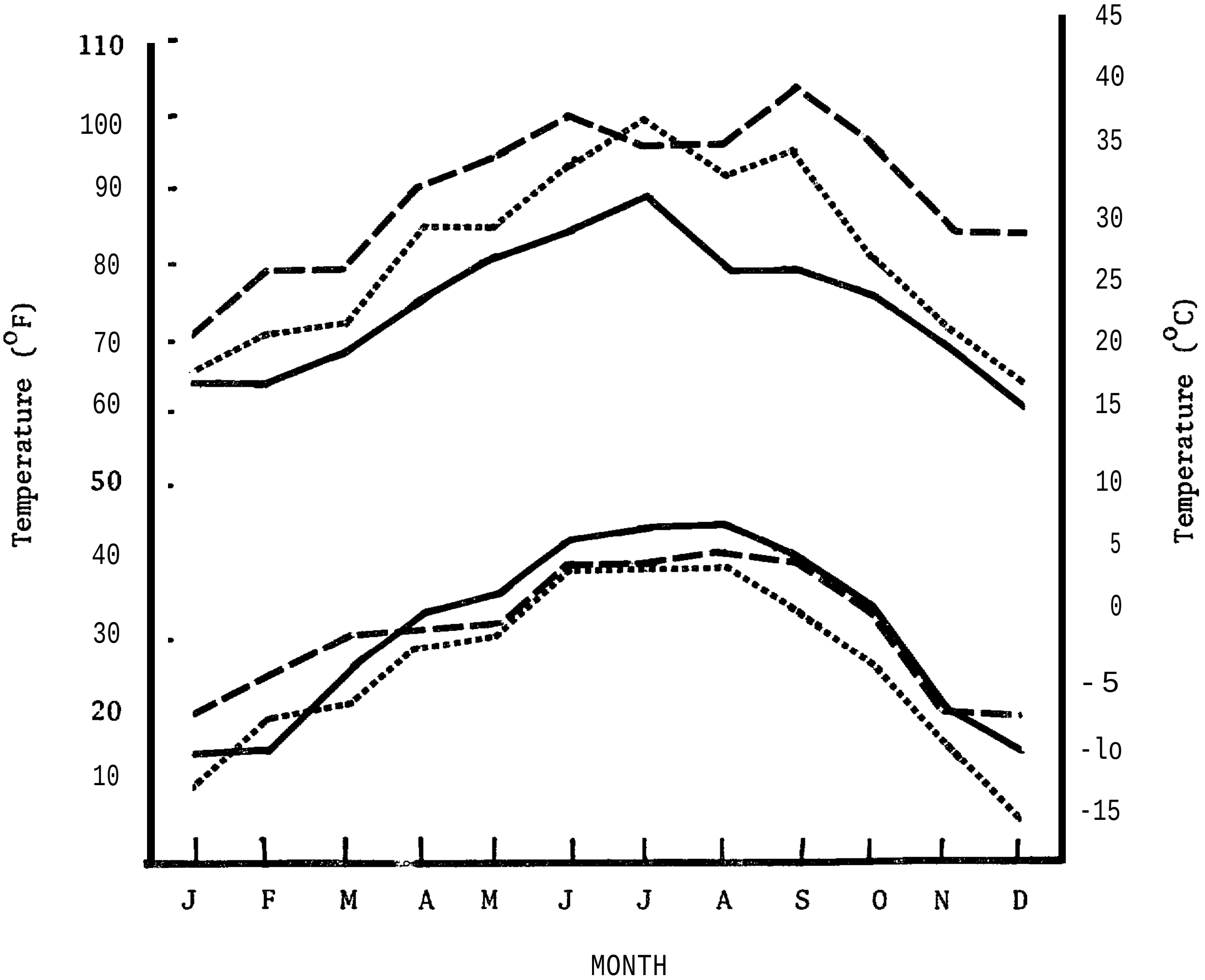
Record high temperatures at various locations range from 33°C to 43°C. The record high at the Olympia Airport was 39°C (Phillips, 1964).

3. Precipitation.

Precipitation in the study area is generally produced by frontal storms moving inland from over the Pacific Ocean and is enhanced by orographic

Figure II-4

Extreme Temperatures for Selected Stations[§]



LEGEND 'Tatoosh Island
...... Astoria
-'- Brookings

§Phillips, 1966 and Phillips, 1968.

lifting along the slopes of the coastal mountains. The southward shift of the semi-permanent Aleutian Low during the winter months results in an increased frequency of frontal storms reaching the Pacific Northwest and a corresponding winter maximum of precipitation over the study area. Frontal storms are discussed in more detail in section 4. About 80% of the annual precipitation along the coast occurs from October to March while 5% or less of the annual total occurs in July and August. Snowfall is generally rare and of brief duration along the coast due to the usually mild coastal temperatures, but becomes more common with increased elevation in the coastal mountains. Most winter precipitation falls as snow in the higher mountains and can be expected to remain on the ground until June or July. Thunderstorms are rare except in the higher mountains.

a. Annual Means.

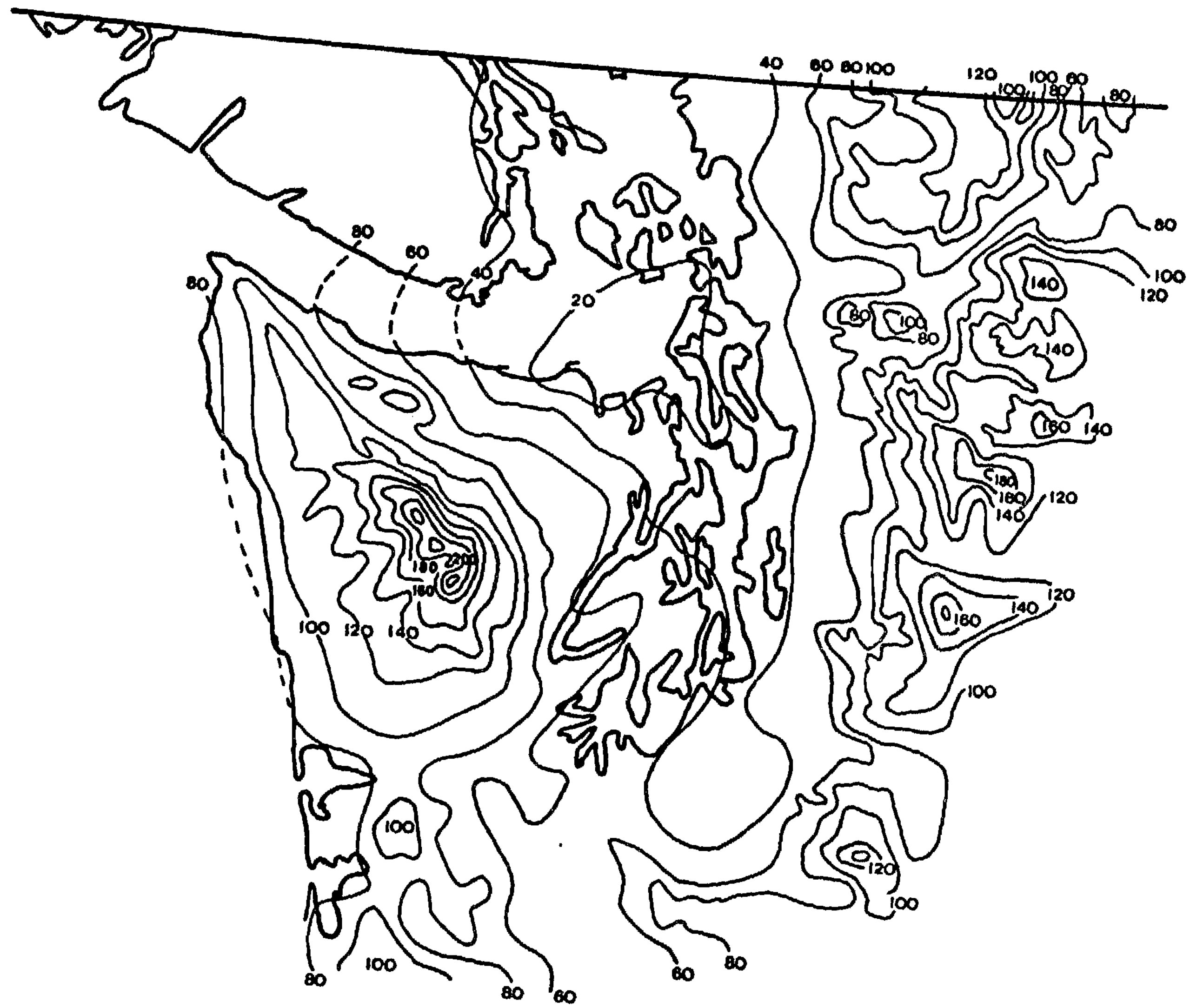
i. Annual Means - Open Coast. Precipitation data for the open coast are quite complete, due to the fairly dense network of coastal meteorological recording stations. Precipitation records for the nearshore ocean are lacking, but precipitation totals over the ocean should correspond to totals at coastal locations due to the frontal nature of most precipitation.

Annual precipitation along the open coast averages 180-200 cm per year, generally decreasing to the south. Figure II-5 shows annual totals for the study area. Dashed lines over the ocean indicate values assumed from the coastal data. Totals for the Washington coast range from over 230 cm at Hoh Head to less than 180 cm at Cape Shoalwater. Orographic lifting produces increased totals inland to nearly 635 cm at the crest of the Olympic Mountains. The extensive "Rain Forest" region along the western slopes of the Olympic Mountains averages 250 to 510 cm per year. Precipitation totals for the Oregon coast range from 280 cm north of Cape Falcon, where the Sugarloaf Mountains lie near the coast, to less than 130 cm south of Cape Arago (Five Mile Point) . Totals increase inland (upslope) to between 380 and 510 cm at the crest of the Coast Range.

ii. Annual Means - Inland Waters. Precipitation totals for the inland waters show a much wider range due to the "rainshadow" effect of the Olympic Mountains. The warming of marine air descending the east slope of the Olympic Mountains produces a light-rainfall belt over the northeast Olympic Peninsula and the San Juan Islands. Drizzle or light rain frequently falls here while the western slopes are experiencing moderate to heavy rain. Gaps in the coastal mountains north of the Willapa Hills and through the Strait of Juan de Fuca allow marine air to move inland without major obstruction and produce high precipitation totals for the Strait of Georgia and the southern portion of Puget Sound. Annual precipitation for the Strait of Juan de Fuca decreases from an average of 250 cm at Neah Bay to 64 cm at Port Angeles and less than 38 cm north of Port Townsend. Totals increase northward in the Strait of Georgia to average over 89 cm near Drayton Harbor and southward in Puget Sound to 86 cm at Seattle, 94 cm at Tacoma, and 163 cm at Shelton. Precipitation increases inland (upslope) and eastward from Puget Sound and the Strait of Georgia to average 190 cm per year in the foothils and 280 to 510 cm on the western slopes of the Cascades.

Figure II-5a

Mean Annual Precipitation
for the Study Area§†‡



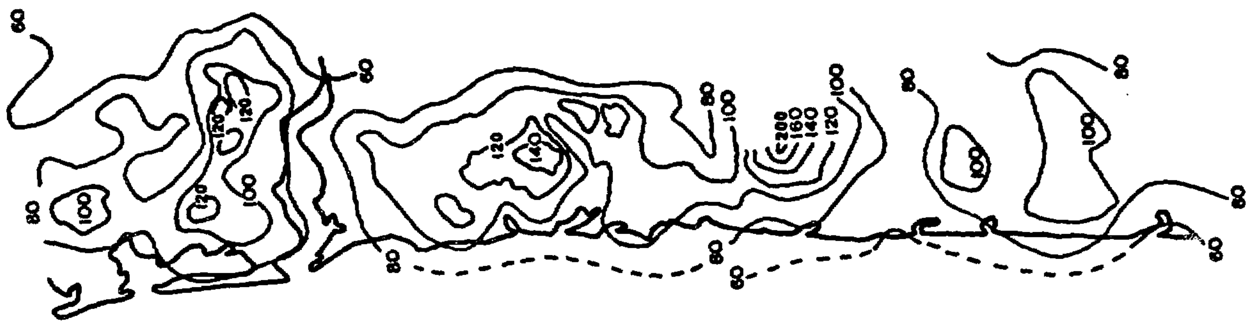
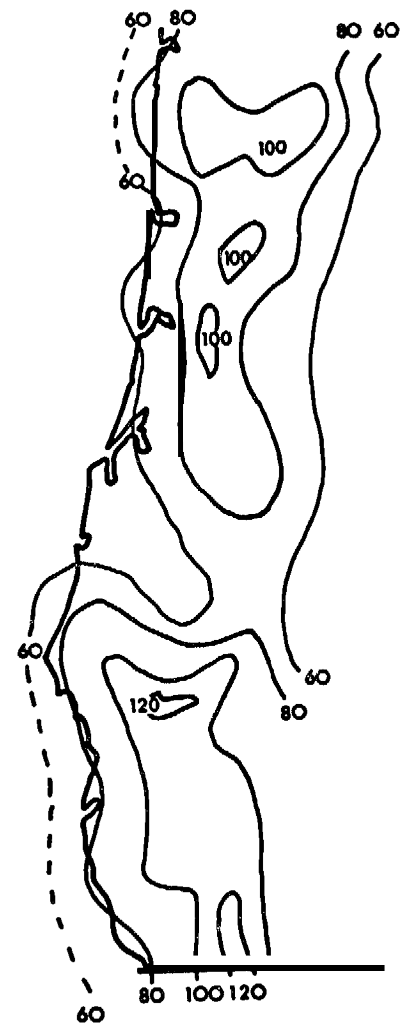


Figure II-5b

Figure II-5c



§Phillips and Donaldson, 1972.
†1 inch = 2.54 cm.
‡Dashed lines indicate values estimated from shoreline data.

b. Seasonal Means.

i. Seasonal Means - Open Coast. The increased frequency of frontal storms arriving from the Pacific Ocean in the winter produces a distinct winter precipitation maximum. Precipitation along the coast is generally light in summer, increases in the fall, reaches a maximum in the winter, and then gradually decreases during the spring. Figures II-6 and II-7 show monthly precipitation averages for selected stations on the Washington and Oregon coasts. July or August is usually the driest month, with monthly precipitation averages of about 2.5 cm at most coastal locations. Dry month averages range from 5 cm at Tatoosh Island to 0.8 cm at Powers. December or January is the wettest month, with averages of 30 to 33 cm along the coast. Wet month averages range from 48.7 cm at Clearwater to 24.4 cm at Bandon.

Inland stations show a similar seasonal pattern, with increased monthly averages due to orographic lifting corresponding to their higher annual averages. Snowfall along the coast averages 2.5 to 20 cm annually and is largely confined to the months of December through February. Snow ground cover rarely lasts more than 2 to 3 days at a time, during outbreaks of cold continental air from the north and east. Snowfall amounts increase significantly inland with altitude to average 1270 cm near the crest of the Olympic Mountains.

ii. Seasonal Means - Inland Waters. Precipitation for the inland waters shows a seasonal pattern similar to that of the open coast, with reduced monthly averages corresponding to reduced annual averages. Figure II-8 shows monthly precipitation averages for selected inland water stations. July or August is the driest month with monthly averages of less than 2.5 cm at most locations. Dry month averages range from 5.2 cm at Neah Bay to 1.4 cm at Victoria (Gordon Head). Dry month averages for the Strait of Georgia and Puget Sound range from 3 cm at Blaine to 1.6 cm at Seattle and 2 cm at Shelton.

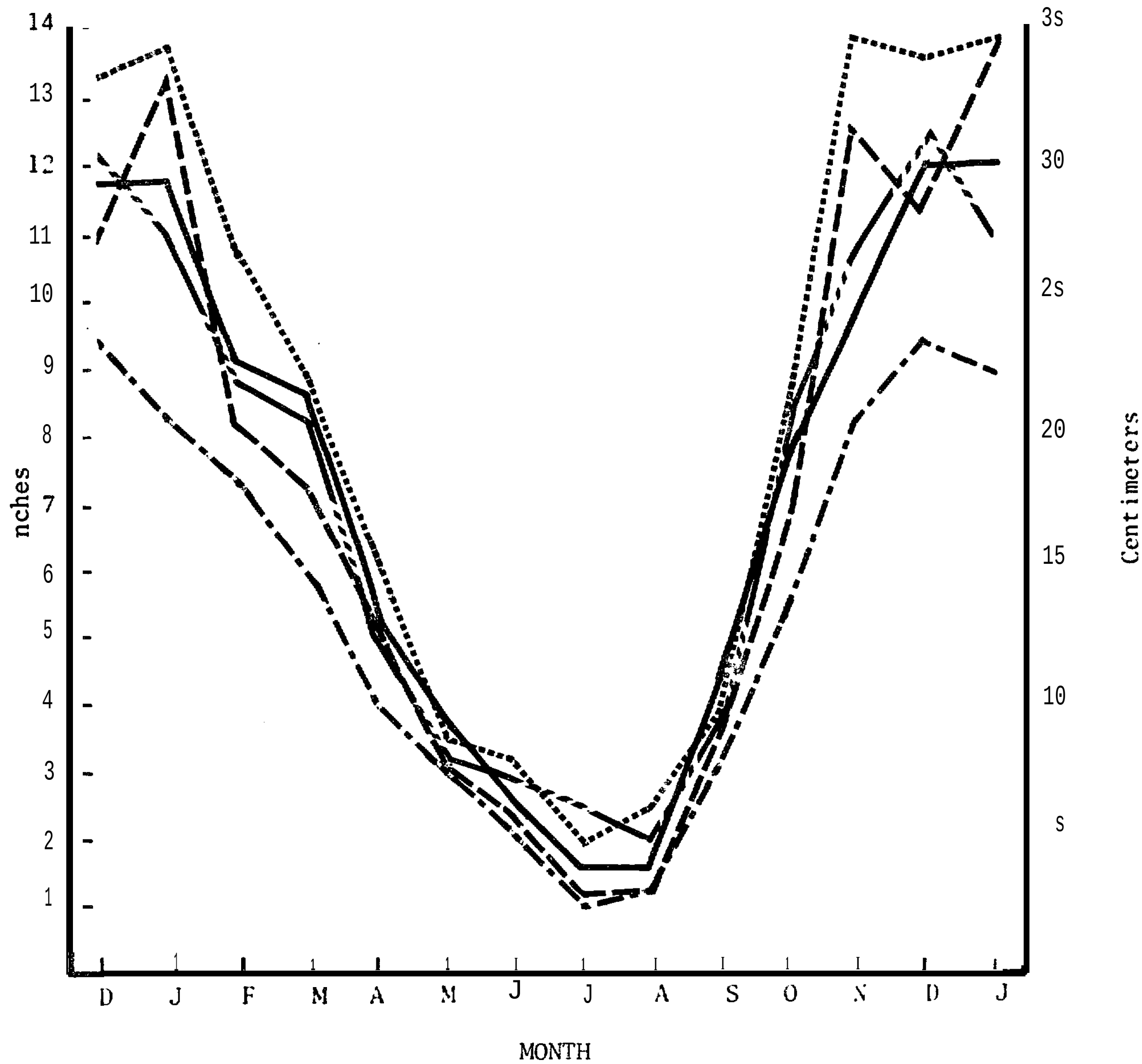
December or January is the wettest month. Wet month averages for the Strait of Juan de Fuca range from 41.7 cm at Neah Bay to 6.1 cm at Port Townsend. Wet month averages for the Strait of Georgia and Puget Sound range from 15.7 cm at Blaine to 9.7 cm at Anacortes and 29.6 cm at Shelton.

Figures II-9 and 11-10 show the percent frequency of occurrence of precipitation for Whidbey Island Naval Air Station by month. Whidbey Island is located in the rainshadow area of the Olympic Mountains. A comparison of Figures II-9 and 11-10 indicate that the principal forms of precipitation at Whidbey Island are rain or drizzle. Figure 11-11 shows the percent frequency of snowfall at Whidbey Island Naval Air Station.

Winter season snowfall ranges from 15 to 38 cm over the lowlands surrounding the inland waters. Table II-3 gives mean monthly snowfall amounts at selected inland water stations. Snow rarely remains on the ground for more than two to three days. Snowfall increases inland with altitude to average 7.62 to 12.70 m in the Cascades. The greatest winter season snowfall in the 48 contiguous United States -- over 25.40 m -- was recorded at Paradise Ranger Station, Mount Rainier.

Figure II-6

Mean Monthly Precipitation for
Washington Open Coast Stations[9]



LEGEND Tatoosh Island (1931-1960) —Destruction Island (1930-1945)
Lone Tree (1909-1921 ---North Head (1883-1952)
Point Grenville (1952-1962)

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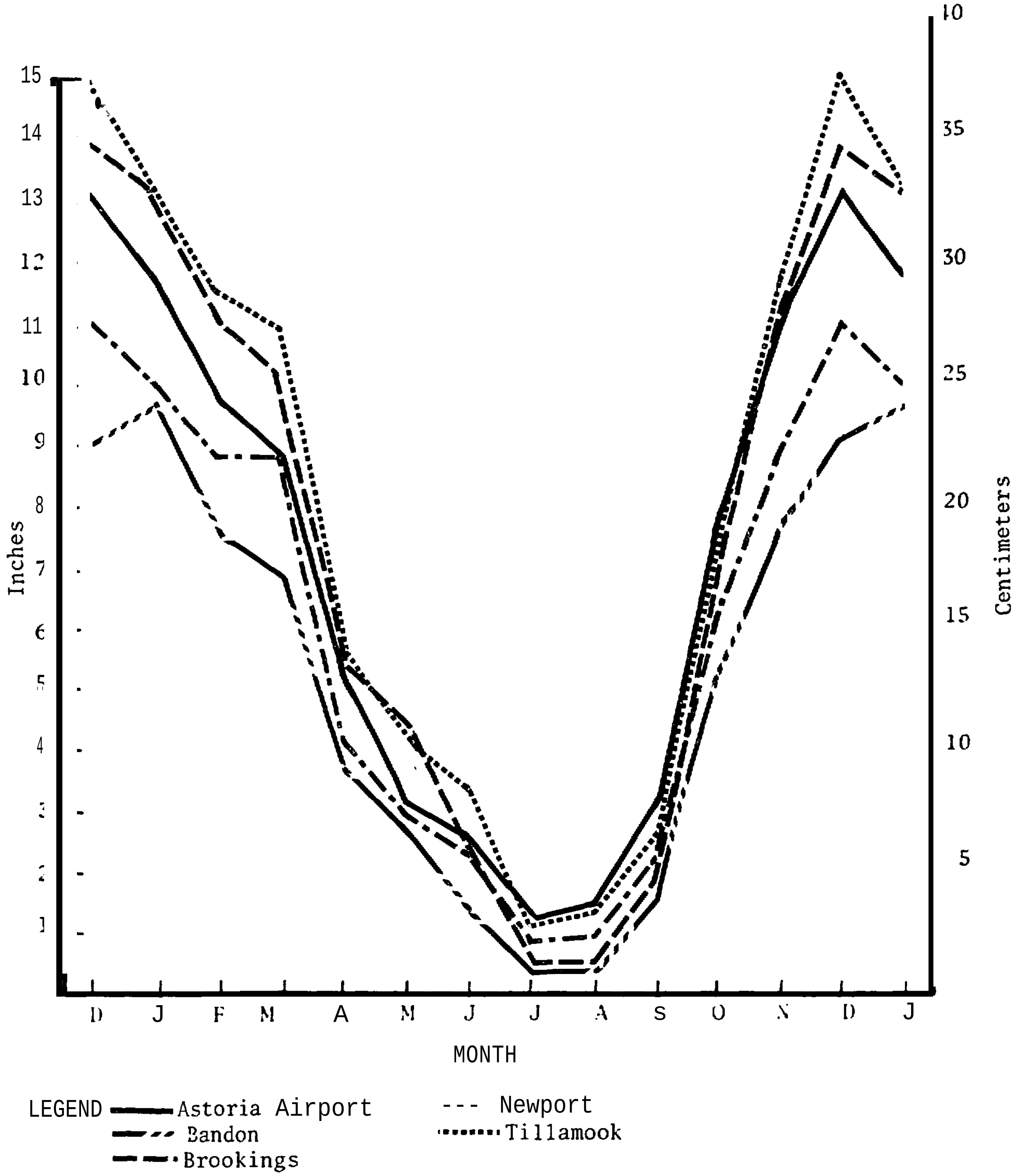
[9] Phillips and Donaldson, 1972.

Figure II-7

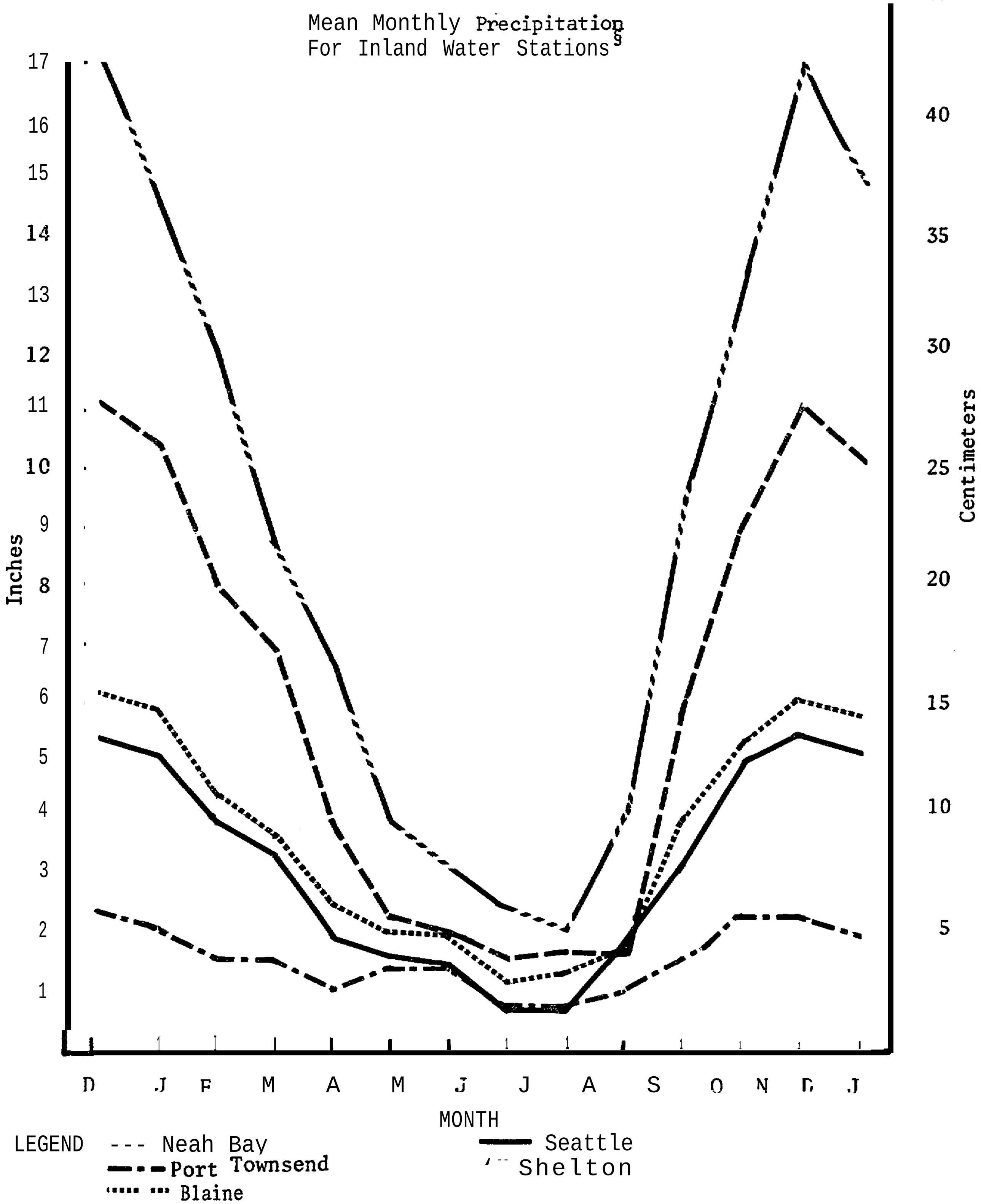
Mean Monthly Precipitation for Oregon Open Coast Stations[§]



§Sternes, 1960.

Figure II-8

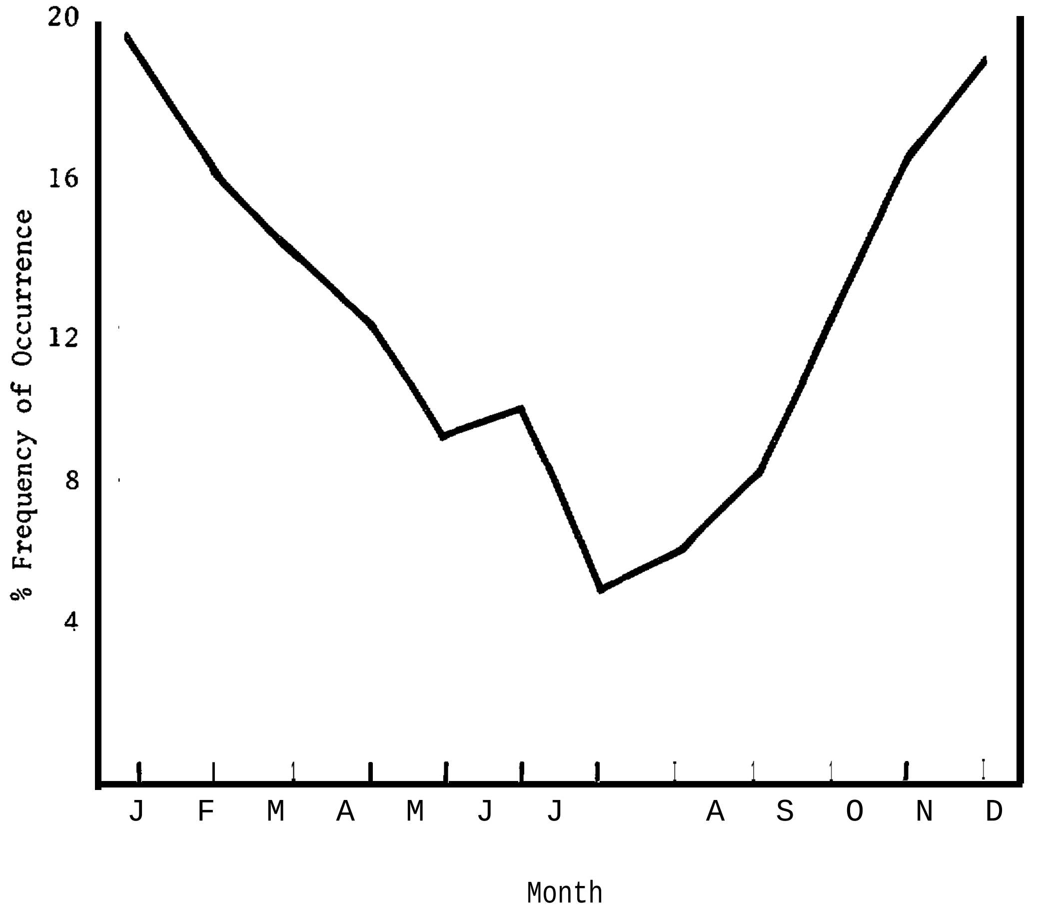
Mean Monthly Precipitation
For Inland Water Stations[§]



§Phillips, 1966 and 1968.

Figure II-9

Percent Frequency of Occurrence of Observations with precipitation at Whidbey Island Naval Air Station[§]



[§]Halladay, 1970.

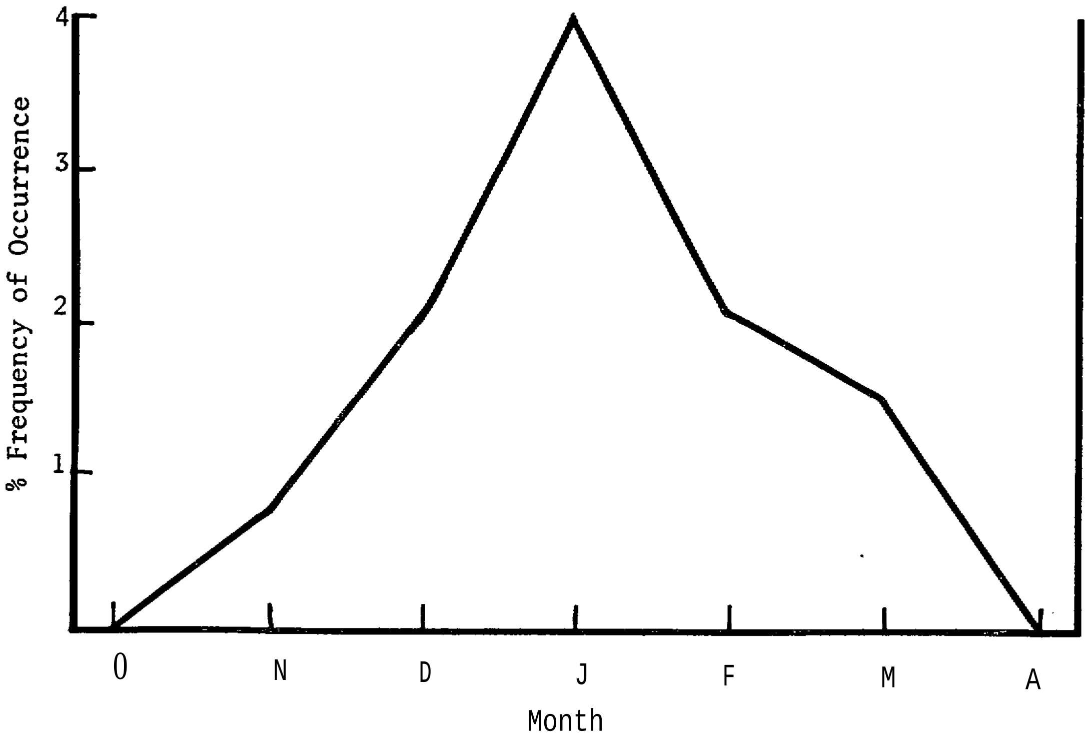
Figure 11-10

Percent Frequency of Occurrence of Observations with Rain and/or Drizzle at Whidbey Island Naval Air Station§

§Halladay, 1970.

Figure 11-11

Percent Frequency of Occurrence of Observations with Snow and/or Sleet at Whibdbey Island Naval Air Station [§]



[§] Halladay, 1970.

Table II-3

Mean Monthly Snowfall Amounts
at Inland Water Stations

Station	Period of Record (Yrs.)	Ott.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Victoria (Gordon Head)	30	0	1.3	8.1	13.7	5.1	5.8	T
Pender Island	30	0	1.3	10.2	13.2	6.4	2.5	0
Becher Bay	30	0	.8	4.6	9.1	3.3	6.6	0
Port Townsend	21	0	.8	.8	7.1	3.1	1.0	T
Quilcene	19	0	2.0	1.8	7.9	3.8	.3	T
Everett	20	T	2.0	2.3	13.2	6.9	4.1	.3
Seattle	17	T	1.3	1.0	10.9	3.3	2.0	T
Bremerton	19	T	.5	.8	14.0	5.6	.5	T
Vashon Island	18	T	1.0	2.3	13.0	3.3	2.0	T
Tacoma	22	T	2.5	2.3	13.2	4.3	2.5	.3
Grapeview	19	T	.5	.3	9.4	1.8	T	T
Shelton	18	0	1.3	1.5	17.3	3.8	2.8	T
Olympia Priest Point Park	17	T	1.3	1.3	9.7	7.1	1.5	T

§ Dept. of the Environment, Canada, 1970 and U.S. Weather Bureau, 1961.

c. Variability of Precipitation.

i. Variability of Precipitation - Open Coast. While the annual precipitation totals along the open coast average 180 to 200 cm per year, these amounts are not recorded year after year. The general southward shift of the Aleutian Low in winter which steers frontal storms into the Pacific Northwest is not as regular an occurrence as one might suspect. Frontal storms may remain north of the study area until well into winter or move south in the early fall. Similarly, storms may not move into the area until well into summer. Indeed, at the time of this writing (Fall, 1976), a high pressure cell has remained entrenched off the Pacific Northwest coast throughout most of the fall, steering frontal storms north of the area and producing the driest fall on record at Seattle.

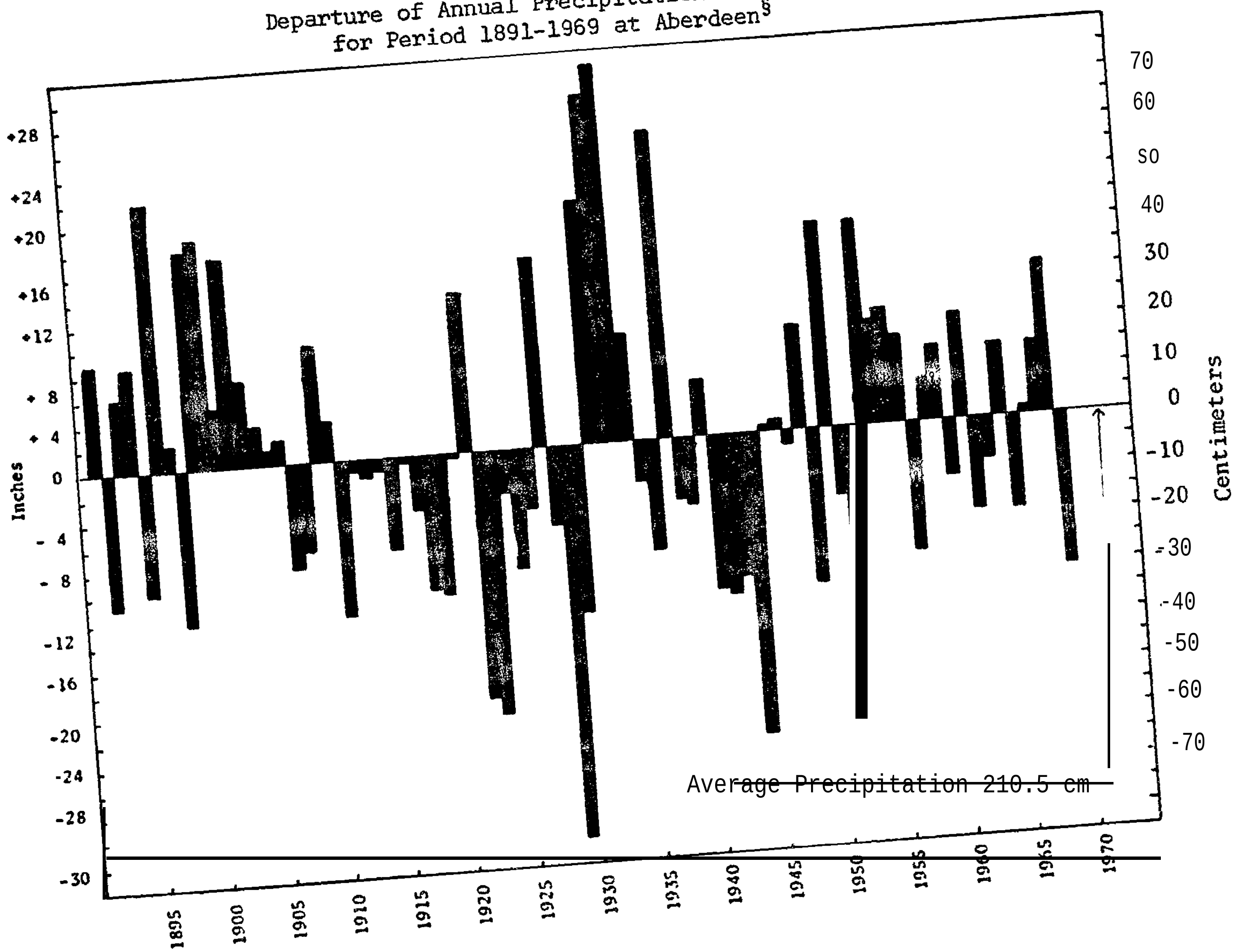
The range in annual precipitation totals from minimum to maximum for many locations along the open coast reaches 127 cm. Figure 11-12 shows the departure of annual precipitation from the average for the period 1891 to 1969 for Aberdeen. The five year period from 1929 through 1933 shows a 150 cm range in annual precipitation totals. During the three year period from 1933 through 1935, Tillamook recorded annual precipitation totals of 331 cm ('33) and 164 cm ('35). Record annual precipitation totals for other locations include: Tatoosh Island, 126-cm to 290.3 cm; North Head, 78 cm to 203 cm; Astoria, 153 cm to 222 cm to 268 cm.

Similar variability in monthly totals have been recorded. Dry month totals varying from near O to 12.7 cm and wet month totals varying from 12.7 to 64 cm are not uncommon.

Snowfall along the open coast is extremely variable, with many years during which there is no snowfall at all. Greatest winter totals of snowfall approach 127 cm at many coastal locations including: Tatoosh Island, 93 cm; Aberdeen, 230 cm; North Head, 60 cm; and Astoria, 81 cm. Snowfall in early November has been recorded at Tatoosh Island, Aberdeen and ClearWater.

ii. Variability of Precipitation - Inland Waters. Precipitation variability similar to that of the open coast is found over the inland waters, with a decreased range in annual and monthly totals corresponding to decreased annual precipitation averages. Figures 11-13 and 11-14 show the departure of annual precipitation from average for the period 1898 to 1968 at Port Townsend and from 1878 to 196S at Olympia. The range in annual totals from minimum to maximum varies from about 38 cm in the rainshadow region to near 102 cm at Neah Bay, Blaine and Shelton. Nearly all inland waters stations have reported dry months with no precipitation. A range in wet month totals of over 38 cm is not uncommon outside of the Olympic Mountains "rainshadow" region. Tacoma has recorded wet month totals ranging from 5.1 to 48 cm, while wet month totals at Shelton range from 9 to 80.3 cm. Within the rainshadow region, wet month totals show less variability, but a 13 to 18 cm range between maximum and minimum wet month totals is found at most rainshadow stations. Figure 11-15 shows the mean, greatest and least precipitation totals for Whidbey Island Naval Air Station by month -- the small range between minimum and maximum totals shows that

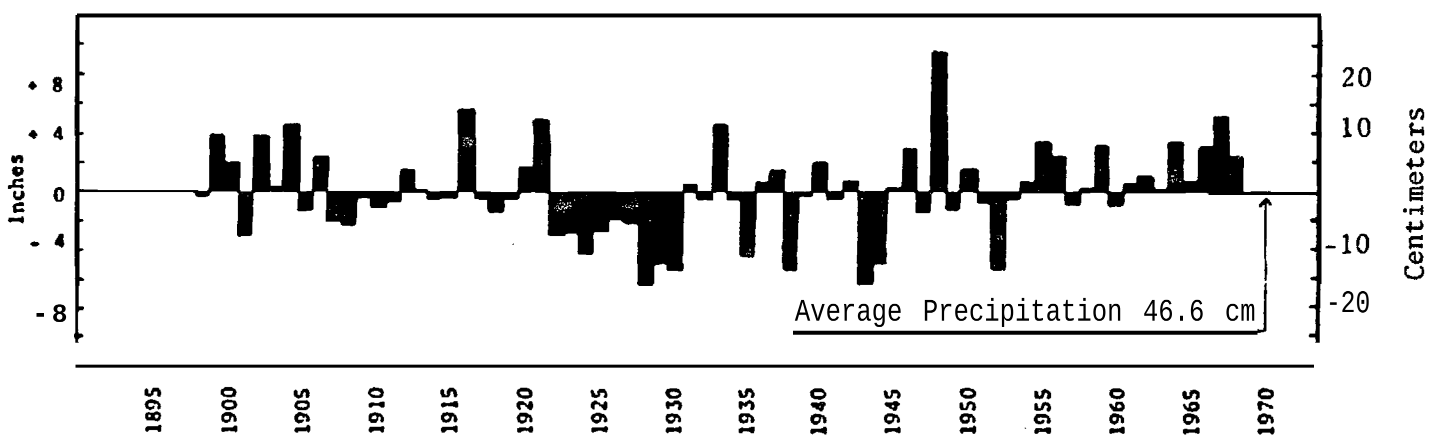
Figure II-12
Departure of Annual Precipitation from Average
for Period 1891-1969 at Aberdeen§



‘Phillips and Donaldson, 1972.

Figure 11-13

Departure of Annual Precipitation from Average
for Period 1898-1968 at Port Townsend[§]



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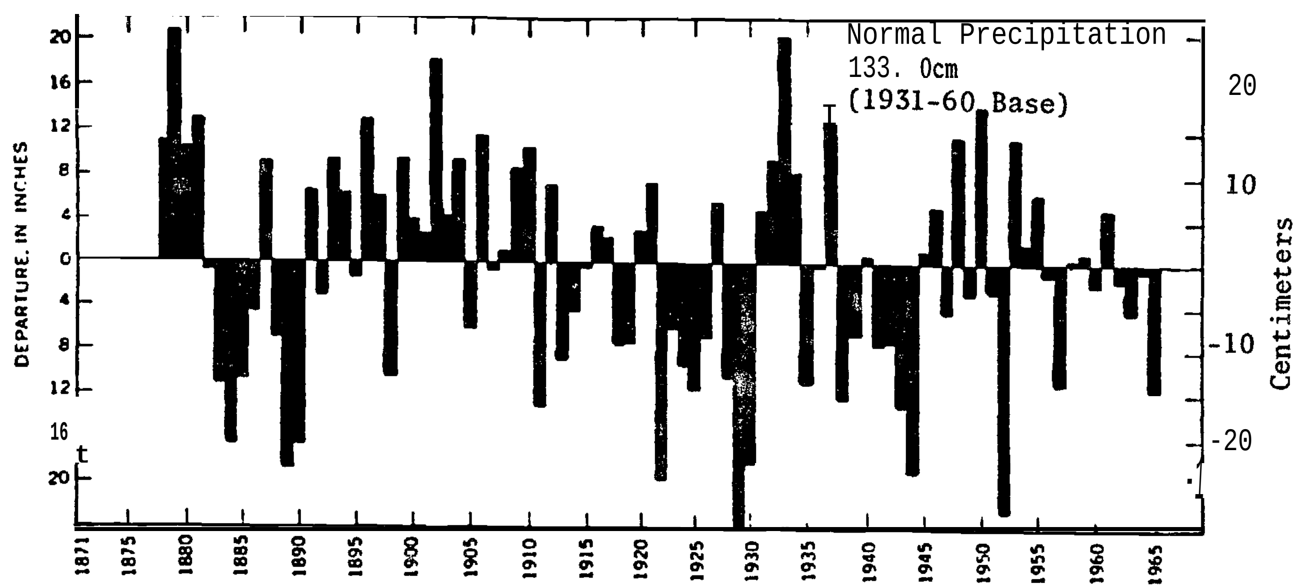
§Phillips and Donaldson, 1972.

Figure 11-14

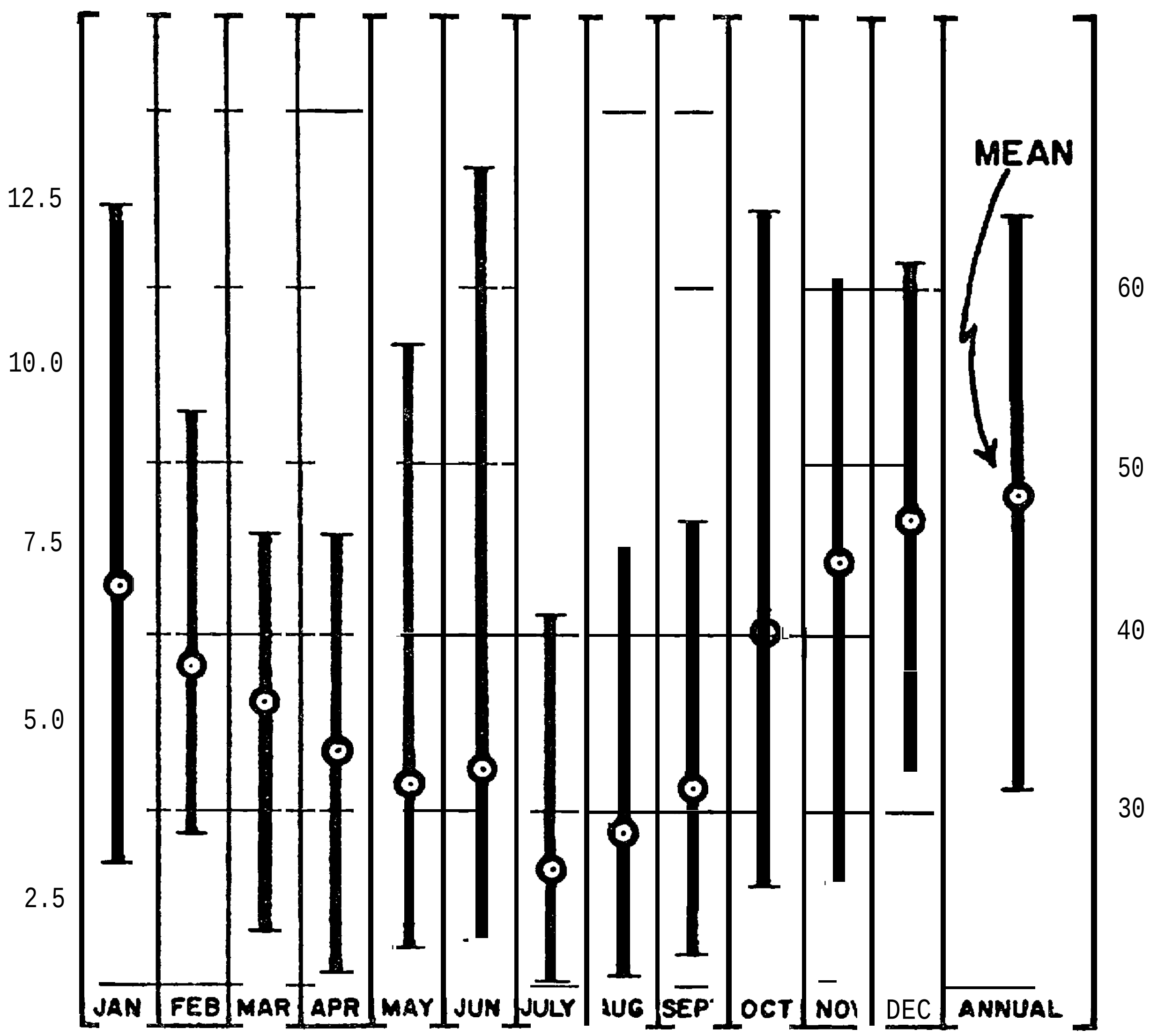
Departure of Annual Precipitation from Average
for Period 1878-1965 at Olympia§



§ Pacific Northwest River Basins Commission. Puget Sound Task Force, 1970.

Figure II-15

Precipitation: Mean, Greatest, and Least (cm) by Month and for One Year at Whidbey Island Naval Air Station§



§Halladay, 1970.

Whidbey Island is in the Olympic Mountain rainshadow.

Snowfall totals for the inland waters show a high variability, with a somewhat higher frequency of occurrence than for the open coast due to the closer proximity of the inland waters to continental air arriving from the north and east. Many inland water locations have experienced winters during which no snowfall was recorded. Maximum monthly snowfall totals average about 89 cm for most inland water locations and range from 44 cm at Whidbey Island Naval Air Station to 99 cm at Blaine. Figure 11-16 shows the mean, greatest and least snowfall totals by month for Whidbey Island Naval Air Station. The months of December through March may have snowfall amounts that will affect vehicular traffic at most inland water locations.

d. Frequency and Intensity.

i. Frequency and Intensity - Open Coast. The frontal nature of most precipitation along the open coast produces prolonged episodes of light to moderate rain, increasing in intensity as one moves inland (upslope), rather than brief episodes of intense rainfall indicative of thunderstorms. Most coastal locations can expect to receive a rainfall amount of 2.5 cm falling in one hour only once in every fifty years. However, measurable precipitation occurs on nearly half the days of the year along most of the open coast. The number of days per year with measurable precipitation averages about 17S, generally decreasing to the south, and ranges from 199 at Tatoosh Island to 187 at Astoria and 122 at Brookings. The number of days with 2.S cm or more of rainfall averages only 20 at Tatoosh Island and 15 at Reedsport.

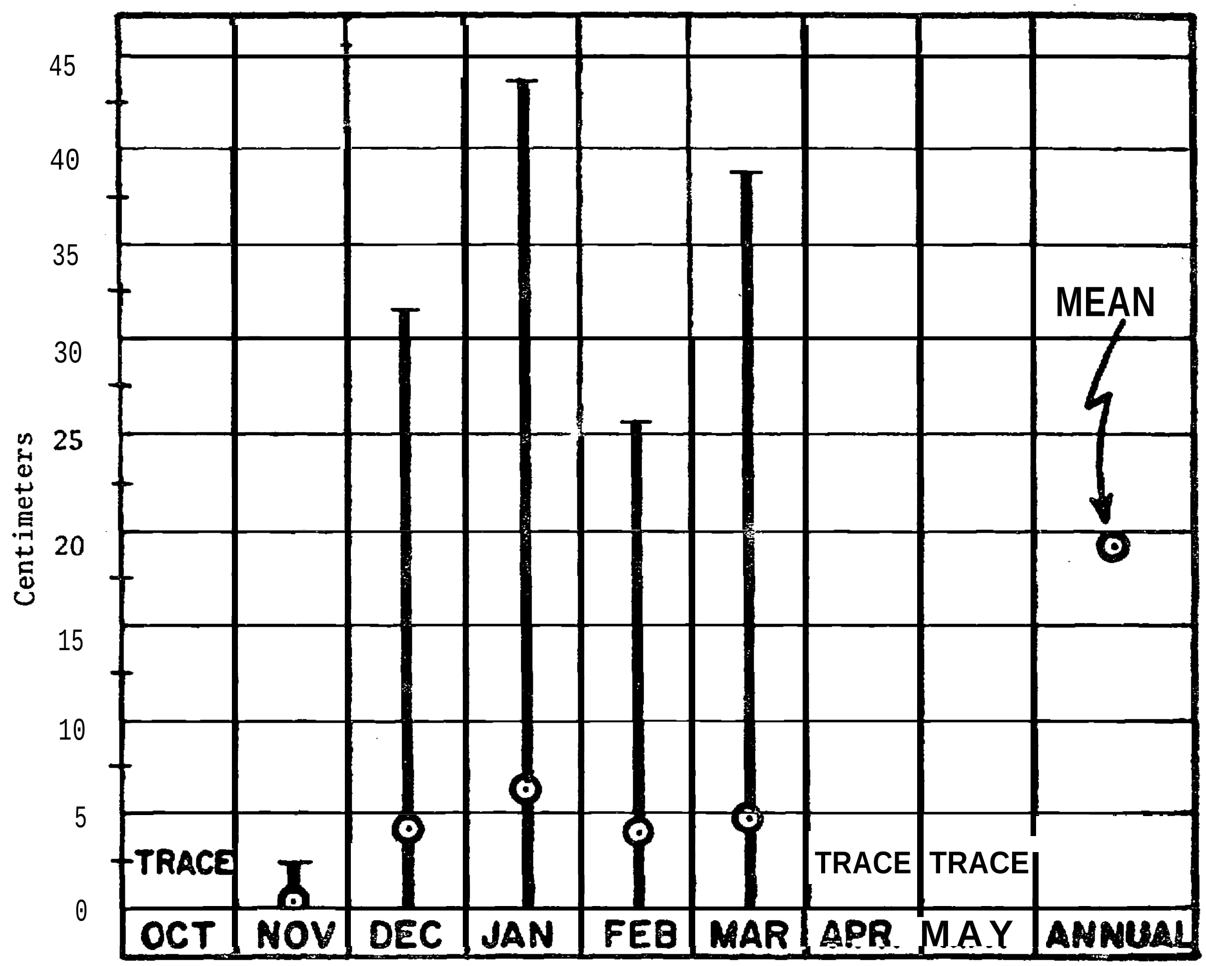
Figures 11-17 and 11-18 show rainfall intensity-duration-frequency curves for Tatoosh Island and North Head, respectively. These graphs are used in estimating the frequency of various rainfall amounts for the open coast. Table II-4 gives similar information in a different format estimated for the coastal lowlands and western slope of the Olympic Mountains. The table shows, for example, that a 24 hour total of 15 cm of rainfall can be expected once every 25 years in the lowlands and every 2 years on the west slope of the Olympics.

The number of days per year with snowfall averages only three to four along most of the open coast and amounts are generally light, melting usually within a matter of hours. Snowfall frequency decreases to the south, with the southern Oregon coast experiencing snowfall about two winters out of five. The maximum snowfall recorded during a 24 hour period averages about 20 to 25 cm along the coast, and ranges from 30 cm at Tatoosh Island to 10 cm at Brookings. Table II-5 shows the greatest 1, 2 and 3 day totals of snowfall by month for Tatoosh Island, Aberdeen, and Clearwater.

ii. Frequency and Intensity - Inland Waters. Precipitation frequency and intensity in the inland waters exhibit a pattern similar to that of the open coast, with rainfall less frequent due to the rainshadow effect of the Olympic Mountains. The number of days per year with measurable precipitation averages about 145 and ranges from 202 at Neah Bay to 116 at Port Townsend and 114 at Pender Island. Averages for the Strait of Georgia and Puget Sound range from 142 at Blaine to 161 at Everett, 151 at Seattle, and 160 at Shelton. The number of

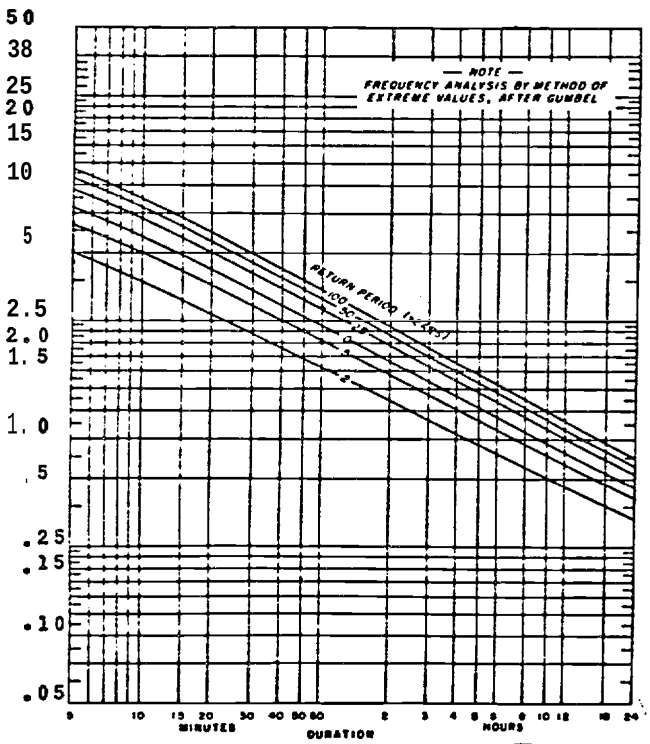
Figure 11-16

Snowfall: Mean, Greatest, and Least (cm) by Month
and for One Year at Whidbey Islands Naval Air Station§



§Halladay, 1970.

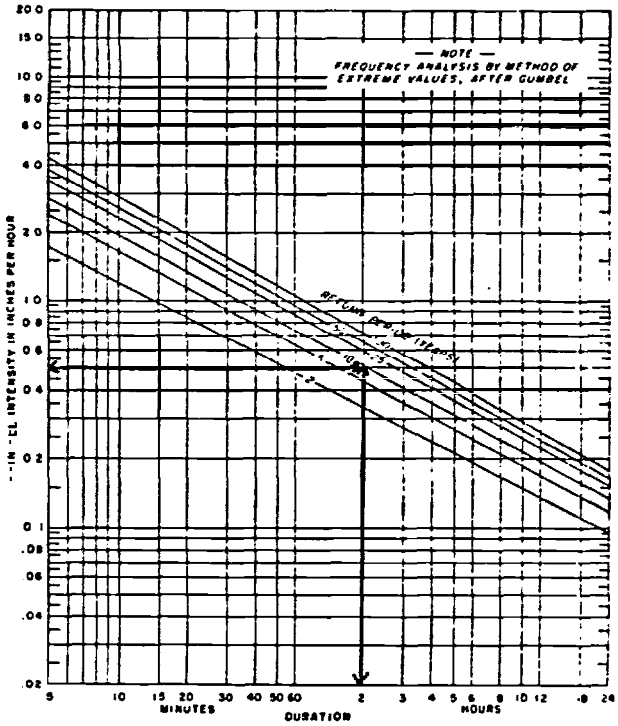
Figure 11-17
Rainfall Intensity (cm per hour) - Duration - Frequency
Curves for Tatoosh Island (1903-1948)[5]



Phillips, 1972.

Figure 11-18

Rainfall Intensity - Duration – Frequency
Curves for North Head (1903-48)[§†]



§Phillips, 1972.
†1 inch = 2.54 cm.

Table II-4

Rainfall Intensity (cm), Duration and Return Periods[9]

LOWLANDS WEST COASTAL RANGE
RETURN PERIODS

Duration	2 Yrs.	5 Yrs.	10 Yrs.	25 Yrs.	50 Yrs.
30 minute	1.0	1.5	1.8	2.0	2.0
1 hour	1.5	1.8	2.0	2.5	2.8
2 hours	2.5	2.8	3.3	3.8	4.3
3 hours	3.3	3.8	5.1	5.1	6.4
6 hours	5.1	6.4	7.6	8.9	10.2
12 hours	7.6	10.2	11.4	12.7	14.0
24 hours	10.2	12.7	14.0	15.2	17.8
2 days	12.7	17.8	19.0	20.3	22.9
4 days	20.3	22.9	25.4	25.4	25.4
7 days	22.9	25.4	30.5	38.1	38.1
10 days	30.5	33.0	35.6	38.1	45.7

WESTERN SLOPE OLYMPIC MOUNTAINS
RETURN PERIODS

Duration	2 Yrs.	5 Yrs.	10 Yrs.	25 Yrs.	50 Yrs.
30 minute	1.3	1.8	2.0	2.5	3.0
1 hour	1.8	2.5	3.0	3.6	3.6
2 hours	3.6	3.8	5.1	5.1	6.4
3 hours	5.1	6.4	6.4	7.6	8.9
6 hours	7.6	10.2	11.4	12.7	15.2
12 hours	12.7	15.2	17.8	20.3	20.3
24 hours	15.2	20.3	22.9	25.4	25.4
2 days	20.3	25.4	25.4	31.8	31.8
4 days	25.4	25.4	38.1	38.1	38.1
7 days	38.1	38.1	50.8	50.8	63.5
10 days	45.7	50.8	50.8	63.5	76.2

§Phillips and Donaldson, 1972.

Table II-5

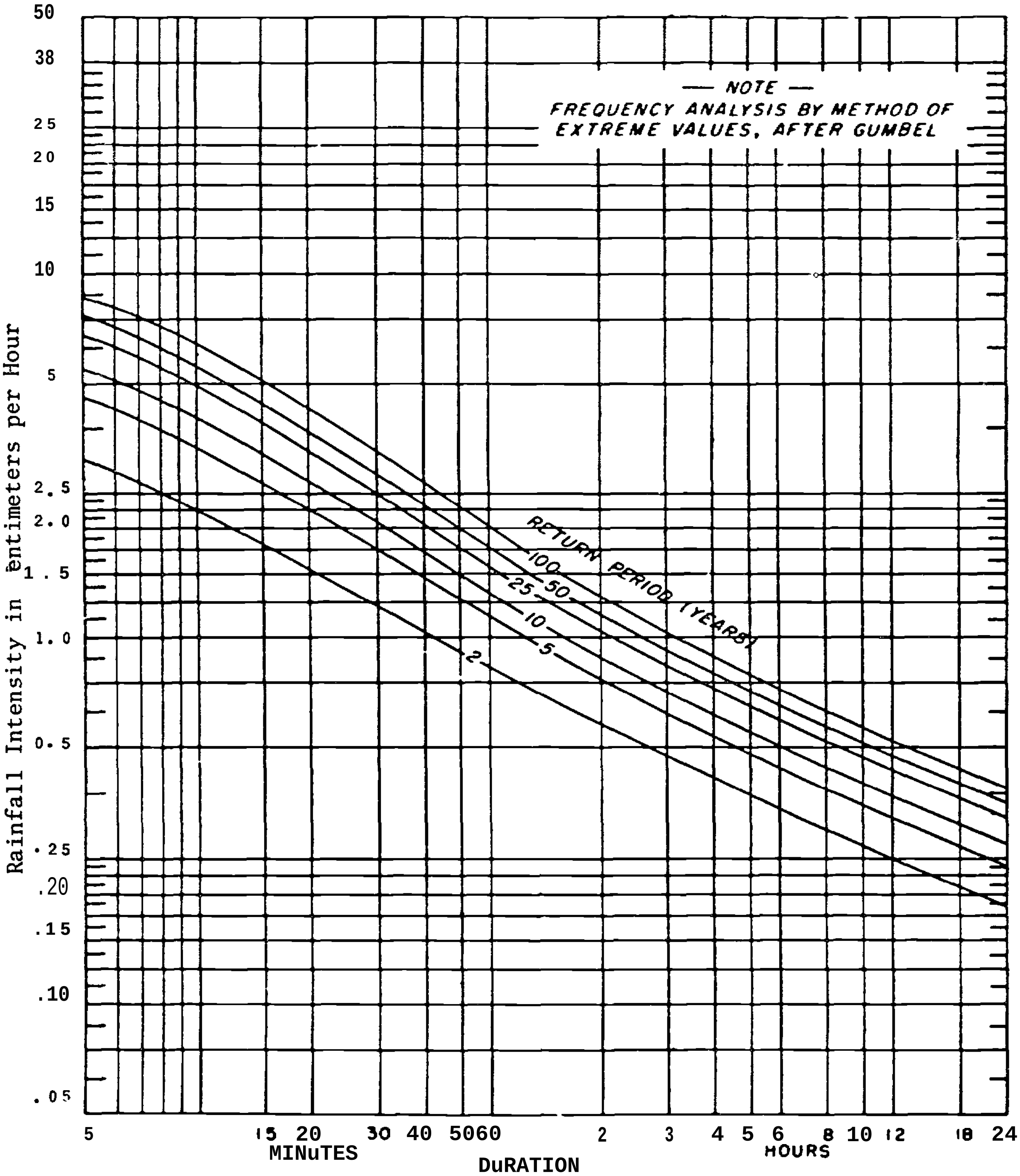
Snowfall: Greatest 1,2,3-day Totals (cm)
at Open Coast Stations[§]

Station	No. of Days	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Tatoosh Island	1	11.9	17.8	21.6	13.2	26.2	2.5
	2	12.2	17.8	24.6	16.5	43.4	.5
	3	16.3	18.8	25.1	16.8	49.3	.5
Aberdeen	1	12.7	15.2	22.9	12.7	10.2	.3
	2	12.7	20.3	30.5	20.3	17.8	.3
	3	15.2	25.4	38.1	20.8	22.9	.3
Clearwater	1	3.8	15.2	22.9	12.7	15.2	7.6
	2	7.6	16.5	38.1	15.2	21.6	7.6
	3	7.6	16.5	39.4	26.7	26.7	7.6

[§]Phillips and Donaldson, 1972.

Figure II-19

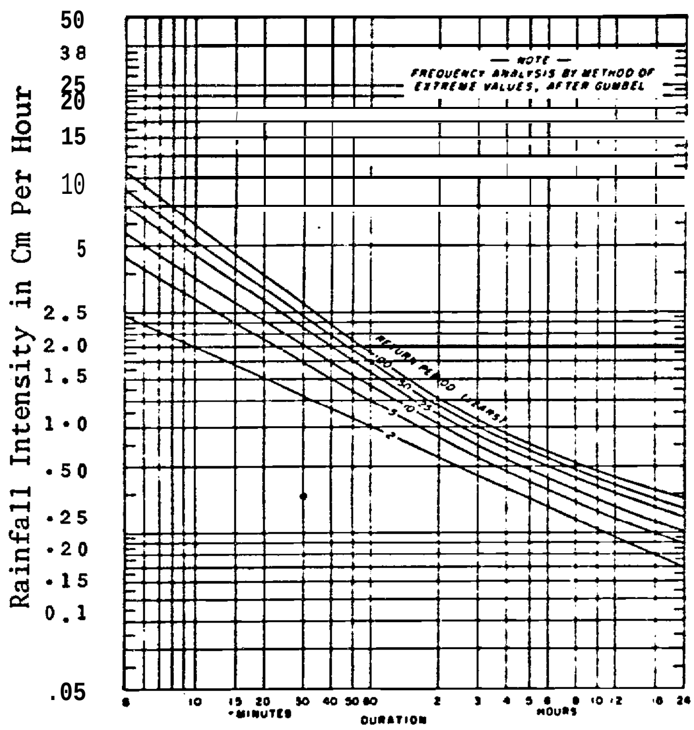
Rainfall Intensity (cm per hour) - Duration - Frequency Curves for Seattle (1903-1951)[§]



[§]Phillips, 1968.

Figure 11-20

Rainfall Intensity (cm per hour) - Duration - Frequency Curves for Port Angeles (1917-1932)[§]



§Phillips, 1968.

Table II-6

Rainfall Intensity (cm), Duration and Return Period[§]

PUGET SOUND LOWLANDS
Return Periods

Duration	2 Yrs.	S Yrs.	10 Yrs.	25 Yrs.	50 Yrs.
30 Minute	1.0	1.3	1.5	1.5	1.8
1 Hour	1.3	1.5	1.8	2.0	2.3
2 Hours	1.8	2.0	2.5	3.0	3.8
3 Hours	2.3	3.0	3.8	4.3	5.1
6 Hours	3.8	4.6	5.1	6.4	7.1
12 Hours	5.1	6.4	7.6	8.1	8.9
24 Hours	6.4	7.6	8.9	10.2	10.7
48 Hours	7.6	10.2	11.4	12.7	14.0
96 Hours	10.2	11.4	14.0	15.2	17.8

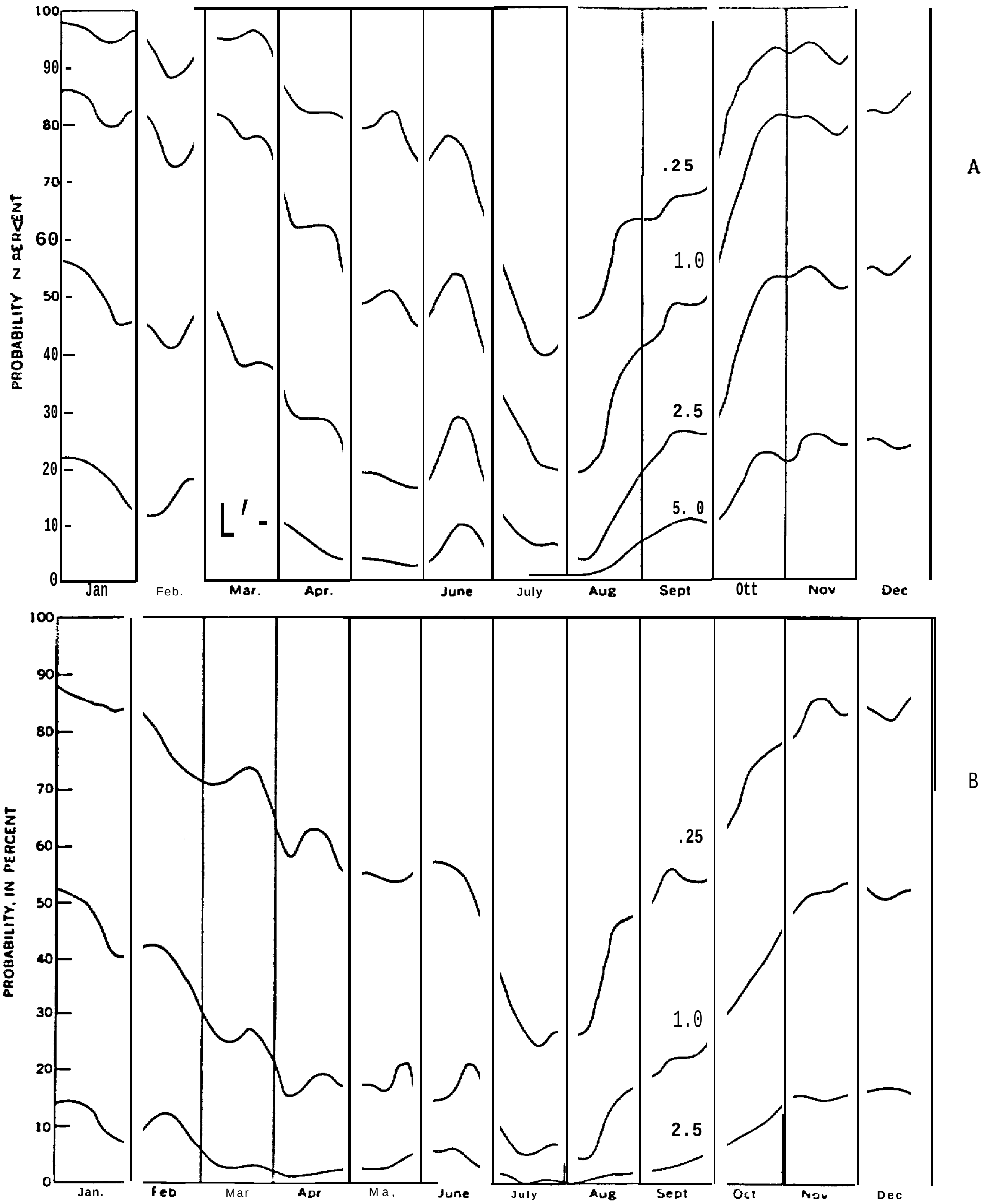
WEST SLOPE CASCADES, SE SLOPE OLYMPICS & FOOTHILLS
Return Periods

Duration	2 Yrs.	5 Yrs.	10 Yrs.	25 Yrs.	50 Yrs.
30 Minute	1.3	1.5	2.0	2.3	2.5
1 Hours	1.5	2.0	2.5	3.0	3.6
2 Hours	2.5	3.0	3.8	4.6	5.1
3 Hours	3.8	4.6	5.1	6.4	7.6
6 Hours	6.4	7.6	10.2	11.4	12.7
12 Hours	8.9	11.4	14.0	15.2	17.8
24 Hours	10.2	15.2	17.8	20.3	25.4
48 Hours	15.2	19.0	20.3	24.1	26.7
96 Hours	20.3	22.9	25.4	26.7	38.1

[§]Phillips and Donaldson, 1972.

Figure II-21§

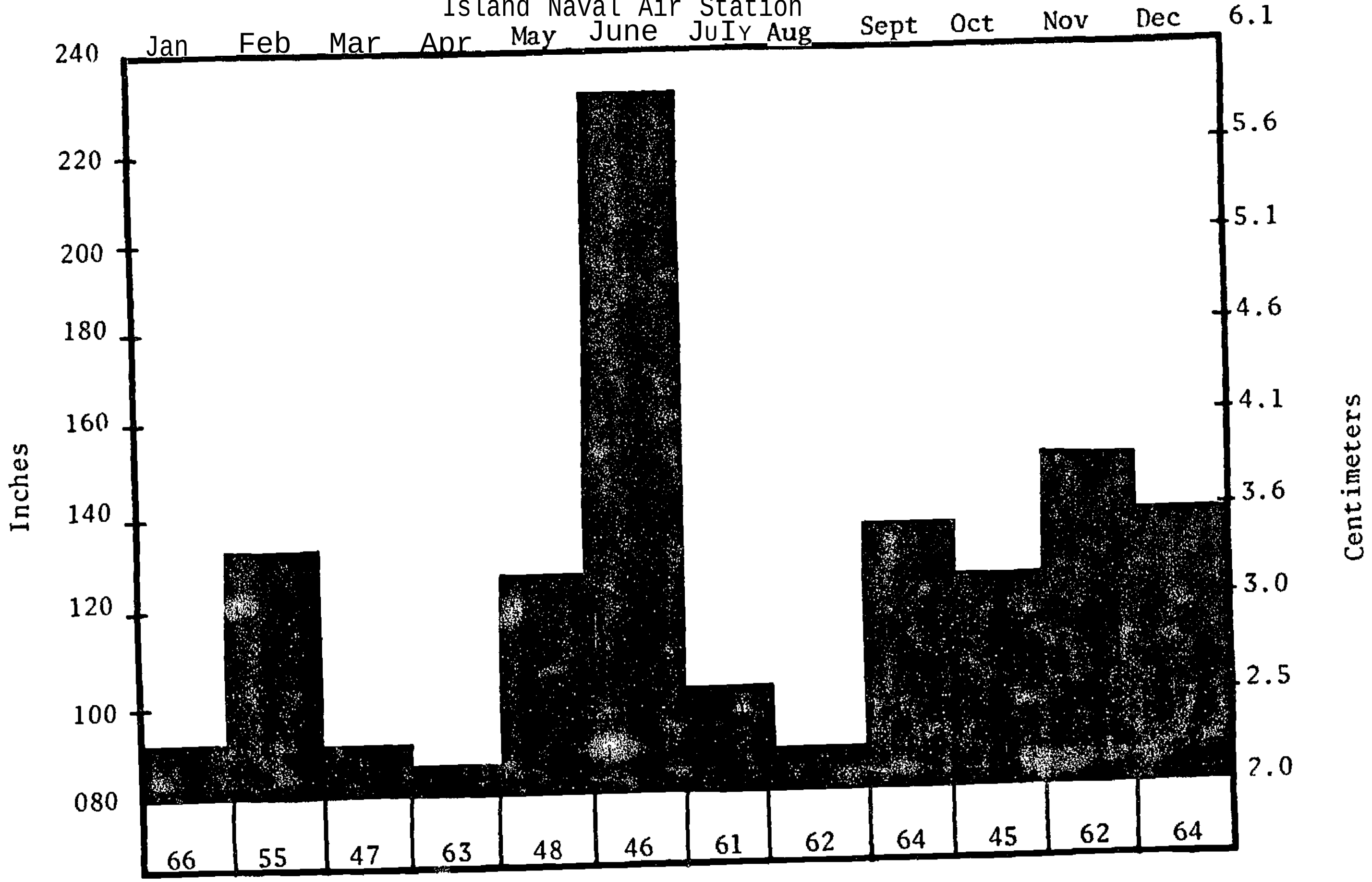
Probability of Receiving Various Amounts of Precipitation (cm) in 7 Days at Sedro Wooley (A) & Sequim (B) (1931-1960)



§ Pacific Northwest River Basins Commission. Puget Sound Task Force,, 1970.

Figure II-22

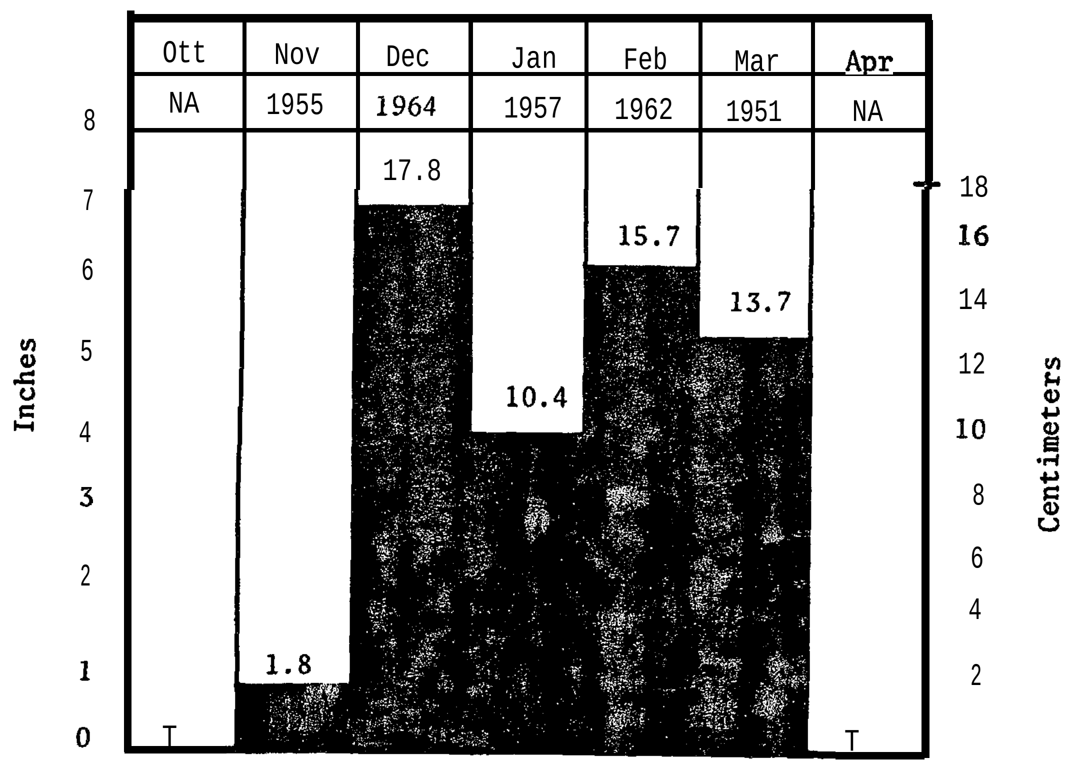
24 Hours Extreme Precipitation Values[§] for Whidbey Island Naval Air Station



§Halladay, 1970.

Figure II-23

24 Hour Extreme Snowfall Amounts for
Whidbey Island Naval Air Station[§]



[§]Halladay, 1970.

northerly flow in the northern regions of Puget Sound, a southerly flow in the southern regions, and a convergence zone where the flows meet in central Puget Sound. Vertical motion, gusty winds, clouds and sometimes precipitation are associated with the convergence zone which can form, migrate over central Puget Sound and dissipate in an apparently transient and random manner. Thunderstorms are occasionally associated with the convergence zone during unstable, post-frontal conditions.

4. Frontal Storms.

Frontal storms which affect the study area develop over the Pacific in conjunction with migrating low pressure areas. Many of these storms develop in the central Pacific and move rapidly in a northeastward direction into the Gulf of Alaska where they intensify and produce the Aleutian Low. The air flow about these low pressure centers is counterclockwise (cyclonic).

Fronts are narrow zones of transition between cold Arctic air flowing south-eastward around the low and warm, moist marine air drawn northward by the low. As the front moves along with the low pressure center, warm marine air is forced to rise over the more dense Arctic air along the front. This frontal lifting produces extensive belts of stratus clouds and precipitation which extend for several hundred kilometers southward and westward across the Pacific and often loop back to the north to connect with the next low pressure center in the central Pacific. Separate low pressure centers (waves) often form on the front and intensify as they travel along it, eventually moving eastward about the original (or steering) low. When a low stalls in the Gulf of Alaska, several successive waves can form and sweep their frontal zones across the coast, bringing prolonged periods of cloudiness, precipitation and strong winds to the study area.

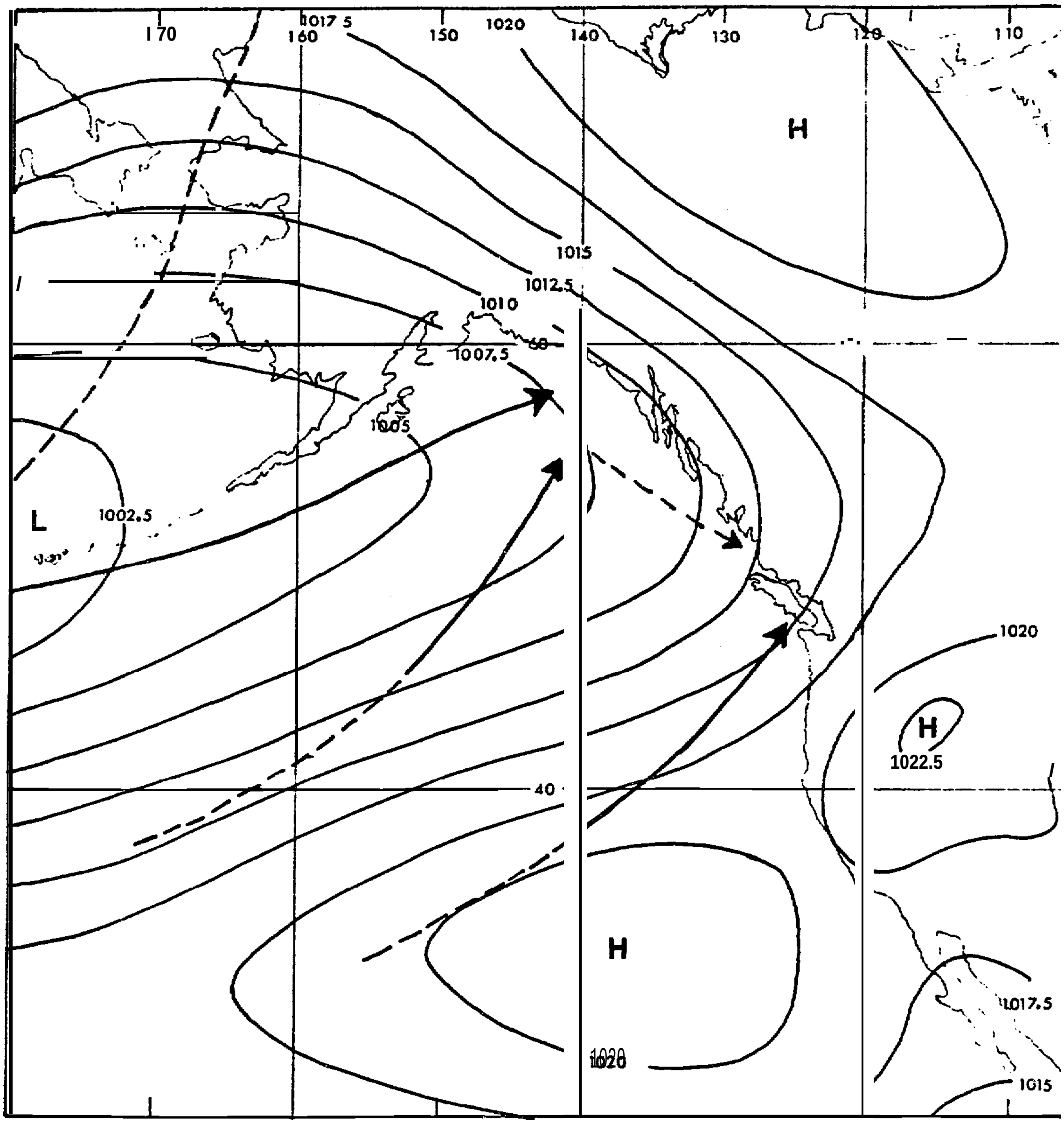
Preceding frontal passage, the air flow is generally southerly and brings moist marine air accompanied by low stratus, drizzle, and occasional fog to the study area. Intense storms can generate strong southeasterly winds with a long fetch and whip up seas of 3.7 m or more. As the front approaches the coast, the stratus layer deepens, precipitation intensifies, and winds become gusty. After frontal passage, the winds veer (turn clockwise) to the west, showers soon end, and temperatures drop. Brief periods of clearing may follow.

When a low pressure center moves directly through the study area the weather changes rapidly. The low center is preceded by a strong southeasterly to southwesterly flow that may reach gale force and whip seas to 6 m or more. Clouds and rain accompany the low center. After the low passes, winds veer to westerly or northwesterly and remain strong for awhile. The clouds soon break and temperatures can drop 5 degrees or more. A high pressure ridge may follow bringing periods of clear, cool, stable weather.

a. Storm Tracks. Low pressure centers appear to follow preferred pathways as they move across the eastern Pacific. During the winter, when the North Pacific High has receded to its most southerly location, the preferred path of storm centers also shifts to the south. Figure II-24 shows the mean surface pressure pattern for the eastern Pacific during January. Centers of high pressure are labeled H, low pressure centers are labeled L. Lines of constant pressure (isobars) are labeled in millibars. The solid lines

Figure II-24

Mean Surface Pressure Pattern and Surface Low Pressure Tracks for January[§†]



§U. S. Navy, 1958.
†Pressures are in millibars.

with arrowheads depict the preferred paths of surface low pressure centers moving across the eastern Pacific. The dashed lines represent secondary paths of lows. These storm tracks are based on all available data for sea level systems from 1866 to 1954. The arrowheads end in areas of maximum storm frequency where tracks may cross, branch, or merge. Primary tracks indicate those which are most frequent and well-defined. It must be kept in mind that frontal zones often extend for hundreds of kilometers to the south and west of the surface low pressure centers. Lows following these tracks can therefore affect the weather of the study area.

Figure II-25 shows storm tracks and the mean pressure pattern for July. A comparison with Figure II-24 clearly illustrates the summertime northward expansion of the North Pacific High and the resultant northward shift of the preferred storm tracks. In addition, summertime storms are usually less intense than those of the winter and their frontal zones rarely reach the study area.

b. Seasonal Frequency. Winter is the season of maximum storm frequency. Low pressure centers moving directly through the study area average 1.7 per month during the winter. The majority of these arrive from the west (29%) and southwest (26%) (U.S. Navy, 1958). Gale force winds generated by moving storms occur an average of three to five days per month and create 6.1 m seas 4% of the time during winter. Low centers arriving from the north (10%) are usually responsible for the occasional snowfalls in the study area. Frontal passage is considerably more frequent than the passage of low pressure centers and produces seas of 3.7 m or more 15 to 20% of the time during the winter season (National Ocean Survey, 1976).

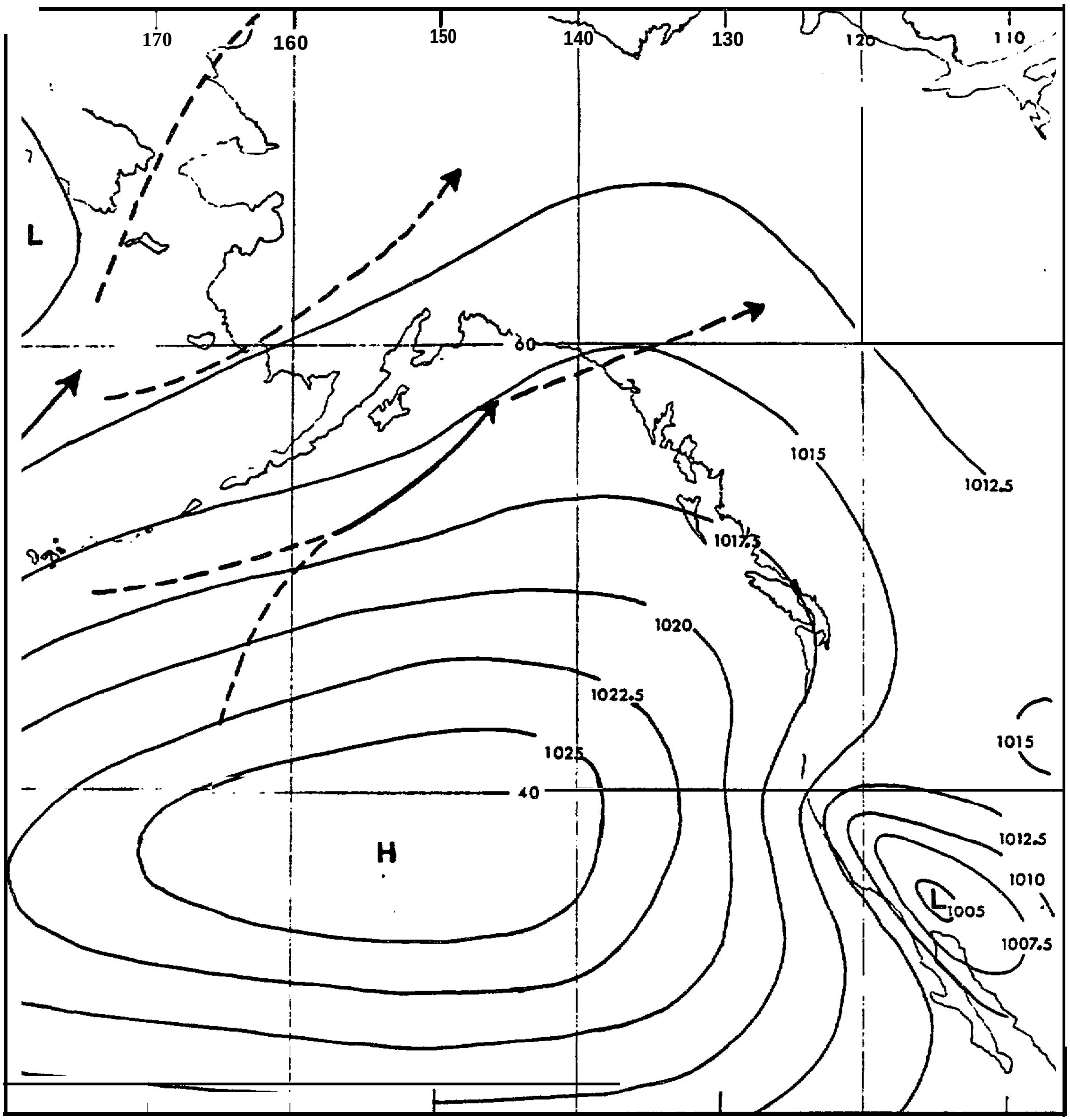
An analysis by Halter (1976) of four years of surface weather charts (1970-1973) used computer correlation? to determine the most frequent weather patterns occurring throughout the study area. During winter (October through March), the most frequent pattern consisted of a front in the vicinity of the coast and occurred 16.7% of the time. Skies averaged 80 to 90% cloud cover with this pattern. A prevailing westerly flow with a succession of weak frontal systems moving through the area occurred 9.1% of the time and brought 95% cloudiness during the morning, reducing to 65 to 85% cloudiness by the afternoon. A deep low located off the Olympic Peninsula was found to occur 7.4% of the time and was associated with 75 to 85% cloud cover.

As the North Pacific High expands during the spring, the increasingly weak and infrequent storms are forced northward into the Gulf of Alaska and the Bering Sea. However, storms occasionally penetrate the study area, particularly in the early spring. An average of 1.1 low centers per month move through the area, most from the west (36%) and southwest (26%) (U.S. Navy, 1958). These storms produce gales on an average of two days in March and rarely in April or May. Frontal passages produce seas of 3.7 m or more 15 to 20% of the time in March, 10% in April and 5% during May (National Ocean Survey, 1976). The warm southerly flow preceding frontal passage brings clouds and drizzle to the study area.

By June, penetration of the study area by storm centers is extremely rare and frontal passage is uncommon. Occasional storms moving into the Gulf of Alaska can still produce southwesterly winds and their associated stratus and drizzle in the study area. July and August are the most storm free months.

Figure II-25

Mean Surface Pressure Pattern and Surface Low Pressure Tracks for July[§†]



§U.S. Army, 1958.
†Pressures are in millibars.

The North Pacific High begins its southward retreat with the coming of fall and the storm tracks gradually shift to the south. In September, some storms move close enough to generate a southeasterly to southwesterly flow off the coast and to bring rain to the area 8 to 13% of the time. Gales blow an average of two to four days during September and generate 3.7 m seas 2 to 4% of the time (National Ocean Survey, 1976). By October and November storms become more frequent and intense, some moving directly through the area. An average of 0.9 low pressure centers penetrate the study area per month during the fall, 44% from the west and 21% each from the northwest and southwest (U.S. Navy, 1958). Gales blow on an average of 2 to 5 days in October and 3 to 6 days in November. These create 3.7 m seas 10 to 16% of the time. Rain falls along the coast 8 to 20% of the time in October and 16 to 30% of the time in November (National Ocean Survey, 1976). By December the winter pattern is in effect and the yearly storm cycle is complete.

c. Intensity and Duration. Storm intensity is a function of the pressure difference between the center of the storm and the surrounding area. It is best measured by the winds generated. Danielson, Burt and Rattray (1957), examined severe storms in the Gulf of Alaska (whose winds and waves can be expected to affect the study area) during 24 winters from 1922 through 1939 and 194S through 1952. Severe storms were defined as those with a geostrophic wind speed of 27 m/s or greater over 10° of fetch and appearing on two consecutive 24 hour weather charts. Fifty-nine severe storms meeting the above criteria were found. These were distributed as follows: 20 in November, 9 in December, 15 in January, and 15 in February. In addition, a very severe storm subcategory was established, requiring geostrophic wind speeds of 36 m/s for 5° of fetch on either of the two charts used above. Fifteen very severe storms were found: 5 in November, 5 in December, 2 in January, and 3 in February.

Severe storms were found to be grouped in particular years. Notably, no storms were severe enough to meet the criteria for the period January, 1935, to November, 1938, inclusive. On the other hand, the winters of 1932-33 and 1951-52 were considerably more severe than average. These storms were responsible for significant wave heights of 7.6 m to 10.7 m or greater, such as those which sunk the S.S. Pennsylvania, en route from Seattle to Yokohama, on January 10, 1952.

Severe storms in the Gulf of Alaska bring gales and high seas to the study area. As discussed above, gales can be expected on 3 to 5 days per month during the winter, 2 days during March, and 2 to 6 days per month in the fall. Seas of 6.1 m or more associated with these gales are not uncommon.

The Marine Climatic Atlas (U.S. Navy, 1958) employs an intensity rating system for low pressure centers based on the pressured difference between the low center and that estimated for a circle 563.2 km away from the center. Storms in the 10° by 10° square enclosing the study area from 1924 through 1938 averaged a 10.3 rating during the winter (the range over the Pacific was 8.7 to 12.7). The rating fell to 8.2 during the spring and 7.8 in the fall.

Storm duration depends on the speed at which the low center moves through the area. Most storms pass the coast in less than 24 hours, moving at an average rate of 9.1 to 14.7 m/s. Storms which approach from the north or south (an average of about 18% of the storms passing through the study area) generally move more slowly (averaging 5.1 to 8.1 m/s) and affect the weather for a longer period (U.S. Navy, 1958). Occasional storms will pass to the north and trail their frontal zones across the study area for two days or more. These occur when there is a fairly strong south to north pressure gradient. When a low stalls in the Gulf of Alaska, a succession of frontal systems or waves may affect the area for up to a week or more, with only brief periods of clearing between fronts. The maxim number of days between frontal storms averages S to 6 each month during the winter (Locatelli, 1976). However, these days are rarely free from a southerly flow and associated stratus and drizzle produced by storms further to the west.

5. Winds.

a. Seasonal Prevailing Wind. The prevailing wind direction for any season is determined by the positions of the Aleutian Low and North Pacific High. Counterclockwise flow-around a low pressure center results in generally westerly and southwesterly winds during winter. Figure II-26 and II-27 show surface wind roses for January for several locations.

In summer, when the North Pacific High is in a more northerly position, clockwise flow around it produces westerly and northwesterly winds. Figures II-28 and II-29 show surface wind roses for July for several locations. Figures 11-30 and 11-31 show annual wind roses for the station.

Meteorologists use the convention that the direction of wind is the direction from which the wind blows. For example, a westerly wind blows from the west and toward the east. Wind speeds are often recorded in miles per hour (mph) or in knots (nautical miles per hour). In this chapter, the units of wind speed will be converted to meters per second for consistency.

Most wind observations are taken on land, so that wind speed and direction over the water must be estimated. Winds over the water are generally faster than over land. The main reasons for this are that the frictional force between air and water is less than the frictional force between air and land surfaces, and the surface of the water is generally flat compared to the land surface.

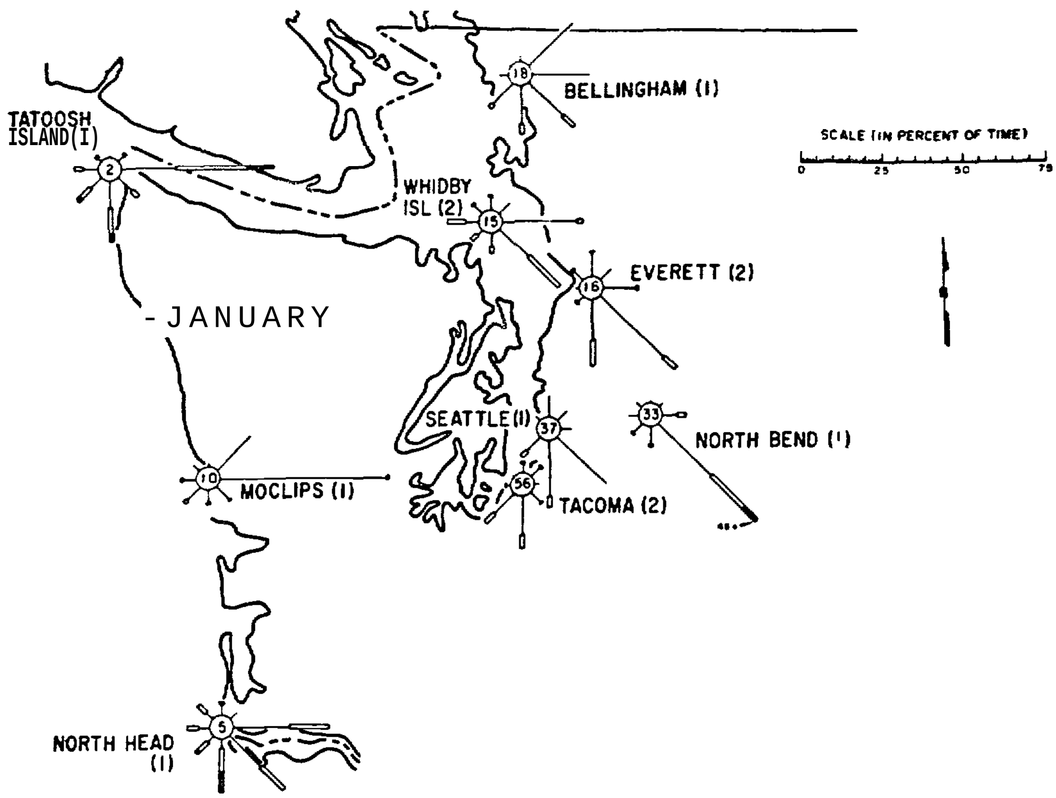
A maximum sustained windspeed is defined as having a duration (≥ the given speed) of approximately 1 minute though the average time for most marine observations is more than 1 minute. Peak gusts (duration usually less than 20 seconds) frequently occur and average 1.4 times the sustained windspeed. The gusts are important to aviation and research activities, but are generally too short in duration to be of significance to ships or to maritime structures (Quayle and Fulbright, 1975).

i. Seasonal Prevailing Wind - Open Coast. In winter, circulation of air around the low centers approaching the coast results in a high frequency of strong southeasterly and southerly winds. The stronger winds are associated with more intense winter storms. During spring and summer, wind direction shifts to the west and northwest. Wind speeds are generally lower than in winter.

ii. Seasonal Prevailing Wind - Inland Waters. During winter, winds

Figure II-26

Surface Wind Roses for Washington Stations for January§



The length of the wind rose speed-direction bars, measured by the scale, indicates the percent of time wind was from the direction and in the speed class represented. An exception is speed of 4.8km per hour or less. Percent of speeds in this range is shown in the center circle of the wind rose. Various sources of data made it necessary to assign slightly different speed classes to the wind roses. The figure following the station name is an index to the speed class for that station and is defined in the legend.

LEGEND

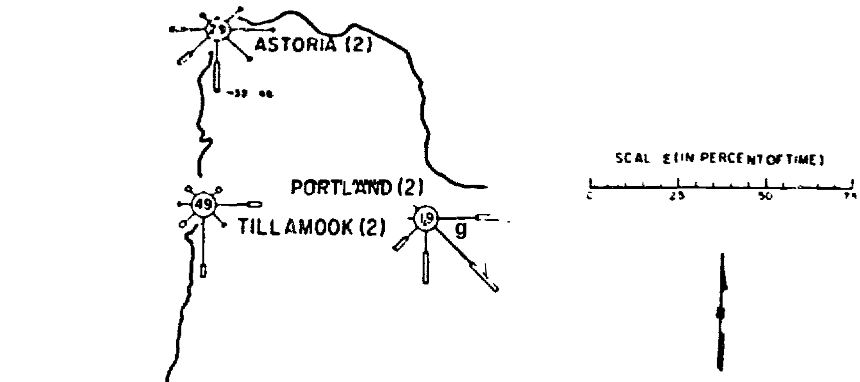
SPEED SYMBOL	INDEX NUMBER AND SPEED CLASSES			
	Index	Class	Index	Class
	(1)	4-15	(2)	4-21
	(1)	16-31	(2)	13-31
	(1)	32-47	(2)	32-46
	(1)	48+	(2)	47+

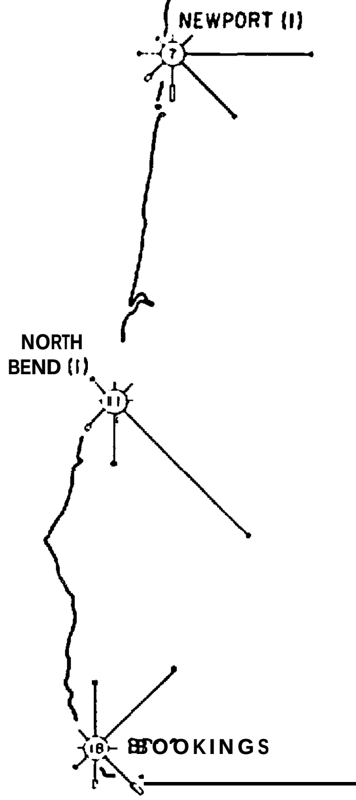
⑤ For this class all stations have the same range of 4.8km.

§Phillips, 1968.

Figure II-27

Surface Wind Roses for Oregon Stations for January[§]





The length of the wind rose speed-direction bars, measured by the scale, indicates the percent of time wind was from the direction and in the speed class represented. An exception is speeds of 4.8km per hour or less. Percent of speeds in this range is shown in the center circle of the wind rose. Various sources of data made it necessary to assign slightly different speed classes to the wind roses. The figure following the station name is an index to the speed class for that station and is defined in the legend.

LEGEND

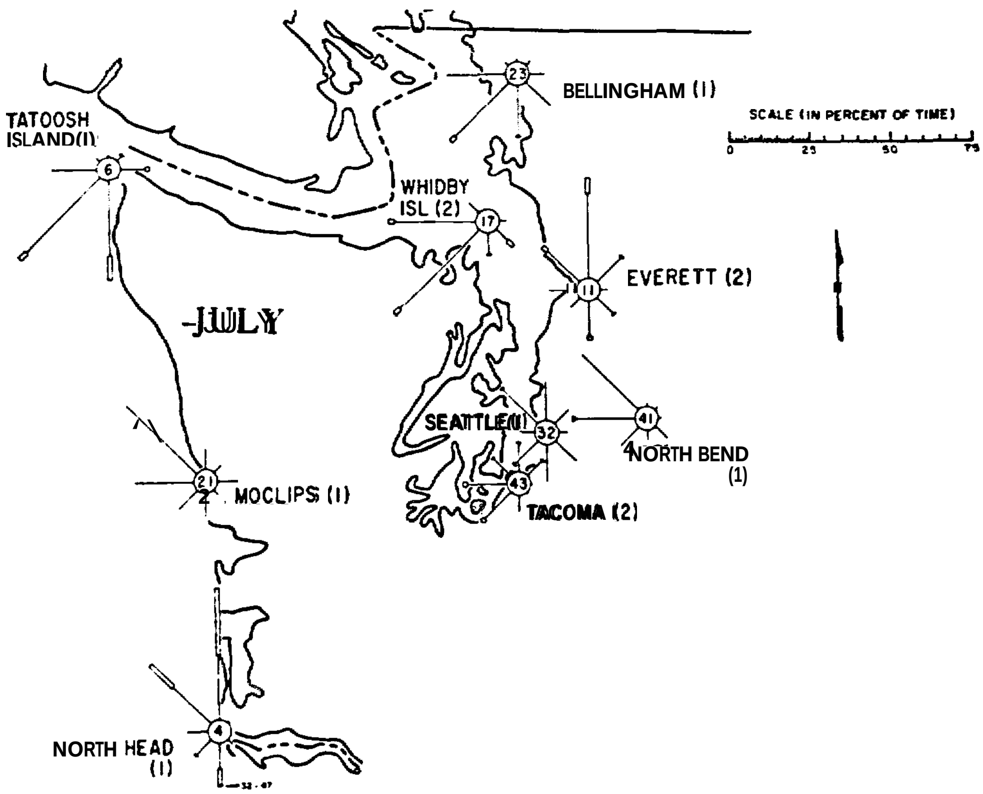
SPEED SYMBOL	INDEX NUMBERS AND SPEED CLASSES Index	Class	Index	Class	Index	Class
—	(1)	4-15	(2)	4-12	(3)	4-17
(open bar)	(1)	16-31	(2)	13-31	[3)	18-35
(hatched bar)	[1)	32-47	(2)	32-46	(3)	36-53
(solid bar)	(1]	48+	(2)	47+	(3)	54+

⑤ For this class all stations have the same range of 4.8km.

§U.S. Weather Bureau, 1965.

Figure II-28

Surface Wind Roses for Washington Stations for July[5]



The length of the wind rose speed-direction bars, measured by the scale, indicates the percent of time wind was from the direction and in the speed class represented. An exception is speed of 4.8km per hour or less. Percent of speeds in this range is shown in the center circle of the wind rose. Various sources of data made it necessary to assign slightly different speed classes to the wind roses. The figure following the station name is an index to the speed class for that station and is defined in the legend.

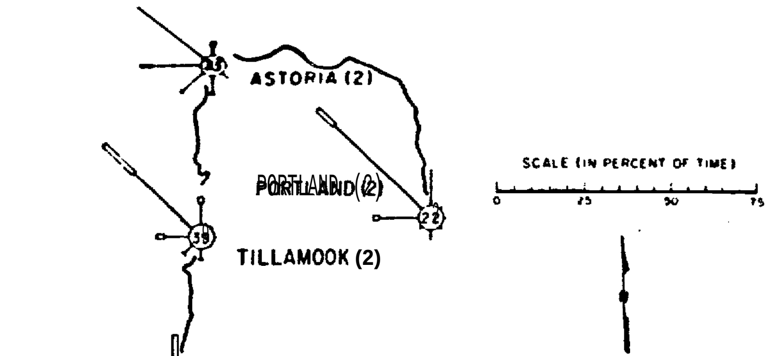
LEGEND	SPEED SYMBOL	INDEX NUMBER AND SPEED CLASSES			
		Index	Class	Index	Class
	thin line	(1)	4-15	(2)	4-21
	open bar	(1)	16-31	(2)	13-31
	solid bar	(1)	32-47	(2)	32-46
	heavy solid bar	(1)	48+	(2)	47+

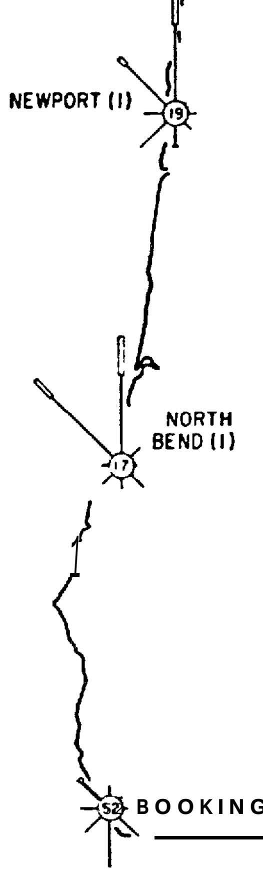
⑤ For this class all stations have the same range of 4.8km.

[5] Phillips, 1968.

Figure II-29

Surface Wind Roses for Oregon Stations for July§





The length **of** the wind rose speed-direction bars, measured by the scale, indicates the percent of time wind was from the direction and in the speed class represented. An exception is speeds of **4.8km** per hour or less. Percent of speeds in this range is shown in the center circle of the wind rose. Various sources of data made it necessary to assign slightly different speed classes to the wind roses. The figure following the station name is an index to the speed class for that station and is defined in the legend.

LEGEND

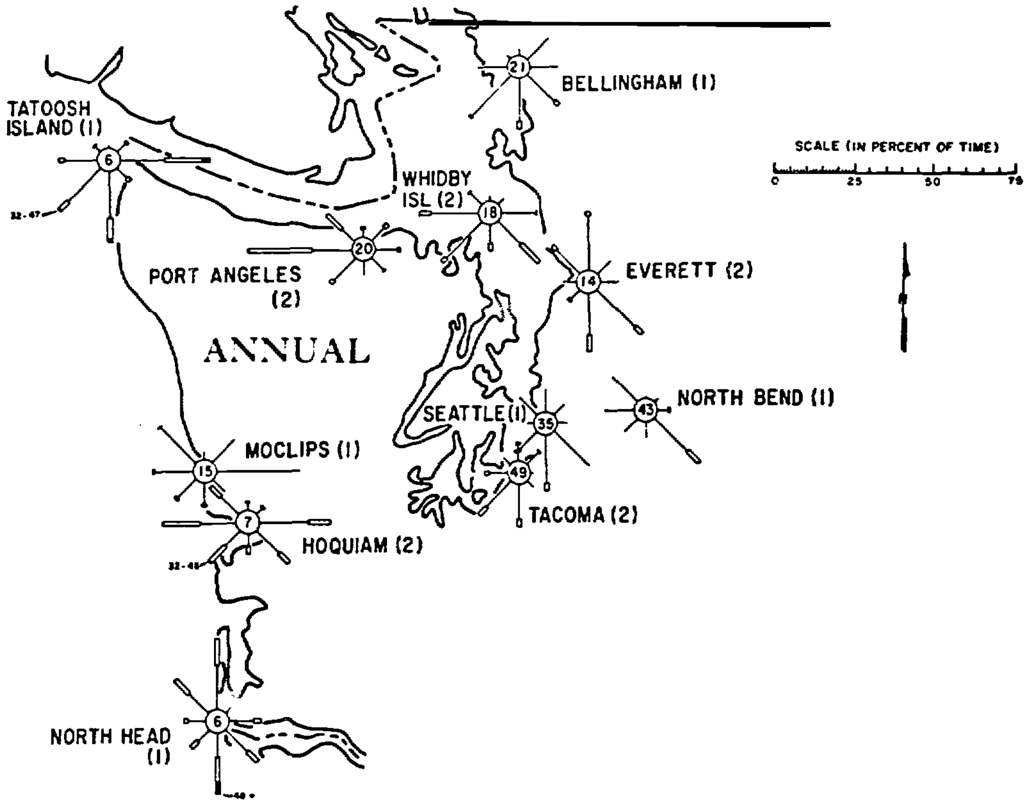
SPEED SYMBOL	INDEX NUMBERS AND SPEED CLASSES Index	Class	Index	Class	Index	Class
(thin line)	(1]	4-15	(2)	4-12	(3)	**4-17**
(open bar)	(1]	**16-31**	(2)	13-31	(3]	18-3S
(hatched bar)	(1)	32-47	(2)	32-46	(3)	36-53
(solid bar)	(1]	48+	(2)	47+	(3)	54+

⑤ **For this** class **all stations** have the same range of **4.8km.**

§U.S. Weather Bureau, 196S.

Table II- 30

Annual Surface Wind Roses for
Washington Stations[§]



The length of the wind rose speed-direction bars, measured by the scale, indicates the percent of time wind was from the direction and in the speed class represented. An exception is speed of 4. 8km per hour or less. Percent of speeds in this range is shown in the center circle of the wind rose. Various sources of data made it necessary to assign slightly different speed classes to the wind roses. The figure following the station name is an index to the speed class for that station and is defined in the legend.

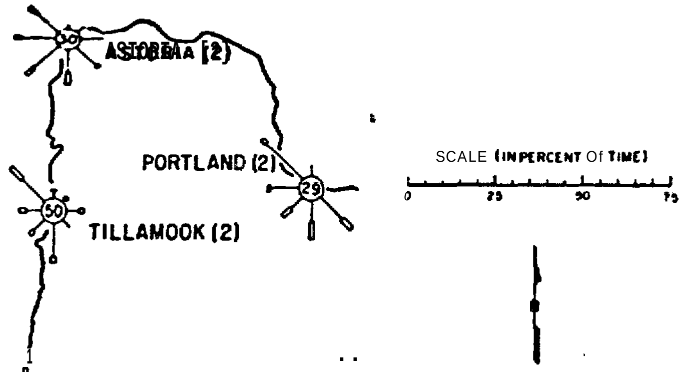
LEGEND	SPEED SYMBOL	INDEX NUMBER AND SPEED CLASSES			
		Index	Class	Index	Class
		(1)	4-15	(2)	4-21
		(1)	16-31	(2)	13-31
		(1)	32-47	(2)	32-46
		(1)	48+	(2)	47+

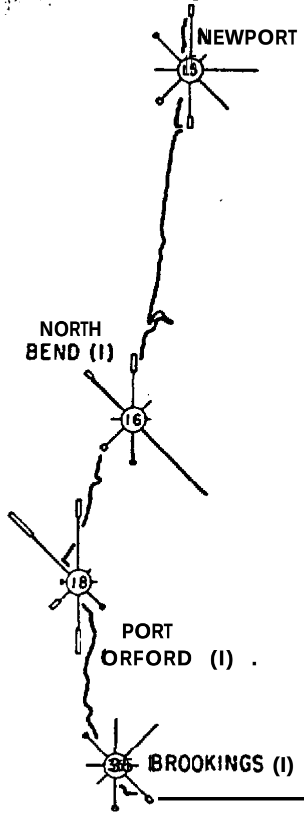
(5) For this class all stations have the same range of 4.8km.

§Phillips, 1968.

Figure II-31

Annual Surface Wind Roses
for Oregon Stations§





The length of the wind rose speed-direction bars, measured by the scale, indicates the percent of time wind was from the direction and in the speed class represented. An exception is speeds of 4.8km per hour or less. Percent of speeds in this range is shown in the center circle of the wind rose. Various sources of data made it necessary to assign slightly different speed classes to the wind roses. The figure following the station name is an index to the speed class for that station and is defined in the legend.

LEGEND

SPEED SYMBOL	INDEX NUMBERS AND SPEED CLASSES Index	Class	Index	Class	Index	Class
	(1]	4-15	(2]	4-12	(3)	4-17
	(1)	16-31	(2)	13-31	(3)	18-35
	(1)	32-47	(2]	32-46	(3)	36-53
	(1)	48+	(2)	47+	(3)	54+

Ⓢ For this class all stations have the same range of 4.8km.

§U.S. Weather Bureau, 1965.

are generally southerly and southwesterly. Along the open coast, strong winds occur during the passage of intense winter storms. Winds are relatively light during the summer months, and they generally come from the north or northwest.

b. Severe Winds.

i. Severe Winds - Open Coast. Wind velocities ranging from 22 to 29 m/s are reported each winter. Brief records from an exposed ridge (elevation 610 m) near Naselle indicate that wind velocities in excess of 45 m/s occur on the higher exposed ridges almost every winter. The fastest wind recorded at the North Head Light House Reservation in a 41 year period was 50.6 m/s in January, 1921. Tatoosh Island has a record high wind of 42.1 m/s from the south in November, 1942 (Phillips and Donaldson, 1972). Rogers (1966) reported winds gusting up to 47 m/s using data from an oil rig off the Oregon coast.

Quayle and Fulbright (1975) have estimated return periods of extreme winds using existing climatological data. They define a mean return period as "the average number of years between successive occurrences of values greater than or equal to some threshold value". See Table II-7 and Figure II-32 for return periods for various wind speeds.

ii. Severe Winds - Inland Waters. Intense storms can produce winds of 20.3 m/s, with 25.4 m/s gusts. Usually the winds are southerly.

Along the Strait of Georgia, the strongest winds recorded are from south to southeast ahead of a front. A particularly violent wind storm occurred on March 30, 1975 as a cold front swept southward from the northern Gulf of Alaska. Southeasterly winds with speeds generally less than 10.2 m/s shifted abruptly to northwest behind the cold front and, at times, reached speeds of over 30.5 m/s. Such storms are relatively rare but can be very dangerous when they occur since they develop almost instantaneously and are difficult to forecast (Guenther and Faulkner, 1976).

The record high wind at Port Angeles, set in December, 1951, was at 26 m/s from the east (Phillips and Donaldson, 1972). At Whidbey Island Naval Air Station, the record peak gusts were from the south-southeast at 31 m/s. This occurred in both October and November, 1945 (Halladay, 1970). In Seattle, the highest sustained wind recorded was 28.5 m/s with gusts to 30.5 m/s (National Ocean Survey, 1976).

c. Local Effects. Local conditions modify both the prevailing flow of air and the wind shift associated with the passing of frontal systems. Topographical features such as hills and valleys can channel wind to change its direction or act as barriers to reduce or increase wind speed or to divert the wind.

Areas near shorelines are affected by land and sea breezes. These breezes tend to make the flow onshore and offshore, thus affecting both direction and speed. A sea breeze develops during the afternoon. The sun warms the land more than the water, and, in turn, the air over land becomes warmer than the air over the water. The air over land rises and is replaced by air from over the water. This creates an onshore flow. At night, a land

Table II-7

Extreme Sustained WindsReed Estimates (in ms^{-1})
for Specific Return Periods for the Open Coast[§]

Area[†]	5 Yr.	10 Yr.	25 Yr.	50 Yr.	100 Yr.
28	34	36	41	44	48
29	33	36	41	44	48
30	33	36	40	44	47
31	29	32	36	39	42

‘Quayle and Fulbright, 1975.

[†]Area numbers refer to Figure II-32.

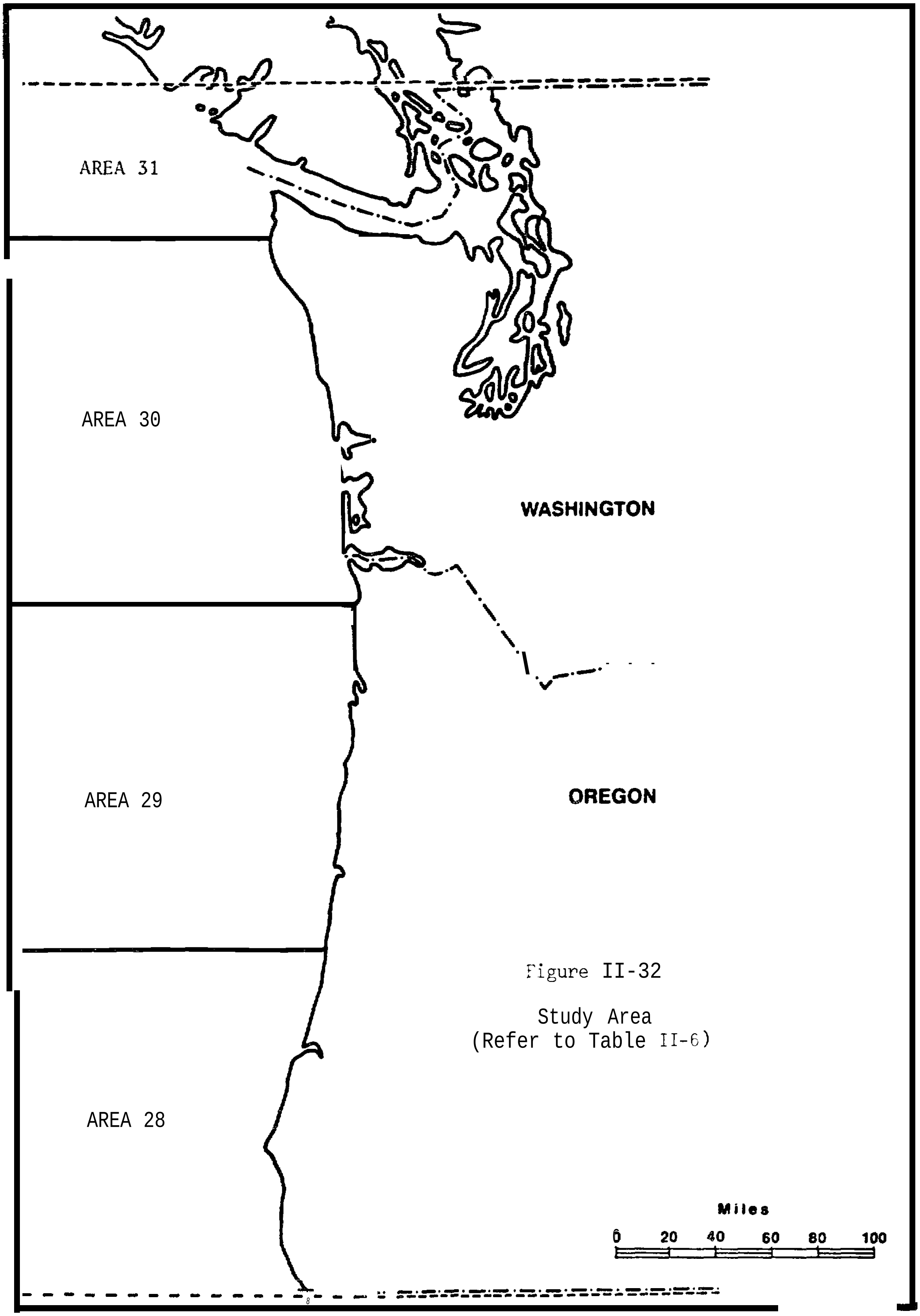


Figure II-32

Study Area
(Refer to Table II-6)

breeze develops because the water cools more slowly than the land. Therefore the air over the water tends to rise and is replaced by air from over the land. This is referred to as an offshore flow.

The location with respect to storm tracks is also a factor since the winds blow in a fairly circular fashion around the center of the low. For example, a more northerly station would frequently experience easterly and southeasterly winds while a station farther south would be more likely to have southerly winds.

i. Local Effects - Open Coast. The mountains running parallel to the open coast produce two major local effects in winter. These mountains act as a barrier and force southwesterly winds from the ocean to shift to southerly, also, cold air from higher elevations drains seaward through the mountain valleys, resulting in a high frequency of low velocity easterlies.

On most summer afternoons, the northwesterly winds are modified to a small extent by the sea breeze. However, since wind velocities associated with sea breezes are usually small, the predominant wind direction in summer is northwesterly.

ii. Local Effects - Inland Waters. The northwest-southeast orientation of the Strait of Georgia, the Coastal Range, and Vancouver Island forces surface winds to blow generally northwesterly or southeasterly.

In winter, the air over the land mass of the mainland of western Canada is generally colder than the air over the water. The cold air tends to drain toward the sea through the valleys and fjords of the Coast ranges. Northerlies or northeasterlies or "Squamishes" occur so frequently, particularly in January, that the prevailing wind direction in the southern Strait of Georgia (e.g., Saturna Island) is northeasterly (Guenther and Faulkner, 1976).

The strongest winds in the Strait of Georgia generally occur in advance of a Pacific front. A pattern frequently repeated is as follows: a Pacific frontal system in a generally north-south line approaches the coast from the west. As it does so, easterly or southeasterly winds increase, reaching their peak, often gale strength or greater, just ahead of the front. After the frontal passage, winds veer (turn clockwise) to the south or southwest, slacken and gradually return to their usually easterly or southeasterly direction. However, if the front is accompanied by a very sharp trough of low pressure (as is often the case), after the frontal passage winds may veer sharply to the northwest for a few hours. They then gradually abate and slowly revert to easterly (Guenther and Faulkner, 1976).

During summer, the winds blow westerly through the Strait of Juan de Fuca. As they reach the southern end of Vancouver Island, they turn northward, rounding the tip of Vancouver Island. Thus a southwesterly flow prevails in the southern extremity of the Strait of Georgia (Harris and Rattray, 1954).

The winds in the Strait of Juan de Fuca are confined generally to easterly or westerly due to the configuration of the land -- Vancouver Island to the north and the Olympic Mountains to the south channel the winds. On many occasions, strong easterly winds (greater than 22.4 m/s) have been observed at Tatoosh Island while other stations such as Port Angeles or Seattle were having less severe winds. Reed (1931) proposed that since the winds could not be explained by pressure or temperature gradients, they must be caused by the converging walls of the Strait of Juan de Fuca. The contracting channel acts like a Venturi tube and increases the speed of the wind.

The counterclockwise flow of air around the winter storms produces mostly easterly winds in the Strait of Juan de Fuca in the winter. Ahead of a front, the winds are easterly. After the front passes, the winds turn westerly but soon after become easterly again. Occasional outbreaks of cold continental air will also cause easterly winds in the strait. The average January Strait of Juan de Fuca windspeed is 10.2 m/s (National Ocean Survey, 1973).

During the summer, winds through the Strait are westerly with speeds up to 7.6 m/s in the afternoon. T'he sea breeze in the afternoon reinforces the prevailing westerly flow. At night, winds die down as the land breeze opposes the prevailing flow (National Ocean Survey, 1976) .

The Cascade and Olympic Mountains form a north-south channel for winds in the San Juan Islands area and Puget Sound. In winter, when frontal storms pass through the area, winds are generally southeasterly in northern locations and southerly in southern Puget Sound.

Some local conditions will modify the wind shift pattern associated with the passage of fronts. For instance, at Whidbey Island, there is usually no wind shift. The winds preceding the front are very strong from the southeast and after the front still come from the southeast but with less speed. When a wind shift to the west does occur, the air mass is unstable (likely to produce strong convection), and gusty winds to about 25.4 m/s are frequently recorded.

Cold continental air will occasionally spill over the Cascade range resulting in cold northerly or easterly winds.

Westerly and northwesterly prevailing winds of summer are modified by smaller scale effects. In a typical 24 hour period in summer on Puget Sound and in the San Juan Islands, the wind will be light and variable at night, increasing to west-southwest, 4 to 6 m/s in the later forenoon with the onset of the sea breeze. The winds become light and variable again after nightfall (Halladay, 1970).

6. Cloud Cover and Visibility.

Due to the predominant onshore flow of moist marine air during all seasons, and the relatively high frequency of frontal storm passage during winter months, cloud cover is a regular feature of the study area. At both open coast and inland water stations, cloudy skies (80 to 100% cloud cover) are reported on about one half the days of the year.

It is well to remember that clouds are formed during the cooling of moist air. Such cooling is generally the result of adiabatic expansion which takes place when air is lifted to higher levels, but also occurs when air flows over a relatively cold surface. The convective lifting of discrete parcels, or bubbles, of air which results from solar heating of the surface, produces relatively small fluffy clouds called cumulus. Stratus clouds are formed when extensive layers of air are forced to rise or are cooled from below and produce the grey overcast which is so common in the Pacific Northwest.

a. Marine Stratus. Marine stratus is the predominant type of cloud cover in the study area. It forms when extensive layers of relatively warm, moist marine air are cooled. Both orographic lifting, which results from air flowing over a significant topographic feature, and frontal lifting, which occurs when relatively warm air is forced to rise over a colder air mass, are responsible for the adiabatic cooling necessary for the formation of marine stratus. In addition, the flow of marine air over colder coastal waters of the California current and coastal upwelling regions can produce a marine stratus layer.

When the North Pacific High dominates the study area during the summer months, large scale atmospheric subsidence inhibits lifting and results in the most cloud free season of the year. However, marine stratus can and does form during the summer by the cooling marine air flowing over cold coastal waters and as a result of orographic lifting during those periods when the North Pacific High weakens. The high frequency of frontal passage during the winter months makes winter the cloudiest season.

i. Marine Stratus - Open Coast. Marine stratus is the predominant cloud cover of the open coast. Summer is the clearest season, winter the most cloudy. There is little difference in the number of cloudy days per year recorded from one station to another along the open coast. The differences observed are generally the result of local topography which influences the formation of radiation fog and sea fogs discussed below. There is a slight tendency for marine stratus to be somewhat less extensive in the southern portion of the coast due to the slightly reduced frequency of frontal storm passage in this area.

Clear or partly cloudy days (0 to 70% cloud cover] average 12 to 18 days per month during the summer and decrease to an average of only 4 to 7 days per month during the winter. Spring and fall average from 8 to 15 clear or partly cloudy days per month (Phillips and Donaldson, 1972). Table II-8 gives the average number of days per month with clear, partly cloudy, and cloudy skies for Tatoosh Island, Hoquiam, North Head and Astoria.

There is also a diurnal variation of cloud cover along the open coast. Marine stratus, particularly when formed by air passage over cold coastal surfaces, often forms at night when surface cooling creates an inversion which prevents the vertical mixing of air near the surface. Such stratus gradually dissipates during the day as solar heating warms the surface layer and allows more extensive vertical mixing. Marine stratus formed by frontal lifting is not usually subject to this diurnal variation. Table II-9 shows the variation in cloud cover by hour for Hoquiam.

ii. Marine Stratus - Inland Waters. Marine stratus predominates over the inland waters. Clear skies are somewhat more common here than at open coast locations, particularly during the summer months, as a

Table II-8

Mean Number of Days with Clear, Partly Cloudy, and Cloudy Skies From Sunrise to 'unset at Open Coast Stations§

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Tatoosh Island												
Clear (0 to 30%)	4	5	5	5	5	4	6	5	7	6	3	3
Partly Cloudy (40 to 70%)	4	4	6	6	8	9	8	8	7	6	5	5
Cloudy (80 to 100%)	23	19	20	19	18	17	17	18	16	19	22	23
Hoquiam												
Clear	5	5	7	7	8	5	10	11	12	9	5	5
Partly Cloudy	2	3	4	4	4	4	3	3	3	3	3	2
Cloudy	24	20	20	19	19	21	18	17	15	19	22	24
North Head												
Clear	4	5	5	5	5	5	7	7	8	7	5	4
Partly Cloudy	5	5	8	9	10	9	9	9	8	7	5	6
Cloudy	22	18	18	16	16	16	15	15	14	17	20	21
Astoria												
Clear	3	3	3	3	3	3	6	7	9	5	3	2
Partly Cloudy	3	3	5	5	8	7	10	9	7	7	5	4
Cloudy	25	22	23	22	20	20	15	15	14	19	22	25

§Phillips, 1972 and U.S. Environmental Data Service, 1930-76.

Table II-9

Percent Frequency of Cloudy Skies (80-100% coverage) by Hour and Month from Hoquiam§

	Jan.	Feb.	Mar.	Apr.	May.	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
00	73	71	59	41	40	46	25	26	33	61	71	75
01	72	72	61	44	41	49	28	30	36	60	70	79
02	75	73	62	48	44	52	29	36	40	64	71	77
03	75	75	62	51	46	57	38	39	43	70	75	78
04	75	73	65	50	53	63	49	49	49	71	75	77
05	78	77	71	59	61	66	58	59	58	71	77	79
06	77	78	74	65	63	68	63	65	61	77	79	79
07	81	82	76	68	64	72	65	65	64	78	83	84
08	85	84	77	66	64	71	60	63	63	79	86	84
09	84	84	77	69	65	72	57	59	60	77	83	85
10	82	84	80	69	64	71	54	55	55	76	84	86
11	83	83	79	69	64	72	49	51	52	72	80	85
12	82	80	78	68	65	67	44	49	44	70	79	83
13	83	79	75	69	64	66	38	48	44	63	78	85
14	82	79	75	68	63	62	36	42	44	60	78	85
15	82	78	74	63	58	61	34	38	42	61	77	85
16	81	78	73	62	56	61	31	36	41	58	77	85
17	81	73	73	61	53	.56	25	34	38	58	76	82
18	77	69	71	58	52	54	23	30	37	56	69	75
19	76	65	65	56	51	51	23	28	36	51	66	77
20	74	62	62	46	45	49	24	26	31	50	69	73
21	74	66	61	44	41	46	22	23	30	53	71	75
22	75	65	60	42	40	42	20	25	31	58	69	76
23	74	67	61	42	39	42	23	23	31	59	70	75
Range	13	22	21	28	26	30	45	42	34	29	20	13

§Phillips and Donaldson, 1972.

result of the shielding effect of the coastal mountains from an onshore marine flow. Frontal storm passage brings cloud cover to the inland waters similar to that at open coast locations and makes winter the season with the fewest clear days. Clear or partly cloudy days average 15 to 22 days per month during the summer and decrease to an average of only 4 to 7 days per month during the winter. Spring and fall average 10 to 15 clear or partly cloudy days per month (Phillips, 1968). Table 11-10 shows the mean number of clear, partly cloudy, and cloudy days per month for selected inland water stations. It is noted that the rain shadow region of the Olympic Mountains (typified by Whidbey Island Naval Air Station) is much less apparent in cloud cover averages than it is in precipitation amounts. This indicates that the effect of the rain shadow is to decrease the intensity of precipitation in the lee of the Olympics rather than to create a particularly cloud free region.

Table 11-11 gives the percentage frequency of occurrence hourly of cloudy skies for Olympia airport. A diurnal variation in cloud cover similar to that observed for the open coast, with maximum cloud cover occurring during the morning hours and minimum shortly after sunset, is apparent. A somewhat greater diurnal range from minimum to maximum cloud cover amounts than for the open coast, particularly during summer and fall, is recorded at inland water stations. This reflects the greater frequency of formation of radiation fogs (discussed below) in the confined regions of the inland waters rather than significant differences in the formation-dissipation process of marine stratus between open coast and inland waters locations.

b. Fog. Fog occurs when a stratus deck lies at the surface. Fog may form in a variety of ways, but two fog types are dominant in the study area: radiation fog and advection (or sea) fog. In either case, surface temperature plays an essential role in fog formation.

Advection fog can form when relatively warm, moist marine air flows over colder water. Because both the temperature and dew point of the overlying air are higher than the sea surface temperature, cooling of the air near the surface by conduction will occur, which may result in condensation and fog. If a temperature inversion is present, vertical mixing of the surface air layer is inhibited, and the fog will remain near the surface. The fog layer cools by radiation from the top of the cloud, and a continuous upward flux of heat and moisture at the surface results, which serves to intensify and maintain the fog layer. Once formed, advection fogs will remain until scattered by a change in the local air circulation or until the temperature inversion is eliminated by sufficient solar heating to allow vertical mixing of the surface layer.

Radiation fog forms over land on clear, calm nights when the surface is cooled by radiation to below the dew point of the overlying air. Moisture in the cooled surface layer may condense to form fog, which will persist in the absence of wind generated mixing. Radiation fog is therefore most common in low-lying sheltered areas. Such fog is intensified if a surface moisture source is present to replace moisture lost by evaporation at the top of the cloud. Radiation fog is generally more localized than advection fog, and usually dissipates by mid-afternoon as solar heating creates convective mixing in the surrounding fog-free areas.

Table 11-10

Mean Number of Days with Clear, Partly Cloudy, and Cloudy Skies from Sunrise to Sunset at Inland Water Stations[§]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Port Angeles												
Clear	3	3	3	5	5	7	10	9	9	5	2	1
Ptly. cloudy	4	4	6	7	11	9	10	8	9	7	5	4
Cloudy	24	21	22	18	15	14	11	14	12	19	23	26
Bellingham												
Clear	5	4	5	6	8	9	15	11	12	7	4	4
Ptly. Cloudy	3	3	5	5	6	5	4	4	4	4	3	3
Cloudy	23	21	21	19	17	16	12	16	14	20	23	24
Whidbey Island Naval Air Station												
Clear	4	4	5	6	7	8	13	12	11	7	5	3
Ptly. Cloudy	4	4	5	5	6	5	5	5	4	4	4	4
Cloudy	23	20	21	19	18	17	13	14	15	20	21	24
Everett												
Clear	3	3	3	5	6	5	13	11	10	5	4	2
Ptly. Cloudy	3	2	4	4	6	5	4	5	4	5	3	3
Cloudy	25	23	24	21	19	20	14	15	16	21	23	26
Seattle												
Clear	3	3	4	5	7	7	12	10	9	5	3	3
Ptly. Cloudy	5	6	8	9	10	8	10	10	8	8	6	5
Cloudy	23	19	19	16	14	15	9	11	13	18	21	23
Tacoma												
Clear	3	4	5	5	7	7	12	11	9	5	2	3
Ptly. Cloudy	6	7	9	11	11	11	11	12	9	9	6	5
Cloudy	22	17	17	14	13	12	8	8	12	17	22	23

[§] Phillips, 1968, Halladay, 1970, and U.S. Environmental Data Service, 1930-76.

Table II-11

Percent Frequency of Cloudy Skies (80-100% coverage) By Hour and Month for Olympia Airport[§]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
00	71	67	58	56	58	64	54	49	S0	59	67	73
01	70	67	56	56	58	64	54	52	51	61	73	75
02	73	68	56	57	59	66	59	55	53	61	77	77
03	77	69	61	56	59	71	64	59	51	60	72	74
04	72	71	61	59	63	76	70	70	52	60	71	74
05	73	71	66	67	70	76	72	75	58	60	70	75
06	69	74	65	72	70	78	73	74	62	61	69	70
07	79	79	71	74	72	82	73	74	66	67	76	79
08	79	84	70	71	72	87	75	76	62	66	73	81
09	80	79	71	68	74	82	74	71	60	64	75	81
10	83	82	70	66	71	81	66	67	56	62	70	79
11	81	79	69	69	64	74	56	57	54	57	72	80
12	81	81	71	68	59	69	51	47	51	58	70	83
13	81	78	69	70	58	69	46	45	52	58	73	83
14	81	77	72	68	53	64	42	47	50	59	77	83
15	82	76	72	68	56	62	40	45	49	61	80	83
16	81	78	71	69	54	65	43	45	50	65	81	84
17	81	74	72	62	S8	65	44	45	49	62	80	79
18	75	73	71	60	S6	69	45	44	49	56	74	76
19	73	68	65	53	58	62	47	44	44	56	73	74
20	74	71	58	51	59	64	51	47	41	57	72	75
21	75	66	56	50	55	67	52	45	42	55	73	77
22	73	63	54	52	52	60	47	44	43	60	69	75
23	72	66	55	52	56	61	52	44	46	.57	69	70
Range	14	21	18	24	22	27	28	32	25	11	14	14

§ Phillips and Donaldson, 1972.

i. Fog - Open Coast. Summer and fall are fog seasons along the open coast when the dominance of the North Pacific High creates frequent subsidence inversions. Subsidence inversions are created by the compression warming of air sinking to lower levels. The sinking air can become warmer than air at the surface which is then trapped beneath the temperature inversion. Strong northerlies cause episodes of intense upwelling of cold water near the coast. The cooling of marine air flowing over these waters can then form advection fog and stratus, which penetrate inland as far as the local topography, height of the inversion base, and land heating allow.

The marine layer is usually confined to the lowest 0.S to 1.5 km by the inversion and does not readily penetrate inland (Halter, 1976). Intense solar heating inland periodically allows surges of marine air in the lowest levels through gaps in the coastal mountains which both move the fog inland and dissipate it through mixing. Advection fog is occasionally associated with frontal passage, forming in the warm southerly flow preceding the front. Radiation fog is not particularly common along the open coast, but can and does form in sheltered bays and estuaries, where it is most pronounced during the summer and fall.

In winter, dense fog that reduces visibility to 0.8 km or less occurs on an average of 2 to 4 days per month. Fog occurrence decreases with the arrival of spring, when frontal passage frequently decreases and before frequent subsidence inversions and coastal upwelling promote the formation of advection fogs. Dense fogs form on an average of less than 2 days per month during the spring.

During summer and fall, the fog season, dense fog occurs an average of 3 to 8 days per month and is most frequent from midsummer on (National Ocean Survey, 1976). Table 11-12 lists the average number of days per month with dense fog that reduces visibility to 0.4 km or less for Tatoosh Island, North Head, and Astoria.

Along the Washington coast, fog is most common near the entrance to the Strait of Juan de Fuca, in Willapa Bay, and in Grays Harbor where radiation fogs often blanket the area during the fall and winter. Dense fog occurs at Tatoosh Island on an average of 16 days in August. The fog signal in Grays Harbor operates on an average of 35% of the time during the fall and winter.

Along the Oregon coast, fog frequency generally increases toward the south, reflecting the increased dominance of the North Pacific High and the related subsidence inversions. Astoria has dense fog an average of 2 to 7 days per month from July through October while North Bend averages from 6 to 13 foggy days per month during the same period. During August (the worst fog month), the Columbia River lightship fog signal operates 12% of the time while the Cape Arago fog signal operates 30% of the time. Figures II-33 through II-36 show the percent frequency of selected risibilities by season for 1° by 1° squares off the coast in the study area.

ii. Fog - Inland Waters. Radiation fog predominates in the inland waters. The enclosed nature of many inland water locations and the shelter from large scale circulation afforded by the coastal mountains

Table 11-12

Mean Number of Days per Month with Heavy Fog
(Limiting Visibility to 0.4km or Less)
for Open Coast Stations[§]

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Ott	Nov	Dec
Tatoosh Island	1	1	1	2	3	5	11	16	11	6	2	1
North Head	3	3	2	2	2	2	4	8	7	6	3	2
Astoria	4	3	2	2	2	2	2	5	6	7	4	4

§Phillips and Donaldson, 1972, and U.S. Environmental Data Service, 1930-76.

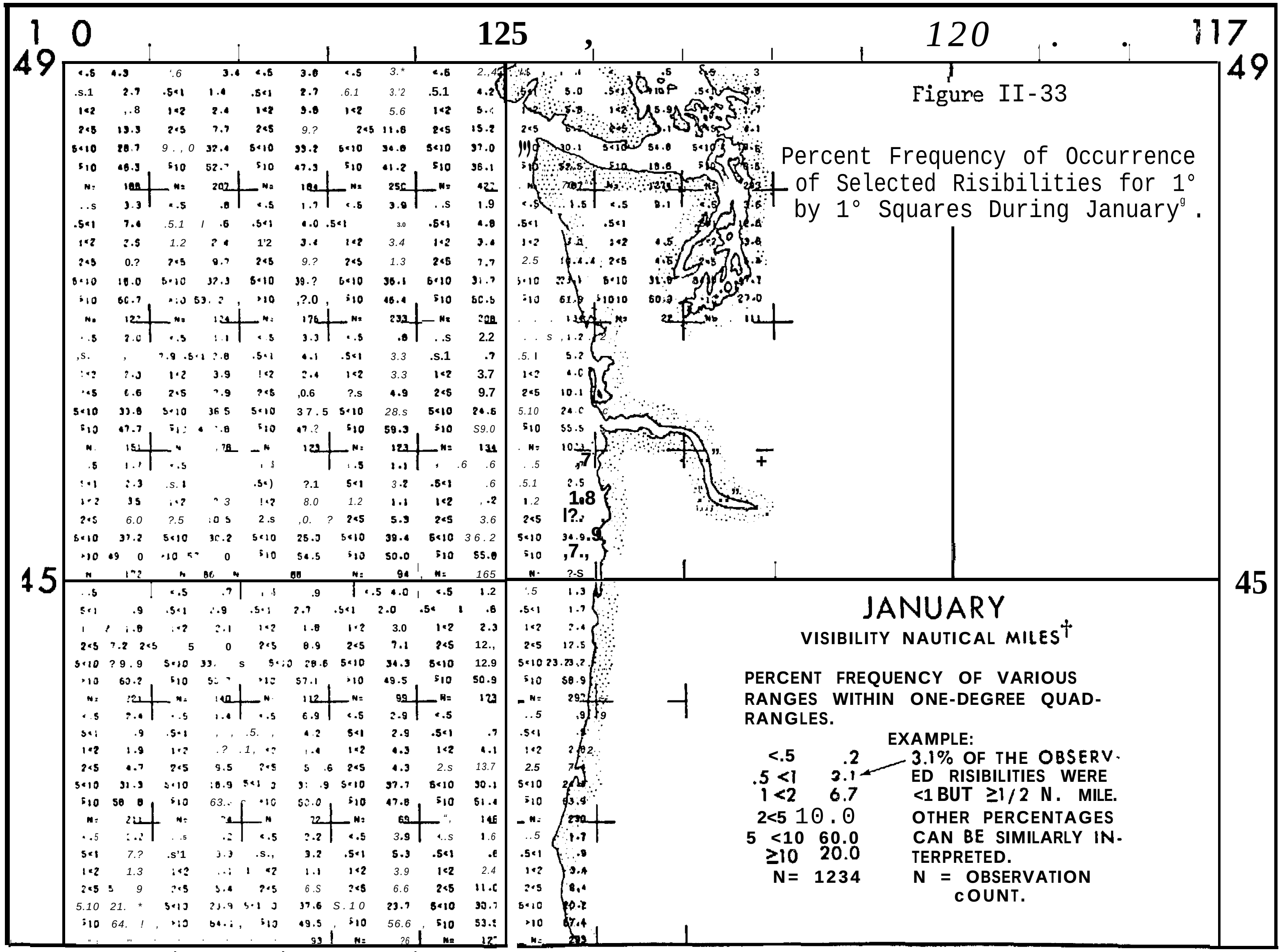


Figure II-33

Percent Frequency of Occurrence of Selected Risibilities for 1° by 1° Squares During January§.

§ U.S. Naval Weather Service Command. Naval Weather Service Detachment. 1976.

† 1 nautical mile = 1.85 km.

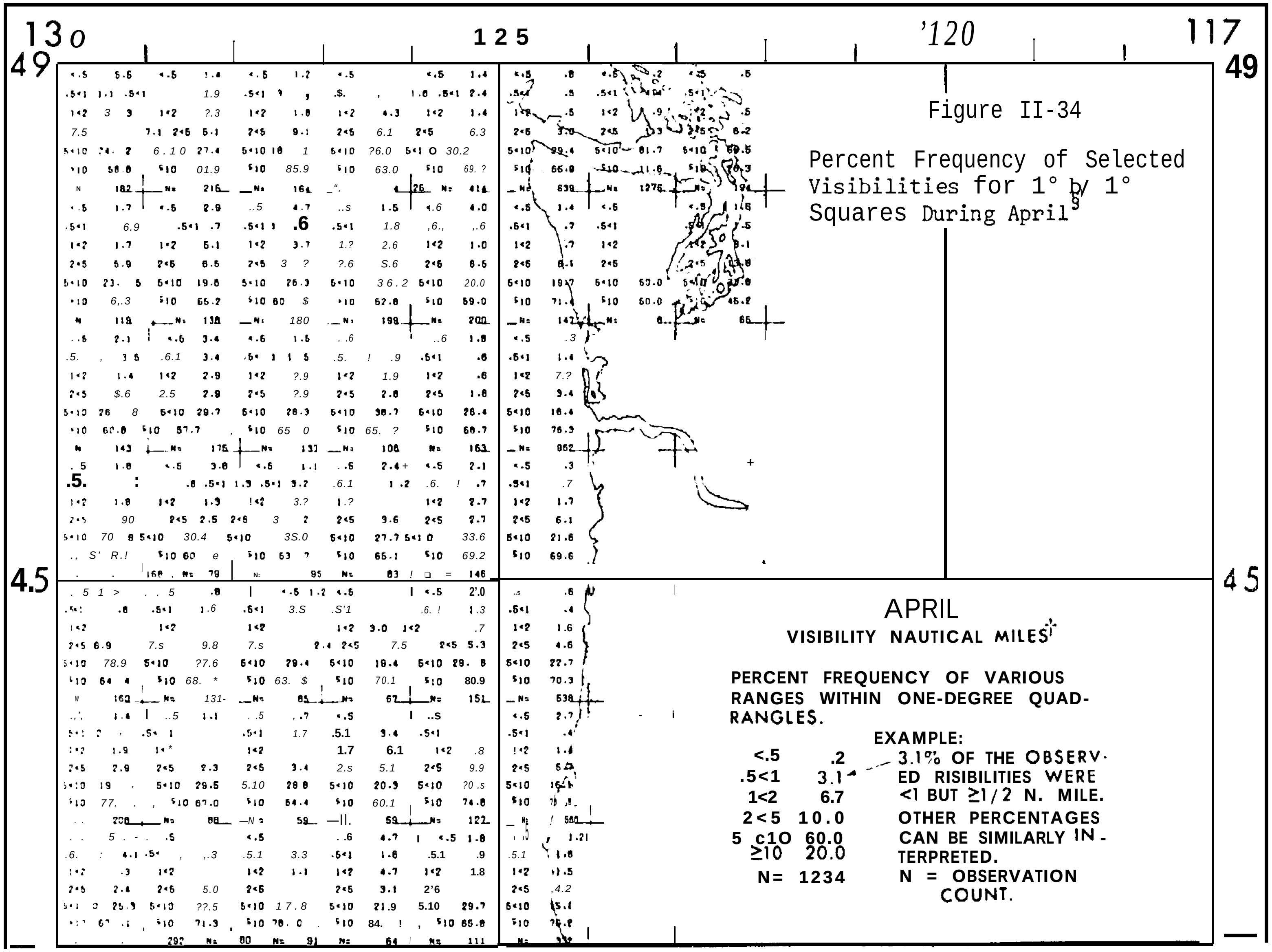


Figure II-34

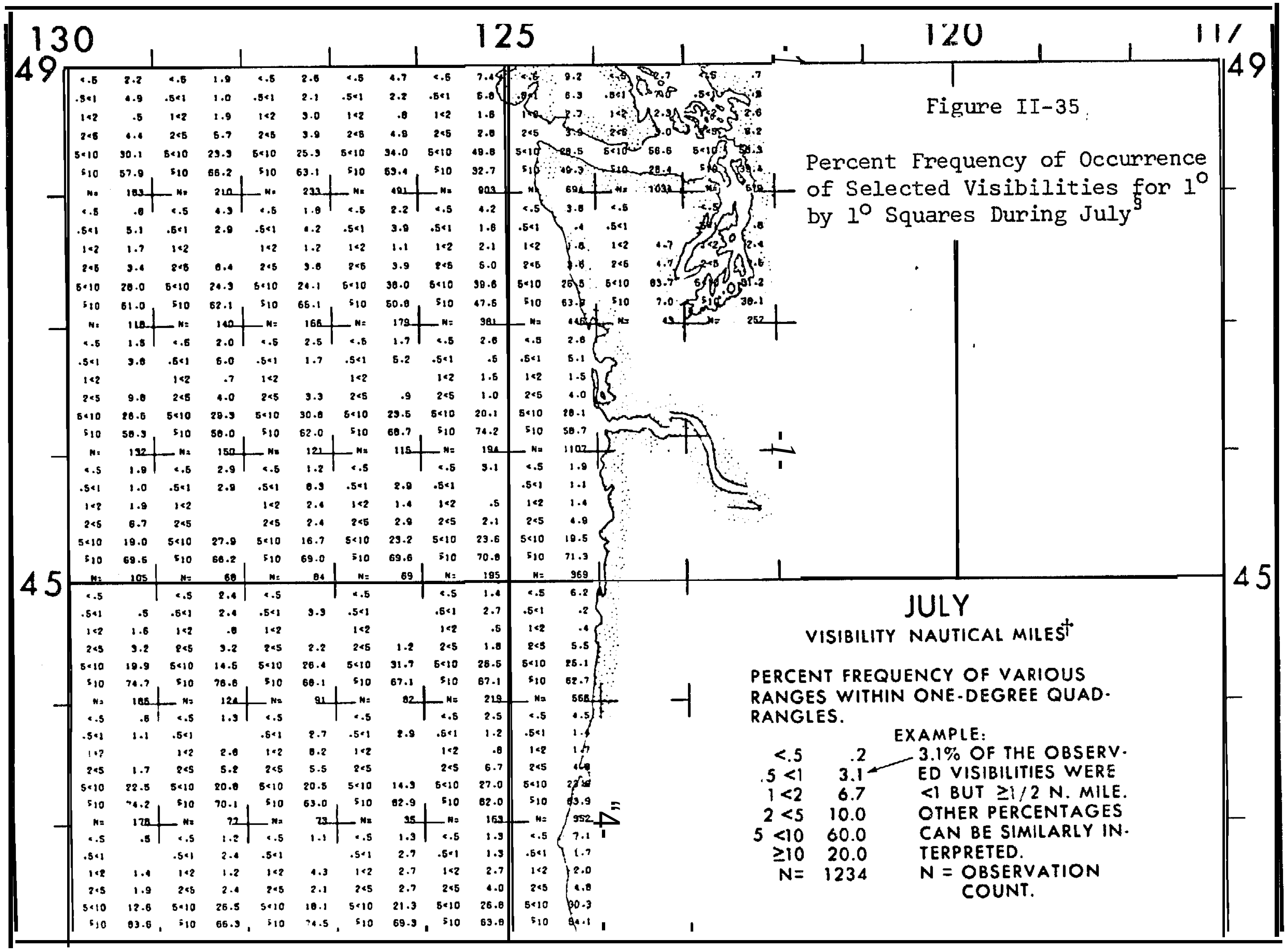
Percent Frequency of Selected Visibilities for 1° by 1° Squares During April[5]

.S. Naval Weather Service Command. Naval Weather Service Detachment, 1976.

nautical mile = 1.85 km

Figure II-35

Percent Frequency of Occurrence of Selected Visibilities for 1° by 1° Squares During July[§]



§U.S. Naval Weather Service Command. Naval Weather Service Detachment, 1976.

†1 nautical mile = 1.85 km.

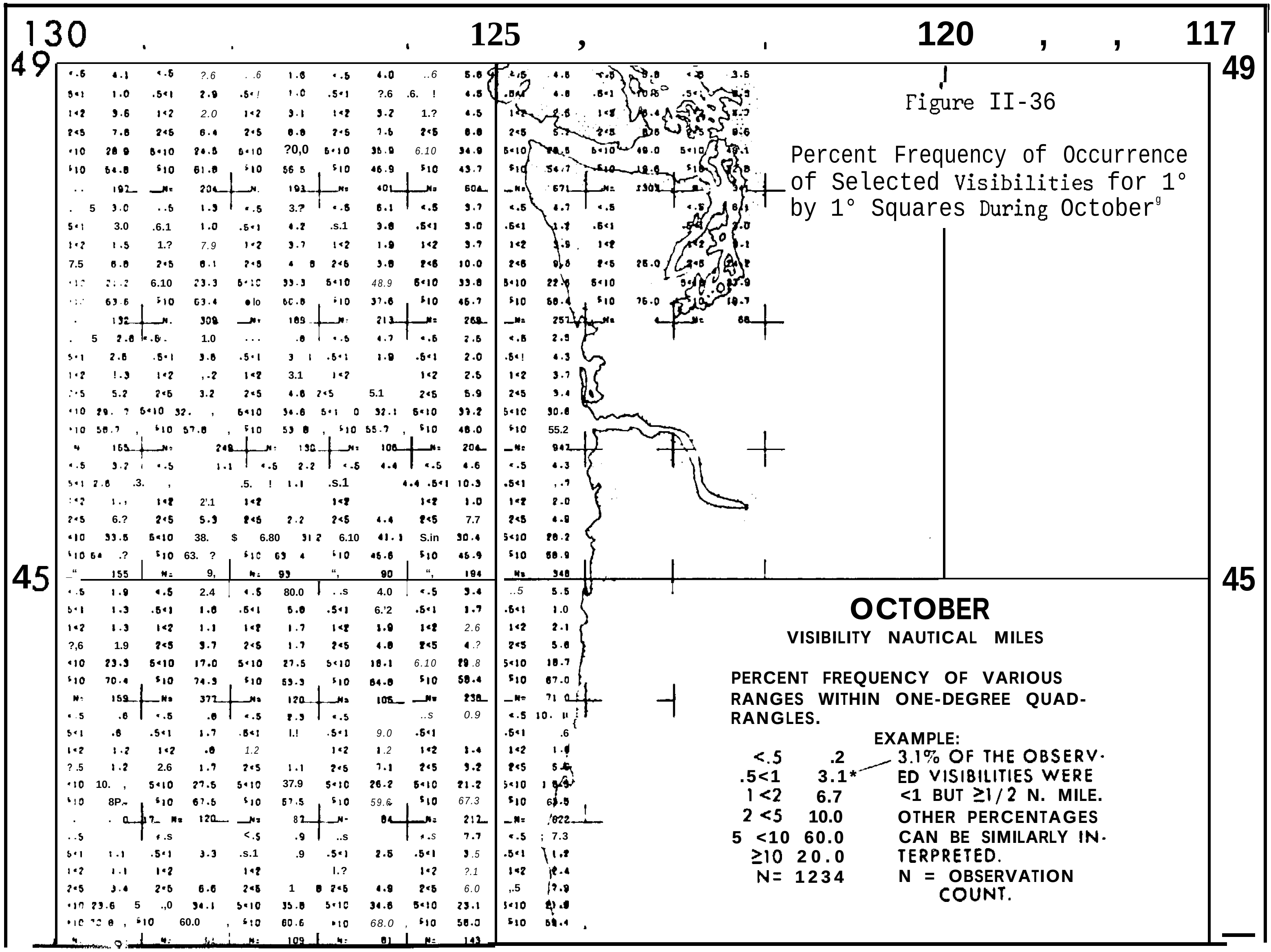


Figure II-36

Percent Frequency of Occurrence of Selected Visibilities for 1° by 1° Squares During October[9]

.S. Naval Weather Service Command. Naval Weather Service Detachment, 1976.
‘1 nautical mile = 1.85 km.

promotes the formation of radiation fog, particularly during the late summer and fall when subsidence inversions are common. Radiation fog often forms at night over sheltered areas of the coastal lowlands, and then gradually flows out over the water which becomes a moisture source for the maintenance of the fog. Such fogs usually dissipate by mid-day, but may persist for several days during extremely settled conditions. Radiation fog can form in winter during the brief settled period between frontal passage. Advection fog from the open coast rarely penetrates inland past the coastal mountains except through the Strait of Juan de Fuca.

Advection fog is the most common near the entrance to the Strait of Juan de Fuca and is worst from July through October. Radiation fog flowing out from the nearby coastal lowlands can extend the reduced visibility hazard into the winter. The frequency of dense fog occurrence in the Strait of Juan de Fuca decreases from an average of 55 days per year at the west entrance to an average of 35 days per year at the east end. Fog is often carried east on a westerly sea breeze and generally penetrates furthest along the south shore, being more apt to reach Port Townsend than Victoria. Within Puget Sound and the Georgia Strait, fog causes visibility problems on an average of 25 to 40 days per year and is most common from midsummer through January. April and May are the most fog free months. Fog conditions are worst in the enclosed waters of the southern portion of Puget Sound and in the vicinity of the San Juan Islands. Fog signals blow on an average of 8 to 15% of the time at Point No Point and in the East Passage (just north of Tacoma) while operating on an average of less than 5% of the time within central Puget Sound (National Ocean Survey, 1976). Table 11-13 shows the average number of days per month with dense fog for Port Angeles, Oak Harbor, Seattle, and Tacoma.

Radiation fogs are particularly common in the vicinity of Seattle due to its location between Puget Sound and Lakes Washington and Sammamish. It should be remembered that fog occurrence data for coastal locations often leads to an underestimate of the frequency of foggy conditions over nearby waters, where fogs are more likely to intensify and persist.

c. Smog. Smog formation requires the trapping of pollutants in a confined area for some length of time. A temperature inversion to inhibit the vertical mixing of the surface layer and topographical features which maintain the surface layer within a confined area, as well as a pollutant source, are necessary conditions for smog formation. Such conditions are not regularly encountered within the study area, but these requirements are met often enough to create a potential hazard of pollution.

i. Smog - Open Coast. During the winter, and to some extent the spring and fall, frontal storms periodically replace and disperse coastal air. Gaps in the coastal mountains serve as pathways for the movement of coastal air to the interior. During the settled periods between storms, when subsidence inversions can develop, these pathways allow cold continental air to drain westward to the coast. Together with the large scale southeasterly flow, this circulation pattern serves to transport effluents from inland population centers to the coast where they-may persist until dispersed by the next storm.

Table 11-13

Mean Number of Days per Month with Heavy Fog
(Limiting Visibility to 0.4km or
for Inland Water Stations§

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Ott	Nov	Dec
Port Angeles	1	1	1	1	2	3	5	10	8	5	2	1
Oak Harbor	1	1	1	1	1	1	3	4	7	5	4	1
Seattle	5	4	3	1	1	1	3	4	8	9	7	7
Tacoma	4	3	2	1	-	-	-	1	3	6	5	5

§U.S. Environmental Data Service, 1930-76.

Wind measurements taken several kilometers offshore suggest only a limited offshore penetration of continental air (Halter, 1976).

In the summer and fall, when subsidence inversions are frequent, coastal air penetrates inland in the form of periodic surges of marine air in the lowest levels through gaps in the coastal mountains. Because of the periodic nature of these surges, pollutants generated along the coast may concentrate in the shallow marine layer for some length of time. With subsidence inversions limiting the mixing depth, the accumulated pollutant may be transported southward for some distance by the prevailing along-shore northerly flow before being dispersed through the natural passageways to the interior. This along-shore channeling effect is greatest where hills and mountains are near the coast, diverting the summertime northwesterly onshore flow to a more northerly along-shore flow. When the along-shore channeling of pollutants is accompanied by the extremely stable conditions characteristic of the formation of advection fog, pollutants may persist in the surface layer for a considerable time.

ii. Smog - Inland Waters. Conditions favorable to the accumulation of pollutants in a confined surface layer are virtually identical to those conditions which result in the formation of radiation fog. However, pollutant accumulation usually becomes a problem only when it continues for a suitable length of time (depending on the rate of pollutant production). Therefore, fog data previously given for inland water locations is not necessarily a good indication of the severity of pollutant persistence, but can serve as a guide to those areas where conditions favorable to its accumulation exist.

The predominant air flow in Puget Sound and the Strait of Georgia is northerly or southerly. The Olympic Mountains and the Cascades effectively block most easterly and westerly flows except through the Strait of Juan de Fuca and the gap north of the Willapa Hills. When the North Pacific High dominates the region, the large scale northerly on-shore flow enters the inland waters through the Strait of Juan de Fuca and produces southerly flow in the Strait of Georgia and northerly flow throughout most of Puget Sound.

A confluence zone is created in southern Puget Sound where the northerly flow encounters air entering the inland waters through the gap north of the Willapa Hills. Consequently, under conditions of large scale subsidence that prevents vertical mixing, pollutants generated within Puget Sound tend to remian in the surface layer and concentrate in the central and southern regions of the Sound. Accumulation of pollutants near the surface becomes a problem when vertical mixing is inhibited for several days at a stretch, and is most marked in the fall when solar heating is often insufficient to promote suitable convective mixing of the surface layer.

Table 11-14 lists the percentage frequency of fog and haze, smoke, or dust with limited risibilities for the Seattle-Tacoma Airport, which is located in the confluence region described above. A comparison of this with Table II-15, which shows the percentage frequency of fog and observations with obstructions to vision at Whidbey Island Naval Air Station, illustrates the tendency for accumulation of pollutants in central and southern Puget Sound.

Table 11-14

Percent Frequency of Occurrence of Fog and Haze, Smoke, or Dust with Limited Visibilities at Seattle-Tacoma International Airport[§]

Month	Fog with Visibility Less than 5 km.	Fog with Visibility Greater than 5 km.	Haze, Smoke or Dust with Visibility Less than 5 km.	Haze, Smoke or Dust with Visibility Greater than 5 km.
Jan .	7.7	5.9	0.5	2.1
Feb.	7.8	4.8	1.8	3.8
Mar.	3.1	2.7	0.7	2.6
Apr.	1.9	2.3	0.3	1.6
May	1.4	1.7	0.3	1.8
June	2.5	2.5	0.1	1.3
July	3.9	2.9	0.4	2.4
Aug.	4.1	3.6	0.8	5.0
Sept.	9.5	5.3	3.7	8.0
Ott .	14.0	6.3	6.2	9.1
Nov.	14.4	6.4	3.5	6.4
Dec.	11.3	S.6	1.7	2.8

[§]U.S. Weather Bureau, 1961.

Table 11-15

Percent Frequency of Occurrence of Fog and Observations with Obstruction to Vision at Whidbey Island Naval Air Station[§]

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Ott	Nov	Dec
Fog	8.6	8.5	4.1	2.8	3.7	4.8	6.7	10.0	15.0	17.6	13.2	8.3
Ohs. with Obstruction to Vision	11.0	10.3	5.9	4.0	4.1	5.3	7.5	11.2	19.8	22.3	1S.0	9.8
Difference	2.4	1.8	1.8	1.2	0.4	0.5	0.8	1.2	4.8	4.8	1.8	1.5

[§]Halladay, 1970.

d. Ceiling. The high frequency of occurrence of stratus overcast and/ or fog creates low ceilings throughout the study area a good deal of the time. Observations reporting no ceiling (cloud base greater than or equal to 2.4 km or cloud cover less than 5/8) are generally recorded less than half the time. Low ceilings are most often reported from midsummer through winter when frontal stratus or fogs blanket the area.

i. Ceiling - Open Coast. Figures II-37 through 11-40 list the percent frequency of occurrence of selected ceiling heights for 10 by 1° squares for the months of January, April, July and October. The lowest frequency of observations reporting no ceiling occurs during January (the frontal storm season) and averages about 31% frequency of occurrence. Ceilings of less than 305 m are reported about 29% of the time. Reports of no ceiling increase to an average of about 50% occurrence during the spring, summer and fall. Reports of ceilings less than 30S m drop to an annual low during the spring (about 15 percent) and gradually rise as summer (and the fog season) approaches. During July, ceilings of less than 91 m are reported about 19% of the time, while ceilings of less than 91 m occur 9% of the time (over the April average). Low ceiling (<91 m) frequency remains at about the July levels through October as the fog season continues and decreases slightly with the arrival of winter. Ceilings of less than 305 m are reported about 18% of the time during October.

Figures 11-41 through II-44 show the percent frequency of low ceiling-visibility combinations for the months of January, April, July and October. Low ceilings produced by frontal passage along the entire open coast are evident on the January map (Figure 11-41) as are the particularly foggy regions of Cape Blanco and near Willapa Bay and the mouth of the Columbia River. The midsummer through fall fog season is particularly noticeable (Figures II-43 and II-44 as is springtime clearing throughout the region (Figure II-42).

ii. Ceiling - Inland Waters. Analyzed ceiling data on a scale suitable to the inland waters complex topography is lacking. Table 11-16 gives percent frequency of occurrence of various ceiling heights for Seattle-Tacoma International Airport. Low ceilings (less than 91 m) reach a maximum during the fall (the radiation fog season). The frontal storms of winter are clearly reflected in the winter maximum of ceilings less than 610 m. As for the open coast, spring is the season with the lowest frequency of ceiling less than 305 m. The percentage frequency of selected ceiling-visibility combination for Seattle-Tacoma International Airport and Whidbey Island Naval Air Station are shown in Tables 11-17 and 11-18.

In addition to seasonal variations in ceiling-visibility combinations, diurnal variations occur. In particular during the fall months with a high incidence of fog, low ceiling-visibility combinations occur with a much higher frequency in the morning than in the afternoon. Figure II-45, which shows the frequency of ceilings below 91 m and/or visibility below 1.6 km for each of 8 discrete three hourly periods by months at Whidbey Island Naval Air Station, portrays this diurnal variation graphically.

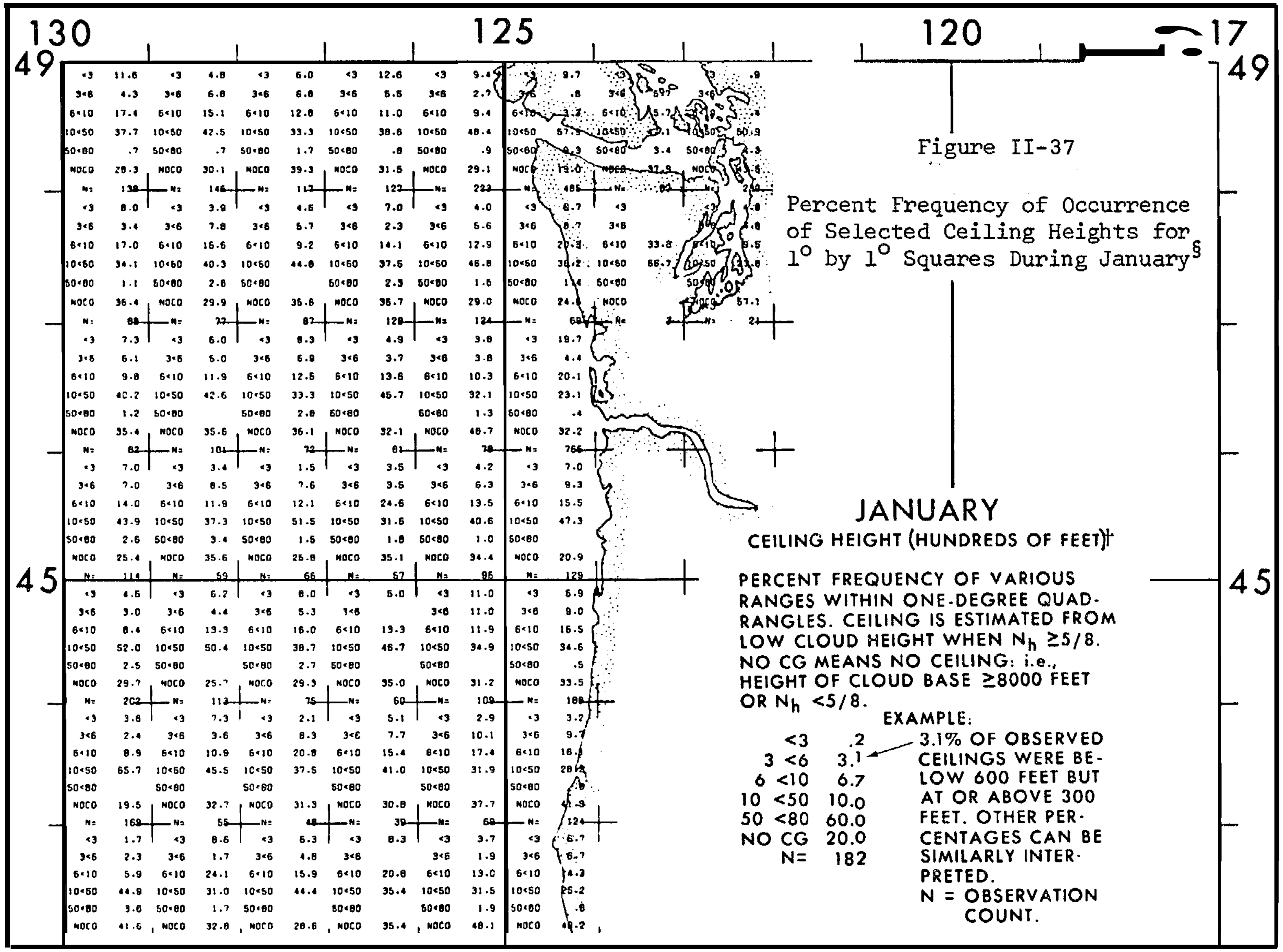


Figure II-37

Percent Frequency of Occurrence of Selected Ceiling Heights for 1° by 1° Squares During January§

U.S. Naval Weather Service mm . Naval Weather Service Detachment, 1976.
1 foot ≅ .305 meter.

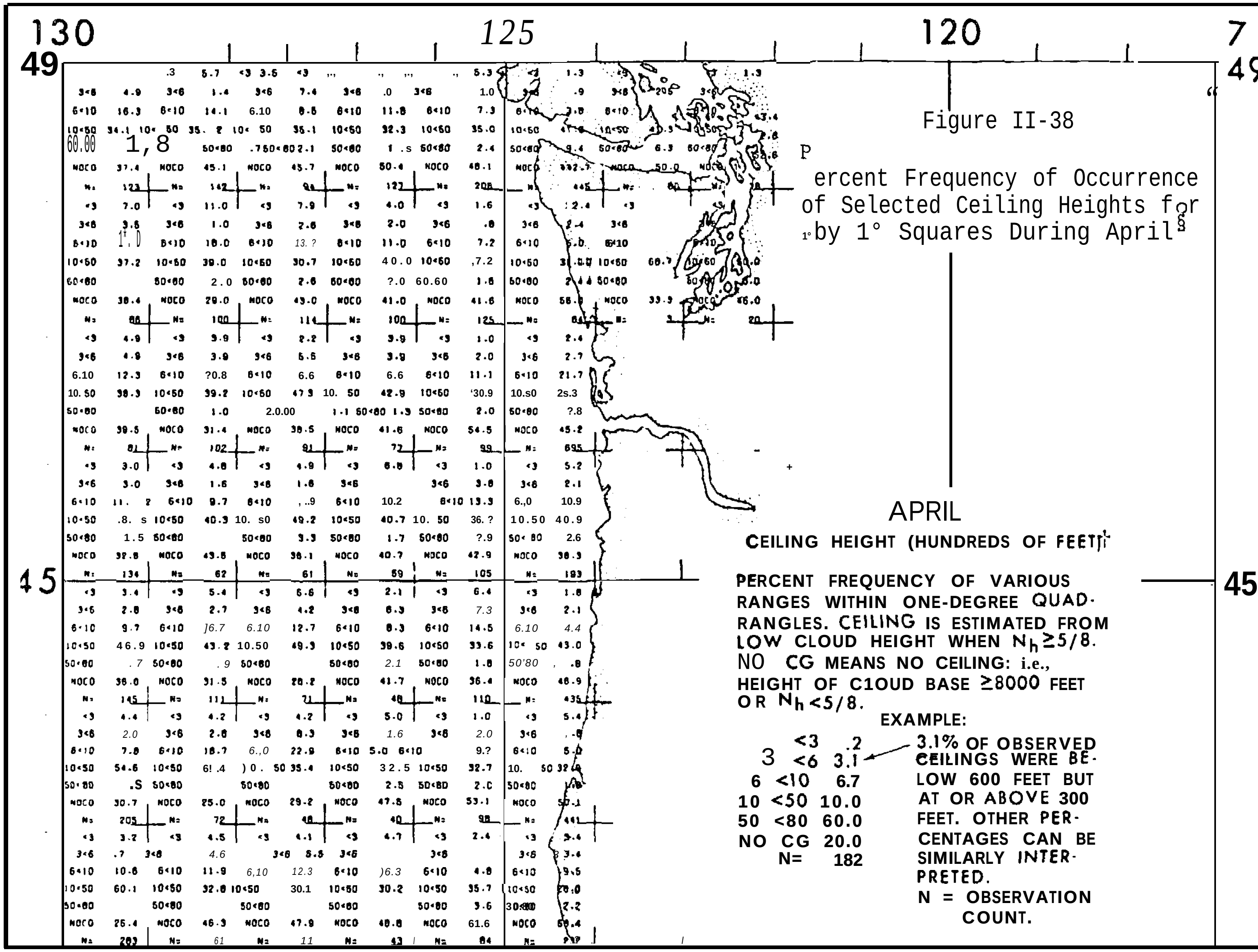


Figure II-38

Percent Frequency of Occurrence of Selected Ceiling Heights for 1° by 1° Squares During April§

§U.S. Naval Weather Service Command. Naval Weather Service Detachment, 1976.

‡1 foot = .305 meter.

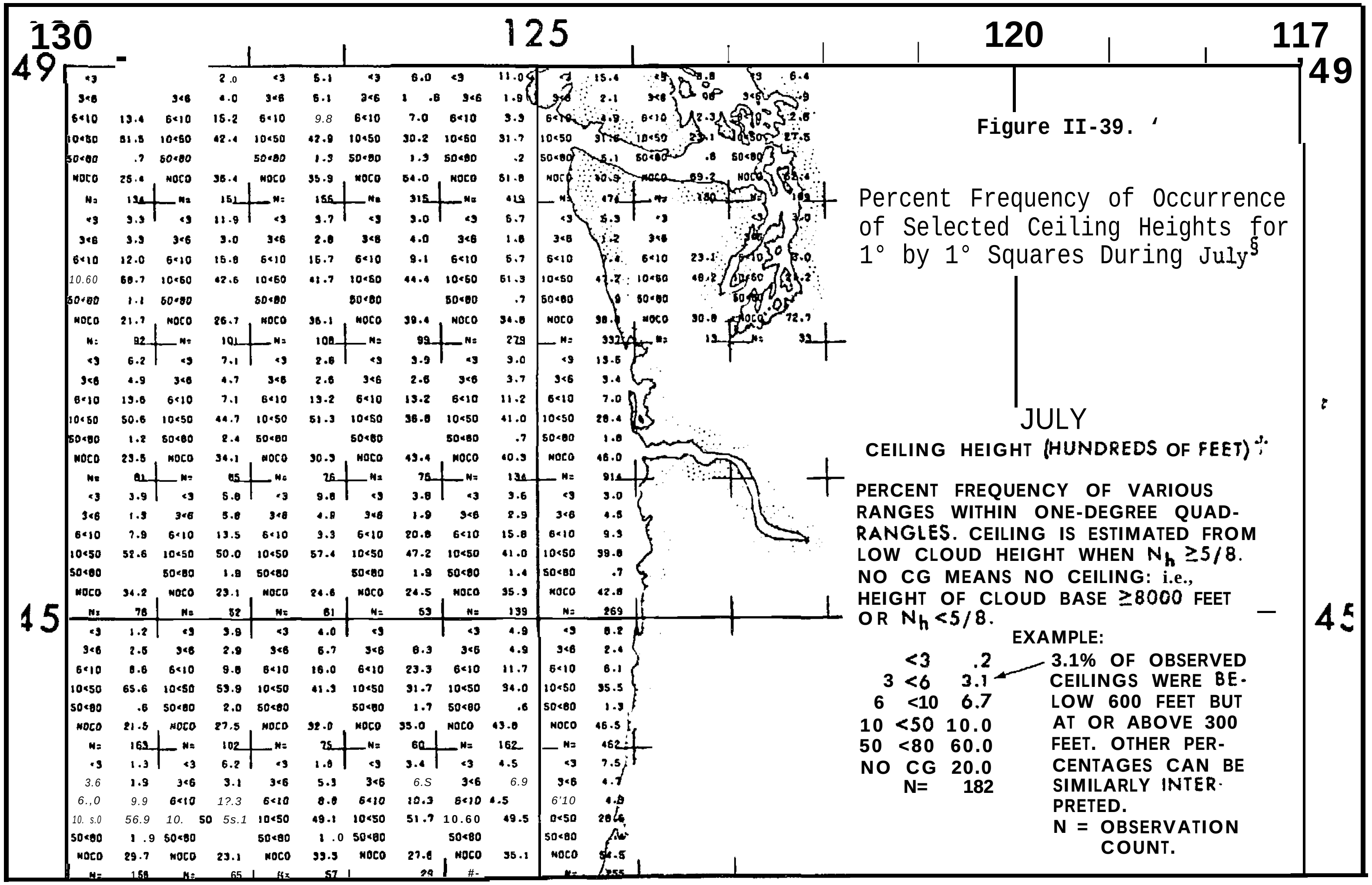


Figure II-39.

Percent Frequency of Occurrence of Selected Ceiling Heights for 1° by 1° Squares During July§

§ U. S. Naval Weather Service Command. Naval Weather Service Detachment, 1976.

† 1 foot = .305 meter.

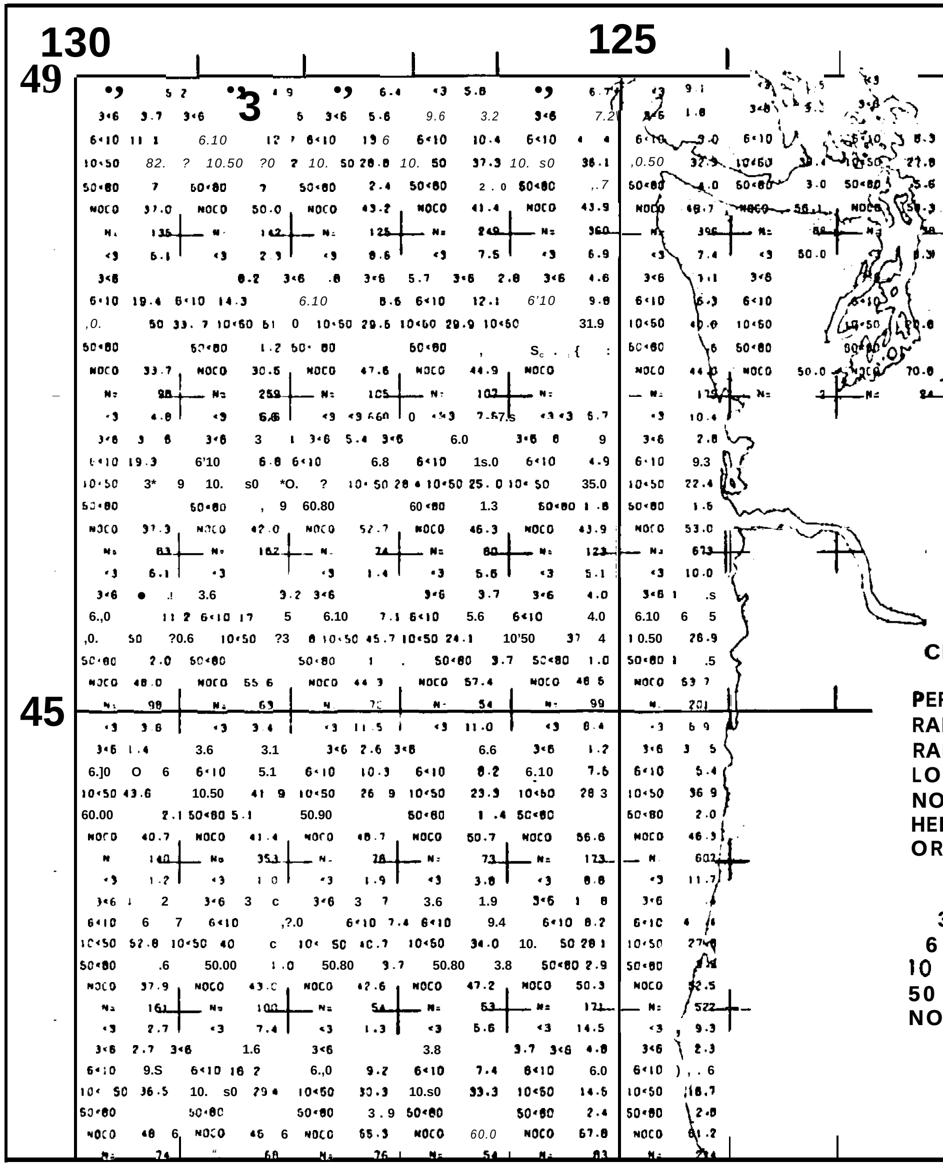


Figure 11-40

Percent Frequency of Occurrence of Selected Ceiling Heights for 1° by 1° Squares During October[§]

OCTOBER

CEILING HEIGHT HUNDREDS OF FEET[†]

PERCENT FREQUENCY OF VARIOUS RANGES WITHIN ONE DEGREE QUADRANGLES. CEILING IS ESTIMATED FROM LOW CLOUD HEIGHT WHEN $N_h \geq 5/8$. NO CG MEANS NO CEILING: i.e., HEIGHT OF CLOUD BASE ≥8000 FEET OR N_h <5/8.

EXAMPLE:

<3	.2
3 <6	3.1
6 <10	6.7
10 <50	10.0
50 <80	60.0
NO CG	20.0
N=	182

3.1% OF OBSERVED CEILINGS WERE BELOW 600 FEET BUT AT OR ABOVE 300 FEET. OTHER PERCENTAGES CAN BE SIMILARLY INTERPRETED.

N = OBSERVATION COUNT.

§ U. S. Naval Weather Service Command. Naval Weather Service Detachment, 1976.

† 1 foot = .305 meter.

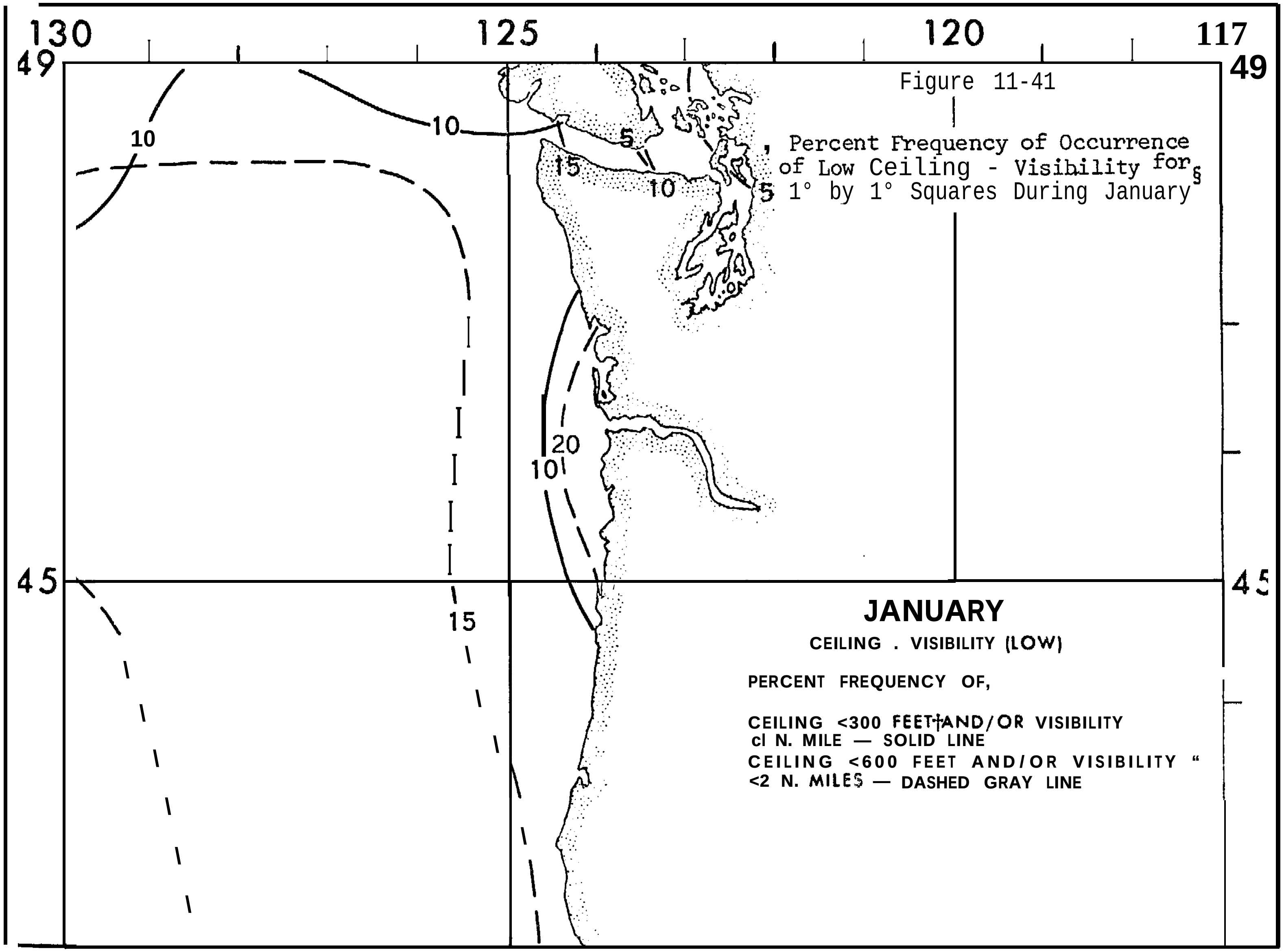


Figure 11-41

Percent Frequency of Occurrence of Low Ceiling - Visibility for 1° by 1° Squares During January§

§U. S. Naval Weather Service Command. Naval Weather Service Detachment, 1976.
†1 foot = .305 meter.

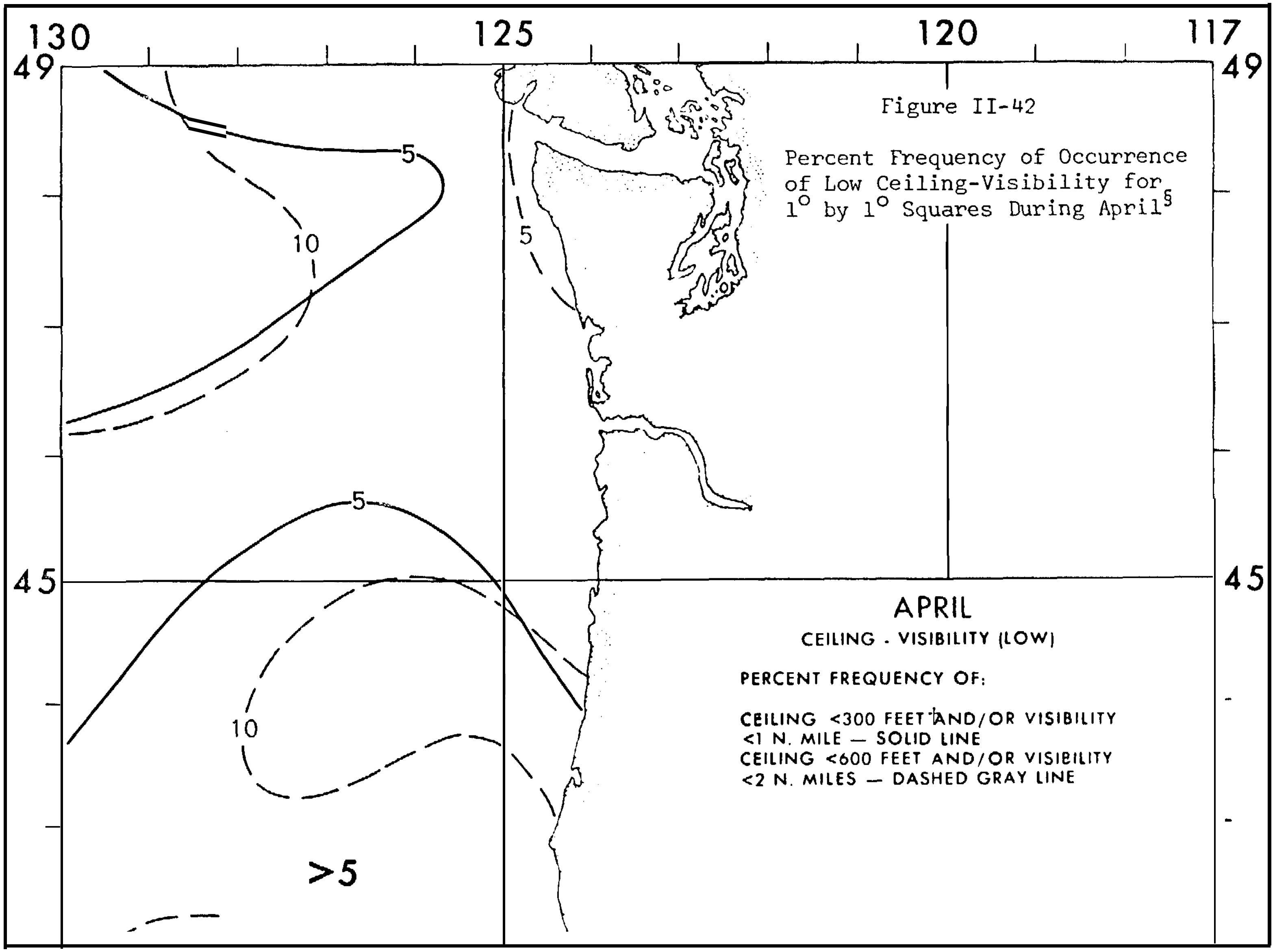


Figure II-42

Percent Frequency of Occurrence of Low Ceiling-Visibility for 1^{o} by 1^{o} Squares During April[§]

[§] U.S. Naval Weather Serv: ce Command. Naval Weather Service Detachment, 1976.

[†] 1 foot = .305 meter.

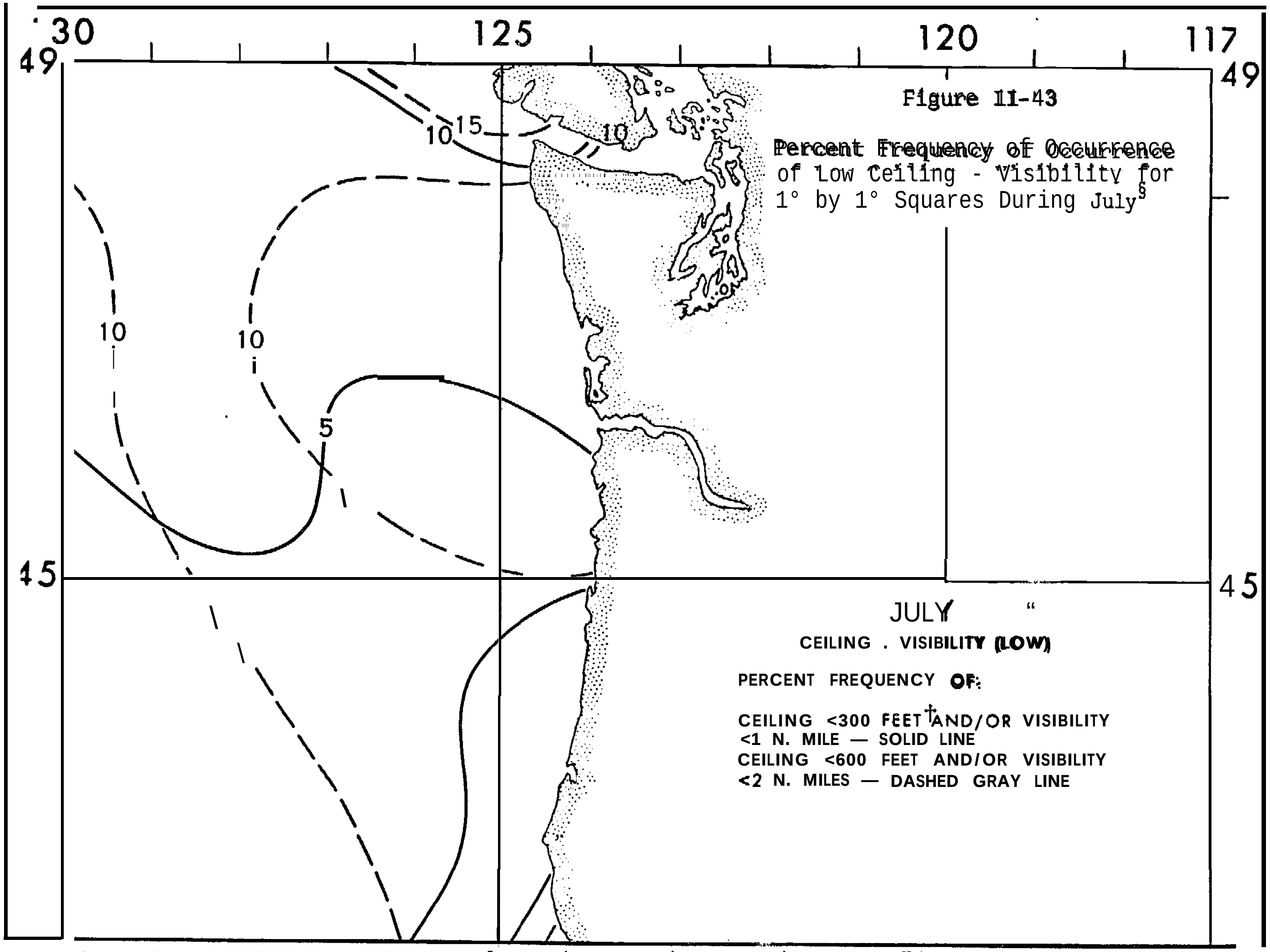


Figure 11-43

Percent Frequency of Occurrence of Low Ceiling - Visibility for 1° by 1° Squares During July§

§U. S. Naval Weather Service Command. Naval Weather Service Detachment, 1976.
†1 foot = .305 meter.

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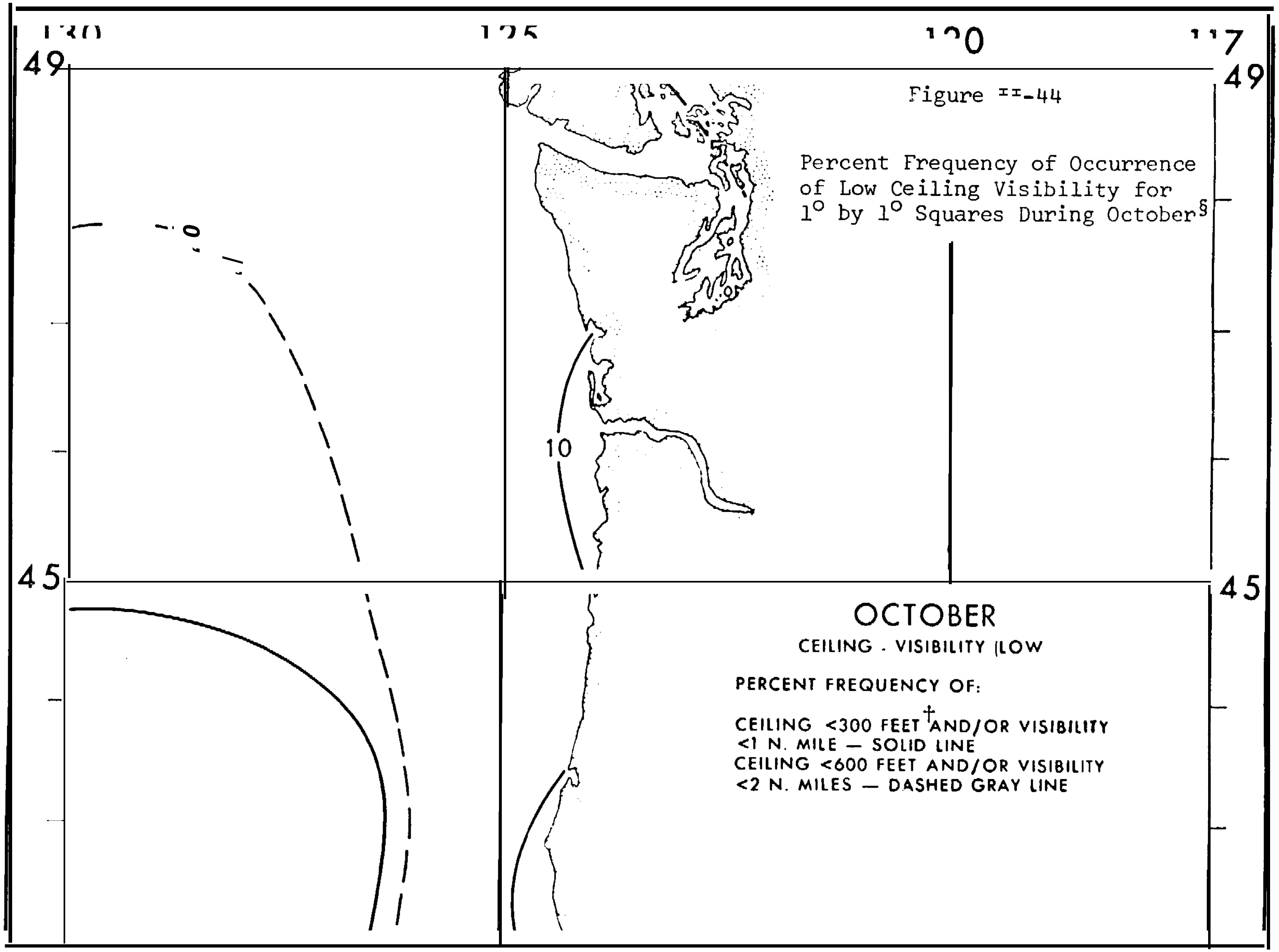


Figure II-44

Percent Frequency of Occurrence of Low Ceiling Visibility for 1° by 1° Squares During October§

§U.S. Naval Weather Service mm Naval Weather Service Detachment, 1976.
†1 foot = .305 meter.

Table II-16

Percent Frequency of Selected Ceiling Heights at Seattle-Tacoma International Airport§

Month \ Ceiling Less Than	Meters							
	30	60	90	150	300	600	1500	3000
January	.4	1.1	1.8	3.8	11.4	26.6	60.3	71.8
February	.9	1.4	2.4	4.0	9.4	23.8	52.7	66.1
March	.1	.3	.7	1.6	5.6	18.7	46.0	59.8
April	.1	.2	.4	.9	3.0	11.4	33.5	47.3
May	#	.1	.3	1.0	3.6	11.7	30.0	44.7
June	#	.2	.5	1.8	5.7	15.0	34.2	53.6
July	.1	1.0	1.7	3.4	7.4	14.5	27.2	36.8
August	.2	.8	1.6	3.2	7.0	15.8	28.4	39.6
September	.9	2.7	4.0	5.9	9.3	16.1	31.1	41.8
October	2.0	3.7	4.9	6.9	9.8	16.9	39.0	52.7
November	1.9	4.4	6.0	8.4	13.8	23.6	46.4	59.1
December	.8	2.9	4.3	6.3	12.5	26.9	57.0	69.8
Annual	.6	1.6	2.4	3.9	8.2	18.4	40.4	53.5

LEGEND # Less than 0.05 percent

§U.S. Weather Bureau, 1961.

Table 11-17

Percent Frequency of Selected Ceiling-Visibility Combinations at Seattle-Tacoma International Airport§

Ceiling Less Than and/or Visibility Less Than	30m 0.3km	60m 0.8km	90m 0.8km	150m 1.6km	300m 4.8km	600m 4.8km	1500m 11.3km
January	1.3	2.1	2.5	5.4	16.0	29.3	63.3
February	1.9	2.7	3.1	5.2	13.8	27.1	59.4
March	0.3	0.6	0.9	2.1	7.4	19.9	48.9
April	0.2	0.3	0.6	1.1	3.9	12.1	35.8
May	0.1	0.2	0.3	1.0	4.1	12.0	31.8
June	0.1	0.3	0.6	2.0	6.4	15.4	35.7
July	0.7	1.4	1.9	3.6	8.1	15.0	29.7
August	0.7	1.4	1.9	3.5	8.3	16.7	33.7
September	2.9	4.1	4.8	6.9	13.2	19.3	42.3
October	4.8	6.4	6.8	9.5	18.0	24.5	55.4
November	5.0	6.4	7.4	10.5	19.9	28.6	56.6
December	3.9	5.1	5.8	8.5	17.6	30.8	63.4
Annual	1.8	2.6	3.0	4.9	11.4	20.9	46.3

§U.S. Weather Bureau, 1961.

Table 11-18

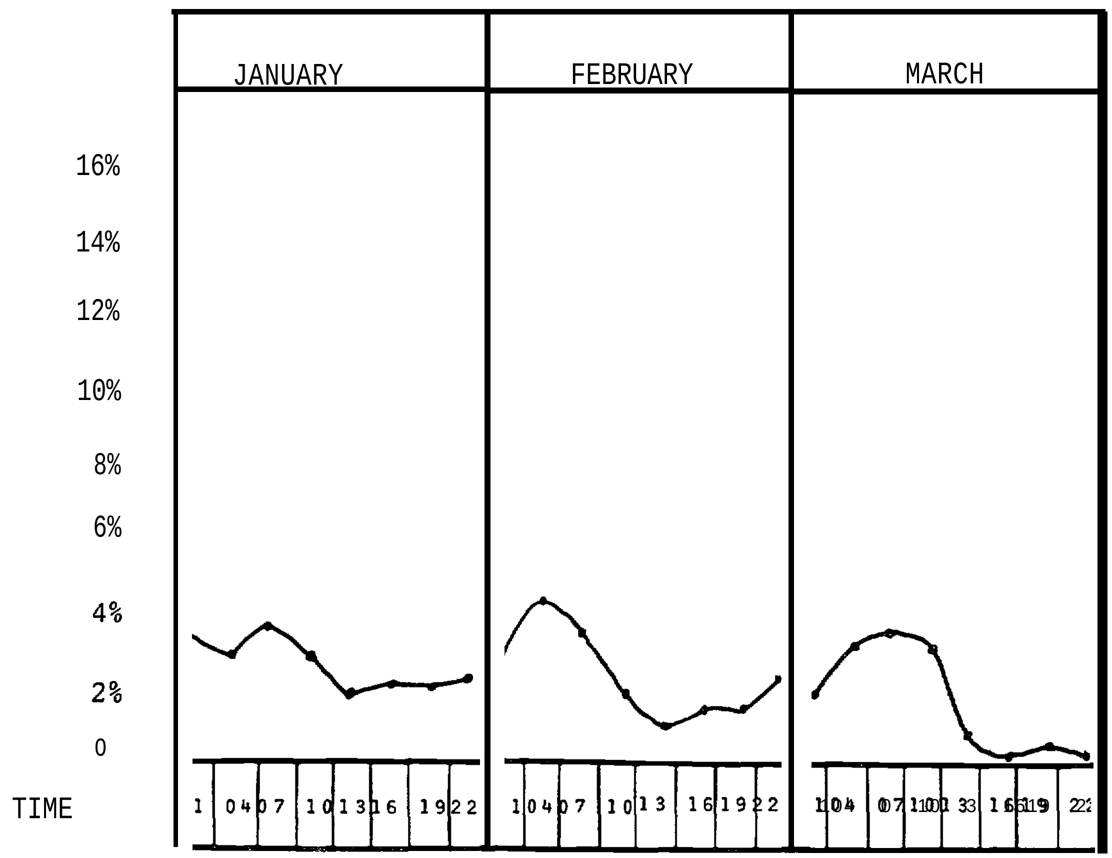
Percent Frequency of Selected Ceiling-Visibility Combinations at Whidbey Island Naval Air Station§

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Ott	Nov	Dec	Annual
365m. and/or 4.8km.	15.6	10.7	6.4	3.9	4.6	7.0	9.4	10.7	14.0	15.7	1s.1	15.4	10.7
90m. and/or 1.6km.	2.7	2.5	1.5	0.7	1.2	1.9	3.6	4.4	7.3	6.8	4.9	2.9	3.4
30m. and/or 0.4km.	1.0	1.1	0.6	0.3	0.4	0.5	0.9	1.7	4.0	3.4	2.6	1.5	1.5

§Halladay, 1970.

Figure II-45

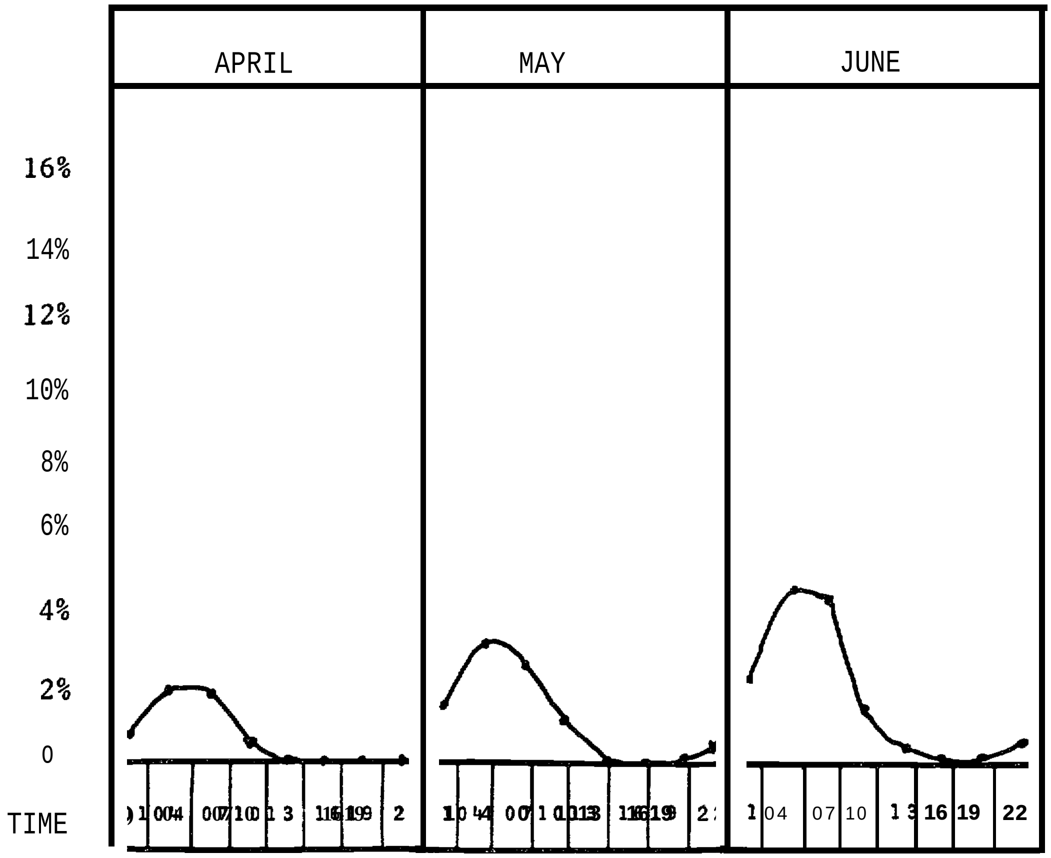
Percent Frequency of Occurrence of Observations with Low Ceiling-Visibility Combinations by 3 Hourly Interval by Month for Whidbey Island Naval Air Station[§]



% OF OBSERVATIONS WITH CEILING BELOW 300 FEET (90M) AND/OR VISIBILITY BELOW 1 MILE (1.6KM).

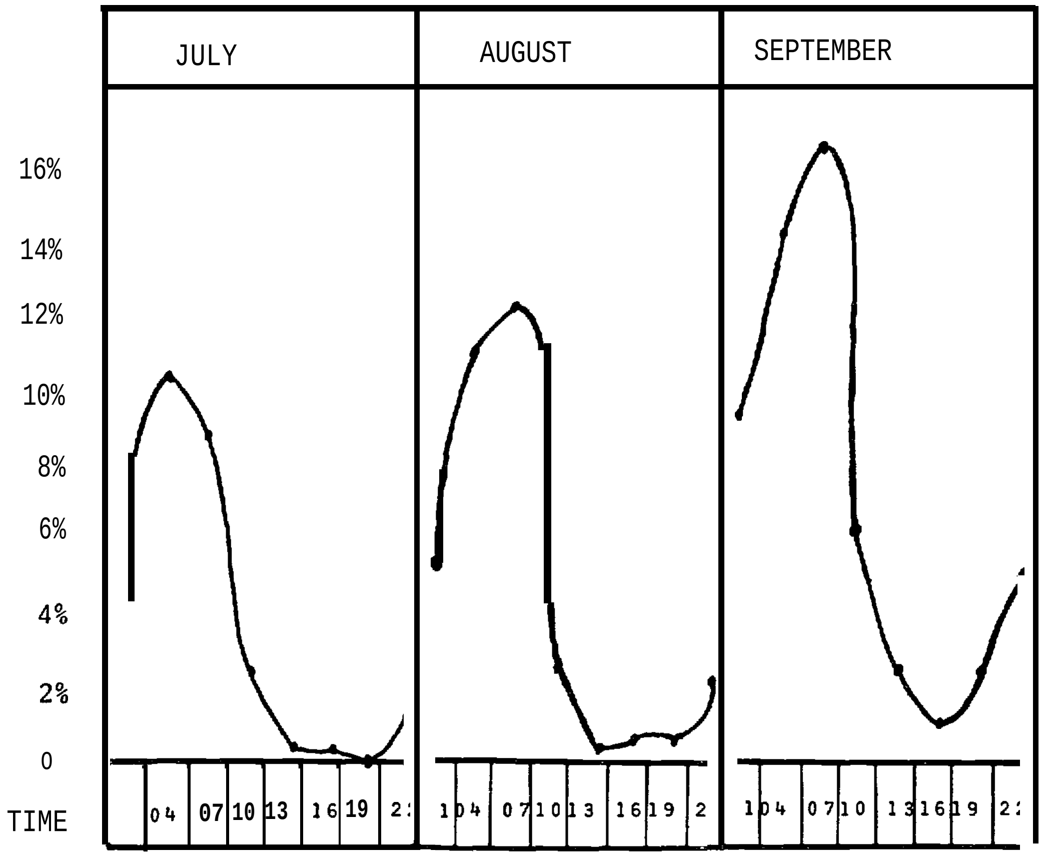
[§]Halladay, 1970.

Figure II-45 (cont.)



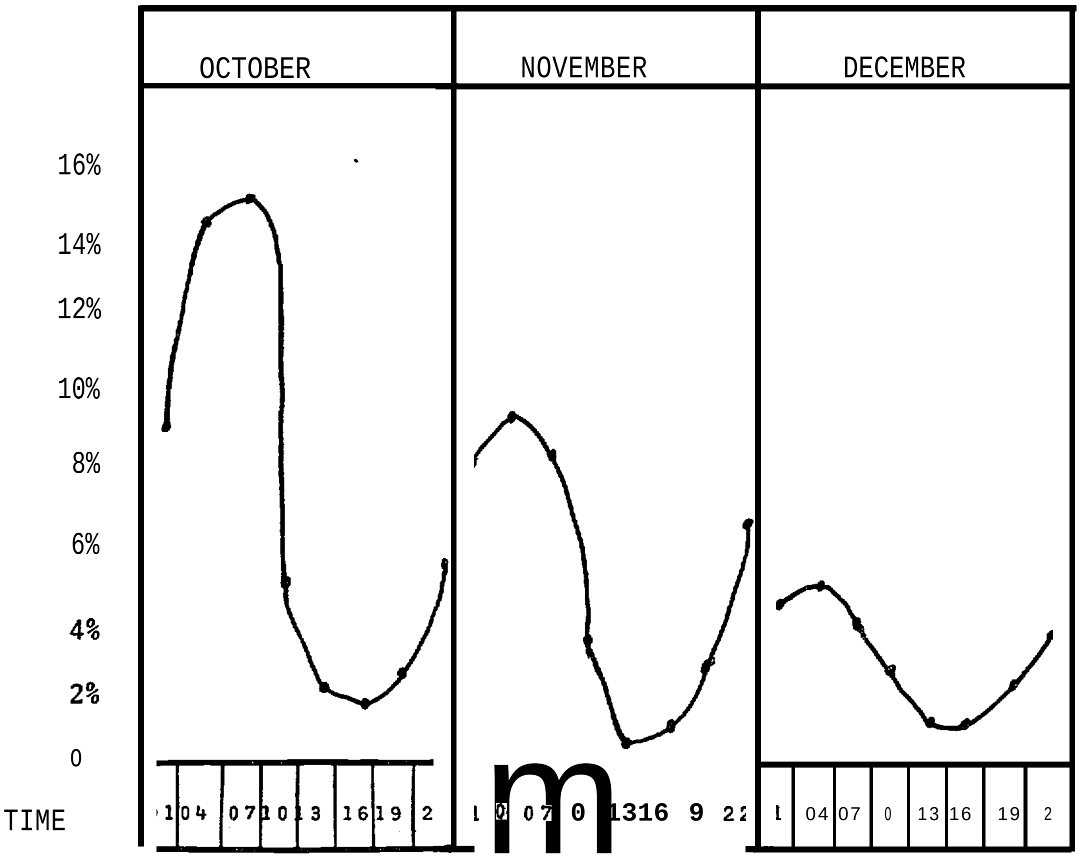
% OF OBSERVATIONS WITH CEILING BELOW 300 FEET (90M) AND/OR VISIBILITY BELOW 1 MILE (1.6KM).

Figure II-45 (cont.)



% OF OBSERVATIONS WITH CEILING BELOW 300 FEET (90M) AND/OR VISIBILITY BELOW I MILE (1.6KM).

Figure II-45 (cont.)



% OF OBSERVATIONS WITH CEILING BELOW 300 FEET (90M) AND/OR VISIBILITY BELOW 1 MILE (1.6KM).

C. Data Gaps

1. Climate Parameters.

The primary data gap for the study area exists in regular observations of surface conditions such as temperature, precipitation, winds, and factors affecting visibility over the Pacific Ocean and the inland bodies of water. Observations have been made by stationary weather platforms for short periods in these areas, and ships passing through often make weather observations that are given to the National Climatic Center. The Naval Weather Service Detachment (1976) has recently published analyses of various parameters for each one degree square. However, the observations used may be biased toward good weather since ships tend to avoid bad weather whenever possible.

Insolation records are not included in this chapter and are probably very sparse. Since cloudiness and insolation are directly related the total solar energy received at different stations can be deduced approximately from cloudiness information. It is, however, dependent on the daily distribution of cloudiness and on cloud type. Frequency distributions such as the ones given for Hoquiam in Table II-9 and for Olympia airport in Table 11-11 would be necessary. Insolation data would be needed, for instance, for determining locations where use of solar energy for power could be contemplated.

Better ceiling data are also needed for the inland waters at locations other than the Whidbey Island Naval Station.

2. Climate Analysis.

Up-to-date and complete climatological data summaries for many locations are not available. Many stations have summaries based upon observations before 1960. This means that extremes of temperature, precipitation, and other parameters may not be accurate. Also, the mean frequency of occurence of many climatological parameters, such as fog and reduced visibility, are not included in many climatological summaries.

Further analysis of storm-related data would be useful for the planning of offshore activities. More detailed analysis of storm tracks, determination of frontal passage frequencies for various months, and determination of the duration of cloud cover and rainfall related to frontal passage would be helpful. Some analyzed storm data will presumably result from the CYCLES Project at the University of Washington under the direction of Professor P. V. Hobbs.

Puget Sound convergence has not been studied effectively. Although a fairly general explanation can be given for this effect, a detailed study using available data from past occurrences would be useful to explain the physical processes involved and the effects in terms of wind speeds, precipitation duration and amounts, and other parameters.

Little analysis of funnel cloud formation and frequency has been done. Although they occur rarely in the study area, they do form under very specific conditions and can be highly destructive.

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III. Oceanography

Lincoln C. Loehr

A. Introduction

This chapter discusses the chemical, physical and biological oceanography of the Oregon-Washington-southern British Columbia coastal and offshore regions. Aspects of geological oceanography of the study area are covered in detail in Chapter I., Geology.

This discussion divides the study area into three sections. The first section is the Oregon-Washington-Vancouver Island coastal and offshore waters. The second section is the Oregon and Washington coastal estuaries. The third section is the Washington and British Columbia inland waters, sometimes referred to as Puget Sound and its adjacent waters (Figure 111-1]. The open coast region is not subdivided as such. Discussions in this region are either of a general nature, or are oriented south to north. The effects of the Columbia River effluent on this entire region receive special attention. Puget Sound and its adjacent waters are subdivided into the Strait of Juan de Fuca, Puget Sound proper (including Hood Canal), North Sound, which includes the San Juan Islands and surrounding water, and the Strait of Georgia.

Since much of the oceanographic work that has been performed in this region is of a descriptive nature, the emphasis of this report is also descriptive. Benchmark (baseline) quality data and predictive data are rare for the open coastal waters. Some benchmark and predictive data are available for the inland waters of Washington and are mentioned.

Whenever possible, interpretive work has been used. In many cases, more interpretation of available data is needed. In cases where some data exist but in insufficient amounts for comprehensive interpretation, the data themselves may be presented and the lack of interpretation cited as a data gap.

Data were collected for this report from the libraries and files of the University of Washington, Oregon State University, U.S. Environmental Protection Agency (EPA), Washington State Dept. of Ecology, Pacific Marine Center (NOAA), Oceanographic Institute of Washington, and the Army Corps of Engineers. In addition, data were extracted from Technical Reports, Special Reports, books, journals, theses, and unpublished works. Considerable long term data of historical significance exist for Puget Sound. Knowledgeable people involved in research in the region were contacted either in person, or by phone. The Oceanographic Institute of Washington's The 1975 Compendium of Current Environmental Studies in Puget Sound and Northwest Estuarine Waters (Schott and Pizzo, 1976) was also used along with personal contacts to identify major on-going projects.

B. Results of Data Collection and Analysis

1. Oregon-Washington-Vancouver Island Coastal Oceanography.

The area considered here is the coastline of the Pacific Northwest, extending from Barkley Sound on southern Vancouver Island (49th parallel) to the Oregon-California border (42nd parallel). The study area extends to 100

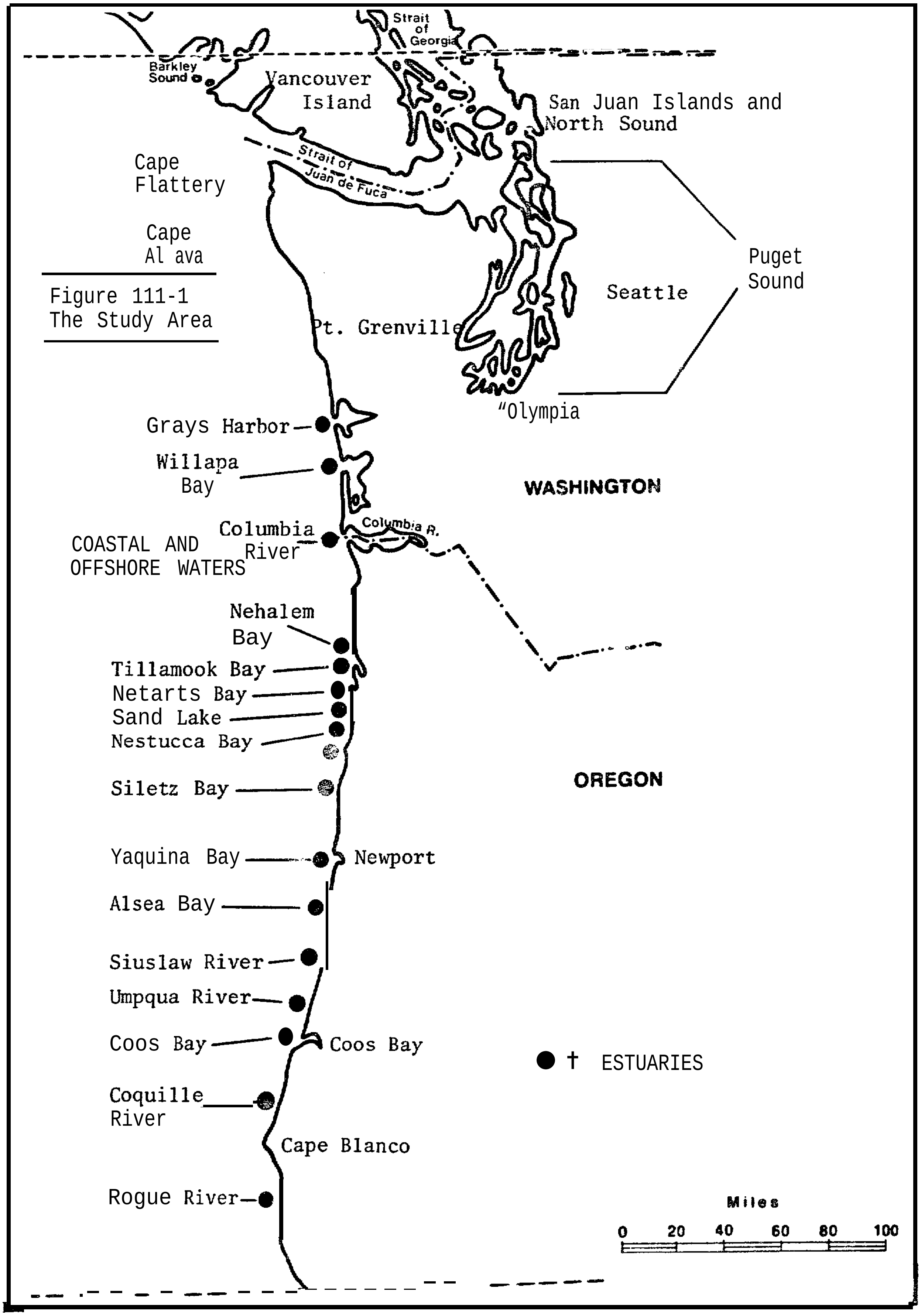


Figure 111-1
The Study Area

miles offshore.

The coastal area can be characterized as a series of sandy beaches interspersed with rocky headlands. This coastline is oriented in a north-south direction and, except for local headlands and bays, is nearly straight. A large portion of the coastline is subjected to the full impact of breaking waves. The wave environment is severe in the winter, producing turbulent mixing from surface to bottom over the shelf, and moving sediment as far out as the shelf edge.

The offshore surface current flow is to the south in summer and to the north in winter, in response to seasonal changes in the winds. Upwe11 - ing occurs nearshore during the late summer months in response to northerly winds which drive the surface waters offshore by Ekman transport (Smith, 1968) . Upwelling brings added nutrients, affecting the productivity of the area, and colder water, which affects the coastal weather.

A number of rivers empty into the region, the most significant being the Columbia River. The dilution effect of the Columbia plume extends to well offshore of Northern California during the summer, and during the winter it heads north and may enter the Strait of Juan de Fuca. The Columbia River plume has been tracked by its salinity, alkalinity, radioactivity, productivity and turbidity. Sediments on the shelf are largely derived from the Columbia River.

The shelf in the region is narrow to the south (about 24 km), widens to SS km off central Oregon, and then varies from 30 to 70 km wide to the north. The shelf off of Washington is scalloped by numerous submarine canyons, of which the Astoria and Juan de Fuca canyons are considered to be active.

The water is relatively free of pollution. Upwelling in summer brings deep water to the surface, with its lower oxygen and higher nutrient and CO_2 concentrations. The operation of plutonium producing reactors at Hanford introduced a large amount of radionuclides into the Columbia River in earlier years, and considerable analysis of its traces in the water column, the sediments, and the biota have been conducted.

The rich supply of nutrients brought to the surface by upwelling stimulates the growth of phytoplankton, producing population explosions or blooms of zooplankton, which feed on the phytoplankton. The region is rich in food for higher trophic levels. The success and timing of the fisheries in the Pacific Northwest is closely correlated with the timing and the location of the upwelling zones.

For the most part, there is a general uniformity to the coastal region. The plant and animal composition of the entire region shows much similarity from south to north. Common species reported in northern Washington have also been reported in Northern California and vice versa. There are no major faunal or floral boundaries in the region, and the differences in biota seen between the boundaries of the region generally occur gradually.

Normally, it is the biologic community that must adapt to the physical, chemical and geologic system. Since the general ecological factors that are thought to control biological distributions (temperature, substrate, salinity) all show a relative uniformity throughout the region, the absence of a biological boundary is not surprising.

a. Physical Oceanography. This section addresses the physical properties of the water and the processes of motion that occur. Waves are included in this section, being a-lateral transfer of energy along the air-water boundary.

From January 1961 through December 1963, the Department of Oceanography, University of Washington, conducted a research program to determine the distribution of Columbia River water in the Northeast Pacific Ocean (McGary, 1971). Thirty-five cruises to the area were made, and more than 3,300 hydrographic stations were established. Figure III-2 presents the station locations that were occupied during this study. Although other studies have been performed more recently, this study was selected to characterize the water because of its duration (3 consecutive years) and because it encompassed the entire coastal study area.

i. Water Characteristics. The following discussion is extracted in part from Budinger, Coachman and Barnes (1964).

The northeast Pacific Ocean is a region of net dilution, in which the precipitation on the sea surface and adjacent land masses exceeds the evaporation. The land runoff acts as a line source of freshwater extending from southern Alaska to the coast of northern California. Along this line the Columbia River is by far the largest single contributer. Figure III-3 shows the Columbia River drainage basin and average seasonal extent of the Columbia River effluent based on the 1961-63 studies. The dominance of the Columbia River is readily apparent.

In the upper kilometer of the water column, the vertical thermohaline structure is characterized by three layers or zones. The surface zone, 75-100 meters thick, is somewhat diluted because of the runoff and net precipitation. The dilution is not, however, accompanied by large changes of salinity with depth in the zone. The temperature within the zone decreases markedly with depth in summer, but in winter is nearly uniform. The second zone, a quasi-isothermal halocline, shows a marked increase of salinity with depth, and lies approximately within the 100-200 meter depth increment. In the deeper waters, which comprise the third zone, the temperature slowly decreases and the salinity slowly increases with depth.

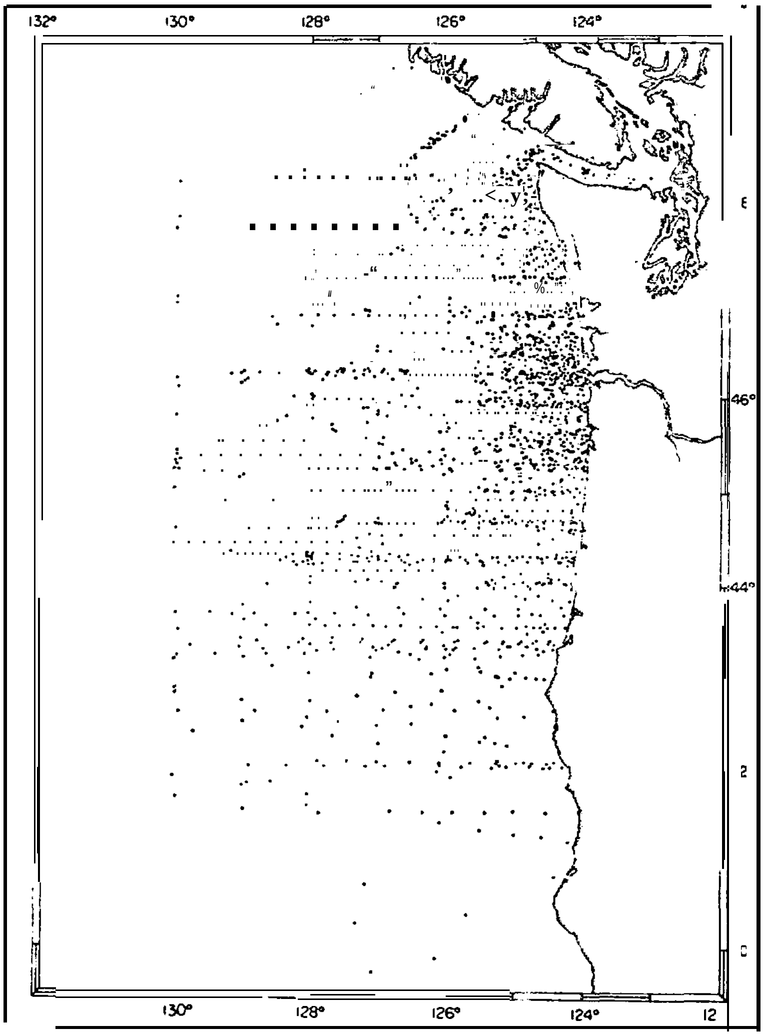
The salinity at the bottom of the halocline is very nearly constant (3.38 ± 0.1 o/oo) throughout the year. The values at the upper boundary of the halocline (which varies in depth from 75 m to 150 m) change over the year 0.2 o/oo or less at any given location. In the area affected by Columbia River discharge, the salinity at the upper halocline boundary is approximately 32.7 o/oo, increasing toward the west and decreasing toward the north.

Within the area, the variation of freshwater contribution with time is small. Although there is a net upward transfer of salt across the halocline, the constant salinity at the upper boundary suggests that a dynamic balance is maintained with water added by precipitation and runoff. The top of the halocline may be considered the lower limit of penetration of seasonal effects.

Immediately along the Washington-Oregon coast is a continental

Figure III-2

Hydrographic Stations Occupied
From 1961 to 1963[§]



[§]McGary, 1971.

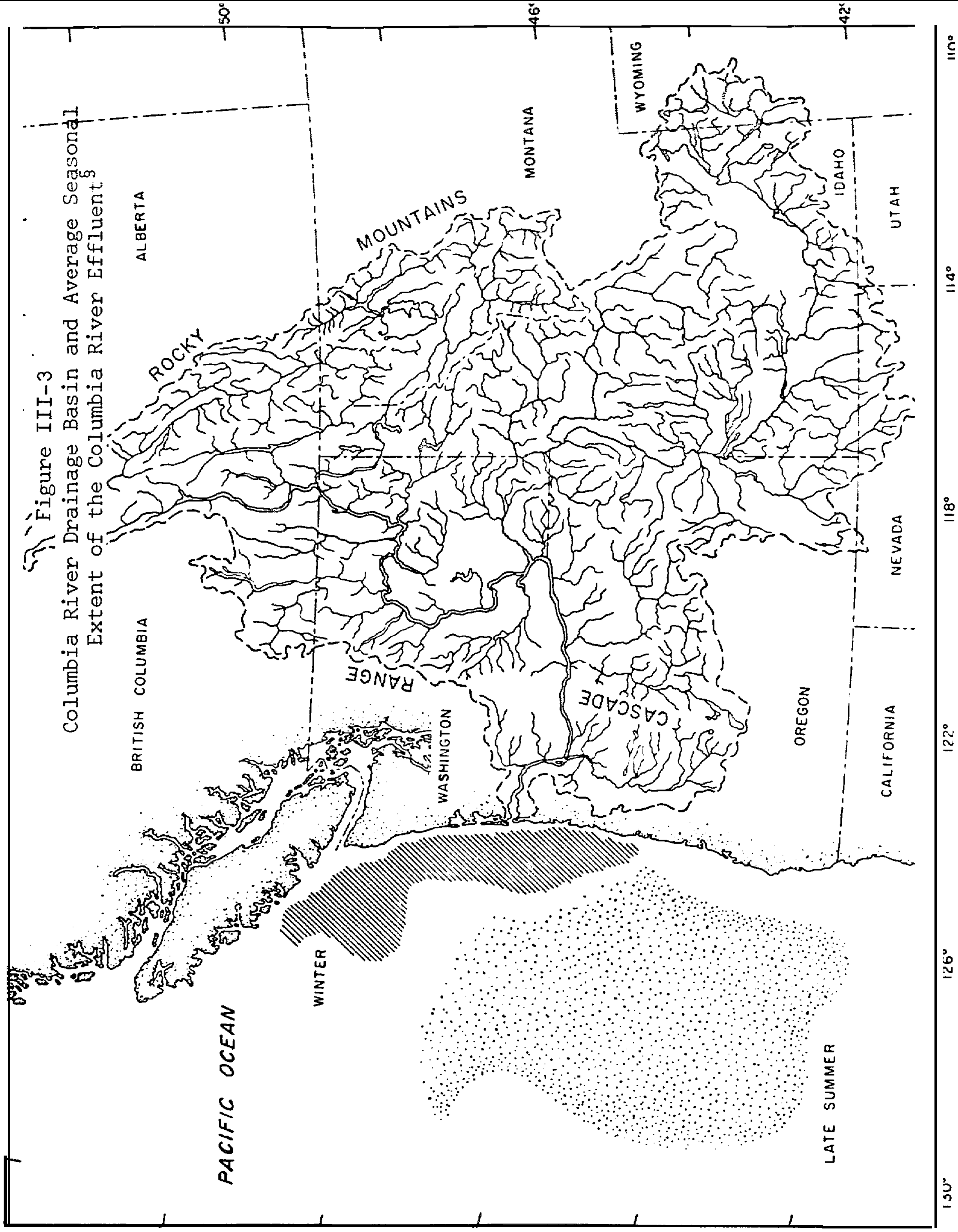


Figure III-3
Columbia River Drainage Basin and Average Seasonal
Extent of the Columbia River Effluent[§]

[§]McGary, 1971.

shelf 30 to 70 kilometers wide. The water lying over the shelf and the adjacent continental slope undergoes somewhat greater fluctuations in temperature and salinity than the water farther offshore. Upwelling of deeper water along the continental slope and tidal or hydraulic forces nearshore help create the rapid changes that are found in this area.

The basic structure described above is modified by the Columbia effluent as shown in Figure III-4. The base of the upper halocline was identified on plots of salinity versus logarithm of depth by a sharp change in slope at a salinity between 32.4 o/oo and 32.7 o/oo. The change in slope in this salinity range, together with the fact that the surface water salinity of the area immediately affected by the plume falls in approximately the same range, suggests that 32.5 o/oo is a good index salinity for ascertaining the horizontal and vertical extent of the river effluent (Budinger, Coachman and Barnes, 1964).

a) Temperature. Seasonally averaged temperature distributions for the study area based on the 1961-63 data are presented in Figures III-5 through III-7 for 0 meters, 50 meters, and 200 meters. Although real temperature values were used in deriving these figures, it must be emphasized that they represent averaged values and are conceptual in nature.

The temperature of the nearshore coastal surface water varies seasonally, ranging from an average high of 17.7°C to an average low of 7.6°C. The annual range in mean temperature is small, however, with mean summer temperatures (14°C) being about 5°C warmer than mean winter temperatures (9°C). Such a small annual temperature range is in sharp contrast to that of many other coastal regions.

Summer temperatures fluctuate within a 4 to 6°C range while winter temperatures are constrained to a 1 to 2°C range. Due to the warming influence of the Columbia River, summer temperatures are 2 to 3°C higher in the vicinity of the river mouth (from Willapa Bay to Tillamook Head).

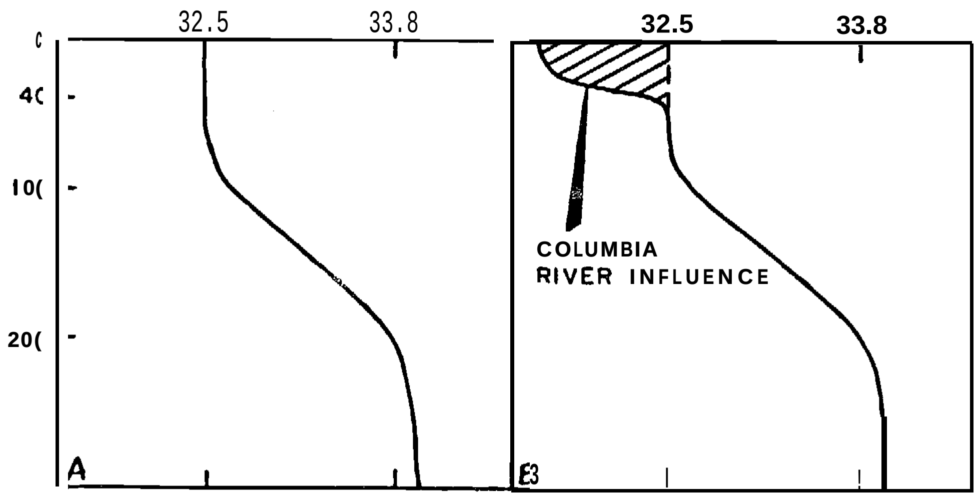
Coastal upwelling, most prevalent off southern and central Oregon and northern California, tends to suppress the high surface temperature normally expected during summer. Average temperatures of 9.5 to 10.5°C are observed in regions of active upwelling. At the same time, temperatures of 12 to 14°C are found in nearby coastal and offshore regions undergoing little or no upwelling. The upwelling of colder deeper water to the surface is evident along the shore in Figure III-5.

Surface temperature measurements have been made from three lightships along the Pacific Northwest coast, the Umatilla (northern Washington), Columbia River, and Blunts Reef (off Cape Mendocino, northern California). Table III-1 presents average monthly surface temperatures, total number of observations, and the period of record. Figure III-8 graphically presents the lightship surface temperature data.

Sea surface temperatures have been measured in the study area

Figure III-4

Salinity Structure of the Oceanic Regime, and the Influence of the Columbia River Effluent on This Structure[§]



[§]Budinger, Coachman and Barnes, 1964.

Figure III-5

Typical Seasonal Temperature Distribution at 0 Meters[$]

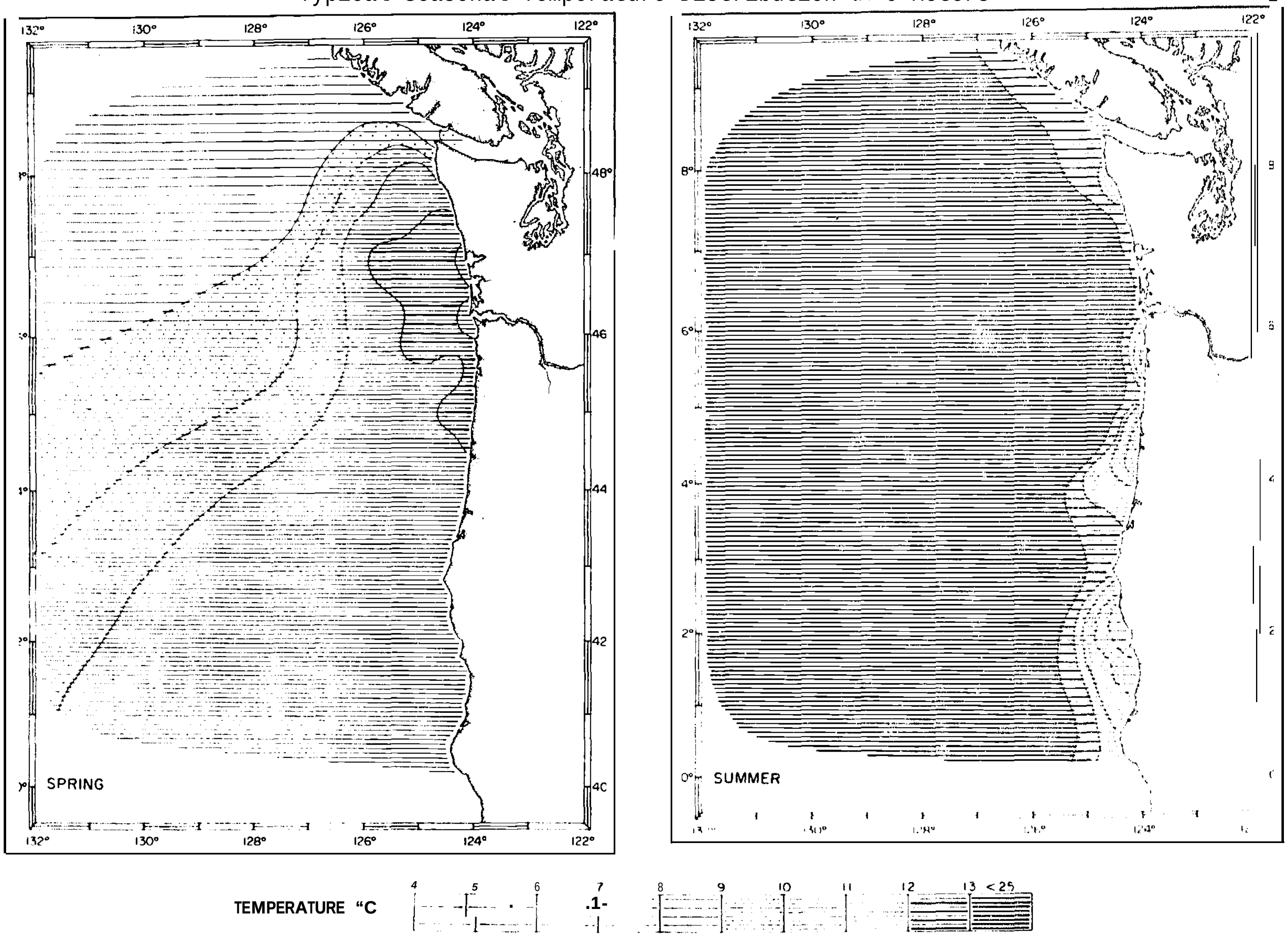
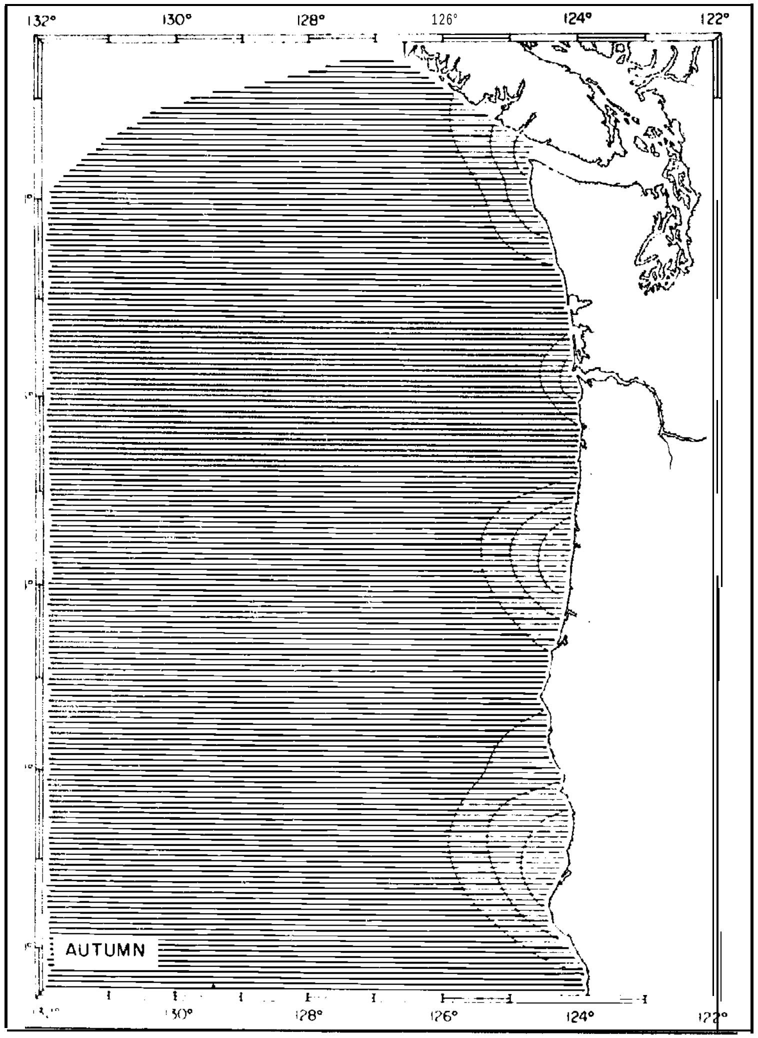
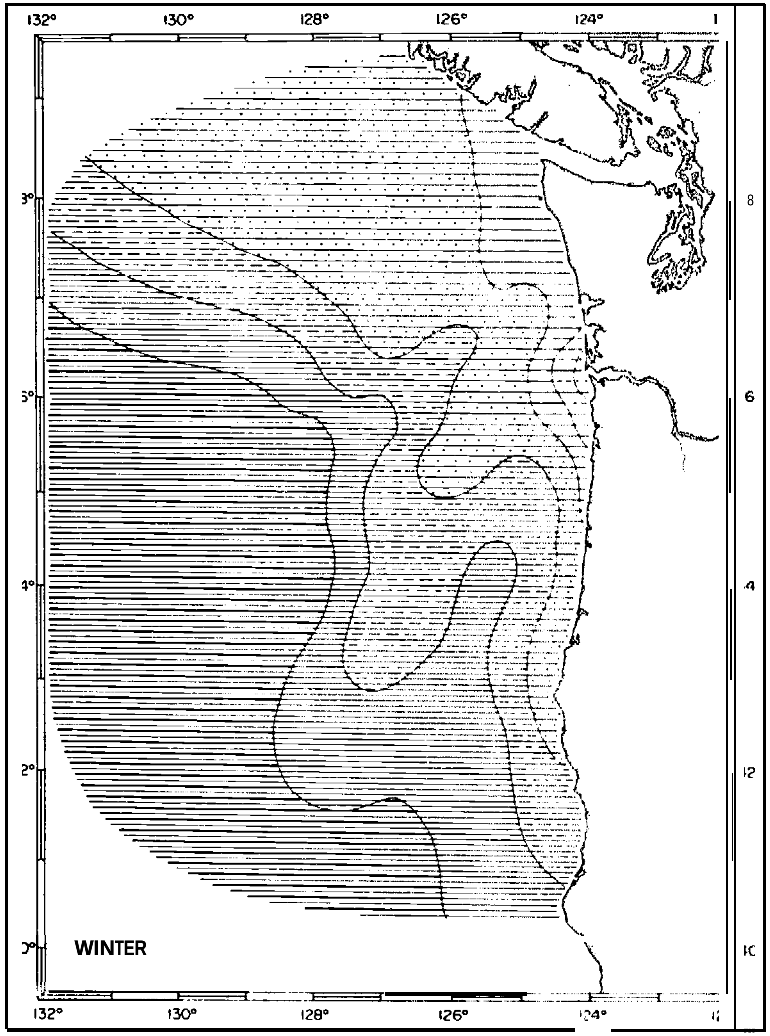


Figure III-5 (cont.)





[§]McGary, 1971.

Figure III-6

Typical Seasonal Temperature Distribution at 50 Meters§

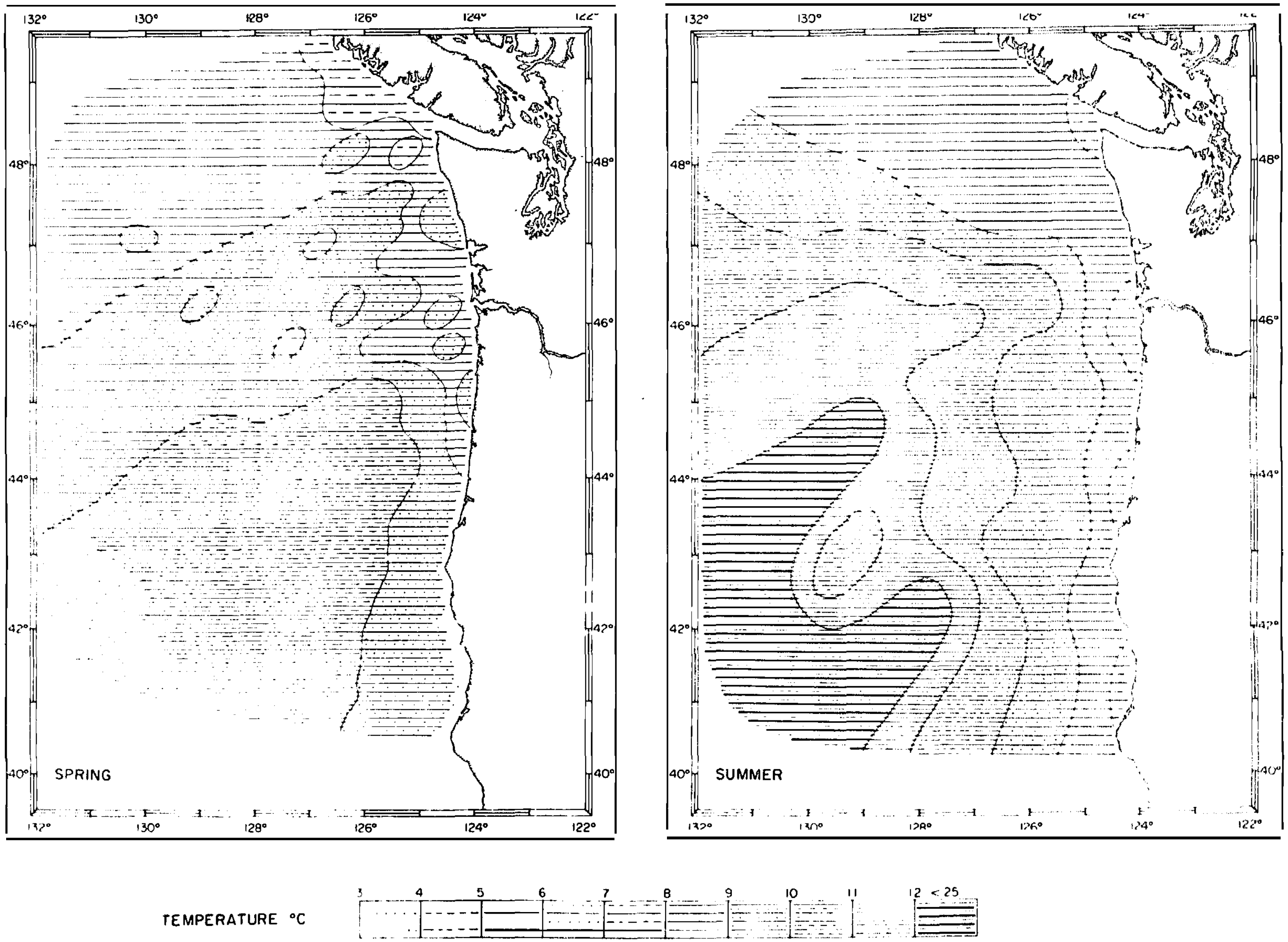
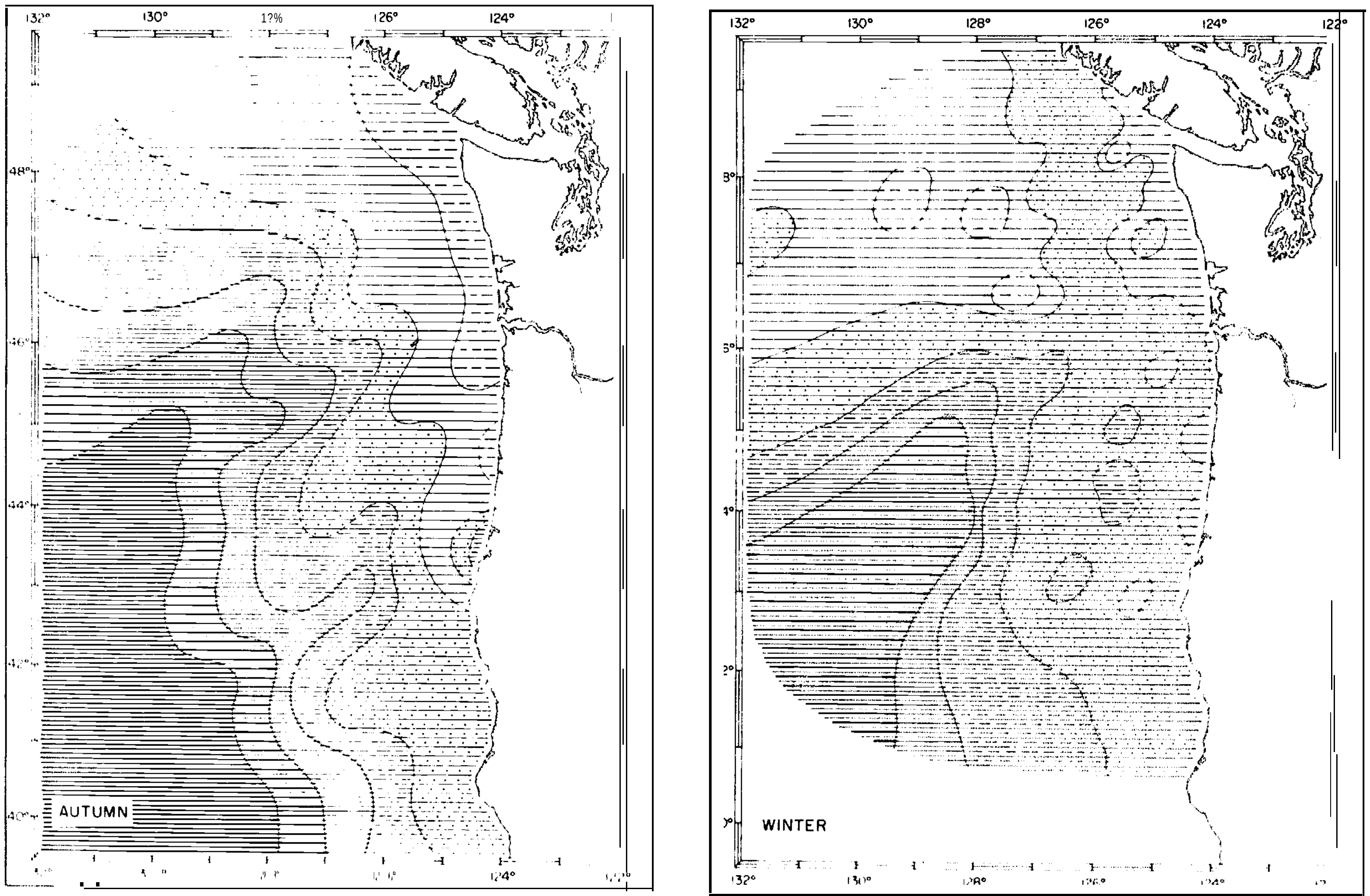


Figure III-6 (cont.)



§McGary, 1971.

Figure III-7

Typical Seasonal Temperature Distribution at 200 Meters§

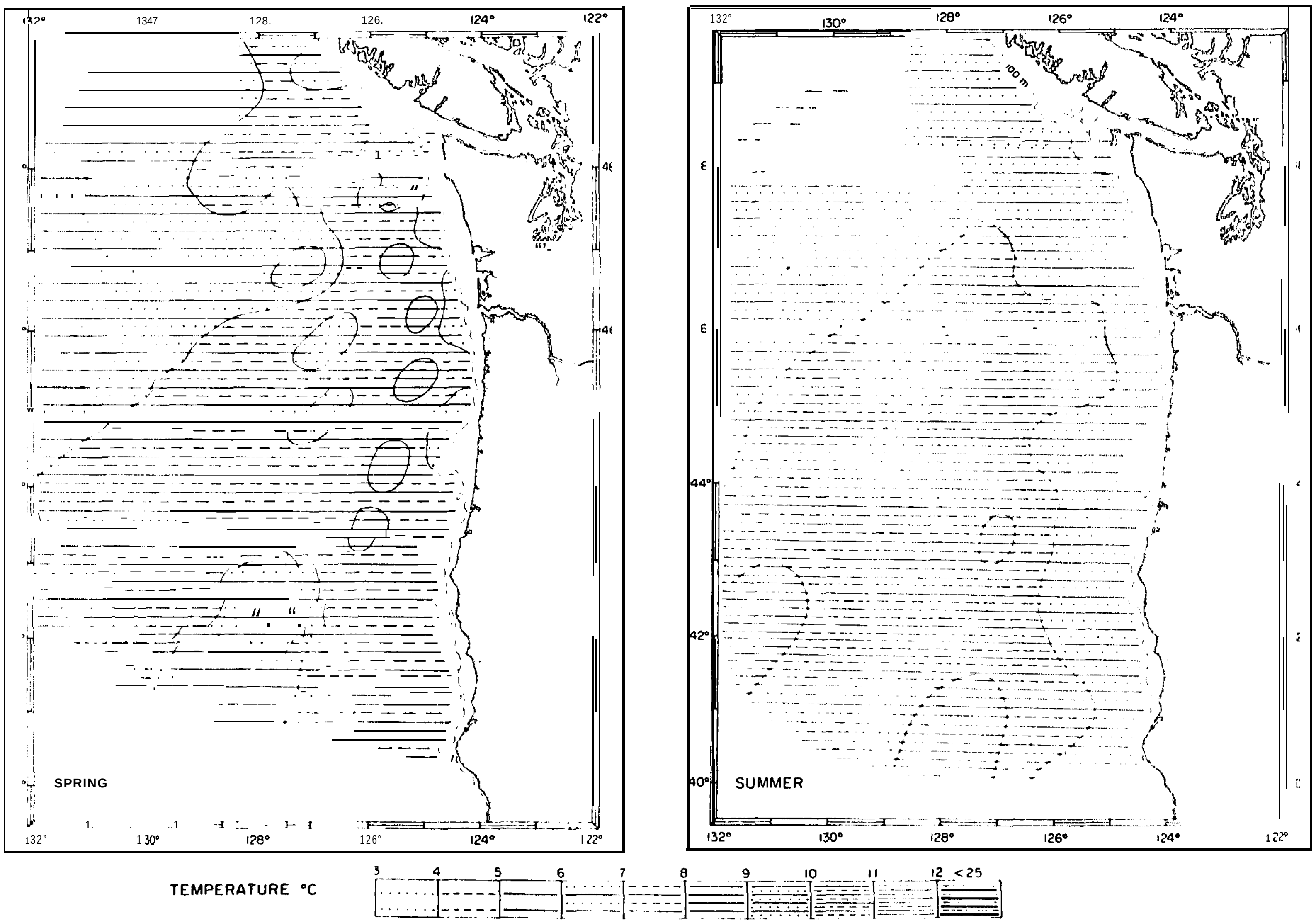
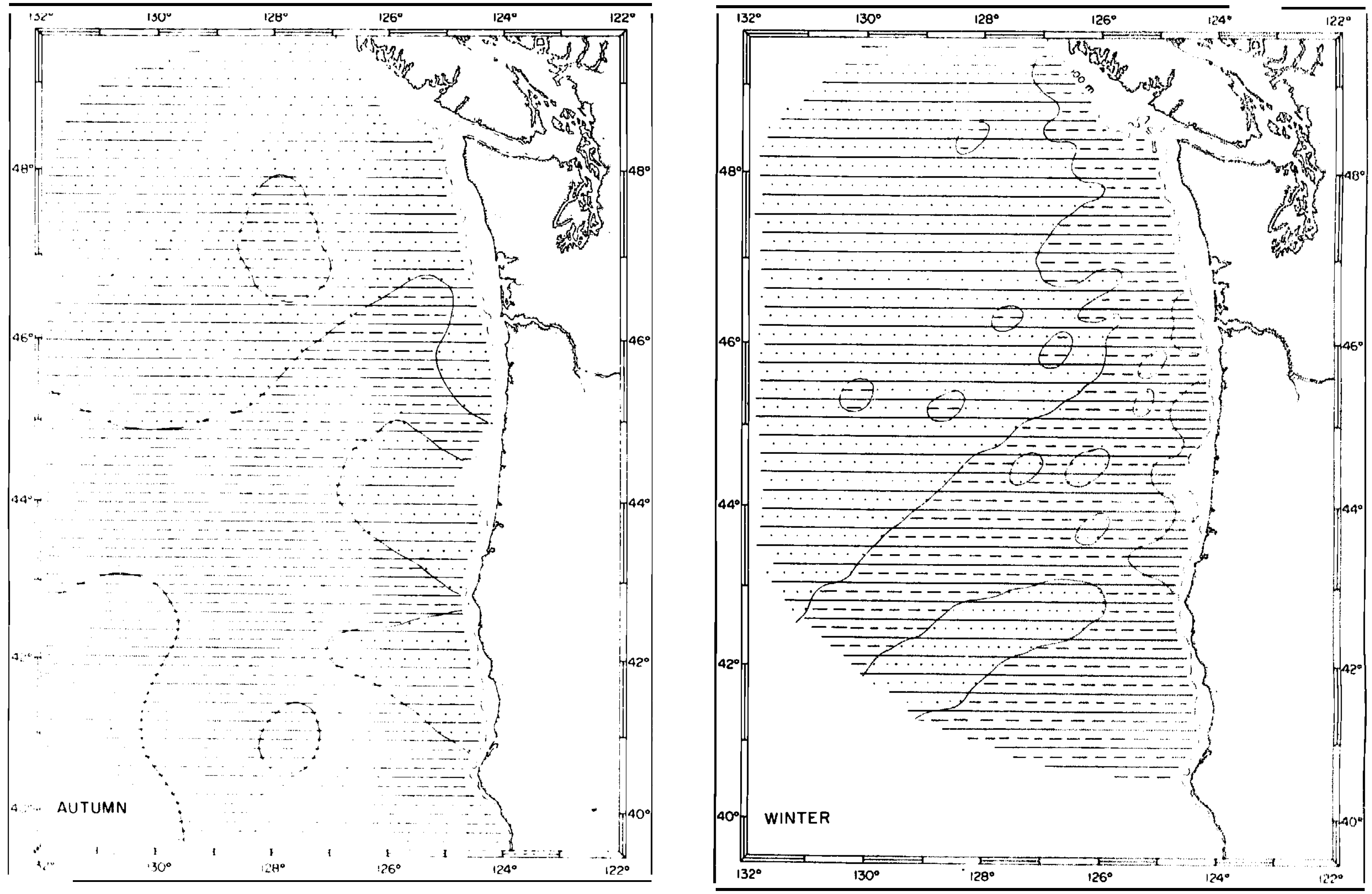


Figure III-7 (cont.)



§McGary, 1971.

Table III-1

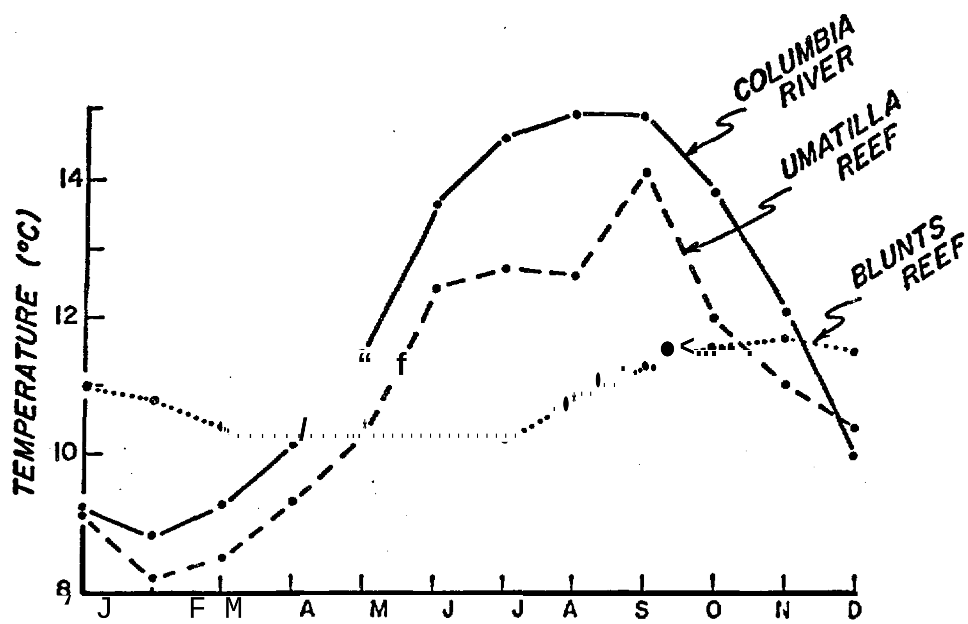
Average Monthly Surface Temperatures (°C) From
Lightships off the Pacific Northwest Coast[§]

Station and Period of Record	Monthly Avgs & Total No Obs	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Ott	Nov	Dec
Umatilla Reef Lightship 1966-1969	Avg. Mean	9.11	8.16	8.49	9.26	10.29	12.40	12.67	12.56	14.05	12.00	10.97	9.40
	Avg. Maximum	10.40	9.10	9.11	11.68	13.07	15.50	14.60	14.58	16.39	14.11	12.04	11.03
	Avg. Minimum	7.97	7.49	7.68	7.62	8.85	12.82	11.22	10.18	11.79	10.64	9.53	8.42
	Total No. Ohs.	93	S7	65	73	88	119	94	88	83	80	80	78
Columbia River Lightship 1965-1969	Avg. Mean	9.30	8.82	9.20	10.10	11.50	13.64	14.S6	14.91	14.92	13.83	12.14	10.00
	Avg. Maximum	10.61	10.63	10.06	11.37	13.07	15.56	16.50	17.07	16.48	15.17	13.46	11.89
	Avg. Minimum	7.55	7.53	8.03	9.22	12.39	11.41	12.71	12.65	12.89	12.29	10.56	7.90
	Total No. Ohs.	77	118	112	109	123	151	152	117	93	89	112	103
Blunts Reef Lightship 1923-1964	Avg. Mean	11.0	10.8	10.4	10.2	10.3	10.3	10.2	10.8	11.3	11.6	11.7	11.5
	Avg. Maximum	12.1	11.8	11.6	11.4	12.0	12.2	11.9	12.7	13.3	13.6	13.3	12.9
	Avg. Minimum	10.1	9.9	9.1	8.9	9.1	8.9	8.9	9.4	9.9	10.1	10.1	10.1

[§]Oregon State University, 1971.

Figure III-8

Mean Monthly Surface Temperature Recorded at Three Lightships Along the Pacific Northwest Coast[§]



[§]Oregon State University, 1971.

using airborne infrared radiometers. Monthly surveys for three Pacific coast areas have been conducted by the Tiburon Marine Laboratory of the Bureau of Sport Fisheries and Wildlife, Department of the Interior, in cooperation with the U.S. Coast Guard. The flight pattern extends from Cape Flattery, Washington to Newport, Oregon and offshore to approximately 96 km. In the summer of 1969 the Department of Oceanography, Oregon State University, conducted daily infrared radiometer surveys along the Oregon coast to approximately 48 km offshore. These daily studies used closer spacing of flight tracks and allowed the temperature contours to be constructed closer to shore and with greater accuracy of detail than the Tiburon Marine Laboratory studies. Figure III-9 presents temperature contours from one of the Oregon State University surveys (Oregon State University, 1971).

The Department of the Environment, Canada is funding a study by S. Tabata and J. Gower of the Institute of Ocean Sciences, Patricia Bay, B.C. to map surface temperatures from thermal imagery from NOAA satellites. Both digital and photographic imagery are used and values are compared with ship measurements. It is hoped that these observations will help deduce oceanographic processes. The project is on-going and some data is available through Tabata and Gower. A report should be out in late 1977.

b) Salinity. Seasonally averaged salinity distributions for the study area based on the 1961-63 data are presented in Figures 111-10 through 111-12 for 0, 50, and 200 m. Although real salinity values were used in deriving these figures, it must be emphasized that they represent averaged values and are conceptual in nature.

The seasonal effects of the Columbia River plume are evident in Figure 111-10. The plume produces dilution of the surface waters to less than 32.5 o/oo.

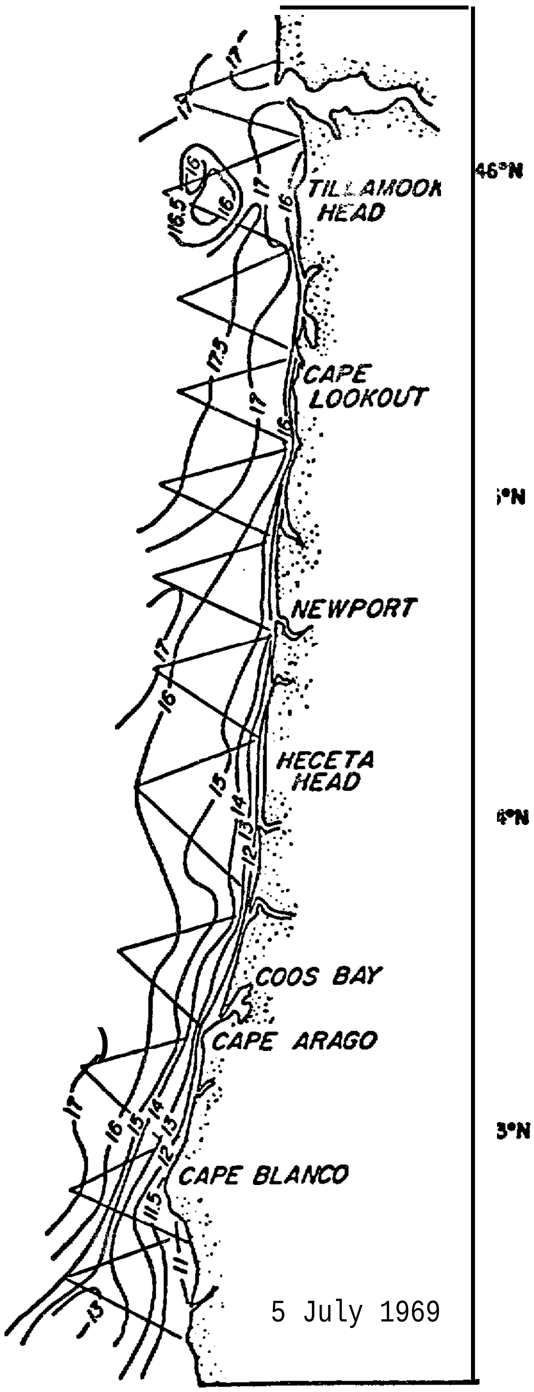
Average surface salinities are higher in summer than in winter (approximately 33.5 o/oo and 32 o/oo, respectively). Coastal upwelling tends to keep salinities high during the summer, while winter rains and high river runoff tend to lower surface salinities. Where coastal upwelling is prevalent, salinities are frequently observed in excess of 33.8 o/oo, but seldom exceeding 34.4 o/oo.

In winter, the discharge from the Columbia River flows northward along the Washington coastline. Mean salinities observed along the southern Washington coast are low (2S to 28 o/oo), with maximum salinities rarely exceeding 30 o/oo. In June, during periods of peak river flow, salinities less than 20 o/oo are observed from Seaside, Oregon to Willapa Bay, Washington.

c) Density. The density of the water depends on salinity, temperature, and to a small extent, pressure (or depth). An abbreviated symbol for density has been introduced in oceanography: $\sigma_{S,t,p} = 1{,}000 \times (\text{density}_{S,t,p} - 1)$. For convenience density is most often computed for atmospheric pressure and is written as σ_t (sigma-t).

Figure 111-9

Temperature Contours (°C) from a Typical Infrared Survey Conducted by Oregon State University's Sea Grant Project "Albacore Central"[§†]



[§]Oregon State University, 1971.

[†]Note close spacing of flight track provides capability to construct contours close to shore.

Figure III-10

Typical Seasonal Salinity Distribution at 0 Meters§

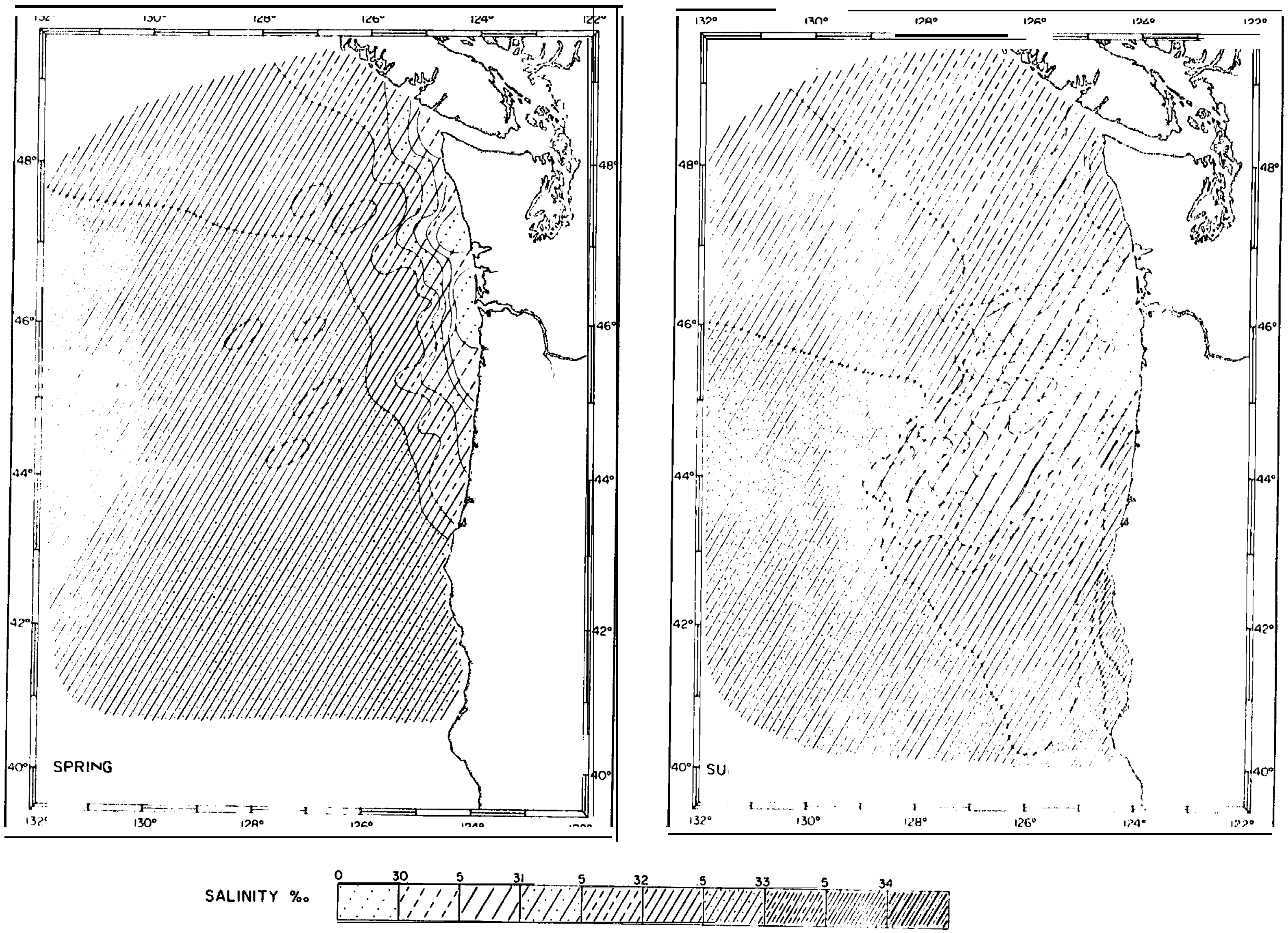
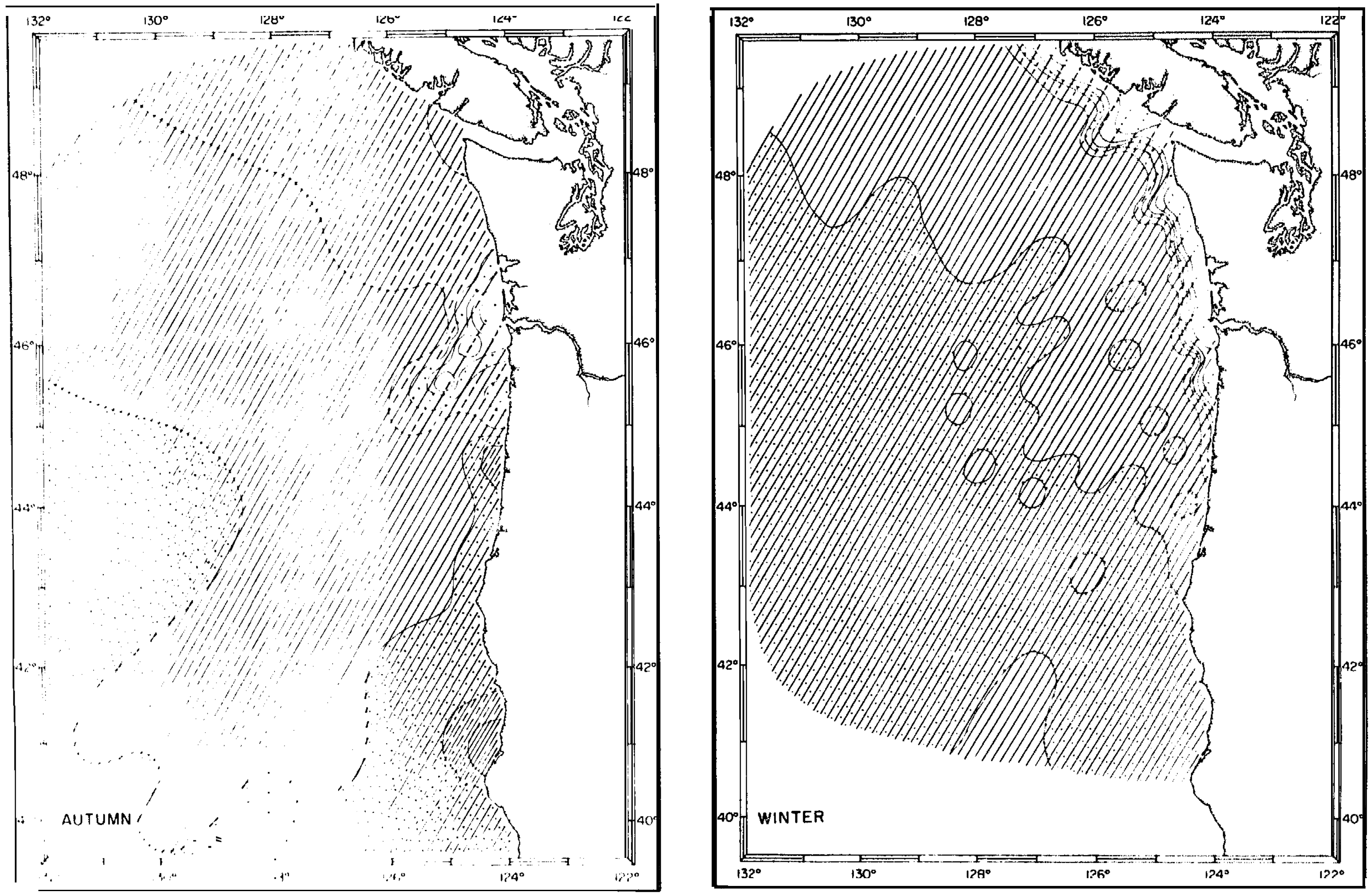


Figure III-10 (cont.)



§McGary, 1971.

Figure 111-11

Typical Seasonal Salinity Distribution at 50 Meters[9]

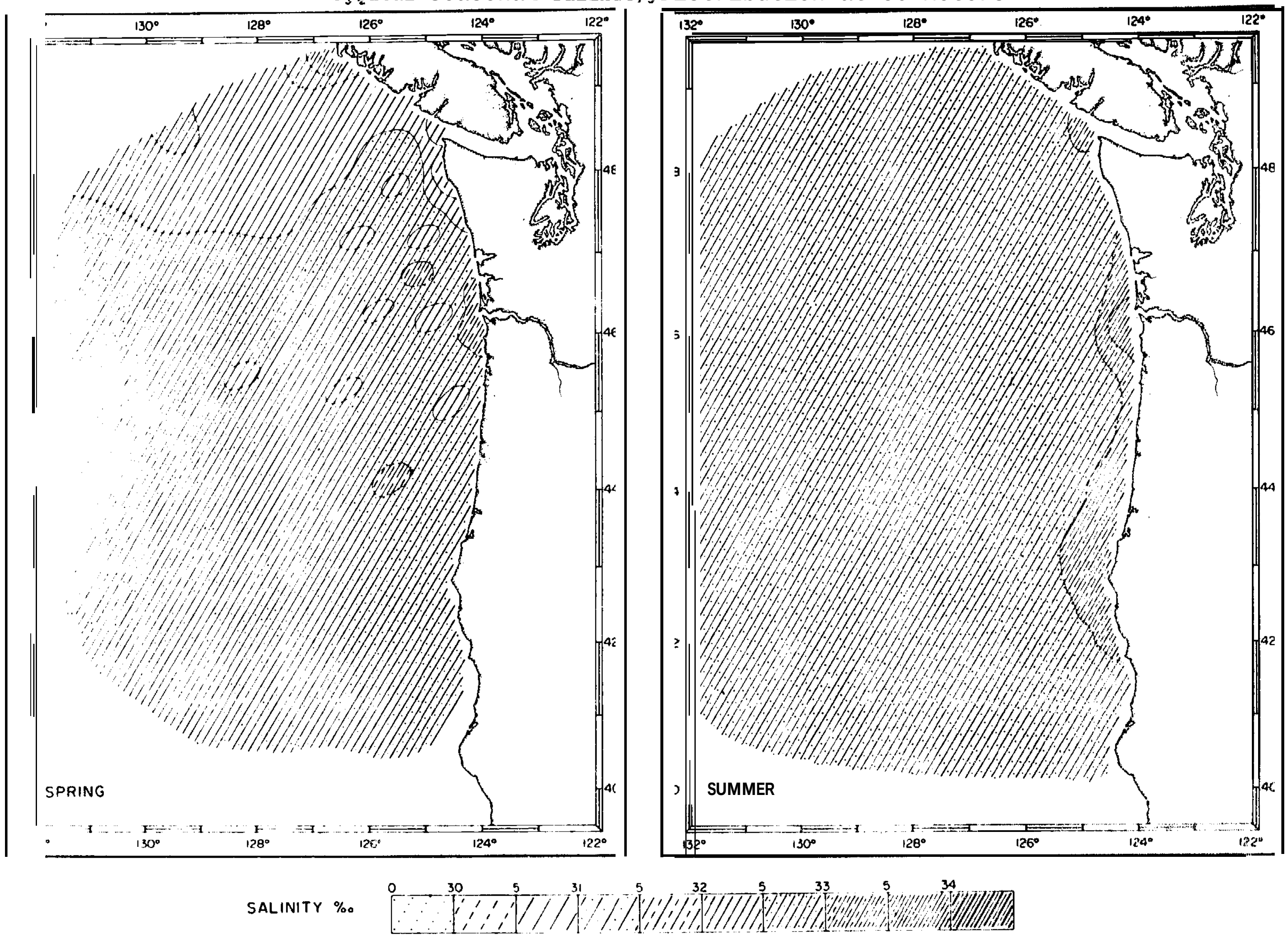
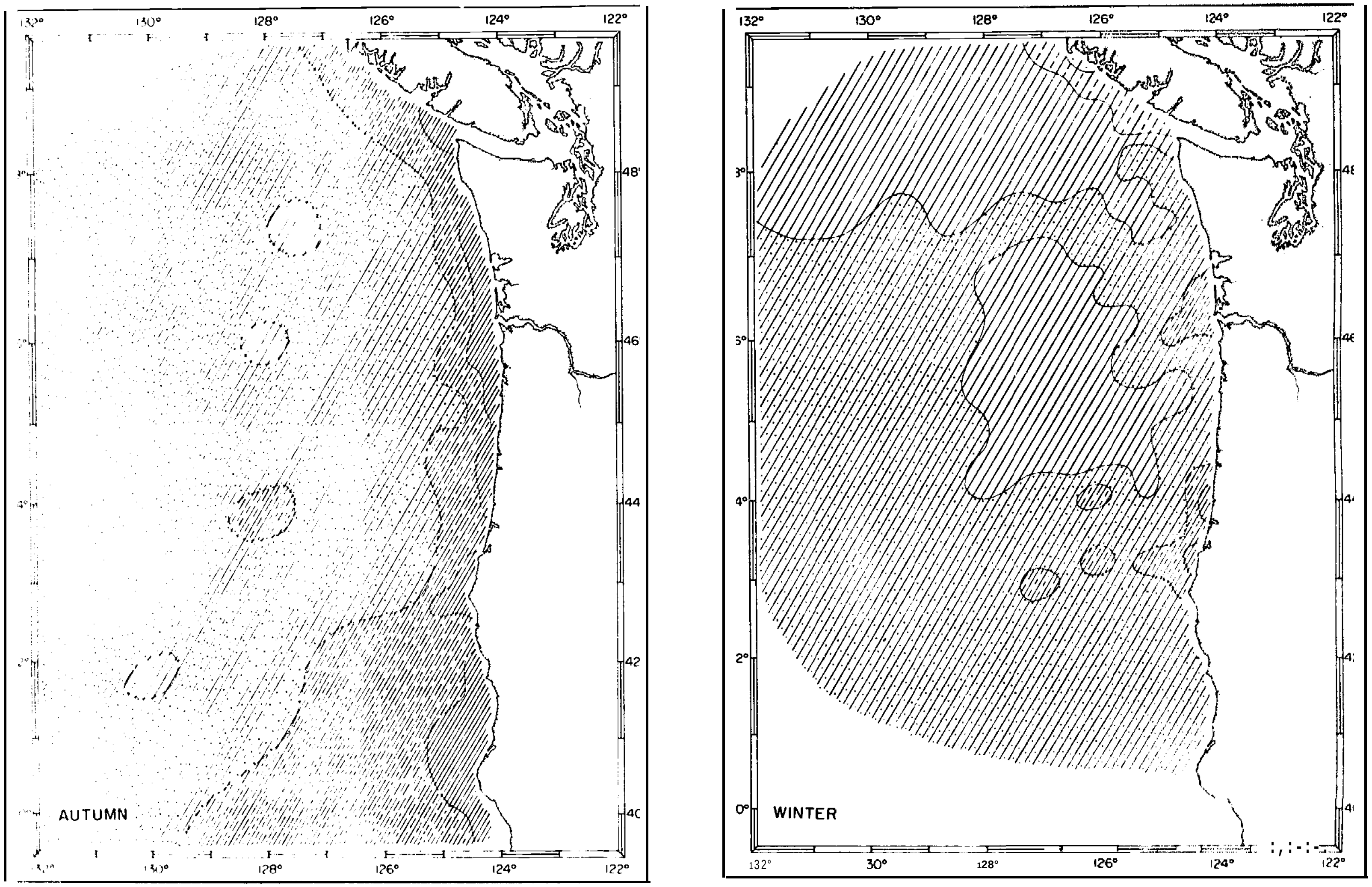


Figure 111-11 (cont.)



§McGary, 1971.

Figure 111-12

Typical Seasonal Salinity Distribution at 200 Meters[9]

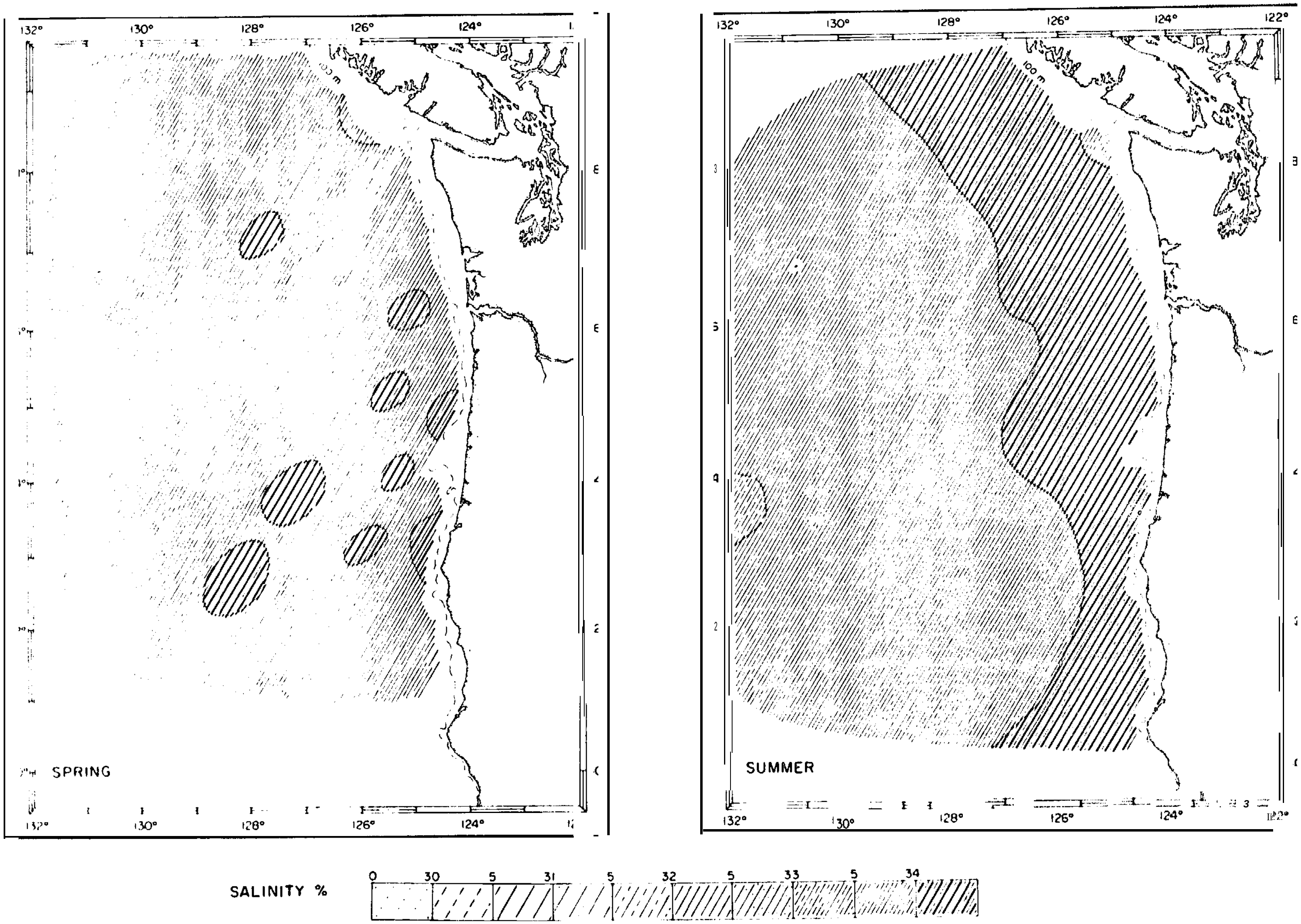
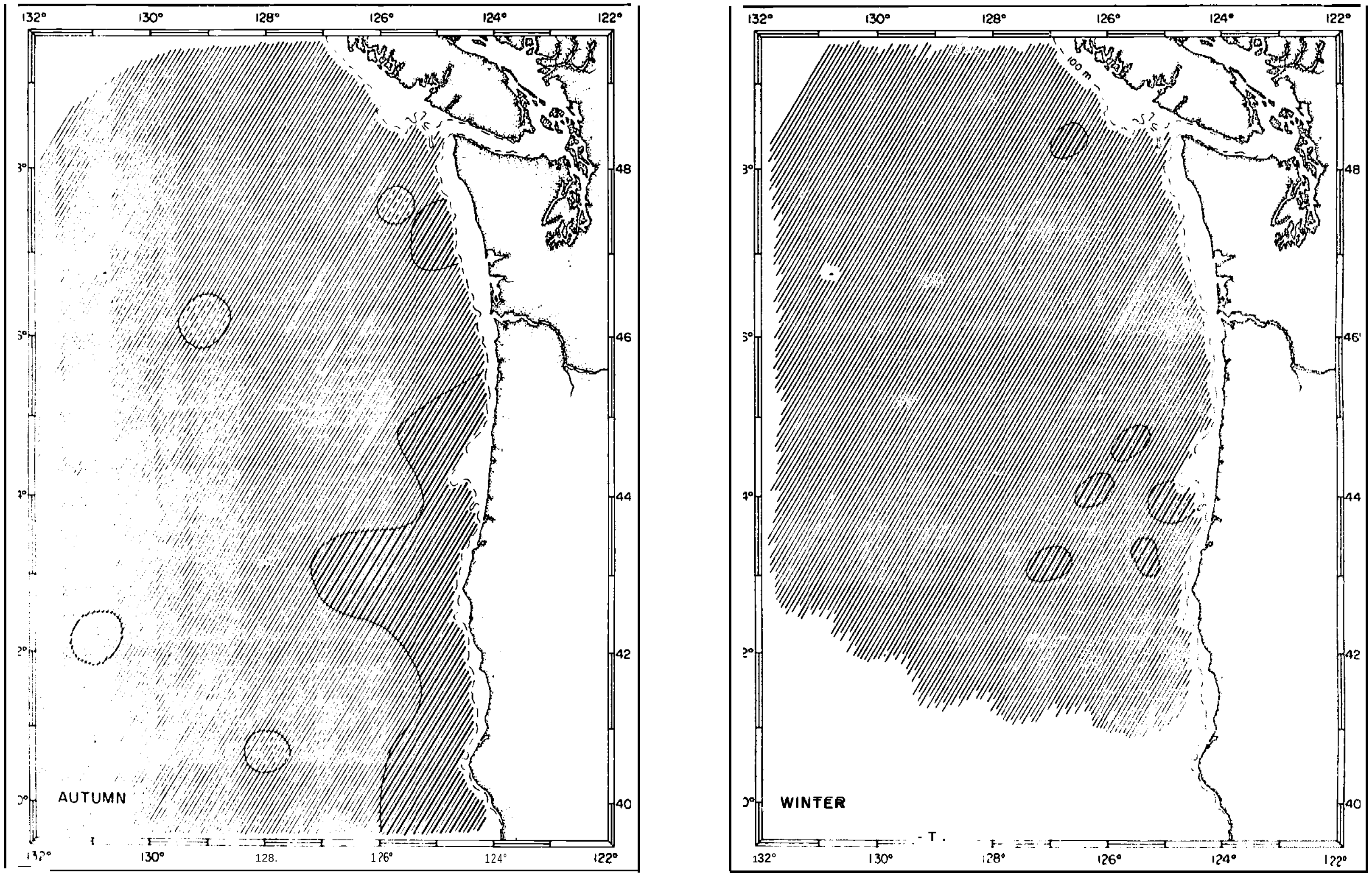


Figure 111-12 (cont.)



§McGary, 1971.

Density (σ_t) of sea water as a function of temperature and salinity (T-S) is presented in Figure 111-13. A single point on the T-S diagram characterizes that particular sample which represents a particular water mass. A T-S plot for discrete samples throughout the water column is a valuable tool in characterizing the water. Figure III-14 presents T-S plots for water off the coast of Oregon. Samples were taken over a ten year period along a line at 44 40'N. Distinctly different water mass characteristics exist, indicative of large scale changes due to advection.

Seasonally averaged density distributions for the study area based on the 1961-63 data are presented in Figures 111-15 through III-17 for O, 50, and 200 m. Although real density values were used in deriving these figures, it must be emphasized that they represent averaged values and are conceptual in nature.

The Columbia River plume is apparent in Figure 111-15. Coastal upwelling is especially apparent along central and southern Oregon in Figure 111-15, and under the Columbia River plume as a density high at 50 meters (Figure 111-16).

Typical year round temperature, salinity, density, and dissolved oxygen values for 1,000 m are presented in Figure 111-18.

Vertical profiles showing temperature, salinity, and density distribution normal to the coast will be presented in section B.1.a. iii. e) in a discussion of upwelling.

d) Turbidity. Harlett and Kulm (1973) reported measurements of turbidity along four transects and at two time-series stations off the coast of northern and central Oregon. Suspended material was found to concentrate principally at the seasonal thermocline, at the permanent pycnocline, and at the bottom. Thickness and intensity of the bottom layer vary with both current strength and the amount of fine material in the surface sediment, whereas the intensity of the midwater layer appears to be related to the distance from the sediment source. The midwater layer also increases in vertical extent away from the shore. Seaward transport in the upper two layers provides a mechanism by which terrigenous sediment and biogenous material bypass the outer continental shelf.

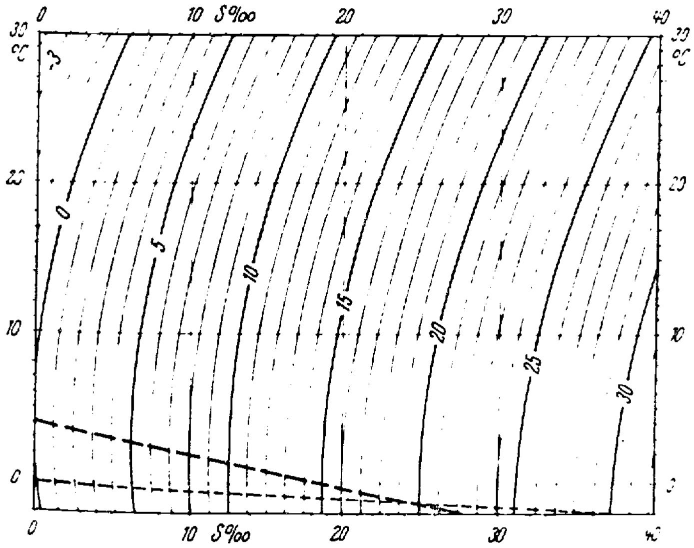
The surface layer is the most turbid of the three layers, especially at the stations near the Columbia River mouth. From the time series studies it was determined that the thickness and intensity of the bottom layer are variable but in every profile the intensity of the surface layer remains nearly constant. The midwater layer migrates vertically with a total excursion of about 5 m, and its thickness and intensity vary considerably.

Figure 111-19 presents turbidity profiles along an east-west transect off northern Oregon. Figure III-20 presents turbidity profiles obtained at a time-series station. The surface, midwater and bottom layers are readily distinguished.

Turbidity results from a concentration of particles in the

Figure III-13

Density σ_t of Sea Water as a Function of Temperature and Salinity§

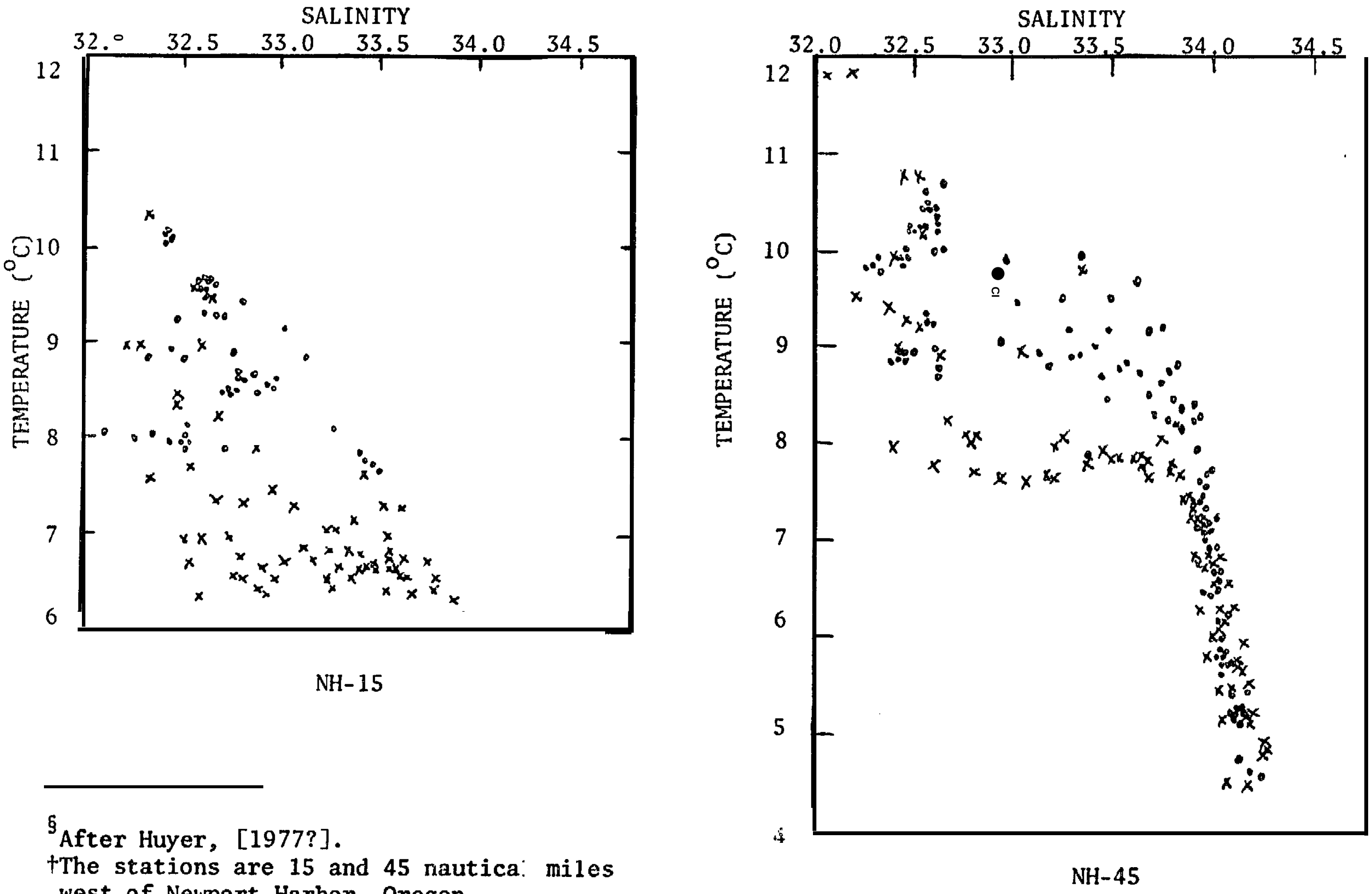


LEGEND — — — Density Maximum
----- Freezing Point

§Dietrich, 1957.

Figure III-14

Temperature-Salinity Plots of Summer (x) and Winter (o) Conditions Over the Period 1961-1970 for a Station on the Continental Shelf (NH-15) and Off the Continental Slope (NH-45)§†



§After Huyer, [1977?].
†The stations are 15 and 45 nautical miles west of Newport Harbor, Oregon.

Figure III-15

Typical Seasonal Density Distribution at 0 Meters§

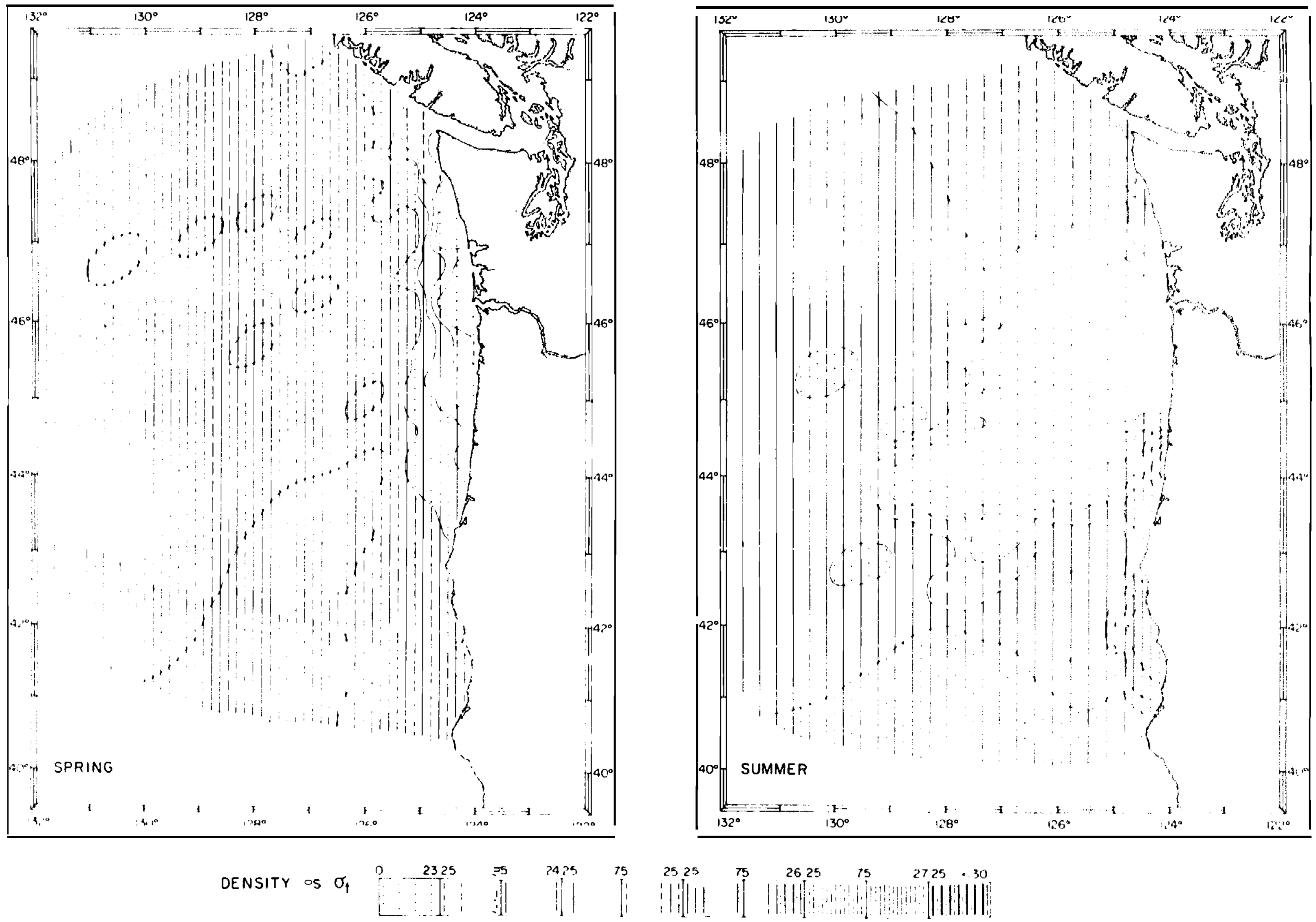
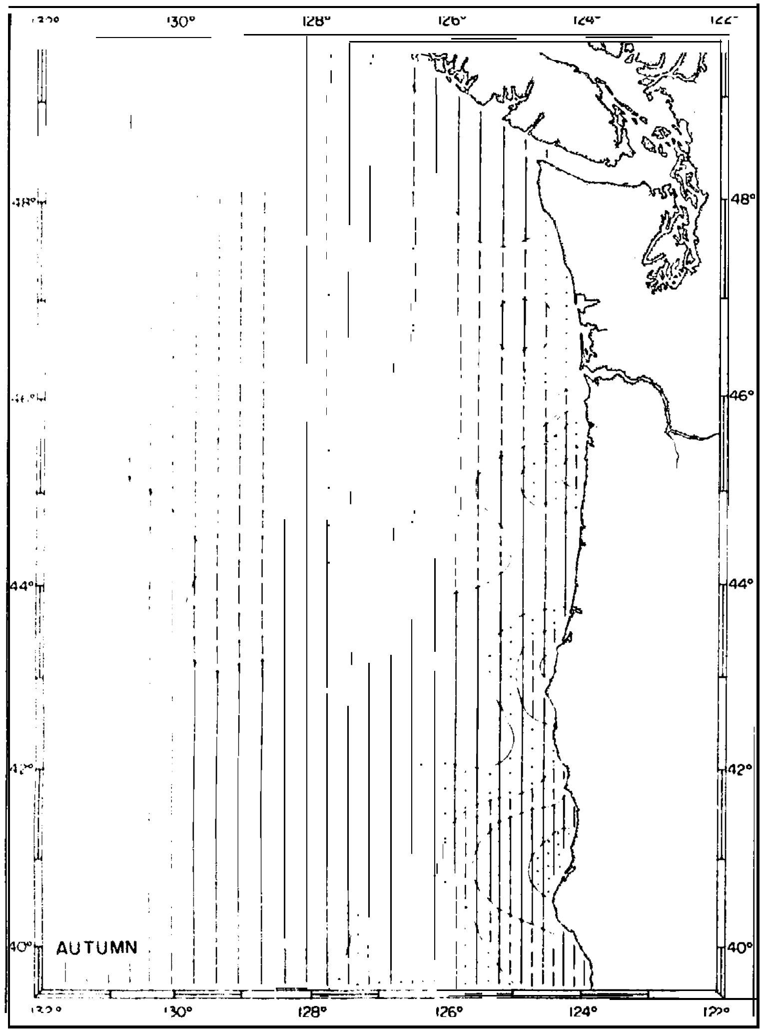
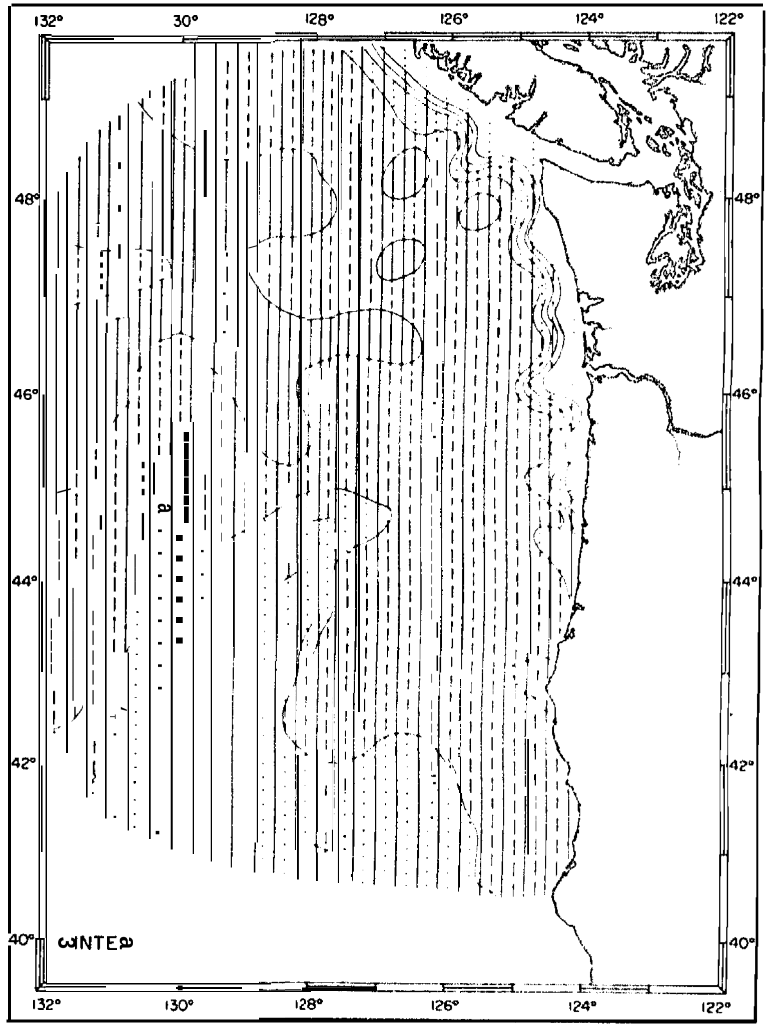


Figure III-15 (cont.)





§McGary, 1971.

Figure III-16

Typical Seasonal De°sity Distribution at 50 Meters§

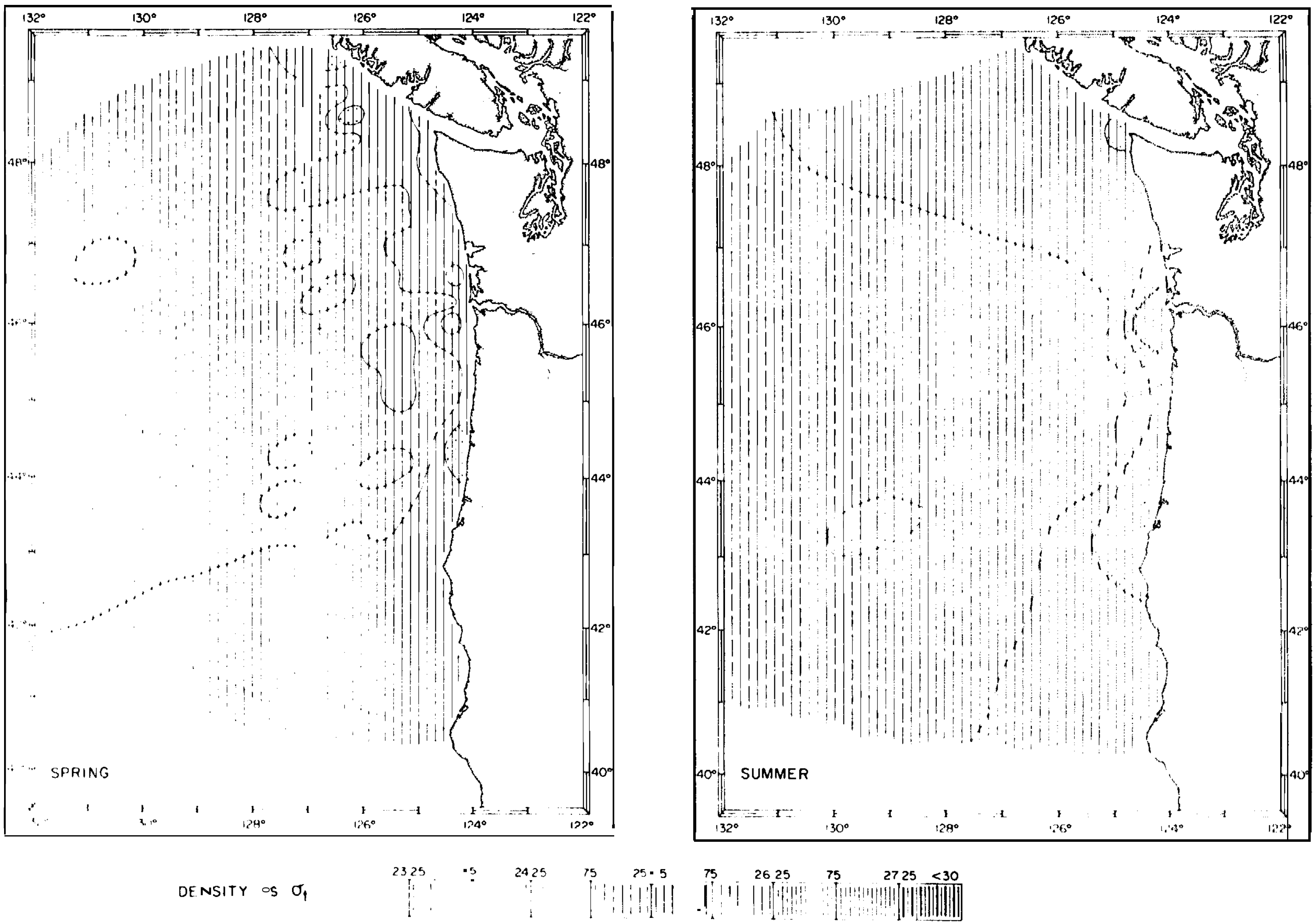
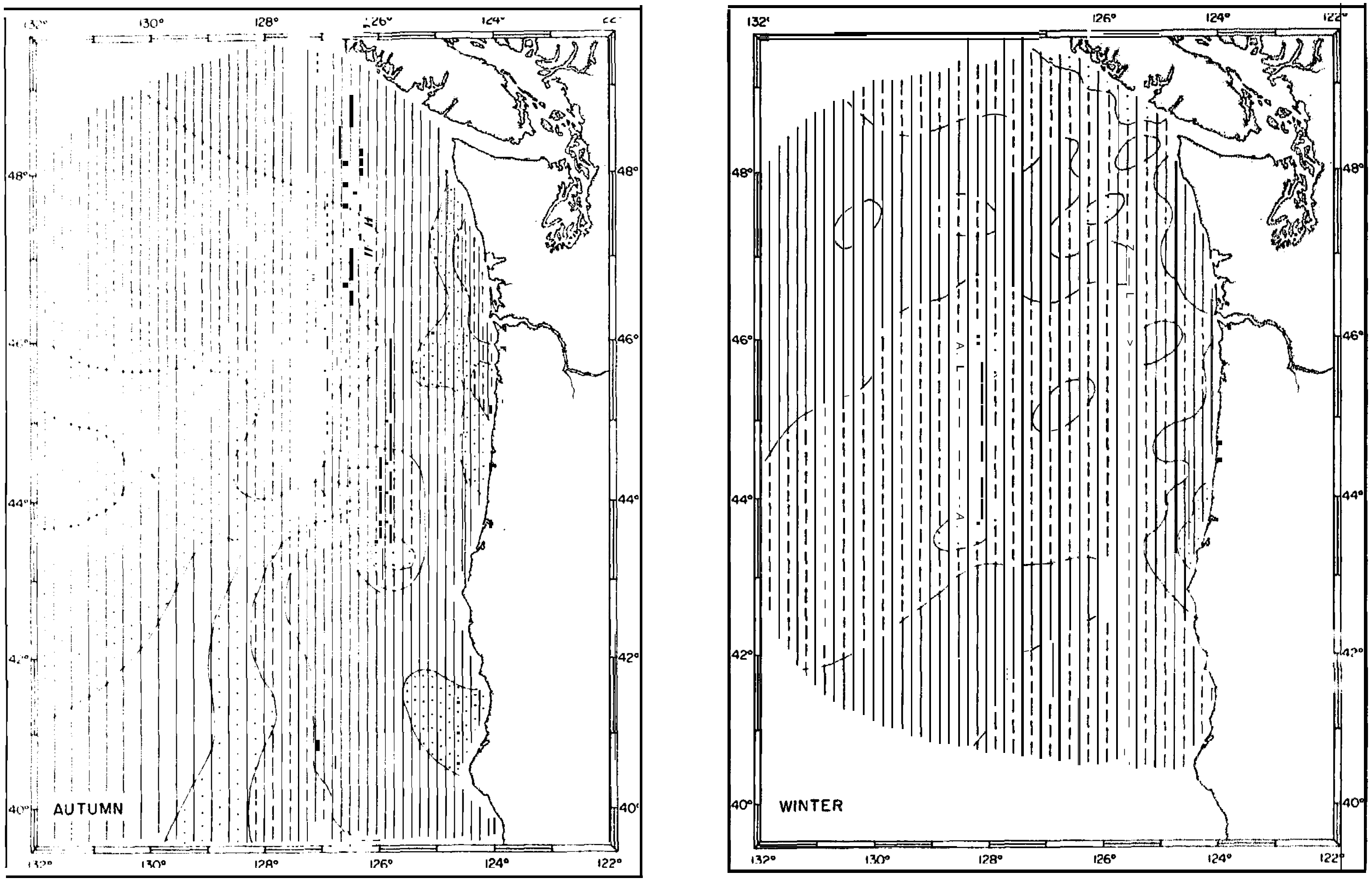


Figure III-16 (cont.)



[§] McGary, 1971.

Figure III-17

Typical Seasonal Density Distribution at 200 Meters§

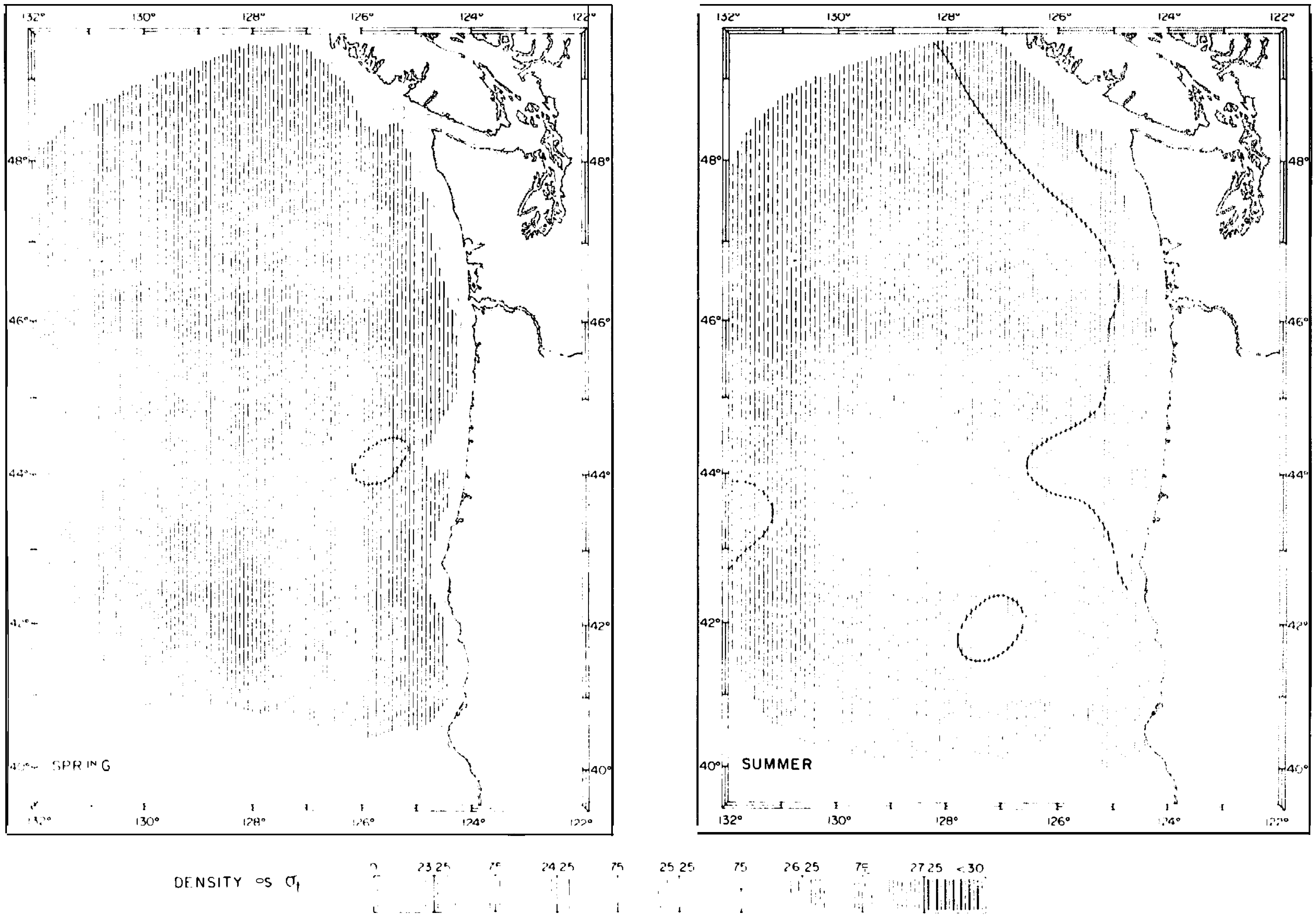
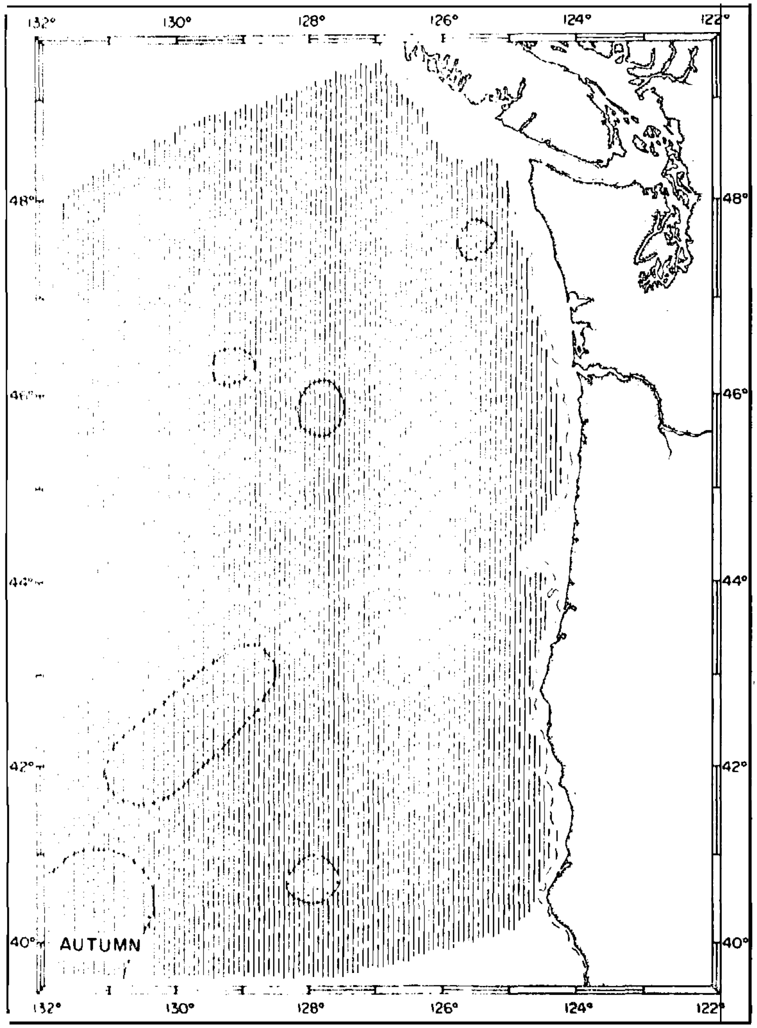
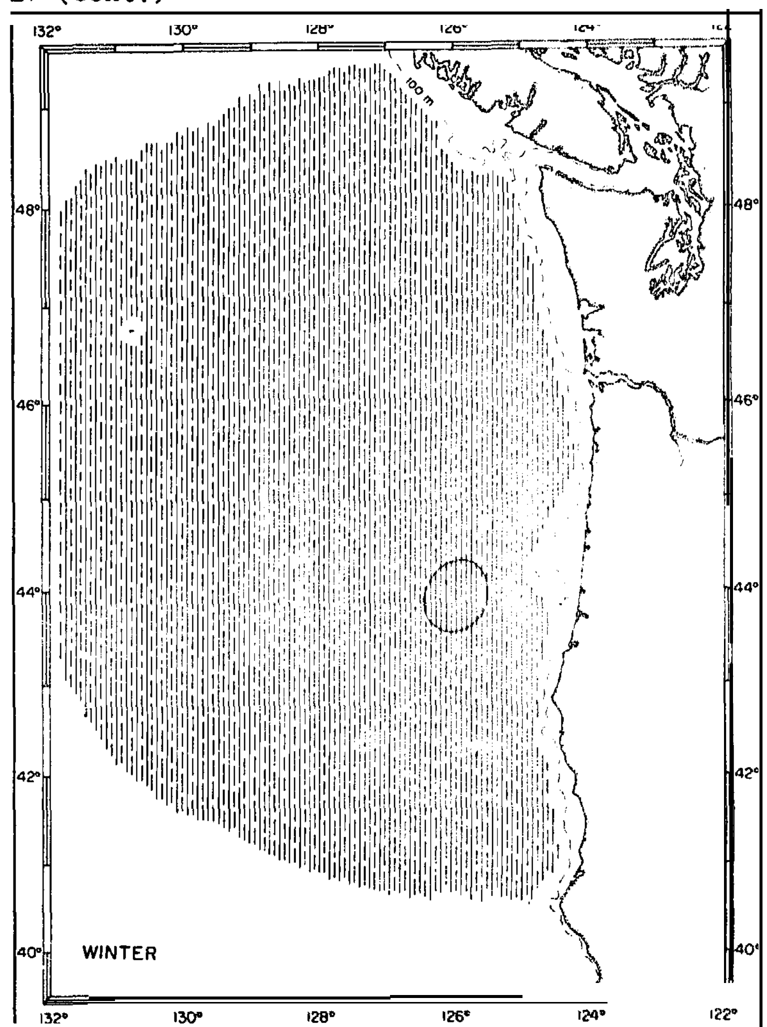


Figure III-17 (cont.)

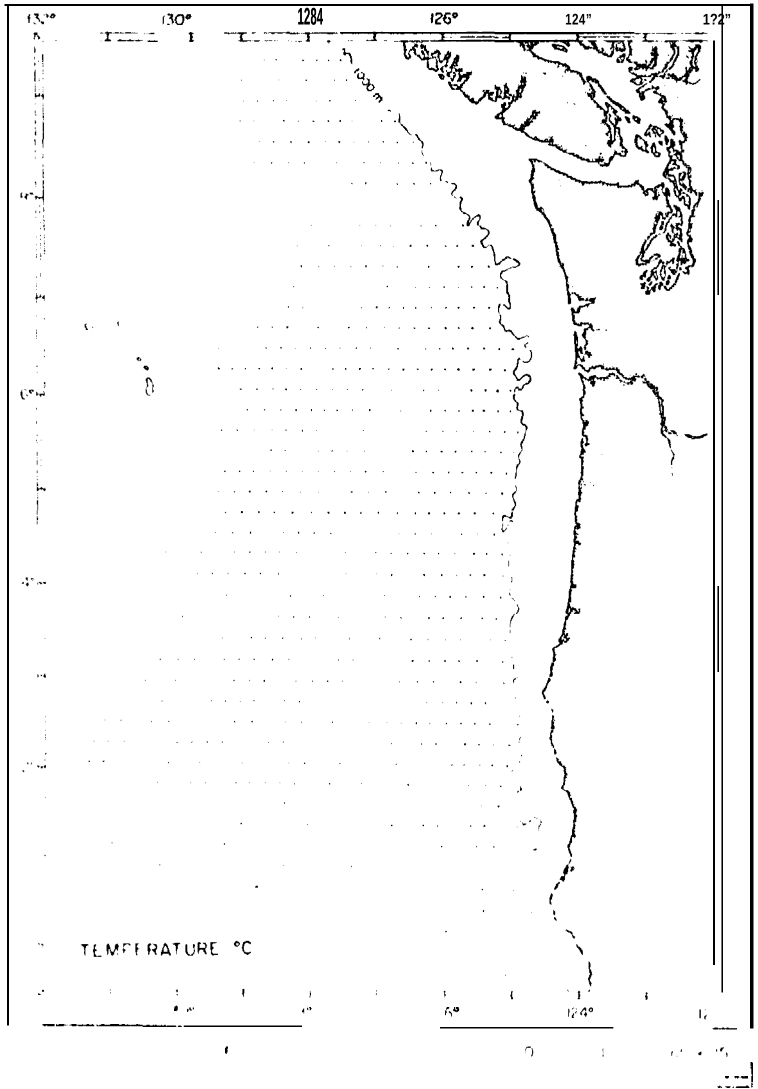




§McGary, 1971.

Figure III-18

Typical Year-round Distribution of Temperature, Salinity, Density and Oxygen at 1000 Meters[§]



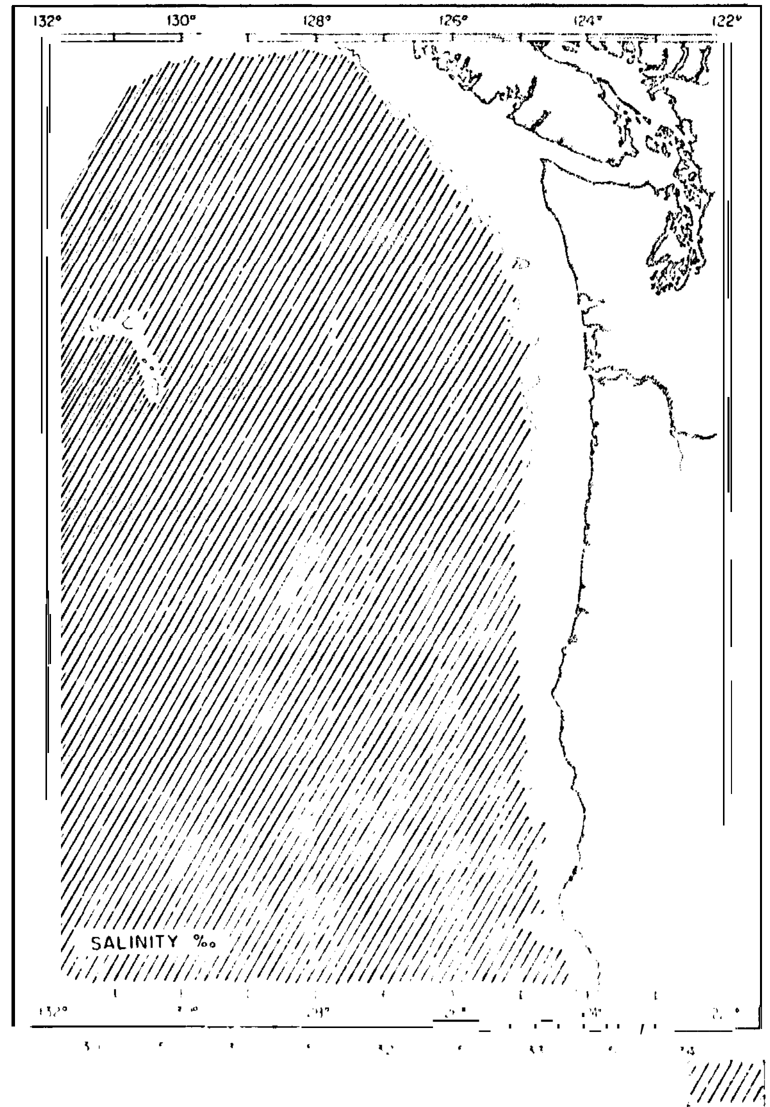
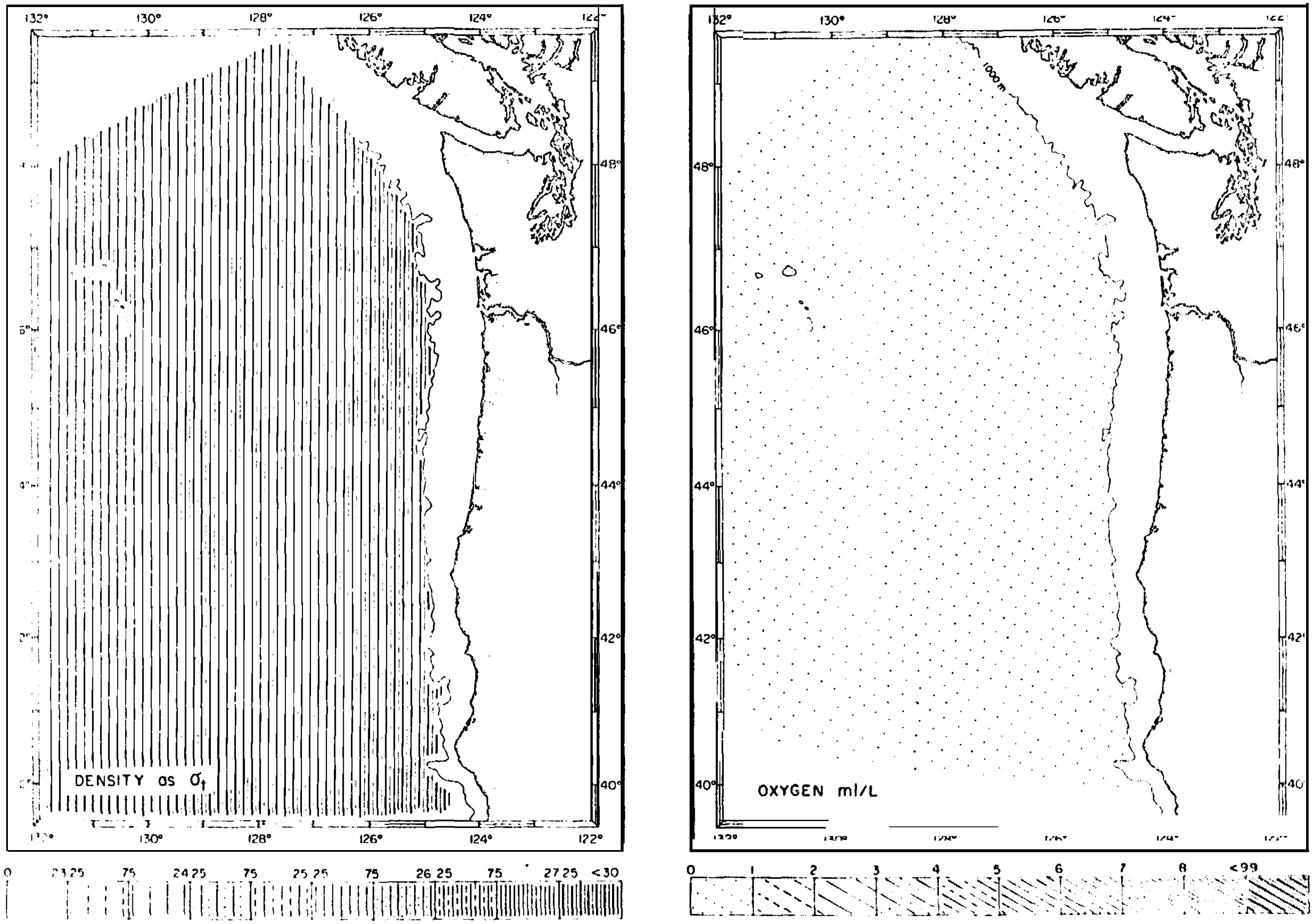


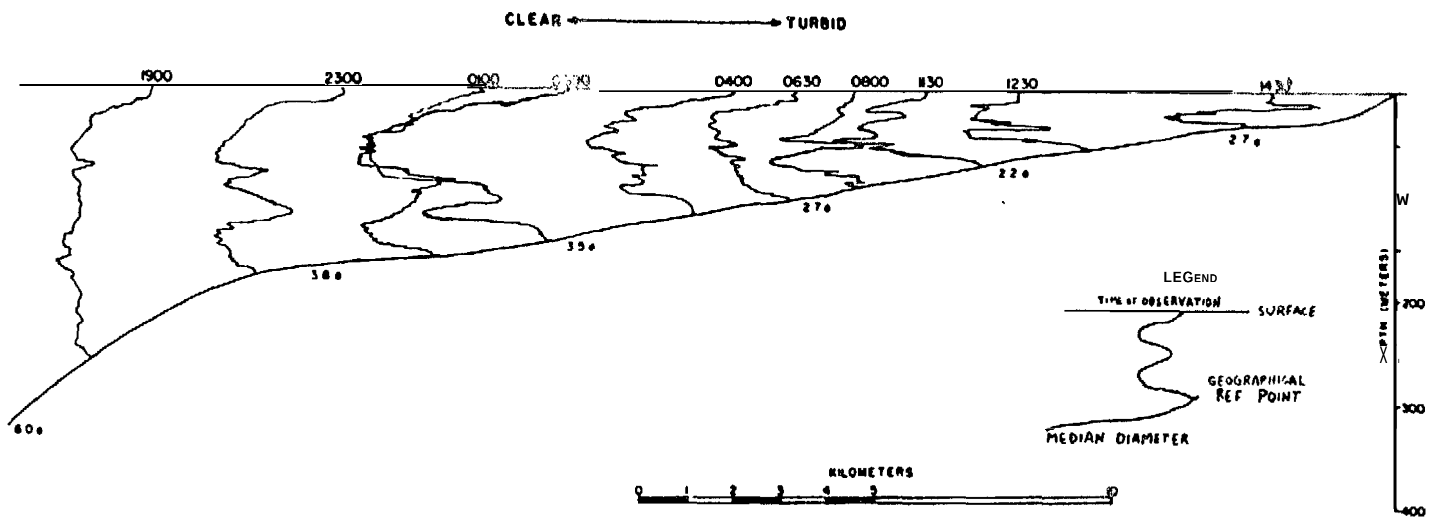
Figure III-18 (cont.)



§McGary, 1971.

Figure III-19

Turbidity Measurements Made Along Profile Located at 45°11"N. Transect was Made February 9, 1971. Comparisons of Turbidity Between Profiles Can Be Made on a Relative Basis[§]

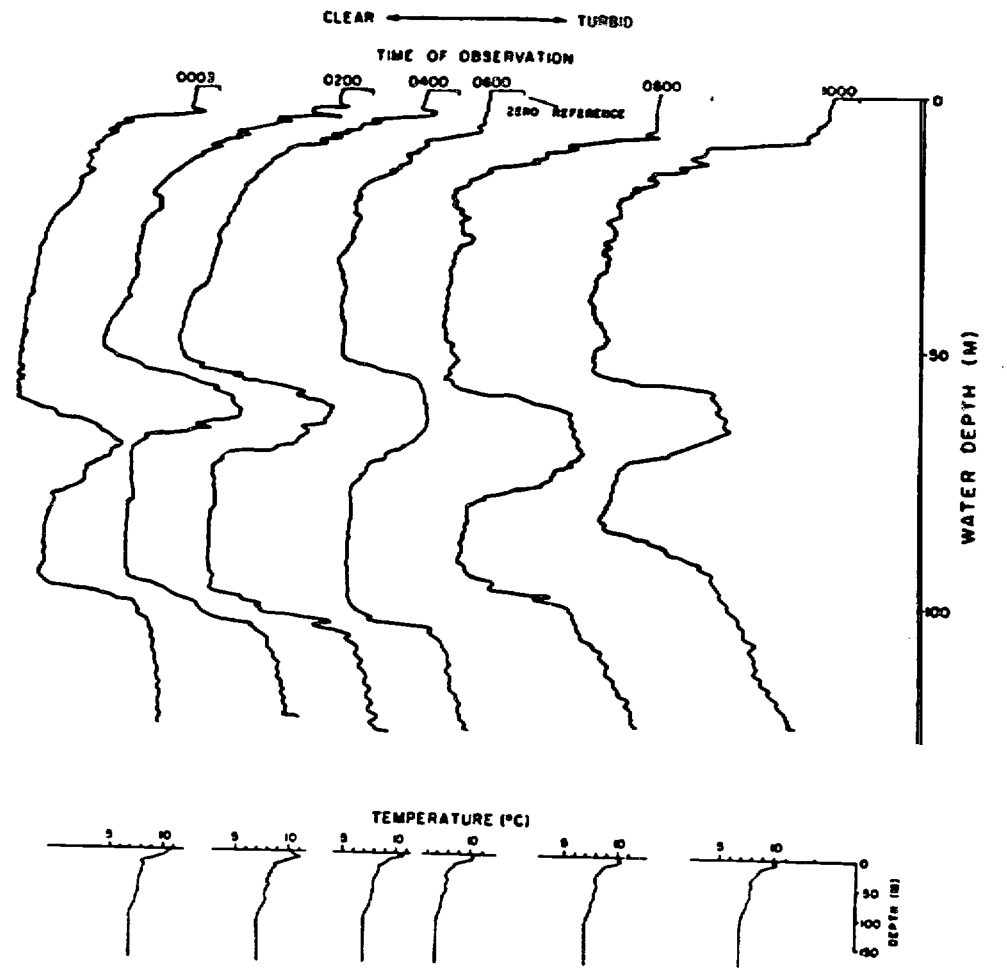


____

[§] Kulm and Fowler, 1974.

Figure 111-20

Turbidity Profiles Obtained at a Time Series Station Located at 45°59'N, 124°20'W (Comparisons of turbidity between profiles can be made by referring to the zero reference --point located to the right of the top of each profile. Temperature profile shown for each turbidity profile.)§



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§ Harlett and Kulm, 1973.

water column. Physical, biological and geological processes all play a part in the formation and movement of turbid water. The turbidity of the water may in turn affect rates of chemical, and biological processes. Pollutants may absorb onto suspended particulate matter and be removed from the water column and introduced to the sediment when the particle sinks. Surface turbidity decreases light penetration and affects productivity.

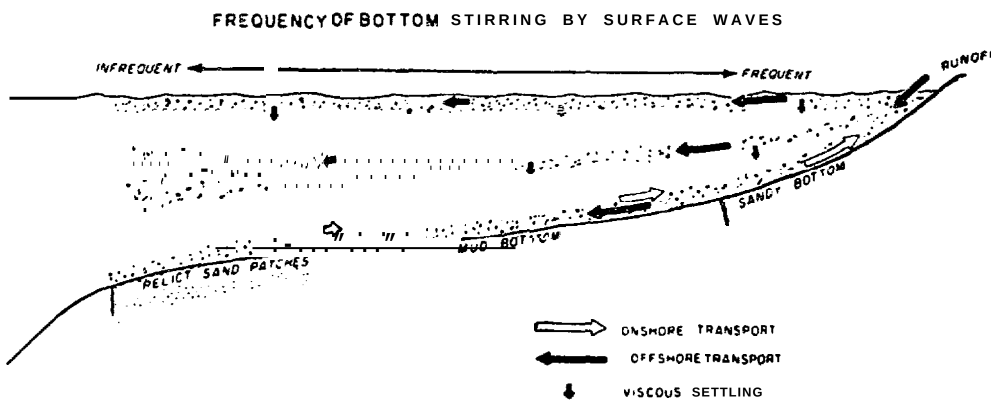
The movement of suspended particulate matter is in itself a geologic process (i.e., sedimentation). Harlett and Kulm (1973) present a conceptual model of suspended material transport across the northern Oregon continental shelf. Figure 111-21 illustrates their model. For reasons of shelf and wave similarity throughout the Oregon-Washington coastal area, and the overall dominance of the Columbia River, this conceptual model may apply for the entire area. The following conclusions are from Harlett and Kulm (1973).

Suspended materials concentrate at levels of density interfaces, The materials move seaward from their source areas along three major surfaces: the seasonal thermocline, the permanent thermocline (pycnocline), and the bottom. Sediments in the upper layer consist of materials diffusing seaward at the surface from the surf zone and fine materials contributed by the Columbia River plume. In the midwater layer; terrigenous sediments and biogenous material that have settled from the water above, and sediments diffusing seaward from the surf zone, travel seaward across the shelf edge providing a mechanism for sediment bypassing the outer shelf. The midwater layer becomes diffuse at the shelf edge and the lower slope regions, where sedimentation rates are five times those on the upper slope (Spiagi, 1970). Furthermore, the amount of biogenous material, while minor in shelf sediments, increases in the slope sediments (Maloney, 1965), indicating the bypassing of this material by transport in the midwater layer. Material in the bottom layer is derived primarily from erosion by bottom currents. Near the surf zone where there is strong onshore transport at the bottom from surface waves, fines are winnowed from the bottom sediments and carried onshore into the surf zone. Once in the surf zone, the fines remain suspended and eventually diffuse seaward at upper levels, with fines introduced from local runoff being transported to outer shelf regions. The resulting pattern of present sedimentation includes sands nearshore grading into muds offshore, with relatively little sedimentation on the outer shelf. Relict sand patches exist on the outer shelf, deposited during periods of lower sea level associated with the ice ages.

e) Heat Budget. A heat budget study for the coastal area of the Pacific Northwest has been completed by Lane (1965) and summarized by Bourke, Glenne and Adams (1971). Lane investigated the area from 40° to 50° North Latitude and from the coastline to 130° West Longitude. This completely encompasses the open ocean study area. A further subdivision in Lane's investigation narrowed this area to include only the region within 111 kilometers of the coast] inc. This subdivided region was established to provide a comparison between a coastal upwelling region and one free from the effects of upwelling. The following discussion is extracted from Bourke's

Figure III-21

Conceptual Model of Suspended Material Transport Across the Northern Oregon Continental Shelf[§†]



[§] Hartlett and Kulm, 1973.

[†] Turbid layers are indicated by stipple pattern in the water column. Sources of suspended material are river runoff, biogeneous material in the surface waters, the surf zone, and the resuspended silts and clays deposited previously on the muddy areas of the continental shelf.

summation of Lane's analysis (Bourke, Glenne and Adams, 1971).

Measured values of sea surface temperature, wet and dry bulb air temperature, wind velocity, solar radiation, and cloud cover were used to compute the terns in the heat budget equation. The data used by Lane were from records of naval vessels for the period 1952-62. These records are on file at the National Weather Records Center in Ashville, N.C. Each heat budget term was averaged month by month over a ten-year period (Table 111-2). The monthly variation of the total net heat exchange across the air-sea boundary was computed from the simplified heat budget equation:

$$Q_t = Q_s - Q_b - Q_h - Q_e \qquad \text{(III-1)}$$

where Qt is net heat transfer; considered positive when the sea receives heat energy,

Q_s is net short wave solar radiation incident on the sea surface,

Q_b is heat loss due to effective back radiation,

Q_h is heat conduction; considered positive when there is a net exchange of heat from the sea to the atmosphere, and

Q_e is heat loss due to evaporation.

All terms are measured in langleys (calories/cm*).

Direct measurement of terms in the heat budget equation (Equation III-1) is presently limited to laboratory experiments, with the possible exception of the radiation terms. In practice, empirical methods are used to compute the heat budget terms. Spatial and temporal measurements of sea surface temperature, wet and dry bulb air temperature, wind velocity, solar radiation, and cloud coverage are observed from which diurnal, monthly or annual means are computed. A variety of empirical relationships have been established for the computation of each heat budget term utilizing the above measurements.

A comprehensive review of the heat budget, including evaluation of the numerous empirical relationships, methods data analysis, and techniques and equipment for obtaining the required meteorological variables may be found in several reports of which Edinger and Geyer (1965), Raphael (1962) and Tennessee Valley Authority, Engineering Laboratory (1969) are the most complete. Average monthly values of the heat budget terms for the Pacific Northwest may also be determined from the heat budget Atlas by Budyko (1964).

Over the ten-year period of Lane's investigation, the total net heat transfer varied considerably from one year to the next. The range was appreciable, varying from over 42,000 langleys gained by the sea in 1956 to almost 2,000 langleys lost by the sea in 1959 (Figure III-22). Lane was able to show that annual fluctuations in both solar radiation and evaporation were the major contributors to the observed net heat differences.

From January through March the net heat transfer was negative, indicating a release of heat from the ocean to the atmosphere (Figure III-23). During March through May the direction of exchange reversed, resulting in a warming of the ocean. During the summer the warming process continued at a relatively constant rate. How-

'i'able III-2

Average Monthly Values (Langleys) for the Major Heat Budget Terms for a Region Where Coastal Upwelling Is Seasonally Present.[§]

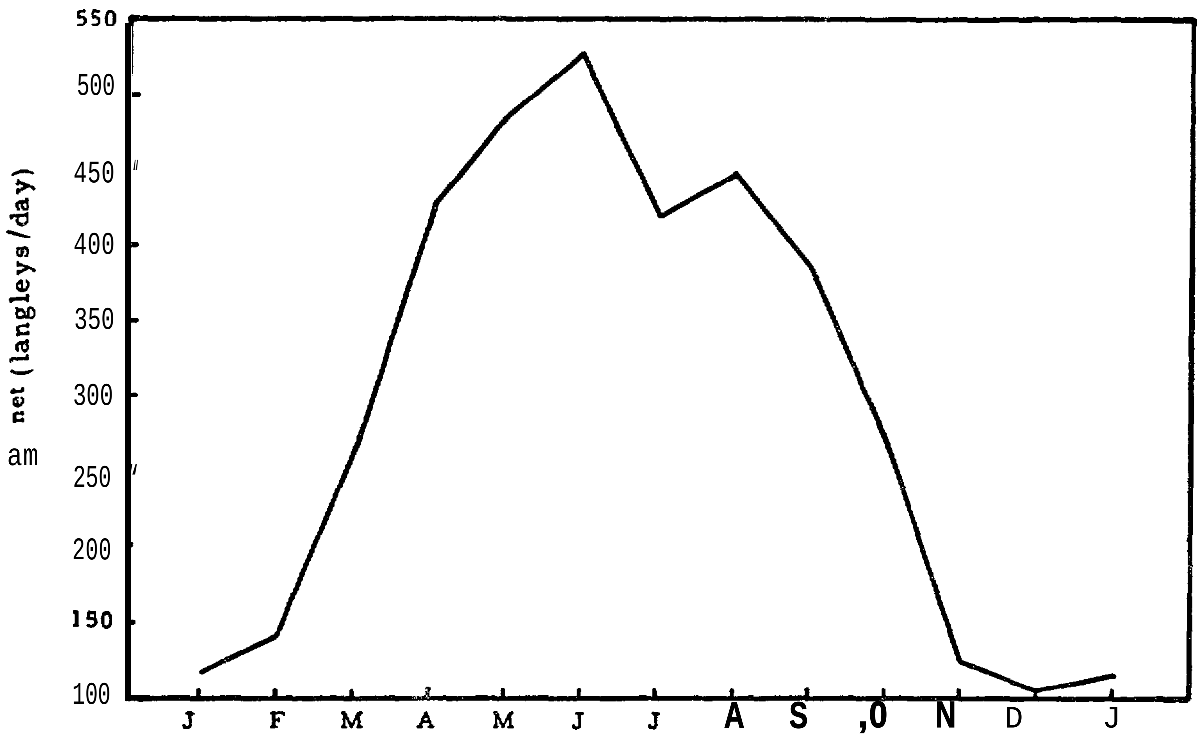
	Q_b	Q_h	Q_e	Q_s net	Q_t	Q_t overall[†]
January	82	38	225	116	-229	-191
February	70	30	200	140	-160	-1oo
March	70	41	167	264	- 14	20
Apri 1	73	-lo	118	423	242	198
May	63	-5	129	486	299	277
June	72	-7	150	S28	313	304
July	51	-22	93	419	297	366
August	63	-15	100	447	299	274
September	75	-42	110	386	243	119
October	113	10	185	272	- 36	- 89
November	80	24	155	126	-133	-205
December	95	-6	106	105	- 90	-203

[§] Bourke, Glenne and Adams, 1971.

[†] Q_t overall includes this region as well as areas further offshore not affected by coastal upwelling.

Figure III-22

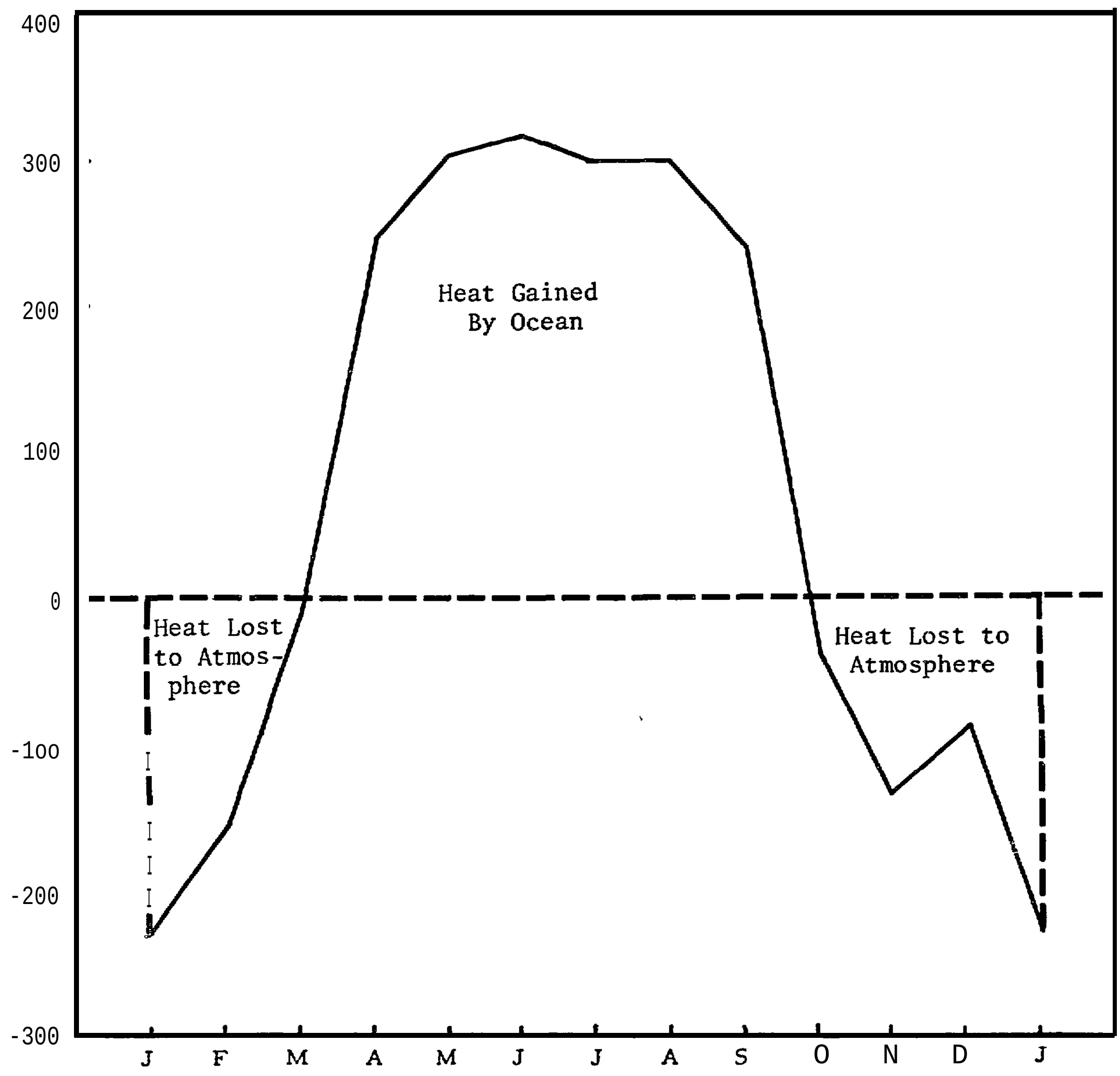
Monthly Mean Values of Net Solar Radiation Incident Upon the Area From the Coastline to 60 Nautical Miles Offshore[§†‡]



§ Bourke, Glenne and Adams, 1971, modified from Lane, 196S.
† The summer months experience more than twice the insolation of the winter months.
‡ One nautical mile = 1.85 km.

Figure III-23

Monthly Mean Values of Net Heat Transferred Across the Air-Sea Interface for the Area From the Coastline to 60 Nautical Miles Offshore[§,†,‡]



[§]Bourke, Glenne and Adams, 1971, modified from Lane, 1965.
[†]From March through October net heat is transferred from the atmosphere to the ocean.
[‡]One nautical mile = 1.85 km.

ever, further offshore beyond the upwelling zone, the mid-summer atmospheric warming of the ocean decreased, due to high surface temperatures caused by warm Columbia River water and high values of cloud cover which reduced the incident solar radiation. By October, the net heat exchange again reversed and the ocean continued to release heat at an increasing rate through December and January.

Net solar radiation and heat loss due to evaporation are the most significant factors affecting the total net heat exchange. The net solar radiation reaches its maximum during the summer months. April through September experience more than twice the insolation of the winter months (Figure III-24). The heat loss due to evaporation is almost double that due to back radiation (Figures III-25 and III-26). However, during the summer months when upwelling is prevalent, the evaporative heat loss is suppressed from its winter maximum. The water transfer to the atmosphere during summer is less by approximately 5 cm per month compared to that in regions beyond the zone of upwelling. Cooling of the surface waters in summer due to upwelling also results in the conduction term, Q_h, being negative, i.e., a net conduction of heat to the sea (Figure III-26). This lowering of the surface water temperature also results in a reduction of the effective back radiation during the summer months.

Based on empirical methods, the following summary conclusions can be made concerning the heat budget for the coastal upwelling off Oregon and Washington:

(1) The net heat exchange across the air-sea boundary varies considerably from year to year. In general, the sea receives a net annual input of heat from air-sea exchange.

(2) The factors most influential in altering the heat budget from year to year are variations in cloud cover, sea surface temperature, and wind speed.

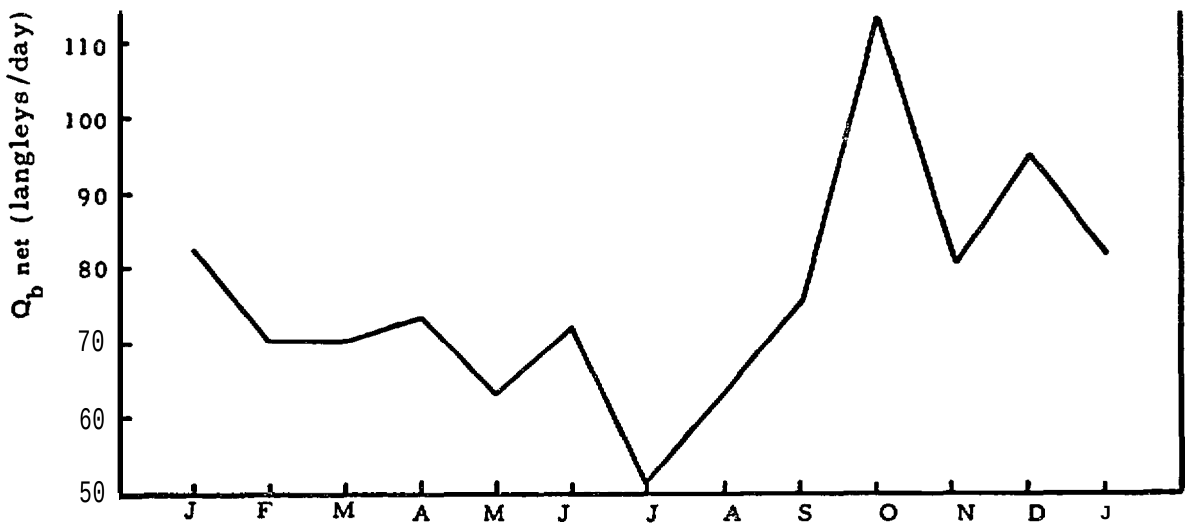
(3] Coastal upwelling results in a lowering of air, sea, and wet bulb temperatures in the nearshore region. These reductions affect the heat budget by slightly reducing the back radiation, greatly reducing conduction from the sea to the atmosphere (conduction to the sea occurs frequently during the upwelling season), and greatly reducing the heat loss due to evaporation. Due to the relative magnitude involved, the reduction of the evaporative flux is the most important effect.

(4) The measurable effects of upwelling on the climate of coastal Oregon and Washington are a suppression of the summer and autumn air temperature values and an increase in relative humidity and fog.

ii. <u>Tides</u>. The tide is a long-period wave consisting of semidiurnal components with nearly 12 hour periods and diurnal components with nearly 25 hour periods. The tides along the coast, including the coastal estuaries and Puget Sound and its approaches, are of the mixed,

Figure III-24

Monthly Mean Values of Net Back Radiation for the Area From the Coastline to 60 Nautical Miles Offshore[§,†,‡]



[§]Bourke, Glenne and Adams, 1971, modified from Lane, 1965.

[†]The low surface temperatures in summer resulting from coastal upwelling suppresses the net back radiation during this season.

[‡]One nautical mile = 1.85 km.

Figure III-25

Monthly Mean Values of Evaporative Flux for the Area
From the Coastline to 60 Nautical Miles Offshore[§,†,‡]

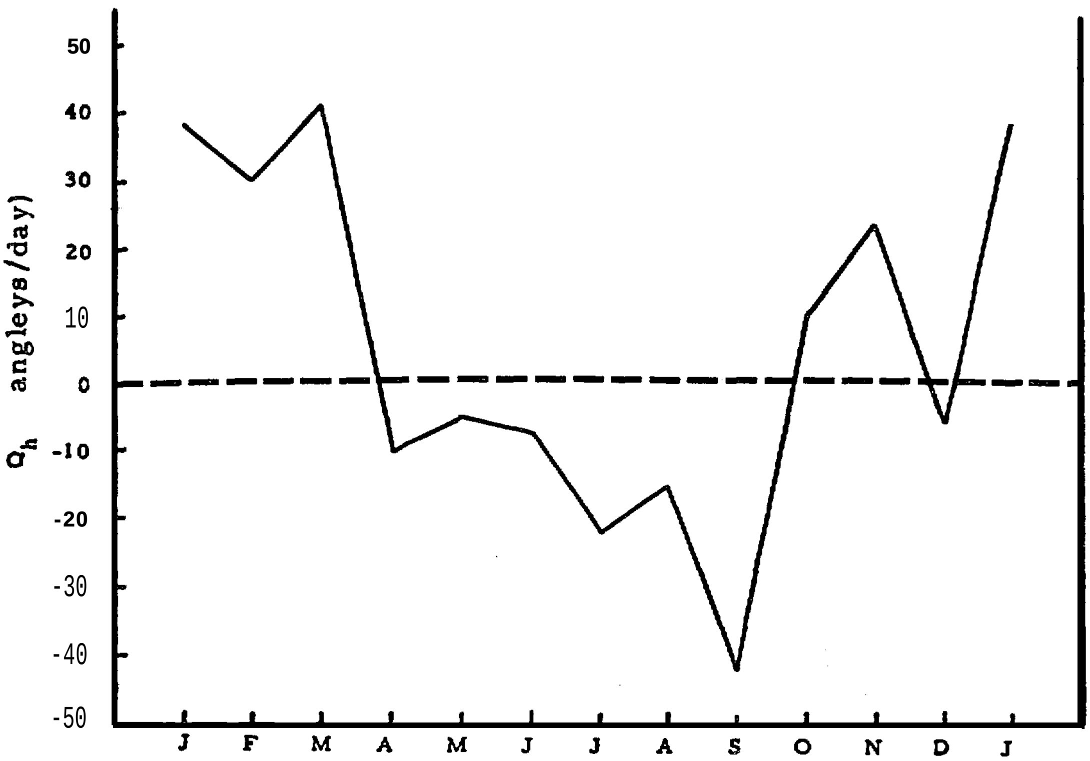
§ Bourke, Glenne and Adams, 1971, modified from Lane, 1965.

† In summer the evaporative heat loss is greatly suppressed from its winter maximum due to cooling effect of coastal upwelling.

‡ One nautical mile = 1.85 km.

Figure III-26

Monthly Mean Values of Sensible Heat Conducted Across the Air-Sea Interface for the Area From the Coastline to 60 Nautical Miles Offshore[§,†,‡]



[§]Bourke, Glenne and Adams, 1971, modified from Lane, 1965.

[†]Since surface temperatures are low in summer due to coastal upwelling, sensible heat is conducted from the atmosphere to the sea.

[‡]One nautical mile = 1.85 km.

predominantly semidiurnal type with an inequality appearing primarily in the low waters. Along the passages inside Vancouver Island the semidiurnal constituent is so small that the resultant tide is diurnal in appearance.

In the northeast Pacific the tide wave rotates in a counter-clockwise direction, causing the tide to occur progressively later in the day as it moves northward along the coast. As the tide wave enters the estuaries and the Strait of Juan de Fuca, it slows (as a shallow water wave, its speed is controlled by the depth). Table III-3 presents a time history of the passage of a trough (low tide) and crest (high tide) as it moves up the coast of Oregon and Washington, enters the Strait of Juan de Fuca, passes through Admiralty Inlet, by Seattle and finally arrives at Olympia, at the southern-most reach of Puget Sound.

Table III-4 presents tide information for stations throughout the entire study area (in standard feet measurements). The table is extracted from the U.S. Department of Commerce Tide Tables High and Low Water Predictions, 1977b, and serves as a detailed illustration of tidal behavior in the study area. The information presented in Table III-4 includes time and height differences, mean and diurnal ranges and mean tide level. This information is essentially constant year to year for each station. All of the Oregon stations presented are near or in estuaries. The Columbia River stations were included to illustrate the tidal effects that are felt upstream beyond Portland. Tide height corrections are excluded for most of the Columbia River, as river stage is the controlling factor. Tide ranges increase as bathymetric effects exert their influence in the inland waters and estuaries. The tidal datum is mean lower low water (MLLW) for all the stations that are referenced to U.S. control stations. Canadian tidal stations are referenced to Canadian chart datums and require separate corrections to equate to MLLW.

Tide studies have revealed patterns and trends of sea level variation. Yearly values of sea level at four stations on the Pacific coast are presented in Figure III-27. Although the information presented is not recent, the following observations are applicable. In general the changes from year to year at the stations are less than a tenth of a foot, although occasionally they may be as much as two or three-tenths of a foot. In general, the variations are in the same direction for the entire coast -- when sea level is high or low at one station it is also high or low at the other stations (Mariner, 1951). Figure III-28 presents curves of annual sea level variation at stations along the Pacific coast and represent long term averages. The Astoria tide station is located about 24 km upstream from the mouth of the Columbia River and reflects the variation in discharge of the Columbia River as well. This historical data illustrates that changes in sea level do occur, but that they are slight and of little consequence to OCS development.

Tide measurements and related studies in support of tide and current predictions are conducted throughout the Pacific Ocean and are coordinated by the Pacific Tide Party, National Ocean Survey, Pacific Marine Center, NOAA, located in Seattle.

Table 111-3

Time History of the Passage of the Tide Wave Along the Oregon-Washington Coast and Inland Waters for 1 January 1977[§]

PLACE	LOCATION	LOW WATER TIME	HIGH WATER TIME
Coos Bay	43°21'N 124°19'W	0238	0852
Columbia River Entrance	46°16'N 124°04'W	0301	0934
Cape Flattery, WA	48°23'N 124°44'W	0318	0912
Port Angeles, WA	48°07'N 123°26'W	0454	1051
Admiralty Head, WA	48°10'N 122°46'W	0637	1213
Seattle, WA	47°36'N 122°20'W	0807	1316
Olympia, WA	47°03'N 122°54'W	0853	1347

§U.S. Department of Commerce, 1977b.

Table III-4

Tidal Differences and Ranges for Selected Locations in Study Area§

PLACE	POSITION		DIFFERENCES				RANGES		
			Time		Height				
	Lat. (N)	Long. (W)	High Water h.m.	Low Water h.m.	High Water feet	Low Water feet	Mean feet	Diurnal feet	Mean Tide Level feet
OREGON			on HUMBOLDT BAY						
Brookings, Chetco Cove	42°03′	124°17′	-0 30	-0 26	+0.6	0.0	5.1	6.9	3.7
Wedderburn, Rogue River	42°26′	124°25′	-0 22	-0 14	+0.3	-0.1	4.9	6.7	3.6
Port Orford	42°44′	124°30′	-0 24	-0 21	+0.9	+0.1	5.3	7.3	3.9
Bandon, Coquille River	43°07′	124°25′	-0 08	-0 02	+0.6	-0.1	5.2	7.0	3.7
Coos Bay									
Entrance	43°21′	124°19′	+0 02	+0 07	+0.7	0.0	5.2	7.0	3.8
Empire	43°24′	124°17′	+0 41	+0 50	+0.3	-0.1	4.9	6.7	3.5
Coos Bay	43°23′	124°13′	+1 30	+1 28	+1.0	-0.1	5.6	7.3	3.9
Umpqua River									
Entrance	43°41′	124°12′	+0 09	+0 03	+0.6	0.0	5.1	6.9	3.7
Gardiner	43°44′	124°07′	+1 00	+1 09	+0.4	-0.2	5.1	6.7	3.5
Reedsport	43°42′	124°06′	+1 15	+1 24	-0.4	-0.2	5,1	6.7	3.6
Siuslaw River									
Entrance	44°01′	124°08′	+0 10	+0 15	+0.6	-0.1	5.2	6.9	3.7
Florence	43°58′	124°06′	+0 48	+0 58	+0.3	-0.2	5.0	6.6	3.5
Waldport, Alsea Bay	44°26′	124°04′	+0 25	+0 31	+1.3	0.0	5.8	7.7	4.1
Yaquina Bay and River									
Bar at entrance	44°37′	124°05′	+0 03	+0 09	+1.5	+0.1	5.9	7*9	4.2
Newport	44°38′	124°03′	+0 13	+0 12	+1.6	+0.1	6.0	8.0	4.3

Table III-4 (cent.)

PLACE	POSITION		DIFFERENCES				RANGES		
			Time		Height				Mean
	Lat. (N)	Long. (W)	High Water h.m.	Low Water h.m.	High Water feet	Low Water feet	Mean feet	Diurnal feet	Tide Level feet
OREGON, cont.			on HUMBOLDT BAY						
Yaquina Bay and River									
Southbeach	44°38′	124°03′	+0 02	+0 03	+1.8	+0.1	6.2	8.2	4.4
Yaquina	44°36′	124°01′	+0 24	+0 25	+1.8	+0.1	6.2	8.2	4.4
Winant	44°35′	124°00′	+0 32	+0 46	+1.8	0.0	6.3	8.2	4.3
Toledo	44°37′	123°56′	+0 58	+1 09	+1.7	-0.1	6.3	8.1	4.2
Taft, Siletz Bay	44°56′	124°01′	+0 17	+0 43	+0.2	-0.3	5.0	6.6	3.4
Kernville, Siletz River	44°54′	124°00′	+0 53	+1 23	†0.95	†0.67	4.6	6.1	3.1
Nestucca Bay entrance	45°10′	123°58′	+0 24	+0 42	+1.2	-0.1	5.8	7.6	4.0
Tillamook Bay									
Barview	45°34′	123°57′	+0 11	+0 26	+1.1	-0.1	5.7	7.5	3.9
Miami Cove	45°33′	123°54′	+0 44	+0 56	+1.0	-0.1	5.6	7.4	3.9
Bay City	45°31′	123°54′	+1 02	+1 30	+0.7	+0.2	5.4	7.1	3.7
Tillamook, Hoquarten Slough	45°28′	123°51′	+1 21	+2 45	†1.03	†0.58	5.2	6.6	3.3
Nehalem River									
Brighton	45°40′	123°56′	+0 20	+0 24	+1.4	0.0	5.9	7.8	4.1
Nehalem	45°43′	123°53′	+0 46	+1 26	+0.8	-0.3	S.6	7.2	3.7
OREGON AND WASHINGTON									
Columbia River‡			on ASTORIA						
Columbia River entrance (N. Jetty]	46°16′	124°04′	-0 46	-1 10	-0.7	+0.1	5.6	7.5	4.0

Table III-4 (cont)

PLACE	POSITION		DIFFERENCES				RANGES		
			Time		Height				
	Lat. (N)	Long. (W)	High Water h.m.	Low Water h.m.	High Water feet	Low Water feet	Mean feet	Diurnal feet	Mean Tide Level feet
OREGON AND WASHINGTON, cont. Columbia River‡			on ASTORIA						
Ilwaco, Baker Bay, Wash.	46°18'	124°02'	-0 15	-0 09	-0.5	-0.1	6.0	7.6	4.0
Chinook, Baker Bay, Wash.	46°16'	123°57'	-0 15	-0 44	-0.2	0.0	6.2	7.9	4.2
Hungry Harbor, Wash.	46°16'	123°51'	+0 02	-0 19	+0.1	+0.1	6.4	8.2	4.4
Point Adams, Or.	46°12'	123°57'	-0 27	-0 48	+0.1	+0.1	6.4	8.3	4.4
Warrenton, Skipanon River, Or.	46°10'	123°55'	-0 15	-0 29	+0.2	+0.1	6.5	8.3	4.4
Astoria (Youngs Bay), Or	46°10'	123°50'	-0 15	-0 24	+0.4	+0.1	6.7	8.6	4.5
Astoria (Port Docks), Or.	46°11'	123°52'	-0 10	-0 13	-0.2	0.0	6.2	8.0	4.2
Astoria (Tongue Point), Or.	46°13'	123°46	Daily predictions				6.5	8.2	4.3
Settlers Points, Or.	46°10'	123°41'	+0 20	+0 43	-0.2	-0.1	6.3	8.0	4.1
Harrington Point, Wash.	46°16'	123°39'	+0 19	+0 42	-0.5	-0.2	6.1	7.7	3.9
Skamokawa, Steamboat Slough, Wash.	46°16'	123°23'	+1 13	+1 35	----	----	5.6	6.9	----
Cathlamet, Wash	46°12'	123°23'	+1 13	+2 05	----	----	5.2	6.4	----
Wauna, Or.	46°10'	123°24'	+1 15	+2 09	----	----	5.2	6.3	----
Eagle Cliff, Wash	46°10	123°14	+1 41	+2 51	----	----	4.5	5.5	----
Stella, Wash.	46°11	123°07'	+1 59	+3 20	----	----	4.0	4.9	----
Longview, Wash.	46°06'	122°57	+2 25	+4 04	----	----	3.3	4.0	----

Table III-4 (cont.)

PLACE	POSITION		DIFFERENCES				RANGES		
			Time		Height				Mean
	Lat. (N)	Long. (W)	High Water h.m.	Low Water h.m.	High Water feet	Low Water feet	Mean feet	Diurnal feet	Tide Level feet
OREGON AND WASHINGTON, cont.									
Columbia River‡									
			on ASTORIA						
Kalama, Wash.	46°00′	122°51′	+2 52	+4 45	----	----	2.6	3.2	----
Saint Helens, Or.	45°42′	122°48	+3 29	+5 34	----	----	2.0	2.5	----
Knapp Landing, Wash.	45°44′	122°45′	+4 24	+6 18	----	----	1.5	2.0	----
Kelley Point, Or.	45°39′	122°46′	+5 24	+7 06	----	----	1.4	2.0	----
St. Johns, Willamette River, Or.	45°35′	122°46′	+5 06	+7 16	----	----	1.7	2.2	----
Portland, Willamette River, Or.	45°31′	122°40′	+5 03	+7 27	----	----	1.8	2.4	----
Vancouver, Wash.	45°37′	122°40′	+5 43	+7 28	----	----	1.3	1.8	----
Ellsworth, Wash.	45°36′	122°33′	+6 09	+7 53	----	----	1.0	1.4	----
Washougal, Wash.	45°351	122°23′	------	----	----	----	0.5	0.9	----
Warrendale, Or.	45°37′	122°00′	----	- -- ---	----	----	0.4	0,6	----
WASHINGTON, cont.			on ABERDEEN						
Long Beach	46°21′	124°03′	-1 05	-o 50	*0.80	*0.80	6.2	8.1	4.4
Willapa Bay and River									
Willapa Bay entrance	46°43′	124°04′	-o 37	-o 43	*0.80	*0.80	6.2	8.1	4.4
Nahcotta, Willapa Bay	46°30′	124°01′	+0 20	+0 16	0.0	-0.1	8.0	10.2	4.6
Tarlatt Slough, Willapa Bay	46°22′	124°00′	_o 21	+0 54	*0.91	*0.47	7.9	9.4	4.6
Bay Center, Palix River	46°38′	123°57′	-o 09	+0 04	-1.3	-0.2	6.6	8.9	4.7
Toke Point, Willapa Bay	46°42′	123°58′	-0 36	-0 19	-1.6	-0.2	6.5	8.S	4.5

Table III-4 (cent.)

PLACE	POSITION		DIFFERENCES				RANGES		
			Time		Height				Mean
	Lat. (N)	Long. (W)	High Water h.m.	Low Water h.m.	High Water feet	Low Water feet	Mean feet	Diurnal feet	Tide Leve 1 feet
Strait of Juan de Fuca, cont.			ON ABERDEEN						
Neah Bay	48°22′	124°37′	-o 37	-o 35	†0.78	†0.78	5.5	7.9	4.3
Clallam Bay	48°16′	124°18′	-o 11	-0 08	†0. 76	†0.76	5.0	7.7	4.3
Twin Rivers	48°10′	123°57′	+0 09	+0 11	†0.71	†0.71	4.4	7.0	4.1
			on PORT TOWNSEND						
Crescent Bay	48°10′	123°44′	-2 34	-2 00	†0.81	†0.81	4.1	6.7	4.1
Port Angeles	48°07′	123°26′	-1 26	-1 21	†0.87	†0.87	4.2	7.2	4.4
Dungeness	48°10′	123°07′	-o 47	-0 36	†0.92	†0.92	4.4	7.6	4.7
Sequim Bay entrance	48°05′	123°03′	-0 32	-0 05	†0.95	†0.95	4.8	7,9	4.8
Gardiner, Discovery Bay	48°04′	122°55′	-o 40	-o 15	†0.95	†0.95	4.8	7.9	4.8
Smith Island	48°19′	122°50′	-0 06	-0 23	†0.84	†0.84	4.2	7.0	4.5
Point Partridge	48°14′	122°46′	-o 04	-o 13	†0.93	†0.93	4.5	7.7	4.7
Admiralty Inlet									
Admiralty Head	48°10′	122°40′	-o 04	+0 22	+0.1	0.0	5.2	8.4	5.1
Port Townsend	48°08′	122°46′	Daily predictions				5.1	8.3	5.0
Port Townsend (Point Hudson)	48°07′	122°45′	-o 04	-o 04	+0.3	+0.1	5.3	8.6	5.2
Marrowstone Point	48°06′	122°41′	+0 09	+0 07	+0.5	0.0	5.6	8.8	5.3
Mystery Bay, Marrowstone Island	48°03′	122°41′	+0 20	+0 50	-0.1	0.0	5.0	8.2	5.0
Bush Point	48°02′	122°36′	+0 39	+1 13	+0.5	0.0	5.6	8.8	5.3
Oak Bay	48°01′	122°43′	+0 15	+0 29	+1.0	+0.1	6.0	9.4	5.6

Table III-4 (cont.)

PLACE	POSITION		DIFFERENCES				RANGES		
			Time		Height				Mean
	Lat. (N)	Long. (W)	High Water h.m.	Low Water h.m.	High Water feet	Low Water feet	Mean feet	Diurnal feet	Tide Level feet
WASHINGTON, cont.			on ABERDEEN						
Willapa Bay and River									
South Bend, Willapa River	46°40′	123°48′	-0 04	-0 08	-0.3	-0.2	7.8	9.8	5.2
Raymond, Willapa River	46°41′	123°45′	+0 02	-0 03	-0.2	-0.1	7.8	9.9	5.3
Grayland	46°49′	124°06′	-1 05	0.59	†0.80	†0.80	6.2	8.1	4.4
Westport (ocean)	46°53′	124°07′	-1 05	-0.56	†0.84	†0.84	6.4	8.5	4.6
Grays Harbor									
Point Chehalis	46°55′	124°07′	-0 32	-0 43	-1.1	-0.1	6.9	9.0	4.8
Bay City	46°52′	124°04′	-0 15	-0 32	-0.9	-0.1	7.1	9.2	4.9
Markham	46°54′	124°00′	-0 19	-0 12	-0.9	-0.2	7.2	9.2	4.9
North Channel	46°58′	123°57′	-0 06	-0 01	-0.4	-0.1	7.6	9.7	5.2
Aberdeen	46°58′	123°51′	Daily predictions				7.9	10.1	5.4
Montesano, Chehalis River	46°58′	123°36′	+1 21	+1 48	†0.80	†0.80	6.7	8.1	4.1
Pacific Beach	47°13′	124°12′	-1 02	-0 59	†0.85	†0.85	6.5	8.6	4.6
Point Grenville	47°18′	124°16′	-1 02	-0 59	†0.85	†0.85	6.5	8.6	4.6
Destruction Island	47°40′	124°29′	-1 01	-1 03	†0.87	†0.87	6.6	8.7	4.7
LaPush, Quillayute River	47°55′	124°38′	-1 00	-0 47	†0.84	†0.84	6.5	8.5	4.6
Cape Alava (Flattery Rocks)	48°10′	124°44′	-0 53	-0 39	†0.81	†0.81	6.0	8.2	4.4
Strait of Juan de Fuca									
Cape Flattery, Tatoosh Island	48°23′	124°441	-046	-0 46	†0.80	†0.80	5.8	8.0	4.3

Table III-4 (cont.)

PLACE	POSITION		DIFFERENCES				RANGES		
			Time		Height				
	Lat. (N)	Long. (W)	High Water h.m.	Low Water h.m.	High Water feet	Low Water feet	Mean feet	Diurnal feet	Mean Tide Level feet
Hood Canal			on SEATTLE						
Port Ludlow	47°55'	122°41'	-0 27	-0 18	0.88	0.88	6.4	9.9	5.9
Port Gamble	47°52'	122°35'	-0 16	-0 08	0.91	0.91	6.7	lo.?)	6.1
Bangor Wharf	47°45'	122°44'	-0 20	+0 04	-0.3	0.0	7.3	10.9	6.4
Zelatched Point, Dabob Bay	47°43'	122°49'	-0 09	-0 05	+0.1	+0.1	7.6	11.5	6.7
Seabeck	47°38'	122°50'	-0 03	+0 03	+0.03	+0.1	7.8	11.6	6.8
Pleasant Harbor	47°40'	122°55'	-0 14	+0 01	+0.2	+0.1	7.7	11.6	6.8
Union	47°21'	123°06'	-0 04	+0 10	+0.4	+0.1	7.9	11.8	6.9
Puget Sound									
Hansville	47°5s'	122°33'	-0 07	+0 04	-1.0	-0.1	6.7	10,3	6.1
Point No Point	47°55'	122°32'	-0 16	-0 16	†0.92	†0.92	6.7	10,4	6.1
Edmonds	47°49'	122°23'	-0 05	+0 02	-0.4	0.0	7.2	10.9	6.4
Port Madison	47°42'	122°32'	-0 08	-0 08	+0.1	0.0	7.7	11.4	6.6
Poulsbo, Liberty Bay	47°44'	122°39'	+0 02	+0 08	+0.6	+0.1	8.1	11.9	6.9
Brownsville, Port Orchard	47°39'	122°37'	+0 02	+0 08	+0.4	0.0	8.0	11.7	6.8
Seattle (Madison St.) Elliott Bay	47°36'	122°20'	Daily predictions				7.6	11.3	6.6
Eighth Ave. S., Duwamish Waterway	47°32'	122°19'	+0 05	+0 07	-0.1	0.0	7.s	11.1	6.5
Port Blakely	47°36'	122°30'	+0 02	+0 03	+0.2	0.0	7.8	11.5	6.7
Pleasant Beach, Rich Passage	47°36'	122°32'	+0 01	+0 07	+0.2	0.0	7.6	11.5	6,7
Bremerton, Port Orchard	47°33'	122°38'	+0 07	+0 12	+0.4	0.0	8.0	11.7	6.8

Table III-4 (cont.)

PLACE	POSITION		DIFFERENCES				RANGES		
			Time		Height				Mean Tide Level
	Lat. (N)	Long. (W)	High Water h.m.	Low Water h.m.	High Water feet	Low Water feet	Mean feet	Diurnal feet	feet
Puget Sound, cont.			on SEATTLE						
Tracyton, Dyes Inlet	47°37′	122°40′	+0 30	+0 56	+1.0	0.0	8.6	12.3	7.1
South Colby, Yukon Harbor	47°31′	122°32′	+0 01	+0 07	+0.3	0.0	7.9	11.6	6.7
Des Moines	47°24′	122°20′	+0 03	+0 09	+0.4	0.0	8.0	11.7	6.8
Burton, Quartermaster Harbor	47°23′	122°28′	+0 07	+0 13	+0.6	0.0	8.2	11.9	6.9
Gig Harbor	47°20′	122°35′	+0 06	+0 14	+0.6	0.0	8.2	11.8	6.9
Tacoma, Commencement Bay	47°17′	122°25′	+0 07	+0 06	+0.5	0.0	8.1	11.8	6.8
Arietta, Hale Passage	47°17′	122°39′	+0 23	+0 36	+1.7	0.0	9.3	13.0	7.4
Home, Von Geldern Cove, Carr Inlet	47°16′	122°45′	+0 27	+0 39	+2.3	+0.2	9.7	13.6	7.8
Wauna, Carr Inlet	47°23′	122°38′	+0 20	+0 36	+1.8	0.0	9.7	13.1	7.5
Steilacoom	47°10′	122°36′	+0 22	+0 35	+1.8	0.0	9.4	X3.1	7.5
Hyde Point, McNeil Island	47°12′	122°39′	+0 23	+0 41	+2.1	+0.2	9.5	13.4	7.7
Sequalltchew Creek, Nisqually Reach	47°07′	122°40′	+0 24	+0 42	+2.1	+0.1	9.6	13.4	7.7
Longbranch, Filucy Bay	47°13′	122°45′	+0 26	+0 39	+2.2	+0.1	9.7	13.5	7.7
Henderson Inlet	47°09′	122°50′	+0 27	+0 45	+2.6	+0.2	10.0	14.0	8.0
Vaughn, Case Inlet	47°20′	122°46′	+0 35	+0 47	+2.8	+0.2	10.2	14.1	8.1
Allyn, Case Inlet	47°23′	122°49′	+0 27	+0 46	+2.8	+0.2	10.2	14.1	8.1
Walkers Landing, Pickering Passage	47°17′	122°56′	+0 35	+0 47	+2.9	+0.2	10.3	14.3	8.1
Arcadia, Pickering Passage	47°12′	122°56′	+0 35	+0 54	+3.0	+0.2	10.4	14.4	8.2
Shelton, Oakland Bay	47°13′	123°05′	+1 12	+1 54	+2.8	-0.2	10.6	14.2	7.9

Table III-4 (cont.)

PLACE	POSITION		DIFFERENCES				RANGES		
			Time		Height				Mean Tide Level
	Lat. (N)	Long. (W)	High Water h.m.	Low Water h.m.	High Water feet	Low Water feet	Mean feet	Diurnal feet	feet
Puget Sound, cont.			on SEATTLE						
Burns Point, Totten Inlet	47°07′	123°03′	+0 36	+0 54	+3.6	+0.2	11.0	15.0	8.5
Rocky Point, Eld Inlet	47°04′	123°01′	+0 34	+0 52	+3.3	+0.3	10.6	14.7	8.4
Dofflemyer Point, Budd Inlet	47°08′	122°54′	+0 29	+0 47	+3.1	+0.2	10.5	14.4	8.2
Olympia, Budd Inlet	47°03′	122°54′	+0 31	+0 46	+3.1	+0.2	10.5	14.4	8.2
Possession Sound and Port Susan									
Mukilteo	47°57′	122°18′	-0 08	-0 12	-0.3	-0.1	7.4	11.0	6.4
Everett	47°59′	122°13′	-o 09	-o 11	-0.2	0.0	7.4	11.1	6.5
Tulalip	48°04 ′	122°171	+0 02	-o 02	0.0	0.0	7.6	11.2	6.6
Kayak Point	48°08′	122°22′	-o 04	-o 01	-0.4	-0.1	7.3	10.9	6.3
Saratoga Passage and Skagit Bay									
Greenback, Whidbey Island	48°061	122°341	-o 01	-0 08	0.0	0.0	7.6	11.3	6.6
Coupeville, Penn Cove	48°13′	122°41′	+0 05	0 00	+0.2	0.0	7.8	11.5	6.7
LaConner, §§ Swinomish Channel	48°23′	122°30′	+0 22	+0 34	†0.88	†0.93	6.5	10.0	6.9
Ala Spit	48°24 ′	122°35′	+0 12	+0 27	†0.92	†0.92	6.9	10.5	6.1
Yokeko Point, Deception Pass	48°25′	122°37′	+0 27	+0 46	-0.3	0.0	7.3	11.2	6.4
Cornet Bay, Deception Pass	48°24′	122°37′	+0 15	+0 26	0.89	0.89	6.6	10.2	6.0
Rosario Strait, etc.			on PORT TOWNSEND						
Reservation Bay, Fidalgo Island	48°25′	122°40′	-0 08	-0 03	†0.92	†0.92	4.5	7.6	4.7
Aleck Bay, Lopez Island	48°26 ′	122°51′	-o 11	-0 06	†0.89	†0.89	4.2	7.4	4.6

Table II I-4 (cont.)

PLACE	POSITION Lat. (N)	POSITION Long . (W)	DIFFERENCES Time High Water h.m.	DIFFERENCES Time Low Water h.m.	DIFFERENCES Height High Water feet	DIFFERENCES Height Low Water feet	RANGES Mean feet	RANGES Diurnal feet	Mean Tide Level feet
Rosario Strait, etc.			on PORT TOWNSEND						
Burrows Bay (Allan Island)	48°28′	122°42′	+0 16	+0 05	†0.96	†0.92	5.0	8.1	4.8
Anacortes, Guemes Channel	48°31′	122°37′	+0 29	+0 35	†0.99	†0.99	4.8	8.2	5.0
Swinomish Channel ent., Padilla Bay	48°28′	122°31′	+0 43	+1 19	+0.1	+0.1	5.1	8.4	5.1
Thatcher Pass	48°32′	122°48′	+0 38	+0 20	†0.99	†0.96	5.0	8,2	4.9
Strawberry Bay, Cypress Island	48°34′	122°43′	+0 41	+0 54	†0.96	†0.96	4.8	8.0	4.9
Peavine Pass	48°36′	122°48′	+0 41	+0 20	†0.99	†0.96	5.0	8.2	4.9
Eagle Harbor, Cypress Island	48°35′	122°42′	+0 43	+0 50	†0.99	†0.96	5.0	8.2	4.9
Bellingham Bay									
Chuckanut Bay	48°40′	122°30′	+0 40	+0 55	+0.1	0.0	5.2	8.4	5.1
Bellingham	48°45′	122°30′	+0 46	+1 10	+0.2	+0.1	5.2	8.6	5.2
Hale Passage									
Point Migley	48°45′	122°43′	+1 03	+0 53	+0.2	+0.1	5.2	8.6	5.2
Rosario, East Sound, Orcas Island	48°39′	122°52′	+0 34	+1 06	†0.98	†0.98	4.9	8.1	4.9
Upright Head, Lopez Island	48°34′	122°53′	+0 33	+0 46	†0.94	†0.94	4.6	7.8	4.8
Orcas, Orcas Island	48°36′	122°57′	+0 40	+0 58	†0.92	†0.92	4.5	7.6	4.7
San Juan Channel									
Richardson, Lopez Island	48°27′	122°54′	-0 14	-0 09	†0.88	†0.88	4.2	7.3	4.5
Friday Harbor, San Juan Island	48°33′	123°00′	+0 42	+0 58	†0.93	†0.93	4.5	7.7	4.8
Strait of Georgia									
Echo Bay, Sucia Islands	48°451	122°54′	+1 08	+1 36	+0.2	+0.1	5.2	8.6	5.2

Table III-4 (cont.)

PLACE	POSITION		DIFFERENCES				RANGES		
			Time		Height				Mean
	Lat. (N)	Long. (W)	High Water h.m.	Low Water h.m.	High Water feet	Low Water feet	Mean feet	Diurnal feet	Tide Level feet
Rosario Strait, etc. cont.			on PORT TOWNSEND						
Strait of Georgia									
Ferndale	48°50′	122°43′	+0 56	+1 22	+0.6	+0.1	5.6	9.0	5.4
Blaine, Semianmoo Bay	49°00′	122°46′	+1 06	+1 29	+1.0	+0.2	5.9	9.5	5.6
Haro Strait									
Kanaka Bay, San Juan Island	48°29′	123°05′	-0 04	0 00	†0.87	†0.87	4.2	7.3	4.5
Roche Harbor, San Juan Island	48°37′	123°09′	+0 36	+0 54	†0.91	†0.91	4.4	7.5	4.7
Turn Harbor, Stuart Island	48°41′	123°14′	+0 31	+0 49	†0.91	†0.91	4.4	7.s	4.7
Pates Island Wharf	48°47′	122°58′	+1 10	+1 32	+0.3	+0.1	5.3	8.6	5.2
BRITISH COLUMBIA									
Passages inside Vancouver Island			on VICTORIA						
Sooke, Vancouver Island††	48°22	123°44′	-0 11	-0 33	+0.8	+0.5	----	6.4	§§§6.6
Esquimalt, Vancouver Island††	48°26′	123°26′	+0 12	+0 17	0.0	-0.1	----	6.2	§§§6.3
Victoria, Vancouver Island††	48°26′	123°23′	Daily predictions				----	6.1	§§§6.3
Sidney, Haro Strait	48°39′	123°24′	-1 01	-1 11	0.71	0.61	----	7.8	§§§7.1
Fulflord Harbor, Saltspring 1s1.	48°46′	123°27′	-0 55	-1 08	-3.5	-1.0	----	8.0	§§§7.6
Active Pass, Mayne Island	48°52′	123°20′	-0 16	-0 30	-1.5	-0.8	----	9.8	§§§8.6
Cowichan Bay	48°45′	123°38′	-0 53	-1 09	-3.0	-0.6	----	8.0	§§§8.1
Chemainus, Stuart Channel	48°55′	123°42′	-0 51	-1 03	-2.2	-1.0	----	9.3	§§§8.3
Ladysmith	48°59′	123°47′	-0 51	-1 02	-2.3	-0.8	-----	9.0	§§§8.4
Vancouver	49°18′	123°07′	Daily predictions				----	10.5	†††9.9

Table III-4 (cont.)

PLACE	POSITION		DIFFERENCES				RANGES		
			Time		Height				Mean Tide Level
	Lat. (N)	Long. (W)	High Water h.m.	Low Water h.m.	High Water feet	Low Water feet	Mean feet	Diurnal feet	feet
Vancouver Island, Southwest Coast			on SITKA						
Port San Juan	48 33′	124 25′	-1 05	-1 08	‡‡0.65	+3.4	5.0	7.2	6.8
Carmanah Point	48 37′	124 25′	-1 10	-1 12	‡‡0.75	+2.3	6.0	7.4	6.2
Bamfield, Barkley Sound	48 50′	125 08′	-1 23	-1 21	‡‡0.86	+2.5	6.6	8.7	7.1

[§] U.S. Dept. of Commerce, 1977b.

[†] Ratio.

[‡] Columbia River is subject to annual freshets. Short range predictions are available at local river forecast centers. The data for stations above Barrington Point apply only during low river stages.

[§§] The data for La Conner apply only during low levels of the channel which usually occur in midsummer. Low water seldom falls below the datum.

[††] Tide is chiefly diurnal.

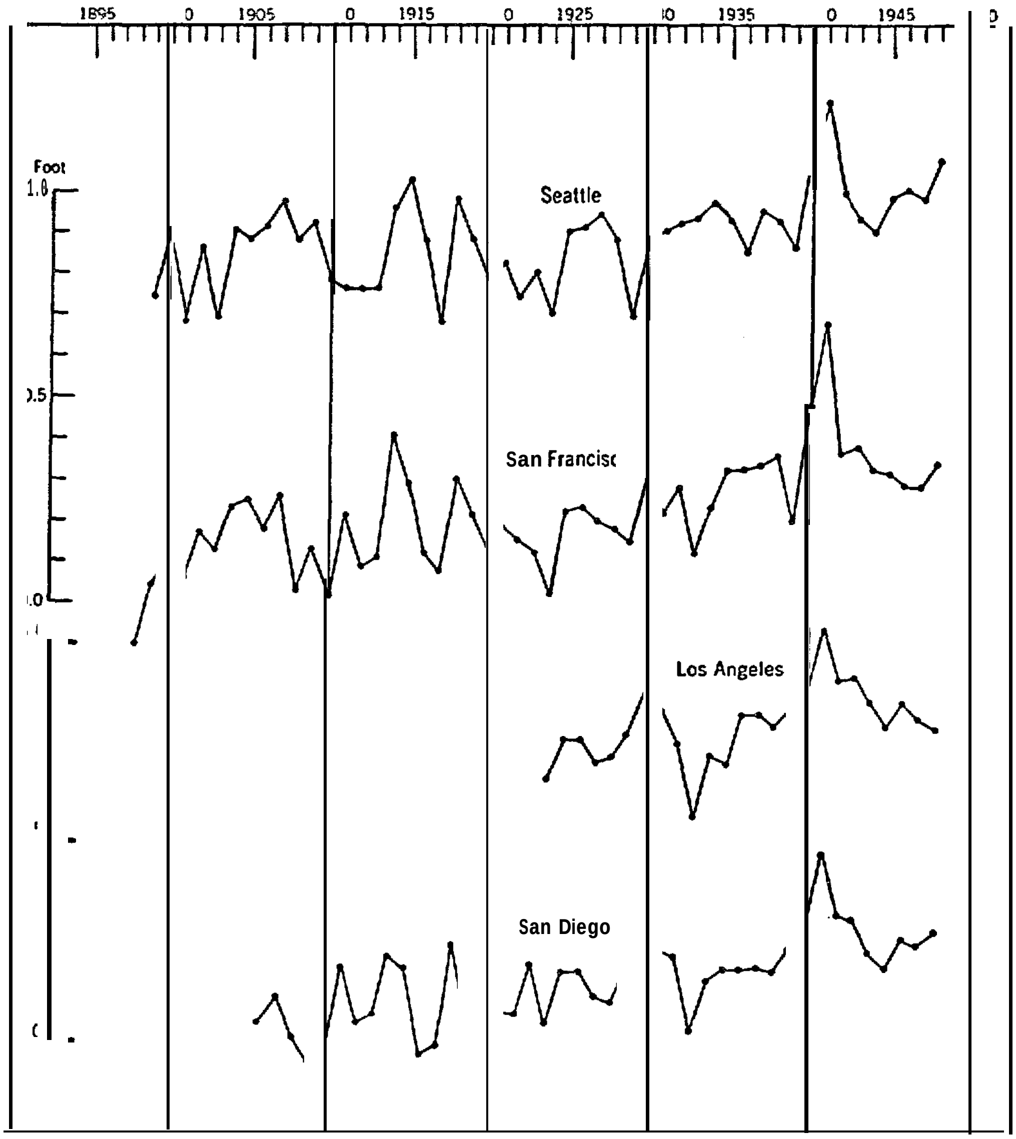
[‡‡] Ratio. Multiply heights at reference station and then apply the accompanying correction.

[§§§] Heights are reckoned from the datum of soundings on Canadian Charts of the locality. 2.5 feet must be subtracted to conform to MLLW datum of the U.S. National Ocean Survey charts.

[†††] Heights are reckoned from the datum of soundings on Canadian Charts of the locality. 3.8 feet must be subtracted to conform to MLLW datum of the U.S. National Ocean Survey charts.

Figure III-27

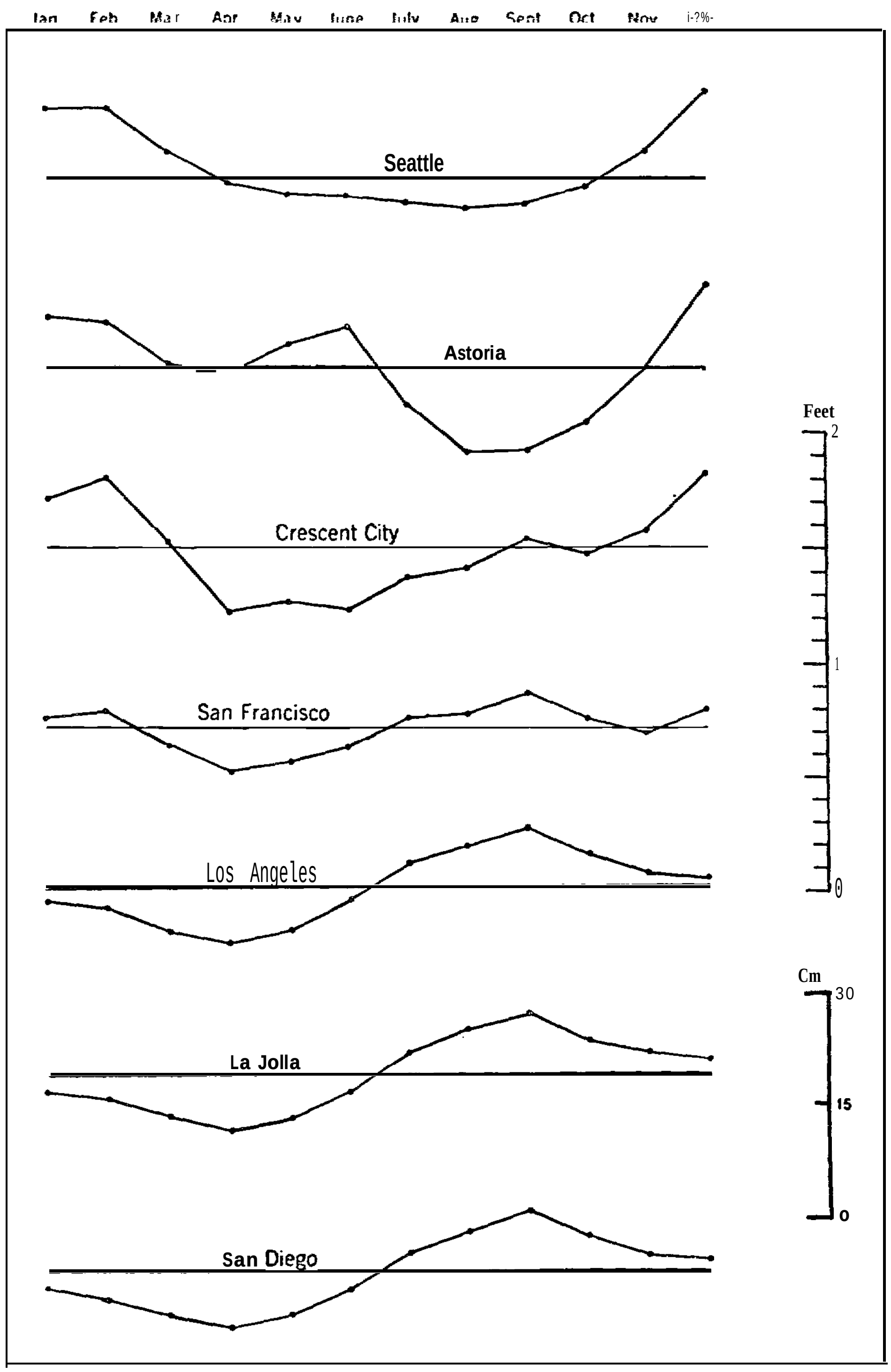
Yearly Sea Level, Pacific Coast[§]



[§]Marmer, 1951.

Figure III-28

Annual Variations in Sea Level, Pacific Coast[§]



[§]Manner, 1951.

On the Oregon-Washington coast, the tides have been analyzed primarily in the bays and estuaries. Hopkins (1971a and 1971b) reports pressure data and tidal analysis for a location on the shelf to the northwest of the Columbia River entrance (46°24.8'N and 124°20.0'W). Seven usable data records of approximately two months duration each were obtained. Figure III-29 presents one of these records.

iii. Currents. Currents in the ocean are determined directly by current measurements or indirectly by applying hydrodynamic relations. The general large-scale features of currents in the region appear to be well documented, but a detailed understanding of the current regime is poor . Much of the general circulation patterns have been deduced from hydrographic and meteorologic observations and in some cases drift studies. Actual measurements of current velocities in coastal waters are sparse. Those measurements that have been made indicate that steady flow is not a common occurrence, but rather eddy flow and current reversals with tide or wind are more characteristics of the nearshore circulation.

A complex circulation pattern prevails along the coast as a result of the interactions of the various types of currents present. This complex regime includes permanent ocean currents, local wind-driven currents, currents produced by the tide, waves, and upwelling. Because of the many forces present to produce currents in this region, current speed and direction are highly variable. Average spatial and temporal values are usually reported due to this variability. In regions where local topography influences the interaction of the driving forces, the current may move as an eddy, fluctuating widely in both speed and direction. Average values may be meaningless for such areas. This greatly compounds the difficulty of predictive efforts on the movement of a pollutant, such as oil.

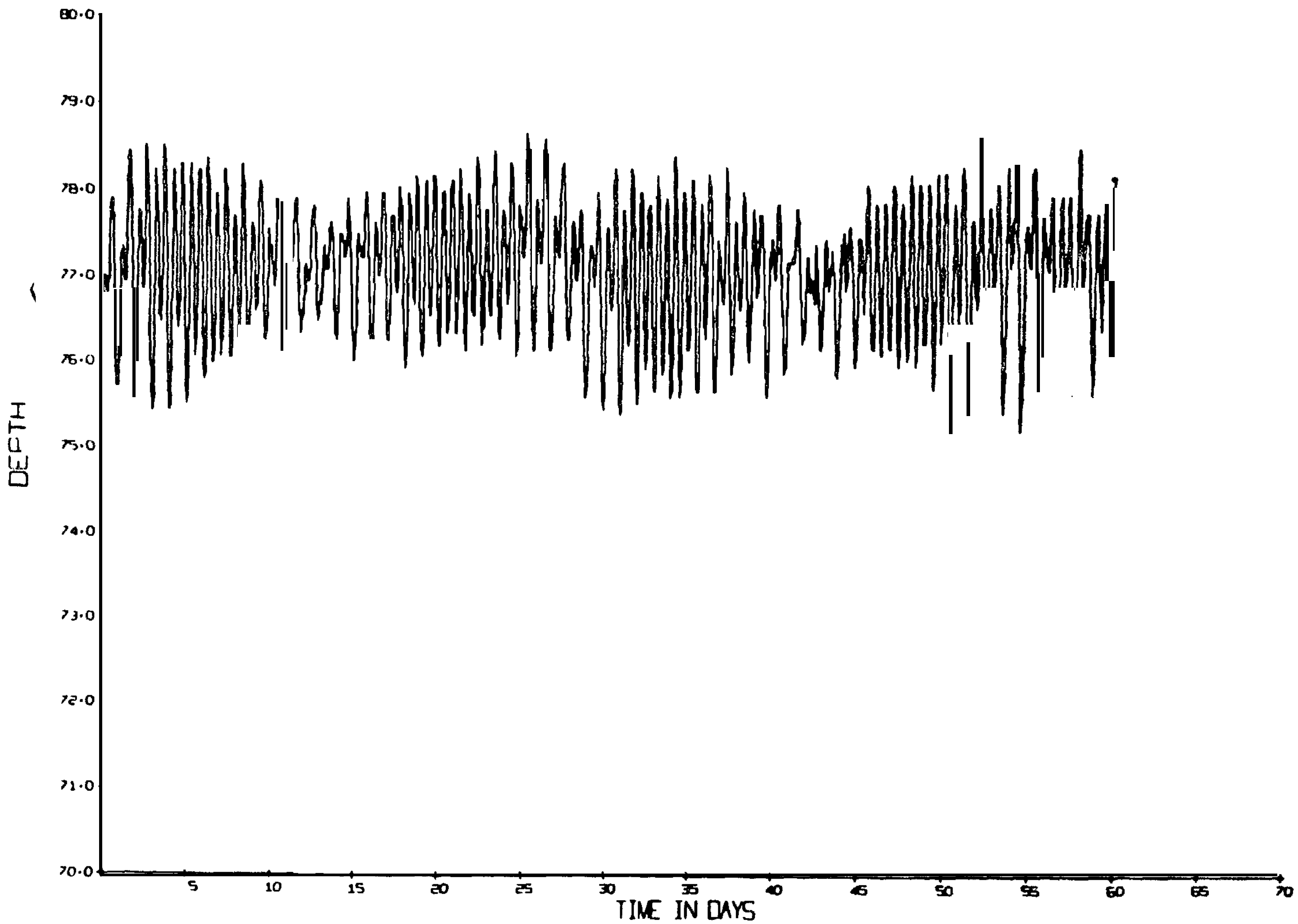
Wind currents occur mainly in the surface layer. The extent of this surface layer is not fully defined, but probably extends to a depth of about 10 meters. Tide currents on the slope and shelf are "shallow water" phenomena and extend theoretically to the bottom of the oceans. Tidal currents are generally thought to be essentially constant with depth in nearshore regions. Oscillatory water motion due to wind waves (sea and swell) decrease logarithmically with depth and are essentially negligible at a depth equal to one half the wave length.

Currents are of great importance in transporting planktonic organisms, particularly the planktonic larvae of benthic plants and animals. Distribution of materials such as nutrients and trace metals are influenced by currents, shelf sediment transport is governed by the currents, and so is the movement of an oil spill.

a) Regional Currents. The Subarctic Current, part of the West Wind (North Pacific) Drift, carries water eastward across the Pacific, and then splits to form the Alaska Current and the California Current. In general, the California Current is a broad, slow, and shallow southward flowing current (Figure 111-30). It flows offshore as a diffuse band about 500 km wide with an average

Figure III-29

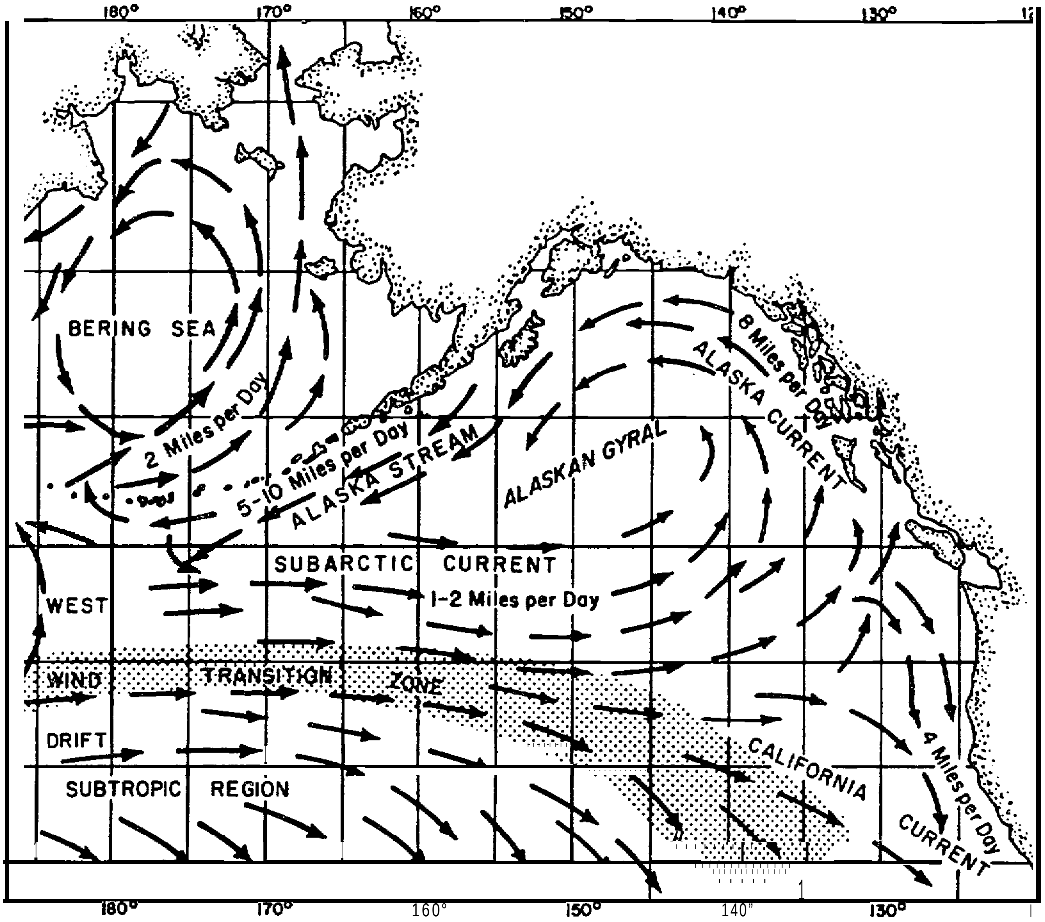
Pressure Record From 21 August to 22 October, 1969 From a Location on the Shelf of Southern Washington§



§Hopkins, 1971a.

Figure 111-30

General Circulation, North Pacific Ocean§÷



§U.S. Bureau of Land Management, 1974.
÷1 mi./day ≅ 2 cm./sec.; 50 cm./sec. ≅ 1 knot.

speed of 10 cm/sec. It attains maximum strength during the summer when surface winds are consistently from the northwest.

The Davidson Current occurs in the winter time and is counter to the California Current. It flows northward, attaining speeds of 25 to 45 cm/sec over extensive distances and has a minimum width of 90 km. It develops off the Oregon-Washington coast in September and becomes well established by January. Toward spring it diminishes and disappears by May.

The Davidson Current is caused by a geostrophic response to uplifted isosteres along the coast (Smith and Hopkins, 1972). Recent measurements at depth in the summer months have often detected a poleward flowing current (Figure 111-31) (Mooers, *et* aZ., 1968) .

b) Tidal Currents. Hopkins (1971b) analyzed the tidal components of currents measured north of the Columbia River lightship. He noted that much of the time the tidal currents were masked by stronger features. Coastal tidal currents found 9 km offshore, as observed by lightships along the Pacific Coast, are reported in the Tidal Current Tables (U.S. Department of Commerce, 1977a). The currents are rotary, turning clockwise, with a 12.5 hour period. Biweekly spring and neap tides respectively increase and decrease the average tidal current by about 20 percent.

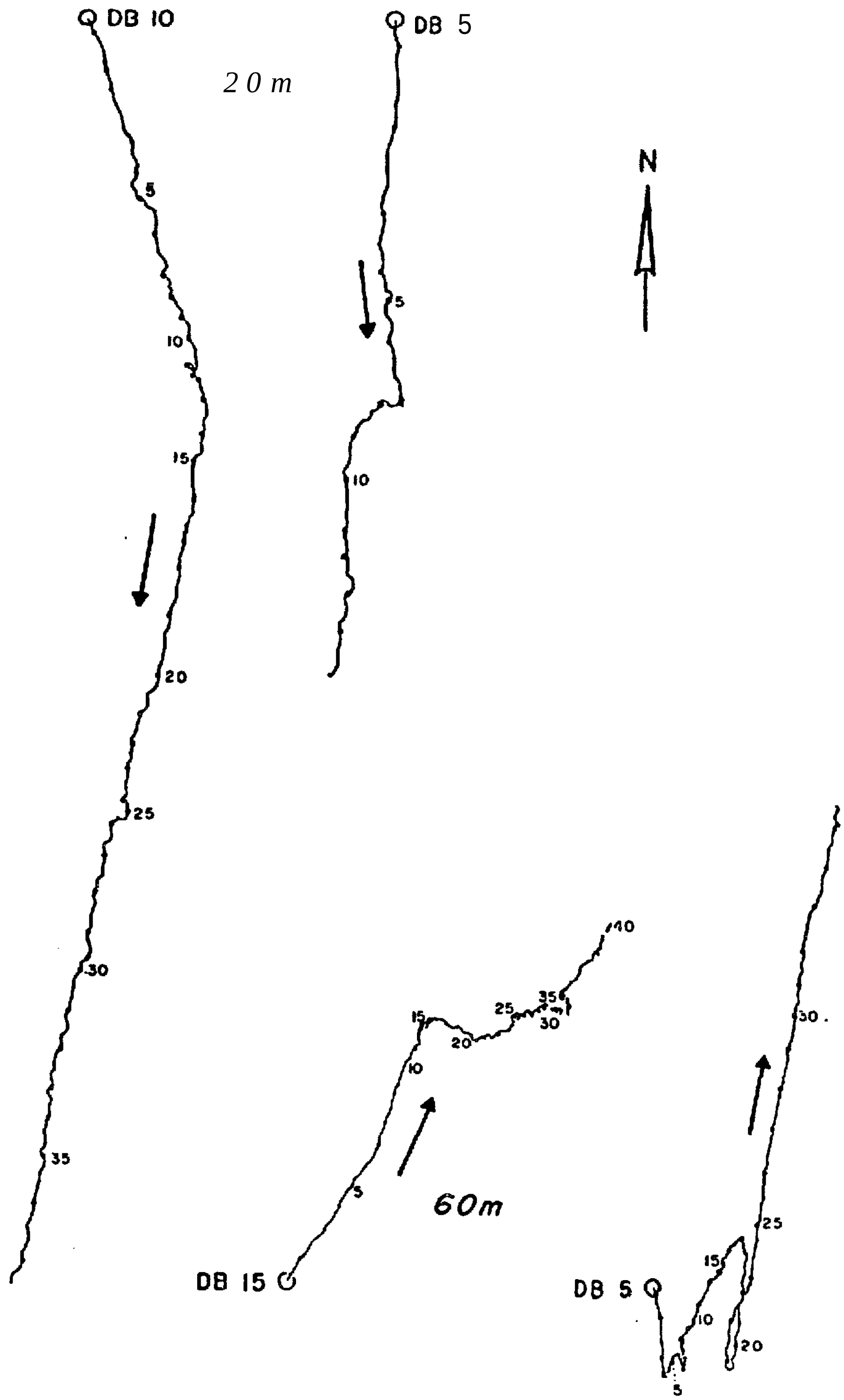
The tidal currents measured at the Blunts Reef Lightship off Cape Mendocino (northern California) show very weak rotary characteristics with average speeds of less than 5 cm/sec. At maximum flood the current sets north; at maximum ebb it sets south. The tidal current is generally masked by a nontidal current averaging 10 cm/sec setting to the southwest from March to November and to the northwest from November to March. The greatest observed velocity at the lightship is 155 cm/sec.

The tidal currents observed at the Columbia River Lightship are also rotary but rather weak, averaging about 15 cm/sec. The set of the maximum flood and ebb currents are 020°T and 200°T, respectively. The discharge from the Columbia River completely masks the flood tide current at the lightship. The set of the nontidal current created by the river flow changes from SW (235°T) during February through October to WNW (295°T) from October to February in response to the seasonal wind pattern. The nontidal current speed ranges from a monthly average of 15 cm/sec in March to 39 cm/sec in June (Duxbury, Morse and McGary, 1966). During periods of high river runoff, the combined tidal and nontidal current frequently is 100 cm/sec or greater to the S.W. The greatest observed velocity at the lightship is 180 cm/sec.

The tidal currents at the Umatilla Reef Lightship of Cape Arago, Washington are weakly rotary. Maximum currents occur 15 minutes after maximum flood or ebb is observed at the entrance to the Strait of Juan de Fuca. The average velocity of flood and ebb currents is 15 cm/sec setting 345°T on flood and 165°T on ebb. Wind driven currents usually mask the tidal current. From November to April the flow is northerly (350°T) at 35 cm/see, peaking

Figure III-31

Progressive Vector Diagrams of Currents, Depoe Bay Array, 15 August-24 September 1966[§†]



§Mooers, *et al.*, 1968.

†The figures indicate the number of days since commencement of current meter recordings.

to 50 cm/sec during December; from April to November the current is variable, generally setting SE at an average speed of 20 cm/sec. The strong southeasterly winds of winter produce a combined current of 100 to 150 cm/sec. The greatest observed velocity at the lightship is 170 cm/sec.

The current tables report that wind driven currents and other nontidal currents are frequently of such strength as to completely mask the tidal current. The nontidal currents must be vectorially added to the tidal current to obtain the resultant current. The Tidal Current Tables provide drift current speed and direction factors that can be applied to the tidal current if the wind speed and direction are known. The resultant current is approximate.

The tables are based on observations at lightships off of northern California (Blunts Reef), the Columbia River, and northern Washington (Umatilla Reef).

Bourke, Glenne and Adams (1971) computed an approximate regional nearshore tidal current of approximately 10 cm/sec by observing the time necessary for the tide to traverse the distance from the Farallon Islands to Cape Alava off the Northern Washington coast. The Tidal Current Tables (U.S. Department of Commerce, 1977a] indicate that the nearshore tidal current is mostly translational all along the Pacific coast, setting approximately 060°T on flood and 240°T on ebb.

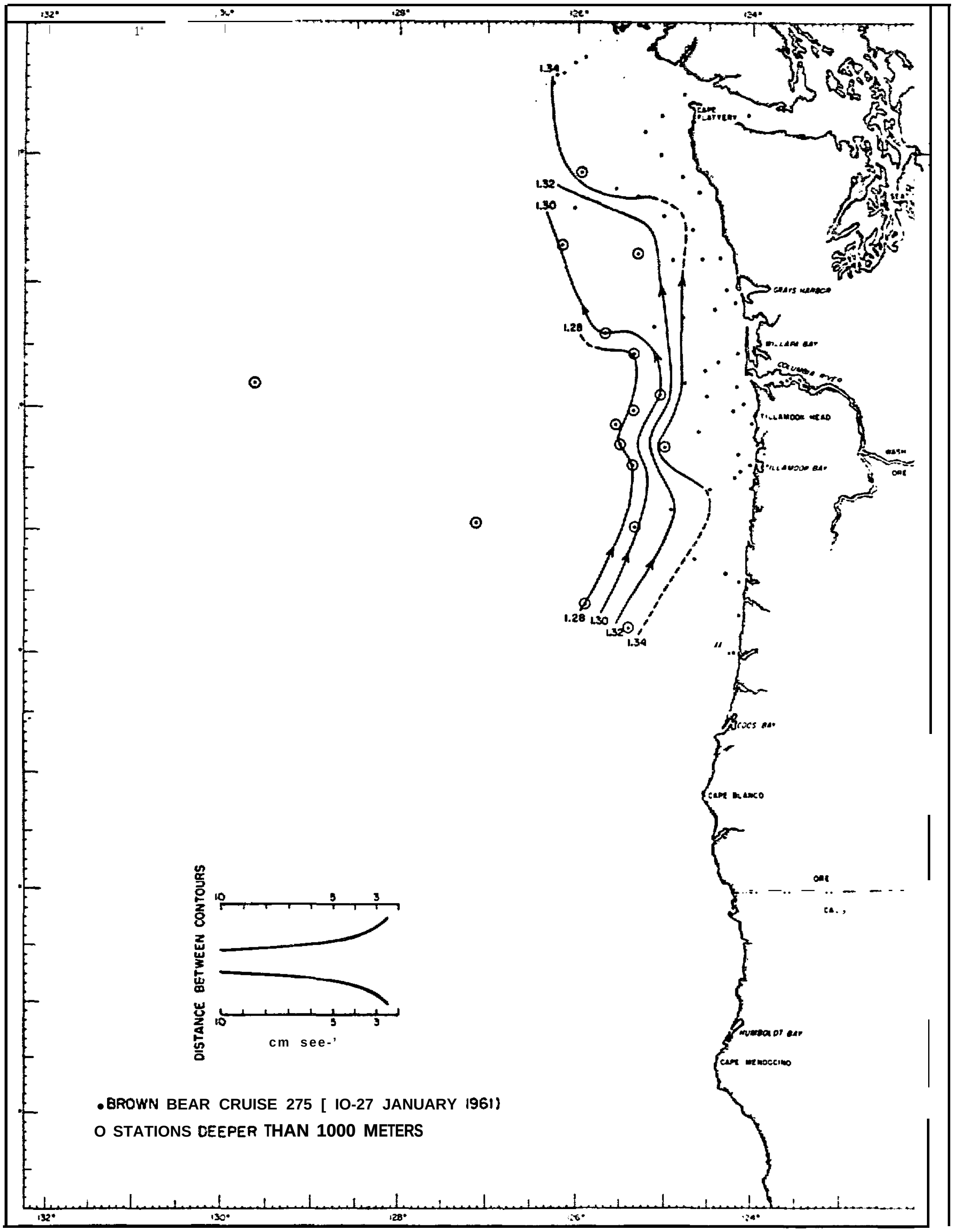
c) Density Currents. Budinger, Coachman and Barnes (1964) performed a season-to-season analysis of the offshore areas adjacent to the Washington, Oregon, and northern California coasts. Geostrophic currents (unaccelerated currents in which the pressure gradient force equalizes the Coriolis "Force") were deduced from calculations of topography of the sea, using 1961-62 hydrographic data. Figures III-32 through III-41 present the geopotential topographies with a contour interval of 2 dynamic centimeters as computed for 10 different cruises. The 1000 decibar level was used as the reference of assumed no motion (0/1000). The direction of geostrophic flow is indicated by arrows, and the speed in interpreted from the contour spacings. The following discussion is adapted from Budinger, Coachman and Barnes (1964).

During January 1961, a current was observed to set northward at approximately 10 cm/sec (Figure III-32). The flow intensified to greater than 20 cm/sec during March (Figure 111-33), and reversed direction during May (Figure III-34). The radical change in current set is associated with a shift in the predominant wind from southerly to northerly. During the summer, a southerly current averaging 8 cm/sec predominated.

The current pattern change from winter to summer is complicated by cyclonic and anticyclonic eddies. There is a suggestion of a cyclonic eddy in the topography of Figure 111-33 and this eddy appears better developed in Figure III-34. The anticyclonic eddy or high near 46°N shown in Figure III-34 to III-37 is well documented

Figure 111-32

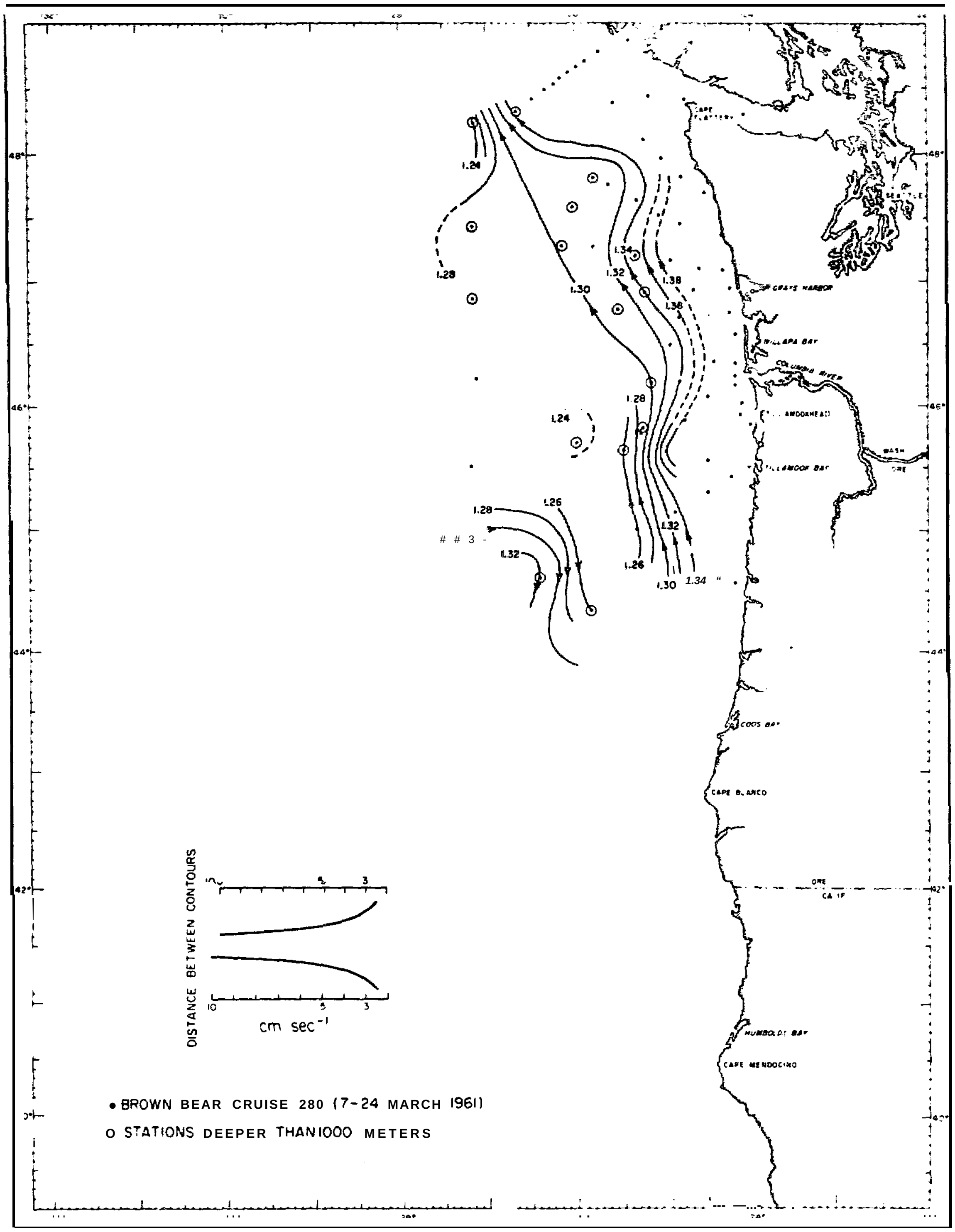
Geopotential Topography, 0/1000 Decibars, Brown Bear
Cruise 257, 10-27 January 1961[5]



[5] Budinger, Coachman and Barnes, 1964.

Figure III-33

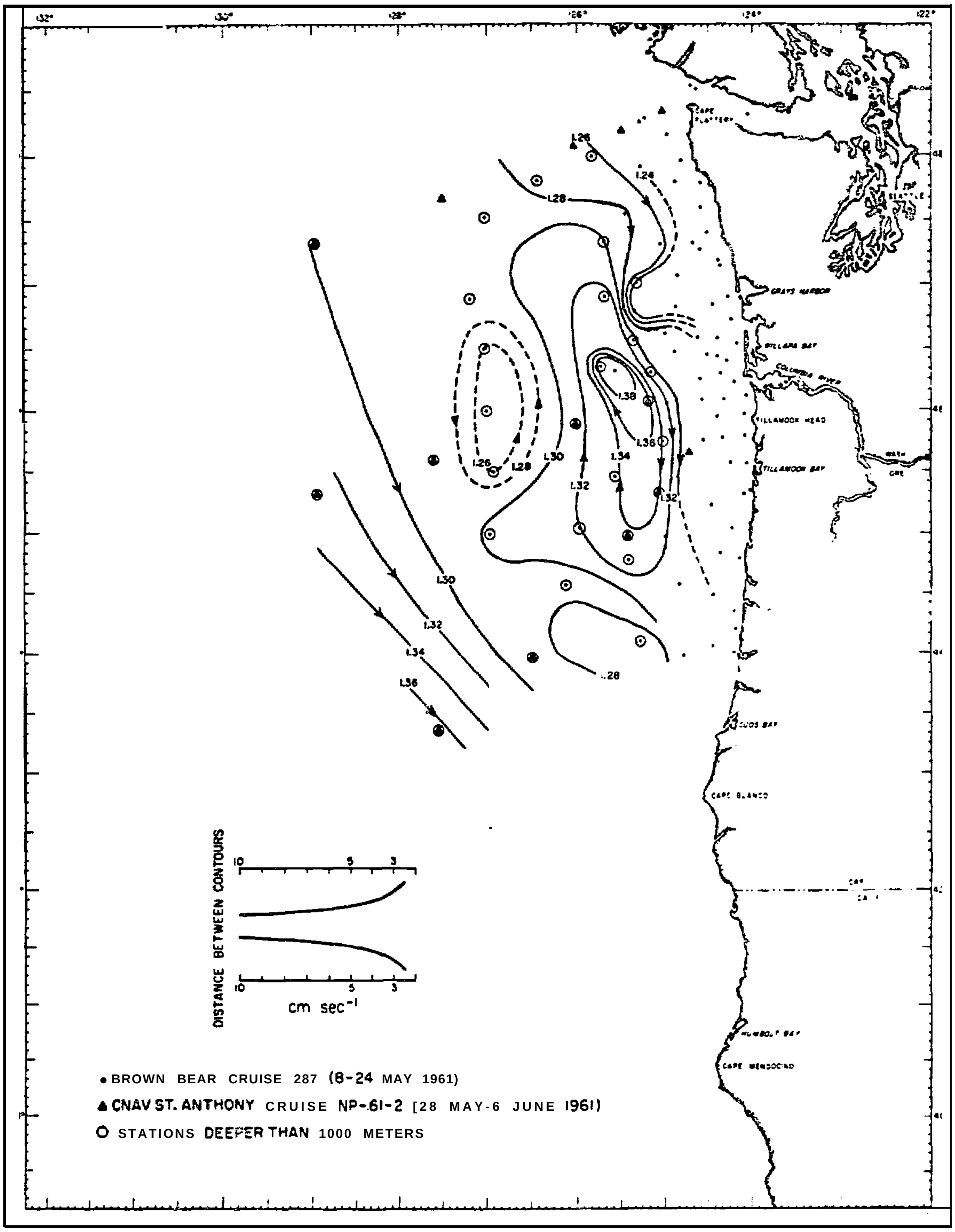
Geopotential Topography, 0/1000 Decibars. Brown Bear Cruise 280, 7-24 March 1961§



§Budinger, Coachman and Barnes, 1964.

Figure III-34

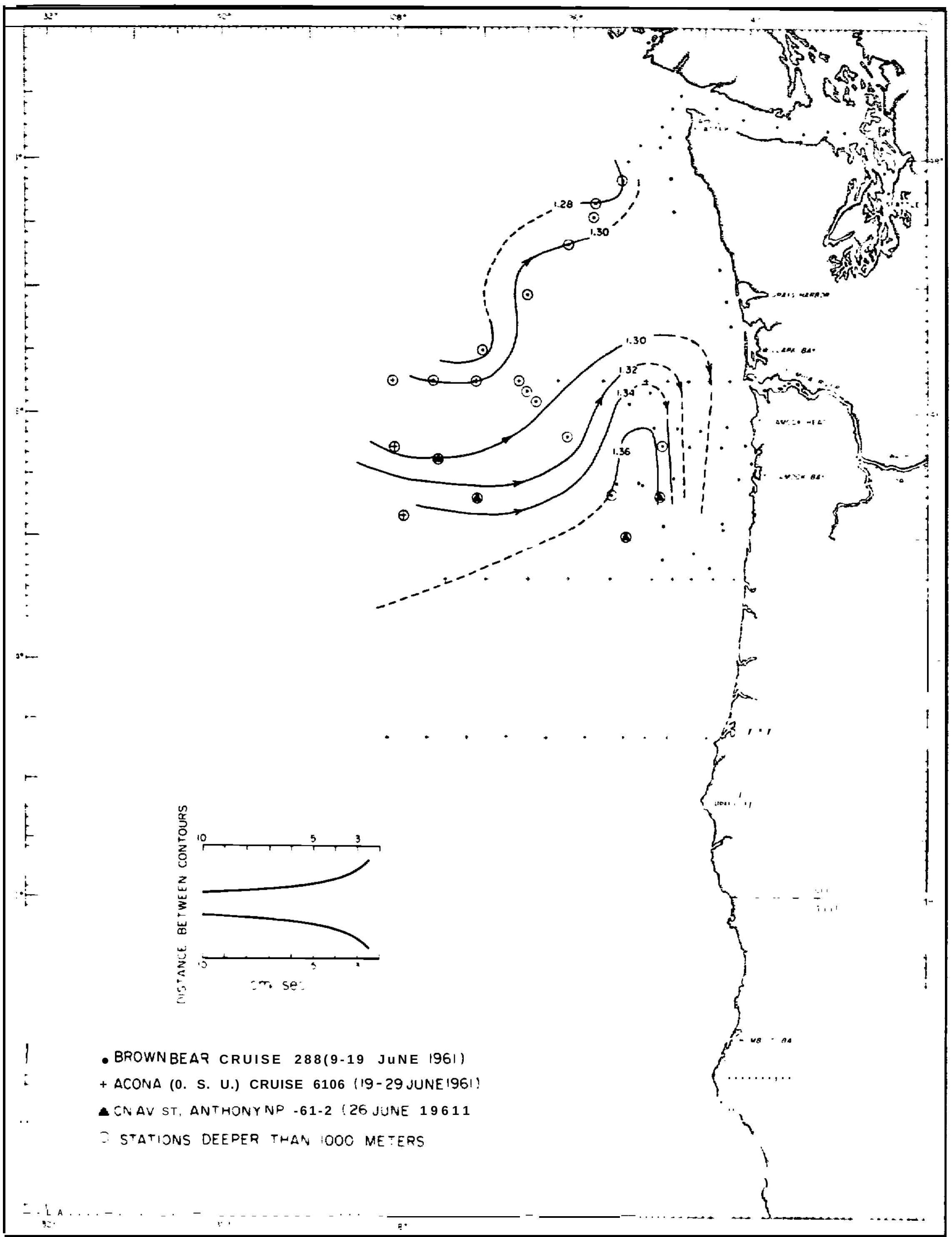
Geopotential Topography, '/1000 Decibars, Brown Bear Cruise 287, 8-24 May 1961§



§ Budinger, Coachman and Barnes, 1964.

Figure III-35

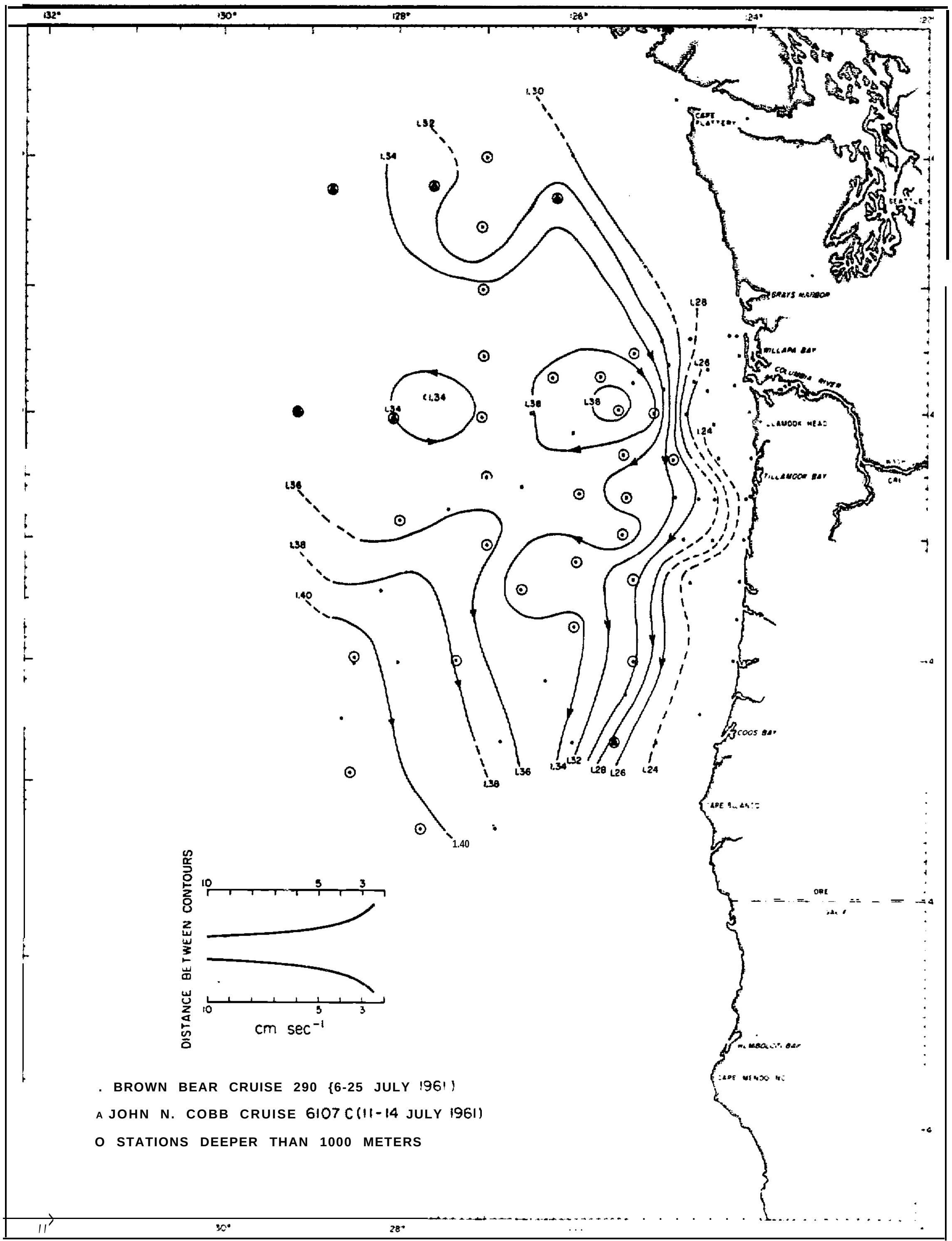
Geopotential Topography, $^{0}/1000$ Decibars§, Brown Bear Cruise 288, 9-19 June 1961§



§Budinger, Coachman and Barnes, 1964.

Figure III-36

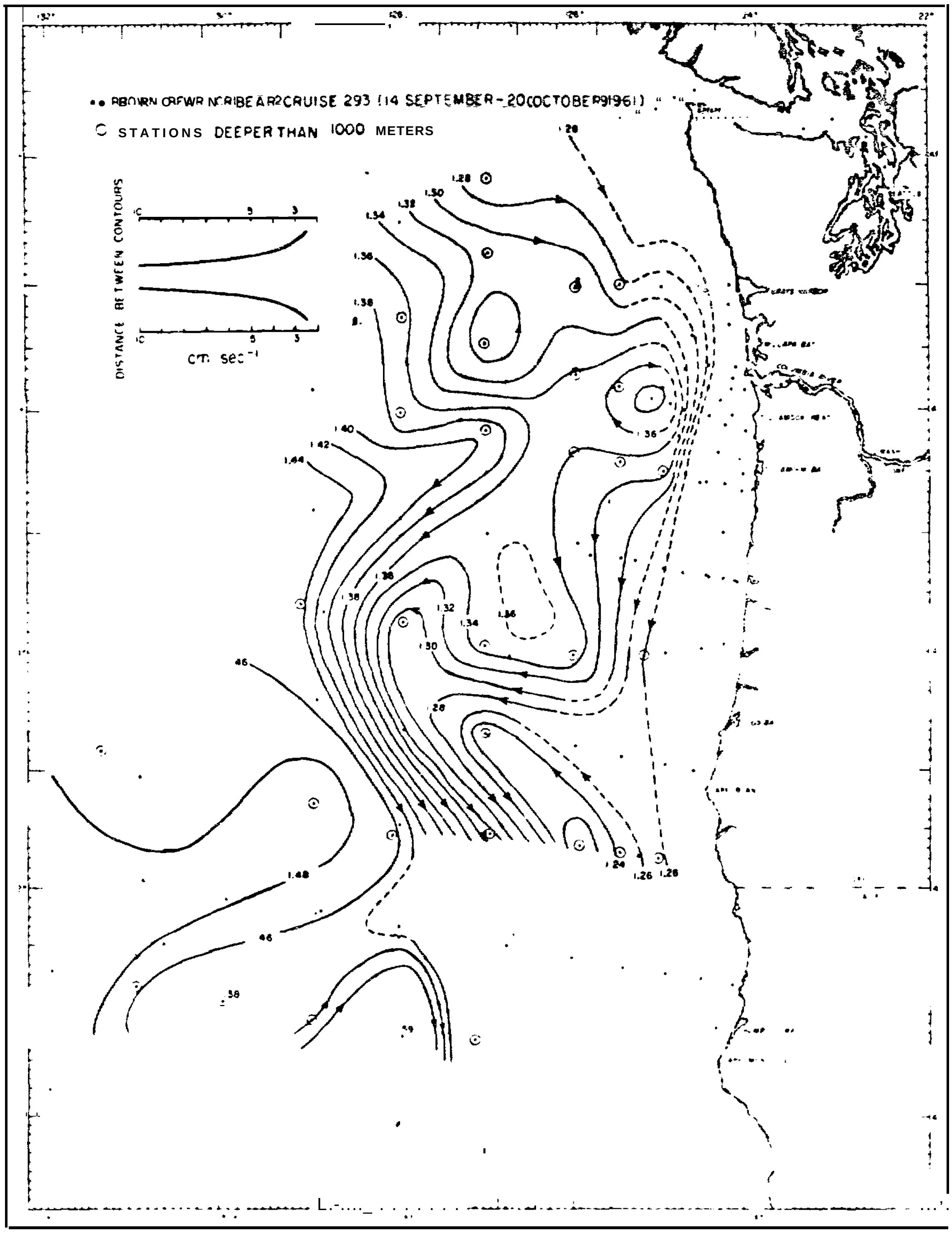
Geopotential Topography, 0/1000 Decibars, Brown Bear Cruise 290, 6-25 July 1961[§]



[§]Budinger, Coachman and Barnes, 1964.

Figure III-37

Geopotential Topography, 0/1000 Decibars, Brown Bear Cruise 293, 14 September-20 October 1961§



§Budinger, Coachman and Barnes, 1964.

by numerous observations and appears rather consistently throughout the summer and autumn; hence it is probably not an artifact associated with the lack of synopticity in sampling and/or internal waves (Defant, 1950).

Reid, Schwartzlose, and Brown (1963) confirmed the existence of a permanent eddy off the California coast using parachute drogues. The drogue movements agree with what might be expected from dynamic topography. This suggests that the eddies are geotrophically in balance. Reid and co-workers suggested that the eddies probably result from the horizontal shear between two currents. McEwen (1948) studied the dynamics of similar eddies and concluded that the decrease in velocity and increase in size noted on successive cruises are probably successive stages of decay from an initial state of maximum intensity and small extent.

The dynamic topography derived from the early fall cruise (September-October 1961) is shown in Figure III-37. Velocities as high as 20 cm/sec are inferred in the cyclonic eddies.

The response of the distribution of mass to the autumnal shift in winds from predominantly north to predominantly south is shown in the geopotential topography from December 1961 (Figure 111-38). The northward setting Davidson Current appears to be in an early stage of development but the isopleths inshore are based on Helland-Hansen (1934) extrapolation over large distances, hence the depiction may not be accurate. The circulation pattern of the surface water is less complex in mid-winter as shown by Figure III-39. Here a trough is evident about 130 to 185 kilometers offshore, with a northerly current inshore and a southerly current seaward, each at about 10 cm/sec.

The southerly winds persisted until after the next sampling in April, 1962. Figure 111-40 shows the northerly (Davidson) current fully developed along the coast. During May and June, 1962, the winds, shifted from southerly to northerly and the spring conditions again appeared with a nearshore southerly current and an offshore northerly current (Figure 111-41).

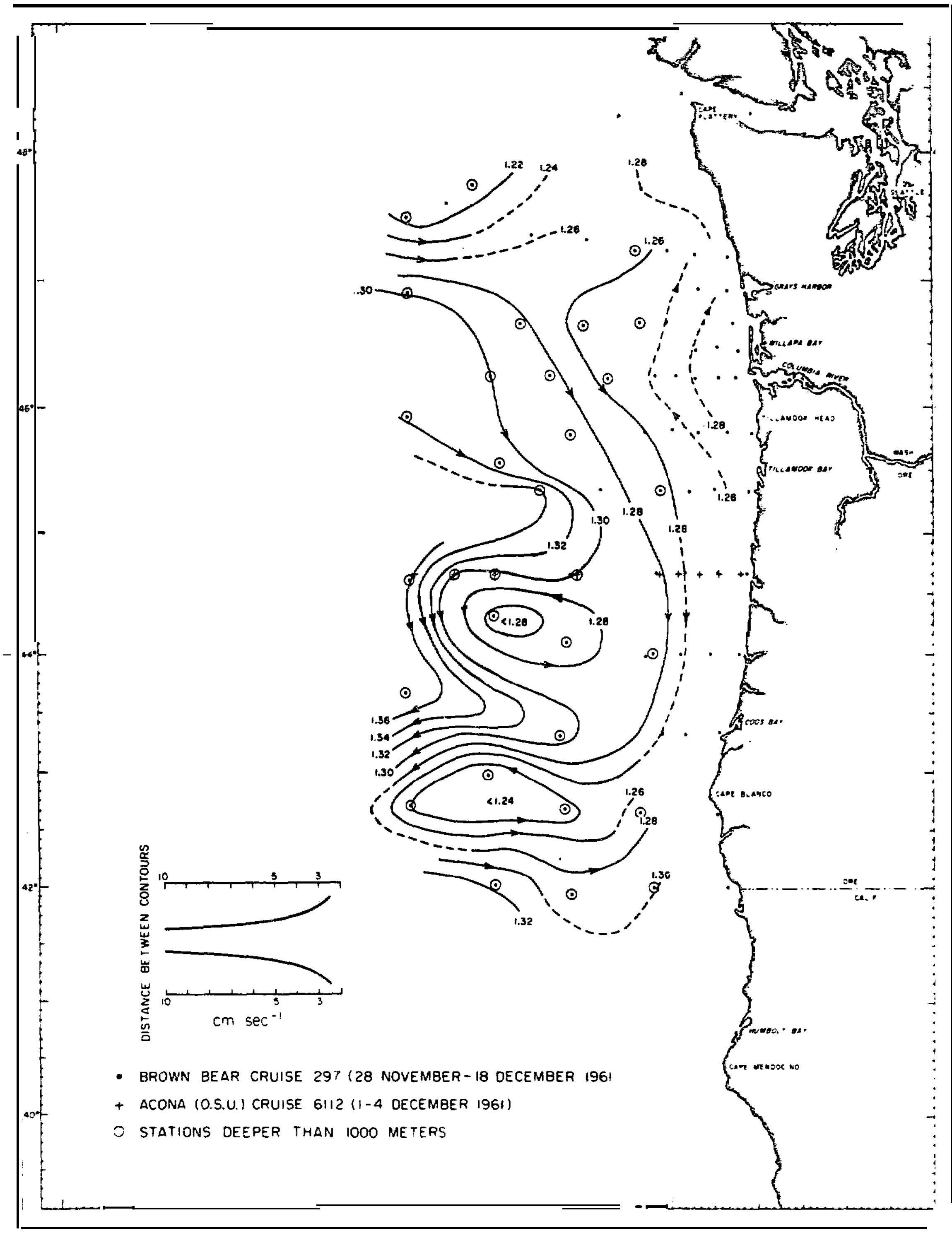
In general, the average surface current pattern deduced from this analysis is northerly at 10 to 20 cm/sec in the winter and southerly at 5 to 20 cm/sec in the summer.

d) Wind Drift. Wind drift current speed is a function of the wind speed and the latitude. The direction of wind drift is affected by the earth's rotation. In the Northern Hemisphere, and in an "infinite" ocean, the direction of the wind drift is 45° to the right of the wind. The vectors of the drift current turn toward the right with increasing depth (in the Northern Hemisphere), forming an exponentially decaying spiral. According to Dietrich (1963), the net mass transport depends linearly on the windstress and is directed perpendicular to the wind direction. This transport is referred to as Ekman transport.

Duxbury, Morse, and McGary (1966) computed the average direc-

Figure III-38

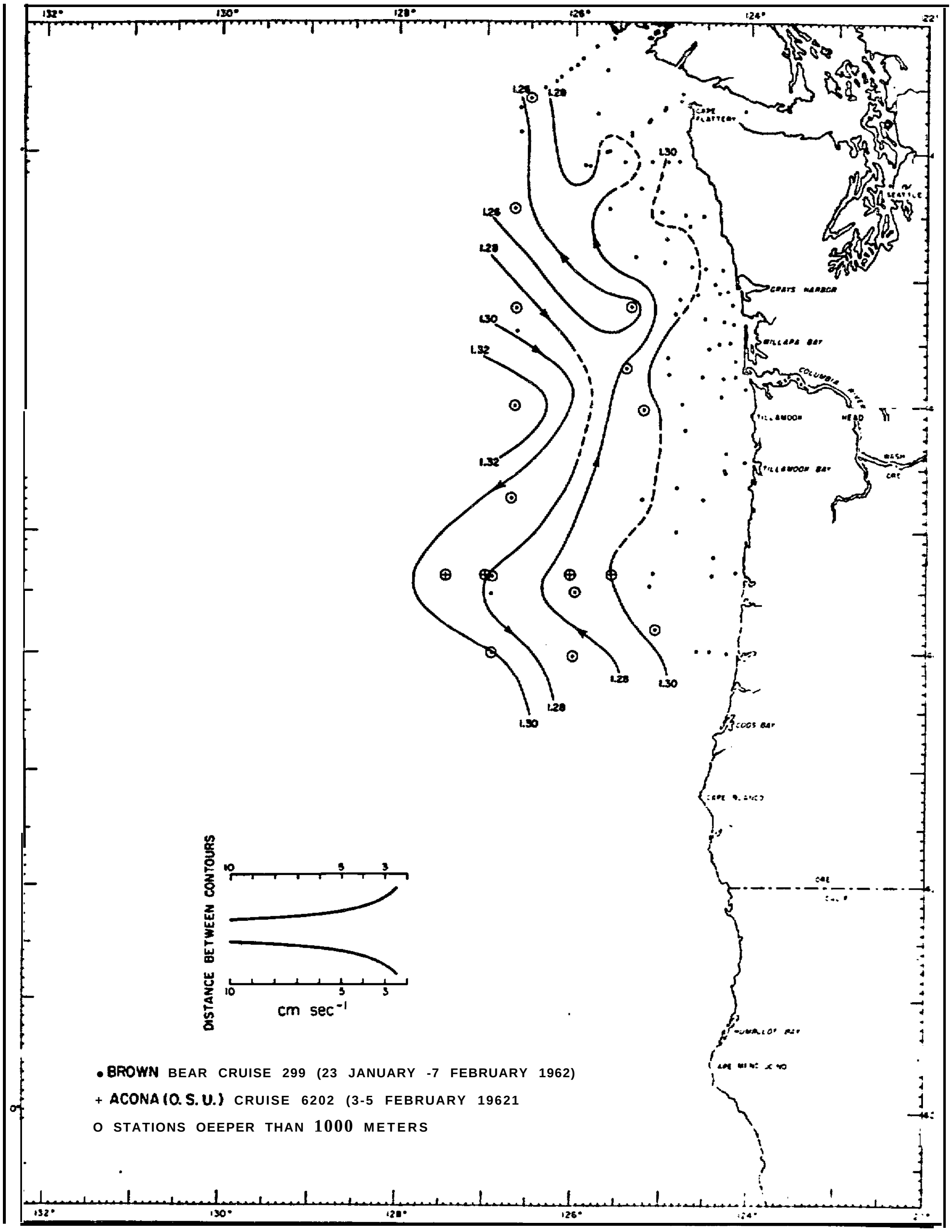
Geopotential Topography, 0/1000 Decibars, Brown Bear Cruise 297, 28 November-18 December 1961[§]



Budinger, Coachman and Barnes, 1964.

Figure III-39

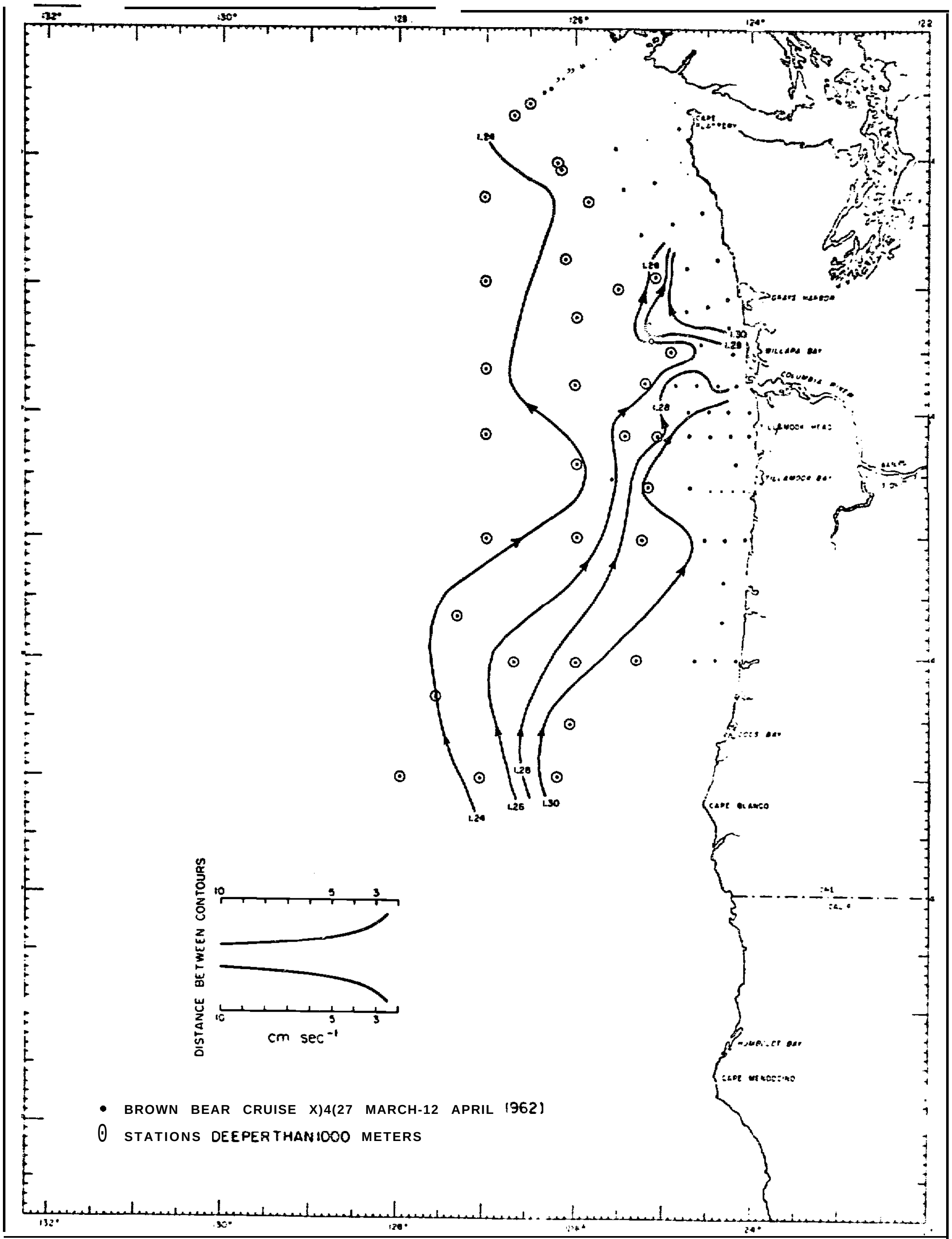
Geopotential Topography, 0/1000 Decibars, Brown Bear Cruise 299, 23 January-7 February 1962§



§Budinger, Coachman and Barnes, 1964.

Figure III-40

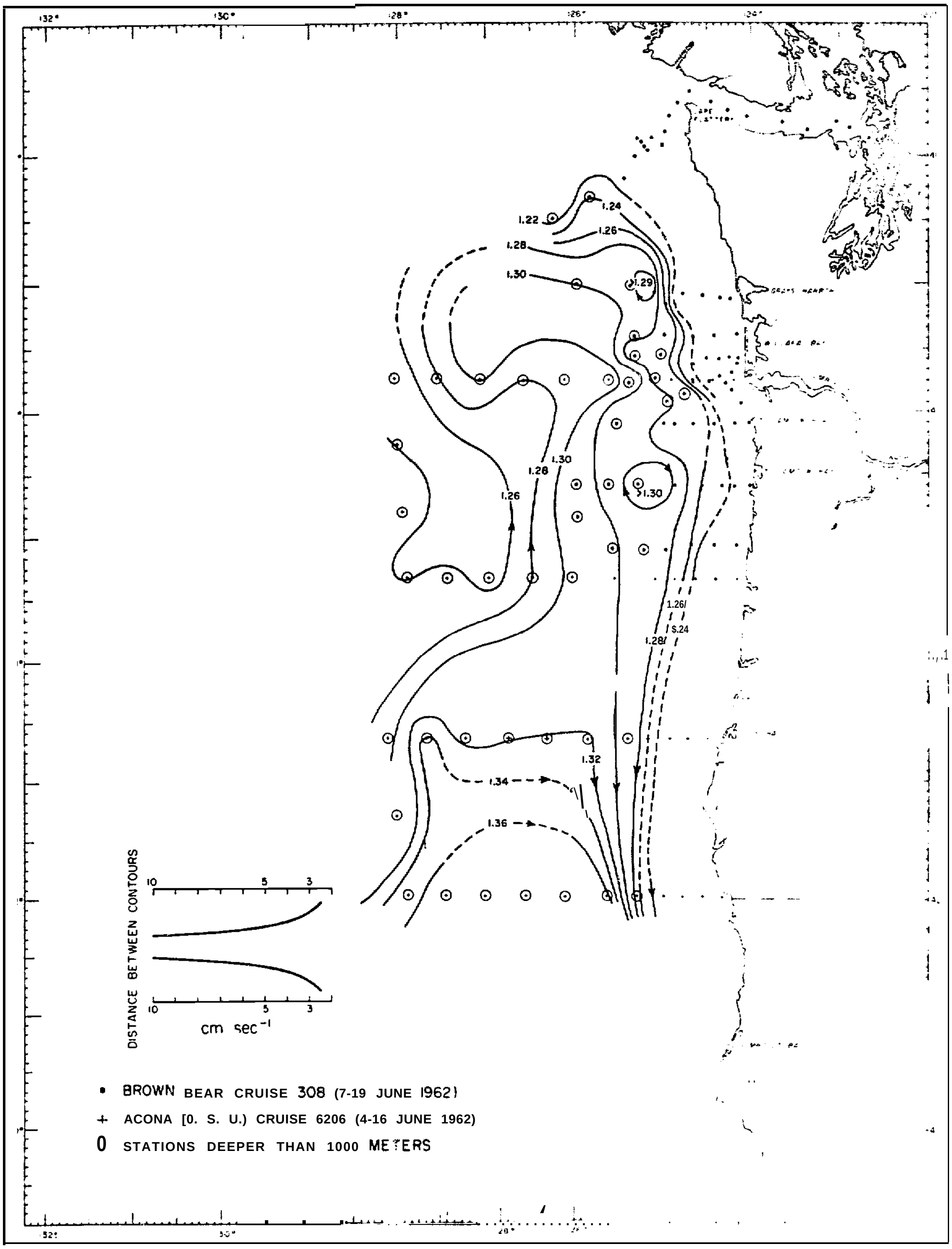
Geopotential Topography, 0/1000 Decibars, Brown Bear Cruise 304, 27 March-12 April 1962§



§Budinger, Coachman and Barnes, 1964.

Figure III-41

Geopotential Topography, 0/1000 Decibars, Brown Bear Cruise 308, 7-19 June 1962[§]



[§]Budinger, Coachman and Barnes, 1964.

tion and magnitude of monthly Ekman transport for 1961-63 off the coast of Oregon and Washington. This is presented in Figure III-42 along with the average direction and velocity of monthly winds for the same time period.

In shallow water, the boundary conditions of bottom and shoreline decrease this deflection to the right and may mask it completely. Observations made at Blunts Reef and Umatilla Reef lightships (8 km off the coast), as shown in Tables III-5 and III-6, indicate that for NW-E winds the surface current is about 30° to the right of the wind direction. For SSW-W winds the same lightship current observations indicate a surface current directed to the left of the wind. This is because of the overriding effect of the coastal boundary.

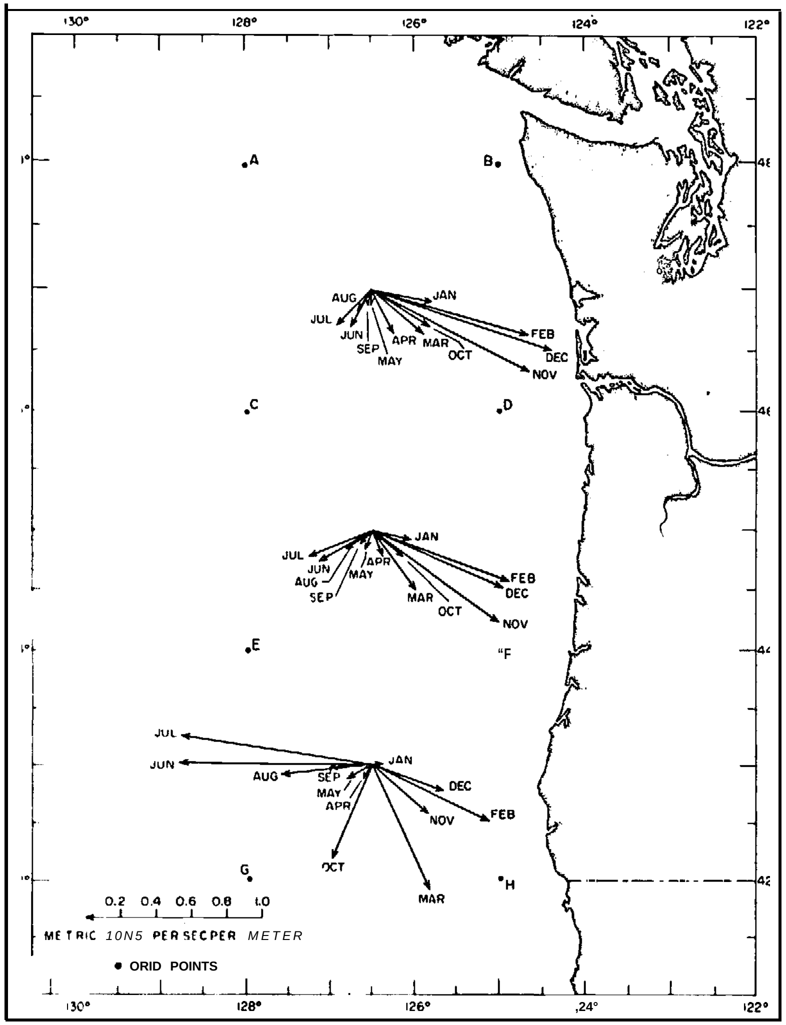
e) Bottom Currents. The first direct measurement of the near bottom current off the Washington coastline was made by Morse, Gross, and Barnes (1969) using sea bed drifters, saucer-like disc arrangements that drift just above the bottom, dragging weighted stems. Data analysis is essentially the same as that employed with surface drift bottles. Figure III-43 presents release points and hypothetical paths of those drifters for which recoveries were made. Over the inner continental shelf (waters less than 40 meters deep) the flow was toward the coast, apparently responding to the influence of waves and the ascending shoreward motion of coastal upwelling. Speeds ranged from 0.8 to 2.9 cm/sec (0.7 to 2.5 km/day), averaging about 1.9 cm/sec (1.6 km/day). Within 10 km of the Columbia River mouth the flow was toward the river mouth at approximately 1.6 cm/sec (1.4 km/day). For shelf waters in excess of 40 meters depth the dominant flow was northward. Figure III-44 presents schematic paths of drifters from release positions outside the river mouth and less than 10 km distant. Paths of drifters released inside the Columbia River estuary are also presented. These measurements were made over a period of 3 years, which indicates that these flows are persistent throughout the year. Seasonal variability in the flow of the near bottom current has not been determined.

Bottom currents measured on the shelf off the Columbia River from 1967 to 1969 are averaged by month and direction, and presented in Figure 111-45. Maximum speeds of 60 to 80 cm/sec occurred in the winter and were associated with local storms.

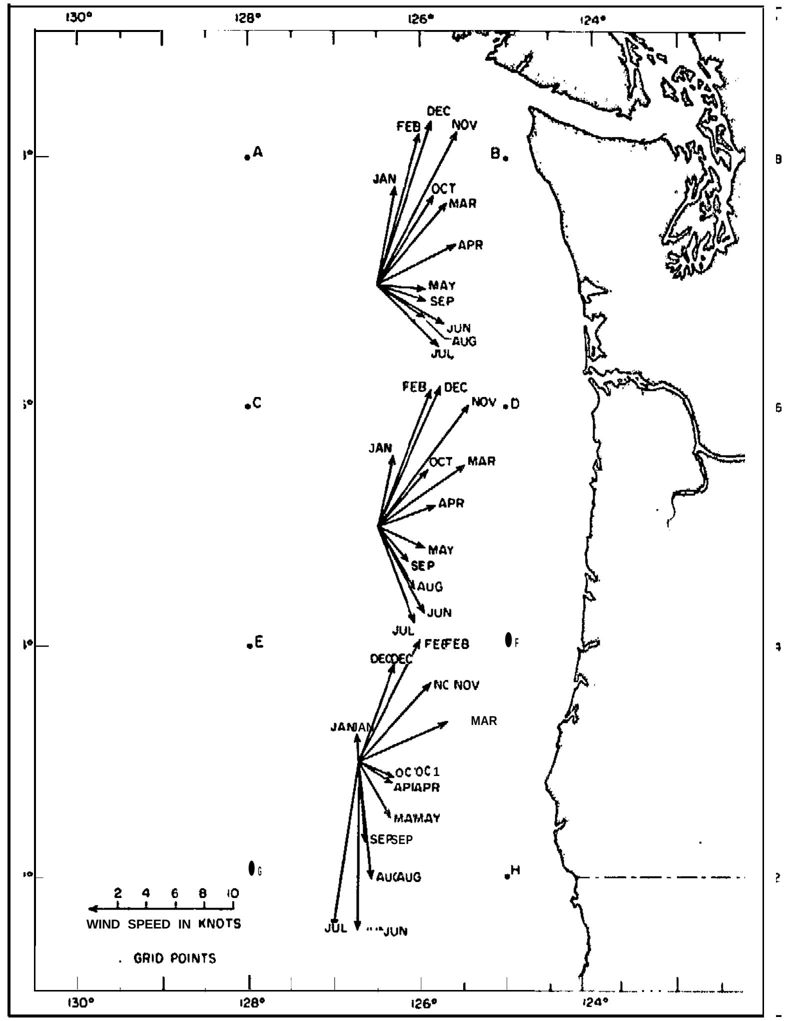
f) Longshore Currents. Waves in deep water cause a slight volume transport, or discharge of water in the direction of wave travel. This discharge increases as the waves pass into shoaling water near shore. The beach, however, presents an almost impermeable obstacle which must reduce to zero the entire component of the discharge normal to the shore, the accompanying discharge has a longshore component and a definite longshore current results. This longshore current is confined largely to within the surf zone. Since the waves continue to discharge water into each unit length of the surf zone, some mechanism must exist to relieve this build-up, since the velocity of the current cannot go on increasing indefinitely. Rip currents serve this purpose and also transport sediment offshore.

Figure III-42

Winds and Ekman Transport[9]



AVERAGE DIRECTION AND MAGNITUDE
OF MONTHLY EKMAN TRANSPORTS FOR 1961-1963



AVERAGE DIRECTION AND VELOCITY
OF MONTHLY WINDS FOR 1961-1963

[9] Duxbury, Morse and McGary, 1966

Table II I-5

Average Speed of Current Due to Winds of Various Strength[§]

Average current (cm/s) due to wind	Wind velocity m/s 10	20	30	40	50
Blunts Reef	5	8	10	18	20
Columbia River	10	13	15	20	20
Umatilla Reef	5	15	23	25	23

[§] U.S. Department of Commerce, 1977a.

Table II I-6

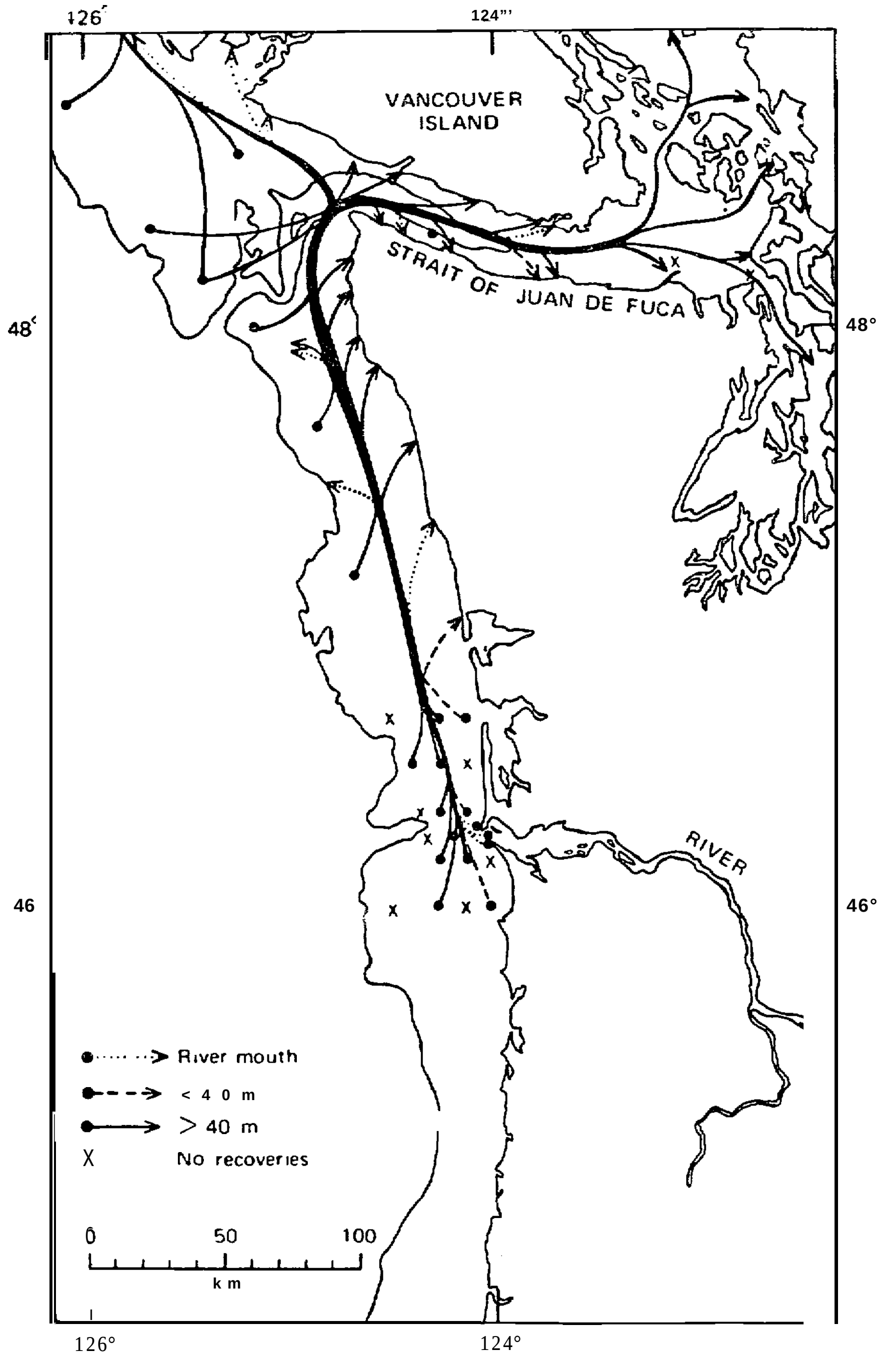
Average Deviation of Current to Right or Left of Wind Direction[9]

Wind from (in degrees)	Blunts Reef		Columbia River		Umatilla Reef	
	L	R	L	R	L	R
N		20		35		44
NNE		6		27		18
NE		10		9		34
ENE		32		29		48
E		28		17		52
ESE		7		2		38
SE	11		8			25
SSE		13	7			6
S		1	19		6	
SSW	11		44		13	
SW	18		74		32	
WSW	28		121		52	
W	60			145	77	
WNW		2		105	6	
NW		31		78		37
NNW		43		53		25

[9]U.S. Department of Commerce, 1977a.

Figure III-43

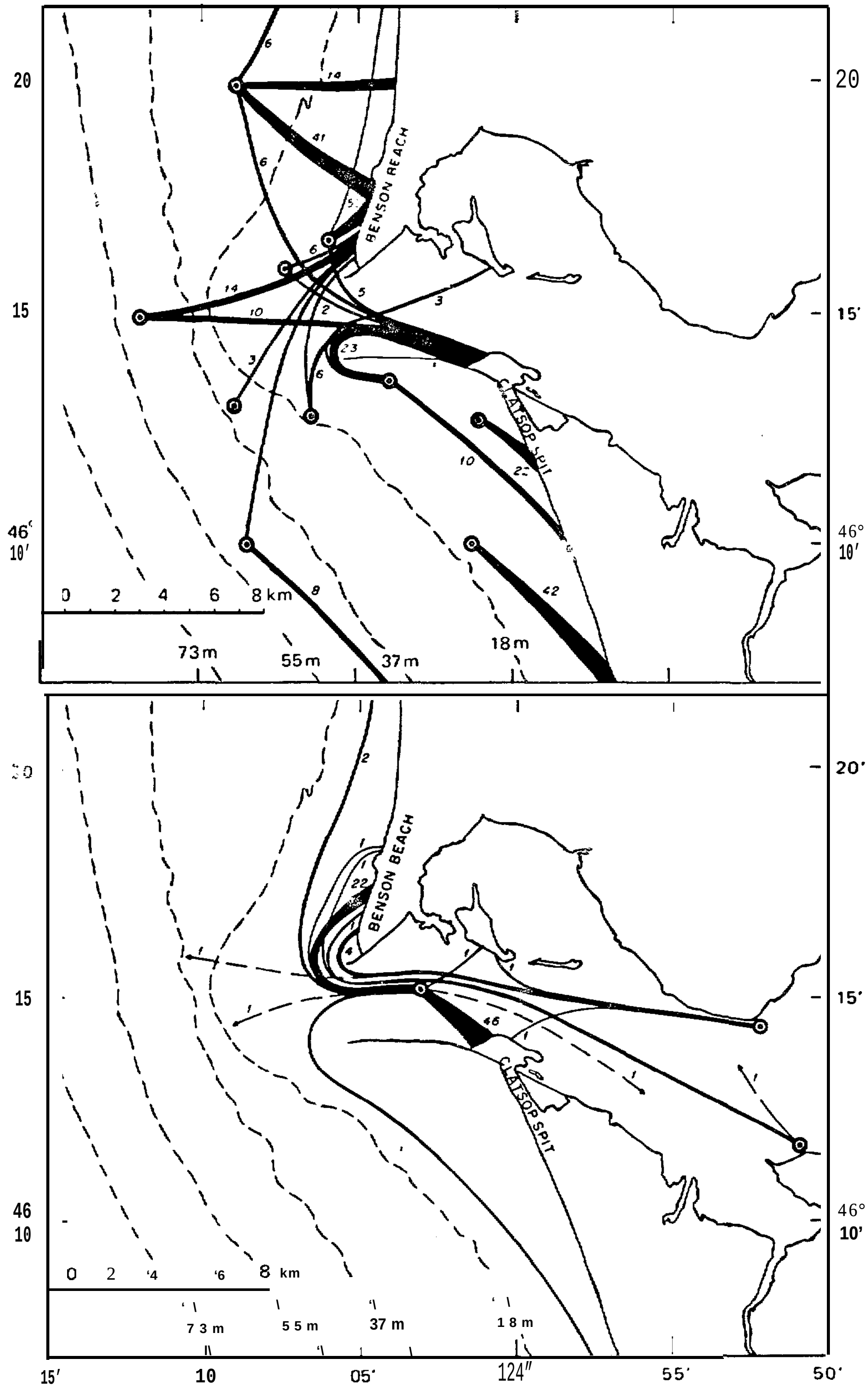
Seabed Drifter Paths[§]



§Morse, Gross and Barnes, 1969.

Figure III-44

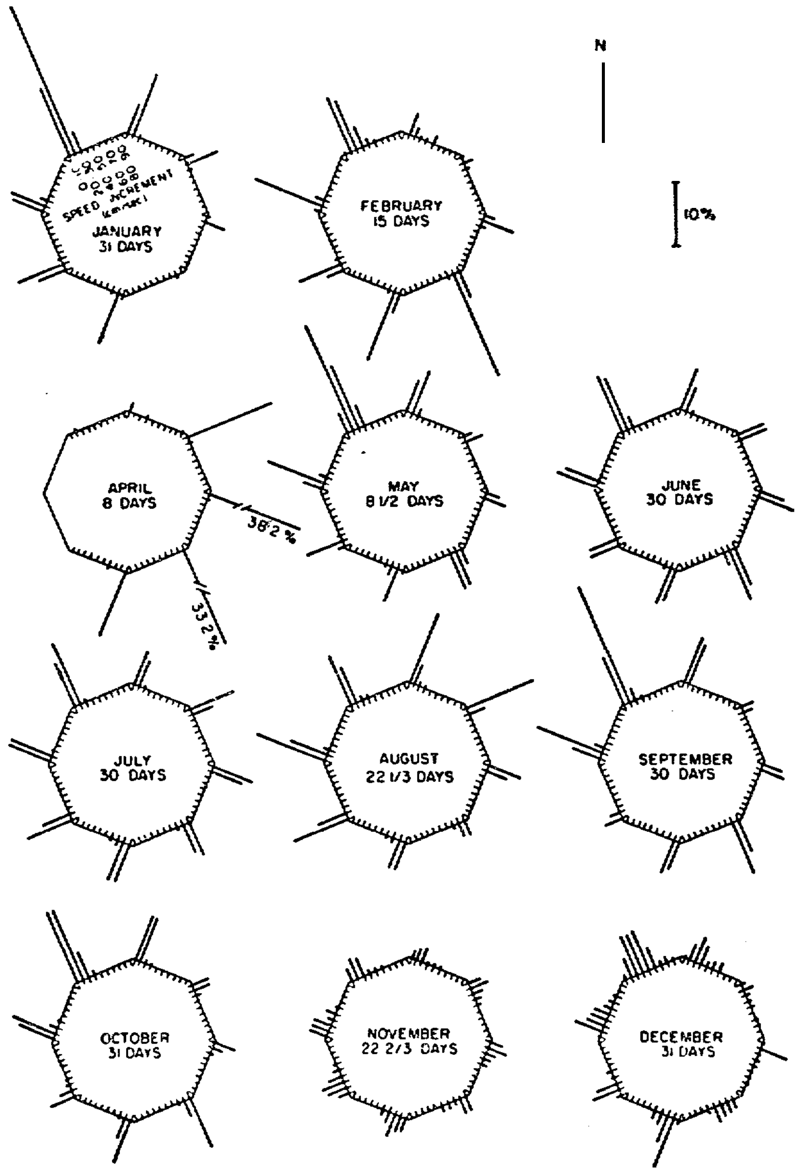
Schematic Paths of Drifters from (Top) Release Positions Outside the River Mouth (<10km Distant) and (Bottom) Release Positions in the River Estuary§



§Morse, Gross and Barnes, 1969.

Figure III-45

Bottom Current Velocity Data† for a Station on the Washington Shelf North of the Columbia River§



§ Sternberg and McManus, 1971.

† Data are sorted according to month, speed class, direction (by octants), and time. The length of a vector represents the percent of the month that a current of a given speed increment and direction occurred. The sum of vectors for each month equals 100%. A velocity of 10 centimeters per second is about 0.2 knots.

Longshore currents and rip currents play important roles in the movement of sediment and shaping of beaches.

Actual measurements of longshore currents are difficult because of the high energy environment in which they occur (i.e., the surf zone). Field measurements of longshore currents (Inman and Quinn, 1952) show that the velocity progressively increases from zero, immediately downstream from a rip current, to some maximum value just preceding its seaward deflection at the next rip current. Also, the spacing between rip currents decreases as the intensity of wave action increase, suggesting that the longshore flow has some limiting value above which it breaks seaward into rip currents. The maximum velocity of longshore currents appears not to exceed 100 to 150 cm/sec. The observed spacing between rip currents ranges from about 30 to 1000 m. Measurements following a period of low waves along a 16 km section of straight beach at Clatsop Spit, Oregon, gave a mean separation between rip currents of 400 m with a standard deviation of 145 m (Shepard and Inman, 1951). The velocity of longshore currents increases with an increase in wave steepness (Ballard, 1964).

Various equations have been derived for the computation of longshore currents (Eagleson, 1965; Dietrich, 1963, and Bagnold, 1963). Some of the variables involved are the beach slope, the angle between the breaker crest and the original wave crest, the bottom roughness, the wave height at the point of breaking, the water depth at the point of breaking, the deep water wave height, the refraction coefficient, and more.

The main significance of longshore currents is the resulting sediment transport. Whether a longshore current will flow north or south is related to the combined total longshore components of all waves striking the area in a given time. The current will vary from minute to minute and hour to hour, but the dominant current will be the result of the dominant waves. The direction of dominant current may be inferred from the beach forms that result. (See offshore geology discussion of estuaries in Chapter I, Section B.4.)

g) Upwelling. Seasonal coastal upwelling is a dominant feature of the oceanographic regime off Oregon and Washington. Upwelling has been defined (Smith, 1968) to mean ascending motion of some minimum duration and extent by which water from the subsurface layers is brought into the surface layer and is removed from the area of upwelling by horizontal flow. Upwelling occurs in the summer months when the prevailing northerly winds produce a wind drift offshore (Figure 111-42). It is an important phenomenon in that it supplies nutrients to the surface waters, allowing high biological productivity. Upwelling along the coast is apparent in the distribution of temperature at the surface as was shown in Figure III-S. The cold water nearshore in summer affects the local climate and produces considerable fog (see Chapter II. Climatology).

There has been considerable study of coastal upwelling. Two Coastal Upwelling Experiments (CUE-I and CUE-II) have been conducted utilizing ships and personnel from many different cooperating institutions. These studies include measurements of currents (by meters and drogues), nutrients, turbidity, phytoplankton and standard hydrographic parameters.

More recent programs include WISP (a program to study the transition between Winter and SPring oceanographic conditions over the Oregon shelf) and uP-75 (a continuation of the study of coastal upwelling off Oregon). In the more recent experiments, data from some of the moored current meters included conductivity as well as temperature, pressure, and velocity. Salinity time series of sufficient accuracy were obtained to yield time series of sigma-t. A data report for the WISP and UP-75 experiments has been published, although detailed analysis of much of the data will not be completed for some time (Gilbert, *et al.*, 1976). During the WISP experiment, eleven current meters were moored in three arrays across the shelf at 45°N from late January to late April, and hydrographic sections were made at intervals of several weeks from late January to mid-May. Wind and adjusted sea level data are also presented.

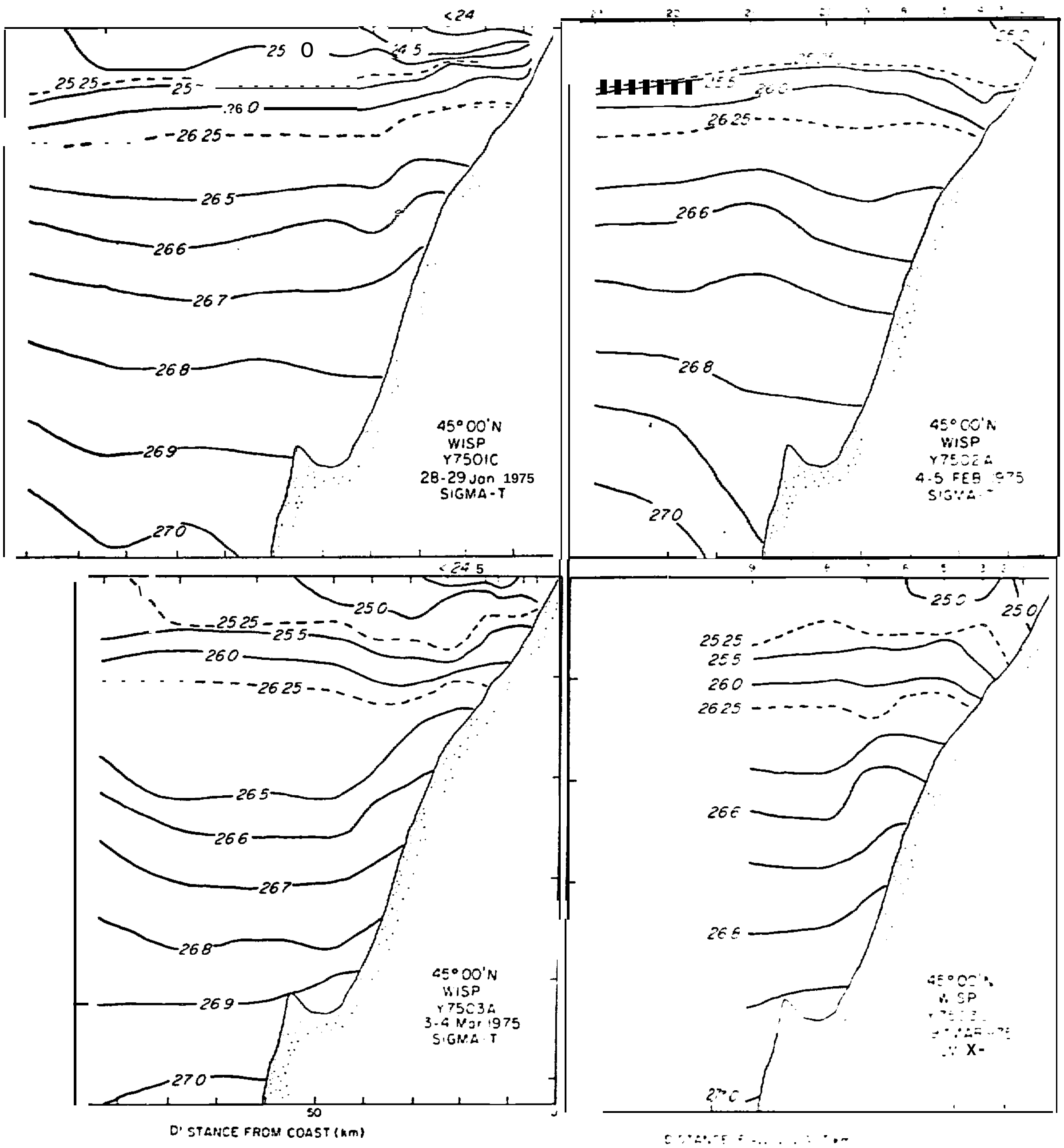
Upwelling is illustrated in the distribution of density isopycnals in cross section over the shelf. In the winter, the isopycnals are more or less level, currents over the shelf are predominantly northward and sea level at the coast is high (in response to the lower atmospheric pressure and pile-up of water along the coast from wind drift. In spring and summer, isopycnals are tilted upward toward the coast, the current is southward at the surface and sea level is low (higher atmospheric pressure, and wind drift is offshore). The flow at the bottom is often northward during spring and summer, and vertical shear occurs. Isopycnals for winter are presented in Figure III-46, and for spring and summer in Figure III-47.

Estimates of vertical velocity from displacement of isopycnals for a short period have been made. Smith, Pattullo and Lane (1966) estimated the vertical velocity to be larger nearshore with values of 7 x 10-3 cm/sec (6 m/day) at 9.25 km (5 nautical miles) offshore and 2 x 10-4 cm/sec (0.2 m/day) at 64.7S km (35 nautical miles) offshore. Halpern (1974) obtained estimates of 6.6 x 10^{-3} cm/sec (5.7 m/day) and 1.25 x 10^{-2} cm/sec (10.8 m/day) for the periods 2-6 August 1972 and 26-30 August 1972 respectively. Huyer (1974) obtained an estimate of about 2 x 10^{-2} cm/sec (17.3 m/day) nearshore between 15 and 16 July 1972. The assumption required to make these estimates (no mixing) always results in an underestimate of the vertical velocity.

h) Analysis of Recent Measurements. Current studies on the shelf by different institutions had the period from 18 July to 18 September 1972 in common. The University of Washington had two arrays moored off southern Washington in 160 m of water (UWOFF) and in 73 m of water (UWIN). Both arrays included a current meter at about 20 m and a deep current meter that appeared to be above the bottom boundary layer. Observations made off Central Oregon as part of CUE-1 included arrays (NH-10 and NH-20). Boths sets of current

Figure III-46

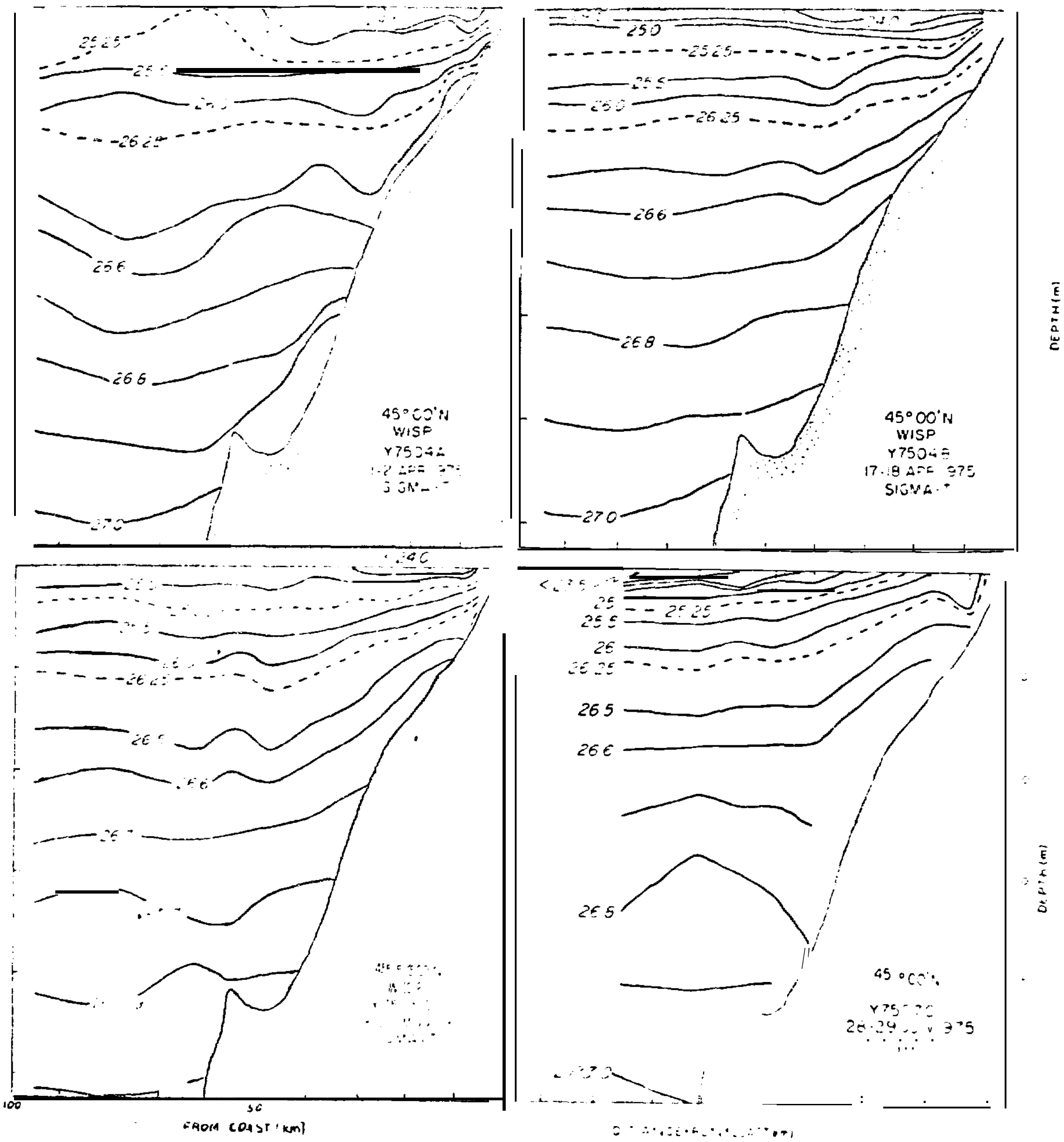
Density Distribution for Winter Off the Oregon Coast[§]



[§]Gilbert, *et aZ.*, 1976.

Figure III-47

Density Distribution for Spring and Summer Off the Oregon Coast[§]



§Gilbert, *et al.*, 1976.

meter data were obtained with Aanderaa current meters with a sampling interval of 5 or 10 minutes. Hourly wind observations were available for both areas at Westport, Washington, and Newport, Oregon. Sea level was obtained from tide gauges at Depoe Bay, Oregon; at Toke Point, Washington; and at Tofino, British Columbia (40°10'N, 125 55'W). Locations of the current meters, tide stations and weather stations are shown in Figure III-48. Sea level exhibits an "inverted barometer" effect due to variations in atmospheric pressure (sea level changes 1 cm for every 1 millibar change in atmospheric pressure). The sea level was adjusted for this effect using atmospheric pressure observations from Newport (Oregon), Hoquiam (Washington) and Tofino (British Columbia). Tidal effects on sea level were also filtered out of the record. The resultant sea level record appears to represent changes brought on by wind and current effects. Figure III-49 presents the inshore and offshore current data for both the Washington and Oregon sites, at 20 m and near the bottom. The adjusted sea levels and wind field are also presented.

The following comments are from Huyer, *et al.* (197S) and relate to Figure III-49. Some similarity between the wind and offshore currents is evident, but greater similarity exists between the wind and the inshore currents. Sea level fluctuations closely resemble the fluctuations in the alongshore component of the current, high sea level being associated with poleward flow. Correlations between current and sea level and between wind and current are higher for the deep current meters than for the shallow current meters. Current fluctuations are more highly correlated with sea level than with wind. A sea level change of 1 cm at Depoe Bay is associated with a change in current velocity of 1.6 cm/sec at NH-10 and 1.5 cm/sec at NH-20; a sea level change of 1 cm at Toke Point is associated with current changes of 1 cm/sec at UWIN and 0.5 cm/sec at UWOFF. At UWIN, current fluctuations have about 4% of the amplitude of wind fluctuations observed at Westpost. At NH-10, current changes are 2% of Newport wind changes.

This sea level-current correlation may be an important step in developing a significant predictive capability for ocean currents by monitoring the sea level. More work is needed if this is to become a predictive tool, useful, for example, in predicting oil spill trajectories.

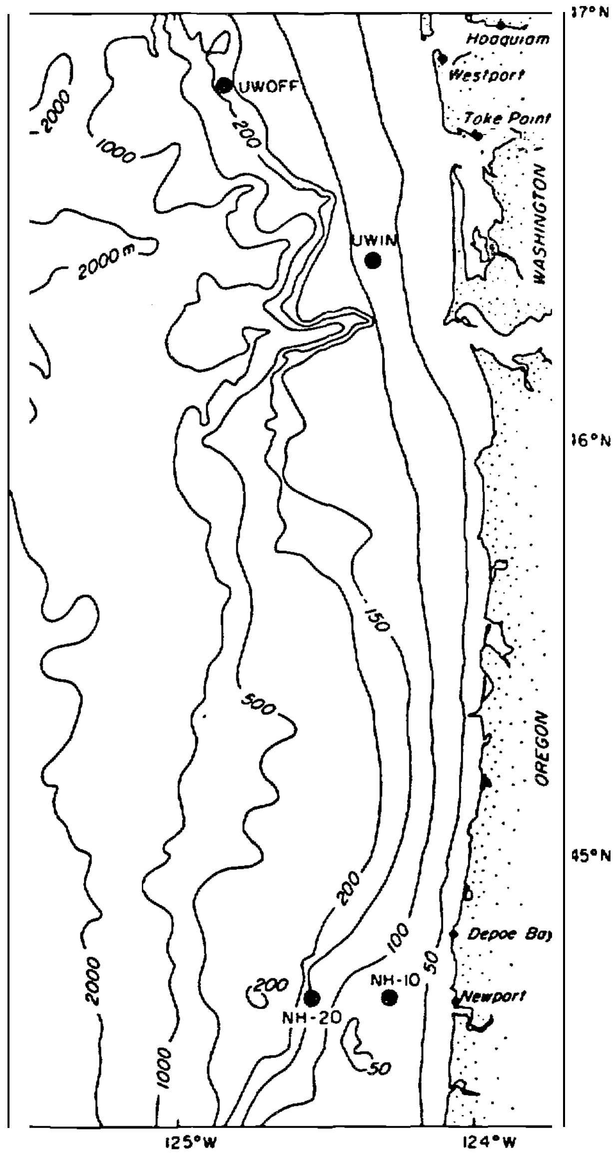
iv. Waves. The wave climate off the Pacific Northwest coast exhibits a definite seasonal pattern in response to the wind regime. The predominant direction of wave approach is from the northwest during the summer months, and from the southwest in the winter months.

Waves may be either swell, sea, or a combination of both. The term refers to ocean waves that have travelled out of their generating area. Swell waves characteristically exhibit a more regular and longer period and have flatter crests than sea waves.

The basic data required to describe the wave regime are the deep water wave direction, wave period, and wave height. From this it is possible to determine the wave length, wave steepness, energy content,

Figure III-48

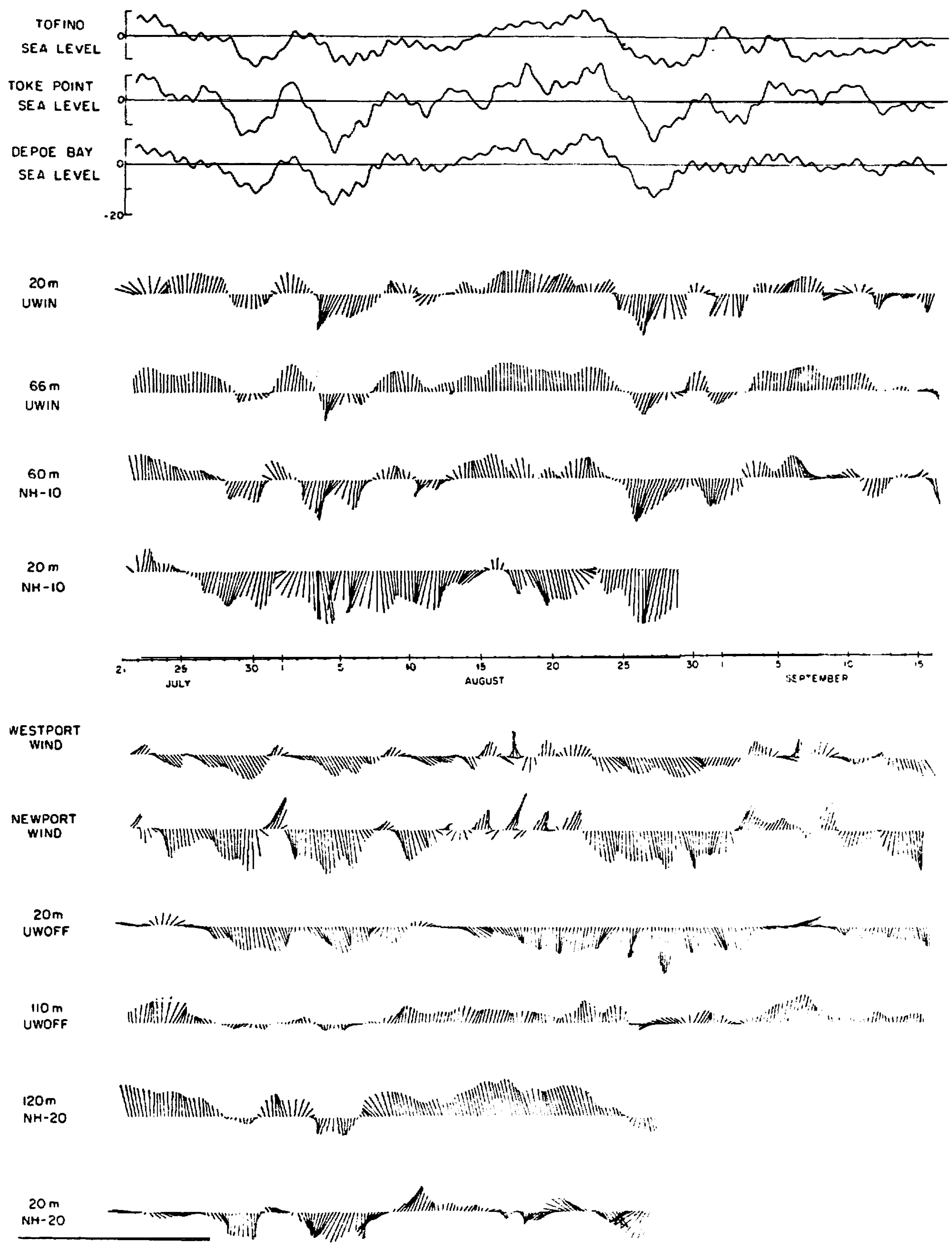
Locations of Current Meter Arrays and Coastal Locations of Supplementary Observations of Sea Level, Wind, and/or Atmospheric Pressure§



§Huyer, *et al.*, 197S.

Figure III-49

Time Series of 6-hourly Vector of Low-Passed Deep and Shallow Current, Wind and Sea Level Observations, July 21 to September 16, 1972[§]



§Huyer, *et al.*, 1975.

and particle motion. As deep water waves cross into the continental shelf, their characteristics start to change due to shoaling and refraction.

In analyzing and presenting wave data, the significant wave height and period are used. The significant height and period are the average height and period associated with the highest one-third of the waves of a given wave group. Sea waves exhibit a range of periods and heights at any given instant, whereas swell is more regular.

The severity of the wave regime off the Oregon and Washington coast is comparable to the North Sea, where offshore structures must be strong and risks are high. Wave action at the surface generates oscillatory currents at depths that contribute to the movement of sediment, even out to the edge of the continental shelf. Wave action affects the passage and moorage of vessels. In the event of an oil spill, the wave regime may set the limits on oil recovery at the scene (as evidenced in the December 1976 grounding of the ARGO merchant). An oil spill drifting into the surf zone becomes partly entrained in the bottom sediments-through wave action. Waves that generate longshore currents then contribute to the movement of this contaminated sediment. Breaking waves must be considered in the design of any structures or pipelines that must pass from the shelf to the land through the surf zone.

a) Sea and Swell Statistics and Data. Actual wave data for the coast is limited. Weather observations made by vessels in transit provide some clues, but these observations are-generally inadequate, providing only estimates of direction, period, and height. The height of the platform that the observations are made from greatly influence the "height" of the waves to the observer. National Marine Consultants (1960 and 1961a,b) performed waves studies in which they analyzed three years of weather data for all of the Pacific and "hindcast" the resultant swell and sea waves that would approach deep water stations off of Washington, Oregon, and California. The locations of four deep water stations off Washington and Oregon are shown in Figure 111-50.

Wave hindcasting was performed in accordance with the theory of wave spectra and statistics (Pierson, Neumann and James, 1954), using a modified equation for wave travel time (National Marine Consultants, 1960). Weather data from 1956, 19S7, and 1958 were utilized because these three years had significantly different storm frequencies. The differences in storm frequency were distributed so as to have a compensating result and helped to present an "average" year. Wave data from these years were presented in monthly and annual tables listing the frequency of occurrence of waves by direction, period, and deep water significant wave height. Tables III-7 and III-8 present wave statistics for Station 3 for the roughest and calmest months (December and August). Table III-9 presents the annual summary statistics for this station. Stations 1 and 2 to the south are a little calmer and station 4 to the north is a little rougher.

The following conclusions of Bourke, Glenne and Adams (1971) were based on the wave statistics of the National Marine Consultants

Figure 111-50

Wave Data"Locations

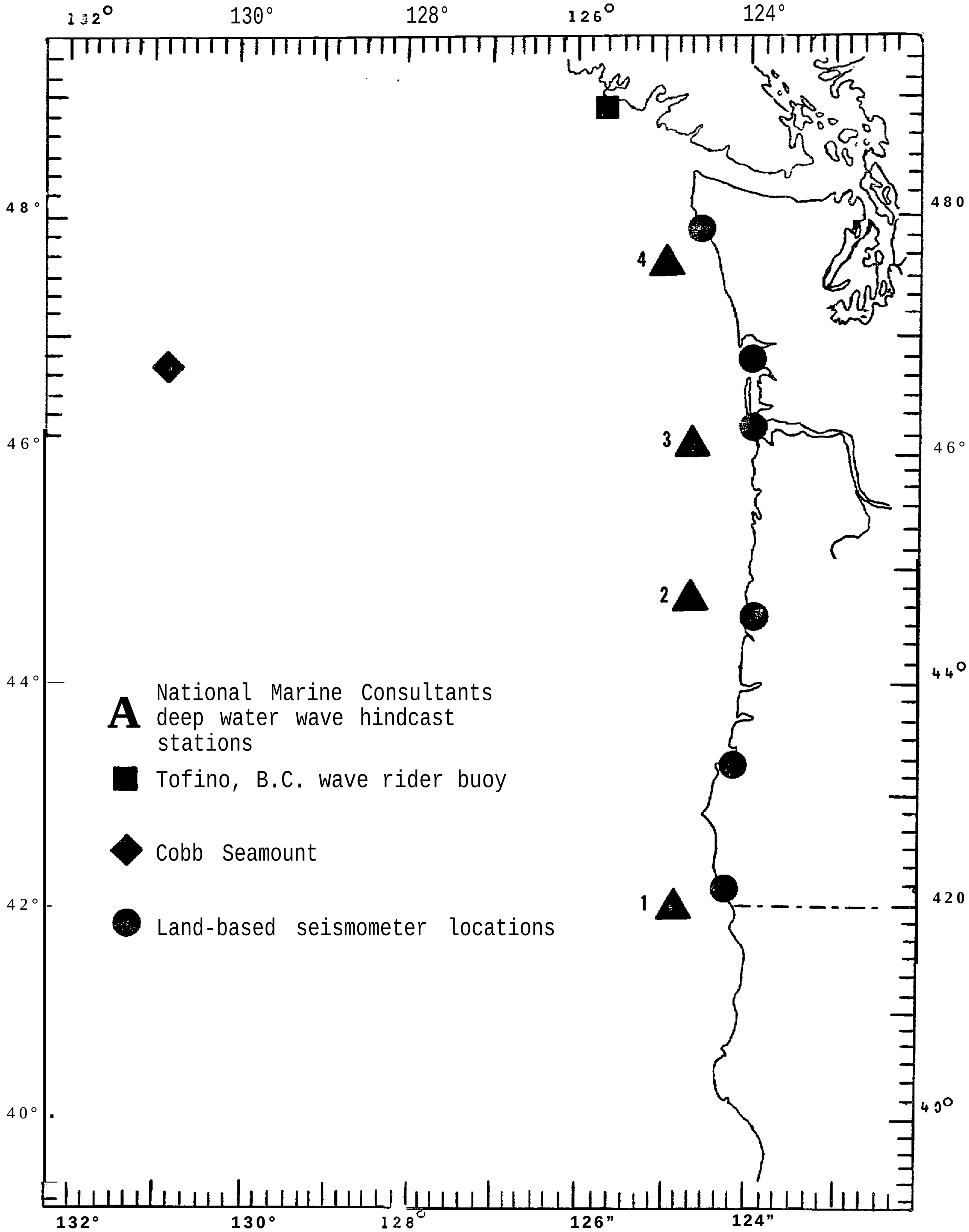


Table III-7

Average Monthly Wave Height-Period-Direction Frequency Distribution (Percent)† for Station 3§

SWELL (AVERAGE TOTAL HOURS 1,152.5) DECEMBER (1956, 1957, 1958)

DIR.	NNW							NW 8.6%							WNW 41.2%						
H_s \ T_s	6-8	8-10	10-12	12-14	14-16	16-18	18+	6-8	8-10	10-12	12-14	14-16	16-18	18+	6-8	8-10	10-12	12-14	14-16	16-18	18+
1-2.9								.3	1.8	.8		.3			4.3	1.8	.3	.5	1.1		
3-4.9								1.3	.8	.3	.5	.3			1.8	7.3	1.6	.5	.5	.3	
5-6.9									1.6	.3	.3				.3	4.8	1.1	1.1	2.2		
7-8.9																1.6	3.2	1.1	.3	.3	
9-10.9																.3	1.6	.8	.5		
11-12.9																	1.1	.3	.3		
13-14.9																			.3		
15-16.9																					
17-18.9																					
19-20.9																					
21-22.9																					
23-24.9																					
25-26.9																					
27 +																					
Σ								1.6	4.2	1.4	.8	.6			6.4	15.8	8.9	4.3	5.2	.6	

DIR.	W 59.6%							WSW 20.2%							SW 7.6%						
H_s \ T_s	6-8	8-10	10-12	12-14	14-16	16-18	18+	6-8	8-10	10-12	12-14	14-16	16-18	18+	6-8	8-10	10-12	12-14	14-16	16-18	18+
1-2.9	4.3	3.2	.5	.5	1.6	.5	.5	1.6	3.8	.8	1.6	.5	.8		.8	1.6					
3-4.9	2.4	8.1	3.5	4.0	2.2	.8		.8	1.1	1.8	.8	.3				.5	.5		.3		
5-6.9		5.6	1.8	1.1	1.1	1.1			1.6						.3	.3	.3		.3		
7-8.9		2.2	1.6	2.2	1.6				.5	.3						.5	.8				
9-10.9		.8	.5	1.6	.5	.3			.5	.5			.3			.3	.5				
11-12.9		.3	.3		.5	.3				.3	.3										
13-14.9		.3	.5	.5	.3					.5											
15-16.9			.3	.3						.3							.3				
17-18.9			.3	.5							.3	.3	.3				.3				
19-20.9												.3									
21-22.9				.3	.5																
23-24.9				.3																	
25-26.9																					
27 +																					
Σ	6.7	20.5	9.3	11.3	8.3	3.0	.5	2.4	7.5	4.5	3.0	1.4	1.4		1.1	3.2	2.7		1.6		

DIR.	SSW 10.6%							S 7.1%							SSE							Σ
H_s \ T_s	6-8	8-10	10-12	12-14	14-16	16-18	18+	6-8	8-10	10-12	12-14	14-16	16-18	18+	6-8	8-10	10-12	12-14	14-16	16-18	18+	
1-2.9	.5	2.7	1.8					.3	1.8													40.9
3-4.9		1.6							1.3													45.2
5-6.9		1.8							.5	.8												28.3
7-8.9		.3	.5						.5	.5												18.0
9-10.9		.3	.8						.5													10.6
11-12.9										.3												4.0
13-14.9												.3										2.7
15-16.9			.3							.3												1.8
17-18.9																						2.0
19-20.9																						0.3
21-22.9																						0.8
23-24.9																						0.3
25-26.9																						
27 +																						
Σ	.5	6.7	3.4					.3	4.6	1.9		.3										154.9

SEA

DIR.	N 1.3%					NNW					NW 2.1%					WNW 5.9%					W 9.3%				
H_s \ T_s	4-6	6-8	8-10	10-12	12+	4-6	6-8	8-10	10-12	12+	4-6	6-8	8-10	10-12	12+	4-6	6-8	8-10	10-12	12+	4-6	6-8	8-10	10-12	12+
1-2.9	.8										.5					.3					1.1				
3-4.9	.5											.5				.5	1.6				.5	2.2			
5-6.9												.5					1.1					.8	.3		
7-8.9																	.3	.5				.8	2.7		
9-10.9																		.8							
11-12.9														.3				.3	.5					.3	
13-14.9																								.3	
15-16.9														.3										.3	
17-18.9																									
19-22.9																									
23-27																									
Σ	1.3										.5	1.0		.6		.8	3.0	1.6	.5		1.6	3.8	3.0	.9	

DIR.	WSW 7.0%					SW 9.9%					SSW 16.0%					S 15.3%					SSE 7.6%					OFFSHORE	CALM‡	Σ
H_s \ T_s	4-6	6-8	8-10	10-12	12+	4-6	6-8	8-10	10-12	12+	4-6	6-8	8-10	10-12	12+	4-6	6-8	8-10	10-12	12+	4-6	6-8	8-10	10-12	12+	4.4	21.2	25.6
1-2.9	.3					1.1					1.1					4.8					.5							10.5
3-4.9	.5	.8					1.3				.3	2.2					1.6				1.3	.3						14.1
5-6.9		1.1					2.4					4.3	.3				2.4					1.1						14.3
7-8.9		1.1	1.6				.5	1.8					2.4				.3	1.1				.5	1.1					14.7
9-10.9			.5	.3				.8	.3			.3	.8	.3				.5	.3			.3	1.1	.5				6.8
11-12.9				.5				.3	.3				.5	.5				.3					.3					4.1
13-14.9				.3				.3	.5					1.6					1.3					.3				4.6
15-16.9														.3				.5	.3									1.7
17-18.9									.3					.8					.8	.3								2.2
19-22.9														.3					.3	.5			.3					1.4
23-27																												
Σ	.8	3.0	2.1	1.1		1.1	4.2	3.2	1.4		1.4	6.8	4.0	3.8		4.8	4.3	2.4	3.0	.8	1.8	2.2	2.8	.8		4.4	21.2	100.0

§National Marine Consultants, 1961b.

†Based on 31 days

‡Includes waves of 0 to 0.9 feet

Table III-8

Average Monthly Wave Height-Period-Direction Frequency Distribution (Percent)[†] for Station 3[§]

SWELL AVERAGE TOTAL HOURS 720.9

AUGUST (1956, 1957, 1958)

DIR.	NNW 1.6%							NW 25.2%						
H_s \ T_s	6-8	8-10	10-12	12-14	14-16	16-18	18+	6-8	8-10	10-12	12-14	14-16	16-18	18+
1-2.9		1.6						5.4	8.3	5.6	.3	.5		
3-4.9								.8	1.3	1.6	.3			
5-6.9										.3	.8			
7-8.9														
9-10.9														
11.12.9														
13-14.9														
15-16.9														
17.18.9														
19-20.9														
21-22.9														
23-24.9														
25-26.9														
27 +														
&		1.6						6.2	9.6	7.5	1.4	.5		

DIR.	WNW 41.5%							W 23.7%						
H_s \ T_s	6-8	8-10	10-12	12-14	14-16	16-18	18+	6-8	8-10	10-12	12-14	14-16	16-18	18+
1-2.9	6.7	5.4	3.5	2.7	.3	.3		2.7	2.2	1.6	1.3	.3		
3-4.9	3.2	5.9	4.8	2.9	.8	.5		2.4	3.8	2.2	1.3	.3		
5-6.9		1.1	2.9	.5					1.8	.8	.8	.3		
7-8.9										1.1	.8			
9-10.9														
11.12.9														
13-14.9														
15-16.9														
17.18.9														
19-20.9														
21-22.9														
23-24.9														
25-26.9														
27 +														
&	9.9	12.4	11.2	6.1	1.1	.8		5.1	7.8	5.7	4.2	.9		

DIR.	WSW 3.5%							SW 1.1%							SSW 0.3%						
H_s \ T_s	6-8	8-10	10-12	12-14	14-16	16-18	18+	6-8	8-10	10-12	12-14	14-16	16-18	18+	6-8	8-10	10-12	12-14	14-16	16-18	18+
1-2.9	.5	.3	.3					1.1							.3						
3-4.9	.5	.5	.5																		
5-6.9		.3																			
7-8.9			.3																		
9-10.9																					
11.12.9		.3																			
13-14.9																					
15-16.9																					
17.18.9																					
19-20.9																					
21-22.9																					
23-24.9																					
25-26.9																					
27 +																					
&	1.0	1.4	1.1					1.1							.3						

DIR.	S							SSE							Σ
H_s \ T_s	6-8	8-10	10-12	12-14	14-16	16-18	18+	6-8	8-10	10-12	12-14	14-16	16-18	18+	
1-2.9															51.2
3-4.9															33.6
5-6.9															9.6
7-8.9															2.2
9-10.9															
11.12.9															0.3
13-14.9															
15-16.9															
17.18.9															
19-20.9															
21-22.9															
23-24.9															
25-26.9															
27 +															
&															96.9

DIR.	N 2.4%					NNW 10.8%					NW 32.7%					WNW 2.6%					W 6.2%				
H_s \ T_s	4-6	6-8	8-10	10-12	12+	4-6	6-8	8-10	10-12	12+	4-6	6-8	8-10	10-12	12+	4-6	6-8	8-10	10-12	12+	4-6	6-8	8-10	10-12	12+
1-2.9	1.8					6.2					22.6					1.8					5.4				
3-4.9		.3				.8	2.7				.5	7.8				.3	.5					.5			
5-6.9		.3					1.1					1.3										.3			
7-8.9													.5												
9-10.9																									
11-12.9																									
13-14.9																									
15-16.9																									
17-18.9																									
19 - 22.9																									
23 - 27																									
Σ	1.8	.6				7.0	3.8				23.1	9.1	.5			2.1	.5				5.4	.8			

DIR.	WSW 1.6%					SW 4.0%					SSW 2.7%					S 1.4%					SSE 1.9%					OFFSHORE	CALM‡	Σ
H_s \ T_s	4-6	6-8	8-10	10-12	12+	4-6	6-8	8-10	10-12	12+	4-6	6-8	8-10	10-12	12+	4-6	6-8	8-10	10-12	12+	4-6	6-8	8-10	10-12	12+	0.4	33.3	33.7
1-2.9	1.3					3.2					2.2					.3					.5							45.3
3-4.9	.3					.3	.5					.5					.3					.3						15.6
5-6.9																												3.0
7-8.9																		.3					.3					1.1
9-10.9																		.5										0.5
11-12.9																								.5				0.5
13-14.9																							.3					0.3
15-16.9																												
17-18.9																												
19 - 22.9																												
23 - 27																												
Σ	1.6					3.5	.5				2.2	.5				.3	.3	.8			.5	.3	.6	.5		0.4	33.3	100.0

§ National Marine Consultants, 1961b.

† Based on 31 days

‡ Includes waves of 0 to 0.9 feet

Table II I-9

Average Annual Wave Height-Period-Direction Frequency Distribution (Percent)[t] for Station 3[§]

SWELL AVERAGE TOTAL HOURS 10,S08.45 (1956, 1957, 19S8)

DIR. H_o \ T_s	NNW .85% 6-8	8-10	10-12	12-14	14-16	16-18	18+	NW 12.43% 6-8	8-10	10-12	12-14	14-16	16-18	18+	WNW 35.97% 6-8	8-10	10-12	12-14	14-16	16-18	18+
1-2.9	04	50	54					145	454	212	07	22			247	454	329	128	80	27	02
3-4.9		02	02					59	69	55	19	12	02		213	544	262	121	61	33	02
5-6.9		02	02					07	50	32	18	11			25	211	210	97	64	05	02
7-8.9		02	02					.02	02	32	09				05	64	109	53	17	02	
9-10.9			05						05	13	02					17	41	25	22		
11-12.9									02		.07					.02	27	32	.05		
13-14.9										02							.07	16	05		
15-16.9										02							.09	02	.02		
17-18.9										05	02						.04			.02	
19-20.9											02	02					.02	.02			
21-22.9																			02		
23-24.9																					
25-26.9																					
27 +																					
Σ	04	36	45					213	562	355	66	47	02		490	1292	1006	476	258	69	06

DIR. H_o \ T_s	W 38.80% 6-8	8-10	10-12	12-14	14-16	16-18	18+	WSW 14.47% 6-8	8-10	10-12	12-14	14-16	16-18	18+	SW 6.43% 6-8	8-10	10-12	12-14	14-16	16-18	18+
1-2.9	256	471	289	192	120	37	04	116	213	166	12	81	.19		.51	96	41	30	05	02	
3-4.9	165	574	307	155	108	52		.57	187	131	70	.17	05		.51	67	32	07	21	05	
5-6.9	21	200	148	115	48	.19		09	47	.42	30	07	02		05	55	17	.14	05	02	
7-8.9	.04	94	84	52	.31	02		.02	20	21	08		02			23	37	.12	02		
9-10.9		.18	.53	46	19	05	02		.12	23	05		07			02	.17	.15	02		
11-12.9		.07	23	17	.12	02	02		.02	07	14	07					07		02		
13-14.9		02	25	20	.12	.02				07	08	05					.02	02	02		
15-16.9			.07	05	07	.02				07	02						.02		02		
17-18.9			05	11		.02	.02				02	02	02				.02				
19-20.9				.05	.02							02									
21-22.9				.02	07																
23-24.9			.02	02							.07										
25-26.9																					
27 +				.04																	
Σ	446	1366	943	626	366	.23	.10	184	481	404	220	121	37		107	245	165	80	41	09	

DIR. H_o \ T_s	SSW 7.03% 6-8	8-10	10-12	12-14	14-16	16-18	18+	S 3.78% 6-8	8-10	10-12	12-14	14-16	16-18	18+	SSE 0.9% 6-8	8-10	10-12	12-14	14-16	16-18	18+	Σ
1-2.9	40	147	87	09	02			35	125	28	02					.05						4902
3-4.9	58	91	32	02	05			.21	42	18												3736
5-6.9	11	52	35	07	02			.05	22	.12						.02						1670
7-8.9	.02	21	23	09					.16	07												772
9-10.9		09	21						14	02												408
11-12.9		.02	09						.02	09	02					.02						203
13-14.9			.02	10						.02		02										134
15-16.9		02	05	04	02					.10												072
17-18.9				.02							.02											045
19-20.9																						017
21-22.9																						011
23-24.9																						0.11
25-26.9																						
27 +																						0.04
Σ	111	324	214	43	.11			61	221	88	.06	02				.09						11985

SEA

DIR. H_o \ T_s	N 3.50% 4-6	6-8	8-10	10-12	12+	NNW 5.04% 4-6	6-8	8-10	10-12	12+	NW 16.47% 4-6	6-8	8-10	10-12	12+	WNW 4.43% 4-6	6-8	8-10	10-12	12+
1-2.9	206					275					152					144				
3-4.9	25	59				35	141				107	418				.35	110			
5-6.9		42					62					169	02				54			
7-8.9			16					28				02	120				.05	48		
9-10.9			02										57					19	02	
11-12.9									04				02	41				.02	.11	
13-14.9									07					05					09	
15-16.9														05						
17-18.9										02				07					02	
19 - 22.9																				02
23 - 27																				
Σ	[illegible]	[illegible]	19			260	203	[illegible]	.11	.02	259	589	181	58		179	169	69	24	02

DIR. H_o \ T_s	W 6.10% 4-6	6-8	8-10	10-12	12+	WSW 3.77% 4-6	6-8	8-10	10-12	12+	SW 7.25% 4-6	6-8	8-10	10-12	12+	SSW 7.43% 4-6	6-8	8-10	10-12	12+
1-2.9	277					100					249					157				
3-4.9	.21	150				31	90				35	126				30	110			
5-6.9		.77	.02				.73					111					142	02		
7-8.9		09	51				.19	27				37	77				.16	86	02	
9-10.9			.14	.02				.12	02				18	05			05	51	07	
11-12.9			07	02				.02	08				22	13				21	24	
13-14.9				.09					10				07	16				05	40	
15-16.9				.08															12	
17-18.9								02						05					9	
19 - 22.9																			05	07
23 - 27															04				.02	
Σ	298	216	74	22		131	182	43	.21		284	274	124	39	04	187	275	163	111	.07

DIR. H_o \ T_s	S 11.31% 4-6	6-8	8-10	10-12	12+	SSE 3.13% 4-6	6-8	8-10	10-12	12+	OFFSHORE	CALM[‡]	Σ
											2 90	2867	3151
1-2.9	307					49							2446
3-4.9	48	195				30	52						1828
5-6.9		183	02				54						975
7-8.9		09	97				02	39					692
9-10.9		.04	71	05			05	21	08				290
11-12.9			40	55				.17	.07				279
13-14.9			18	27				12	05				170
15-16.9			05	18	02				04				0.55
17-18.9				31	04			.02	.02				076
19 - 22.9				04	02			02					022
23 - 27					04								0.10
Σ	[illegible]	391	235	140	12	79	115	93	26		2 90	2867	100 00

§ National Marine Consultants, 1961b.

† Based on 365-1/3 days

‡ Includes waves of 0-to 0.9 feet

(1961b).

1. The highest waves always occurred in winter, when waves approached from the southwest to south-southeast.

2. The shortest period waves occurred in summer.

3. In all seasons, the predominant direction of swell was from the northwest to west. Long period swell also approached from this direction.

4. The predominant direction of local sea was from the southwest to south-southeast in autumn and winter, from the north to northwest in spring and summer, and showed more variability in dominant direction than the swell.

5. In all seasons, the longest period sea approached from the southwest to south-southeast.

6. Sea was generally higher than swell, but the periods of the swell exceeded the periods of the sea.

7. The longest period swell occurred in August and were from southern hemisphere storms.

8. The longest period sea waves occurred in winter.

9. In all seasons, periods of calm occurred at the frequency of 25% to 30%, but the calmest season was autumn.

National Marine Consultants (1961) computed wave statistics for the twelve most severe storms affecting deep water stations 2, 3, and 4 (Figure 111-50) during the period 1950-60. The storms selected for analysis occurred during the months listed below:

October, 1950	January, 19S1	February, 1951
December, 1951	December, 1952	December, 1953
February, 1954	November, 1954	January, 1956
March, 1956	December, 1957 (stations 2 and 3 only)	
December, 1959	February, 1960 (station 1 only)	

Storm wave statistics for station 3 show the date and time of the storm history versus significant wave height (H_s), the range of wave period (T_r), the significant wave period (T_s), and the mean direction of wave approach (θ) (Table 111-10). The table describes the characteristics of the deep water significant waves that preceded, included, and followed the largest significant waves that occurred during the selected storms. Thus, they are in effect a significant time history of wave heights around the maximum significant wave height.

A severe storm in the North Pacific in January, 1952 sank the S.S. Pennsylvania with the loss of all hands (45 people) and has been referred to as the Pennsylvania storm ever since. Legal investigations into the disaster resulted in a wave study by Danielsen, Burt,

Table 111-10

SEVERE STORM WAVE CHARACTERISTICS (Sig. Height H ft (m), Sig. Period T_s (sec.), Period Range T_r (see.), Di~ection θ)
STATION 3 (46°12'N, 124°30'W)

DATE	TIME	H_s	T_r	T_s	θ
OCT 50					
26	2230	8 (2.4)	6-7	7	SSW
27	0430	11 (3.4)	6-8	8	WSW
	1030	17 (5.2)	7-9	9	Sw
	1630	24 (7.3)	7-12	11	Sw
	2230	21 (6.4)	7-16	12	Sw
28	0430	21 (6.4)	7-16	12	Sw
	1030	21 (6.4)	7-16	12	Sw
	1630	21 (6.4)	7-16	12	Sw
	2230	17 (5.2)	7-12	11	SW
29	0430	12 (3.7)	7-8	8	SW
JAN 51					
20	2230	12 (3.7)	6-8	8	Sw
21	0430	26 (7.9)	7-18	14	WSW
	1030	27 (8.2)	7-18	14	WSW
	1630	24 (7.3)	7-15	14	WSW
	2230	20 (6.1)	7-14	13	WSW
22	0430	20 (6.1)	7-14	13	WSW
	1030	17 (5.2)	7-11	11	WSW
	1630	13 (4.0)	7-9	9	WSW
FEB 51					
1	2230	11 (3.4)	6-8	8	Ssw
2	0430	19 (5.8)	6-10	10	Ssw
	1030	19 (5.8)	6-11	11	SW
	1630	25 (7.6)	7-18	13	WSW
	2230	25 (7.6)	7-18	13	WSW
3	0430	24 (7.3)	7-15	13	WSW
	1030	18 (5.5)	7-12	12	WSW
	1630	12 (3.7)	7-9	9	WSW
DEC 51					
17	1630	12 (3.7)	6-8	8	S
	2230	15 (4.6)	7-9	8	S
18	0430	7 (2.1)	5-6	6	WSW
	1030	21 (6.4)	7-10	10	WNW
	1630	23 (7.0)	7-12	11	WNW
	2230	23 (7.0)	7-12	12	NW
19	0430	23 (7.0)	7-12	12	NW
	1030	22 (6.7)	7-12	11	NW
	1630	8 (2.4)	7-8	8	NW
DEC 52					
5	2230	16 (4.9)	7-9	9	SSE
6	0430	18 (5.5)	7-10	10	Ssw
	1030	24 (7.3)	6-13	12	WSW
	1630	22 (6.7)	6-13	12	WSW
	2230	25 (7.6)	6-12	11	Sw
7	0430	25 (7.6)	6-12	11	Sw
DEC 52 (cont.)					
7	1030	22 (6.7)	6-12	10	SW
	1630	25 (7.6)	7-16	13	W
	2230	22 (6.7)	7-14	13	W
8	0430	19 (5.8)	7-14	12	W
	1030	14 (4.3)	7-12	11	W
DEC 53					
3	1030	8 (2.4)	3-8	8	WNW
	1630	12 (3.7)	4-13	10	WNW
	2230	17 (5.2)	5-15	11	WNW
4	0430	17 (5.2)	5-15	11	NW
	1030	17 (5.2)	7-16	12	WNW
	1630	21 (6.4)	6-16	12	W
	2230	21 (6.4)	7-16	12	W
5	0430	21 (6.4)	7-16	12	W
	1030	24 (7.3)	7-17	14	WSW
	1630	22 (6.7)	7-17	13	WSW
	2230	21 (6.4)	7-16	12	W
6	0430	21 (6.4)	7-16	12	W
	1030	23 (7.0)	7-18	14	W
	1630	20 (6.1)	7-18	14	W
	2230	18 (5.5)	7-16	13	W
7	0430	13 (4.0)	7-14	12	W
FEB 54					
11	2230	10 (3.0)	6-9	9	S
12	0430	18 (5.5)	7-10	10	S
	1030	25 (7.6)	7-11	11	S
	1630	30 (9.1)	7-14	13	Ssw
	2230	30 (9.1)	7-14	13	Ssw
13	0430	30 (9.1)	7-13	12	Ssw
	1030	21 (6.4)	9-11	11	Ssw
	1630	9 (2.7)	7-8	8	SSW
NOV 54					
17	1030	12 (3.7)	6-8	8	S
	1630	16 (4.9)	6-10	9	S
	2230	21 (6.4)	7-12	11	SSW
18	0430	21 (6.4)	7-12	11	Ssw
	1030	21 (6.4)	7-12	11	Ssw
	1630	14 (4.3)	7-9	9	Ssw
	2230	19 (5.8)	7-10	10	Ssw
19	0430	23 (7.0)	7-13	12	Sw
	1030	23 (7.0)	7-13	12	Sw
	1630	21 (6.4)	7-12	11	Sw
	2230	19 (S.8)	7-10	10	Sw
20	0430	13 (4.0)	7-9	9	Sw

Table 111-10 (cont.)

DATE	TIME	H_S	T_r	T_s	θ
JAN 56					
14	1630	12 (3.7)	4-13	10	SSW
	2230	18 (5.5)	5-13	11	s
15	0430	24 (7.3)	7-13	12	s
	1030	24 (7.3)	7-13	12	SW
	1650	24 (7.3)	7-13	12	SW
	2230	24 (7.3)	7-12	12	WSW
16	0430	24 (7.3)	7-12	12	WSW
	1030	24 (7.3)	7-12	12	WSW
	1630	18 (5.5)	7-15	11	w
	2230	14 (4.3)	7-12	11	W
MAR 56					
2	1630	16 (4.9)	6-9	9	s
	2230	14 (4.3)	6-8	8	Sw
3	0430	18 (5.5)	6-9	9	WSW
	1030	30 (9.1)	7-14	12	w
	1630	30 (9.1)	7-14	12	W
	2230	24 (7.3)	7-12	11	w
4	0430	16 (4.9)	11-18	14	w
	1030	21 (6.4)	7-18	14	w
	1630	19 (5.8)	7-15	13	w
	2230	15 (4.6)	7-11	11	w
5	0430	10 (3.0)	7-9	9	W
DEC 57					
25	0400	8 (2.4)	5-8	8	S
	1000	19 (5.8)	7-11	11	Ssw
	1600	16 (4.9)	5-11	11	Sw
	2200	16 (4.9)	5-11	11	WSW
26	0400	22 (6.7)	7-13	13	w
	1000	23 (7.0)	7-13	13	w
	1600	17 (5.2)	7-11	11	w
	2200	8 (2.4)	7-8	8	W
DEC 59					
10	1600	11 (3.4)	5-8	8	S
	2200	15 (4.6)	6-9	9	s
11	0400	15 (4.6)	5-11	10	Ssw
	1000	17 (5.2)	6-14	11	Sw
	1600	25 (7.6)	7-18	13	Sw
	2200	25 (7.6)	7-18	13	Sw
12	0400	24 (7.3)	7-15	13	Sw
	1000	17 (5.2)	7-11	11	Sw
	1600	10 (3.0)	7-8	8	Sw

§National Marine Consultants, 1961a.

and Rattray (1957). Using actual wave measurements at weather ship PAPA (located 800 km to the west-northwest of Cape Flattery) and additional weather data, the authors hindcast significant wave heights of 15 m in the area where the Pennsylvania went down. Given a significant wave height of 15 m, occasional waves on the order of 30 m are possible. Waves of this magnitude are possible off the Pacific Northwest.

Quayle and Fulbright (1975) using existing climatological data and a statistical approximation technique to estimate mean return periods for maximum sustained winds, and significant and extreme wave heights for coastal areas of the United States. Maximum sustained windspeed is defined as having a duration (at or above the given speed) of approximately 1 minute. Peak gusts (duration usually less than 20 seconds) frequently occur and average about 1.4 times the sustained windspeed. Table 111-11 presents the results of Quayle and Fulbright's analysis.

The preceding data and statistics represent deep water conditions. In order to obtain wave characteristics at a shallow water location, factors such as shoaling, refraction, scattering and diffraction must be considered. Generally, these factors will decrease the wave energy, but they may concentrate it in places.

Rogers (1966) obtained wave data from an oil rig off the Oregon coast and reported seas with waves of 15 m height occurring under winds gusting up to 240 km/hr. Watts and Faulkner (1968) reported waves up to 18 m with one wave 29 m high generated by the constructive summation of large waves from *two* separate storms. Both these observations from oil rigs represent exceptional waves off the Pacific Northwest coast, but they do not give the long term measurements of daily wave height and period needed to completely describe the wave environment. For offshore structure design purposes, the extreme conditions are vitally important, but for coastal erosion studies and other applications, a long term data base is needed.

Larsen and Fenton (1974) successfully obtained wave records from Cobb Seamount for the winter of 1972-73. Cobb Seamount lies about 500 km to the west of Willapa Bay and the peak rises to within 35 m of the surface (Figure 111-50). The instrument recorded waves for 30 minutes every 8 hours. It is assumed that the waves crossing Cobb Seamount are representative of the waves approaching the coast of the Pacific Northwest. Significant wave heights and highest waves observed at Cobb Seamount are presented graphically in Figures 111-51 and 111-52 (Loehr and Ellinger, 1974). The waves observed at Cobb Seamount are somewhat larger than those hindcast by the National Marine Consultants, which reflects the constructive summation of sea and swell from different storms.

The maximum wave heights observed at Cobb Seamount were on the order of 20 m. From personal communication with Larsen (1974), the winter of 1972-73 for which the Cobb Seamount wave measurements were made is considered to be a mild one in terms of severe storms.

Table 111-11

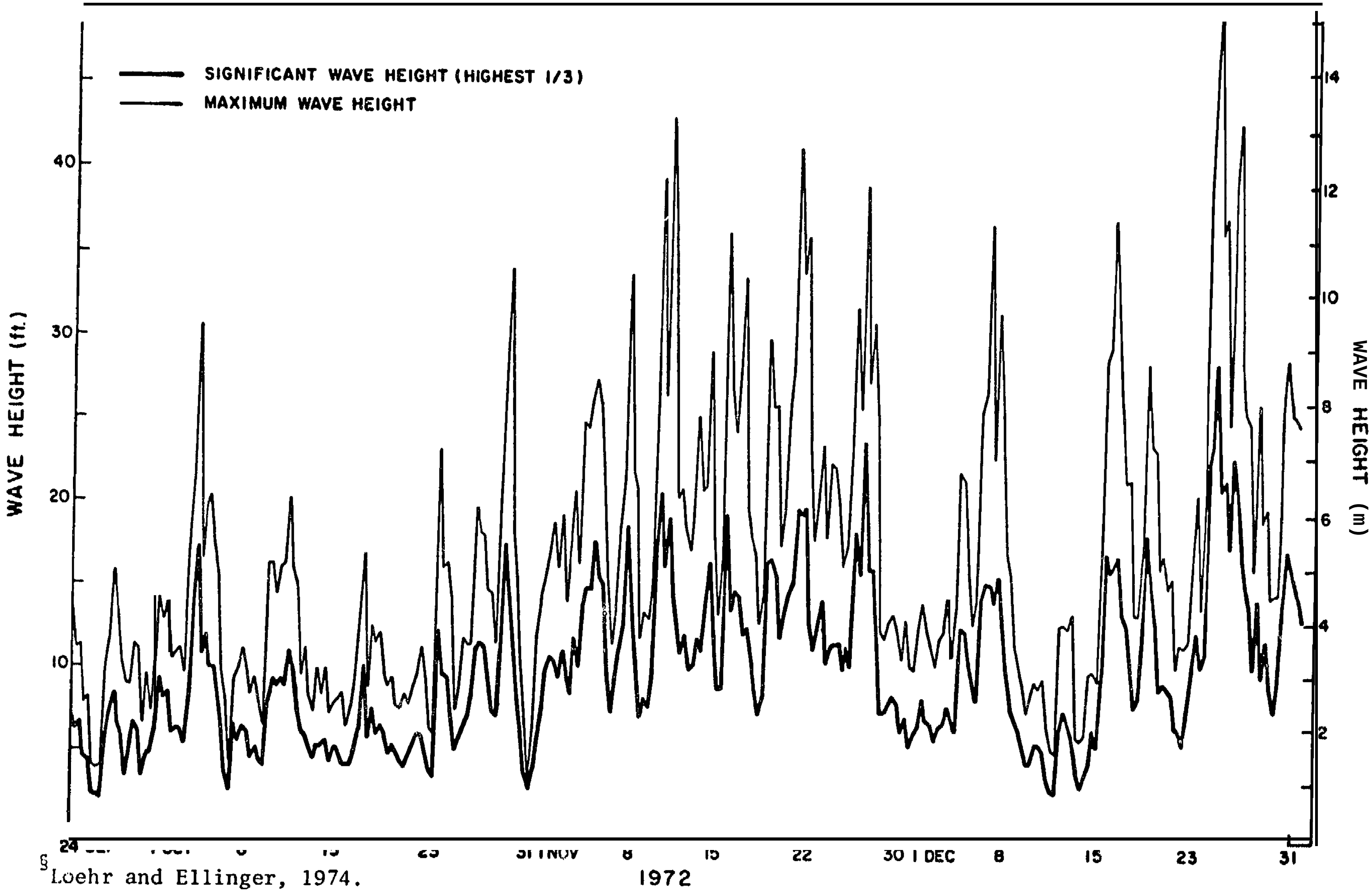
WIND AND WAVE EXTREMES FOR SPECIFIED RETURN PERIODS[§]

Coastal Area	Extreme sustained wind-speed estimates km/hr (knots)					Significant wave height estimates meters (feet)					Extreme wave height estimates meters (feet)				
	5yr	10yr	25yr	50yr	100yr	5yr	10yr	25yr	50yr	100yr	5yr	10yr	25yr	50yr	100yr
Southern Oregon	126 (68)	135 (73)	152 (82)	165 (89)	178 (96)	12 (39)	13 (44)	16 (52)	18 (58)	20 (65)	21 (70)	24 (80)	28 (93)	32 (105)	36 (118)
Northern Oregon	124 (67)	135 (73)	152 (82)	163 (88)	178 (96)	12 (39)	13 (44)	16 (52)	18 (58)	20 (65)	21 (70)	24 (79)	28 (93)	32 (104)	36 (117)
Washington	124 (67)	135 (73)	150 (81]	163 (88)	176 (95)	12 (39)	13 (44)	16 (51)	18 (58)	20 (65)	21 (70)	24 (79)	28 (93)	32 (104)	36 (117)
Vancouver Island	109 (59)	120 (65)	133 (72)	144 (78)	157 (85)	10 (34)	12 (39)	14 (45)	16 (51)	17 (57)	19 (61)	21 (70)	25 (81)	28 (92)	31 (103)

[§] Quayle and Fulbright, 1975.

Figure III-51

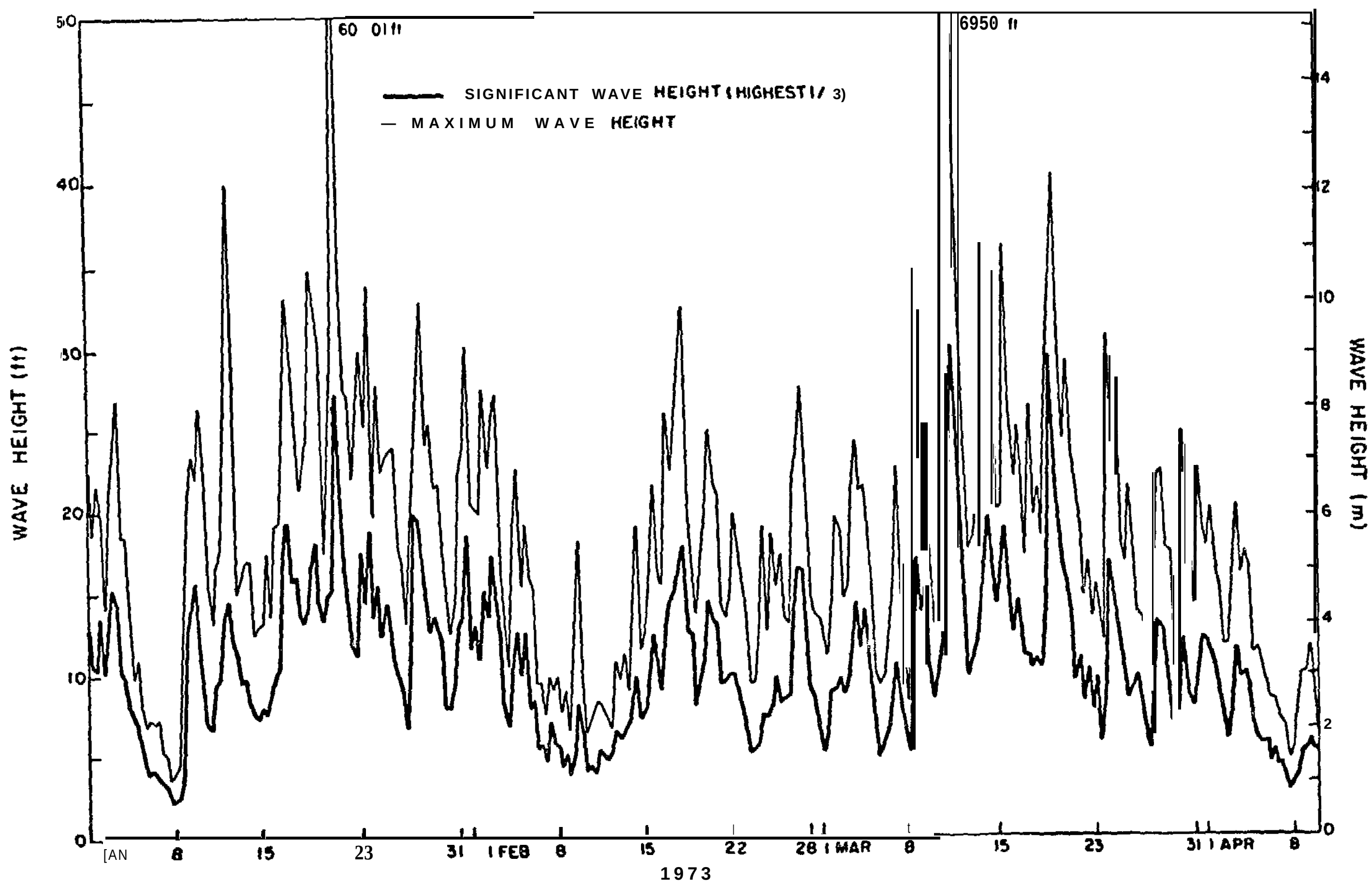
Cobb Seamount Wave Data, September - December 1972[§]



§ Loehr and Ellinger, 1974.

Figure III-52

Cobb Seamount Wave Data, January-April 1973[§]



§Loehr and Ellinger, 1974.

Larsen believes that the actual "average" wave conditions are more severe than portrayed in the National Marine Consultants study.

Four years of interrupted wave data are available from off Tofino, British Columbia on the shelf at 48°59.45'N and 125°44.65'W. The measurements were taken 5 km offshore where the depth is 40 meters. Wave data were obtained for two months (February and March, 1973) during which the Cobb Seamount instrument was also recording. Figure III-53 graphically expands the Cobb Seamount data and compares it to the Tofino data. The graphs represent the significant wave heights only.

By comparing the two sets of wave data, it is evident that Cobb Seamount data is representative of the waves that approach the shelf and coasts of the study area. It is also evident that the shelf produces a general reduction of the open ocean wave heights. As previously mentioned, this is because of shoaling and refraction. The February 1973 Tofino data correlate very well with the Cobb Seamount data. The two peak storms showed very little reduction at Tofino. This implies that the direction of wave approach for both these storms was such that minimal refraction losses resulted.

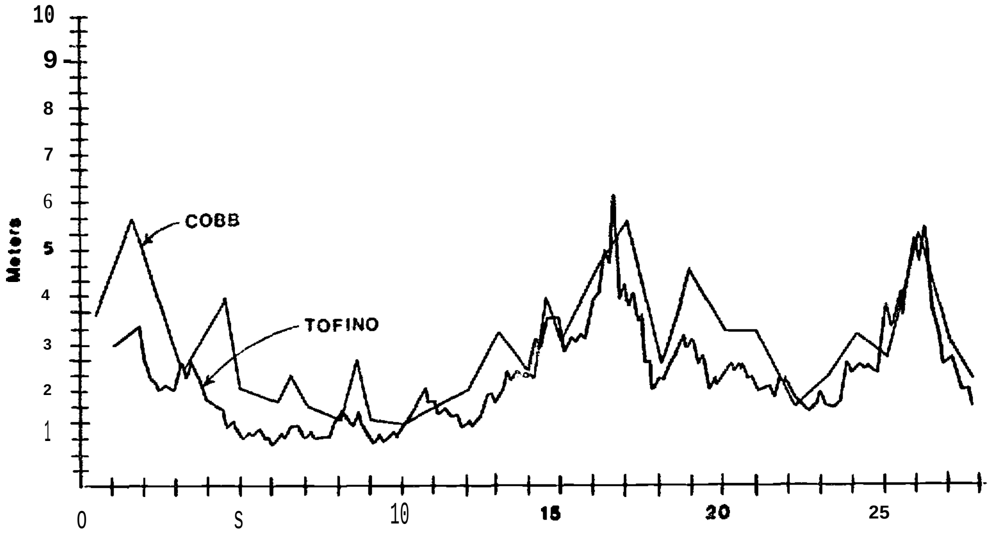
The March 1973 data correlate well also, but a greater reduction of significant wave height occurred in Tofino indicating a different direction of approach for the peak waves than for the February storms. This reduction emphasizes the significance of refraction on the continental shelf. For calm periods, where the significant wave heights at Cobb Seamount were less than 1.5 m, the significant wave heights at Tofino were virtually the same. Most of these waves were probably of shorter periods (less than 7 seconds) and would be significantly refracted at the depth of the Tofino instrument. The Tofino data also included significant period statistics that correspond well with the National Marine Consultants (1961b).

Zopf, Creech and Quinn (1976) have developed a system to improve nearshore ocean wave forecasting along the Oregon and Washington coast. They have developed a method for measuring nearshore ocean wave characteristics with a land-based, long-period vertical seismometer. The method is based on the theory of Louguet-Higgins (1950) which "predicts that the interaction of incident and reflected waves will result in the formation of standing waves, and that the standing waves will produce a pressure field on the ocean bottom which will generate seismic waves propagating in the horizontal plane which can be detected at some distance from their source." The first seismometer was installed at the Oregon State University Marine Science Center, Newport, Oregon in May 1971. Seismometers are now installed at six Coast Guard stations on the Pacific Northwest coast (Figure 111-50).

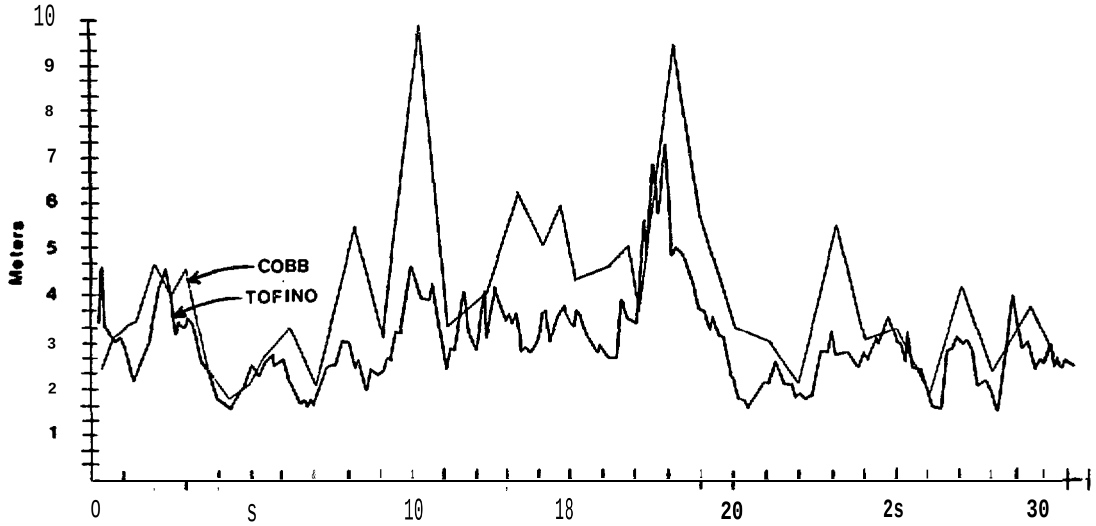
Creech (1973) summarized the statistics of 2781 seismometer inferred wave observations made at Newport, Oregon between July 1971 and June 1973. Monthly and seasonal wave height and period statistics from his analysis are presented in Table 111-12. The

Figure III-53

Corresponding Wave Height Recordings at Tofino and Cobb Seamount
February, March, 1973[§]



February, 1973 Time in Days



March, 1973 Time in Days

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§ Loehr and Ellinger, 1973.

Table III-12

SEISMOMETER INFERRED WAVES
YAQUINA BAY, OREGON.
1 JULY 1972 - 30 JUNE 1973[§]

SIGNIFICANT WAVE HEIGHT, $H_{1/3}$, METERS (FEET)

	JUL	AUG	SEP	JUL-SEP	OCT	NOV	DEC	OCT-DEC	JAN	FEB	MAR	JAN-MAR	APR	MAY	JUN	APR-JUN	JUL-JUN
Mean	1.3 (4.2)	0.8 (2.7)	1.2 (4.0)	1.1 (3.6)	1.5 (4.8)	2.9 (9.4)	2.5 (8.2)	2.3 (7.4)	2.6 (8.6)	2.3 (7.5)	2.5 (8.3)	2.S (8.2)	1.6 (5.4)	1.7 (5.5)	1.3 (4.4)	1.6 (5.1)	1.8 (6.0)
Standard Deviation	.5 (1.8)	.3 (1.1)	.5 (1.6)	.5 (1.7)	.6 (2.1)	.9 (2.8)	1.2 (4.0)	1.1 (3.7)	1.1 (3.7)	0.8 (2.6)	0.7 (2.4)	0.9 (3.0)	0.5 (1.7)	0.8 (2.6)	0.7 (2.3)	0.7 (2.3)	1.0 (3.3)
Highest, $H_{1/3}$	2.4 (8)	2.1 (7)	2.4 (8)	2,4 (8)	3.4 (11)	4.9 (16)	7.3 (24)	7,3 (24)	5.2 (17)	4.6 (1S)	4.9 (16)	5.2 (17)	2,7 (9)	4.0 (13)	3.4 (11)	4.0 (13)	7.3 (24)
Lowest, $H_{1/3}$	.6 (2)	.3 (1)	.6 (2)	.6 (2)	.6 (2)	1.5 (5)	.9 (3)	.6 (2)	.6 (2)	.9 (3)	.9 (3)	.6 (2)	.6 (2)	.3 (1)	.3 (1)	.3 (1)	.3 (1)
Sample size	124	124	120	368	124	120	124	368	124	112	124	360	120	124	120	364	1460

WAVE PERIODS, SECONDS

	JUL	AUG	SEP	JUL-SEP	OCT	NOV	DEC	OCT-DEC	JAN	FEB	MAR	JAN-MAR	APR	MAY	JUN	APR-JUN	JUL-JUN
Mean	8.2	7.8	8.4	8.1	10.0	11.6	10.3	10.6	10.5	10.9	10.0	10.4	9.3	9.2	8.3	8.9	9.5
Standard Deviation	1.3	1.2	1.1	1.2	1.5	1.8	1.9	1.9	1.4	1.8	1.8	1.8	1.1	1.8	1.5	1.6	1.9
Highest	11	12	11	12	14	15	17	17	15	15	16	16	12	13	12	13	17
Lowest	5	5	6	5	7	7	6	6	7	7	7	7	6	5	5	5	5
Sample size	124	124	120	368	124	120	124	368	124	112	124	360	120	124	120	364	1460

[§]Creech, 1973.

Table III-12 (cont.)

SEISMOMETER INFERRED WAVES
YAQUINA BAY, OREGON
1 JULY 1971 - 30 JUNE 1972[§]

SIGNIFICANT WAVE HEIGHT, $H_{1/3}$, METERS (FEET)

	JUL	AUG	SEP	JUL-SEP	OCT	NOV	DEC	OCT-DEC	JAN	FEB	MAR	JAN-MAR	APR	MAY	JUN	APR-JUN	APR-JUN
Mean	.82 (2.7)	1.22 (4.0)	1.49 (4.9)	1.25 (4.1)	1.98 (6.5)	2.87 (9.4)	3.09 (10.1)	2.62 (8.6)	2.71 (8.9)	2.29 (7.5)	1.98 (6.5)	2.32 (7.6)	1.83 (6.0)	1.13 (3.7)	1.25 (4.1)	1.40 (4.6)	1.95 (6.4)
Standard Deviation	.37 (1.2)	.64 (2.1)	.76 (2.5)	.64 (2.1)	.98 (3.2)	1.04 (3.4)	1.13 (3.7)	1.16 (3.8)	1.01 (3.3)	.70 (2.3)	.67 (2.2)	.85 (2.8)	.64 (2.1)	.55 (1.8)	.46 (1.5)	.64 (2.1)	1.04 (3.4)
Highest, $H_{1/3}$	1.8 (6)	2.7 (9)	3.0 (10)	3.0 (10)	4.9 (16)	6.1 (20)	6.1 (20)	6.1 (20)"	5.5 (18)	4.0 (13)	3.7 (12)	5.5 (18)	4.0 (13)	2.7 (9)	2.4 (8)	4.0 (13)	6.1 (20)
Lowest, $H_{1/3}$	.3 (1)	.6 (2)	.3 (1)	.3 (1)	.3 (1)	.6 (2)	.6 (2)	.6 (2)	1.2 (4)	0.9 (3)	.6 (2)	.6 (2)	.6 (2)	.3 (1)	.6 (2)	.3 (1)	.3 (1)
Sample Size	79	88	85	252	97	120	124	341	124	116	124	364	120	124	120	364	1321

WAVE PERIOD, SECONDS

	JUL	AUG	SEP	JUL-SEP	OCT	NOV	DEC	OCT-DEC	JAN	FEB	MAR	JAN-MAR	APR	MAY	JUN	APR-JUN	APR-JUN
Mean	6.7	7.7	7.7	7.4	9.0	10.9	10.5	10.1	10.7	10.1	9.5	10.1	8.9	7.9	8.0	8.2	9.1
Standard Deviation	1.0	1.3	1.7	1.4	1.8	1.7	2.o	2.0	2.0	1.3	1.4	1.7	1.2	1.7	1.1	1.4	2.0
Highest	9	12	12	12	14	14	15	15	16	13	14	16	12	14	10	14	16
Lowest	4	6	4	4	5	6	5	5	7	7	7	7	5	5	5	5	4
Sample Size	72	86	85	243	82	120	124	341	124	116	124	364	120	124	120	364	1314

[§]Creech, 1973.

monthly mean significant wave height varied between 1 and 3 m, and the range of significant heights varied between 0.3 and 7.3 m. Significant wave heights exceeded 2.4 m for more than 2500 hours (30%) of each year, and 6 m for about 20 hours (0.2%) of each year. The monthly mean significant wave period varied between 7 and 12 seconds, and the range of significant periods varied between 4 and 17 seconds.

The steepness of a wave (H/L) is important in determining its capacity to move sediment (Saville, 1950). Using the National Marine Consultants hindcast data for station 3, 32 km (20 miles) west of the Columbia River, Ballard (1964) calculated the steepness values for annual average deep water conditions for both sea and swell. Table III-13 presents the relative frequency of waves with given steepness (H/L) values by direction. Ballard noted that most of the swells (81.5%) fell in the H/L range of <0.015 while seas were dominant (90.3%) in the 0.015 to 0.025 range.

High waves can occur as close in as the depth of the water will support them. Therefore, the values for significant and extreme deep water wave conditions do not occur in the shallow coastal zone. The height of waves that can be supported is approximately 78 percent of the water depth (Quayle and Fulbright, 1975). Wave refraction will also alter the characteristics of the deep water wave conditions.

b) Refraction Studies. The local shelf bathymetry and the direction of wave approach determines the manner in which waves will refract. As a wave enters shallow water at some angle to the bottom contours, it will slow down at differing rates along the wave front. This results in the wave front bending, generally shoreward. This bending is called refraction. Waves refract when the water shoals to about one half the deepwater wave length. In deep water (greater than one half the wave length) the wave length, period and speed are related in the following equation:

$$c_o = \sqrt{gL/2\pi} \qquad \text{(III-3)}$$

where co is the celerity (the wave speed relative to the water, not relative to the bottom], L is the wave length in deep water, g is the gravitational acceleration, and T is the wave period. As the period increases, the deep water wave length increases and the speed increases. As a wave moves into shallow water (less than one half its wave length) it will start to slow, and its wave length will decrease. The wave period will remain constant and hence is the best parameter to identify waves as they refract, shoal, build up and break. The shallow water wave speed is given by

$$c = \sqrt{gd} \qquad \text{"(III-4)}$$

where d is the water depth.

Wave refraction studies have been carried out by P. Hamilton (University of Washington, Department of Oceanography) for portions of the Oregon and Washington coasts. The Oregon studies were site specific and related to intended developments (Draft Environmental Impact Statement, Corps of Engineers Activities in the Chetco, Coquille, and Rogue River Estuaries and Port Orford, Oregon, U.S. Army Corps of Engineers, Portland District, 1975c). The Washington

Table III-13

Relative Frequency of Waves with Given Steepness (Ho/Lo) values[†] from Various Directions[§]

H_o/L_o	Condition	Percent Occurrence from various wave directions: N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	Σ
< 0.015	sea	---	---	---	---	---	---	---	0.1	---	---	0.1
	swell	---	0.6	9.0	24.2	26.4	10.2	4.7	4.0	2.3	0.1	81.5
0.015-0.025	sea	4.8	6.9	22.2	5.9	8.5	4.8	9.4	10.2	13.8	3.8	90.3
	swell	---	0.1	1.3	5.6	4.9	1.9	1.4	1.7	0.9	0.1	17.9
>0.025	sea	0.4	0.5	1.7	0.6	0.5	0.8	1.3	1.2	1.8	0.8	9.6
	swell	---	---	0.1	0.1	0.2	0.1	0.1	---	---	---	0.6

[§] After Ballard, 1964.

[†] Values represent average annual conditions for the years 1956, 1957, and 1958.

studies were to assist in potential site selection for an offshore oil terminal in a feasibility study by the Oceanographic Institute of Washington (1974). This refraction work by Hamilton was presented in detail by Loehr and Ellinger (1974). The Washington studies looked at a region north of Grays Harbor, and also the western half of the Strait of Juan de Fuca.

For the Grays Harbor area, significant wave periods and directions were selected from the National Marine Consultants statistics and related to the refraction studies. Figure III-54 presents the portion of the Washington shelf that was studied. Waves with periods of 7, 9, 11, 13, 16 and 18 seconds were simulated by computer for the study from the southwest, the west-southwest, the west, the west-northwest, and the northwest. Figure III-55 illustrates wave orthogonal from the west with a period of 11 seconds. The letters A and O represent approximate best and worst overall sites based on analysis of all the refraction diagrams in the study. Figure III-56 presents a combination of waves of the five different periods all approaching from the west. The areas where the orthogonal are massed together represent areas of high focusing and concentration of wave energy. Areas where the lines are scarce represent areas of reduced wave energy. The west approach is considered the most significant. Figure III-57 presents a combination of 11 second period wave orthogonal from the five directions analyzed. Ten to twelve second period waves are considered *to* be most representative of winter waves in the Pacific Northwest (Creech, 1973) .

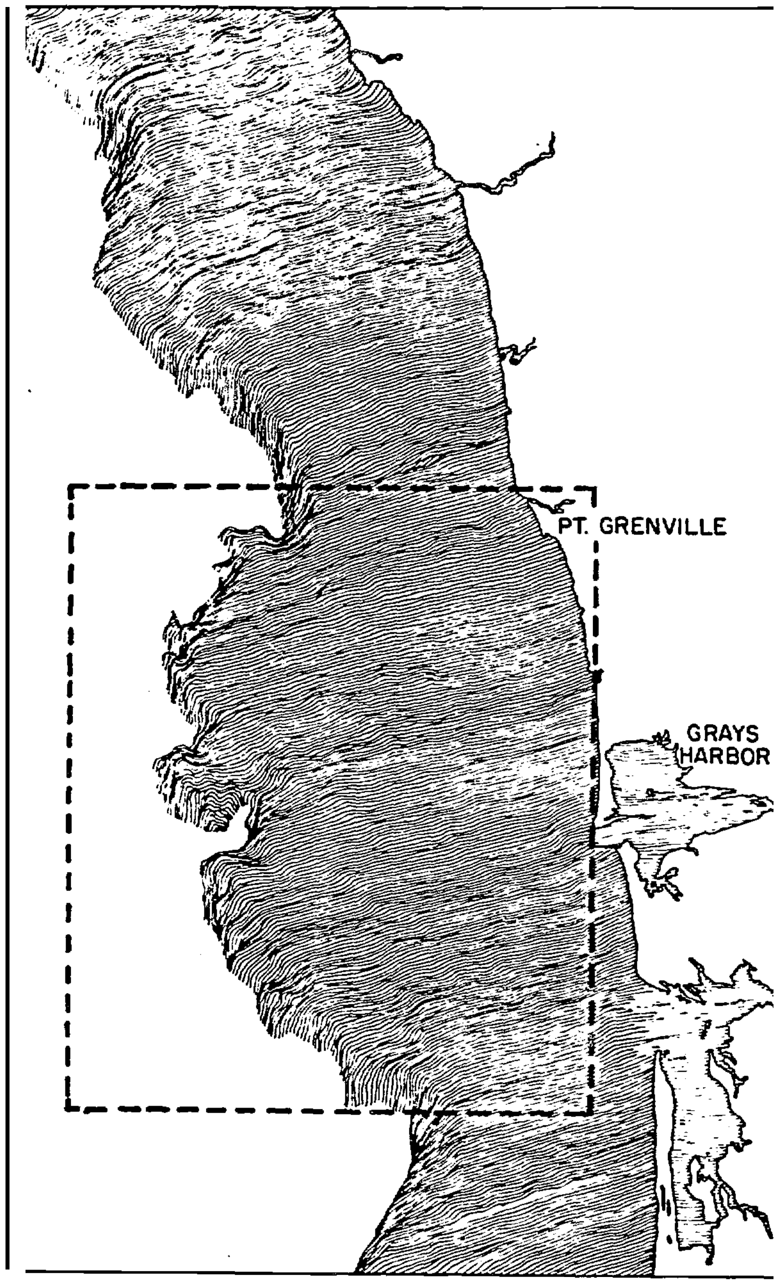
Wave refraction studies conducted for the western part of the Strait of Juan de Fuca were to estimate the penetration of open ocean waves into the Strait. Figure III-58a presents the orthogonal for 11 second waves from the west-northwest and illustrates that these waves are well dispersed by refraction. Moderate to long period swell or sea generated off the coast will not have much effect on the inland waters of Washington and British Columbia. The west-northwest orientation of the Strait of Juan de Fuca effectively filters out open ocean waves from most other directions, and refraction disperses the waves that do enter the Strait.

The wave orthogonal for the Grays Harbor area were evaluated as follows. Combinations of diagrams were studied, unfavorable and favorable sites (O and A in Figure III-55) selected, and refraction coefficients computed for the different period-direction combinations (Table 111-14). The coefficients were weighted based on the National Marine Consultants (1961b) statistical data, and deep water wave height reduction factors were computed for the two sites using a test wave with a significant period of 11 seconds and significant height of 3.7 m (Table 111-15).

The usefulness of refraction studies coupled with wave statis*tics is* that areas of relatively high or low energy can be determined. Shadow zones for particular storms may be useful as refuges for ships or small craft while they await a lull to enter port, for example, refraction studies for the entire Oregon and Washington shelf could add a new dimension *to wave* forecasting.

Figure III-54

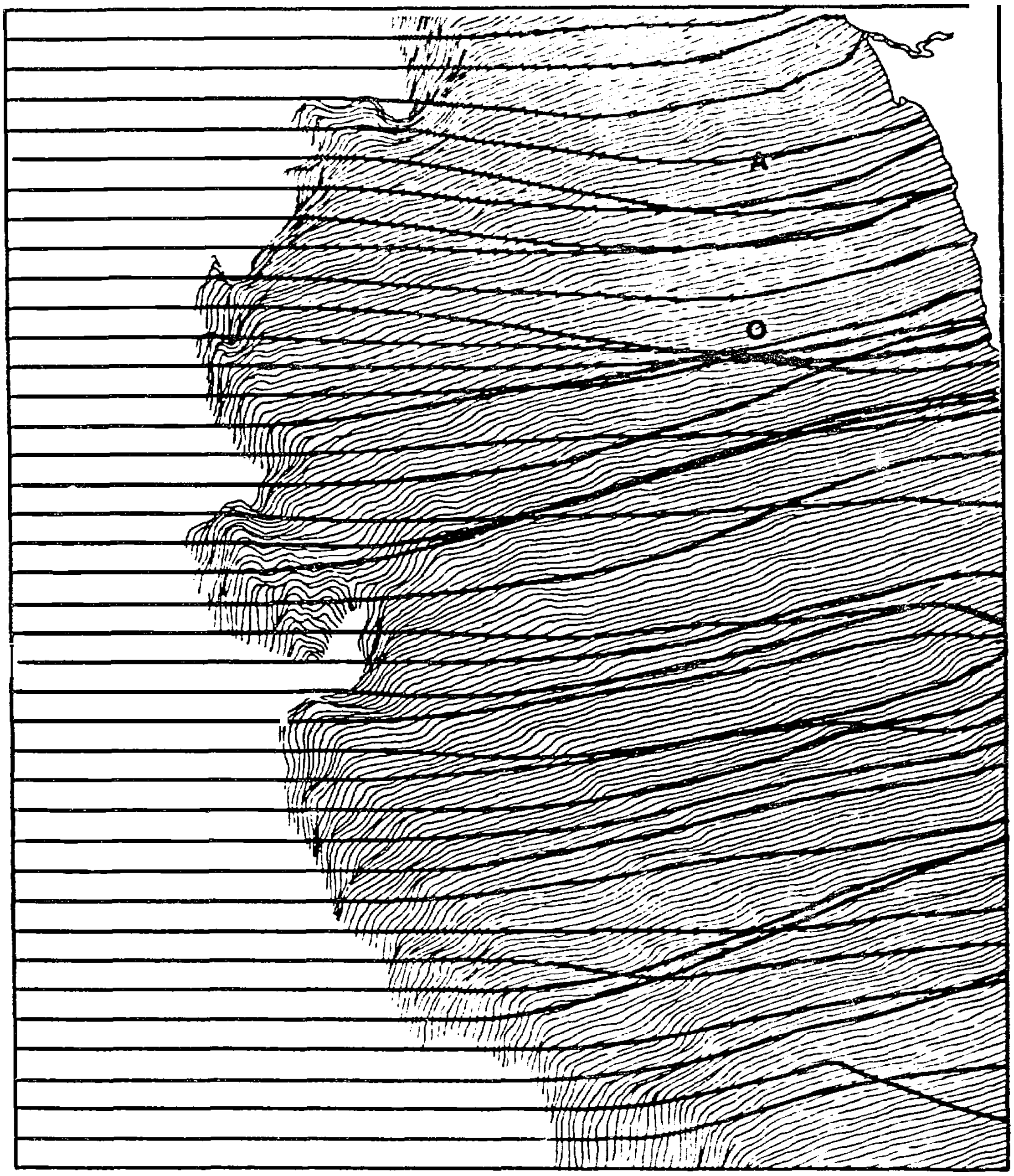
Oblique Profile of the Washington Shelf (Wave refraction studies were conducted for the boxed area.)§



§Loehr and Ellinger, 1974.

Figure III-55

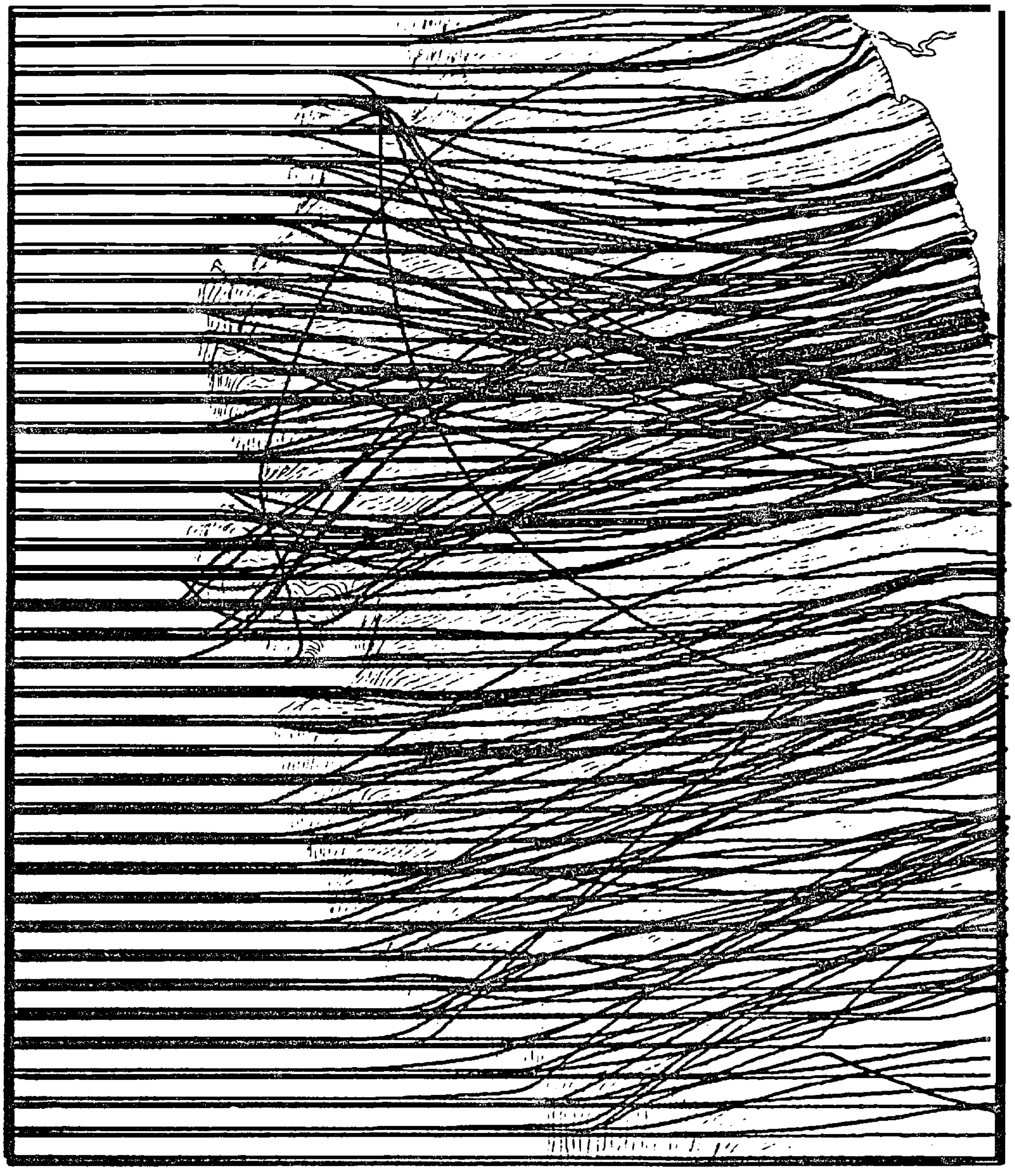
Wave Orthogonal for 11 Second Period Waves from the West for the Grays Harbor Siting Zone[§]



[§] Loehr and Ellinger, 1974.

Figure III-56

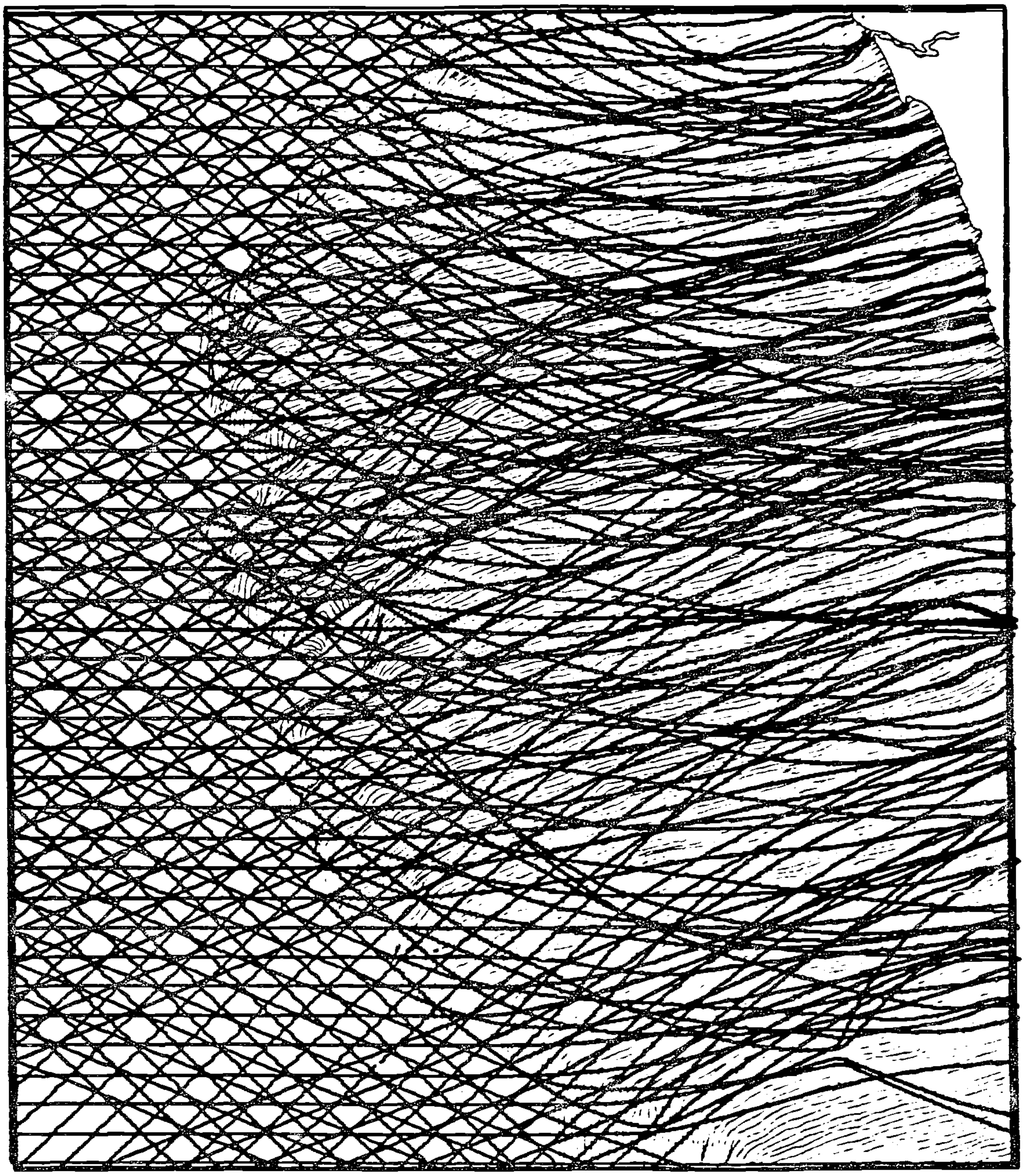
Wave Orthogonal for Waves from the West.[§] Wave Periods are 9, 11, 13, 16 and 18 Seconds[§]



[§]Loehr and Ellinger, 1974.

Figure III-57

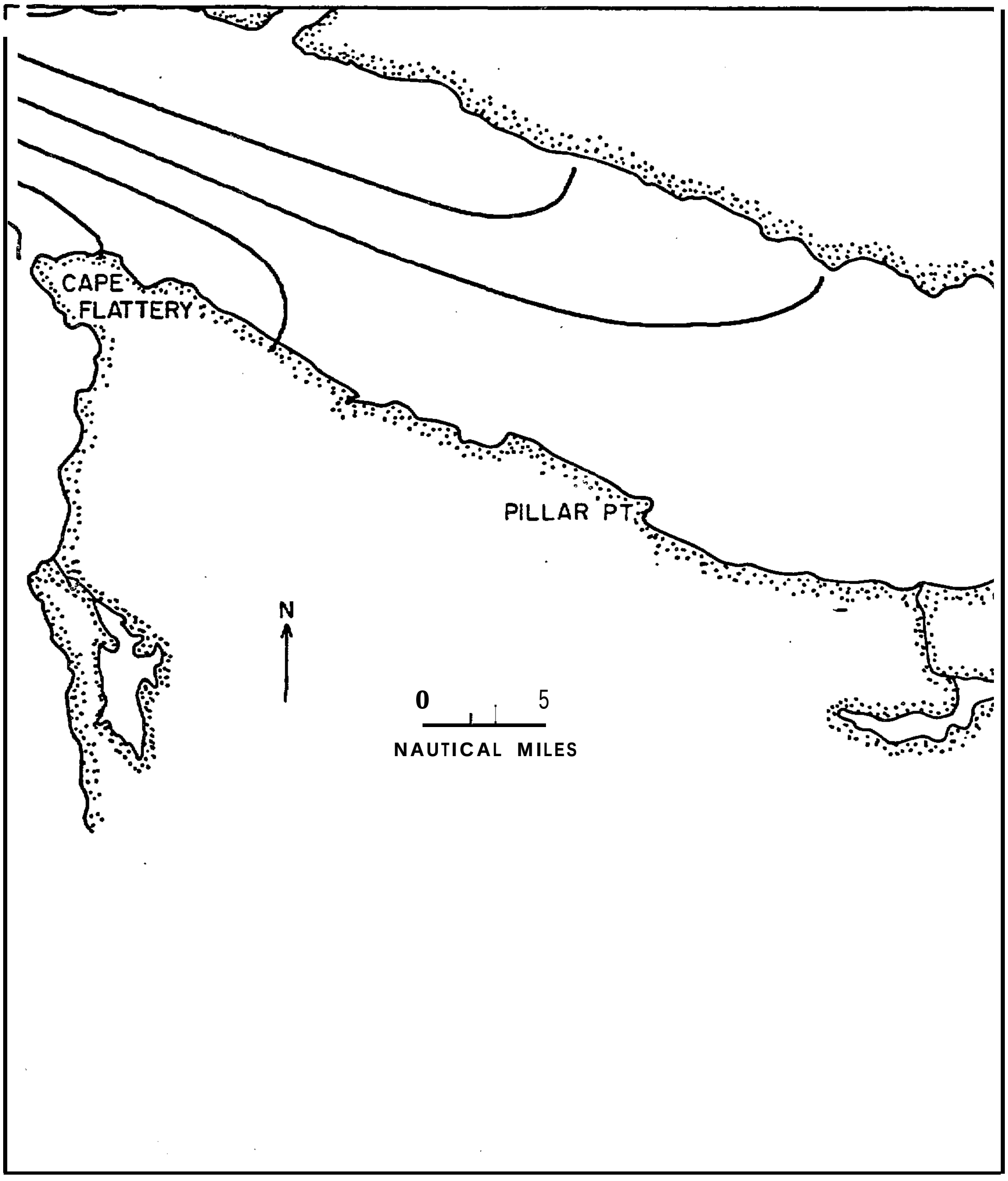
Wave Orthogonal for 11 Second Period Waves from the Southwest, Westsouthwest, West, Westnorthwest, and the Northwest[5]



[5] Loehr and Ellinger, 1974.

Figure III-58a

Wave Orthogonal from the Westnorthwest for the Outer Strait of Juan de Fuca[§†]



§ **Loehr** and **Ellinger,** 1974.
† Period = 11.0 sec. wave from Bearing 293.

Table III-14

Refraction Coefficients for Waves at Site A[§]

DIRECTION	7 sec	9 sec	11 sec	13 sec	16 sec	18 sec
Sw	----	0.74	1.04	2.00	0.43	0.37
WSW	1.07	0.74	0.43	0.11	0.08	0.11
W	0.86	0.57	0.54	0.08	0.09	0.05
WNW	0.92	0.49	0.26	0.09	0.11	0.10
Nw	0.59	0.45	0.50	0.15	0.15	0.15

Refraction Coefficients for Waves at Site O[§]

DIRECTION	7 sec	9 sec	11 sec	13 sec	16 sec	18 sec
Sw	----	0.60	0.17	0.25	0.58	1.49
WSW	0.92	0.90	0.78	0.32	0.34	0.53
W	0.72	0.70	1.56	0.65	1.00	0.74
WNW	1.29	0.50	0.39	0.34	0.78	0.68
Nw	0.40	0.55	0.48	0.42	0.30	0.35

[§] Loehr and Ellinger, 1974.

Table 111-15

Significant Wave Height Reductions for Moderate Test Wave
at Sites A and O[§]
(deep water wave characteristics, H_s = 3.7 meters, period = 11 seconds)

DIRECTION	OPEN SEA	A	%	O	%
SW	3.7	3.5	97	2.6	70
WSW	3.7	3.1	86	3.3	91
W	3.7	2.9	79	3.4	94
WNW	3.7	2.7	74	3.1	85
NW	3.7	2.5	70	2.5	68
unweighed mean % of open sea height =			81%		82%

Significant Wave Height Reductions for Moderate Test Wave
at Sites A and O[§]
(Weighted by Frequency of Occurrence of 11 Second, Waves of H_s = 3.7 meters)

DIRECTION	REDUCTION	FREQUENCY	FACTOR A	REDUCTION	FREQUENCY	FACTOR O
SW	97	x 0.00	= 0.00	70	x 0.00	= 0.00
WSW	86	x 0.11	= 9.46	91	x 0.11	= 10.01
W	79	x 0.64	= 50.56	94	x 0.64	= 60.16
WNW	74	x 0.11	= 8.14	85	x 0.11	= 9.35
NW	70	x 0.15	= 10.50	68	x 0.15	= 10.20
weighted % of open sea height =			79%			90%

[§]After Loehr and Ellinger, 1974.

From this discussion, it is apparent that seasonal predictability based on averaging past data is fairly good. Short term forecasting based on climatological data for the Pacific is also good. More data is required to further refine predictive capabilities.

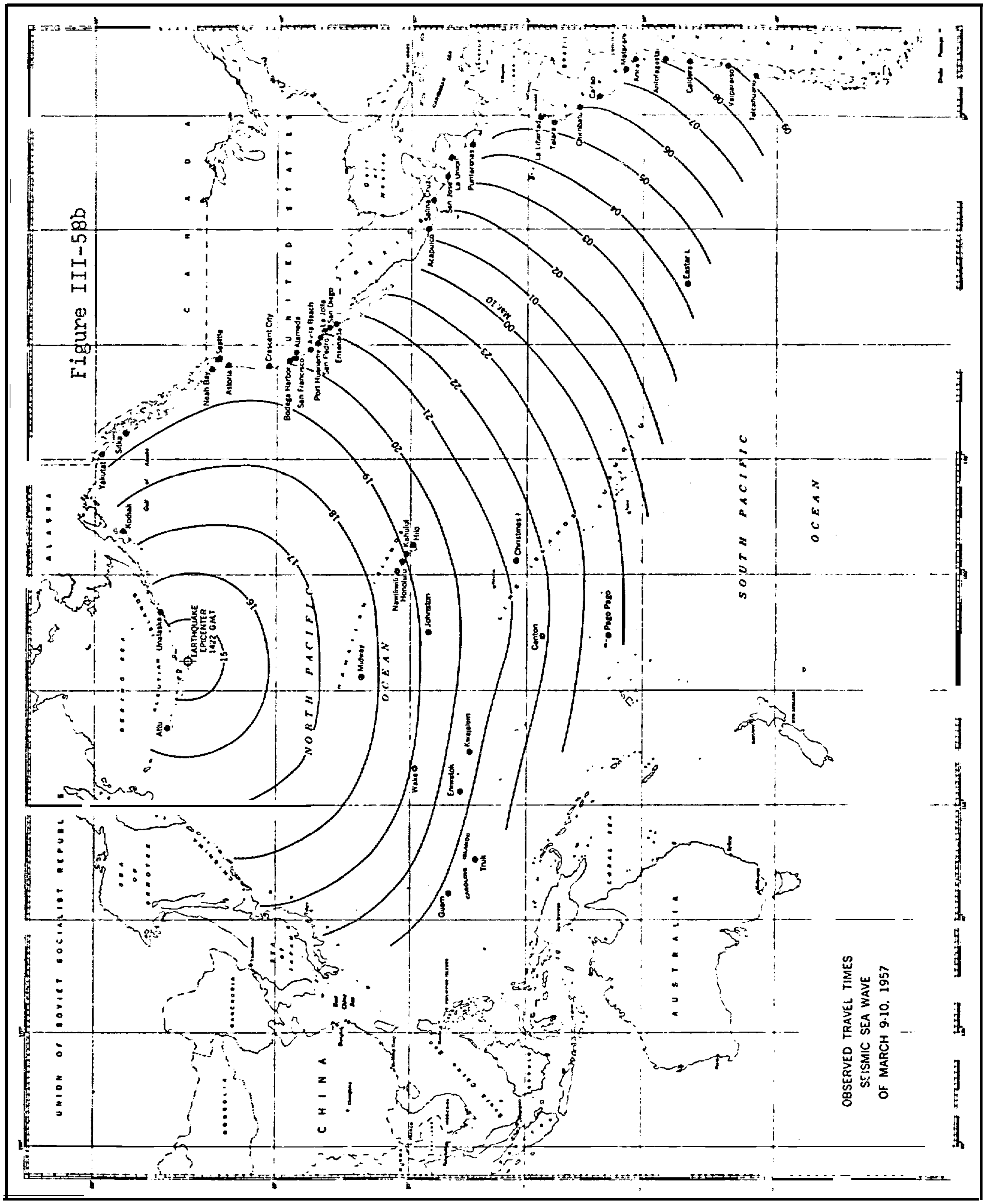
c) Seismic Sea Waves. Seismic sea waves (sometimes called tsunamis or "tidal waves") are long period waves (5 to 60 minutes) generated by any powerful undersea disturbance that vertically displaces a large volume of water. Seismic sea waves are most commonly associated with earthquakes around the Pacific Rim, but have been generated by volcanic and atomic explosions in the ocean and by massive landslides or slumps of earth into coastal waters.

The hazards associated with a seismic sea wave are primarily associated with the rapid change in water level that is the difference between the wave crest and sea level. A warning system exists for the Pacific, called the Tsunami Information Center, Hawaii. Between 1946 and 1976, tsunami warnings and partial evacuation along the coast occurred in 1952, 1963, 1964, and 1965. The 1964 event destroyed two bridges and temporarily stranded 100 residents and recreationists in Washington (Marts, 1976) and in Oregon four people were swept to sea and drowned (Day of the Alaskan Earthquake, 1964).

The behavior of a seismic sea wave is difficult to predict for any particular part of the coast, and it is also difficult to generalize data from areas damaged by seismic sea waves. The beavior of a seismic sea wave is a function of the generating force, the origin, the direction of approach, the local shelf bathymetry, basin or harbor configurations that could amplify the wave run-up, local tide height at time of arrival, the seismic *sea* wave period and, very importantly, any natural resonant oscillation period of a harbor or bay. If a harbor has a natural resonant frequency that closely approximates the period of an arriving seismic sea wave train, each arriving wave crest may serve *to* amplify the earlier ones with extreme effects.

Tide records are useful in preserving local seismic sea wave data. The Department of Commerce has published reports on tsunamis as recorded at tide stations (U.S. Coast and Geodetic Survey, 1953, 1967, and Salsman, 1959). Figure III-58b presents the observed travel times for the tsunami of March 9, 1957, which originated in the Aleutian Island chain, and identifies this as a critical area of origin for the Pacific Northwest. The tsunami struck Oregon and Washington perpendicular to the coast. Fortunately, the tsunami was not a major one. Figure III-59 presents the tide gauge records of the tsunami of March 28, 1964 for Tofino, Vancouver and Victoria, B.C.; Neah Bay, Friday Harbor and Seattle, Washington; Astoria, Oregon and Crescent City, California. This was the largest seismic sea wave to strike the west coast in recent times, and the first waves arrived coincident with a high tide. The effects on Crescent City were disastrous.

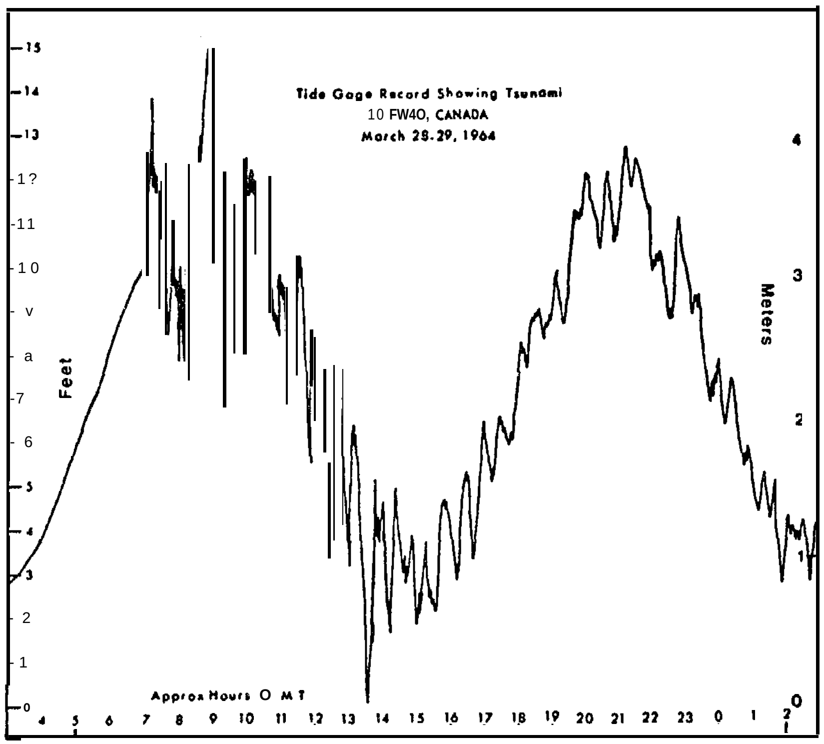
Tide gauge records are not the only records of importance.

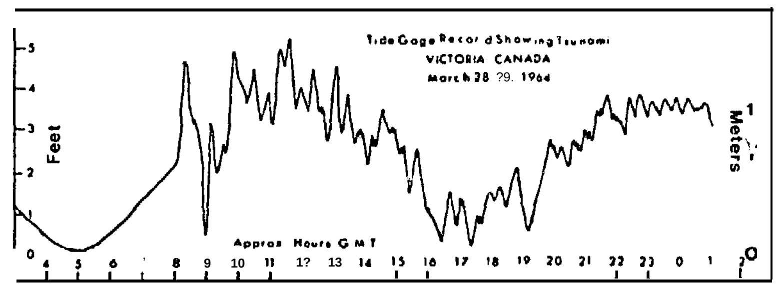


§ Salsman, 1959.

Figure III-59

Tide Gage Records of the Tsunami of March 28, 1964
for Selected Locations[9]





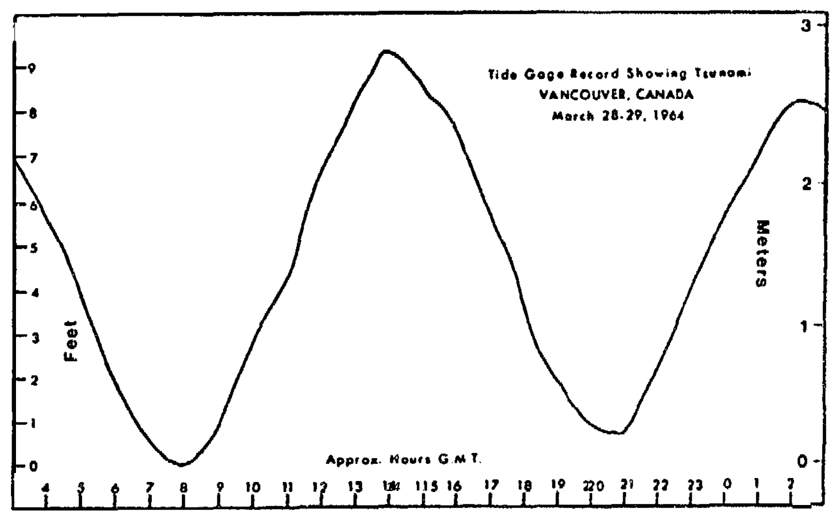
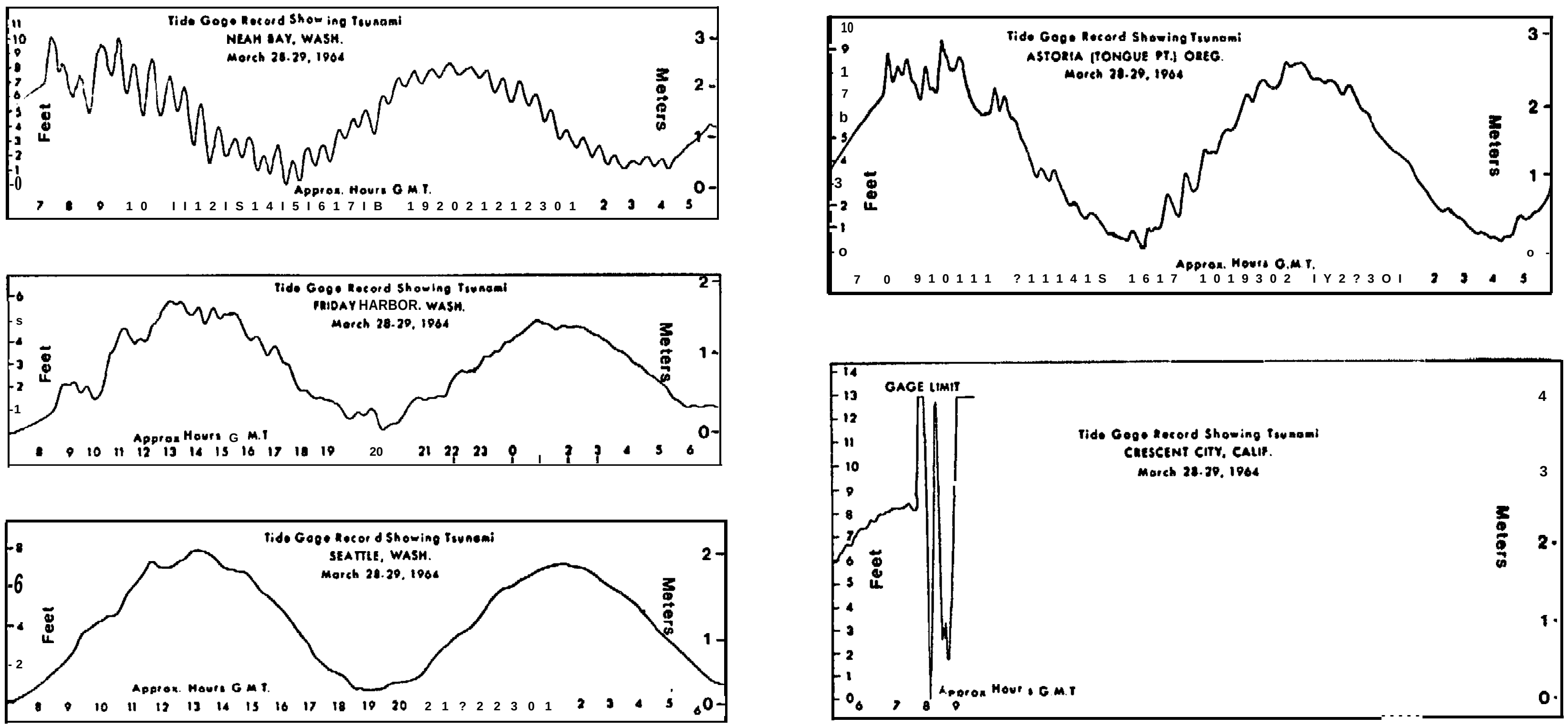


Figure III-59 (cont.)



§U.S. Coast and Geodetic Survey, 1967.

Debris pushed inland by a tsunami leaves a good indication of its highest reach. Visual observations also complement the record. Schatz, Carl and Bart (1964) indicated that maximum wave heights in Oregon estuaries varied from 2.1 to 4.2 m (7 to 14 feet) as a result of the 1964 tsunami. Figure 111-60 presents the record of wave heights at coastal stations and estuaries along the Oregon and Washington coast.

Brunson, *et aZ.* (1971) considered design problems and wave forces on a hypothetical offshore Nuclear Power plant using the 1964 tsunami as a design wave.

Houston, *et al.* (1975) performed a computer investigation of the effect of orientation and location of elliptically shaped tsunamigenic ground displacements of earthquakes along the Aleutian Trench on resulting tsunami amplitude along the Pacific Coast of the United States. Leading wave amplitudes were computed for the Pacific Coast for a common water depth of 180 m (shelf edge). They concluded that seismic sea waves generated from the eastern end of the Aleutian Trench were the most significant due to source orientation effects. This is because waves radiated from the center of an elliptic uplift area perpendicular to the major axis (in this case, the axis of the Trench) have significantly greater amplitudes than waves radiated from other parts of the uplift area.

Refraction and shoaling effects of the shelf were not considered. Refraction would tend to diminish energy for seismic sea waves approaching the shelf at angles less than head on. Hence, refraction would provide some sheltering for waves from the eastern part of the Trench, and very little sheltering for waves from the western part of the Trench.

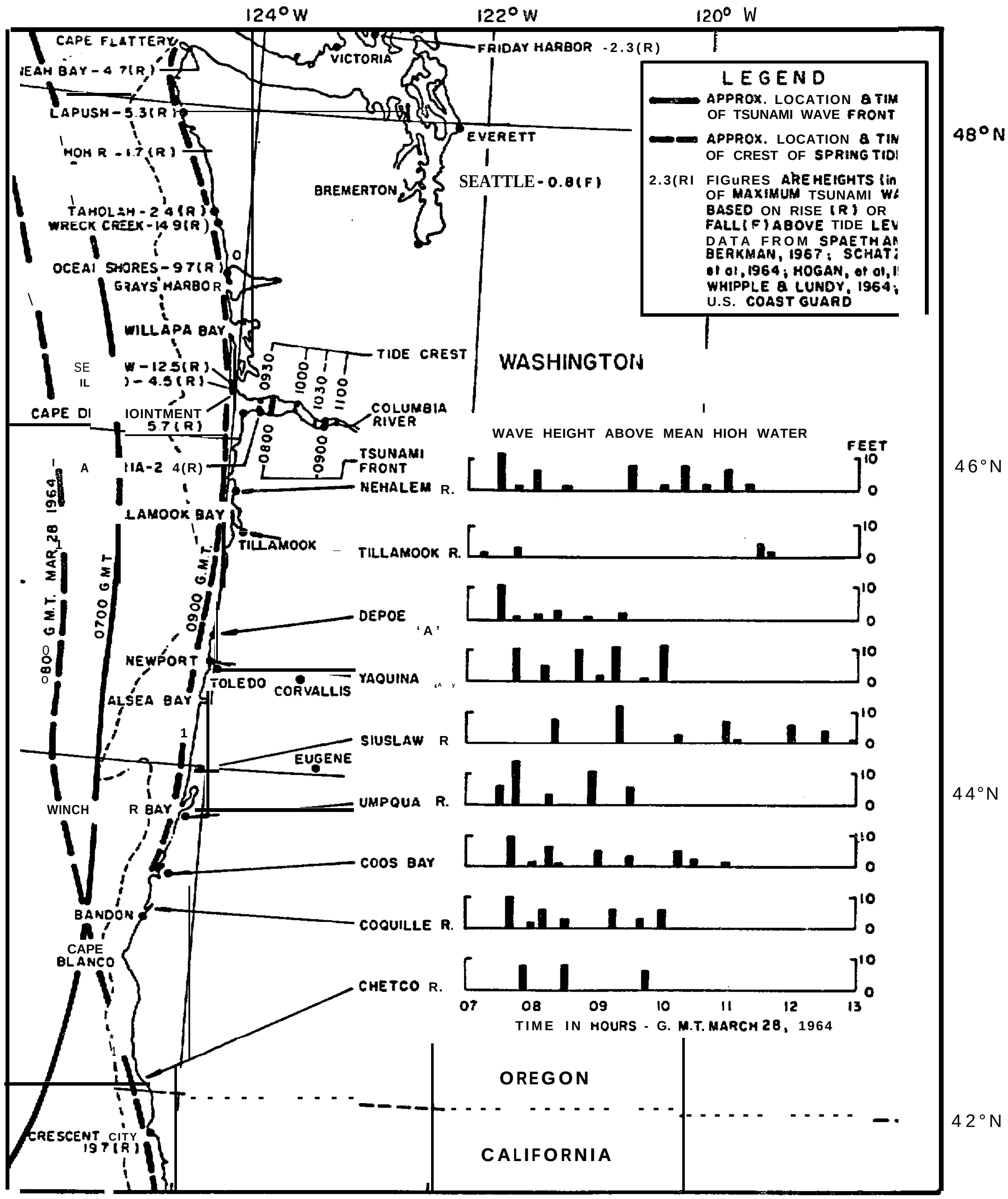
The sheltering effects of refraction are evidently less important regionally than the orientation of the primary axis of ground displacement at the source. There have been four great tsunamis generated in the Aleutian Trench during this century. However, three of them occurred in the western half of the trench and had little effect on the Pacific Northwest coast. Only the 1964 Alaskan tsunami occurred in the eastern half of the trench and this was the most damaging, in spite of any refraction effects.

In conclusion, the eastern Aleutian Trench, because of its orientation, is more likely to generate a large tsunami heading toward the Pacific Northwest coast than is the eastern Aleutian Trench.

Tsunamigenic earthquakes also create very low frequency, high amplitude, acoustic effects whose pressure changes alter the ionization in the ionosphere (the ionized portion of the upper atmosphere that refracts radio signals up to about 30 MHz). This causes changes in refracted signals that can be detected on radio receivers. Dr. Katzutoshi Najita of the University of Hawaii is evaluting the usefulness of this effect in providing earlier warnings of tsunamis for the Hawaii-based Pacific Tsunami Warning System (Sea Technology, 1976).

Figure 111-60

Record of Wave Heights at Coastal Stations
Due to the 1964 Alaskan Earthquake



§Wilson and Torum, 1968.

b. Chemical Oceanography. Chemical oceanography is the study of the chemical components of sea water and the processes that alter or maintain their distribution.

i. Dissolved Oxygen Concentration. Oxygen is a product of plant photosynthesis, that in turn is used by plants and animals in their metabolic processes. The dissolved oxygen *content* of the ocean is determined mostly by these *in situ* processes and by exchange with the overlying atmosphere, a boundary process. The distribution of oxygen within the ocean is controlled by these processes, by the mixing of different water masses, and by advection.

The State of Washington in its Administrative Code of 1973 has adopted the following minimum dissolved oxygen limits in establishing water quality standards for management purposes:

	Class AA	Class A	Class B
Dissolved Oxygen shall exceed	7.0 mg/l	6.0 mg/1	S.0 mg/1

The California State Water Resources Control Board gives a dissolved oxygen value of not less than 5 mg/1 as one of the criteria for the water quality of water used for the propagation of fish. This is not meant to say that fish are not found or cannot survive in waters with a concentration of dissolved oxygen less than 5 mg/l. Also, this classification should not be construed as indicative of man induced deterioriation, but rather the capability of the waters to absorb certain oxygen demanding wastes and still support life.

Oxygen is reported as milligram atoms/liter (mg.at./l), milligrams/liter (mg/l) or milliliters/liter (ml/l). Conversion factors are as follows:

1 ml/1 = 0.70 mg/l
1 ml/1 = 11.2 mg.at./l
1 mg/1 = 16 mg.at./l

Dissolved oxygen concentrations may be expressed in terms of percent saturation, the ratio of the observed concentration to the equilibrium volubility at the sea surface. The surface equilibrium solubility is mainly a function of salinity and temperature. Because of biological activity, saturation values in excess of 100% can occur near the surface during phytoplankton blooms.

Figures 111-61 through 111-63 present the seasonal average oxygen distribution at O, 50, and 200 m in ml/l. The oxygen data are from studies made during 1961-63 by the University of Washington. Although real oxygen values were used in deriving these figures, it must be emphasized that they represent averaged values and are conceptual in nature. The average year-round oxygen distribution at 1,000 meters was presented in Figure 111-18. An oxygen minimum of about 0.25 ml/1 occurs between 700 and 900 m in this part of the Pacific (Stefansson and Richards, 1964). Below this depth, concentrations with values of about 3 ml/1 have been found between about 3,000 and 4,000 m.

Figure 111-61

Typical Seasonal Oxygen Distribution at 0 Meters[9]

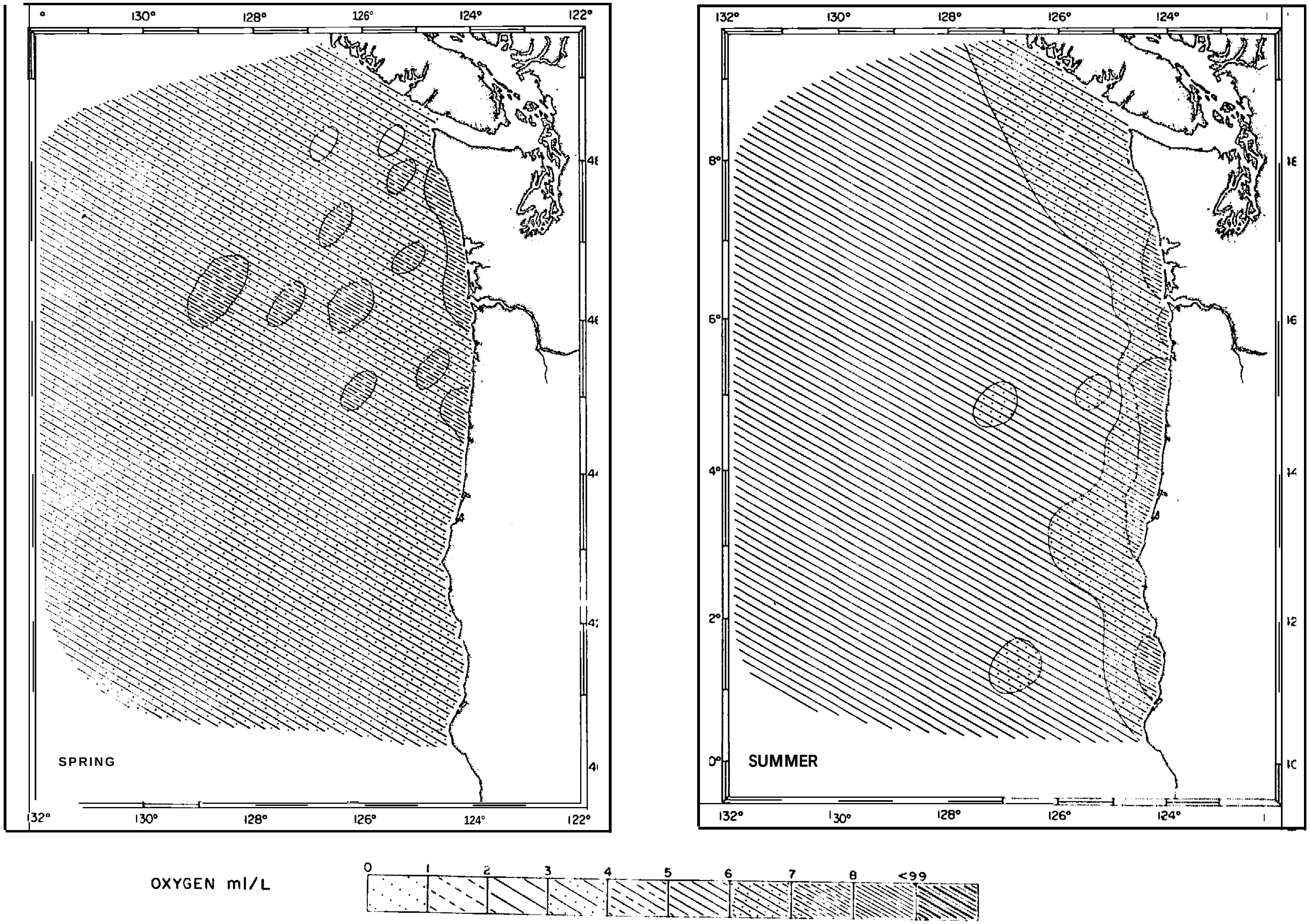
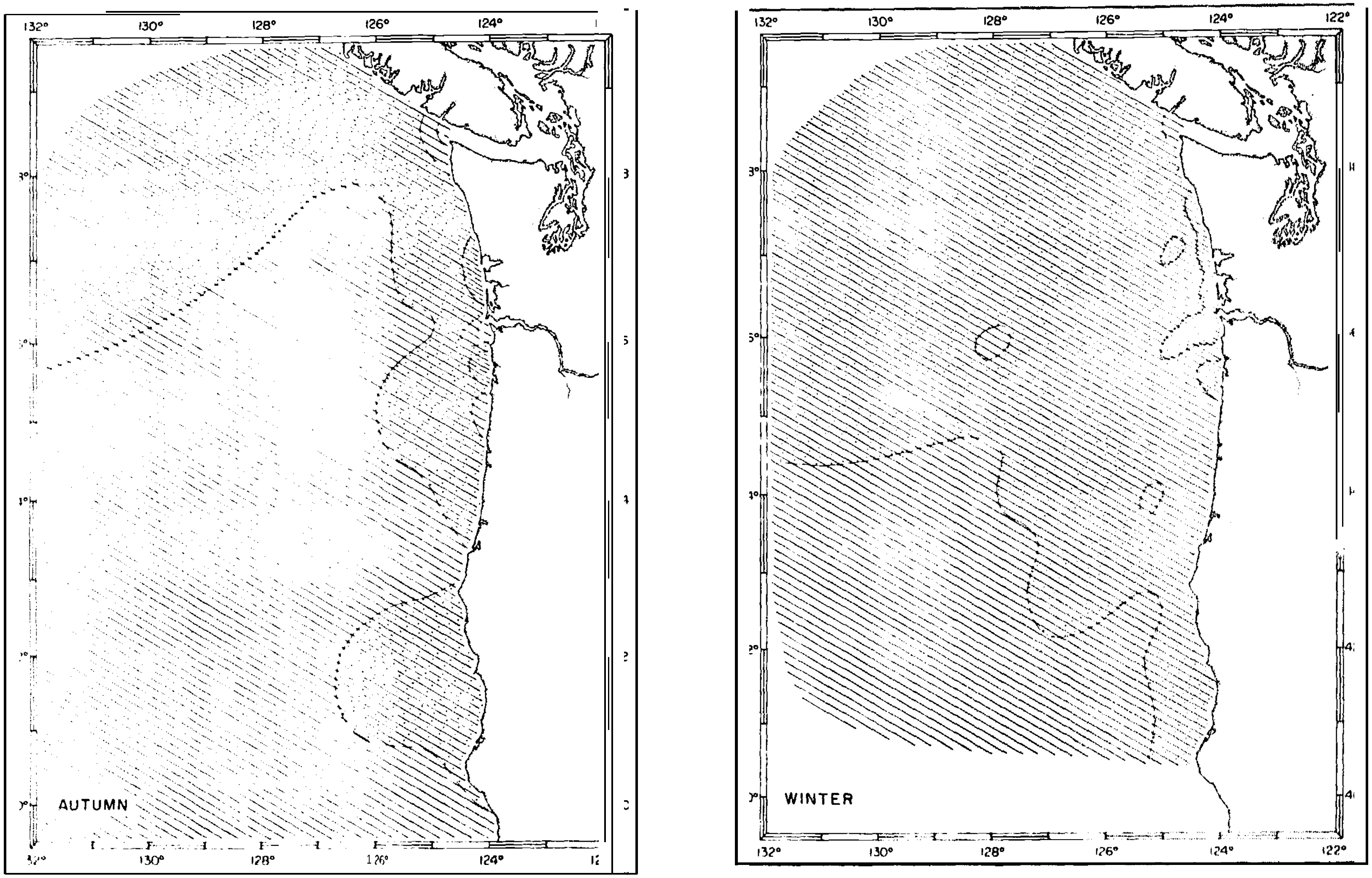


Figure 111-61 (cont.)



§McGary, 1971.

Figure III-62

Typical Seasonal Oxygen Distribution at 50 Meters[5]

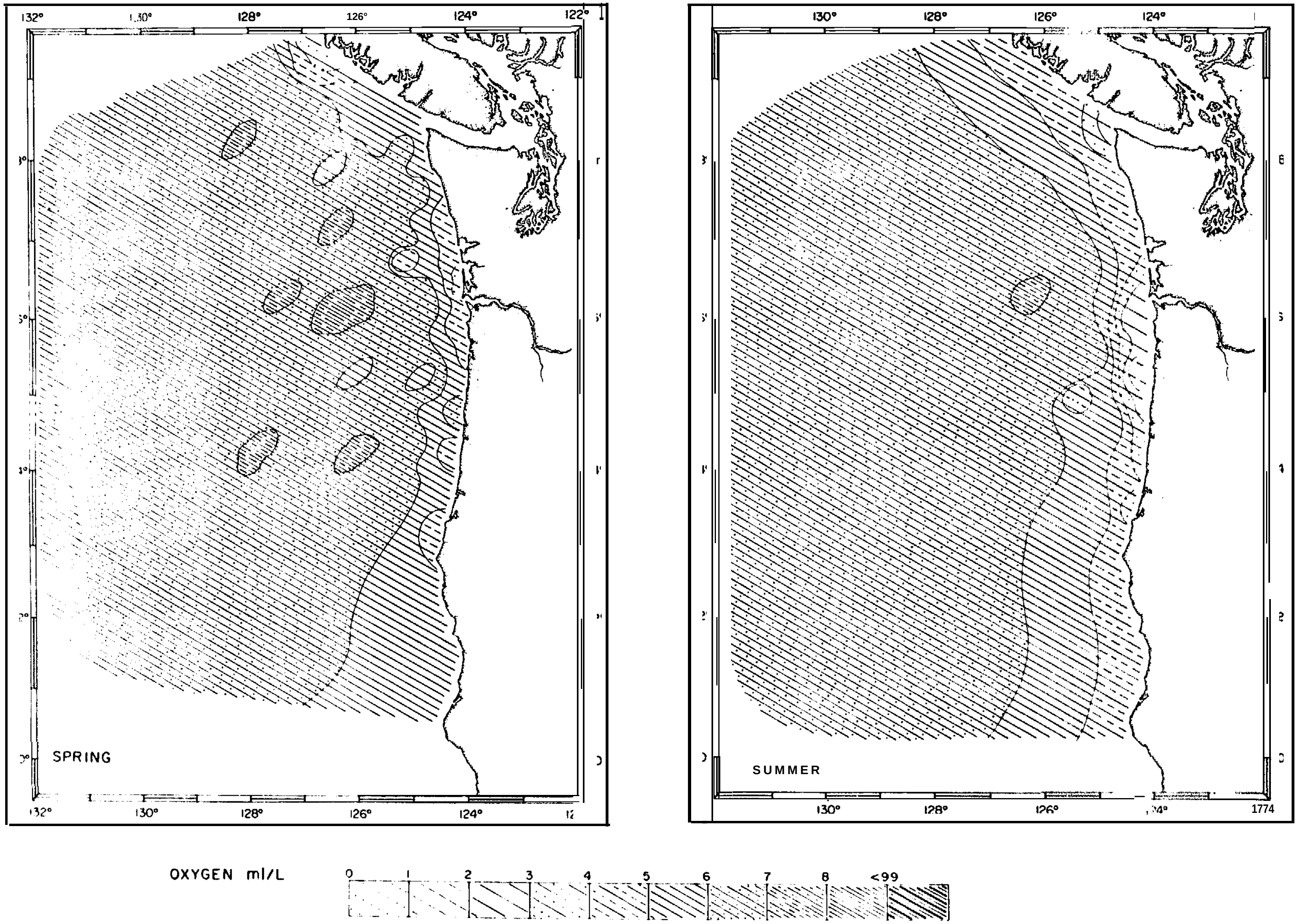
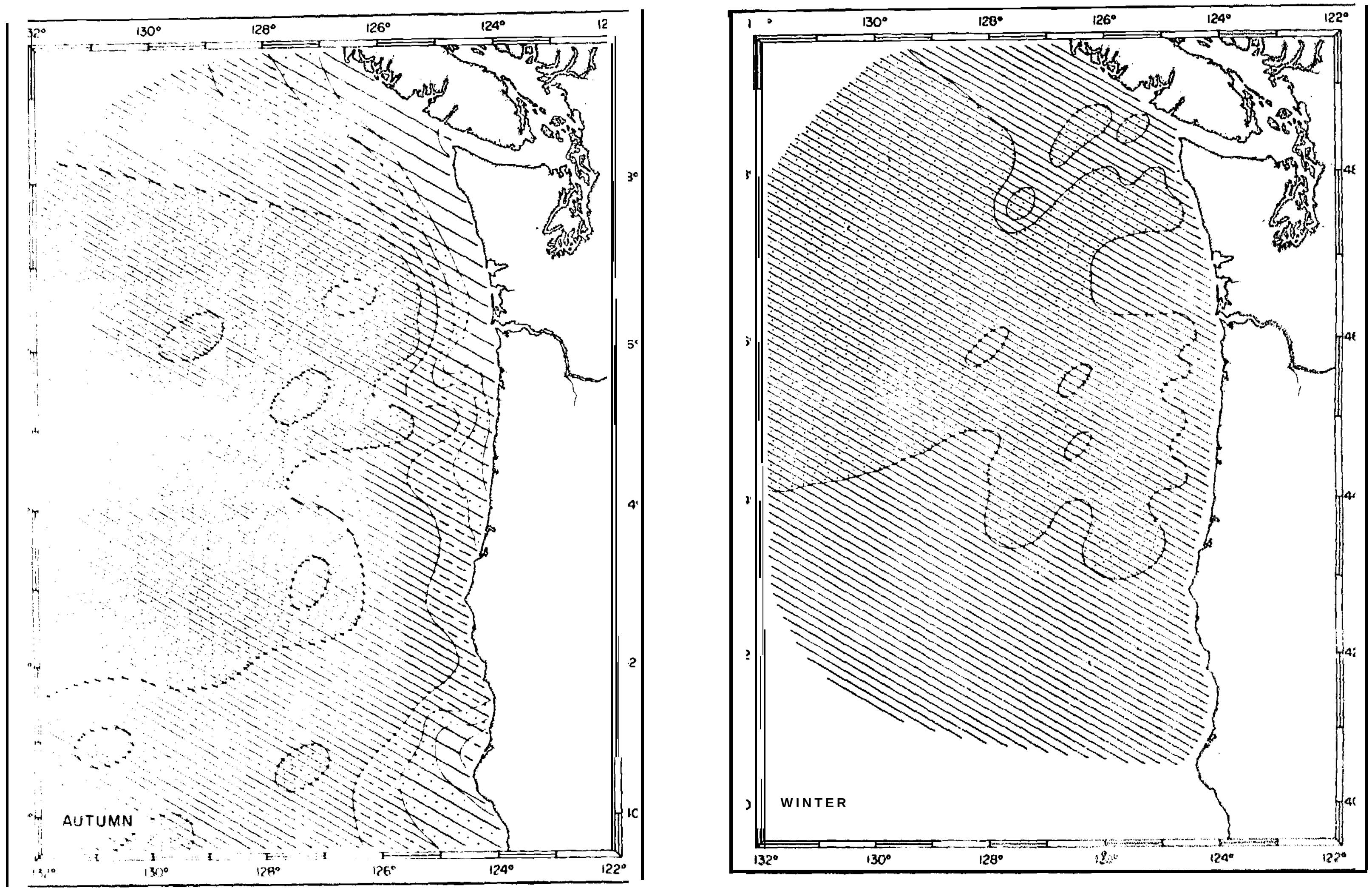


Figure 111-62 (cont.)



§McGary, 1971.

Figure III-63

Typical Seasonal Oxygen Distribution at 200 Meters[§]

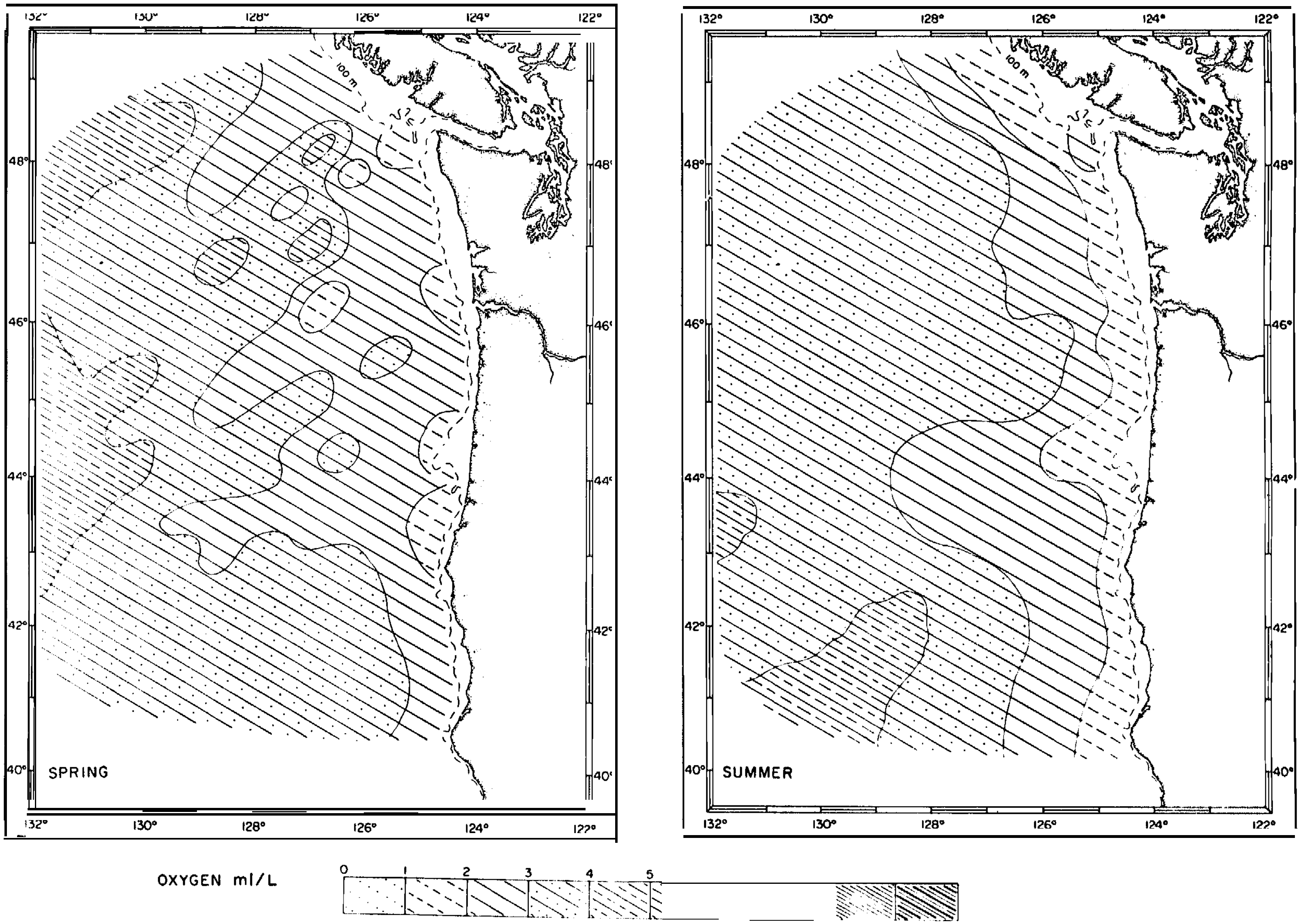
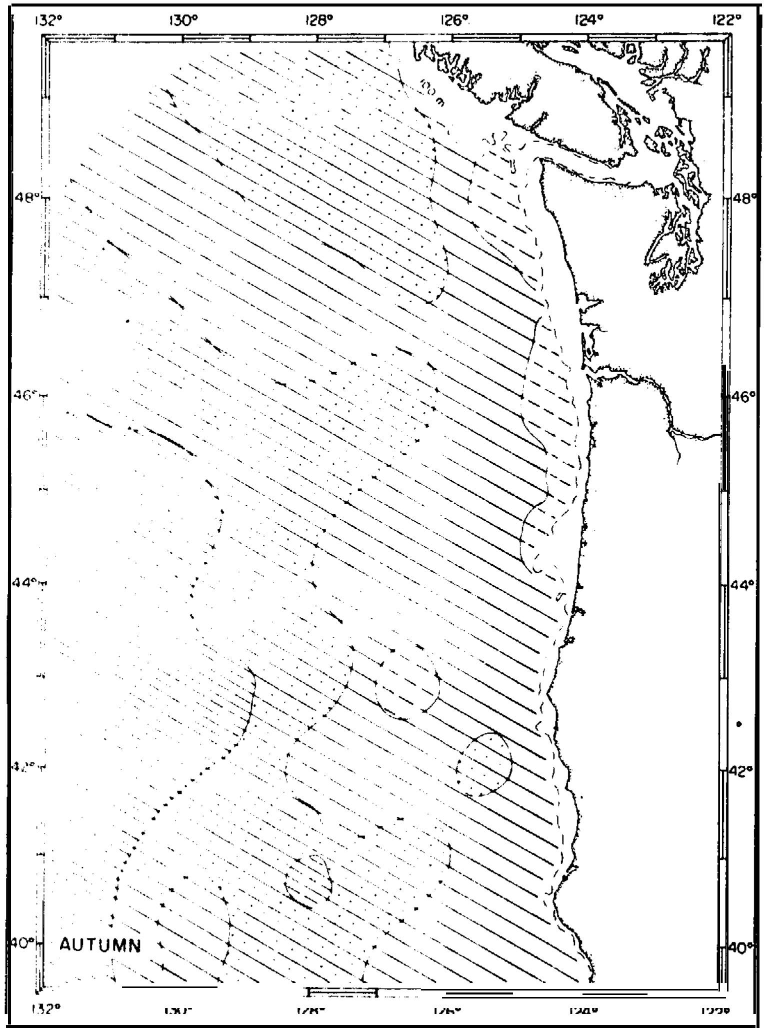
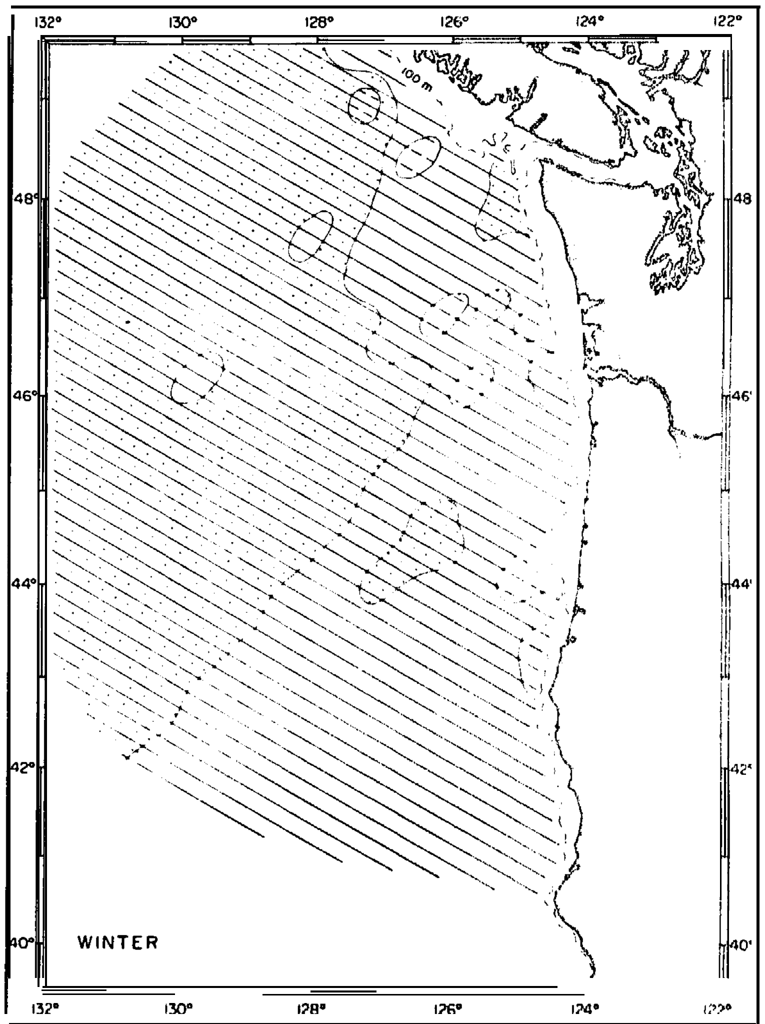


Figure III-63 (cont.)





§McGary, 1971.

The effects of winds and waves produce significant seasonal changes in surface and nearsurface oxygen concentrations. Wind driven coastal upwelling brings colder, nutrient-rich, but oxygen-depleted water close *to* the surface in the summer. In the uppermost layers (the photic zone) the combination of the nutrients supplied by the upwelling and the relatively high light levels promotes rapid phyto-plankton growth. This adds considerable quantities of oxygen to these layers, thereby obscuring the effects of upwelling. At SO m (Figure III-62), however, oxygen concentrations are relatively low during the summer. During the winter, the stronger winds and resultant waves break up the surface layering and increase the effective surface area for air-water boundary processes.

The nearshore dissolved oxygen distribution was evaluated in the Oregon State University report (1971) using data obtained from NODC, OSU data reports and the California Water Quality Control Board. The data were divided geographically into 5 sections that covered most of the nearshore areas off Washington and Oregon. Nutrient (phosphate, nitrate, and silicate) and pH data were also evaluated. Monthly means for O, 10, 20, 30 and 50 m were obtained and graphed along with ex-treme values. No apparently significant latitudinal variations within the area were noted. Figure III-64 presents 02, nutrient and pH values for O, 20, and 50 m, for the nearshore coastal area between Newport, Oregon and the Columbia River. The following observations are taken from the OSU report (1971).

1. Average surface values are higher than 20 m values throughout the year.

2. The highest and lowest surface 0_2 values are found in summer months: June, July and August. This is probably due *to* the competing influences of photosynthetic production and up-welling.

3. The averaged gradient between the surface and 20 m is steeper in the summer months. Surface values are not lowered as much as 20 m values.

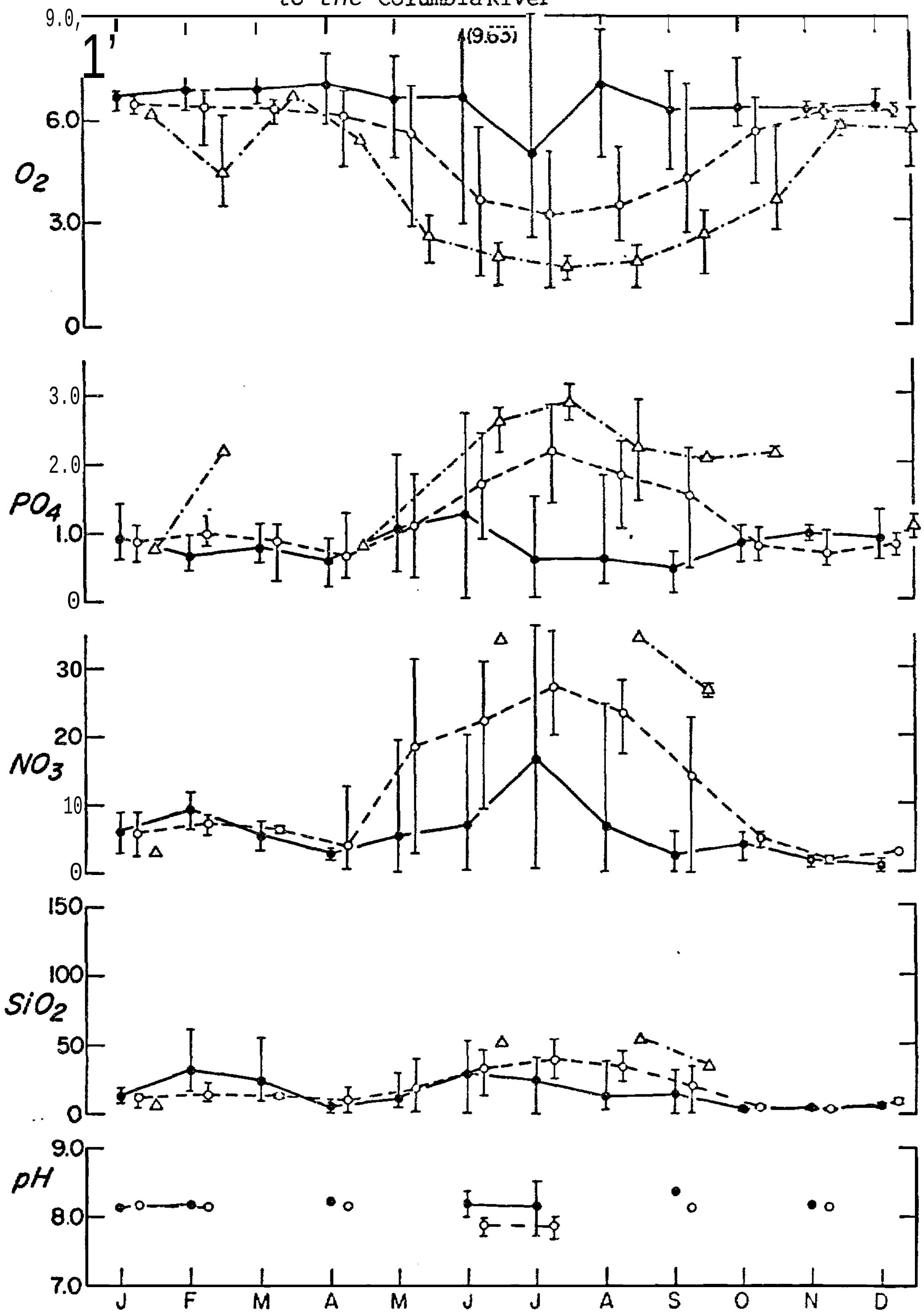
4. Surface 02 values are about 6.3 to 7.0 ml/1 unless affected by strong upwelling.

As can be seen in Figure III-64, an inverse relationship exists between the dissolved oxygen concentration and the nutrient concentra-tions. Figure III-65 presents the relationship between oxygen and phosphate concentrations from the surface to 1,000 m as determined for a region off the shelf of northern Oregon (Pytkowicz, 1964). Figure III-65 also presents a subsurface oxygen maximum that forms in the summer. Pytkowicz (1964) postulates that this is because more of the excess oxygen produced by phytoplankton is lost above this layer due to higher respiration and exchange with the atmosphere.

The subsurface oxygen maximum appears over large parts of the north Pacific in summer at a depth corresponding to the deeper part of the winter-mixed layer (Kitamura, 1958, and Ried, 1962). Stefannson and Richards (1964) conclude that processes taking place in spring and summer along the Washington and Oregon coasts have an effect on the

Figure III-64

Northwest Coastal Data From Newport, Oregon, to the Columbia River[§†]

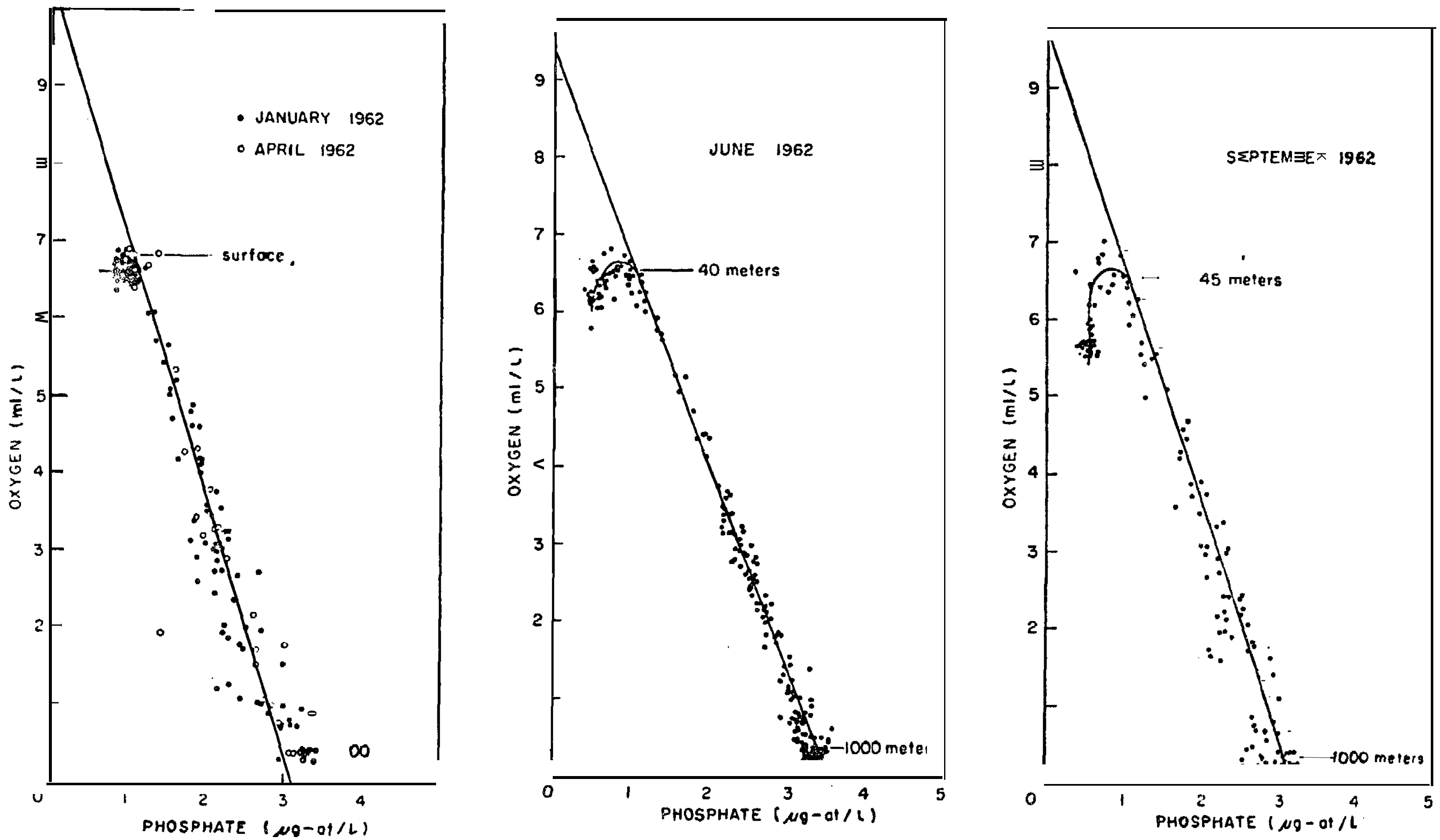


§Oregon State University, 1971.

†Oxygen is in ml/l(N.T.P.). Nutrients are in μg-at/l.

Figure III-65

Oxygen and Inorganic Phosphate Concentrations on the Region 44-46°N and 125-129°W§



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§ from Pytkowicz, 1964.

concentrations in this subsurface maximum to positions at least 400-500 km from the shore. Upwelled water close to the shore is denser than the offshore surface water. As the upwelled water moves offshore it is enriched rapidly with oxygen by photosynthesis and mixing with water richer in oxygen. Stefansson and Richards concluded that this offshore movement and sinking along sigma-t surfaces of the upwelled water, which was photosynthetically enriched in oxygen in the near-shore area, contributes largely to the formation of the subsurface oxygen maxima. They further concluded that whether or not the oxygen produced by photosynthesis escapes fairly quickly to the atmosphere depends on the balance of the rates of upwelling, photosynthesis, and the subsequent removal of these waters offshore and their sinking below the immediate surface layer.

ii. Nutrients. Nutrients can be defined as the substances that are needed for life. In the marine ecosystem, phytoplankton constitute the primary producers and as such depend on an adequate supply of light energy and a number of essential inorganic nutrients. The essential nutrients that are most in demand are inorganic carbon, inorganic combined nitrogen, inorganic phosphorus and dissolved silicon (silicate). Inorganic carbon is plentiful in the ocean, but the three others are often reduced to growth limiting concentrations.

The common inorganic nitrogenous nutrients are nitrate, nitrite, and ammonia. In natural sea water, nitrate is the dominant form. These nitrogen compounds frequently may be the most limiting substances for marine phytoplankton growth. Dissolved silicon is utilized almost exclusively by diatoms. In relation to the needs of phytoplankton, phosphates (inorganic phosphorus) appear *to* be relatively abundant.

The major natural processes that provide the sunlit upper layers with these limiting nutrients are upwelling, mixing and advection. Processes such as the discharge from rivers, inputs from the atmosphere, nitrogen fixation, denitrification and sedimentation exert a considerable influence over geologic time, but have only a small effect on the yearly supply of nutrients to the photic zone. Industrial and domestic sewerage contribute nutrients to some of the rivers and estuaries and therefore supply nutrients to the open ocean. Locally, these inputs may have considerable effects, but their effect on the open ocean is small. Respiration and excretion allow nutrients to be recycled in the photic zone, but there is a net loss to depths with insufficient light to support phytoplankton growth. This loss is compensated by the supply processes mentioned above.

Biological processes in the ocean tend to alter nitrogen and phosphorus concentrations in the ratio AN/AO = 16.1 (by atoms) (Richards, 1965) and, in the open ocean, inorganic nitrogen and total phosphorus are generally found in similar but somewhat smaller ratios. This relationship is not nearly so constant in nearshore waters, which are affected by generally higher rates of organic production and subject to influences from land-based nutrient sources. The ratio of preformed N to preformed P [inorganic nutrients that were present as such in the water at the time it sank from the surface) is about 7:1 for stations approximately 300 km off the Oregon coast (not influenced directly by either the Columbia River plume or coastal upwelling) (Park, 1967).

Mean nitrate, phosphate, and silicate concentrations in microgram atoms/liter (μg-at/l) are given in Figure III-64 for the nearshore (within 18.5 km or 10 nautical miles) area off northern Oregon. General observations from the Oregon State University report (1971) concerning the nearshore nutrients for Oregon and Washington are:

1. The highest and lowest surface nutrient values are found in the summer months. Dissolved silicon [silicate] values are strongly affected by runoff and may be higher at other times of the year. Primary production and upwelling are probable causes of the wide variations in the surface values.

2. The averaged gradient between the surface and 20 m is steeper in the summer months.

3. Exclusive of upwelling, representative surface nutrient values are:

    $PO_4^{\equiv}$: 0.7 μg-at./l
    NO_3^-: 5 μg-at./l
    $Si(OH)_4$: 10 μg-at./l

Stefansson and Richards (1964) evaluated the distribution of nutrients, temperature, sigma-t, oxygen concentration, and apparent oxygen production (AOP) for the Washington and Oregon coasts. Figure 111-66 presents the mean seasonal variations of these properties in the upper 100 m for the offshore region (beyond the shelf and slope) for the period January 1961 to March 1962. The subsurface oxygen maximum that occurs in summer is evident in the offshore region. Figure III-67 presents mean seasonal variations of properties in the upper 30 m in the nearshore region off central Washington, for the period January 1961 to June 1962. No subsurface oxygen maximum exists in the nearshore zone.

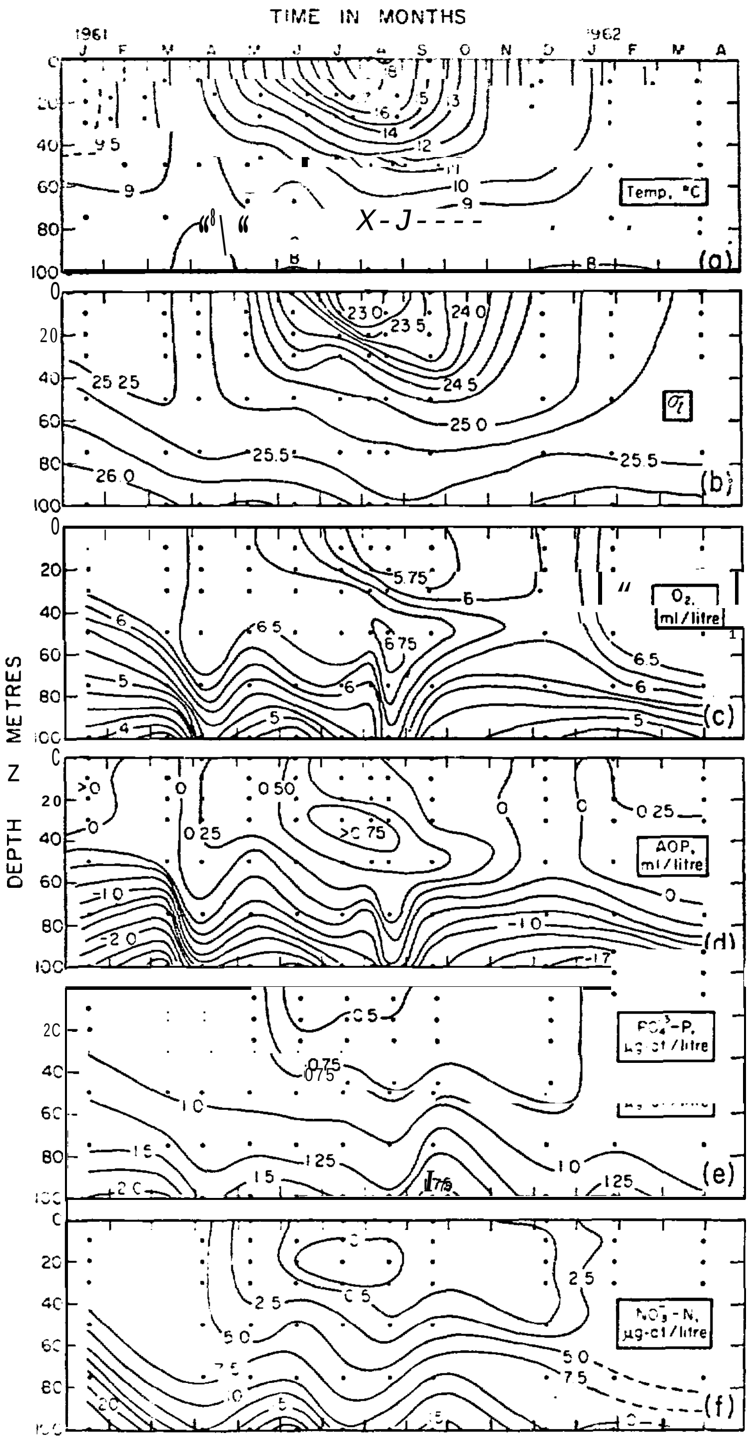
From Figures III-66 and III-67, the following observations can be made: In the spring, nutrients are used up rapidly in both areas. In the offshore area, near-surface phosphate concentrations decreased from about 0.90 μg-at/l in April to less than 0.5 μg-at/l in late May, and nitrates decreased from 5-6 μg-at/l to almost undetectable values. The low values persisted through September but the concentrations increased in the late fall and winter due to vertical mixing, returning to the levels observed offshore in May. From late May on, the surface layers in the nearshore area are replenished with nutrients by upwelling, and nutrient concentrations approach their winter values in late summer. In 1961, the spring depletion in the nearshore area occurred only during a short intermediate period preceding the onset of the most active upwelling.

Figure III-67 is representative of the nearshore region off central Washington and is not completely representative of the entire region. As noted earlier, upwelling is more intense off central and southern Oregon so nutrient concentrations or biological processes may be higher in these regions.

The Columbia plume stays nearshore and to the north in the winter

Figure 111-66

Mean Seasonal Variations of Properties in the Upper 100m Inside the Area Between 44°30'-47°30'N Lat. and 126030'- 130°30'W Long., January 1961-March 1962[§†]



(a) Temperature

(b) **Sigma-r**

(c) oxygen **concentration (ml/l)**

(d) AOP (ml, i)

(e) Inorganic **phosphate (µg atom, 1)**

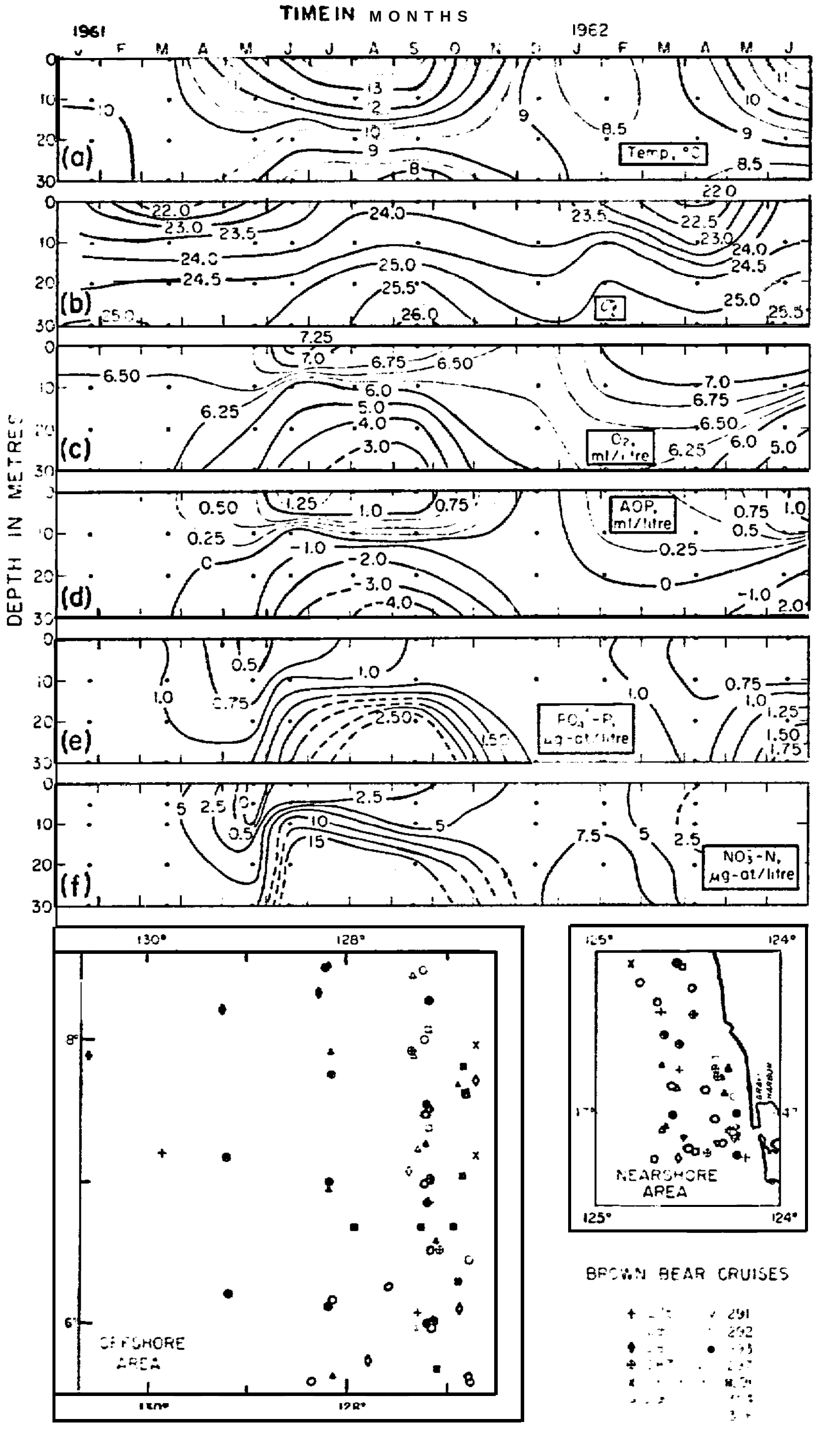
(f) Inorganic nitrate **(µg atom/l)**

[§]Stefansson and Richards, 1964.

[†]For locations of stations, see Figure III-67.

Figure III-67

Mean Seasonal Variations on Properties in the Upper 30m Inside the 150-m Isobath Between 46°50 and 47°40'N Lat., January 1961-June 1962§†



(a) Temperature

(b) Sigma-t

(c) Oxygen concentrations (ml/l)

(d) AOP (ml/l)

(e) Inorganic phosphate (μg atom/l)

(f) Inorganic nitrate (μg atom/l).

§Stefansson and Richards, 1964.

†Maps show locations of stations for which the mean values in Figs. 67 and 68 were computed.

and moves to the southwest during summer. Duxbury (1972) noted that water properties near the mouth of the Columbia River change rapidly with both time and space. He noted that short-term advective processes largely associated with local winds and tides shift the river effluent with respect to both ambient surface water and geographic coordinates. Within hours this can effect local changes in the upper 15 m of the water column comparable in magnitude to seasonal changes.

iii. The Carbonate System and pH. The marine carbonate system is important for a number of reasons. For example, it provides the inorganic carbon needed by phytoplankton; it is intimately involved with the ocean's ability to absorb some of the CO_2 produced by the combustion of fossil fuels; and it exerts an important control on pH. The pH of sea water is altered by reactions occurring in the oceanic carbon dioxide system (Sverdrup, Johnson and Fleming, 1942), such as the biological production and uptake of inorganic carbon. Any changes in the seawater-buffering substances other than carbon dioxide and carbonate also influence the pH (Park, 1968).

Both pH and dissolved oxygen are affected by photosynthesis, biochemical oxidation, and the influence of the atmosphere. Not surprisingly, they exhibit similar distribution patterns. Figure III-68 presents simplified pH-salinity and oxygen-salinity relationships for the water off Newport, Oregon. The surface layers in Figure III-68 represent the Columbia River plume water and very little pH change occurs with changes in salinity. The second type of water is between the top of the pycnocline and 200 m, where the pH drops almost linearly and moderately with an increase in salinity. Upwelling, photosynthesis and aeration may alter the pH-salinity relationships in these layers. The third body of water lies below 200 m, has a pH minimum of about 7.5 at 34.3 o/oo, and is not affected by seasonal changes.

Some pertinent features of the CO_2 distribution off Oregon and Washington include:

1. The concentration of dissolved CO_2 in sea water in equilibrium with the atmosphere in nearshore areas is about 320 ppm (ppm = 10^{-6} atmospheres partial pressure) (Park, *et al.*, 1969).

2. The concentration of dissolved CO_2 at a depth of 2.5 m in the Columbia River in December 1968 ranged from about 600 to 1000 ppm (Park, *et aZ.*, 1969).

3. Sea water values in nearshore areas were as high as 525 ppm and as low as 155 ppm (Gordon and Park, 1968).

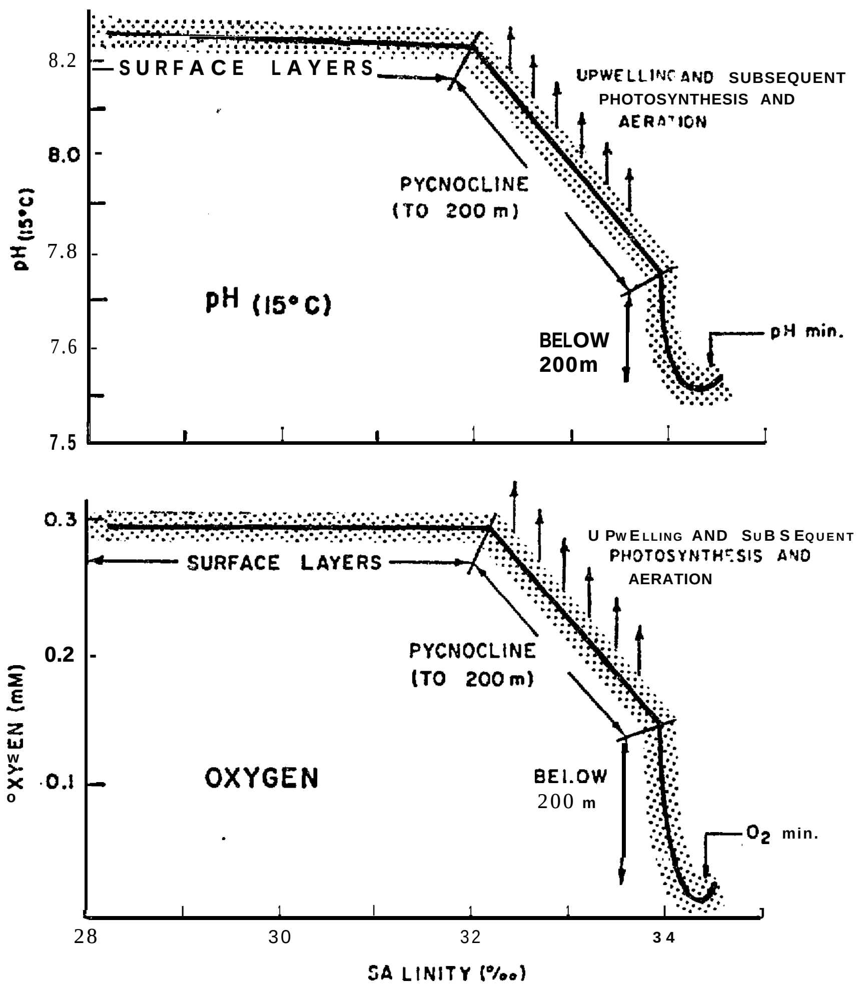
The specific alkalinity has been used by Park (1966) in identifying the Columbia River plume. In oxygenated sea water-the alkalinity is approximately equal to the sum of

$$2CO_3^{=} + HCO_3^{-} + OH^{-} - H^{+} + B(OH_4)_1^{-}$$

in milliequivelents. The specific alkalinity, a ratio between alkalinity and salinity, is not affected by rainwater dilution at sea and allows for more precisely delineating the extent of the plume at times when high rainfall lowers the surface water salinity. Park concludes that a specific alkalinity of 0.126 may be taken as a reasonable lower

Figure III-68

Simplified pH-Salinity and Oxygen-Salinity Relationships
Off Newport Oregon[§†]



§Park, 1968.

†The striking resemblance between pH and oxygen distributions is due to the biochemical oxidation in the ocean. Oxygen concentration is in mM (millimole/litre).

limit for the specific alkalinity of the plume, and closely corresponds to the 32.0 o/oo salinity isocline.

iv. Radionuclides. The Pacific Northwest coastal region is unique from a radiochemical viewpoint, due to the operation of plutonium producing reactors at Hanford, Washington from 1944 to 1971 (Figure 111-69). An estimated 95% of all low-level radioactive wastes released in the natural waters of this country went into the Columbia River and an estimated 1 kiloCurie/day of neutron-induced radionuclides entered the Pacific Ocean prior to the last old-design reactor shutdown.

Other sources of radionuclides in the marine and estuarine environment include naturally occurring radionuclides and fallout fission products from nuclear weapons tests. As use of nuclear reactors for electric power generation increases, these reactors will also become sources of radionuclides, although not to the extent of the plutonium producing reactors of the past, because of improved design and use of air or secondary coolant systems.

Radionuclides may be taken up by organisms and transported by biological pathways. They may be deposited in the sediments, where they may be transported in the bedload or taken up by benthic organisms. Radionuclides will also be dispersed throughout the water column and transported by currents. The presence and history of radionuclides from the Hanford reactors serve as valuable tags for studies of the dispersion of the river water and of the mechanisms and rate through which complex physical, chemical, and biological processes proceed.

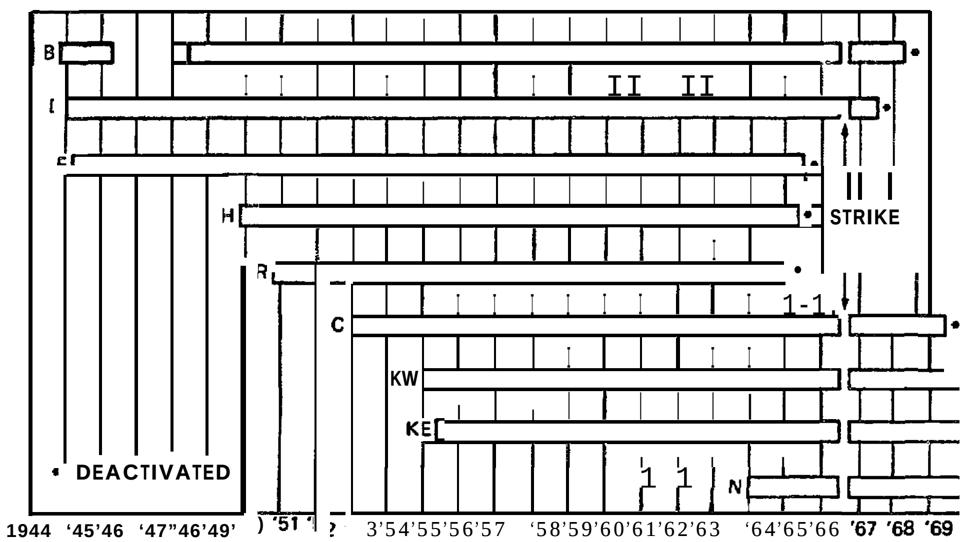
Extensive studies of the Columbia River, its estuary and the adjacent North Pacific have been funded by the U.S. Atomic Energy Commission (now part of the U.S. Energy Research and Development Administration). Various types of research dealing with radioecological problems have been conducted from 1943 to the present. Gross, Barnes and Riel (1965) measured the radioactivity of the Columbia River plume at sea.

Perhaps the greatest combined efforts occurred in the early to mid 1960's. The book The Columbia River Estuary and Adjacent Ocean Waters (Pruter and Alverson, 1972) presented thirty-three studies carried out by the University of Washington, Oregon State University, Battelle Memorial Institute, and the U.S. National Marine Fisheries Service. Most of the studies were interpretations and analyses of the data gathered in the 1960's. Each chapter includes extensive bibliographies, in many cases referencing other technical reports, theses, and contributions pertaining to the area. Analyses of samples and reduction of data obtained during the 1960's is still continuing. Recently completed research, on-going research, recent pertinent theses and papers concerning ecological and radioecological studies in the Columbia River estuary and adjacent Pacific Ocean are reported by Holton, Pearcy and Cutshall (1976).

The Oregon State University report (1971) on the oceanography of the nearshore coastal waters of the Pacific Northwest relating to possible pollution includes a 22 page discussion summarizing the knowledge of radionuclides for the study area. Significant radio-

Figure III-69

Operating History of Plutonium-Producing Reactors at Hanford, Washington[5]



[5]From Pruter and Alverson, 1972.

nuclides are discussed on the basis of their origin. The following summary statements are extracted from the report:

1. Coastal waters of the Pacific Northwest contain naturally-occurring radionuclides, fission fragments from nuclear test fallout, neutron-induced radionuclides from nuclear weapons tests, and radionuclides from the plutonium production reactors at Hanford, Washington.

2. Man has no control over the primordial or cosmic ray-produced radionuclides in the ocean. However, these radionuclides occur in very low concentration except for potassium-40, which is present in all sea water, living matter, and sediments.

3. Radioactivity from Hanford has declined *due* to serial shutdown of the plutonium production reactors.

4. Fallout radioactivity has dimished since the nuclear ban of 1963. Nevertheless, France and Mainland China continue *to* create radioactive fallout through atmospheric weapons tests.

s. Research on the cycling of radionuclides now in the marine ecosystem will aid in understanding the environmental impact of future coastal nuclear facilities.

V. Trace Metals. The term trace metals is applied to all elements found in trace quantities (less than 1 mg/l according to the OSU report, 1971) that show the characteristic chemical behavior of metals to a greater or lesser degree. Because of the small concentrations involved, often near the limit of detection by analytical techniques, there is not a great deal of specific information on trace metals.

The Oregon State University report (1971) presents a detailed review of trace metals in the marine environment and includes tables on the following:

1. Predominant physico-chemical forms of 54 trace elements in sea water, with references for each.

2. Direct comparisons of nearshore and oceanic values for 9 trace metals with references.

3. Probable values of 54 trace metals in oceanic and nearshore waters with references.

4. Concentration by plankton for 21 trace metals, with references.

5. Comparison of 26 trace metal concentrations in rivers and in sea water, with references.

6. Responses of various marine organisms of the Pacific Northwest to various concentrations of trace metals with references and correlation *to* other factors.

e

The tables are lengthy and appear comprehensive, but are not duplicated here as they are based on very limited world-wide data. The Oregon State University report in summary states, "Very little is known about nearshore trace metal concentrations on the open coast of the Pacific Northwest. Inference from other 'similar' locales is not justified at the present state of knowledge about factors which control trace metal concentrations." The Southern California Coastal Water Research Project (1975) worked up tables presenting concentrations of eight trace metals causing sublethal responses in marine organisms, and what the responses were.

The metals mercury (Hg), copper (Cu), lead (Pb), and zinc (Zn) were discussed in greater detail in the Oregon State report because of their high potential for pollution of nearshore waters of the Pacific Northwest (Oregon State University, 1971). The following is summarized from the Oregon State University report (1971).

Mercury has great pollution potential. Mercury concentrations in sea water may be around 0.1 to 0.3 µg/l. The behavior of mercury in the natural environment is not well understood. Certain conditions favor the production of methyl-mercury in sediments -- marine organisms concentrate mercury and methyl-mercury is even more highly concentrated. The toxicity of mercury to marine organisms is high and temperature may have an effect on the toxicity.

Copper is common in many industrial effluents, particularly those of heavy industry. The processes by which the environment deals with copper are complicated by organic involvement. Some organisms use and require copper (e.g., crab blood). Copper has a high toxicity to most marine organisms. Sublethal copper pollution can make oysters unfit for human consumption, and may slow growth of other marine organisms.

Lead concentrations in coastal waters of the Pacific Northwest is unknown. Rivers in the area have around 4 µg/l. Man has significantly changed the lead content of surface sea waters. Sublethal effects are probably more important than acute toxicities. Lead concentrations in mussels taken from intertidal areas along the Washington coast had concentrations ranging from 0.07 µg/g (dry weight) to 2.11 µg/g (dry weight) (Schell and Barnes, 1974).

vi. Chlorinated Hydrocarbons. DDT is a chlorinated hydrocarbon pesticide that was widely used for 25 years in the United States before its prohibition in the early 19701s. DDT is still manufactured in the U.S. for foreign usage. It is no longer legally discharged into municipal wastewater systems. Small amounts of DDT and its degradation products still reach the sea from old deposits in sewer lines and global atmospheric transport.

The PCB's (polychlorinated biphenyls) primarily used in industry are chlorinated hydrocarbons with physical and chemical properties similar to DDT. PCB's are not deliberately released into the environment.

The residence time for DDT in the water is difficult to determine (Peterle, 1969). Data on the rates of output (breakdown into nontoxic substances and loss of sediments and other sinks) and the size of reservoirs of DDT in the environment are insufficient to establish the existence of a steady state condition. The pesticide residue levels in marine organisms in the Pacific Northwest are generally low. Acute toxicities of pesticides to marine organisms are probably less of a concern than sublethal effects. Residues may be important to higher predators such as sea birds and man.

Williams and Robertson (1975) have reported PCB values in the subsurface water in the outer California Current. Their values, including filtrate and filtered fractions, were 2.5 x 10^{-12} g/g.

Acute toxicity of DDT and PCB's is species-dependent and depends *on* such parameters as temperature and dissolved oxygen content. The chronic effects of both are of major ecological concern. Table 111-16 presents laboratory determined sublethal effects of DDT and PCB's on marine animals.

A "Mussel Watch" program will examine mussels from coastal sites for PCB and other chlorinated hydrocarbons, as well as for plutonium isotopes, petroleum compounds, and selected metals (Goldberg, 1975). The program is intended *to* provide a start at finding out how levels of chlorobiphenyls change in a marine environment in response to changes in production and use practices.

Risebrough (1976) summarized recent studies of PCB transports to marine environments and noted that data on PCB levels in seawater are as yet unsatisfactory or too sparse to permit a reliable estimate of the amounts of PCB that have so far entered the oceans. Formulation of a global mass balance equation for the major kinds of PCB compounds would be useful in predicting future contamination levels.

vii. Suspended Particulate. Suspended particulate in the water column may be divided into two broad categories, lithogenous and biogenous. Lithogenous particles are inorganic, generally crystalline, ultimately derived from chemical decomposition and mechanical disintegration of rocks. Biogenous particles are formed by organisms and may be either living (phytoplankton and zooplankton) or nonliving matter (Parsons, 1963). Biogenous matter in the Pacific Northwest may be further subdivided into riverborne, (i.e., that portion contributed directly by the river) and ambient, (i.e., that portion in the oceanic, transition, and estuarine areas) (Conomos and Gross, 1972).

An understanding of particulate touches on all four of the major divisions of oceanography. Physical processes affect their distribution. This distribution may be measured quantitatively by discrete sampling and filtration, or qualitatively by turbidity measurements. Biological processes contribute to the biogenous fraction of the suspended particulate. The transport and ultimate settling of suspended particulate may be thought of as a geological process. The chemical composition of the particulate may play an important role in the distribution of chemical parameters in the ocean. Specifically, nutrient distribution is affected by settling of biogenous wastes; trace metals or hydrocarbons may be absorbed onto the surface of suspended particulate and transported to the sediments by deposition; radio-

Table 111-16

Seawater Concentrations of Two Chlorinated Hydrocarbons Causing Sublethal Responses in Marine Organisms in the Laboratory[§][†]

Response[*]	Minimum Concentration (ppb)	Approximate Times Greater than Background	Reference
PCB's (0.001 ppb)			
Phytoplankton			
o Inhibited growth.	0.1	100	Fisher and Wurster, 1973,
Invertebrates			
o Decreased shell growth.	1.0	1,000	Duke, *et al.*, 1970.
o Decreased mating success.	10,000	10,000,000	Wildish, 1972.
o Caused brachial necrosis.	1.0	1,000	Wildish, 1970.
o Caused hepatopancreatic cellular alterations.	3.0	3,000	Couch and Nimmo, 1974.
Fish			
o Inhibited embryonic development.	10.0	10,000	Schimmel, *et al.*, 1974.
o Inhibited enzyme activity.	75,000	75,000,000	Kinter, *et al.*, 1972.
o Inhibited osmoregulation.	75,000	75,000,000	Kinter, *et al.*, 1972.
Birds			
o Caused hypothyroidism.	50,000	50,000,000	Jeffries and Parslow, 1973.
DDT (0.001 ppb)			
Phytoplankton			
o Inhibited growth.	10	10,000	Mosser, et aZ., 1972.
Invertebrates			
o Decreased shell deposition and growth.	1.0	1,000	Butler, 1966.
0 Caused abnormal sensory responses (tactile and chemoreceptor).	0.1	100	Mieth-Avcin, 1974.
o Inhibited exzyme activity.	0.05	50	Nimmo and Blackman, 1972.

Table III-16 (cont.)

Response[§]	Minimum Concentration (ppb)	Approximate Times Greater than Background	Reference
DDT (0.001 ppb) (cont.)			
Fish			
o Inhibited exzyme activity.	7,000	7,000,000	Kinter, *et al.*, 1972.
o Inhibited osmoregulation.	5,000	5,000,000	Janiki and Kinter, 1971.
o Retarded fin regeneration.	10	10,000	Weis and Weis, 1975.
Bird			
o Caused hypothyroidism.	3,000	3,000,000	Jeffries and Parslow, 1973.

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§ Southern California Coastal Water Research Project, 1975.

† Most tests performed at normal temperature and salinity.

‡ Number in parentheses is the estimated background concentration in seawater in part per billion (10^{-6} g/l); 0.001 ppb is 1 part per trillion.

nuclides may appear in the lithogenous or biogenous particulate and be removed to the sediments, etc. Municipal and industrial wastes may increase the suspended particulate, thereby increasing turbidity, nutrients, and possibly toxic pollutants as well. Resuspension of sediments by offshore drilling will affect biological productivity locally by reducing light transmission. The lack of knowledge concerning the role of suspended particulate in pollutant transfer and transport is a significant data gap.

Conomos and Gross (1972) discuss the Columbia River-Pacific Ocean suspended particulate matter relations. Table 111-17 presents the typical bulk compositions and particle diameters (in microns) as functions of geographic areas. The area breakdown in the table is river, estuarine, transition, and oceanic. The transition zone is considered to be off the coast but still in the Columbia River plume as indicated by a well-defined halocline. The lithogenous matter dominates in the river and estuarine areas, becoming less important further offshore because of settling. Marine biogenous matter constitutes 70 to 95% of the total suspended particulate in the oceanic area. The particle diameter decreases rapidly from the river to the oceanic, and is a partial function of the stronger, more turbulent currents associated with river and estuarine conditions.

Hobson (1967) measured concentrations of particulate matter, particulate organic carbon, and particulate carbohydrate for an area in the northeast Pacific Ocean (1,000 km west of Oregon and Washington], at depths between the surface and 4,000 m. Below 250 m, concentrations of particulate matter ranged from 30 to 1,000 mg/m^3, particulate organic carbon from 8 to 110 mg/m^3, and particulate carbohydrate from undetectable to 30 mg/m^3. There was more particulate matter in winter than in spring and summer, a temporal variation possibly related to variations in advection. Ratios of particulate organic carbon to particulate matter ranged from 0.12 to 0.70. The fraction of particulate carbohydrate-carbon in the particulate organic carbon was generally in the range of 0.10 to 0.20. Hobson determined that 90% of the mass of the particulate matter obtained ranged between 9 and 44 microns in diameter. (The infiltration technique had a lower particle size limit of about 2 microns). Sinking rates for these particles were calculated *to* be between 0.1 *to* 10 m/day and were slow compared with horizontal speeds.

The character and distribution of suspended particulate on the outer continental shelf are currently being studied by Drs. R. E. Burns and E. T. Baker at the University of Washington.

viii. Other Forms of Man-Made Pollution.

a) Petroleum. The open coast of Washington and Oregon has remained relatively free of oil pollution. Regional hydrocarbon concentrations for the North Pacific are about 0.2 parts per billion (ppb). The concentration of surface tar balls along a line from Toyko to Victoria decreases from a high of 3 g/m^2 to a low of 0.4 g/m^2, but the distribution is not smooth. There appears to be an accumulation of tar in gyres, and a tendency for contaminants to move eastward. By 1980 it is predicted that the density of contaminants

Table III-17

Typical Bulk Compositions and Particle Diameters As Functions of Geographic Areas[§,†]

Area		Biogenous Matter		Lithogenous Matter	
	Fraction of total, vol.%	Phyto-plankton, % marine	Detritus/living	Particle diam. (maximum) μ	Particle diam. (modal) μ
River	5-15	0	<1	100-200	4-40
Estuarine	5-30	10-50	<1	∼200	<4-60
Transition[‡]	5-90[§§]	10-90[§§]	<1[§§]		<40[§§]
	50-95[††]	95-100[††]	>1	40-70[§,††]	4-50[††]
Oceanic[‡‡]	70-95[§,††]	95[§,††]	>1[§,††]	<4[§,††]	<4[§,††]

[§] Conomos and Gross, 1972

[†] Combination of all survey periods.

[‡] Stations characterized by well-defined halocline; Surface Oceanic Water, if present, is not at sea surface.

[§§] Above base of effluent halocline.

[††] Below base of effluent halocline.

[‡‡] Stations characterized by ill-defined halocline; Surface Oceanic Water at sea surface.

(tar balls, etc.) in the eastern North Pacific will be as high as in the Kuroshio region now (Wong, 1975).

Natural oil and gas seeps have been reported from the coastal area of the Olympic Peninsula of Washington (Rau, 1973). No significant effects from these seeps have been detected in the marine environment.

In August 1975, samples of phytoplankton, zooplankton, neuston, sediment cores and water were collected at over 20 stations off the Washington coast under the supervision of Dr. Carpenter, University of Washington. Similar samples were collected from within Puget Sound. The sampling program and analyses were undertaken to provide some baseline data for the region with the anticipation of future increase of petroleum handling activity in the state. The priority in analysis is to determine the quantities and types of hydrocarbons present in organisms, then sediments and lastly in the water itself. This is partly because the impact on the organisms is of greatest concern and also because the analysis of hydrocarbons dissolved in sea water is still a very difficult task. Analyses of the shelf samples and the water samples are deferred, as the oil spill pollution threat is perceived to be greatest in Puget Sound (University of Washington, Dept. of Oceanography, 1976).

Drs. Cretney and Wong of the Department of Environment, Canada, Institute of Ocean Science, Ocean Chemistry Division, are studying the occurrence, pathways and fate of hydrocarbons in the marine environment, for the British Columbia coastal waters (McIntosh and Pizzo, 1977).

b) Dredge Spoils. An annotated bibliography of the effects of dredging and dredge disposal on aquatic organisms in the Pacific Northwest with selected references on biological studies of the lower Columbia River and on related dredge and disposal studies has been prepared for the U.S. Army Corps of Engineers (Ellinger and Snyder, 1975). An on-going project is investigating the hydraulic regime and physical nature of bottom sedimentation in the dump site just seaward of the mouth of the Columbia River (Sternberg, Creager and Glassley, 1976). Effects of the benthic communities of dredge disposal off the Columbia River have been studied concurrently with the current and sediment studies and a report of baseline quality is in preparation (Richardson, 1976). The following findings are of interest and are from Sternberg, Creager and Glassley (1976) and Richardson (1976).

1. It is possible to recognize disposal sites used over some decades by the U.S. Army Corps of Engineers both bathymetrically and through the use of textural and mineralogical properties of the sediment disposed. This is particularly significant because the main disposal areas have been located on the outer tidal delta where the greatest dispersal energies are expected.

2. Natural variations in the sediments occur in response to variations in the Columbia River flow. The benthic assem-

blages rearrange themselves accordingly. Concurrent with the sedimentological and bathymetric investigation, measurements of bottom currents, tides, waves, and suspended sediment have been made at the disposal sites during all seasons of the year. It is the long range intent of the studies to relate observed changes in the deposits of dredged material to the physical processes controlling dispersal.

C. Biological Oceanography. In the Northeast Pacific, photosynthesis is largely a function of available light, nutrients, temperature, and species assemblages. Salinity and pH are seldom a factor except near river mouths. Metabolic rates increase with temperature, but the effect is minor compared to other seasonal variables. Light and nutrient availability may be considered together. A typical pattern of annual production is low winter production, an increase in spring, decrease in summer, and a minor increase in fall.

The major limiting nutrient off Washington and Oregon is usually nitrate/nitrite, sometimes silicate or phosphate. Trace or micronutrients such as iron or boron may also be limiting; but these affect rates of production rather than the total production possible, since they are generally used in enzymes.

Measurements of the standing stock of phytoplankton are determined in various ways. The plankton quantity found is generally described as the biomass. Unfortunately, this term has been defined in a great variety of of ways (such as the wet weight, dry weight, dry weight of the organic substance, displacement volume, cell- and cytoplasmic volume, chlorophyll- and protein content) (Schlieper, 1972). It may be presented as a quantity per unit volume or it may be related to a 1 m^2 water surface.

Productivity is determined by the carbon-14 technique and is a measure of the quantity of bound carbon produced in a period of time. The daily productivity rate is related to 1 m^2 water surface and is most often given by, $mgC/m^2/day$ (Schlieper, 1972). This value represents the total productivity of the water column beneath this 1 m^2 water surface.

Acclimation to suboptimal conditions helps to increase production and eliminate fluctuations in production. Small, Curl and Glosschenko (1972) demonstrate that cells are adapted to low-nutrient conditions offshore in Oregon waters relative to inshore, and production is higher for the same light field. Inshore populations under ideal conditions had less efficient chlorophyll, apparently because abundant nutrients permitted manufacture of larger quantities of chlorophyll-a (chl-a) and efficiency was not crucial. Phytoplankton have been shown to increase or decrease chl-a content, or change the morphology of pigment content of chlorplasts, in order to adapt to high or low light levels, thus decreasing the detrimental effects of inadequate or excessive light.

Contributing *to* the nutrient supply is the excretion of ammonia by zooplankton which may contribute 90% of required nitrogen to phytoplankton (Jawed, 1973). During photosynthesis, the phytoplankton may release considerable quantities of dissolved organic matter that is part of the primary production but is not measured by the Carbon-14 technique. This loss has averaged from 7% in upwelling regions to 26% in the oceanic area (Anderson and Zeutschel, 1970).

The following two sections examine upwelling and the freshwater input of the Columbia River as they affect phyto- and zooplankton off Washington and Oregon.

i. Upwelling. The permanent boundary between oceanic deep water and neritic water, defined by the 25.5 σ_T to 26.0 σ_T surface (Collins, 1964), is horizontal in the absence of upwelling but slopes upward to the surface during active upwelling, forming a front between the warmer neritic water seaward and upwelled deep water landward. The front usually is found at 10 km from shore but may be at 30 km during very intense upwelling. The upward slope of isopleths develops within one or two months of the onset of northerly winds and is relatively stable after June except above 20 m and within 10 to 15 km of the coast (Smith, 1974].

Upwelling brings nutrient-rich water to the surface during the summer, when light is not limiting. Laurs (1967) found a positive correlation between higher standing stocks of phytoplankton inshore than offshore and upwelling events. Between upwelling events, little difference exists between inshore and offshore areas. Upwelling occurs in episodes rather than continually, as the driving winds are not consistent (Smith, 1974). During relaxation of upwelling, the permanent pycnocline becomes horizontal. Inshore waters are warmed by solar heating and mix with waters from seaward of the former front, producing a uniform water type in the surface water.

During active upwelling, three hydrographically distinct zones may be defined. Zone I is the nearshore region shoreward of the intersection of the permanent pycnocline with the surface, at or about 10 km from shore. It is characterized by freshly upwelled water of 8 *to* 9°C and 33.5 to 33.8 o/oo salinity, with abundant nutrients. Zone 11 is the surface water off shore of the front. It extends down to 20 m and is well-mixed within this layer. Its salinity (32 to 33 o/oo) and temperature (10-13 °C) are the product of solar heating and mixing of less saline water of the Columbia River plume, which in summer is directed southwest along the Oregon coast. Zone III lies beneath Zone 11 and extends through the pycnocline to the bottom. Its water type grades from Zone 11 to Zone I with depth. Zone I has no net alongshore flow, although temporary flows may be strong (30 cm/see) to the north or south. Zone II has southward flow at 20 cm/sec which becomes northward in Zone 11 by 80 m, at 5 to 10 cm/sec (Huyer, 1974, and Peterson, 1976).

Peterson and Miller at Oregon State University have conducted a program of sampling within 18 km of the coast in order to examine the planktology of the zone of most intense upwelling (Huyer, 1974). The results were described by Peterson (1976). The greatest abundance of phytoplankton occurred in Zone 11 during active upwelling, with chlorophyll-a (chl-a) concentrations exceeding 10 µg/l. This persists throughout the upwelling season as nutrient input continues. Nutrient availability is not decreased by thermal and haline stratification of

Zone II due to the Columbia River plume and solar heating, because upwelling brings nutrients to the surface water in this area. Anderson (1964) indicated that further seaward, where the effects of upwelling are not felt, the stratification of surface water by the Columbia plume does not restrict nutrient availability.

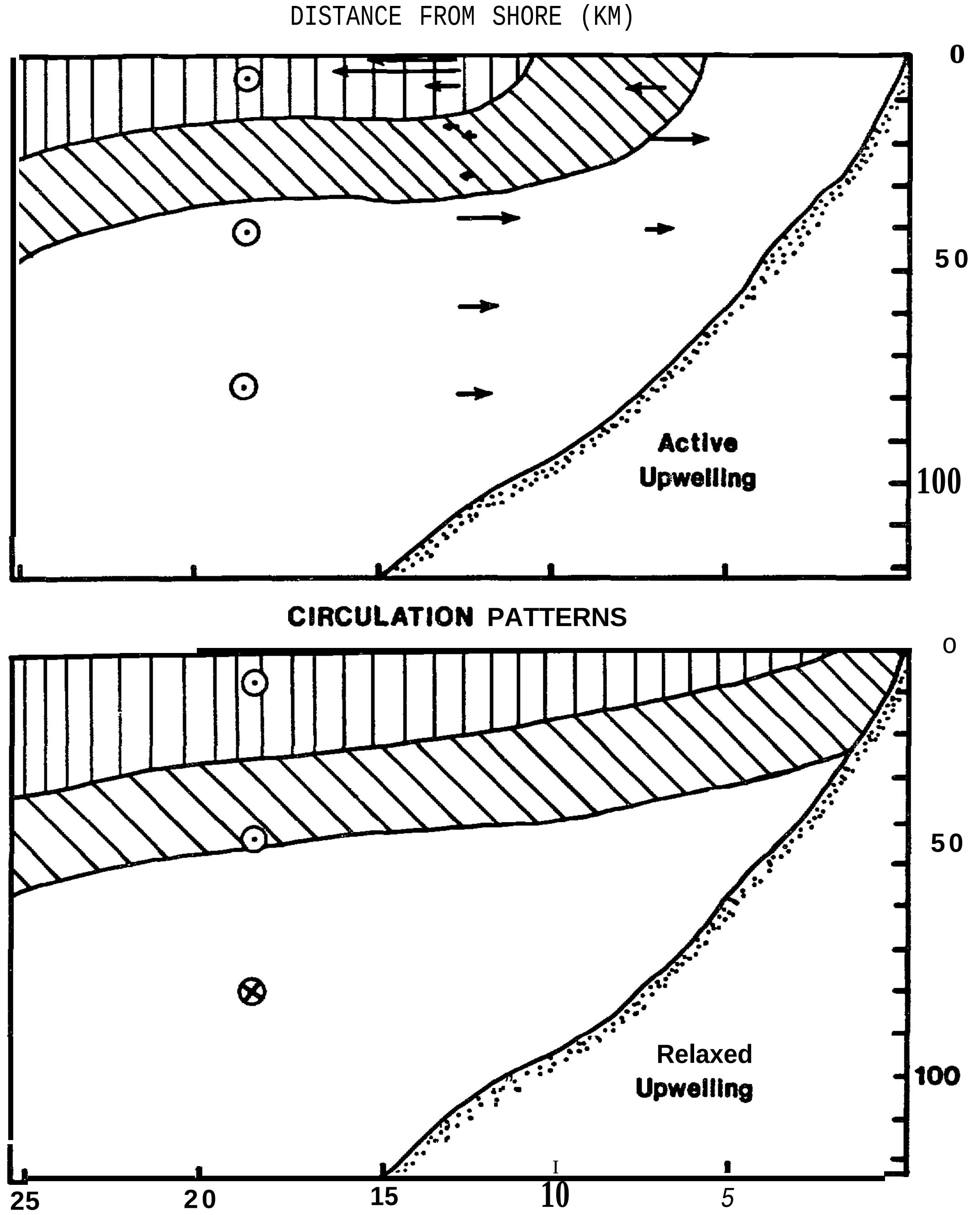
In the nearshore region (Zone I), a low of less than 1 μg/l chl-a occurs. This is similar to the value obtained in the deep water of Zone III, suggesting that low values of chl-a in Zone I are the result of a lag before phytoplankton respond to light availability as they are upwelled to the surface, or that low starting populations of phytoplankton delay the appearance of a visible increase in biomass. An alternative suggestion was offered by Laurs (1967), who explained a similar pattern of phytoplankton abundance by high grazing rates in the nearshore area. According to this explanation, phytoplankton productivity increases on entering surface water, but high grazing prevents a visible phytoplankton bloom, while supporting an increase in zooplankton biomass.

Peterson and Miller (1975) observed highest abundance of total zooplankton in stations nearest the shore. Richardson (1973) observed that the dominant primary carnivores, *Engraulus mordax* larvae (northern anchovy), were found almost exclusively in the warmer water of the Columbia River plume, and undoubtedly increased predation on herbivore zooplankton in this region. The maximum of zooplankton biomass nearshore may thus be a function of higher predation offshore rather than greater primary production inshore.

Upwelling presents a problem to populations that maintain themselves close to *shore,* presumably to take advantage of high food availability. Peterson (1976) describes distributional patterns of several common species of copeopods that clarify how zooplankton may maintain themselves in upwelling areas, and also refine the model of upwelling zonal flows. *Acartia clausii* is found almost exclusively within Zone I, indicating that Zone I is a discrete "cell" with little or no flow to Zone II. *Pseudocalanus* species (possibly *P. minutus*) are found in a narrow band 5 to 10 km offshore *at* 20 km when upwelling is relaxed. During active upwelling, the band is split into two centers, one at 2 km and the other at 10 to 15 km, both at shallower depths of 10 m. This indicates a divergence of surface water about 10 km offshore during active upwelling. The offshore population may be lost if upwelling continues or might be transported onshore if northward winds occur. Only the inshore population is reproductive, so that the total population of *Pseudocalanus* is maintained near shore. *Acartia longiremus,* unlike *A. clausii, is* found in Zone II. Nauplii occur only in the region just seaward of the front at 10 m. In Zone III only late copepodites (juvenile) and adults are found. The population is probably maintained in the upwelling zone by behavioral response during ontogeny. Copepods must migrate to landward-moving deeper water as late copepodites mature into adults at depth, and spawn as they reach the surface during upwelling. Most development (nauplii through late copepodite) occurs in the food-rich Zone II surface water.

From these distributional patterns a refined picture of upwelling can be developed, Figure 111-70 from Peterson (1976) shows the zones

Figure 111-70
A Cross-Sectional View of the Oregon Continental Shelf
Looking Northward Showing Zonal and Meridional Flow
Patterns and Distribution of Chlorophylls



§ Peterson, 1976

† Lengths of zonal component arrows are indicative of averaged relative speeds taken from published data. The permanent pycnocline is indicated by [diagonal hatching]. Its positions defines the state of the upwelling process: winds blowing toward the south result in active upwelling while calm or northward winds result in relaxed upwelling. Chlorophyll is indicated by [vertical hatching] and is abundant only above and seaward of the pycnocline.

and probable flows during active upwelling. Outward flow of surface water occurs only in Zone II. Zone I has little or no flow seaward and may have some landward flow at the surface.

During relaxation of upwelling, Zone II and the surface water of Zone I mix, and Zone I is further stratified by solar heating. Typically this results in a bloom of phytoplankton over the nearshore area, with chl-a concentrations exceeding 20 µg/l (Peterson, 1976). This is probably the result of the mixing of nutrient-rich Zone I water with an already high standing stock of phytoplankton from Zone II. If upwelling does not resume, one might expect eventual nutrient limitation and a decrease in phytoplankton biomass similar to that observed by Anderson (1964) in non-upwelling areas.

Upwelling is not only episodic within a season; it may also vary annually in intensity. Peterson and Miller (1975) show that, in 1971, when there were no sustained periods of southward wind and only four weak upwelling events, this resulted in a decrease of about 70% in the abundance of zooplankton in the inshore region. The periods of northward winds in that year also tended to favor offshore species and reduce the abundance of neritic species. The decrease in abundance was noted only for stations within 10 km. Hubbard and Pearcy (1971) noted that the species composition of salps 28 km offshore changed markedly during 1963, another year of low upwelling (Bakun, 1973). The relationship between upwelling intensity and inshore versus offshore plankton is not clear.

Peterson and Miller (1975) also documented lows in growth of a number of higher trophic level organisms in 1971, such as coho salmon, razor clams, and the shrimp *Pandalus jordani*, all of which were relatively smaller at harvest than in previous years. The effects of upwelling are thus felt at higher trophic levels as well as by primary or secondary production.

The interactions between an upwelling system and plankton de-described above have been determined for the mid-Oregon area. Laurs (1967) found that upwelling was discontinuous along the southern Oregon coast, possibly due to local bathymetry. Seasonal changes in surface currents associated with upwelling that were determined for the Oregon coast (Wyatt, Burt and Pattullo, 1972) extend as far north as the coast of Vancouver Island. The major variable is the position of the Columbia River plume, which affects only Oregon during the upwelling season. Anderson (1964), however, has found that the Columbia plume affects only the timing of productivity and not the amount of production, so it is probably not important to upwelling processes.

In Chapter IV., Marine Ecology, the distribution of benthic organisms is described. Oregon appears to have higher standing stocks than Washington, possibly reflecting greater productivity in overlying water resulting from greater upwelling. To date, no investigator has chosen to compare primary production of Washington and Oregon. It is probably safe to say that upwelling processes affecting production in Washington and Oregon are similar, if not identical.

ii. Columbia River Plume. Budinger, Coachman and Barnes (1964) defined the Columbia River plume as that area of surface bounded by the 32.5 o/oo isohaline. During winter the plume extends along the-Washington coast. Stefannson and Richards (1963) found that plume water in winter had three times as much silicate as ambient water, potentially promoting increased production of diatoms. Hobson (1966) found that winter standing stocks of diatoms increased from less than 3 mg/m^3 offshore to 10-35 mg/m^3 in coastal waters within the plume, with a high of 40 mg/m^3. The measured potential productivity was relatively constant and equal for plume and ambient water at 2.6 to 6.7 mgC/mg chl-a/day. Hobson suggested that the plume stabilized the water column and decreased mixing depth to permit a net increase in biomass within plume-affected areas, although chlorophyll-specific productivity indicated that a given cell had equal potential productivity in either area.

Hobson (1966) also showed that the presence of the plume allowed a greater seaward extent of neritic species of diatoms in winter off Washington. Small and Cross (1972) indicated that the copepod *Acartia danae* was excluded from low salinity plume water off Oregon in summer, while *Centropages mcmurrichi* showed no relation to plume distribution. Richardson (1973) found a positive correlation between plume water and presence of larval *Engraulis mordax*. The Columbia River plume may be expected to affect species composition throughout the year.

Stratification of the water column by the Columbia plume in offshore water increases the rate of production during the spring and early summer, but eventually results in nutrient depletion (Anderson, 1964). Anderson (1964) noted that production was augmented in winter near the Washington coast, as Hobson (1966) observed. The net effect over the year was to equalize the productivity of plume and ambient oceanic water, at about 60gC/m^2/year. Anderson also noted that during intense freshwater runoff productivity of phytoplankton was reduced near the river mouth. Jawed (1973) determined that ammonia excretion by zooplankton, as a source of nitrogen for primary production, provided 90% of required nitrogen in the plume, 36% in ambient water, and a negligible amount in inshore waters. This supports Anderson's (1964) observation of nutrient limitation in summer within the plume, and Park, Osterberg and Forster (1972) that the plume waters are low in nitrate relative to phosphate during the summer.

iii. Horizontal Distribution of Productivity, Standing Stocks of Phytoplankton (major species). Anderson (1964) described the distribution of chl-a as a measure of the standing stock of phytoplankton, and the distribution of primary productivity (using simulated *in situ* techniques) for the coasts of Washington and Oregon in 1961. In later papers (Anderson, 1969, 1972) the estimates of production were found to be too low, because of underestimation of the importance of subsurface chlorophyll maxima, an error in the C^{14} technique used at that time, and anomolously-low upwelling in 1961. The values provided, however, are illustration of distributional patterns of standing stocks and productivity. The suggested correlations will also be given (from Anderson, 1972).

Chl-a values during winter (January, 1961) were <10mg chl-a/m^2

in oceanic waters beyond the continental slope, in the nearshore region of Washington, and over the shelf of Oregon. The Columbia River plume at that time was directed north over the Washington slope and outer shelf. Chl-a values in the plume were 15 to 36 mg chl-a/m^2. In spring a bloom occurred near the coasts of Washington and Oregon, chl-a reaching 20 to 30 mg chl-a/m^2. No increase was noted offshore. During summer upwelling, areas on the shelf reached values >100 mg chl-a/m^2 while off shore water affected by the Columbia plume were at 5 to 10 mg chl-a/m^2 (now off the Oregon coast). Ambient offshore waters of Washington and further offshore waters of Oregon had values of <5 mg chl-a/m^2.

Productivity in winter was similar in distribution to standing stocks. Values were <.09 gC/m^2/day in oceanic and nearshore waters, while in the Columbia plume over the Washington shelf values were from 0.5 to 2.0 gC/m^2/day. Productivity in spring increased to 0.3 to 0.5 gC/m^2/day in areas near the Columbia River mouth. The plume at this time was less well defined, but was generally close to the coasts of both Washington and Oregon. Anderson (1964) does not state whether nearshore areas generally have increased productivity.

In summer, a minimum of productivity occurred in non-upwelling areas away from the Columbia River mouth, typically 0.1 gC/m^2/day within the plume and somewhat less in ambient water. Near the river, values were 0.14 to 0.38 gC/m^2/day, and in coastal upwelling areas values reached 1.21 gC/m^2/day.

In autumn, oceanic ambient water increased production to 0.16 to 0.29 gC/m^2/day, and in the plume to 0.08 to 0.35 gC/m^2/day. All areas, including former upwelling areas, declined to 0.10 gC/m^2/day by December, 1961. During winter and spring 1962 the distributional patterns were repeated.

The plume seemed to increase production off Washington in winter, but decrease production in autumn off Oregon. The stratification induced by the plume was slower to break down than that of ambient water, so that an overturn and input of nutrients to the surface did not occur until light began to be limiting. The stratification induced by the plume also caused an earlier spring bloom (when light was limiting), but subsequent nutrient exhaustion came earlier in the plume as well. The net effect in spring was to change only the timing of a spring bloom.

Overall, the plume does not increase or decrease productivity relative to ambient water on an annual basis. Both were estimated to have a production rate of 60 gC/m^2/year. The river mouth and upwelling areas had a production rate of 90 and 150 gC/m^2/year, respectively. Anderson (1972a) suggests that correcting for the known errors [mentioned previously) would yield 125 and more than 300 gC/m^2/year for oceanic and upwelling areas respectively. These corrections have not been verified as yet, but are based on continued study after 1962 by Anderson. Anderson (1972a) also notes that the spring bloom in biomass observed in 1961 is not regular feature of this area. In 1963 no increase was observed, although nutrients were decreased during the appropriate period. Anderson suggests that zooplankton grazing may prevent an actual bloom in primary biomass in some years.

Laurs (1967) presents chl-a concentrations for 1962-64 transects off southern Oregon (see Table 111-18, Laurs, 1967). Upwelling areas show highs of >100 mg chl-a/m^2, and offshore areas of about 50 mg chl-a/m^2 at 180 km from shore during summer. No values were as low as Anderson's original estimates of offshore standing stocks for 1961 (5-10 mg chl-a/m^2). It is possible that 1962 to 1964 were years of high upwelling which had a greater seaward extent than in 1961. Anderson's data also includes stations further offshore than Laurs's, lowering the estimate of offshore standing stocks. Hobson (1966) provides estimates of productivity (per "light-day", i.e., sunrise to sundown) for stations near the Columbia River in winter 1961. Values inshore averaged 31 mgC/m^2/light-day, and offshore in the plume averaged 72.83 mgC/m^2/light-day. This is in agreement with Anderson's (1964) observation of increased production in plume water. The actual values are about double those given by Anderson due to use of a 12-hour light-day rather than a 24-hour day.

Small, Curl and Glosschenko (1972) measured daily production during 1962-66 for a station off Newport, Oregon at the continental shelf break (83 km offshore). This would be within the plume area and at the limits of upwelling influence in summer. Production was about 0.2 gmC/m^2/day in winter and 0.75 - 1.50 gmC/m^2/day in summer. Offshore stations beyond the area of upwelling influence (100 - 530 km) were generally 0.1 - 0.5 gmC/m^2/day in summer. These values are very similar to those given by Anderson (1964) for corresponding areas.

A major feature of offshore areas is the presence of a well-developed maximum of chlorophyll beneath the pycnocline at about 60 m (Anderson, 1969). Its presence might be explained *in situ* productivity in the nutrient-rich subsurface water, by sinking of surface cells (Steele and Yentsch, 1960), and also in part by increased chlorophyll content of low-light adapted cells (Steele, 1964). Postel (1975) determined that subsurface chlorophyll maxima existed over the mid-Oregon slope in summer 1968 as well as further offshore, and provided estimates of the standing stocks of total phytoplankton, and of contributing taxa. Distinct subsurface chl-a maxima were present on the slope and offshore, generally with chl-a values twice that of overlying water. In oceanic water the biomass of the subsurface maximum was greater than that of surface water. Over the slope they were more nearly equal. This does not support the suggestion of Steele (1964) that low-light adaptation increases chl-a at depth without an increase in biomass. Postel (1975) found that no significant difference existed between communities in the subsurface chlorophyll maxima and those in overlying surface water. The observed distribution supports the hypothesis of sinking of surface cells to the depths where nutrients are available, but could be equally well explained by growth of those cells that were present at depth at the time of stratification of the water column (Postel, 1975). *In situ* growth has been observed by Anderson (1969).

The contributions of various taxa are given in Tables 111-19 and 111-20 (Postel, 1975). In general, diatoms dominated the shelf in

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Table III-18

Standing Stocks of Chlorophyll "a" (milligrams per m^2). Distance Offshore in Kilometers (and in nautical miles)§

Date	9.3 (5)†	27.9 (15)	46.5 (25)	6S.1 (35)	83.7 (45)	120.9 (65)	158.1 (85)	195.3 (10s)	232.5 (125)	269.7 (145)	306.9 (165)	$\bar{x}$†
June 62	ns	ns	136.60	186.88	56.66	57.19	48.80	53.13	43.19	45.88	56.80	76.13
Aug. 62	262.10	74.82	99.90	189.03	138.37	63.14	41.77	59.16	48.20	61.76	27.2S	80.34
Ott. 62	9.43	35.50	54.57	52.16	84.78	46.33	69.60	41.25	51.14	55.54	64.36	55.52
Mar, 63	19.92	64.15	93.18	92.38	92.50	96.14	86.70	104.56	82.70	85.57	86.60	88.45
May 63	27.18	119.80	73.09	73.63	67.42	93.41	92.90	123.49	122.69	107.49	ns	97.10
July 63	57.98	75.10	37.95	34.66	33.00	22.55	38.13	45.29	31.37	26.53	17.97	36.26
Aug. 63	88.28	36.47	28.01	39.77	37.20	48.78	20.66	44.41	43.52	41.73	56.88	39.74
Apr. 64	ns	230.84	134.23	38.57	36.77	56.05	41.84	49.75	37.66	27.63	49.00	70.25
$\bar{x}$	78.48	90.95	82.19	88.39	68.35	60.45	55.05	65.13	57.56	56.62	51.27	
s	86.66	50.74	38.47	60.32	33.73	22.83	23.70	29.09	28.48	26.31	21.29	

§ Laurs, 1967.

† Values recorded at 9.3 kilometers (5 nautical miles) offshore are not included in the computation of the mean standing stock of chlorophyll "a" for each sampling period. Chlorophyll "a" standing crop values for the 9.3 kilometers (5 nautical miles) station are for a 25-meter water column, while those for all other stations are for a 100-meter column.

Table III-19

Means and Standard Deviations of the Percentage Contribution of Major Taxonomic Categories of Phytoplankton to Total Cell Number and Total Cell Carbon (in parenthesis) in Each Sample Group[§†]

Group (# of Obs.)	Diatoms	Dinoflagellates	Microflagellates	Coccolithophorids	Others
A (21)	58 ± 14† (46 ± 17)†	12 ± 5 (33 ± 20)	18 ± 12 (5 ± 5)	7 ± 6 (3 ± 2)	2 ± 2 (8 ± 8)
B (14)	56 ± 12† (41 ± 14)	22 ± 6 (53 ± 14)†	17 ± 6 (5 ± 2)	< 1 (1 ± 1)	< 1 (< 1)
C (12)	30 ± 11 (23 ± 11)	25 ± 5 (63 ± 12)†	40 ± 13† (13 ± 8)	2 ± 2 (1 ± 1)	< 1 (< 1)
D (17)	14 ± 12 (20 ± 16)	27 ± 9 (63 ± 14)†	44 ± 14† (13 ± 8)	4 ± 3 (3 ± 3)	1 ± 4 (1 ± 2)
E (9)	22 ± 11 (35 ± 14)	19 ± 6 (51 ± 16)†	49 ± 13† (12 ± 10)	5 ± 3 (2 ± 1)	< 1 (< 1)
F (6)	18 ± 8 (35 ± 21)	20 ± 8 (44 ± 16)†	56 ± 6† (19 ± 8)	3 ± 1 (2 ± 1)	< 1 (< 1)
G (6)	35 ± 8 (68 ± 9)†	15 ± 4 (20 ± 5)	47 ± 11† (11 ± 5)	1 ± 1 < 1)	< 1 (< 1)

§ Postel, 1975.
† Denote the dominant type of phytoplankton within each group.

Zooplankton §†

	% Cell Number	% Cell Carbon
Coscinodiscus spp.	15 (l-34)	12 (0-62)
Small *Fragilaria* spp.	8 (2-30)	1 (o-4)
Thalassionema nitzschioides	9 (l-28)	4 (0-17)
Miscellaneous dinoflagellates	6 (1-11)	19 (3-65)
Miscellaneous microflagellates	15 (6-31)	4 (0-17)
Bacteriastrum delicatulum	7 (1-12)	5 (1-12)
Hyalochaete *Chaetoceros* spp.	25 (8-43)	12 (2-21)
Gymnodinium spp.	8 (5-13)	6 (2-10)
Miscellaneous dinoflagellates	10 (5-19)	23 (9-48)
Miscellaneous microflagellates	13 (6-23)	4 (2-9)
Hyalochaete *Chaetoceros* spp.	13 (0-32)	9 (0-24)
Gymnodinium spp.	8 (3-16)	8 (2-24)
Miscellaneous dinoflagellates	13 (9-17)	31 (13-s3)
Solenicola setigera	7 (0-20)	1 (o-5)
Miscellaneous microflagellates	28 (17-52)	10 [3-29)
Gymnodinium spp.	7 (5-12)	6 (1-15)
Miscellaneous dinoflagellates	14 (6-22)	20 (10-38)
Tear-shaped microflagellates	11 (1-17)	3 (o-5)
Miscellaneous microflagellates	26 (9-38)	8 (2-22)
Miscellaneous dinoflagellates	10 (5-15)	15 (3-43)
Box-shaped microflagellates	7 (1-14)	1 (o-4)
Tear-shaped microflagellates	16 (3-48)	4 (1-18)
Miscellaneous microflagellates	21 (13-27)	5 (2-11)
Gymnodinium spp.	7 (6-8)	7 (4-15)
Miscellaneous dinoflagellates	10 (3-18)	19 (5-35)
Tear-shaped microflagellates	14 (10-18)	5 [2-7)
Miscellaneous microflagellates	34 (23-52)	13 [7-23)
Rhizosolenia alata	20 (10-33)	58 (46-71)
Gymnodinium spp.	7 (3-14)	5 (o-lo)
Miscellaneous dinoflagellates	6 (2-9)	11 (5-16)
Tear-shaped microflagellates	7 (3-9)	1 (o-2)
Miscellaneous microflagellates	35 (20-53)	9 (4-16)

§ Postel, 1975.
† "Prominent" reflects the fact that a given taxon constituted at least 5% of all the cell numbers in one-half or more of all samples in a given group. The means and ranges (in parentheses) of percentage of cell number and cell carbon are given for each prominent taxon.

both numbers and biomass. Dinoflagellates dominated biomass off the shelf, while microflagellates dominated numerically. In all areas, diatoms formed a significant contribution to numbers (55% shelf, 30% subsurface chl-a maxima, 15% surface oceanic). Table 111-21 shows the distribution of species found in characteristic areas.

Anderson (1972) discusses data obtained by Sumiko Koga (1972) in 1961 off the Columbia River in winter and spring (Table III-22), where all depths are combined. Differences in abundance of particular species may be attributed to seasonal differences, closeness to the Columbia River mouth, and to differences over a number of years (1961-68) . Koga's data showed an abundance of dinoflagellates, coccolithophorids, and microflagellates offshore, as was found by Postel (1975). This may be a more general feature, while particular species may vary in abundance or relative importance.

Hobson (1966) also examined species of phytoplanton in winter 1961, but chose to use a volume basis for standing stock estimates. This makes his data difficult to compare to that of Koga or Postel, who used cell numbers to estimate dominances. In general, using either method, the major species are comparable for Koga's and Hobson's data. The winter 1961 species appear quite different from Postel's summer 1967 species, with the exception of *Thalassionema nitzschoides* and possibly some *Chaetoceros* species, which may be significant. T. *nitzschoides* is known to be a pelagic coastal diatom (Cupp, 1943) that may be characteristically important at all times in Washington and Oregon coastal waters.

Postel (1975) states that preliminary estimates of size-dependent production indicates 90% of production at the surface and in subsurface chlorophyll maxima in slope waters is due to the 20 µm fraction, compared to 45% on the shelf. Anderson (1965) found that the 3S µm fraction, accounted for 60-95% of production at the surface for shelf, slope, and oceanic stations over 3 years. Postel (1975) suggests that most of production at subsurface chl-a maxima may be due to small cells, but regarded this as highly tentative.

iv. Zooplankton. Some discussion of zooplankton with regard to upwelling processes has already been given.

Several theses at Oregon State University have examined distribution and abundance of zooplankton. Laurs (1967) examined seasonal variations in a single transect off Brookings, Oregon and Hebard (1966) in a line off Newport, Oregon. Cross (1964) considered special variations using 4 lines off the Oregon coast. Lee (1971) examined a small grid during August, 1963. Hebard and Laurs, using large (570 µm) mesh nets, found that the euphausiid *Euphausia pacifica* dominated numerically (Hebard) or by biomass (Laurs). Cross and Lee, using 240 µm mesh nets, found that the copepods *Oithona similis*, *Pseudocalanus* (possibly *minutus*), and *Acartia longiremis* were numerically dominant, but did not determine whether these small copepods dominated biomass as well. Peterson (1976) using 111 µm nets found that *Pseudocalanus*, *Oithona similis*, *Acartia longiremis*, and *Calanus finmarchicus* were numerically dominant. Less abundant but still

Table III-21

Distribution Patterns of Pytoplankton Taxa Found Primarily Within Certain Areas Along a Section (44°40'N) off the Oregon Coast in July 1968[§]

Area of Primary Occurrence	Species or Taxa Observed
Over the Continental Shelf (upwelling)	*Actinoptychus undulatus* *Chaetoceros decipiens* *Eucampia zoodiacus* *Ethmodiscus rex* *Lauderia* borealis *Schroederella delicatula* *Thalassiosira nordenskiöldii* *Thalassiosira pacifica* *Licmphora* abbreviate *Navicula* oblongs *Stephanopyxis nipponica* *Distephanus octangularis* *Dictyocha fibula* Miscellaneous blue-green algae
Over the Continental Shelf	*Cerataulina bergonii* *Rhizosolenia delicatula* *Rhizosolenia setigera* *Cochliodinium* spp. *Dinophysis* spp.
Over both the Continental Shelf and Slope	*Leptocylindrus danicus* *Skeletonema costatum* *Thalassiosira decipiens* *Achnanthes longipes* *Asterionella japonica* *Navicula* spp. *Tropidoneis antarctica* var. *polyplasta* *Halosphaera viridis*
In Oceanic Waters	*Biddulphia aurita* *Chaetoceros atlanticus* *Coscinodiscus oculus irdis* *Planktoniella sol* *Rhizosolenia alata* f. *inermis* *Rhizosolenia hebetata* f. *semispina* *Navicula calida* *Nitzschia longissima* *Pseudoeunotia doliolus* *Amphidinium* spp. *Ceratium* spp. *Oxytoxum* spp. *Acanthoica* spp. (large)

[§]Postel, 1975.

Table III-22

Numerically Dominant Diatoms off the Columbia River in 1961[§]

Area	Winter	Spring
Inshore	*Asterionella formosa*	*Asterionella japonica*
	Melosira islandica	*Chaetoceros compressus*
	Thalassionema nitzschoides	*Chaetoceros radicans*
		Rhizosolenia alata
		Rhizosolenia brazilissima
Transitional	*Asterionella kariana*	*Chaetoceros convolutus*
	Fragilaria sp.	*R. alata*
	Synedra ulna	
	T. nitzschoides	
Offshore	*C. convolutes*	*C. compressus*
	Dactyliosolen mediterraneus	*C. radicans*
	T. nitzschoides	*A. japonica*
		B. deliculatum
		Fragilaria sp.
		R. brazilissima

[§]Koga, 1972.

important were *Paracalanus parvus, Ctenocalanus vanus, Clausocalanus arcuicornis, Centropages abdominalis (mcmurrichi), Metridia lucens, Acartia clausii,* and *Calanus tenuicornis.* These samples ranged from Cape Flattery, Washington, to southern Oregon and were taken on a quarterly basis. Most stations were beyond the continental shelf break. Peterson ranked these by biomass for his entire study area. The top ten in decreasing order were: C. *finmarchicus, F'. minutus, Calanus plumchrus, Octhona similis, Paraeuchaeta elongata, Metridia lucens, Calanus christatus, C. tenuicornis, Acartia longiremis,* and *Eucalanus bungii.*

Ranks by numerical abundance were similar, but smaller species such as *Oithona similis* were more important by abundance than by biomass. Average total abundance of copepods for 1961 and 1962 in surface waters is shown in Table 111-23.

Comparisons of plume and ambient water show fewer copepods in the plume but relatively more in winter at depth (60% at depth in the plume, 30% in ambient water). Abundance below 40 m was usually less than 25% of that of surface water. No explanation was suggested by Peterson for a deeper plume population in winter. The differences between annual totals for plume and ambient waters are not significant, tending to support Anderson's conclusion (1964) that the plume does not increase phytoplankton productivity on an annual basis. Since euphausiids and other non-copepod herbivores were not considered, their relative importance by biomass remains unresolved.

The distribution of the major species or taxa with distance from shore was examined by Hebard (1966), Laurs (1967), Cross (1964), Lee (1971), and Peterson and Miller (197S, 1976). Peterson and Miller examined the nearshore region of 18 km, within which maximum upwelling effects are observed (Huyer, 1974). In this narrow zone they found that the most numerically dominant zooplankton were the copepods *Calanus marshallae, Pseudocalanus* sp., *Centropages abdominalis, Acartia clausi, A. longiremis,* and *Oithona similis.* Figures 111-71 and III-72 from Peterson and Miller (1975) shows the seasonal and spatial variation of these copepods. In general, *Pseudocalanus* sp., *A. clausi,* and C'. *abdominalis* were found close inshore in higher abundance; *A. longiremis* was found offshore; and O. *similis* was not apparently correlated with distance *to* shore in this area. Maximum densities attained were 25,000/m^3 for A. *clausii,* and 53,000/m^3 for *Pseudocalanus* in summer. Most other species were found at less than 2,000/m^3 during their maxima in summer. Lee (1971) found that at August, 1963, 0. *similis* was present at 200 to 800/m^3, *Pseudocalanus* at 200 - 1,000/m^3, *A. clausi* at 50 - 200/m^3, and *A. longiremis* at 50/m^3, all for stations from 5 to 83 km from shore in southern Oregon. These lower values may indicate the rapid decrease in abundance with distance from shore. Total abundance of zooplankton averaged 500/m^3 for the entire area, compared to Peterson and Miller's value of 1,000/m^3 in summer at 18 km. Peterson and Miller give values for 3 year averages of total zooplankton (Table III-24).

Considerable variation was present from year to year. Average zooplankton catches for June through September are listed in Table III-25. The annual variations are significant only within 9.0 km off-

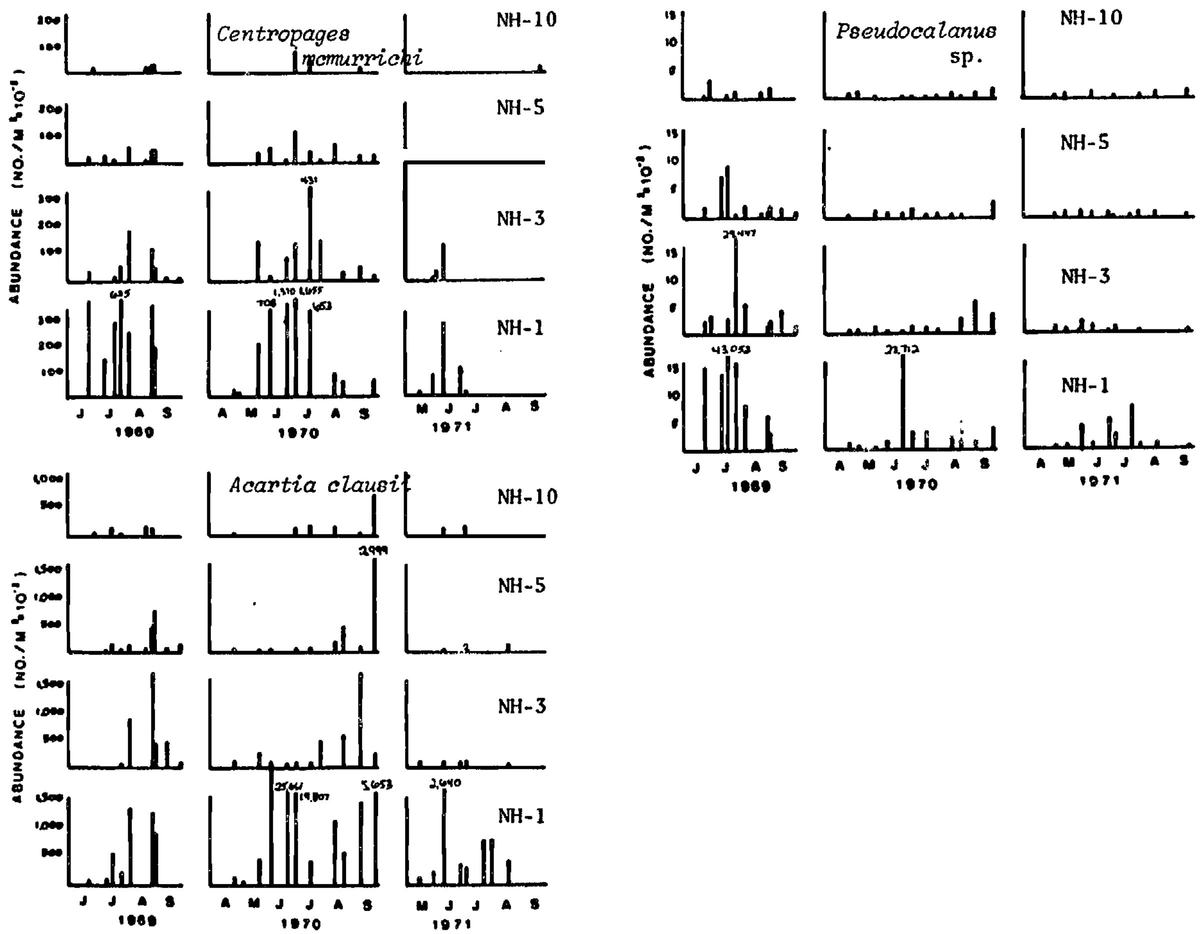
Table III-23

Average Total Abundance of Copepods for 1961 and 1962 Off the Coast of Washington and Oregon§

Regime	Total Copepods/m^3 Summer	Winter
Shelf	.5700	5200
Slope	7900	3100
Oceanic	8000	4200
Plume	6900	4500
Ambient	8700	4000

§Peterson and Miller, 1975.

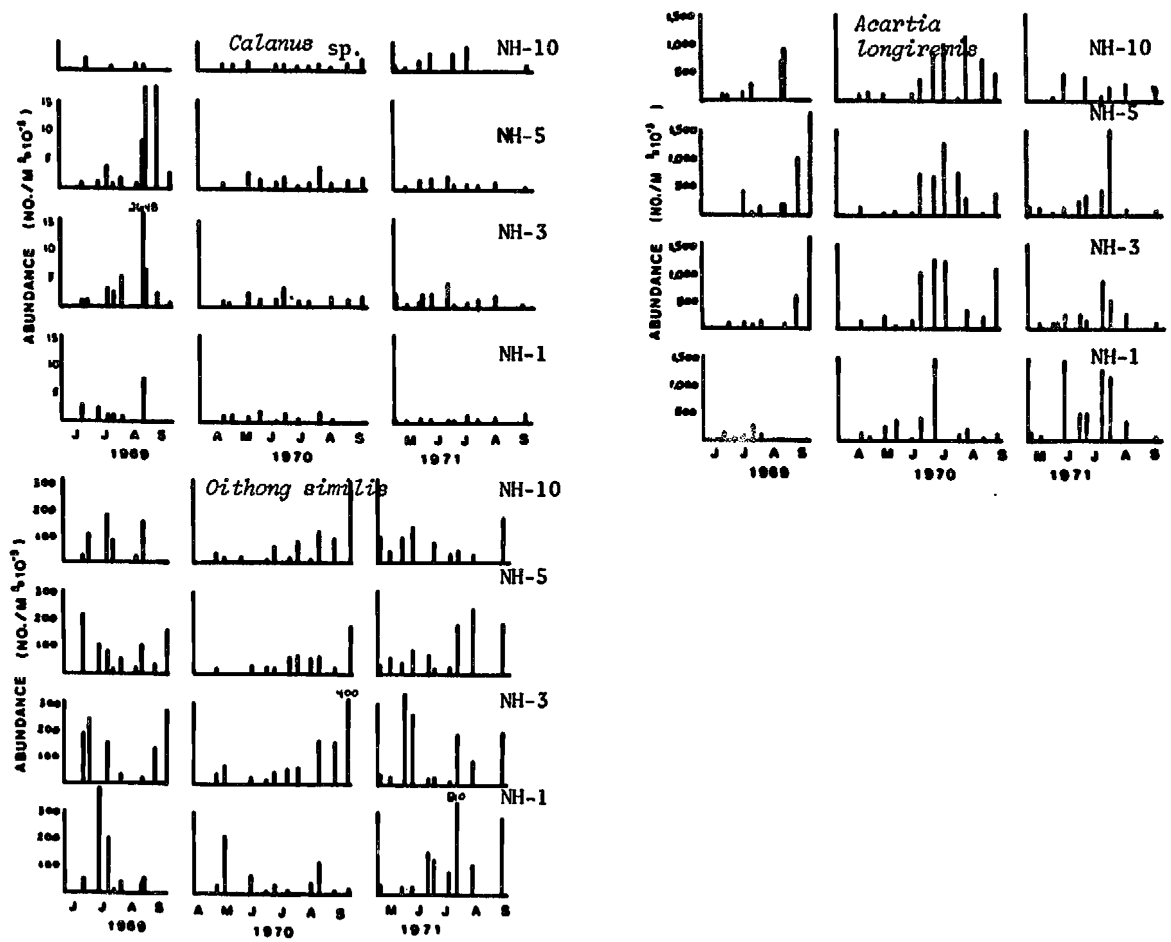
Figure III-71
Density of *Pseudocalanus* sp., *Acartia clausii*, and *Centropages mcmurrichi* (= *C. abdominalis*) at NH 1, NH 3, NH 5, and NH 10 in the Upwelling Seasons of 1969, 1970 and 1971[§]



[§]Peterson and Miller, 1975.

Figure III-72

Density of *Calanus* sp., *Acartia longiremis*, and *Oithona similis* at NH 1, NH 3, NH 5 and NH 10 in the Upwelling Seasons 1969, 1970, and 1971[§]



§Peterson and Miller, 1975.

Table III-24

Three Year Averages for Total
Zooplankton Off Oregon[§]

Station	Total/m^3 Summer	Winter
1.8 km	4350	850
5.4 km	2250	800
9.0 km	1ss0	530
18.0 km	1000	365

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§Peterson and Miller, 1976,

Table III-25

Average Zooplankton Catches for June Through September for Three Years, off Oregon[§]

Year	1.8 km	5.4 km	9.0 km	18.0 km
1969	16344	7379	4090	1528
1970	16196	4618	2300	1828
1971	5012	1433	1233	1086

[§] Peterson and Miller, 1976.

shore and can be correlated with degree of upwelling.

Laurs (1967) provides biomass estimates of euphasiids, total copepods, salps, and total zooplankton (Tables III-26 to III-29). The copepod biomass are underestimated due to large net mesh size. Salps were found to comprise 13.1% (range 0.0-31.7%) of biomass of zooplankton, euphausiids 72% (44-93%) and copepods 14.3% (4.4-31.7%). In general, euphausiids were abundant in late winter and copepods and salps in spring. Euphausiids were most abundant at 27 km, copepods and salps at 45 to 63 km offshore. Hebard (1966) found approximately the same distributions using numerical abundance as Laurs (1967) using biomass .

Laurs (1967) found an inverse correlation between phytoplankton and zooplankton standing stocks, suggesting that zooplankton are locally responsive to changing phytoplankton productivity but that phytoplankton may increase over zooplankton grazing pressure on occasion.

Laurs (1967) found that, of the copepods sampled using larger mesh nets, the dominant ones were *Metridia pacifica, M. lucens, Eucalanus bungii, Calanus finmarchicus,* and *C. pacific-us.* A comparison to Peterson's data indicates that these are about as abundant by biomass as are some smaller copepods. Since Laurs found that 72% of biomass was due to euphausiids and 14.3% to copepods, inclusions of small copepods might result in more nearly equal importance of euphausiids and total copepods by biomass.

Larger carnivorous zooplankton were also considered by Laurs (1967) . Fishes formed 47.1% of the total biomass of the third trophic level, and were relatively more abundant in fall (.42 gm/m^2) than summer (0.2 gin/m^2). The major species were *Lampanyctus leucopsarus, L. titter-i, Diaphus theta, Tarletonbeania crenularis* (Myctophidae), and *Tactostoma macropus* (Melanostomiatidae). Fall maxima were probably due to summer recruitment and possible migration shoreward. Other major carnivores were chaetognaths; medusae, siphonophores, and ctenophores; shrimps and amphipods; polychaetes; and cephalopods. Table 111-30 from Laurs (1967) gives the percent contribution of each of these groups. The values for total mean biomass of primary carnivores are shown in Table 111-31. The distribution of trophic level 3 was generally shifted offshore from that of herbivores. Chaetognaths were most abundant at 81 km offshore, shrimps at 45 km, and other carnivores were variable with season or not clearly variable. The mean biomass over all seasons for all carnivores was highest at 81 km (12.52 $gm/10m^2$) and lowest at 9 km (1.05 $gm/10m^2$). Lower values occurred offshore of the maximum (6.0 $gm/10m^2$).

Richardson (1973) used bongo nets and Isaacs-Kidd trawls more suitable for capture of larger carnivorous zooplankton. In June and July-August she found that *Engraulis mordax* (northern anchovy) comprised 89.4% (by number) of shallow-tow fishes and 73.1% of deep-tow fishes, while combined myctophids comprised 5.7% and 23.8% of shallow and deep tows. The important myctophids were *Stenobrachius leucopsarus, T. crenularis, Protomyctophyn thompsoni, Lampanyctus regalis,* and *Diaphus theta.* Richardson found that *E. mordax* and *L. leucopsarus*

Table III-26

Standing Stocks of Trophic Level III (dry weight in grams per 10 m^2)[§]
Distance Offshore in Kilometers (and nautical miles)

Date	9.3 (5)	27.9 (15)	46.5 (25)	65.1 (35)	83.7 (45)	120.9 (65)	158.1 (85)	195.3 (105)	232.5 (125)	269.7 (145)	306.9 (165)	$\bar{x}$	$\bar{x}_1$
Aug. 62	ns	72.34	29.72	20.36	8.74	2.68	4.03	3.26	1.93	1.50	2.65	14.72	8.32
Oct. 62	0.58	ns	52.28	40.76	45.16	19.90	10.80	6.96	6.20	13.54	13.92	21.10	26.19
Mar. 63	1.72	174.48	4.86	4.06	ns	6.32	[illegible]	4.82	4.70	11.90	3.32	22.12	5.63
May 63	0.47	53.34	9.86	6.44	8.36	11.24	17.84	13.71	27.82	ns	ns	16.56	13.61
July 63	6.57	2.78	4.50	3.48	2.8[illegible]	3.04	1.76	6.04	3.28	2.10	ns	3.[illegible]4	3.39
Sept 63	3.17	27.09	47.70	57.09	25.82	7.00	9.35	1.18	3.02	2.98	4.54	17.18	17.63
Apr. 64	10.94	110.83	2.4[illegible]	17.62	4.72	11.82	12.80	9.36	ns	ns	14.80	21.76	10.59
$\bar{x}$	3.91	73.48	21.63	21.40	15.94	8.86	8.81	6.55	7.83	6.40	7.85		
s	3.7[illegible]	56.50	19.87	18.93	15.09	5.[illegible]8	5.19	3.88	8.81	5.20	5.36		

[§] Laurs, 1967.

Table III-27

Standing Stocks of Euphausiids (dry weight in grams per 10 m^2)[§]

Distance Offshore in Kilometers (and nautical miles)

Date	9.3 (5)	27.9 (1s)	46.5 (25)	65.1 (35)	83,7 (4s)	120.9 (65)	158.1 (8S)	195.3 (105)	232.5 (12s)	269.7 (145)	306.9 (165)	$\bar{x}$
Aug. 62	ns	72.34	26.80	16.70	6.89	0.34	0.45	1.67	0.81	0.76	0.74	12.80
Oct. 62	0.05	ns	52.20	39.56	34.86	10.66	5.08	2.68	5.52	11.12	11.62	17.34
Mar. 63	0.09	174.47	4.22	1.90	ns	5.40	1.44	2.20	3.56	11.20	2.54	20.70
May 63	0.00	53.55	2.32	0.62	5.26	4.36	9.16	3.58	11.90	ns	ns	10.06
July 63	4.77	1.93	2.62	0.90	1.72	0.98	0.56	1.44	0.34	0.74	ns	1.60
Sept. 63	1.89	22.40	17.26	27.59	13,19	4.95	8.78	0.30	0.92	0.52	2,24	9.09
Apr. 64	0.06	105.05	1.46	0.90	0.18	0.60	0.88	2.06	ns	ns	0.84	12.45
$\bar{x}$	1.14	71.59	15.27	12.60	10.35	3.90	3.76	1.99	3.29	4.87	3.60	
s	1.76	56.73	17.49	14.64	11.72	3,41	3.53	0.95	3.74	5.14	4.08	

[§] Laurs, 1967.

Table III-28

Standing Stocks of Copepods (dry weight in grams per $10\ m^2$)[§]

Distance Offshore in Kilometers (and nautical miles)

Date	9.3 (5)	27.9 (15)	46.5 (25)	65.1 (35)	83.7 (45)	120.9 (65)	158.1 (85)	195.3 (105)	232.5 (125)	269.7 (145)	206.9 (165)	$\bar{x}$
Aug. 62	ns	T	2.80	2.68	1.66	1.10	3.08	1.59	0.89	0.55	1.87	1.62
Oct. 62	0.53	ns	0.08	1.20	10.30	5.60	5.38	1.62	0.68	2.42	2.30	3.01
Mar. 63	0.63	T	0.52	1.96	ns	0.84	2.12	1.60	0.58	0.70	0.78	0.97
May 63	0.47	T	1.70	1.78	1.86	4.40	2.42	3.50	7.46	ns	ns	2.62
July 63	0.92	0.86	1.40	1.26	1.16	1.06	0.58	0.90	1.62	1.36	ns	1.11
Sept. 63	0.16	0.27	2.14	1.48	1.75	2.05	0.57	0.02	0.52	1.30	1.72	1.09
Apr. 64	10.39	5.34	0.64	16.54	2.28	10.18	8.04	5.00	ns	ns	3.70	6.90
$\bar{x}$	2.18	1.08	1.33	3.84	3.17	3.60	3.17	2.03	1.68	1.27	2.07	
s	3.68	1.93	0.90	5.20	3.21	3.18	2.50	1.50	2.30	0.66	0.9s	

[§] Laurs, 1967.

Table III-29

Standing Stocks of Salps (dry weight in grams per 10 m^2)[§]

Distance Offshore in Kilometers and (and nautical miles)

Date	9.3 (5)	27.9 (15)	46.5 (25)	65.1 (35)	83.7 (45)	120.9 (65)	158.1 (85)	195.3 (105)	232.5 (125)	269.7 (145)	306.9 (165)	$\bar{x}$
Aug. 62	ns	0.00	0.07	0.97	0.19	1.24	0.00	0.00	0.23	0.19	0.00	0.29
Oct. 62	0.00	ns	0.00	0.00	0.00	3.64	0.34	2.64	0.00	0.00	0.00	0.66
Mar. 63	0.00	0.00	T	0.00	ns	0.00	0.10	0.00	0.00	0.00	0.00	T
May 63	0.00	0.00	3.64	3.96	6.20	2.40	5.04	6.54	8.46	ns	ns	4.03
July 63	0.87	0.00	0.48	1.30	0.00	1.00	0.62	3.70	1.32	0.00	ns	0.93
Sept. 63	1.11	4.42	28.30	28.30	11.20	0.00	0.00	0.86	0.16	0.11	0.60	6.82
Apr. 64	0.00	0.00	0.00	0.00	2.22	0.84	3.88	2.80	ns	ns	10.20	2.22
$\bar{x}$	0.33	0.74	4.64	4.93	3.30	1.30	1.43	2.36	1.70	0.06	2.16	
s	0.47	1.64	9.74	9.63	4.15	1.22	1.96	2.17	3.06	0.10	4.03	

[§] Laurs, 1967.

Table 111-30

Percent of Biomass of Trophic Level III Formed by Constituents[§]

	Aug. 62	Oct. 62	Mar. 63	May 63	July 63	Sept. 63	Apr. 64	$\bar{x}$
Fishes	48.7	52.3	53.9	32.7	39.4	55.6	47.3	47.1
Chaetognaths	13.0	17.5	13.9	10.1	20.9	14.9	16.5	15.3
Med., Siph. & Cten.	9.3	11.4	10.9	30.3	12.4	10.8	16.0	14.4
Shrimps	12.6	8.4	8,9	1s.1	12.5	8.7	9.8	10.9
Amphipods	8.3	5.9	2.6	4.5	9.7	7.0	2.8	5.8
Polychaetes	2.1	1.1	6.1	5.3	4*3	1.1	2.9	3.3
Cephalopods	3.3	3.3	3.4	1.7	0.7	1.0	3.8	2.4
Heter. & Ptero.	2.6	0.1	0.2	0.3	0.3	0.8	0.8	0.3

[§]Laurs, 1967.

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Table III-31

Total Mean Biomass of Primary Carnivores[§]

	Aug. 1962	Ott . 1962	Mar. 1963	May 1963	July 1963	Sept. 1963	Apr. 1963
Biomass gm/10m² (dry weight)	6.33	8.81	5.16	8.62	4.46	8.25	4.88

[§] Laurs, 1967.

became too large to be effectively captured by fall, when *Sebastes* spp., *T. leucopsarus*, and T. *crenularis* became the major species present. Richardson's data indicate that Laurs's estimates of biomass are probably underestimated due to net avoidance by many species. The species listed by Laurs may not be the dominant ones present, but comparison to Richardson's data is not possible as conversions of numerical abundance to biomass have not been developed for these species.

Considerable foraminifera research has been carried out and reported by the Cushman foundation for foraminiferal research. Smith (1963) evaluated 176 plankton samples and made the following observations concerning the distribution of living planktonic foraminifera in the northeastern Pacific.

1. The distribution of foraminifera off the Oregon and Washington coast is extremely patchy; concentrations ranged from nil to 9618 organisms per cubic meter of water filtered.

2. The area of maximum concentration is directly above the area of *Globigerina*-rich sediments about 560 km off the coast.

3. Foraminifera were rare below 200 m and most abundant within the upper 100 m.

4. With the coming of daylight, diurnal vertical migration from the surface to about 50 m was observed.

Most of the organisms mentioned thus far are permanent members of the plankton, spending all the stages of their life-histories drifting in the upper layers of the ocean. In addition, there are a vast number of the young, or larvae, of the bottom-living invertebrates which ascend to live for a time in the plankton and so facilitate distribution of the species. Flatworms, segmented worms, different kinds of polyzoa, starfish, sea urchins and the bottom-living crustacea all have their own characteristic larval forms which are adapted to their part-time existence in the plankton. Fish eggs may also drift with the plankton prior to hatching. A detailed description of pelagic larval forms is available in Hardy (1965).

Diurnal vertical migrations of zooplankton occur, in which zooplankton rise near the surface at night time to feed on the phytoplankton, and then return to depth in the day time, possibly to avoid the light. These migrations may contribute significantly to the rate of transport of surficial pollutants to depth. This enhancement of mixing may be an important mechanism in bringing a pollutant into food-chains utilized by man.

7. Oregon - Washington Coastal Estuaries.

An estuary is a region of transition from river to ocean. Its definition varies from author to author, but probably the most useful definition for purposes of this study is that given by Cameron and Pritchard (1963): "An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage." Estuaries are characterized by highly variable physical, chemical, and biological conditions.

The Oregon coast is lacking in any large embayments or harbors, but has numerous rivers and well developed estuaries. The Columbia River estuary is the largest estuary on the Washington and Oregon coast. Washington has Willapa Bay and Grays Harbor, two large estuaries on its southern coast, and minor estuaries in the north coast area.

The Oregon and Washington coastal estuaries are of the "drowned river valley" type (also called coastal plain estuaries). They were formed by the sea level rising and flooding back into previously incised valleys. Characteristics of drowned river valley estuaries include 1) maximum depths seldom as much as 30 m, 2) the cross-section of subaerial valleys which deepen and widen toward their mouths, and which may be modified by spits, 3) outline and cross-section are often triangular, 4) width to depth ratio is usually large, 5) the central channel is often sinuous, 6) the entire estuary is usually floored by varying thicknesses of recent sediment, often mud in the upper reaches, but becoming increasingly sandy toward the mouth. River flow is generally small compared with the volume of the tidal prism (the volume between high and low water levels) (Dyer, 1973).

Significant estuaries exist within Puget Sound, but will be dealt with separately. Vancouver Island has Barkley Sound, a fjord-type estuary facing the open coast in the study area. Puget Sound itself is fjord-like.

Figure III-I presented the major estuaries of the coastal area. Estuaries less than 2 km^2 in area were not included.

Two recent professional symposia on the geophysics of estuaries have been held. Geophysics, Estuaries and the Environment was held at the American Association for the Advancement of Science meeting in February 1976, and Transport Processes in Estuarine Environments was held at the University of South Carolina under the auspices of their Institute for Coastal Research. A general conclusion from both symposia was that not enough is known about the physics, chemistry, geology, and biology of estuaries to greatly facilitate environmental decision-making. We cannot predict with certainty the environmental effects of some changes; we do not even know the physical processes involved in others (Officer, 1976).

a. Physical Oceanography of Estuaries. A physical method commonly used for classifying estuaries is based on fresh water -- salt water mixing patterns (Cameron and Pritchard, 1963). Three general classifications are recognized for estuaries: 1) stratified (two layers), 2) partially-mixed, and 3) well-mixed (vertically homogeneous).

In a stratified system river flow dominates tidal forces and the fresh water tends to flow over the intruding salt water creating a two layered system with a distinct density interface between them. Little mixing occurs at this interface. In a partially-mixed estuary, vertical mixing is more pronounced. The boundary between the salt water and fresh water still exists but is less well defined than in a stratified system. A well-mixed estuary has a barely detectable density interface. Because tidal forces dominate the system, there is considerable turbulence generated and as a result the fresh water and salt water tend to mix thoroughly.

One method used to determine the mixing characteristics of an estuary measurement of the salinity difference. The procedure involves finding t point in the estuary where the mean salinity is 17 parts per thousand (o/oo) at high tide, then measuring the bottom and surface salinities at this point. If the difference between bottom and surface salinities is equal to or greater than 20 o/oo, the estuary is considered to be stratified; an estuary with a difference between 4 and 19 o/oo is partially-mixed, and one with a difference equal to or less than 3 o/oo is well-mixed. This estuary classification scheme is useful in evaluating the limits of salt water intrusion and the flushing characteristics.

Salinity data is generally insufficient to classify all of the coastal estuaries in the study area. Those classifications that have been made are discussed below in specific estuary accounts.

Table III-32 presents the total area, relative size, tideland and submerged land area data for the Oregon-Washington coastal estuaries greater than 2 km^2 in area.

Dr. Slotta of the Ocean Engineering Department at Oregon State University recently completed a seven year project to study the physical and chemical processes of Oregon's estuaries. No summary report has been published, but masters theses on the physical and chemical processes on the Suislaw, Alsea, Siletz, and Coos Bay estuaries (Utt, 1974; McKenzie, 1974; Rauw, 1974, and Arneson, 1975) have been completed. Other related projects included a circulation study of the Netarts Bay estuary (Boley and Slotta, 1974), a tidal study of three Oregon estuaries (Yaquina, Alsea and Siletz) (Goodwin, Emmett and Glenne, 1970), a model study of tidal hydrodynamics and marine flushing for the Chetco River (a small estuary near the California border] (Slotta and Tang, 1976), and the 4th Annual Technical Conference on Estuaries of the Pacific Northwest (Oregon State University, Engineering Experiment Station, 1974).

A considerable amount of work on the sedimentation processes has been undertaken by the U.S. Army Corps of Engineers. The build-up of sediment interferes with navigation and the Corps coordinates any and all navigation improvements. Any dredging projects or construction of jetties or groins to protect the entrances of estuaries now are evaluated in advance and impact statements prepared. The impact statements provide varying coverage on the hydrology, tides, water quality, sediment distribution, composition and sedimentation rates, as well as wave and littoral drift data for the open coast by the mouth of the estuary. Physical models have been used to study the Columbia River, Coos Bay, Umpqua River and Grays Harbor estuaries. Percy, *et al.* (1974] provide a summary of much of the known information about the estuaries of Oregon and give numerous citations of literature and agencies from which supporting information may be obtained.

Physical oceanographic data are presented for some of the coastal estuaries but not all. For many of the estuaries, very little is really known or understood about the physical and chemical processes that go on.

i. Rogue River. The Rogue River flow averages about $232 m^3/sec$ annually. The mean maximum flow of $518 m^3/sec$ occurs in February and

Table 111-32

Area of Oregon-Washington Estuaries[§]

Estuary	Total Area (km′)	Relative Size	Tideland Area (km′)	Submerged Land (km′)
Rogue River	2.5	15	0.6	1.9
Coquille River	3.1	14	1.2	1.9
Coos Bay	50.1	4	25.1	25.0
Umpqua River	27.6	6	6.2	21.4
Siuslaw River	9.1	10	3.1	6.0
Alsea Bay	8.7	11	4.0	4.7
Yaquina Bay	15.8	7	5.5	10.3
Siletz Bay	4.8	12	3.1	1.7
Nestucca Bay	4.0	13	2.3	1.7
Sand Lake	2.1	16	1.6	0.5
Netarts Bay	9.4	8	6.1	3.3
Tillamook Bay	33.5	5	16.8	16.7
Nehalem River	9.3	9	4.4	5.0
Columbia River	379.5	1	99.2	280.3
Willapa Bay	347.4	2	189.S	157.9
Grays Harbor	259.0	3	170.9	88.1

[§]Hamilton, 1973; U.S. Army Corps of Engineers, Seattle District, 1974, 1976a.

the mean minimum flow is 34m^3/sec in September. The dams being constructed for flood control upstream of the project area have had little influence upon the river flow and thus the tidal prism.

The tidal prism of Rogue River is approximately 4.25 x $10^6 m^3$. The river flows above represent 446%, 994% and 65% of the tidal prism. Thus, generally, there is sufficient river flow to flush the estuary in a very short time period even during the low flow summer months. This enhances removal of sediment from the river mouth (U.S. Army Corps of Engineers, Portland District, 1975b).

Because of the high river flow, this estuary would be stratified near the mouth. Salt water intrusion would be greatest in September. No measurements have been made to confirm this.

ii. Coquille River. The surface area of the Coquille River estuary was estimated at high water and low water conditions. The change in area per tide was calculated for the estuary below the U.S. Highway 101 bridge. The high tide surface area was calculated to be 2.38 x $10^6 m^2$; the volume was estimated at 3.17 x 106m3. At low tide the volume decreased to 1.41 x $10^6 m^3$. The difference between these *two* volumes results in a tidal prism of 1.76 x $10^6 m^3$. Using these approximations, 55% of the water in the Coquille River estuary is replaced in one tidal cycle, 70% in two tidal cycles, and 83% in three tidal cycles. If any two adjacent high and low tides are of nearly equal height, the tide cycle may be considered to be 12.43 hours long. If there is considerable inequality in the tide, the cycle must be considered to be 24.85 hours in length (U.S. Army Corps of Engineers, Portland District, 1975b) .

River runoff is quite low in the summer (5 to 10h/see) (Oregon Coastal Conservation and Development Commission, 1974) and tidal forces dominate this estuary. Winter runoff may be 25 times this. This estuary would be well-mixed in summer and partially-mixed in winter. No measurements have been made to confirm this.

iii. Umpqua River. In the Umpqua River estuary, the relationship between the volumes of freshwater inflow and the volume of the tidal prism varies considerably. During the winter months, the volume of freshwater entering the estuary during a half-tidal cycle frequently exceeds the volume of the tidal prism. Conversely, during the summer months when stream flow is lowest, the volume of freshwater inflow is normally less than 10% of the tidal prism volume. Thus, if tidal and basin characteristics remain constant, river discharge into the estuary is the primary influence on the hydrographic system and its classification.

The Umpqua estuary is well-mixed during the summer and two-layered during the winter; however, estuarine classification changes frequently because circulation changes abruptly many times throughout the year. Thus, during the winter, high stream flows and high tides presumably create a partially or well-mixed condition for short periods. During the summer, low flows and low tides can combine to shift the classification toward a two-layered system. These fluctuations in circulation patterns are probably most pronounced during the spring months.

Records from 1905 to 1970 at an Umpqua River stream gauging station at River Kilometer 91, where the drainage area is 9,539 km^2 (80% of the total basin), show an average discharge of 210 m^3/sec and extremes of 7,500 m^3/sec and 18 m^3/sec. During the 14-year period between 1953 and 1967, the average maximum and minimum daily flows at this same spot were 3,500 m^3/sec and 25 m^3/sec.

The Umpqua River drainage basin yields an average of 8.26 km^3 of fresh water annually with extremes ranging from 3.39 km^3 to 14.80 km^3 (U.S. Army Corps of Engineers, Portland District, 1976b).

The estuary is fully exposed to waves at the throat. Tidal effects extend up the Umpqua River as far as Scottsburg at River Kilometer 44. The mean range is 1.5 m, the diurnal range 2.1 m and the extreme range 3.4 m. Tidal prism on mean range is 3.34 x $10^7 m^3$ with a diurnal range of 4.S2 x $10^7 m^3$. The estuary has an entrance gorge of 3,500 square meters below mean tidal level.

Salinity measurements were taken in the Umpqua River in June, 1956, October, 1957, and January, March and July, 1958. Maximum intrusion was found on 6 October 1957 at HHW when it reached a point 27 km from the ocean at concentrations of 1.3 o/oo on the surface and 1.5 o/oo on the bottom (1.7 m) with a concurrent temperature of 15.8°C at both points.

The Corps of Engineers measured surface and bottom salinity at River Kilometers 1.6 and 3.2 of the estuary when verifying its physical model of Umpqua Bay (U.S. Army Corps of Engineers, Portland District, 1976b) . The measurements were taken during 1966 on 30-31 March and 3-4 August. The greatest range in concentration on the surface was found during the 30-31 March period at Kilometer 1.6 where it ranged from 3 o/oo to 26.5 o/oo. Freshwater discharge at that time was 480 m^3/see, The greatest range on the bottom also occurred during 30-31 March at Kilometer 3.2 and ranged from 5 o/oo to 30 o/oo salinity. Measurements are also available in the Umpqua Estuary Model Study (Gladwell and Tinney, 1962).

The Umpqua River estuary is classified on the basis on mixing as a two-layered system in January and February; a partly mixed system in March, May, and October; and a well-mixed system in July (U.S. Army Corps of Engineers, Portland District, 1976g).

Water temperatures in the Umpqua River range from near freezing to 27°C. Warm summer water temperatures during low flow pose a threat to anadromous fish.

iv. Yaquina Bay Estuary. Throughout the year, the normal daily volumes of fresh water flowing in to the Yaquina estuary are consistently much less than the volume of the tidal prism.

If tidal and basin characteristics are viewed as constant, river discharge is the principal factor which affects the changes in the type of hydrographic system during the year. River discharge is, in turn, directly related to seasonal precipitation in the river's drainage basin. Hence, circulation patterns change with river discharge and precipitation patterns.

During the summer and early fall, the volume of the tidal prism substantially exceeds the volume of fresh water discharged into the estuary from the river. Under this condition, tidal action forces mixing of the fresh and saltwater to the extent that, on a given cross section through the estuary, the salinity is essentially constant from top to bottom. With this flow regime, there is a general slow net drift of water outward at all depths -- with the back and forth tidal movement superimposed on the slow drift. The net outward drift under these conditions has been measured in Yaquina Bay and is reported as about 5 cm/sec. Salt moves upstream against the drift by means of diffusion enhanced by tidal mixing. Intrusion of saltwater during low river discharge periods of summer extends as far up as River Kilometer 32. Occasionally, an incoming tide may flood more strongly at the surface and override the slightly less dense and less saline waters of the Bay. This is an unstable relationship and it further increases turbulence and mixing.

During the winter, when river discharge is high, fresh water flowing downstream partially overrides the more dense saline water forced inland by the tides. Although salinity is least at the surface due to the dilution from fresh water and is greatest near the bottom, salinity changes in the vertical direction are normally gradual so that the interface is not well defined. In the transition zone, saltwater from the bottom mixes upward with the less saline water near the surface and is carried back toward the ocean. There is an upstream movement of saline water at the bottom -- with a superimposed back and forth tidal movement. (This is in contrast to the general net outward drift which characterized the estuary in the low river regime.) Some of the water in the lower zone is constantly being lost to the upper, fresher zone (U.S. Army Corps of Engineers, Portland District, 1975d).

Under the low flow conditions, the estuary is classified overall as a “well-mixed” system. Top and bottom salinity measurements reveal the estuary to be well mixed during the summer from the Highway 101 bridge up to at least 4 km above Toledo, the farther inland observation station. Due to the larger depth-to-width ratio seaward from the bridge, currents in the throat of the estuary appear to be characteristic of a partly-to well-mixed system depending on the tides. Reported intrusion of marine sediments inland through the throat during the summer suggests that there is a net upstream current along the bottom in this area.

Under high flow conditions, the estuary is classified overall as a "partly-mixed" system. Under normal winter flow conditions in the river, this classification is applicable to the channel up to at least River Kilometer 16. Top and bottom salinity measurements are not available during the winter months above about River Kilometer 16.

In some areas of the estuary, particularly in the areas of the tidal flats, local circulation patterns even during high-river discharge probably are conducive to an appreciable greater degree of mixing. Hence, a "partly to well-mixed” classification may be appropriate in some local areas of the estuary.

When unusually high river discharge coincides with relatively small tides that do not furnish much energy for mixing, fresh water can completely overrun the more dense saltwater. Under this condition, a so-called "two-layered" system develops. On at least one occasion, fresh water has been recorded at the surface as far through the estuary as Kilometer 1.6, which indicates that under the proper circumstances a two-layered system can, in fact, develop for almost the entire length of the estuary. It may be that a two-layered system is well defined only in the immediate channel area where the depth-to-width ratio is relatively large (U.S. Army Corps of Engineers, Portland District, 1975d) .

Tidal elevations were measured at five stations within the Yaquina Bay estuary. A sample plot for 23-24 July 1969 is presented in Figure 111-73. "From this plot, time lags and instantaneous water surface profiles were calculated and tidal range amplification factor versus distance from the mouth were computerized. Tidal currents were also measured for the five stations (Figure 111-74]. These investigations showed amplifications of the entrance tidal range throughout the Yaquina estuary. A phase difference of 90-100 degress was found to exist between tidal elevations and tidal currents. This phase difference, and the tidal amplification indicate the presence of reflected waves and/or resonance conditions (Goodwin, Emmett and Glenne, 1970).

V. Siletz Bay. The mixing classification of the Siletz Bay estuary varies seasonally and spatially. During winter, the estuary is partially-mixed to well-mixed. During spring, the estuary varies from stratified to well-mixed.

In general, the Siletz estuary tends toward stratification when river flow is high (greater than 113 m^3/see), and tidal range is less than 1.3 m. It tends toward a well-mixed system when river flow is low (less than 40 m^3/see] and tidal range is greater than 1.3 m.

In the Siletz estuary, the limit of salt water intrusion varies with tidal range and river flow. The approximate limit is River Kilometer 5 at low tide and high river flow, and River Kilometer 34 at high tide and low river flow.

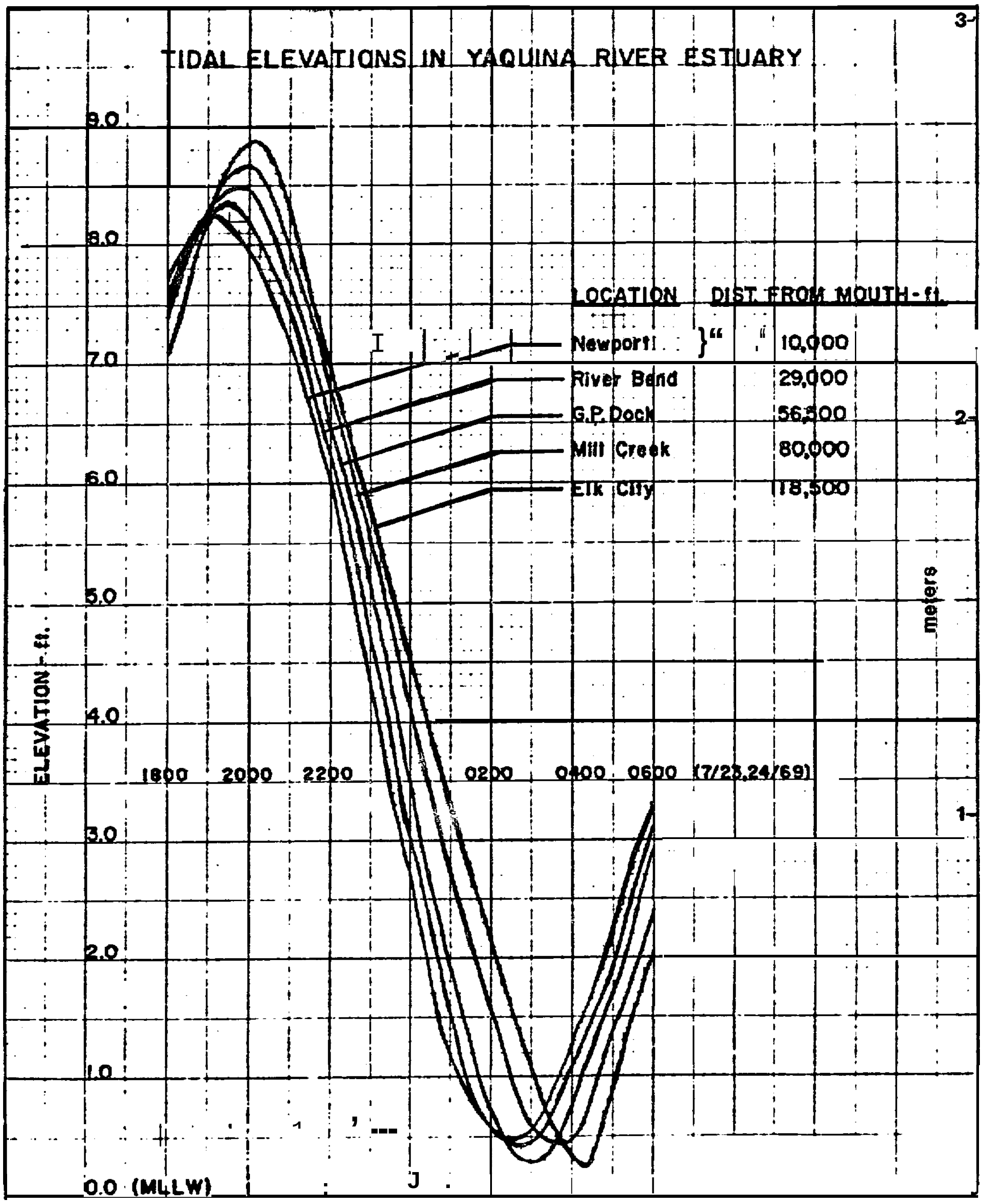
At high river flow, the estimated flushing time at Siletz is one tidal cycle, as compared to 13 tidal cycles at low river flow [U.S. Army Corps of Engineers, Portland District, 1976e).

Tidal currents measured at Taft, by the entrance of the estuary show considerable amplification clue to the narrowness compared to the total tidal prism. Figure III-75 presents the tidal currents in Siletz estuary for 12 September 1969 at Taft and three stations upstream (Goodwin, Emmett and Glenne, 1970).

Temperature ranges in Siletz estuary for 1973 were 6.0°C in winter to 17°C in summer, while the ocean temperatures ranged from 9.5 to 12°C. The summer temperatures show longitudinal gradients throughout the estuary due to differences in river and ocean temperatures. Fall temperatures are more uniform. Higher summer temperatures are probably for stagnant unflushed portions of Millport Slough and in the lower bay, though no data are known (U.S. Army Corps of Engineers,

Figure III-73

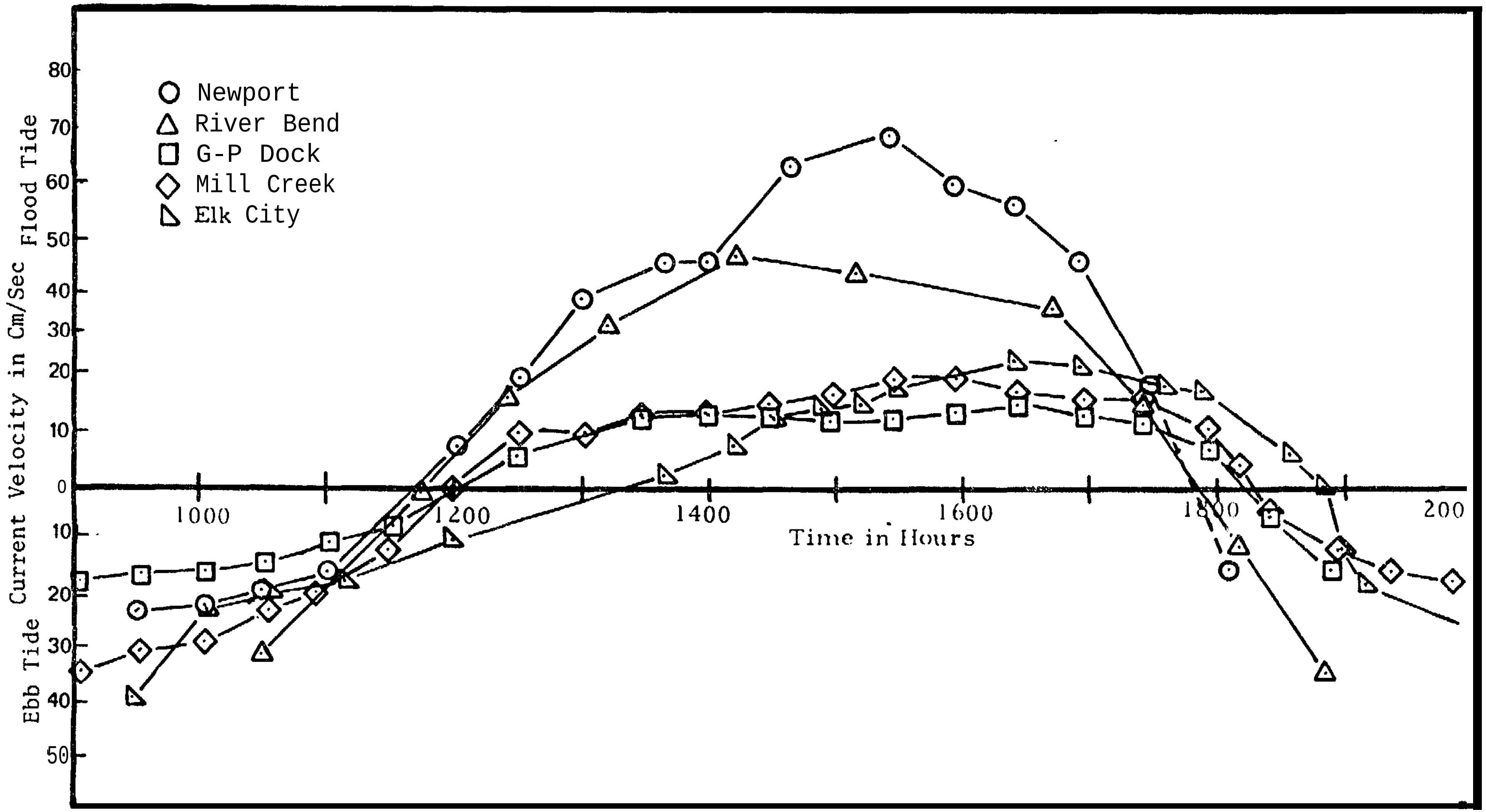
Tidal Elevations in Yaquina River Estuary[§]



§Goodwin, Emmett and Glenne, 1970.

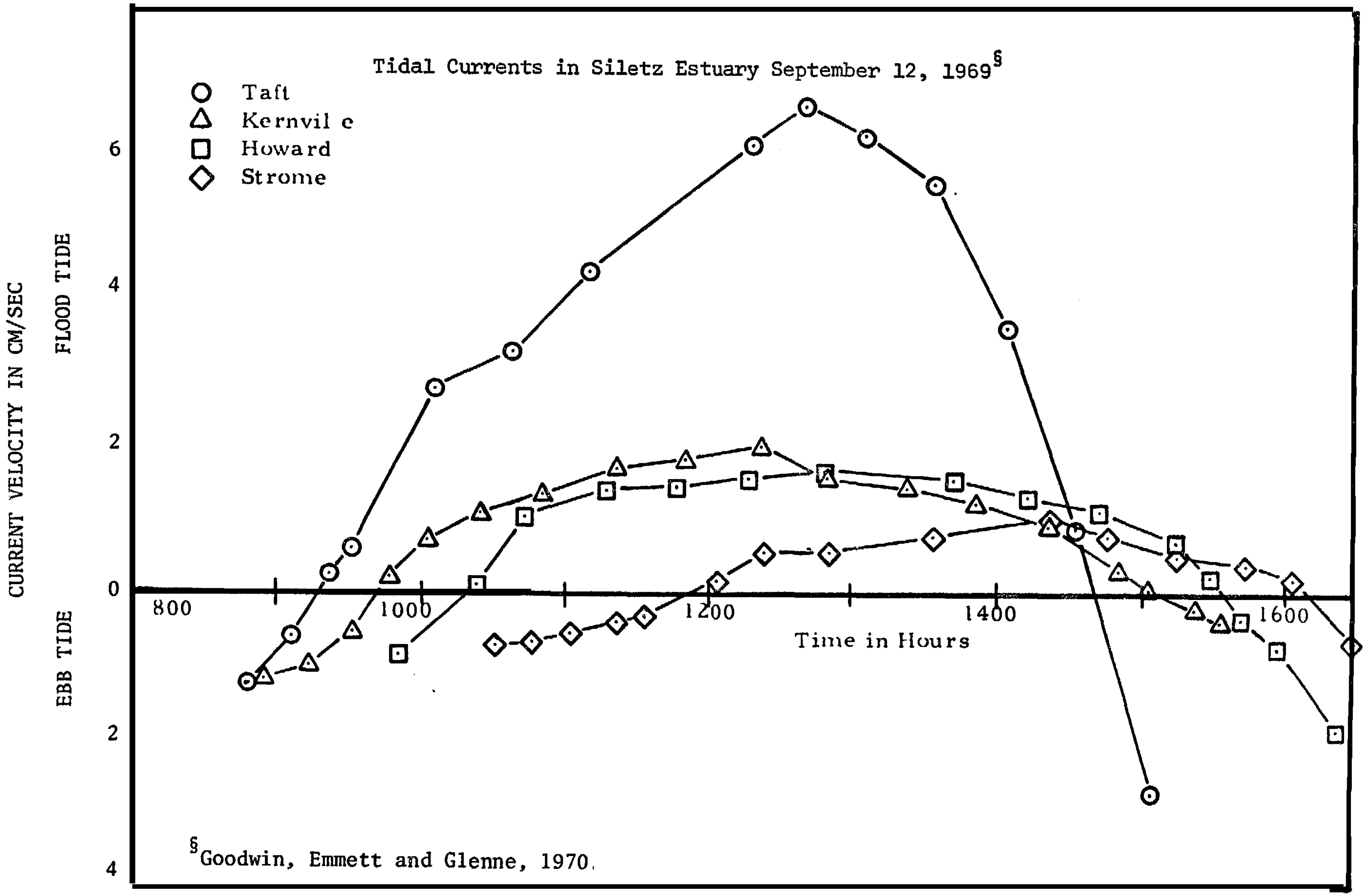
Figure III-74

Tidal Currents in Yaquina Estuary July 21, 1969§



§Goodwin, Emmett, and Glenne, 1970.

Figure III-75



Portland District, 1976e).

vi. Columbia River Estuary. A study of the salinity, temperature and velocity of the Columbia River between Kilometer 84 and the river mouth was made by the Corps in 1959 (U.S. Army Corps of Engineers, Portland District, 1960). Data were collected from a number of cross sections at different depths and under conditions of low, medium and high river flow. According to these measurements, the river hydraulic current is reversed on flood tide during all seasons of the year up to 40 km from the mouth. During the September low discharge period of 1959, flood tide reversed the river flow at the highest upriver measuring section (84 km). The intrusion of salt water extended upriver past 21 km but less than 32 km during September 1959, and not past 19 km (Astoria, Oregon) during the high discharge period of May and June 1959. Maximum intrusion of seawater during low river flow may be as far as 37 km at higher high water (Neal, 1972).

The Pacific Ocean tides can be measured upstream as far as Bonneville Dam where the diurnal range is 0.2 km. Tides reverse the river current in the lower 40 to 80 km, depending upon tide range and river stage (Hansen, 1965). Columbia River water enters the nearshore environment in 12 hour pulses as clouds of low salinity effluent. The tidal prism volume for the Columbia River from the mouth to Bonneville Dam (234 km upriver) is about 0.85 km^3 (Budinger, Coachman and Barnes, 1964).

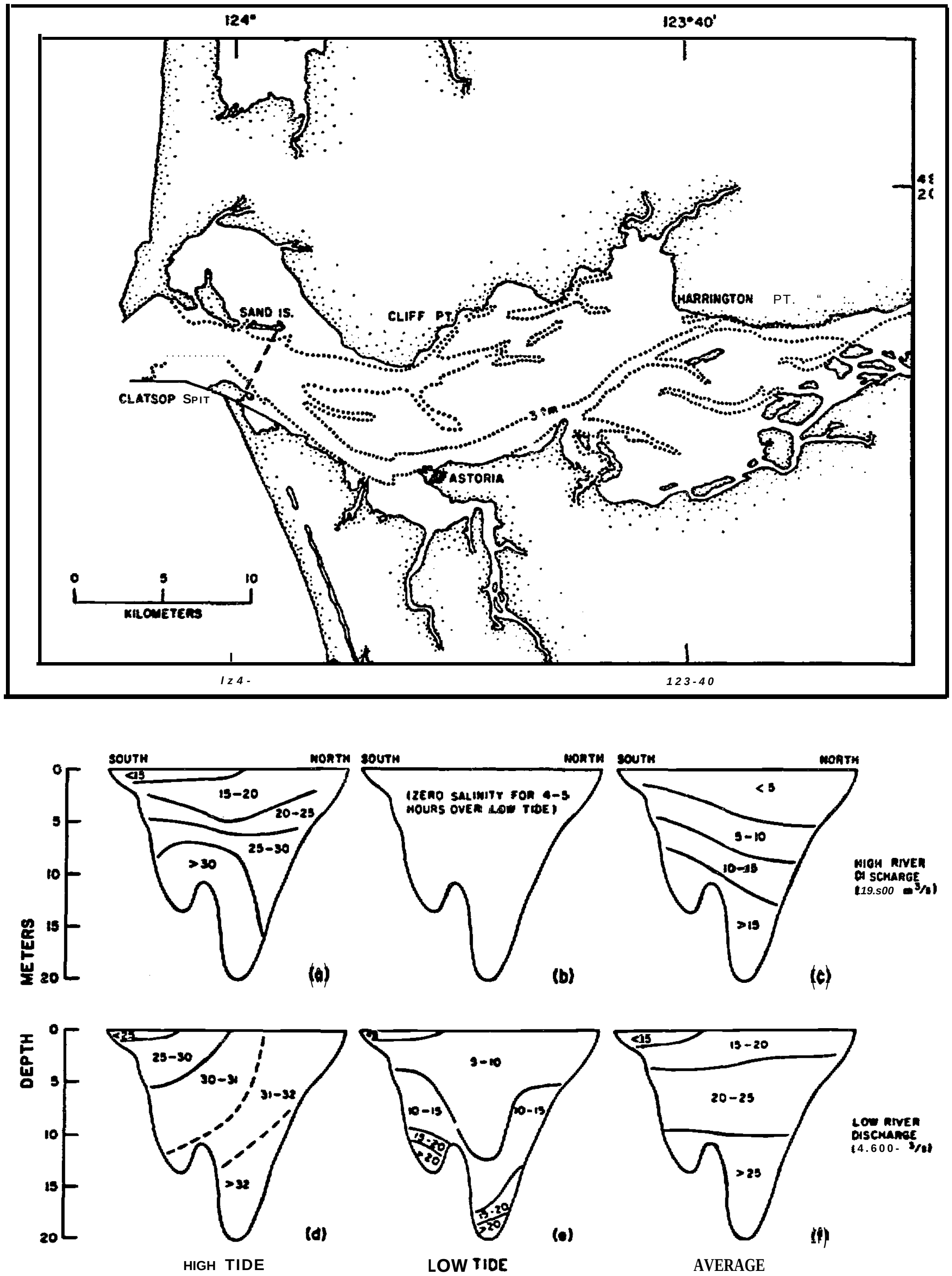
The mean annual discharge of the Columbia River is estimated at 7,300 m^3/sec, ranging annually between approximately 3,000 m^3/sec and 20,000 m^3/sec. Thus, although the tides are moderately strong, the flow ratio (ratio of river discharge during 12.4 hour tidal cycle to tidal prism) is on the order of 1 to 1/5, making the river current 1/2 to 1/10 the tidal currents at the mouth.

Because the salinity intrusion is so short and its variation in time so great, a sampling pattern very dense in both time and space would be required to adequately describe the longitudinal salinity distribution and its variations in this estuary. The estuary is so short relative *to* its width that the customary manner of portraying conditions by means of data from a mid-channel line of stations obscures some of its more interesting aspects. Figure III-77, constructed from the Corps of Engineers data from the section between Clatsop Spit and Sand Island, indicates the great variability of salinity in time and space. The salinity at this section ranges from zero at low tide and high discharge to nearly oceanic at high tide and low discharge. During the high-runoff season, the water along the right side of the cross section is on the average somewhat fresher than that along the left, in accordance with the idea that the seaward flow of river water should be deflected to the right by Coriolis Force. During the low-runoff season, however, the situation is reversed -- the fresher water occurs along the left bank of the estuary. A location map of the Columbia River estuary is also provided in Figure III-76. Figure III-77 presents a longitudinal? salanity distribution during high tide for low river flow and for high river flow.

The degree of mixing within the estuary varies with the river

Figure III-76

Variations in Salinity (on 0/00) Over the Tidal Range--Clatsop Spit-Sand Island Section§



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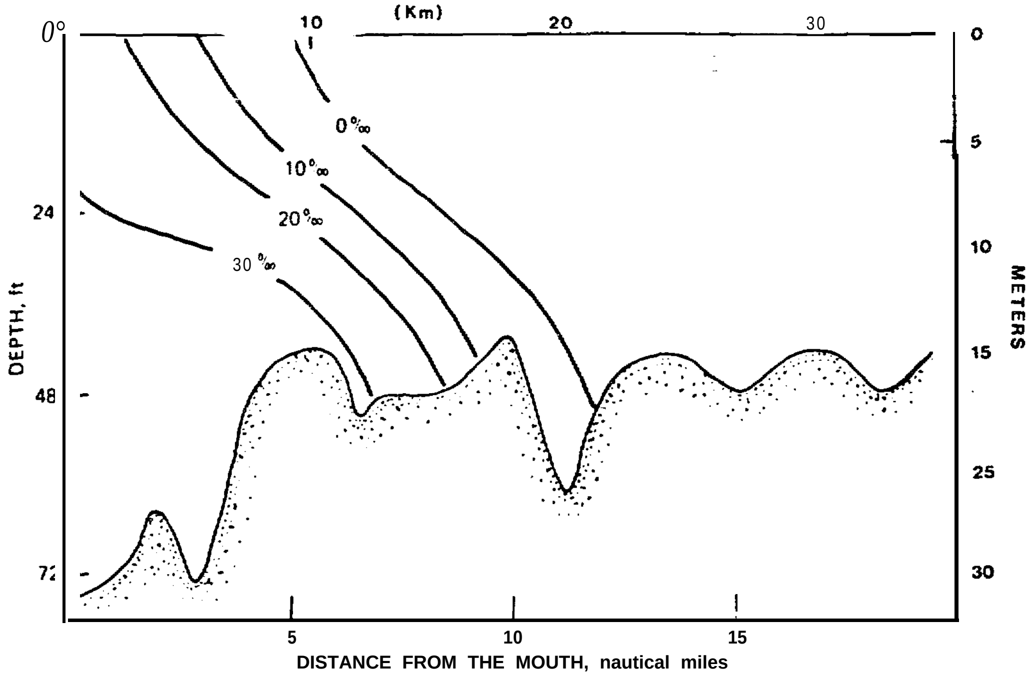
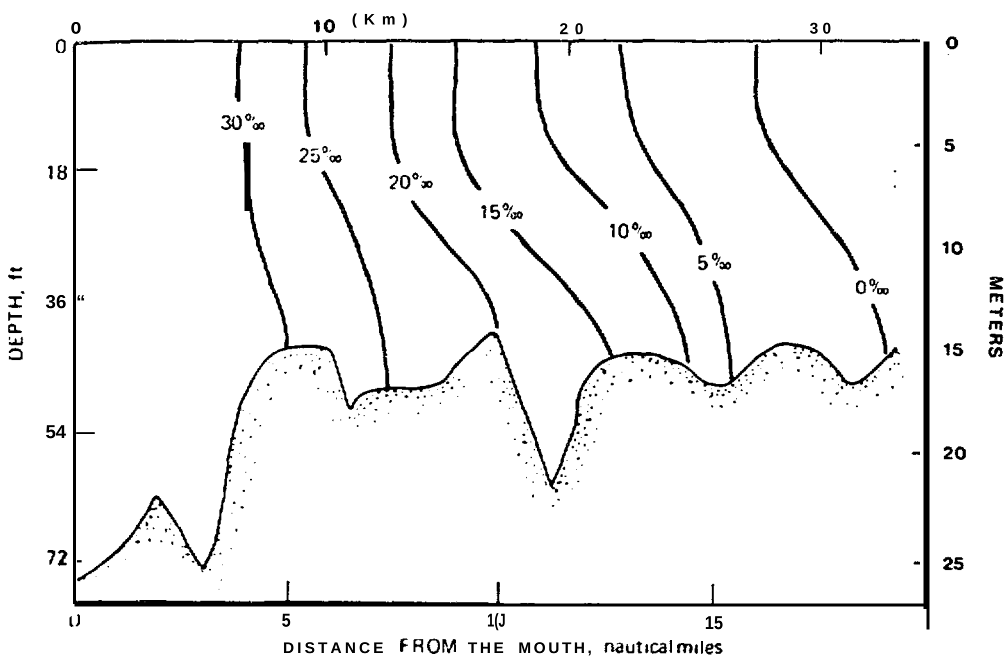
§Hansen, 1965.

Figure III-77

Longitudinal Salinity Distribution During High Tide for Low River Flow (top) and for High River Flow (bottom)[§]





[§]Neal, 1972.

flow, the tidal *stage,* and the point of measurement. The estuary is classified as partially mixed near the river mouth except during periods of low river flow when it can be considered well mixed. Near Tongue Point (about 20 km from the mouth), the estuary may also be partially mixed, except during stages of high river flow when it may become stratified or even completely fresh at low tide (Neal, 1972).

The distribution of freshwater or seawater within an estuary can be used to indicate the probable distribution of pollutants if the point of entrance and the rate of entrance of pollutants are known. Neal (1972) summarized results of different methods of predicting flushing rates and presented comparative results. Table 111-33 from Neal (1972) presents flushing times predicted by a modified tidal-prism method for various combinations of river flow, salinity intrusion, tidal range, and ocean salinity.

vii. Willapa Bay. Willapa Bay is a large estuary located in southern Washington. The bay is formed by two arms. The southern arm, created by the-Long Beach Peninsula, extends 29 km south from the entrance, and the eastern arm extends 19 km east of the entrance. The interior of the bay is a complex of channels, shoals, sloughs, and flats. The area of the bay is 284.9 km^2 at mean higher high water, but this is reduced to 155.4 km^2 at mean lower low water and additionally, 46.6 km^2 of the area at MLLW are under only 2 m of water. Willapa Bay is considered to be one of the most biologically productive estuaries of the Pacific Coast of the United States.

Mean annual runoff in the Willapa Basin ranges from about 1.25 m at lower elevation in the west and north to about 3.0 m in the upper Naselle River Basin in the southeast. Runoff is continuous throughout the year, although there are seasonal changes, corresponding to changes in rainfall and snowmelt. Peak flows occur in December and January and low flows occur in August and September.

The runoff is a factor in providing flushing action to remove pollutants from the bay and in providing nutrients and oxygen to the bay. Vertical mixing of the runoff with seawater is important in promoting exchange of the seawater in the tributary arms of the estuary. Volume of mean daily runoff is only 0.004% of the volume of the bay and, except for peak periods, the runoff is a relatively insignificant flushing influence in the open bay. Extreme peaks in riverflow are only 0.10% of the tidal prism, and thus do not suggest as great a contribution to the nutrient level of the bay by the rivers, as compared with that of the ocean.

Water conditions are influenced greatly by the exchange of water carried in by the tidal currents. Most of the bay is very shallow, with about S5% of the area of the bay drained at MLLW. Of the total volume of the bay, 1.6 x $10^6 m^3$, the tidal prism or volume exchanged during one tidal cycle is 0.7 x $10^6 m^3$. This means that approximately 45% of the water in the bay is emptied into the Pacific Ocean on a tidal cycle from MHHW to MLLW.

While it might appear that the large tidal prism would bring about a fast turnover of bay water, this is not always the case. Conditions in the ocean, with which the bay waters mix, determine how

Table III-33

Flushing Times predicted by the Modified Tidal-Prism Method for the Columbia River Estuary[§,‡]

River flow, m^3/tidal cycle	Tidal range, m	Maximum salinity intrusion, km	Total flushing time, tidal cycles
16×10^7	2	35	9.00
16×10^7	2	41	9.91
16×10^7	2.5	35	9.00
16×10^7	2.5	41	9.12
19×10^7	2	41	8.59
19×10^7	2.5	41	8.66
21×10^7	2	35	8.23
21×10^7	2.5	35	7.78
48×10^7	2	22	4.40
48×10^7	2.5	26	4.28

§Neal, 1972.
‡Summary of results obtained by the modified tidal-prism method for various combinations of river flow, salinity intrusion, tidal range, and ocean salinity.

much of the water that leaves the bay will return on the next incoming tide. In the summer, strong northwesterly winds bring upwelled water from the ocean into the bay, promoting a rapid turnover. storms and high wave action will also promote mixing. At other times, the Columbia River plume, acting as a discrete water mass, prevents much mixing from occurring and the water from the bay moves back and forth for days. The survival of oyster larvae long enough to set in the bay indicates that, at times, complete flushing must take more than 20 days (U.S. Army Corps of Engineers, Seattle District, 1976b).

In general, this estuary is well mixed from May through October, while it alternates between well mixed and partly mixed, November through April. During periods of heavy runoff, a layer of fresh water can be found in the upper estuary near tributary streams. During the winter, the water of the Pacific Ocean just outside the bay's entrance is less saline due to the north tending Columbia River plume.

The annual temperature in the bay exhibits the trends that would be expected in a shallow estuarine situation. Temperatures in the Willapa River at Raymond and South Bend exhibit high and low extremes, ranging from less than 3°C in February 1969, to 20.4°C in August of the same year. Temperatures closer to the ocean at Toke Point show a lesser range of temperatures ranging from 7.2°C in January to 17.4°C in July, due to the moderating effect of the ocean. There is little variation in temperature between surface and bottom waters, indicating a high degree of mixing throughout the bay and up the Willapa River most of the year.

Although the salinity varies greatly from year to year, most of the layering appears in the winter, when freshwater inflow is highest. The greatest recorded difference was in the Willapa River at Raymond in November when the surface salinity was 7.5 o/oo and 2.4 o/oo at a depth of about 6 m. The figures indicate the presence of a salt wedge, over which a great deal of freshwater runoff was flowing. Layering is usually less well defined with surface salinity usually remaining within 1-2 o/oo of bottom salinity. Where layering does occur, there is still some mixing at the interface between the seawater and freshwater. This mixing lets the outflow remove some of the seawater in the salt wedge, thus providing for renewal of seawater that might otherwise be trapped in the upper reaches of the estuary.

In the open bay, the greatest recorded layering was a difference of 16 o/oo near the mouth of the Willapa River. Surface and 6 m salinities usually remain within 1 o/oo around Toke Point and in the center of the bay.

viii. Grays Harbor. At mean higher high water, Grays Harbor has a surface area of approximately 260 km^2. At mean lower low water, the surface area of the water is reduced to about 90 km^2. This provides roughly 170 km^2 of intertidal lands. Grays Harbor has the greatest percentage of tidelands of any of the estuaries on the Oregon-Washington coast. The maximum depth within the harbor is approximately 20 m.

The watershed that drains into Grays Harbor includes some 6630

km^2, with tributary headwaiters in all of the surrounding mountainous regions of Grays Harbor, Jefferson, Pacific, Mason, Lewis, and Thurston Counties. The Chehalis River drains over 5,100 km^2, or 80% of the tributary watershed. Approximately 1300 km^2 are drained by the Humptulips (the principal tributary to North Bay), Hoquiam, Wishkah, Johns and Elk (principal South Bay tributary) Rivers; the remaining 130 km^2 includes smaller local tributaries. The mean daily fresh water inflow to Grays Harbor is 300 m^3/see, which is roughly three times that of Willapa Bay. Surface runoff in the summer may be as low as 30 m^3/sec (U.S. Army Corps of Engineers, Seattle District, 1976a).

The volume of the harbor at mean higher high water is about 0.96 km^3 and at mean lower low water about 0.45 km^3 giving a tidal prism of 0.51 km^3, representing over 50% of the total MHHW volume. Like Willapa Bay, circulation in Grays Harbor is dominated by the tides and not runoff.

The currents in the harbor are complex. They do not change appreciably with depth, but do alter considerably over small horizontal distances. Their speed changes constantly with the stage of the tide. At the turn of the tide, and for an hour before and after, the water is almost still. At the peak movement of flow and ebb, the current moves about 2/3 of the tidal prism in about 1/3 of the time period of the change. At the harbor entrance, peak currents in normal weather are about 2.5 m/see, a large flow of freshwater, increasing the outbound speed and a prolonged offshore ocean gale increasing the inbound speed. In the north and south bays, currents rarely exceed 1,5 m/see.

All this is complicated by the inflow of water from the tributary rivers. It is further complicated by the fact that the tide is not at the same stage all over the harbor at the same time. For instance, high tide takes 40 minutes to progress from the harbor entrance to the Port docks in the City of Aberdeen.

Measurements made to find out how far the water moves on a single turn of the tide showed floats carried upstream on a flood tide from 13 to 16 km, and carried downstream on an ebb from 16 to 18 km. Wind waves in the harbor entrance are limited by water depth to a height of about 2 m. During an ebb tide there can be breakers the full width of the entrance, 2.S km each way (Grays Harbor Regional Planning Commission, 1972).

The water ranges from fresh at the head of the harbor to ocean water of 30 to 31 o/oo just inside the harbor entrance. Incoming tides push the salt water farther east, river freshets push it farther west. During the summer, the salinity just east of the mouth of the Hoquiam River ranges from 16 to 23 o/oo with the higher figure at high tide. During the winter, the water at this point is almost completely fresh at all tide stages. The degree of mixing varies, but at some times the fresh water rides on top of the salt water. During summer low-flow, it takes a given drop of water 80 tides to get from the head of the harbor to the mouth, nearly all this time being spent in the bottleneck and the tidal reaches of the tributary rivers.

The greatest variation in water temperature in any one day is only about 6°C, but seasonally the water temperature follows the air temperature. The highest on record is 23 °C and the lowest 0.4 °C. In spring and summer, the harbor water temperatures are higher than the ocean water temperature just outside the harbor. In winter this is reversed.

b. Chemical Oceanography of Estuaries. The processes of flushing, mixing, runoff, and the wide ranges of salinity and temperature that occur, affect the chemical processes and the distribution of chemical components within estuaries. Seasonal changes of Pacific Ocean source water (upwelling, Columbia River plume, etc.) affect them. Man's activities around the estuaries increase the waste loading, and concentrations of pollutants are generally higher. The Columbia River was unique during the operation of the Hanford plutonium producing reactors because of its high radioactivity. Chemical oceanographic data for some of the estuaries is presented here.

i.. Coos Bay Estuary. Oxygen levels of one to two mg/1 have been reported during late summer and early fall (Pacific Northwest River Basins Commission, 1971).

ii. Yaquina Bay Estuary. Table III-34 presents selected water quality data for Yaquina Bay at River Kilometers 1.6, 3.5, 6.0, 19.0 and 24.6 from the mouth. Maximum, minimum and mean values for identified sampling periods are presented. The pH decreases upstream from 8.1 at Kilometer 1.6 to 7.05 at Kilometer 24.6. The dissolved oxygen concentration reflects the oceanic conditions at Kilometer 1.6 with the minimum value of 3.5 mg/1 being related to coastal upwelling, and the higher values such as 10.4 mg/1 at Kilometer 6.0 reflecting the productivity. Five day biochemical oxygen demand (BOD) is also presented. Too few samples were obtained at the 19.0 and 24.6 River Kilometer stations to deduce any limits or trends.

iii. Siletz Bay Estuary. The Siletz River has a pH range of 6.8 to 7.3 with a neutral mean of 7.0. In general, a slight decreasing trend in pH value is shown in the upstream direction. In the winter and spring, the heavy rainfall and runoff cause the estuary to become acidic. Low December tides can lower the pH to the 3.0 to 6.0 range (Rauw, 1974).

iv. Columbia River Estuary. Park, Osterberg and Forster (1972) measured chemical parameters on a monthly basis during 1966 and 1967 within the Columbia River estuary. The chemical properties routinely monitored were alkalinity, pH, dissolved oxygen, total carbon dioxide, phosphate, dissolved silicon (silicate), nitrate, nitrite, and salinity. The data, along with the stream flow rate, enabled them to calculate the monthly and annual budgets of these properties. Plots of the various properties as a function of salinity are presented in Figure III-78. Where the lines slope down to the right, the river concentrations (or values) exceed the ocean concentrations, such as with silicate and oxygen year round. Where the lines slope up to the right, the river concentrations (or values) are less than the oceanic concentrations, such as with pH, alkalinity and total CO_2. The winter nitrate values for the river are higher than for the summer, and exceed the oceanic concentrations in the winter, but not in the summer. For the most part, phosphate concentrations remain higher in the oceanic

Table 111-34

Selected Water Quality Data for Yaquina Bay and River[s]

(a) Yaquina Bay at Newport Bridge (Hwy-101), River Mile 1.0, Water Quality Analysis 1960-1973

Parameter	No. of Samples	Maximum	Minimum	Mean
DO (mg/1)	31	9.8	3.5	8.4
BOD (mg/1, 5-day)	30	6.6	0.0	1.2
pH (SU)	31	8.6	7.6	8.1
Salinity (ppt)	22	34.1	22.4	29.7

(b) Yaquina Bay at McLean Point, River Mile 2.2, Water Quality Analysis 1960-1973

Parameter	No. of Samples	Maximum	Minimum	Mean
DO (mg/1)	32	9.8	4.5	8.4
BOD (mg/1, 5-day)	32	6.6	0.0	1.2
pH (SU)	32	8.4	7.6	8.1
Salinity (ppt)	23	34.1	17.8	28.2

(c) Yaquina Bay at Coquille Point, River Mile 3.7, Water Quality Analysis 1960-1973

Parameter	No. of Samples	Maximum	Minimum	Mean
DO (mg/1)	32	10.4	4.8	8.3
BOD (mg/1, 5-day)	29	4.3	0.0	1.2
pH (SU)		8.3	7.6	8,1
Salinity (ppt)	24	33.5	9.4	27.3

(d) Yaquina River below Toledo, River Mile 11.8, Water Quality Analysis 1960-1967

Parameter	No. of Samples	Maximum	Minimum	Mean
DO	4	7.40	4.00	5.05
DO (% Saturation)	4	71.00	43.00	52.75
BOD (mg/1, 5-day)	4	3.70	.20	1.58
PH (SU)	4	7.40	6.90	7.20
Total Alkalinity (mg/1 $CaCO_3$)	4	88.00	49.00	68.50
NH3-N (mg/1 Total)	1	.31	.31	.31
NO_3-N (mg/1 Total)	4	.12	.01	.05
Ortho-PO_4 (mg/1 P04)	4	.10	.01	.053

Table III-34 (cont.)

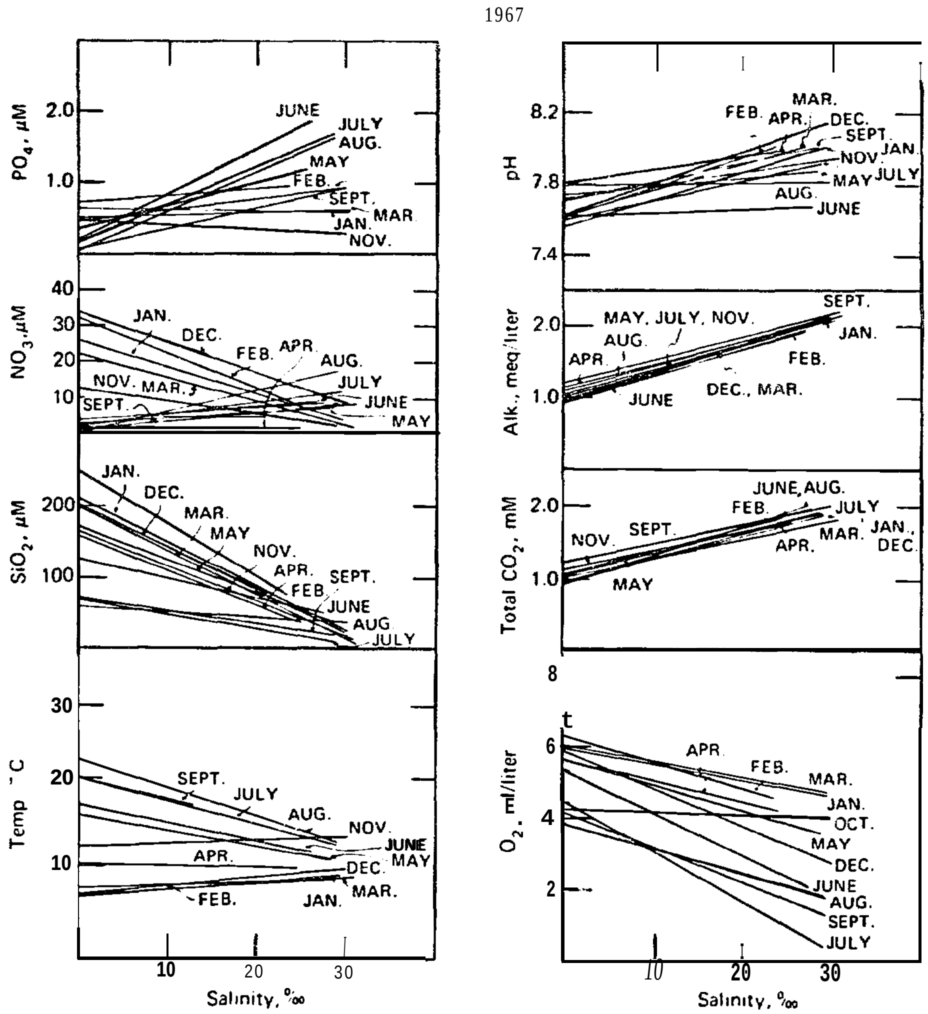
(e) Yaquina River above Toledo, River Mile 15.3, Water Quality Analysis 1966-1967

Parameter	No. of Samples	Maximum	Minimum	Mean
DO (mg/l)	3	6.20	4.10	5.13
DO (% Saturation)	3	60.00	44.00	53.00
BOD (mg/l, 5-day)	3	3.40	.60	1.70
pH (SU)	4	7.20	6.90	7.05
Total Alkalinity (mg/l $CaCO_3$)	4	70.00	22.00	48.50
NH_3-N (mg/l Total)	1	.31	.31	,31
NO_3-N (mg/l Total)	4	.08	.02	.06
Ortho-PO_4 (mg/l P04)	4	.11	.01	.04

[5]U.S. Army Corps of Engineers, Portland District, 1975d.

Figure III-78

Temperature and Chemical Parameters as a Function of Salinity in the Columbia River Estuary, 1967[§†]



§Park, Osterberg and Forster, 1972.

water than in the river water. Large variations occur in phosphate, pH, oxygen and nitrate for the oceanic waters because of summer upwelling.

Based on 1966 and 1967 data the average chemical composition of the river water (not the estuary) is 0.5 μM phosphate, 12 μM nitrate, 160 μM silicate, 1.0 meq/liter alkalinity, 1.0 mM total carbon dioxide, and 7.4 ml/liter oxygen. Average pH is 7.7.

The effect of the Columbia River effluent on the "limiting nutrient" can be studied by estimating the nutrient ratio from monthly nutrient concentrations. During May to September the nitrate/phosphate ratio is generally less than the normal assimilation ratio of 16:1 and reaches a minimum of 1 in June and July 1966. Therefore, the river water flowing into the ocean during these months helps nitrate to become the limiting nutrient. Conversely, during the rest of the year the nitrate/phosphate ratio is greater than 16:1 and reaches a maximum of 67 in December 1967. Therefore, it 'tends to reverse the selection of the limiting nutrient locally (Park, Osterberg and Forster, 1972).

v. Willapa Bay Estuary. In Willapa Bay, the dissolved oxygen level appears to be influenced most strongly by physical factors such as wind and waves, which move in from the ocean and add to the dissolved oxygen level by agitating the surface of the water, and temperature, which affects the water's ability to hold dissolved oxygen.

Maximum dissolved oxygen levels found in the bay are 1S mg/l. This extreme is not representative of the level found throughout the bay but shows the influence that low winter temperatures and wind and wave action can have on the dissolved oxygen.

Representative winter levels are between 8 and 11 mg/l. These levels stay more or less steady through May or June, and then drop off to a summer level between 6 and 9 mg/l. The coming of autumn brings an upturn in the seasonal curve. Coastal upwelling and high water temperature in the bay are responsible for the lower summer values. Occasionally, in the Willapa River near Raymond, levels of 5 mg/l have been recorded (U.S. Army Corps of Engineers, Seattle District, 1976b) .

vi. Grays Harbor Estuary. Herrman (1975] conducted fish bioassays in which test vessels were supplied with constantly renewed water pumped directly from Grays Harbor. The character of the water was dynamic, that is, constantly changing with tide and current patterns. Water quality changes over time were characterized and related to mortality or signs of distress in juvenile chinook salmon. The test site selected was off the west end of Port Dock Slip No. 1 (at Hoquiam) because of an oxygen sag that occurs in the upper harbor. The ITT Rayonier Pulp Mill (and effluent outfalls) is located about 1 km west of the test site, and the Weyerhaeuser Pulp Mill outfall is located about 2 km east of the site. Water was pumped from the surface and from off the bottom into separate bioassay troughs which held the test fish. Table III-35 presents water quality data averages for the time periods of the bioassay studies, and Table III-36 presents metal levels observed. The following discussion of the test results is drawn from

Table III-35

Water Quality Averages in Bioassay Troughs by Testing Period, 1974[§]

Parameter	May 21-25	June 24-28	July 2-6	July 29-August 2
Temperature ‘c				
Surface	12.7	15.7	16.1	18.3
Bottom	13.0	15.2	15.9	17.9
Dissolved Cxygen (mg/L)				
Surface	7.45	6.35	5.88	5.60
Bottom	6.90	6.05	5.78	5.43
Salinity (0/00)				
Surface	3.2	10.1	11.3	12.7
Bottom	6.1	13.9	14.1	15.4
pH				
Surface	6.99	7.07	7.15	7.14
Bottom	6.94	7.15	7.25	7.22
BOD (mg/L)				
Surface	4.5s	2.08	1.60	2.27
Bottom	5.13	2.58	1.45	1.97
Carbohydrate (mg/L)				
Surface	4.04	2.41	3.4	2.46
Bottom	4.44	2.47	3.3	1.91
Turbidity (JUT)				
Surface	13.5	4.95	5.30	4.06
Bottom	16.1	6.80	6.70	4.98
T.S.S. (mg/L)				
Surface	30.9	17.0	14.90	12.2
Bottom	38.4	26.5	20.1	14.2
NH_3-N (µg/L)				
Surface	-†	-1-	-†	-i
Bottom	-i	-t	-†	-t
NO_3-N (µg/L)				
Surface	40.9	43.3	39.9	46.4
Bottom	17.8	34.1	39.4	55.3
Total PO_4-P (µg/L)				
Surface	54.8	45.6	35.8	25.8
Bottom	70.9	59.6	45.2	31.7
Chlorophyll “A” (µg/L)				
Surface	2.52	4.17	3.04	2.58
Bottom	3.74	6.45	3.92	3.20
Carotenes (µg/L)				
Surface	1.86	2.86	1.74	1.03
Bottom	3.03	4.43	1.91	1.24
Sulfides (mg/LO				
Surface	--1-	0‡	0‡	0‡
Bottom	-i	0*	0‡	0‡

§Herrman, 1975.
†No data; test methodology failure
‡Below limit of detection

Table III-36

Analysis of Grays Harbor Benthic Substrate Samples† Collected May 25, 1974§

	Gross Features - Per Cent							Metals - mg/kg (ppm)														
	Moisture	TVS		COD		Kjeldahl-N		Cadmium		Chromium		Copper		Lead		Mercury		Nickel		Zinc	
		Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Pile Dolphin 50 ft west of Port Oock	67.7	3.9	10.1	3.8	11.6	0.09	0.29	0.4	1.3	21	66	19	60	0.16	0.51	0.01	0.03	13	40	30	93
Port Slip No. 1	53.7	3.5	7.S	3.0	6.4	0.07	0.16	0.4	.0	25	54	25	S4	0.15	0.32	0.02	0.04	19	40	38	82
Off East End of Test Barge 50 ft	s9.9	3.8	9.4	4.0	9.9	0.11	0.27	0.7	.7	23	58	26	64	0.21	0.53	0.02	0.0s	13	32	37	92
Off West End of Test Barge so ft	S2.3	3.S	8.3	3.5	8.3	0.08	0.19	0.4	1.1	25	60	22	53	0.32	0.75	0.02	0.05	17	39	34	81
Rennie Island at Station 2A	58.6	3.8	9.1	3.S	8.4	0.08	0.10	<0.4	<1.0	14	34	16	39	0.26	0.62	0.02	0.05	<3	<6	19	46

§Herrman, 197S.
†Analyses expressed on wet weight end dry weight basis.

Herrman (1975) .

In the two tests in mid-May and late June no chinook died (0/28 and 0/58). Chehalis flows during the tests were high (183 m^3/see and 91 m^3/see, respectively), promoting good bay flushing, but pulp mill effluent loading, measured by Biochemical Oxygen Demand (BOD) also was high (163,470 kg/day and 69,600 kg/day). BOD levels in the test troughs were higher in these two tests than in the two July tests, but salinities and water temperatures during the May and June tests tended to be lower and DO (dissolved oxygen) higher.

TWO chinook (2/40) died in the bottom trough during the July 4 holiday testing, when the pulp mills closed and greatly reduced their effluent BOD load (7,54S kg/day). Chehalis flows averaged 59.6 m^3/sec indicating reduced bay flushing rate; salinities and temperatures increased perhaps as a result. Dissolved oxygen and BOD improved during the course of the testing period as flushing removed the effluents; PBI remained relatively stable.

Five chinook died (5/40) in late July bioassays, four in the bottom trough and three in the surface trough. The three latter mortalities showed a positive test for vibriosis disease. Chehalis flows were similar to those in early July (56.9 m^3/see), but flushing was poorer due to a neap tide situation. The effluent BOD load averaged 32,204 kg/day, less than half the level during the late June testing. BOD in the test troughs was only slightly lower than in the June bioassays. Perhaps more concentrated pulp wastes were being stored during this final test. Salinities during the testing reached 22.5 o/oo and temperatures, 19°C; minimum DO values of 4.5 mg/1 were recorded; these suboptimal conditions for fingerling chinook and the diagnosed incidence of vibriosis seemed responsible for poorer survival compared *to* the three earlier tests.

Except for the diagnosed incidence of vibriosis, no single factor could be linked with the instances of mortality, indicating perhaps that cumulative effects of salinity acclimation, capture and handling, sublethal high temperatures, low DO, heavy metals and pulp effluents caused the observed losses.

c. Biological Oceanography of Estuaries.

i. General Discussion. Coastal embayments may vary from essentially oceanic-neritic ones in which little freshwater input occurs, to ones in which large volumes of freshwater dilute surface waters greatly. On the Washington and Oregon coasts, the tidal range is large and tidal mixing may vary the bottom salinity regularly. Tidal salt wedges penetrate some bays as nearly undiluted marine water. The species present in an estuary are a function of tidal cycles, river volume, and turbidity. For general information, see Lauff (1967].

Estuarine phytoplankton have been examined for the Columbia River estuary (Haertel, *et al.*, 1969), and Yaquina Bay (McMurray, 1976; Deason, 1975, and Karentz, 1975). The Columbia River is characterized by high freshwater input and a well-developed tidal wedge. Distinctly fresh, brackish, and marine waters are present and occupied by identifiably distinct species assemblages.

... Specific Data. Dominant phytoplankton species of the Columbia River were (Haertel, *et al.*, 1969):

FRESHWATER	MARINE/BRACKISH WATER
Melosira granulata	*Nitzschia closterum*
M. italica	*Thallasionema nitzschoides*
Fragilaria crotonensis	*Fragilaria oceanica*
Asterionella formosa	*Asterionella japonica*
Synedra ulna	

Freshwater phytoplankton varied in abundance from nearly zero in winter to 17,000 cells/ml in May 1967 and 26,000 cells/ml in May 1968. Marine and brackish species varied from zero in winter to 600-1,600 cells/ml in late summer, never contributing more than 8% of total phytoplankton numbers. Marine species were always restricted to the salt wedge. The Columbia River freshwater and marine species show affinities to Koga's inshore and offshore species, respectively.

High turbidity apparently caused light limitation, as variations in abundance were closely correlated with light in freshwater species. Marine species, as intruders, were not controlled by light levels in the estuary, but rather by variations in the source population outside the estuary.

McMurray (1976) found that in Yaquina Bay, *Chaetoceros debilis* co-dominated phytoplankton biomass, contributing from 20% to 74% in April and May 1974. The second major contributor was *Thalassiosira decipiens*, ranging from 20% to 60% of biomass. The remainder of biomass for all other species was typically 10%. Flagellates were occasionally significant (up to 20% of biomass]. Total biomass ranged from 1.11 x $10^8 \mu m^3/l$ to 71.06 $\mu m^3/l$. Biomass is given by volume because of the counting method used. Deason (1975) found that during the same period, *Skeletonema costatum* and *Thalassiosira fluviatilis* also reached large numbers for a brief period.

Productivity was measured at 4.7 $mgC/m^2/hr$ to 172 $mgC/m^2/hr$ (McMurray, 1976). Production increased at high tide due to a larger water column. The diatoms dominated production at high tide but flagellates dominated at low tide. This suggests that diatoms were introduced at high tide, but flagellates were indigenous. Deason (1975] estimated productivity at nearby stations only 10-20 minutes later, and found that productivity was about 5 times lower for some stations. McMurray attributed this to the effects of tidal current velocity on production. The rate of tidal current change is quite rapid.

Closest agreement of Deason's and McMurray's data was at slack tide. McMurray also suggested Deason's incubator bags may have been too close to the surface and experienced light inhibition.

Karentz (1975) determined that C. *debilis*, *Plagiogramma brock-*

manni, *T. nitzschoides*, and *T. decipiens* were washed in at high tide, while *Melosira sulicata* and T. *fluviatilis* were indigenous. These were the most abundant species in fall 1974 and summer 1975.

The major difference between the Columbia estuary and Yaquina Bay appears to be the large tidal prism that is mixed daily in Yaquina Bay. The large freshwater input of the Columbia results in domination of freshwater species. Tidal variations in production are more pronounced in Yaquina Bay. Yaquina Bay is also more nutrient limited and less light limited, due to lower turbidity (McMurray, 1976). Other estuaries of the Washington and Oregon coasts should show a greater contribution of freshwater species with increasing river input or decreasing tidal mixing.

Estuarine zooplankton have been examined at Yaquina Bay, Netarts Bay, Alsea Bay, and the Columbia River. The Columbia River has an extensive brackish-water zone. Netarts Bay is essentially identical to coastal neritic water, and Yaquina Bay has a pronounced horizontal salinity gradient but little vertical gradient.

Table III-37 from Haertel and Osterberg (1967) shows the freshwater, brackish, and marine species of dominant zooplankton. The overall abundance was dominated by the brackish-water copepod *Eurytemora hirundoides* (= *E. affinis*), which reached numbers of up to $100{,}000/m^3$ in April, and averaged $100/m^3$ to $1000/m^3$. Freshwater species averaged $100/m^3$ in cold water in winter and up to $2000/m^3$ in warm water in summer. Marine species were essentially the same as the nearshore species reported by Peterson and Miller (1975), and averaged $500/m^3$.

Yaquina Bay, Netarts Bay, and Alsea Bay all are dominated by *Acartia clausi*, *A. longiremis*, *Pseudocalanus minutus*, *Paracalanus parvus*, and *Oithona similis* (Zimmerman, 1972, and Frolander, *et al.*, 1973). *Eurytemora americana* and *Arctia tonsa* are significant in Yaquina Bay, where there is a freshwater head, but not in Netarts Bay, which has no freshwater area. *A. clausi* is also less important in Netarts Bay than in Yaquina Bay. Total zooplankton in Yaquina and Netarts Bay ranged from $170/m^3$ in winter to $13{,}000/m^3$ in summer (Zimmerman, 1972), lower than in the Columbia River.

Again, the major difference between the Columbia River and other estuaries is volume of river input. Freshwater and brackish species are more abundant in the Columbia, and the extensive brackish habitat allows large numbers of zooplankton, dominated by the brackish-water copepod *Eurytemora affinis*. Higher copepod abundance may contribute to greater input of regenerated nutrients, so that the Columbia estuary is not nutrient-limited (Haertel, *et aZ.*, 1969). This may also increase phytoplankton production (Deason, 1975), but the available data are inadequate to evaluate this.

As with upwelling zones, river flow tends to remove populations from embayments. *E. affinis* centers its distribution below the zone of maximum flow (Haertel, *et al.*, 1969). The means by which other species maintain themselves in estuaries is not definitely known, but

Table III-37

Seasonal Occurrence of Common ZooPlankton Measuredein avg no. /m^3 at the Station of Greatest Abundance[§]

CATEGORY	SPRING '64	SUMMER '64	FALL '64	WINTER '65	SPRING '65	SUMMER '65
Freshwater group						
Rotifera:						
Brachionus spp.	. **IV**			II	III	**II**
***Asplanchna* sp.**		III	II	III		II
Ciadocera:						
Alona costata	II	III	I	II		
Chydorus globusus	II	III	III	II	II	
Diaphanosoma brachyurum		III	III			I
Ceriodaphnia quadrangula			IV			III
Bosmina spp.	**IV**	**IV**	III	11	**II**	**IV**
Daphnia longispina	**III**	v	III	II	**II**	IV
Copepoda:				II		
Diaptomus	**IV**	III	**II**	III	I	**III**
Cyclops vernalis	**IV**	IV	IV	111	**III**	IV
Total	**IV**	**V**	**V**	III	III	v
Brackish group:						
Eurytemora hirundoides	**VI**	VI	VI	**III**	III	IV
Salt-intrusion group						
Cladocera:						
Evadne nordmanni		III	III			III
Copepoda:						
Acartia clausi		II	IV		III	**III**
A. longiremus		II	III	II	III	**II**
Pseudocalanus minutus		II	**IV**	**III**	IV	II
Calanus finmarchicus	**III**	II	II	II		
Oithona similis			III	II		
Total	**III**	III	IV	**III**	IV	Iv

LEGEND I **0.1-0.9/m^3**
II 1.0 **-9.9/m^3**
III **10.0-99.9/m^3**
IV **100.0-999.9/m^3**
V l,000.0-9,999.9/m^3
VI 10,000.0-99,999.0/m^3

[§]**Haertel** and Osterberg, **1967.**

probably is by growth rates in excess of advective losses -- not by use of reversed bottom flows, since few or no species can tolerate both fresh and marine waters.

3. Washington-British Columbia Inland Waters. The inland waters for this study extend from Cape Flattery on the west to Everett on the east, south to Olympia and north to the U.S.-Canadian border (40-00°N) in the southern Strait of Georgia. The following physical description of the area is adapted from Parker [1977?].

The Strait of Juan de Fuca - Strait of Georgia Basin is a 470 km waterway separating Vancouver Island from the mainland of British Columbia and the State of Washington. As discussed later, the great length and geographical complexity of this basin result in a complicated tidal hydrodynamic system.

About 100 km to the west of the entrance to the Strait of Juan de Fuca the Pacific Ocean decreases to a depth of 180 m (La Perouse Bank). However, water depths greater than 180 m extend 7S km into the Strait in the form of a submarine canyon. Near the strait entrance this canyon is almost 13 km wide and on both sides the water depth decreases to approximately 55 III.

The Strait of Juan de Fuca is about 165 km long. It is 22 to 28 km wide from the entrance to the Race Rocks-Angeles Point area, where it narrows to 18 km. Eastward it widens again to as much as 45 km. Water depth is greatest in the western half, where it reaches 275 m in the canyon at the entrance. The eastern half is shallower and more irregular, with deep spots varying from 70 to 110 m and numerous shallow areas occurring even in the middle (including several banks and Smith and Protection Islands).

The eastern end of the Strait of Juan de Fuca leads into three smaller waterways (Admiralty Inlet, Haro Strait, and Rosario Strait) and a very small pass (Deception Pass). Admiralty Inlet, in the southeast corner, is the 6 1/2 km wide main entrance to Puget Sound; it averages about 55 m in depth. Deception Pass connects the northeast corner of Juan de Fuca (near the Rosario Strait entrance) with Skagit Bay, which is part of the Puget Sound system. This pass is about 4km long and less than 1/2 km wide.

Haro and Rosario Straits are formed by the San Juan Islands separating the Strait of Juan de Fuca from the Strait of Georgia to the north. Both Haro and Rosario Straits are nearly perpendicular to the lengthwise axis of Juan de Fuca. Rosario Strait is approximately 39 km long and is 55 to 90 m deep over most of its length. Its width varies from almost 11 km at the southern entrance to a minimum of 3 km between Blakely and Cypress Islands then increases to 6.5 km between Orcas and Lummi Islands. It is connected by several channels with two shallower bays to the east, Bellingham Bay (30 m deep and less) and Padilla Bay (generally less than 20m deep except near Guemes Island where it reaches over 60 m in places).

Haro Strait is 61 km long and has a 100° bend in the middle near Moresby and Stuart Islands. It is much deeper than Rosario, as great as 290 m at several central locations along the Strait. At the southern entrance the depth in the western half averages 73 m while the depth in the eastern half reaches over 200 m. Further north, the shallower west half eventually leads into islands and channels. The northern half of Haro Strait has entrances to shallower channels to the northwest that run parallel to the Strait of Georgia for some 83 km. Waldron Island separates the northeastern half of Haro Strait from President Channel, which is also very deep (reaching approximately 195 m). This channel is approximately 10 1/2 km wide and runs between Waldron and Orcas Islands. At its northern end Haro Strait meets the Strait of Georgia (via Boundary Pass] at an approximate right angle.

The San Juan Islands between Haro and Rosario Straits consist of three large islands (San Juan, Orcas, and Lopez) and many smaller ones. The several inner channels formed by these islands, though narrow, are relatively deep, reaching a maximum depth of 180 m at the northern end of San Juan Channel. Three main entrances to these inner channels account for most of the water exchange with the surrounding waterways -- the northern end of the San Juan Channel connected to Haro Strait, Middle Channel connected *to* the Strait of Juan de Fuca, and Thatcher Pass connected to Rosario Strait. To the north of Orcas Island, four groups of islands (Pates, Sucia, Matia, and Barnes and Clark) tend to limit access to the Strait of Georgia to the passages between them. Boundary Pass in the deepest with a maximum of 265 m; the other passages reach about 90 m.

The Strait of Georgia makes up the greatest length of this entire system, being approximately 280 km long. Its width varies from about 15 to S7 km. Except for its southernmost end, the Strait of Georgia is very deep at least 275 m over *its* entire length and attaining 410 m at several locations. The Fraser River and several large inlets run into the Strait of Georgia from the east; most of these inlets are as deep as the main strait (Desolation Sound at the northern end is even deeper, reaching 500 m. At its northernmost end, the Strait is connected to the Pacific Ocean via several narrow but fairly deep passsages (e.g., Discovery Passage and Johnstone Strait) and the wide Queen Charlotte Strait.

Puget Sound may be divided into five general sections that are partly isolated by vertical or lateral constrictions. Admiralty Inlet winds 47 km to the south-southeast from the east end of the Strait of Juan de Fuca. Its average width is 5 to 6 km and it is narrowest to the west of Bush Point (about 4.5 km). Admiralty Inlet has a threshold sill depth of 73 m.

The main basin of Puget Sound runs 70 km north-south from the southern end of Whidbey Island to Tacoma. Depths of 180 to 240 m prevail in this section with occasional deeper holes, and a maximum of 283 m off Point Jefferson (northwest of Seattle). Bainbridge Island isolates Liberty Bay, Port Orchard, Dyes and Sinclair Inlets from the main basin with narrow shallow sills at both the south and north end of the island. Vashon and Maury Islands at the south end of Puget Sound offset the north-south alignment of the sound, and separate the waters into East and Colvos Passages.

Tacoma Narrows, less than 1.5 km wide, 10 km long and 55 m deep separates the main basin from Southern Puget Sound, a primary basin in excess of 150 m with many branching channels and inlets. The main inlets are Case Inlet (30 km) and Carr Inlet (23 km). This area has numerous islands, the larger being Hartstene, Fox, Anderson and McNeil Islands. The Nisqually River empties into Southern Puget Sound and has built a sizeable delta.

Hood Canal, averaging less than 4 km wide and 180 m deep, extends about 75 km south-southwest from Admiralty Inlet, then turns more than 90° to the east and continues another 23 km to the head of Lynch Cove. Dabob Bay branches off 17 km to the north from the middle of Hood Canal. A 55 m sill near Bangor, in the northern half of Hood Canal, partly separates the waters of the Canal. Dabob Bay reaches 195 m depths and has an entrance sill of about 125 m.

Whidbey Basin , also referred to as Possession Sound, winds 65 km to the north on the east side of Whidbey Island, with diminishing depth to Deception Pass, a very restricted channel about 180 m wide and 30 m deep, leading to the Strait of Juan de Fuca. Extensive tide flats occur on the deltas of the Skagit, Stillaguamish, and Snohomish Rivers. Table III-38 presents physical descriptive data for Puget Sound.

The areas have been divided into the following oceanographic regions (Collias, 1970):

1. Strait of Juan de Fuca

2. Puget Sound, including
   Admiralty Inlet
   Hood Canal
   Main Basin Puget Sound
   Whidbey Island
   Southern Puget Sound

3. San Juan Island Passages and North Sound

4. Strait of Georgia

The inland waters and their subdivisions are presented in Figure III-79.

More than 40 oceanographers working on various aspects of the Puget Sound System, are collaborating on a book to be entitled Puget Sound: Oceanography of the Inshore Waters of Washington. It will be published by the University of Washington Press.

a. Physical Oceanography. As a result of glaciation, the bathymetry of the inland waters is complex. The water is generally quite deep (200 to 300 m), the basins are steep-sided, and shallow areas (sills) promote mixing and isolate bottom water in some of the inlets. Narrow channels separating bodies of water with relatively large tidal prisms results in strong currents in places.

The bathymetry serves to ampify the tide heights in places, controls and channels the tidal currents, and affects mixing at sills. This in turn affects water characteristics, flushing times, and biological processes.

Freshwater from precipitation and runoff forms a surface low-salinity layer that flows seaward, while oceanic water flows landward near the bottom. Coastal upwelling changes the characteristics of the oceanic source water for the inland waters, bringing considerable nutrients with it and influencing productivity. This upwelled water is also dense and

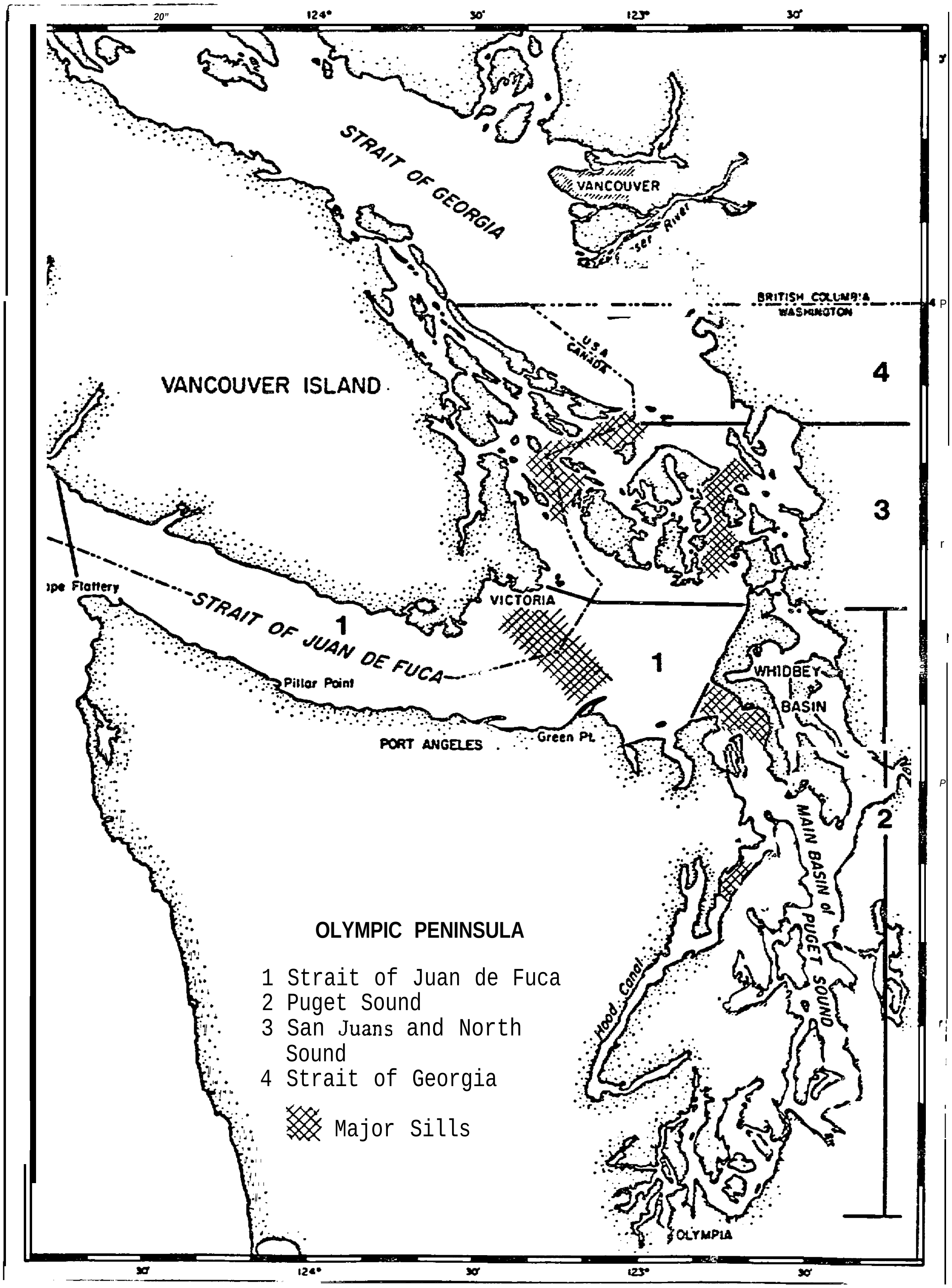
Table III-38

Physical Description of Puget Sound[§]

	Admiralty Inlet	Central Puget Sound	Southern Puget Sound	Hood Canal	Possession Sound	Total
Length of shoreline km (rim]						
	178 (96)	534 (288)	621 (335)	343 (185)	469 (253)	2144 (1157)
Horizontal area km^2 (nm^2)						
at MHW	396 (115.3)	767 (223.5)	449 (130.7)	389 (113.2)	635 (184.9)	2636 (767 .6]
at MLLW	376 (109.6)	720 (209.6)	384 (111.7)	347 (101.2)	505 (147.0)	2332 (679.1)
at 50 m	175 (50.9)	450 (131.2)	91 (26.4)	180 (52.4)	207 (60.2)	1102 (321.0)
at 100 m	56 (16.2)	354 (103.0)	30 (8.8)	95 (27 .8]	111 (32 .2]	460 (134.0)
to MHw	21.7 (3.4]	77.0 [12.1)	15.8 (2.5)	25.0 (3.9]	29.1 (4.6)	168.6 (26.5)
to MLLW	20.7 (3.3)	75.1 (11.8)	14.2 (2.2)	23.9 (3.8)	27.3 (4. 3)	161.0 (25 .3)
Mean tidal range m (ft)						
	2.63 (8.6)	3.26 (10.7)	3.86 (12.7)	3.20 (10.5)	3.15 (10.3)	
Annual river runoff m^3/sec. (ft^3/sec.)						
	2.83 (loo)	168.4 (5950]	66.2 (2340)	57.7 (2040)	836.9 (29572)	1132.1 (40002)
Minimal (maximum) river flow in:						
	Aug. (Jan.)	Aug. (Jan.)	July (Jan .]	Aug. (Dee.)	Aug. (Jan .)	Aug. (Jan.)
Total rainfall cm (in)						
for July	1.8 (0.7)	1.5 (0.6)	2.0 (0.8)	2.3 (0.9)	2. 0 (0. 8)	
for Dec.	7.9 (3.1)	15.2 (6.0)	26.7 (10.5)	30.7 (12.1)	10.9 (4.3)	
for year	63.5 (25.0)	89.0 (35.0)	140.0 (55.0)	152.4 (60. 0)	76.2 (30.0)	

[§]Duxbury, 1976.

Figure III-79
The Strait of Juan de Fuca - Georgia Strait - Puget Sound System



serves to flush out the deeper basins where bottom water may be trapped behind sills.

The Strait of Juan de Fuca is the connection between the ocean and the inland waters. It supplies salt water from the Pacific and it is the exit for freshwater. Because the waters of Puget Sound at the Strait of Georgia are not becoming fresh, a considerable volume of sea water must enter the Strait of Juan de Fuca in order to maintain a salt balance. With average tidal conditions and average river flow, the volume of Pacific Ocean water entering the Strait of Juan de Fuca off Cape Flattery is about 18 times the average flow of the Columbia River. The currents in the Strait are not strong because this region is deep (up to 200 m) and wide (averaging 18 km). At the eastern end of the Strait, the waters divide, with a large portion going into the Strait of Georgia and the remainder into Puget Sound.

The total system can be thought of as having three types of water masses: 1] the brackish surface water from runoff in the basins and Strait of Georgia, 2) the deep water of oceanic origin in the Strait of Juan de Fuca, and 3) a mixture of the two masses which forms at the sills. This mixture contributes to the deep water in the Strait of Georgia and the other basins, and to the upper seaward-flowing layer in the Strait of Juan de Fuca.

The principal approach for water entering the Strait of Georgia is Haro Strait, and Admiralty Inlet is the main approach for Puget Sound. Relatively minor exchanges of water occur through Seymour Narrows at the north end of Vancouver Island (for the Strait of Georgia) and at Deception Pass, between Whidbey Island and the mainland (for Puget Sound).

Superimposed upon the net circulation of surface outflow and deep in-flow are the large tidal currents, which provide the primary source of power for the vertical and horizontal mixing that occurs over the sills and in eddys around points of land.

i. Water Characteristics. The entire inland water system is technically an estuary (i.e., a semi-enclosed body of water, open to the ocean, in which there is significant dilution by freshwater), but within the system are separate component parts that function as distinct estuaries.

One may look at the inland waters as a mixture of seawater and freshwater. At any one time, the amount of fresh water in this mixture may be determined by calculating the volume of freshwater that is required to suppress the average salt concentration below that of the salt concentration of undiluted seawater available at the coast. Friebertshauser and Duxbury (1972) evaluated the salt and freshwater budget for different components of Puget Sound. Waldichuk (1957) did the same for the Strait of Georgia.

Every fall, in response to precipitation and lowland river discharge, the average salt content of Puget Sound decreases while the stored freshwater increases. A peak in freshwater storage occurs in late February. At this time the stored freshwater starts to decrease in response to decreasing lowland river discharge and the steady influx of salt water at depth. Then freshwater storage in the Sound increases again as rivers discharge the melting snow pack from the mountains. In summer, the river discharge to the Sound decreases rapidly and the stored freshwater in the Sound is displaced by incoming seawater. However, the period of greatest salt content for the Sound follows the minimum river input by at least a month, if not longer (Duxbury, 1976).

The freshwater discharged into Puget Sound is not distributed equally among its subregions. Approximately three-fourths of the freshwater flows through the Whidbey Basin system, and the freshwater stored in this portion of the Sound corresponds almost exactly to the local freshwater discharge.

The Fraser River discharge is more than twice the total discharge of all the rivers in Puget Sound. It is the single most significant source of freshwater in the inland waters (Roden, 1967). Most of the runoff of the Fraser is snow melt, so the peak discharges occur during the spring and summer. Consequently, the amount of freshwater within the Strait of Georgia is highest in the summer and a lesser peak in freshwater content occurs in the winter, associated with lowland drainage from lesser rivers.

a) Temperature. From October 1952 through September 1954, monthly surveys were made throughout Puget Sound and the Strait of Juan de Fuca to determine the longitudinal distribution and variations of physical and chemical properties. From 1955 *to* the present, intensive studies were made at various times unselected portions of Puget Sound. Data from these cruises have been published in tabular form and have been cataloged by Collias (1970). These data are also recorded on magnetic tape and area available for computer recall or analysis. In addition to data reports, an atlas has been prepared allowing a visual analysis of the distribution of properties as they change in space and time (Collias, McGary and Barnes, 1974). The 1952 and 1954 data is perhaps the most valuable, as it attempted to cover the entire Puget Sound region and over half the Strait of Juan de Fuca. Temperature, salinity, density, oxygen, and phosphate data from the atlas will be presented in this report for a longitudinal profile extending from Pillar Point in the Strait of Juan de Fuca to Devils Head in southern Puget Sound (Figure 111-80). The dashed line in Figure III-80 presents the track for which longitudinal profiles for the Strait of Juan de Fuca-Strait of Georgia system are presented.

Overall, the surface temperatures follow the insolation cycle, with a variable time lag. In summer, surface temperatures generally are highest in the slowly circulating extremities of the various embayments and lowest in turbulent channels. In winter, the lowest surface temperatures occur in the shallow, slowly circulating areas. The temperatures at depth respond more quickly to advective processes than to local heat surface exchange and in some basins may be as much as six months out of phase with the surface temperature cycle.

Figure 111-81 presents longitudinal profiles of temperature distribution for the Strait of Juan de Fuca to southern Puget Sound. Note that the Strait of Juan de Fuca *is* colder than the main basin of Puget Sound in the summer, and that the bottom water in the Strait is even colder than the winter profile (indicative of coastal

Figure III-80

Tracks for Which Temperature, Salinity, Density, Oxygen and Phosphate Data are Presented for the Strait of Juan de Fuca - Puget Sound Region (solid line) and the Strait of Juan de Fuca - Georgia Strait Region (dashed line)

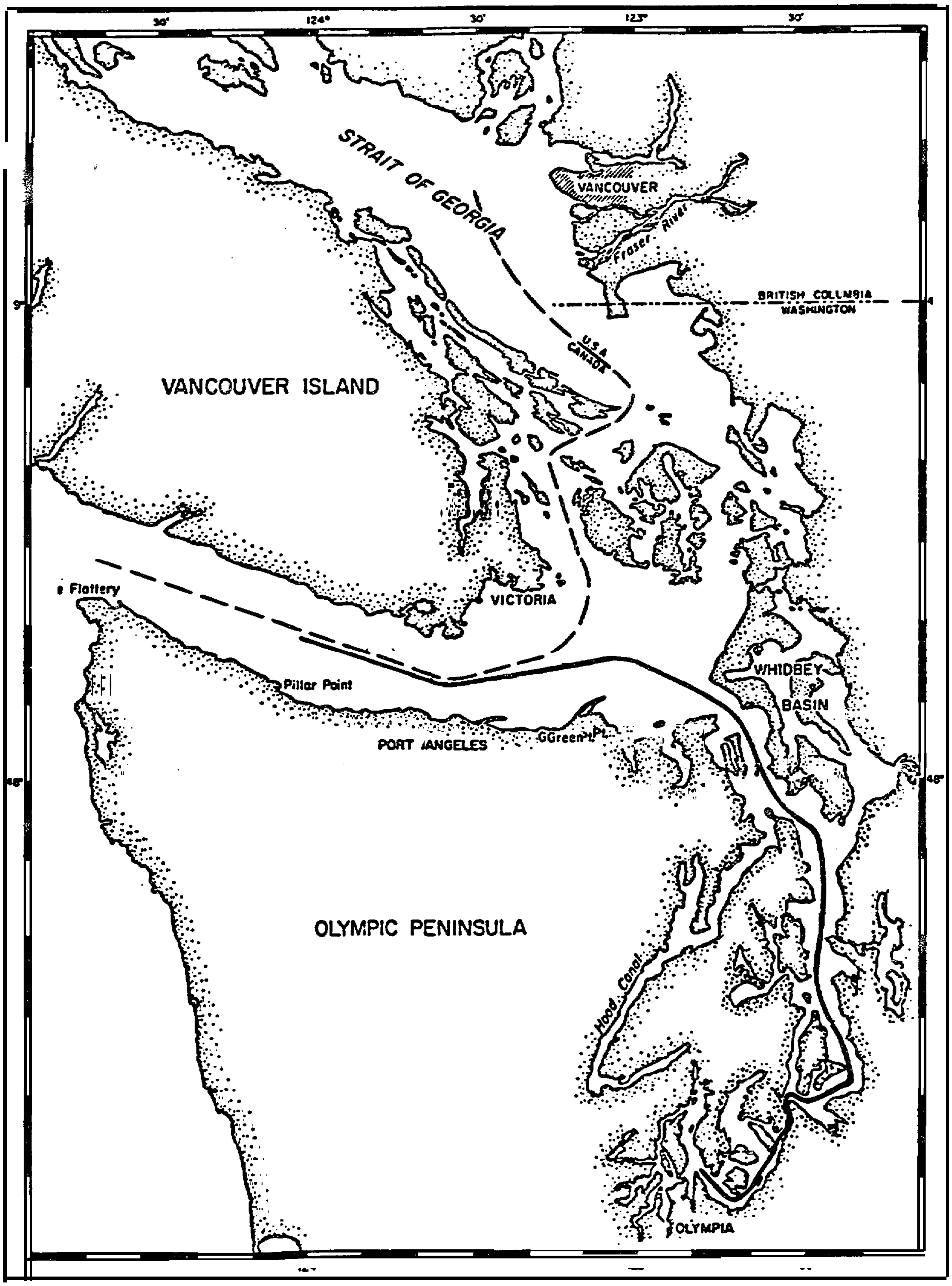
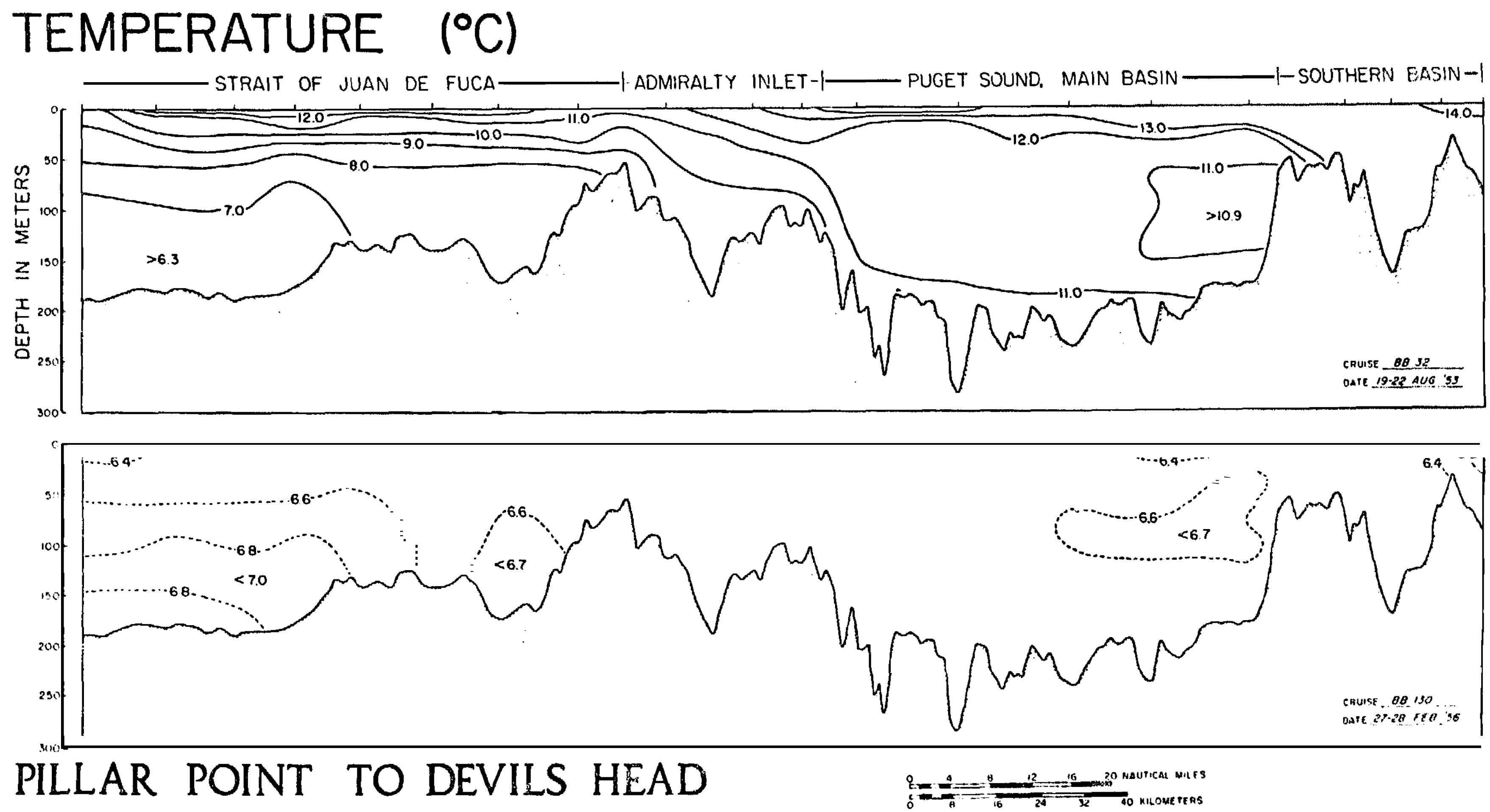


Figure III-81

Longitudinal Temperature Profile for Puget Sound[§]



[§]Collias, McGary and Barnes, 1974.

upwelling). Figure III-82 presents average and extreme temperatures for the surface and bottom water off of Pillar Point, based on data obtained from 1932 to 1966. The colder bottom waters from coastal upwelling are clearly distinguished.

Figure III-83 presents temperature, salinity, density and dissolved oxygen profiles for the Strait of Juan de Fuca-Haro Strait-southern Strait of Georgia complex for September 1952. Figure III-84 presents the same parameters for March 1953.

'Fable III-39 presents average temperature and salinities of the separate basins of Puget Sound for the surface, 50 m and 100 m.

b) Salinity. Factors affecting salinity have already been discussed. Table 111-39 included salinity data for Puget Sound. The higher river discharge in the Whidbey Island basin is evident by the lower surface salinities.

Figure III-85 presents the longitudinal salinity distribution for a summer and winter condition from the Strait of Juan de Fuca to southern Puget Sound. The effects of coastal upwelling are evident in the increased salinities in the bottom water of the Strait of Juan de Fuca and in Puget Sound. Near river mouths, the surface salinity may be near zero, and at times of high discharge all of Puget Sound may be highly salinity stratified. In Figure III-85, the salinity minimum at the surface near the southern basin-main basin border is associated with runoff from the Puyallup River at Tacoma.

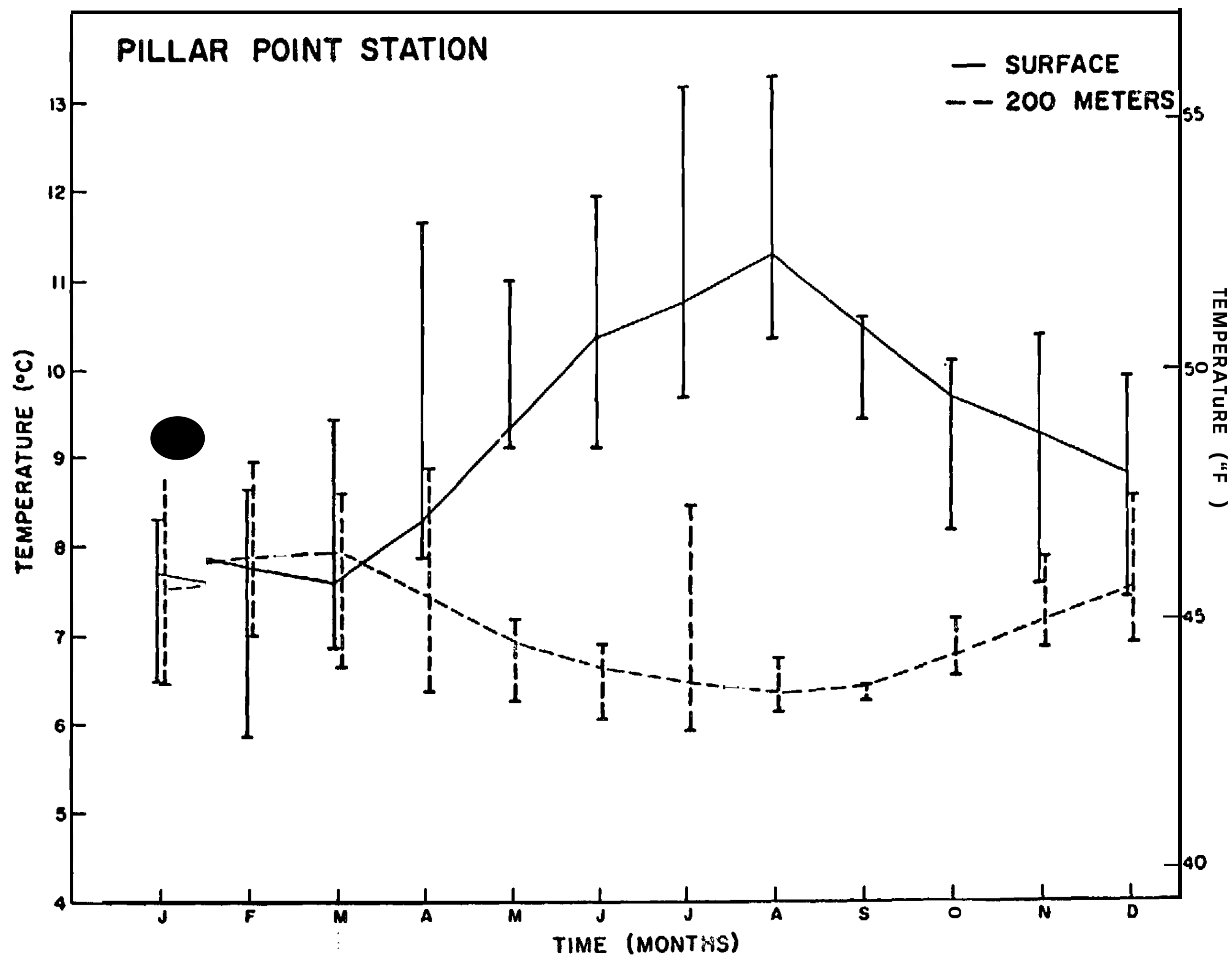
Figures III-83 and III-84 present salinity data for a summer and a winter condition for the Strait of Juan de Fuca to southern Strait of Georgia system. The surface salinities are lower in the Strait of Georgia during the summer because of the runoff from the Fraser River. The upwelled bottom water is quite evident in the salinity distribution in the Strait of Juan de Fuca in this illustration.

c) Density. Density distributions were portrayed in Figures III-83 and III-84 for the Strait of Georgia-Strait of Juan de Fuca system, and in Figure III-86 for the Strait of Juan de Fuca-Puget Sound system. These illustrations show the degree of mixing that occurs over the entrance sills. The sigma-t lines are nearly vertical at times at the entrance to Haro Strait and at Admiralty Inlet.

Ebbesmeyer (1973) studied the replacement of bottom water in Dabob Bay (an arm of Hood Canal) by frequent water sampling and analysis of the density structure.

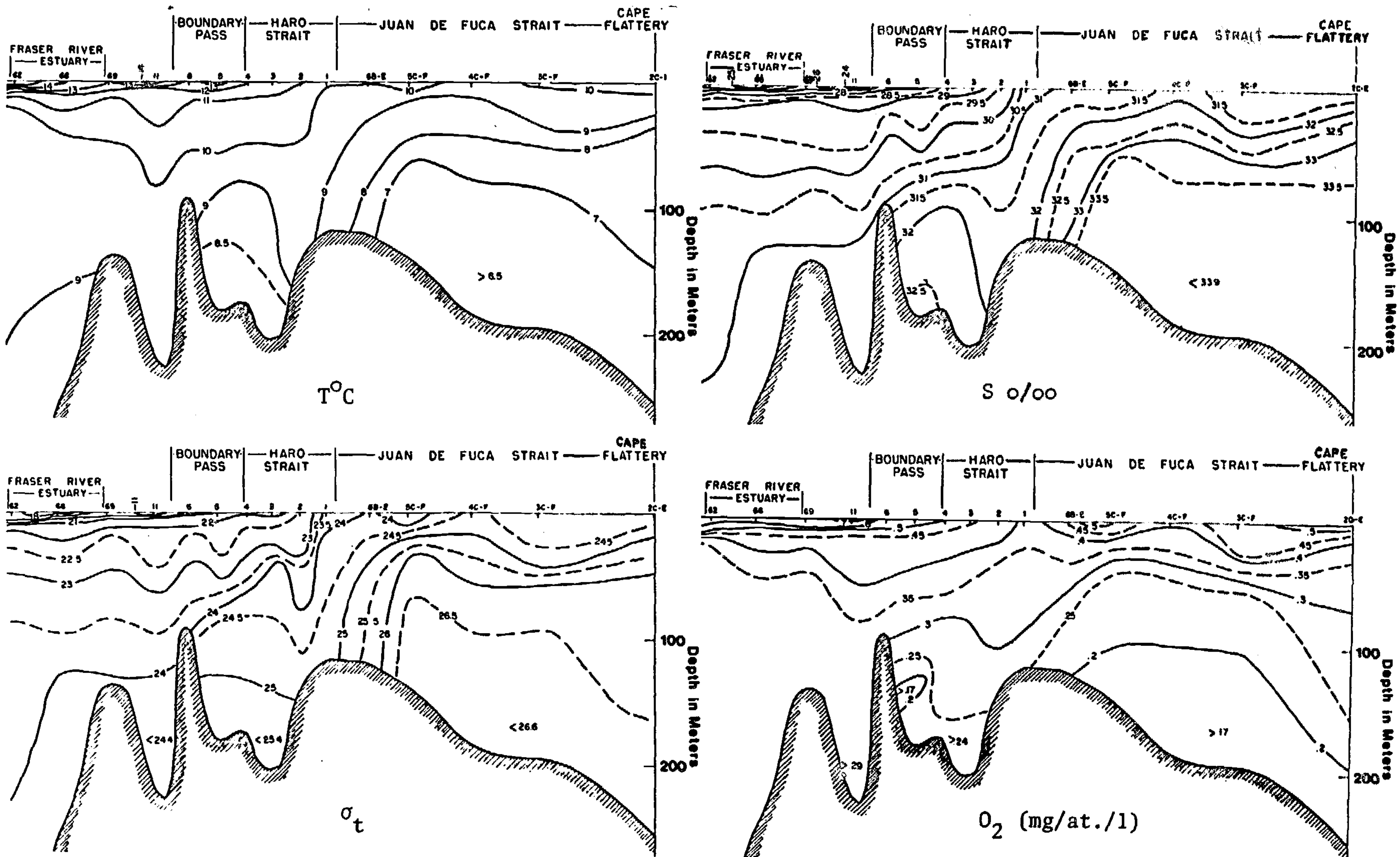
The density of the water near the surface is almost entirely controlled by salinity and increases with increase in salinity. In the surface waters, isopleths of equal salinity and equal density are closely parallel and in a static situation are horizontal. An increase in temperature tends to decrease density, but in this region the range is limited so this effect is small compared to the salinity effect. At depth in the basins, where the salinity gradient is small, the effect of temperature on density is more

Figure III-82
Average and Extreme Surface and Bottom Water Temperatures
for Northeast of Pillar Point, 1932-1966[§]



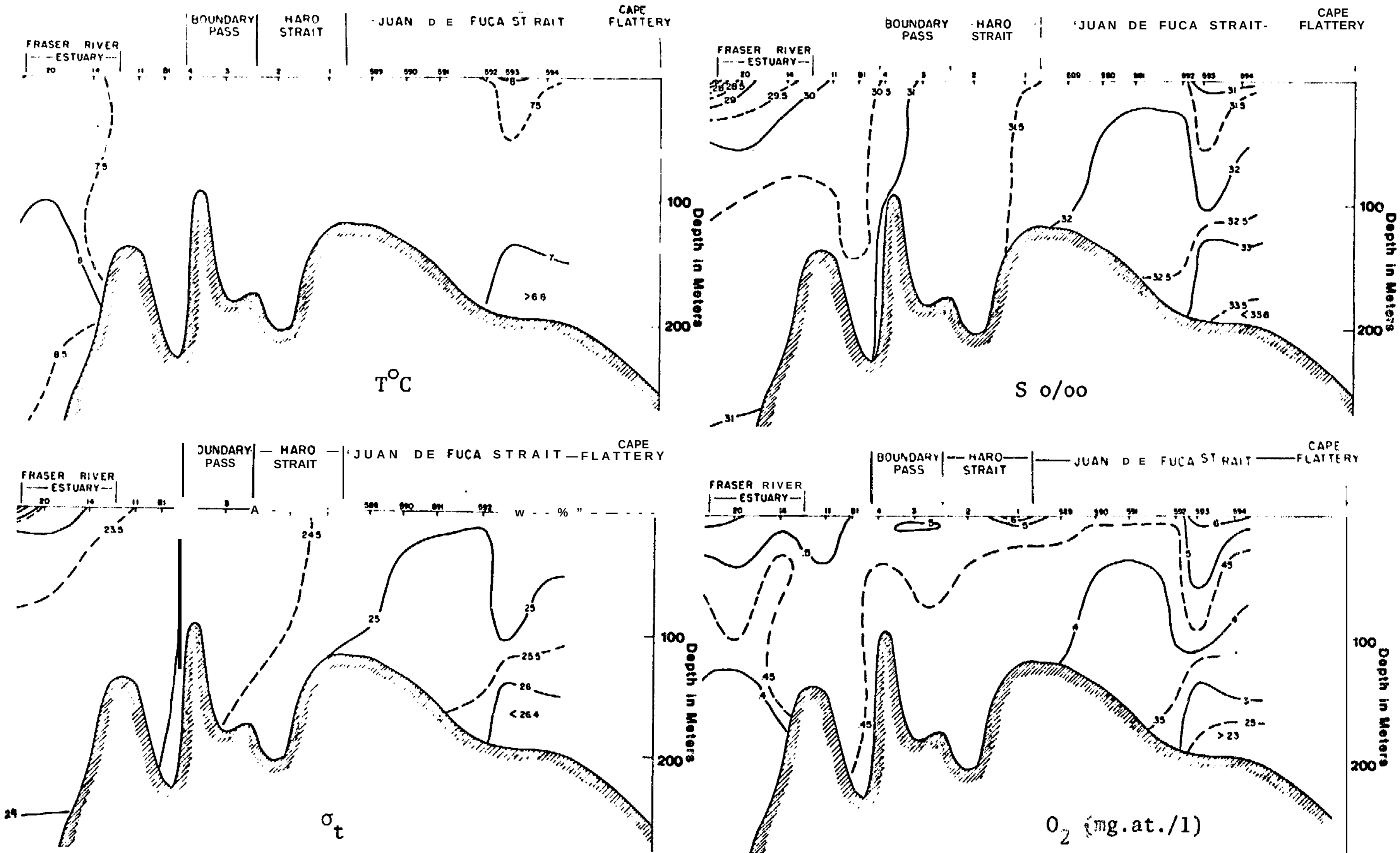
§Loehr and Ellinger, 1974.

Figure III-83. Longitudinal Distribution of T°C, S o/oo, σ_t, and O (in mg./at./l)[§] Through Strait of Juan de Fuca-Strait of Georgia for Sept. 1952[§]



§Waldichuk, 1957.

Figure III-84. Longitudinal Distribution of T°C, S o/oo, σ_t, and O2 (in mg./at./l) Through Strait of Juan de Fuca-Strait of Georgia for March 1953[§]



[§] Waldichuk, 1957.

Table III-39

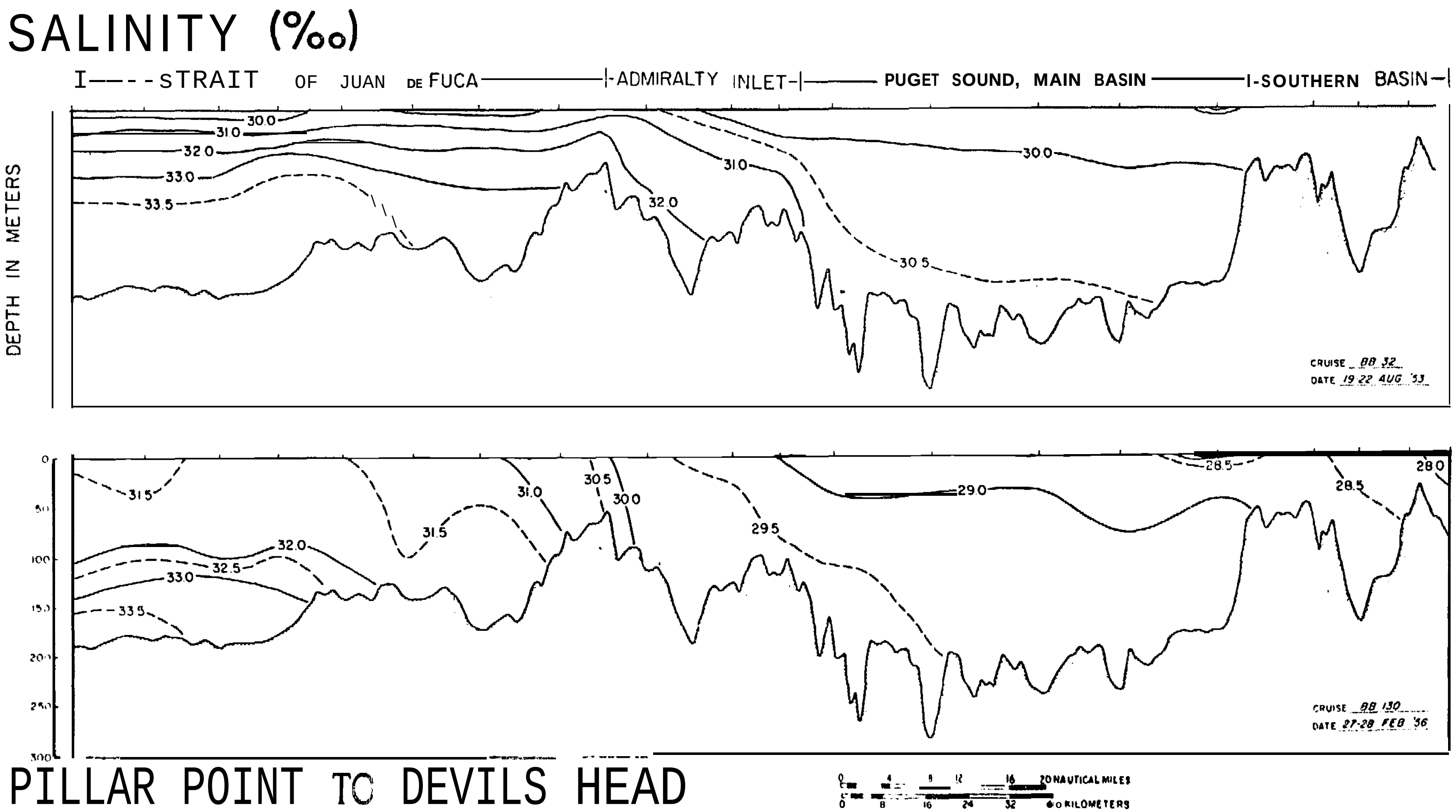
Average Temperature and Salinity of -the Five Puget Sound Basins§

	Admiralty Inlet	Central Puget	Southern Puget	Hood Canal	Whidbey Island
Temperatures					
at 0 m	'C				
Mean	9*3	10.2	11.0	13.0	11.5
Minimum	6.5 Feb.	6.6 Mar.	6.2 Feb.	6.7 Feb.	5.9 Feb.
Maximum	12.8 Sept.	16.6 Aug.	15.0 Sept.	19.8 Aug.	16.5 Aug.
at 50 m					
Mean	9.0	9.0	9.6	9.0	9.5
Minimum	6.5 Feb.	6.6 Feb.	6.4 Feb.	7.1 Mar.	7.0 April
Maximum	11.5 Sept.	12.1 Aug.	13.8 Sept.	10.9 Sept.	12.0 Nov.
at 100 m					
Mean	8.8	8.8	9.s	9.0	
Minimum	6.5 Feb.	6.6 Feb.	6.4 Feb.	6.6 Mar.	
Maximum	11.1 Sept.	11.6 Aug.	13.6 Sept.	11.0 Sept.	
Salinities					
at 0 m	Parts per thousand, (o/oo)				
Mean	30.2	28.1	29.0	27.0	23.0
Minimum	22.6 May	23.7 June	28.0 Mar.	24.4 June	9.2 Mar.
Maximum	30.7 Oct.	30.5 Oct.	30.1 Dec.	29.6 Oct.	27.9 Aug.
at 50 m					
Mean	30.3	29.8	29.4	30.0	29.5
Minimum	29.4 May	29.0 Mar.	28.3 Apr.	29.4 Apr.	28.6 Apr.
Maximum	30.s Oct.	30.6 Oct.	30.2 Dec.	30.6 Oct.	30.9 Nov.
at 100 m					
Mean	30.9	30.2	29.4	30.3	
Minimum	28.8 May	29.6 May	28.5 Apr.	29.8 Apr.	
Maximum	32.4 Oct.	30.9 Nov.	30.2 Dec.	30.7 Oct.	

§Duxbury, 1976.

Figure 111-65

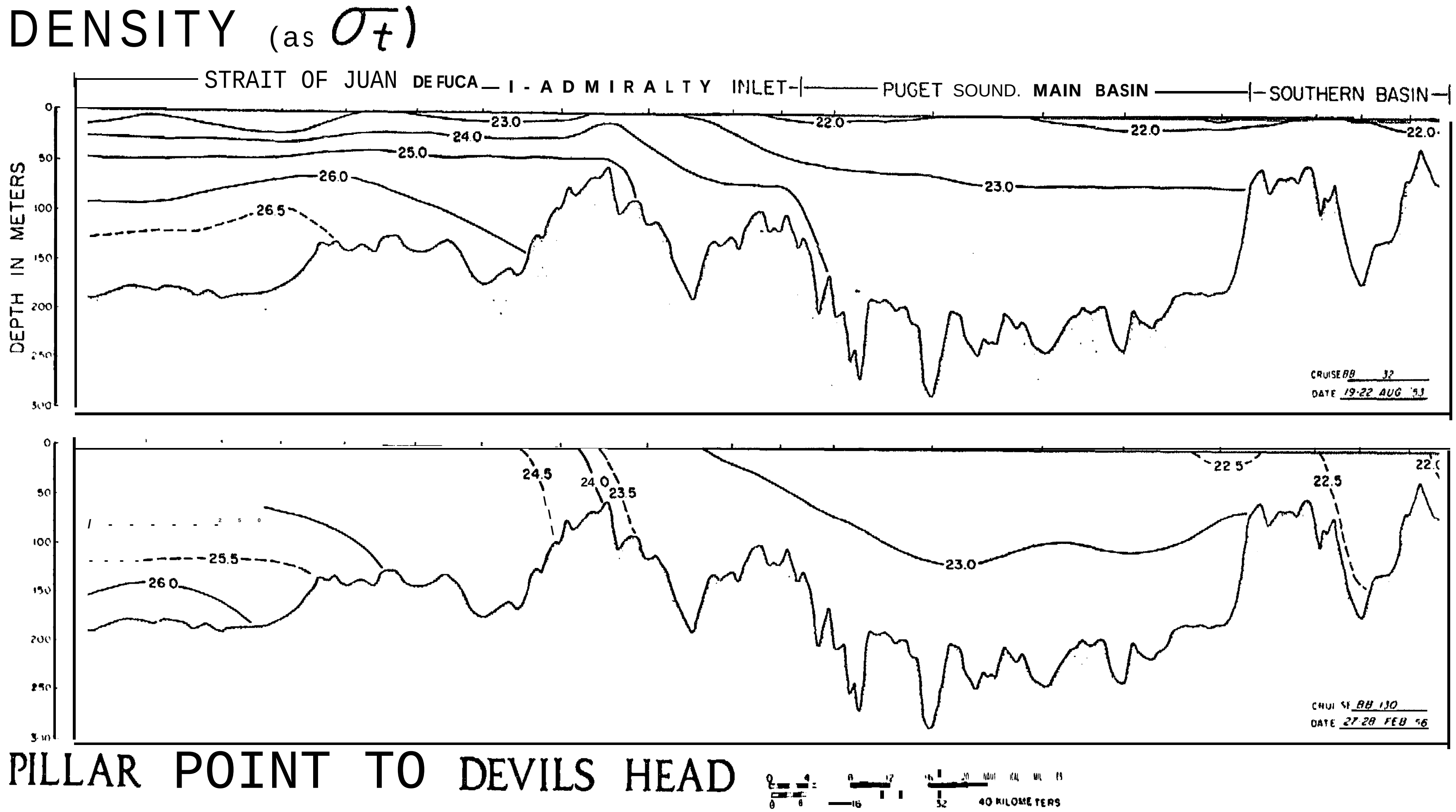
Longitudinal Salinity Profile for Puget Sound[§]



[§]Collias, McGary and Barnes, 1974.

Figure III-86

Longitudinal Density Profiles for Puget Sound[§]



[§]Collias, McGary and Barnes, 1974.

apparent.

d) Turbidity. The main source of turbidity in the inland waters is silt-laden river runoff. This is concentrated at the surface and near the river mouths. The surface waters will also be turbid at times of high productivity, due to the concentration of phyto- and zooplankton.

Turbidity may be measured by light transmission. Transmission of light has been used to measure sewer outfall plumes in the water column. Routine hydrographic observations during the day time in Puget Sound include the measurement of surface light transmission using a white, weighted "secchi disc", which is lowered until it disappears. The depth at which it disappears is called the secchi reading. Observed values have ranged from less than 0.5 m near the mouth of rivers at high runoff to greater than 15 m in the middle of the channel during winter when productivity was minimal. Phyto- and zooplankton blooms can decrease the secchi reading to as little as 2 or 3 meters in places, and sewage or industrial wastes can also lower the surface values when the water column is not stratified and the effluent can rise to the surface.

ii. Tides and Currents. Tide tables for the entire study area, including Puget Sound, and its adjacent waters, were presented in Table III-4.

The passage of the tide is slowed by the area configuration, resulting in a delay of the highs and lows of several hours compared to the highs and lows in the Strait of Juan de Fuca. Tide ranges are smallest at the central eastern part of the Strait of Juan de Fuca (3 m maximum), and the greatest at the head of long basins and inlets, such as at Olympic in southern Puget Sound (6 m maximum).

Two tidal models for Puget Sound are in use today. One is at the University of Washington and the other at the Pacific Science Center, Seattle. The six major components of the tide are mechanically summed, and daily tides and currents are generated. Numerous studies have been conducted at the University using the tide model, and comparisons with field data have indicated a good degree of correlation. The model cannot scale wind effects, which are very important in surface drift, especially in a stratified condition.

Generally speaking, currents are moderate (close to 50 cm/see) and mixing is good except at the heads of inlets. Currents are quite strong over the sills, or where channels narrow -- Admiralty Inlet currents may attain 150 to 255 cm/sec (3 to 5 knots), 255 cm/sec (5 kts) in Tacoma Narrows, greater than 100 cm/sec (2 kts) over the Hood Canal sill.

Flood-tidal currents move inward along the Strait at typical speeds of 75 to 125 cm/sec although values of 180 cm/sec can be associated with large tides; the largest currents of the tidal cycle occur near high and low waters. Flood currents are slightly stronger and of longer duration on the southern (U.S.) side than on the northern (Canadian) one. Speeds increase to as much as 310 cm/sec near

Victoria, primarily because of the shoaling bottom. Maximum ebb currents are generally the reverse direction of the flood. The current rotates through 180° gradually from flood to ebb (and vice-versa); its speed decreases and then slightly increases as it acts in the opposite direction. Ebb currents are slightly stronger and of larger duration on the northern (Canadian] side of the Strait.

In about the shallowest 100 m of the Strait, the ebb-tidal currents are normally stronger than the flood movements. Below this depth, the reverse condition occurs. This is due to the seaward drift of freshwater (e.g., from the Strait of Georgia) and seawater in the upper layers, and to the inflow at depth necessary to compensate for this loss of water to the open Pacific. Wind-induced currents in the Strait should attain speeds of about 3% of the generating wind speed, and move slightly (10°] to the right of the wind, in the central part of the Strait. Near the shore they will parallel the coastline and be smaller in value because of the effects of bottom friction. Currents in Rosario Strait may attain 360 cm/sec and in Haro Strait may attain 310 cm/sec.

During 1951-52, three anchor stations were occupied between Pillar Point and Sheringham Point (approximately along the 124°W Meridian). The stations were approximately equally spaced, with station A near the British Columbia coast, station B in midstream and station C near the Washington coast. Each station was occupied during both spring and neap tides during March, July and October of 1952. On each occasion the station was occupied for about thirty hours, with current measurements made every 30 minutes. A total of 412 hours of current records were obtained. Surface currents were measured with a 4.9 m drift pole, and subsurface currents with an Ekman current meter. These methods do not sample the current continuously, but in spite of this the data appear reasonably smooth.

There is no clear indication in the data that the mean current speed is related to either the wind or the state of the tide. Within each measurement period, however, the current was highly variable and there is obvious evidence of both a diurnal (about 25 hour) and semi-diurnal (about 12 hour] tidal period.

In summary, the data indicate that in any 24 hour period the following conditions may be reasonably anticipated:

1. An average surface current of about 57 cm/see; however, an average as high as 82 cm/sec would not be exceptional.

2. A maximum surface current of about 103 cm/see; however a maximum in excess of 154 cm/sec would not be exceptional.

3. An average subsurface 60-165 m current of about 36 cm/see; however, a subsurface average current of 51 cm/sec would not be exceptional.

4. A maximum subsurface current of about 103 cm/see; however, a maximum subsurface current of 129 cm/sec would not be exceptional.

5. The current is highly variable. During any 24 hour period, a minimum current of less than one quarter of the maximum can be anticipated to occur twice (12 hour period) or once (2S hour period), for a duration of about 2 to 4 hours.

During 1964, a second study was conducted along the same line of stations. Four stations of moored current meters were successfully completed. Records of varibale length were obtained, mostly of several days duration. The results of this study are summarized in Table 111-40.

The methods of the 1951-52 and the 1964 study were different, and information about the methods of data collection and analysis is fruitful. First, the mean currents appeared to be quite similar -- they agree to within about 50 cm/sec at similar depths. Second, the maximum currents measured by the second study are somewhat lower than in the first study. This difference is probably real, and may be attributed to the difference in the measuring techniques. The 1964 (lower maximum) study seems more accurate, but this is not certain. Third, the decrease of current speed with depth is similar for both studies.

Table 111-40 contains the modal directions of the current. The current direction (frequency distribution) is bimodal, with a mode at WNW and at ENE. Close to the bottom, or near the shore, local bathymetric effects may cause the current to deviate from these two preferred directions.

The 1964 report also contains a harmonic analysis of the data. The diurnal (25 hour) and the semidiurnal (12 hour) tides are both important.

In summary, the 1964 study indicates that:

1. The basic results of the 1951-52 study are confirmed.

2. The mean and maximum currents were 10-15% smaller in 1964, which is probably attributable to different measuring techniques.

3. The flow is basically WNW or ENE in direction, although locally or for short periods of time other directions of flow may occur.

4. At 12 m, currents exceed 50 cm/sec 36% of the time, at 80 m 29% of the time, and at 150 m 12% of the time.

Since the fall of 1973, the National Ocean Survey has been carrying out detailed circulatory surveys in the Strait of Juan de Fuca, the Strait of Georgia, and the connecting waterways through the San Juan Islands. The purpose of the study has been to provide an accurate and detailed description of water movement in this area. The need for the study was in part due to anticipation of future increases in tanker traffic through these waters to the refineries at Anacortes and Cherry Point. Most of the data from these surveys have come mainly from the eastern half of the Strait of Juan de Fuca including Admiralty Inlet,

Table 111-40

Current Measurements in the Strait of Juan de Fuca along 124°00' N. (Station 1 is nearest the Washington Coast)§

STATION	DEPTH (m)	CURRENT SPEED (in cm/see] MEAN	MAXIMUM	% Above .508 m/see (1 knot)	CURRENT DIRECTION MODES
1	12	36	94	36	345, 135
	55	31	94	27	275, 125
3	12	36	103	37	285, 115
	80	31	67	27	285, 095
	148	27	67	12	285, 135
4	12	36	103	38	295, 115
	80	36	94	32	275, 125
5	12	40	94	39	275, 125
	45	36	85	32	275, 105
	80	31	94	29	275, 115

§Kinder, Loehr and Back, 1975.

the southern end of the Strait of Georgia, and the connecting waterways. This area is the most dynamically complicated portion of the system.

Harmonic analysis has been undertaken for data from 95 tide stations and 90 current stations in the system. The results are still unpublished, but volume transport during one half of the M_2 tidal cycle has been worked out for several locations (Table 111-41) (Parker, [1977?]).

Drs. Charnell, Halpern and Cannon of the Pacific Marine Environmental Lab, National Oceanic and Atmospheric Administration, are currently engaged in circulation studies in the Strait of Juan de Fuca. The primary objective of their studies is to identify the transport mechanisms that affect the redistribution of spilled oil. Emphasis is given to surface transport since the bulk of the hydrocarbons remain at the water's surface. The field program is examining the local response to wind variations, cross-stream variations in flow, the magnitude of the geostrophic effects, and correlation of short-term flow structure to longitudinal pressure gradients. In 1976 they studied the western Strait of Juan de Fuca. In 1977 they will be studying the eastern Strait and in 1978 the San Juan Islands. Three deployments of current meter arrays have been completed for the western Strait, ranging from 60 to 90 days each. The preliminary analysis or data report should be out by the end of 1977 (Charnell, 1977).

Dr. Jerry Gait, of the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Lab (PMEL) has worked on a computer model that, given wind and tide inputs, would construct a probable trajectory for an oil spill in Puget Sound. The purpose is to make projections and predictions, so as to identify serious problems. This model is being expanded to include the San Juans. Dr. Gait is also developing a diagnostic model for the open ocean that uses a realistic assumed or known density distribution and single point current measurements to infer a spill pathway (Cannon, 1977).

iii. Waves.

a) Local Generated Waves. Only the Strait of Juan de Fuca is exposed to open ocean waves and, due to its orientation, is only exposed to open ocean waves from a west-northwest direction. Longer period waves are rapidly dispersed as they enter the Strait of Juan de Fuca because of refraction. Some degree of sheltering is also produced by the Swiftsure and La Perouse Banks off the coast of Vancouver Island. In the Strait of Juan de Fuca, the fetch can be considered as unlimited from the west-northwest, and the largest waves for the inland waters are possible here.

Table III-42 presents the significant wave heights in feet produced by winds of different strengths and fetches. From this table, a wind of 15.4 m/see from the WNW with a fetch of 185 km could produce waves of 4.5 m height. This probably represents an extreme situation for the inner Strait of Juan de Fuca.

The U.S. Army Corps of Engineers, Seattle District (1971)

Table III-41

Volume Transport During
One Half an M_2 Cycle§

Cross Section	Location	Volume Transport (m^3)	Percentage of Transport Through Cross Section A	
A	Strait of Juan-de Fuca	21.30×10^9	---	
B	Admiralty Inlet	5.08×10^9	23.9	
C	Rosario Strait	4.22×10^9	19.8	
L	Haro Strait	10.98×10^9	51.5	76.1
M	Middle Channel (between SanJuan and Lopez Island)	1.02×10^9	4.8	

§Parker, [1977?].

Table III-42

The Heights of Waves, in Feet, Theoretically
Produced by Winds of Various Strengths
Blowing Over Different Fetches§

Wind Velocity in nautical miles per hour	Fetch in nautical miles 10	50	100	300	500	1000
10	1.5	2.0	2,0	2.0	2.0	2.0
15	3.0	4.0	4.5	5.0	5.0	5.5
20	4.0	6.5	8.0	9.0	9.0	9.s
30	6.0	12.5	15.0	18.0	19.0	19.5
40	7.0	17.5	23.0	30.0	32.0	35.0
50	9.0	22.0	30.0	43.0	47.0	52.0

LEGEND 1 ft. = 0.305 m
1 knot = 0.508 m/see
1 naut. mile = 1.85 km

§Bigelow and Edmondson, 1947.

calculated sea conditions for Ediz Hook. They forecasted waves for a 5 year period and the maximum forecast waves had significant wave heights of about 2.4 m and came from both the northeast and from the northwest. Table III-43 presents the wave forecasts off Ediz Hook .

For the rest of the inland waters, well defined fetch limits exist and wave computations can be made from wind data and fetch. Table III-44 presents the significant height, period, and length of waves obtainable for various fetches, wind velocities and durations.

Significant fetches for Puget Sound are:

Southern Hood Canal to head of Dabob Bay: 56 km to the north-northwest.

Maury Island to Point Jefferson in the southern part of the main basin of Puget Sound: 48 km to the north.

Bainbridge Island to Everett, from the main basin of Puget Sound into the southern part of the Whidbey Basin: 46 km to the north-northeast.

From Table III-44 and given these fetches, it is apparent that sustained 12.9 m/see winds could produce waves with a significant wave height of up to 2.4 m.

The significant fetch for the southern part of the Strait of Georgia is the entire length of the Strait, 157 km, and the significant wind direction for maximum waves is from the northwest. From Table III-42, a sustained 12.9 m/see wind could produce about 3 m significant wave heights (interpolated value).

b) Seismic Sea Waves. A study was conducted to determine 100 year and 500 year runup due to tsunamis of distant origin for parts of the Strait of Juan de Fuca and Puget Sound (Garcia and Houston, 1975) . Results were presented in a series of charts showing segments of the shoreline and giving the 100 year and 500 year runup values. For the entire area the 100 year runups were computed as greater than 1.2 m and less than 1.8 m. For the 500 year runup, the range is between 1.5 and 2.4 m.

No locally-generated seismic sea wave data or studies are available, although the area is seismically active and features such as Hood Canal could be drastically affected by the slosh effect of a locally originated wave or surge.

iv. Flushing Mechanisms. As previously mentioned, the upwelling of dense, cold, nutrient rich, oxygen poor oceanic water supplies the bottom water of the Strait of Juan de Fuca. This mixes with surface and intermediate depth water as it crosses the various sills, providing the source water for the next basins landward.

The large influx of freshwater from the rivers establishes the

Table 111.43

Wave Forecasts for Local Generated Sea Waves
at Ediz Hook[§†]

Direction of Approach	Annual % of Occurrence	
	H_s=1'-3' (0.3-0.9m)	H_s=3'-5' (0.9-1.5m)
West	28.0%	2.0%
Northwest	1.5.5%	2.0%
North	3.5%	
Northeast	5.0%	0.5%
East	6.3%	0.5%

[§] U.S. Army Corps of Engineers, 1971.
[†] The wave height forecasts covered a 5 year period and the significant wave values are for deep water waves. The maximum forecast waves in this 5 years were significant waves of 8′ (2.4 m) from the northeast and 7.7′ (2.3 m) from the northwest.

Table 111-44

Height, Period, and Length of Waves for Various Fetches‡,
Wind Velocities, and Durations in Puget Sound§

DURATION OF WIND (Hours]	10			15			20			2S			FETCH OF WIND (Miles)
	WAVE (height and length in feet† period in seconds)												
	HEIGHT	PERIOD	LENGTH	HEIGHT	PER1OD	LENGTH	HEIGHT	PERIOD	LENGTH	HEIGHT	PERIOD	LENGTH	
1	1	1 1/4	8	1 1/4	1 2/3	14	1 3/4	2	29	2 1/3	2 1/3	28	
2	1 1/4	1 1/2	12	2	2	20	3	2 1/2	32	4	2 3/4	39	
2 2/3										4 3/4	3	36	
										-----10 miles -------			10
3	1 1/2	1 3/4	16	2 2/3	2 1/4	36	4	2 3/4	39	5 1/3	3 1/4	54	
							----10 miles --------						
3 1/2				2 3/4	2 1/2	32							
				----10 niiles --------									
4	1 3/4	2	20	3	2 1/2	32	4 3/4	3	46	6 1/2	3 1/2	62	
4 1/4	1 3/4	2	20										
	----10 miles*------												
4 2/3										7	3 3/4	7 2	
										----20 miles --------			20
s	1 3/4	2 1/3	28	3 1/3	2 3/4	39	5 1/4	3 1/3	57	7 1/3	3 3/4	72	
5 1/4							5 1/3	3 1/3	27				
							----20 miles --------						
6	1 3/4	2 2/3	37	3 1/2	3	46	5 1/2	3 1/2	62	8	4	82	
				----20 miles --------									
6 1/3										8	4 1/4	93	
										----30 miles --------			30
7	2	3	46	3 2/3	3 1/4	54	6	3 3/4	72	8 1/2	4 1/3	96	
							----30 miles --------			----35 miles --------			35
7 1/4	2	3	46										
	----20 miles -------												
7 3/4							6	4	82				
							----35 miles --------						
8	2	3	46	3 3/4	3 1/3	57							
				----30 miles --------									
9	2	3	46	4	3 1/2	62							
				----35 miles --------									
9 2/3	2	3	46										
	----30 miles -------												
10 1/4	2	3	46										
	----3S miles -------												

§University of Washington, Dept. of Oceanography, 1953-1954.
†One foot = 0.305 m.
‡One mile = 1.6 km.

two layer flow -- fresher water at the surface flowing seaward, saltier water flowing landward at depth to maintain the salt balance. Mixing between the two layers occurs, bringing nutrients to the surface and oxygen to the deeper water.

Tidal currents provide back and forth oscillations of water masses. In the cases of small, shallow bays, the tidal prism may be a considerable percentage of the total water volume, and if currents outside the bay (or inlet) are strong, the water that leaves on the ebb may be completely carried away and new water returned on the flood. In the larger basins or straits, the tidal action may gradually serve to "pump" water seaward as differences between the ebb and flood at a given point or depth produce a net direction of movement. Tidal action pumps water clockwise around Vashon Island for example.

Winds may speed up or slow down flushing processes. Southerly winds in Case Inlet have been shown to hold surface waters at the northern head of the inlet for extended periods of time, while the same southerly winds have sped up the flushing action in Hood Canal (which has its head to the south) (Collias and Loehr, 1974).

Friebertshauser and Duxbury (1972) used an analysis of the salt and freshwater balances for all of Puget Sound to estimate replacement times in days for Whidbey Basin, Southern Puget Sound, Hood Canal, and the entire Puget Sound area. Replacement time referred to the time it takes for the system to replace the freshwater within it, and is referenced to a base salinity of the source water supplying the basin. Table III-45 presents monthly replacement times from Friebertshauser and Duxbury (1972). The negative value for November in Hood Canal occurs in the calculations because insufficient information about the total freshwater input was utilized. Possibly, effects of Fraser River runoff mixing to depth at Admiralty Inlet still affected the source water, or possibly the contribution from Cushman reservoir used for electricity generation wasn't considered.

From the table, it is evident that Whidbey Basin flushes the most , rapidly. This is because of the dominating flow of the Skagit, Stillaguamish and Snohomish Rivers. Southern Puget Sound also flushes rapidly as a whole, although water in some of the smaller inlets may be retained for longer periods. Hood Canal is slow, partly because of its tremendous length relative to its width.

b. Chemical Oceanography.

i. Dissolved Oxygen Concentration. Longitudinal profiles for oxygen concentration in mg-at/l for a summer and winter condition are presented in Figure III-87 for the Strait of Juan de Fuca to Southern Puget Sound system. Similar profiles for the Strait of Juan de Fuca to Strait of Georgia system were presented in Figures III-83 and III-84.

The intrusion of upwelled water is evident in the August 1953 profile (Figure 111-87) as a low oxygen concentration wedge of less than 0.35 mg-at/l extending into the main basin of Puget Sound.

Oxygen concentrations in the deeper waters of Puget Sound and the

Table III-45

Monthly Replacement Times[§]
for Areas in Puget Sound[†]

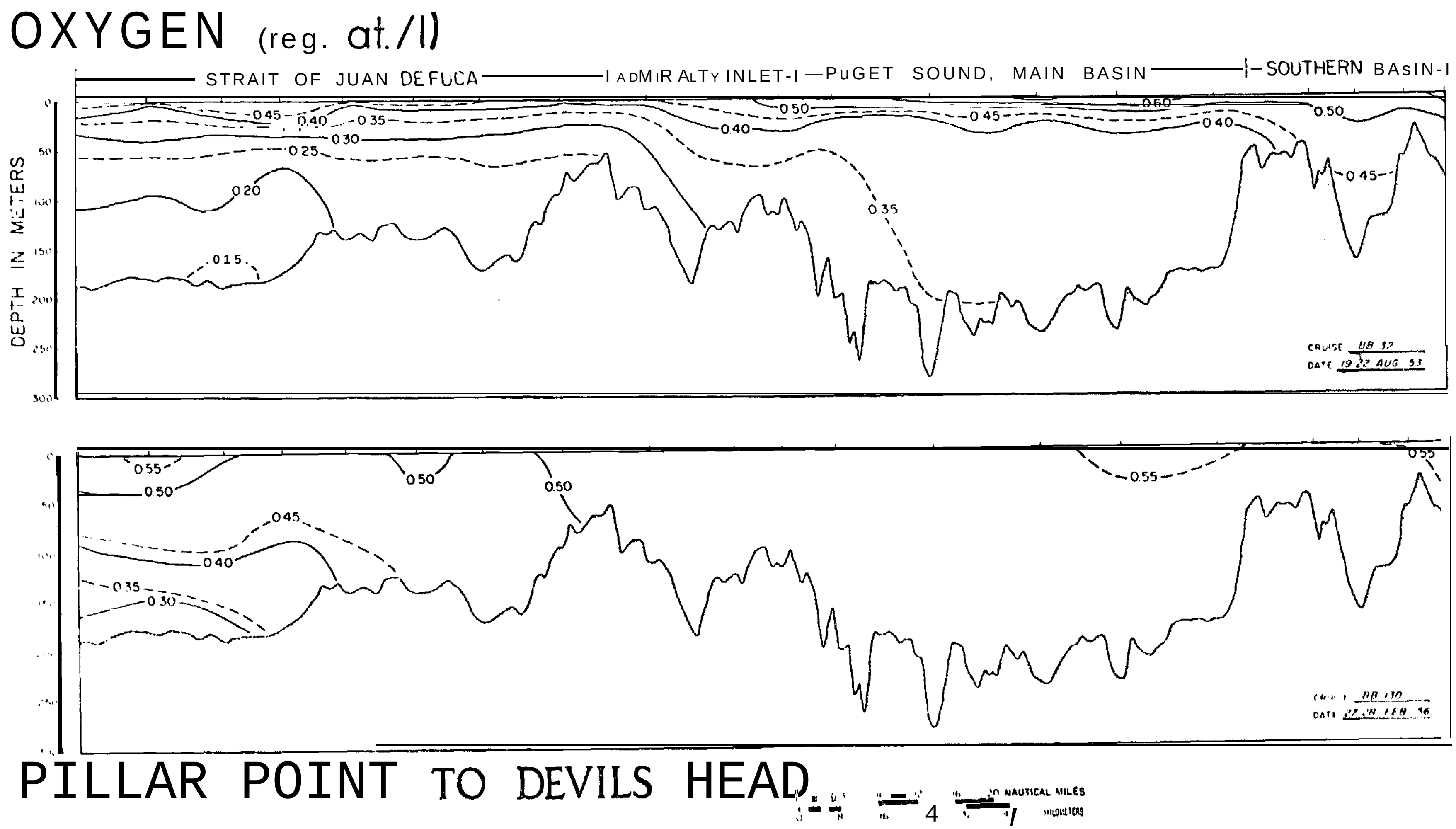
	Whidbey Basin	Southern Puget Sound	Hood Canal	Entire Puget Sound
January,	46	33	272	113
February	32	45	85	62
March	54	41	202	582
April	30	28	97	166
May	44	114	672	184
June	2s	54	328	99
July	30	80	152	124
August	47	70	191	132
September	93	80	149	407
October	57	51	215	120
November	76	174	-183	480
December	18	35	101	146
Mean	40	56	177	152

---

§Replacement time = basin volume/T.
†Friebertshauser and Duxbury, 1972.

Figure III-87

Longitudinal Oxygen Profiles for Puget Sound§



§Collias, McGary and Barnes, 1974.

Strait of Georgia are controlled by sills. Sills either promote mixing, such as in Admiralty Inlet and the Tacoma Narrows, or they confine the deep water behind them and prevent free circulation with the surrounding waters.

Two good examples of deep sills are found in Dabob Bay at the north end of Hood Canal and Port Susan north of Everett. In Dabob Bay, the water behind the sill is physically trapped and can be changed only by physical replacement with more dense water. This sill has a depth of 12S m and the basin is 195 m deep. This bottom 70 m will usually remain trapped for about 9 months, but on one occasion was observed to remain nearly unchanged for 22 months. As organic detritus rains down from above and decomposes, the oxygen content of the water decreases with time until it may drop below one part per million. Then, when the water is replaced, usually in mid-October, this low-oxygen content water is displaced upwards toward the surface. This natural but transient condition may have significant effects on fish.

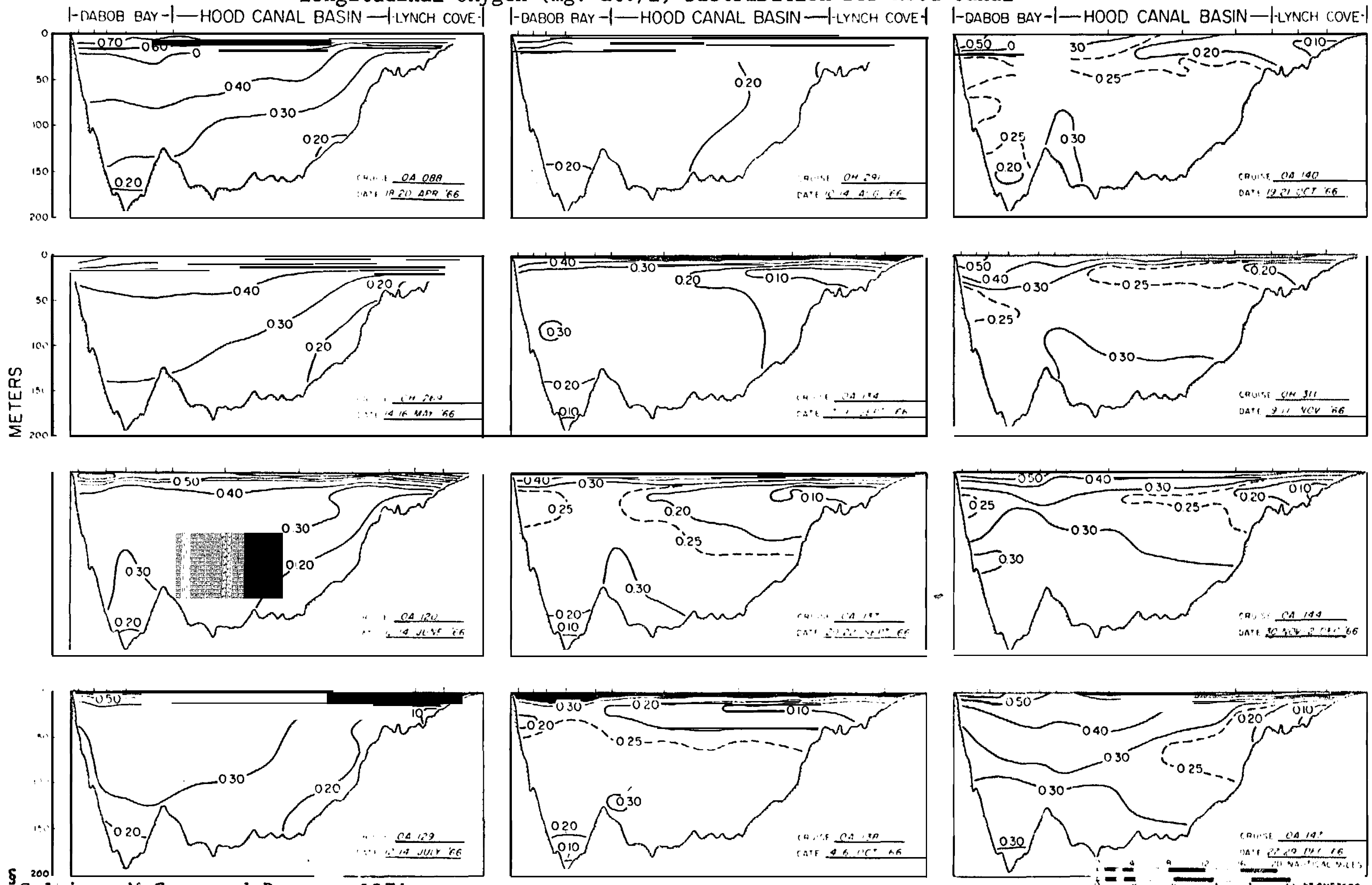
Another region where low oxygen water is formed is Lynch Cove at the southern end of Hood Canal. During the summer, a lid of fresh, arm water from the Skokomish River penetrates into Lynch Cove and remains there for most of the summer. This layer is about 6 m deep and prevents circulation of the deeper water with the surface. Also, because tidal action is limited, the deeper water will remain here for a considerable length of time. Living organisms thrive in the warm upper layer so that a constant rain of detritus into the deeper water occurs. This organic matter decomposes, consuming oxygen in the process. The oxygen content drops to near zero and the bottom sediments will frequently contain hydrogen sulfide. In October, this water is replaced by new water. As the oxygen deficient water moves seaward, it may surface near Hoodsport on the west side of southern Hood Canal causing a fish kill. Fish kills occur on nearly an annual basis and are due to these natural conditions. Similar phenomena occur in Port Susan and in Holmes Harbor in the Whidbey Basin, but to a lesser extent.

Figure III-88 presents profiles of oxygen distribution from Dabob Bay to Lynch Cove for 12 different cruises. The formation of the low oxygen water is evident both for the bottom of Dabob Bay and for the southern end of Hood Canal and Lynch Cove. The bottom waters of Dabob Bay flushed between 4-6 October and 9-11 November 1966. Actual replacement was underway on 19-21 October 1966. The low oxygen water from southern Hood Canal has extended north almost 20 km in the 4-6 October 1966 profile, but has been drastically cut back by the 19-21 October 1966 profile. The high oxygen values in the surface waters, especially in the southern end of Hood Canal in May, June and July are the result of high phytoplankton productivity.

Saanich Inlet, on the eastern side of southern Vancouver Island is similar in that it too has an entrance sill (70 m) and inside depths of 236 m. Its bathymetry and a strong vertical pycnocline isolate the deep water, resulting in more drastic changes in the chemical composition. Biochemical processes reduce the oxygen concentration to the point where aerobic respiration is no longer favored. Organic matter

Figure III-88

Longitudinal Oxygen (mg. at./l) Distribution for Hood Canal§



§ Col ias, McGary and Barnes, 1974.

is then reduced by nitrate reducing bacteria. Finally, when the nitrate concentration of the deep water reaches zero, or nearly so, sulfate reduction begins and hydrogen sulfide is produced. The bottom waters of Saanich Inlet frequently contain significant amounts of hydrogen sulfide in the spring and summer. In late summer or early fall, dense oxygenated water reaches the sill of Saanich Inlet from Haro Strait and flows down into the basin, displacing the resident deep water. Anderson and Devol (1972) provide a more detailed analysis of the chemical and physical process accompanying deep water renewal in this intermittently anoxic basin.

Lake Nitinat, on Vancouver Island bordering the western end of the Strait of Juan de Fuca, is a truly anoxic basin, with a sill depth of about 10 m and a basin depth reaching 200 m in places. The surface waters show a high concentration of oxygen in the summer months due to high phytoplankton productivity.

ii. Nutrients. Longitudinal profiles of phosphate distribution for summer and winter conditions from the Strait of Juan de Fuca to southern Puget Sound are presented in Figure III-89. Reduction in surface values are due to uptake by phytoplankton productivity. Dissolved oxygen and phosphate data for the various parts of Puget Sound are presented in Table III-46.

Detailed nutrient studies have been carried out for the main basin of Puget Sound from November 1974 to November 1975. Cruises were conducted every three weeks and rapid onboard analysis of the phosphate, nitrate, nitrite, ammonia and silicate were conducted. The following description of the nutrient distribution is extracted from Collias and Lincoln (1977).

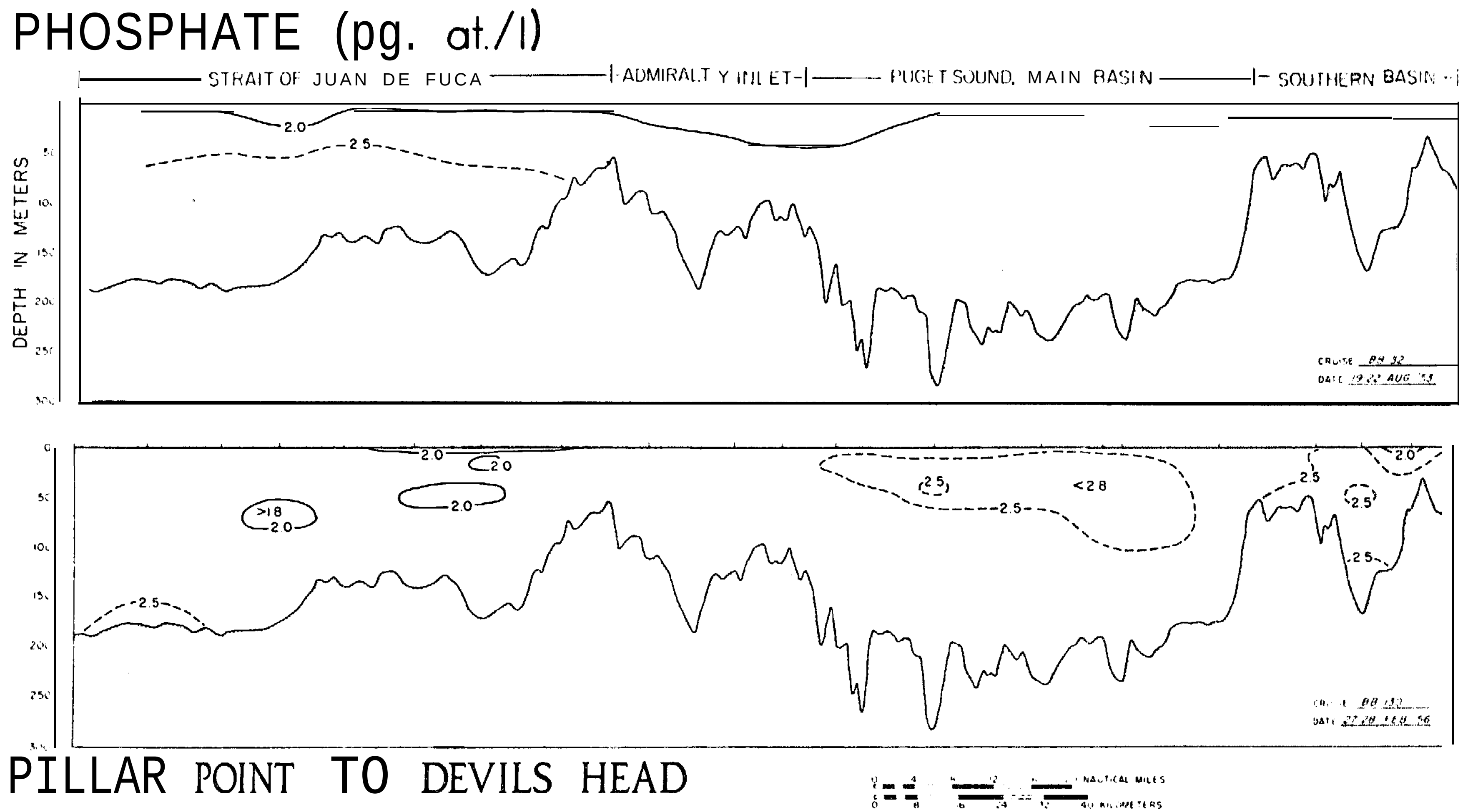
"The highest values of phosphate were observed in late fall when the maximum intrusion of oceanic type seawater into Puget Sound occurred. Late fall is also the time of most rapid degradation of plankton after the summer bloom, which releases the bound phosphate to the water. At depth, phosphate values varied from 2.1 µg-at/l to a high of 3.2 µg-at/l. With increased phytoplankton production, phosphate depletion of the surface layer was evident from May through August.

"Silicates showed similar trends to phosphate. Maximum values occurred in late fall 1974 followed by a decrease with the introduction of new source water from Admiralty Inlet. The utilization of silicate by phytoplankton was evident by decreasing silicate in the surface during the spring and summer months.

"Compounds containing nitrogen in the forms of nitrate, nitrite, and ammonia underwent seasonal variations as did oxygen, phosphate, and silicate. Features of the seasonal cycles for the nitrogen constituents were not precisely coincident. Biological activity tends to maintain a nearly fixed ratio between the number of phosphorus and nitrogen atoms. As productivity in the euphotic layer increases, phosphate and nitrate are removed. When productivity decreases in the fall, organic detritus sinks and decomposes, and the nutrients are returned to the water in about the same proportion as originally utilized. Thus, the seasonal phosphate and nitrate curves tend to

Figure III-89

Longitudinal Phosphate Distribution for Puget Sound[§]



§Col lias, McGary and Barnes, 1974.

Table III-46

Average Measurements of Dissolved Oxygen and Phosphates in the Five Puget Sound Basins[§]

	Admiralty Inlet	Central Puget	Southern Puget	Hood Canal	Possession Sound
Dissolved Oxygen mg atom/1					
At 0 m					
Mean	.50	.53	.60	.60	.60
Minimum	.39 Oct.	.41 Ott.	.45 Oct.	.49 Oct.	.49 Sept.
Maximum	.67 May	.70 May	.83 May	.72 May	.72 May
At 50 m					
Mean	.45	.45	.45	.35	.30
Minimum	.36 Mar.	.34 Sept.	.36 Oct.	.21 Aug.	.17 Sept.
Maximum	.55 Mar.	.54 April	.59 May	.45 Mar.	.49 Mar.
At 100 m					
Mean	.45	.45	.45	.45	
Minimum	.36 Oct.	.34 Sept.	.36 Oct.	.19 Aug.	
Maximum	.55 Mar.	.53 Apr.	.57 May	.50 Mar.	
Phosphates µg atom/1					
At 0 m					
Mean	1.4	1.8	1.8	1.8	1.8
Minimum	1.0 June	0.4 June	0.6 June	0.2June	0.3 June
Maximum	2.9 Feb.	3.5 Feb.	2.7 Jan.	2.9 Dec.	2.9 Oct.
At 50 m					
Mean	2.0	2.2	2.2	2.3	2.5
Minimum	1.1 June	1.4 June	1.3 June	1.5 June	1.3 June
Maximum	2.7 Oct.	3.0 Dec.	3.1 Dec.	3.2 Oct.	3.8 Sept.
At 100 m					
Mean	2.0	2.0	2.2	2.5	
Minumum	1.1 June	1.4 June	1.3 June	1.7 June	
Maximum	2.9 Oct.	3.0 Dec.	3.1 Dec.	3.2 Oct.	

§Duxbury, 1976.

follow each other. Data for nitrate obtained during the study period confirmed this relationship. Maximum nitrate was observed in January 1975 with the minimum occurring in early August 1975. Depletion of nitrate in the surface layer by phytoplankton was quite evident from May through August,

"Seasonal variations of nitrite concentration within the study area were appreciably different from those observed for nitrates. From November 1974 through May 1975, nitrite followed an approximate inverse relationship to nitrates. In February 1975, the maximum nitrate occurred at about the same time as the nitrite minimum. Nitrites increased until June when both nitrates and nitrites decreased to a minimum from mid-July to mid-August. At this time nitrites were not as low as those observed in February 1975. Nitrites again increased until October, reaching a maximum average value of 0.65 µg-at/l in the upper 20 m.

"Observations showed that ammonia also followed a seasonal trend but was more erratic than the constituents previously discussed. Minimum amounts were observed from early January through March 1975. From mid-March to May, ammonia gradually increased. During summer, concentrations were generally highest but were also the most variable. In the northern part of the central basin from Point No Point to Point Jefferson, peak values observed in the upper layer tended to coincide with peaks at depth. But from West Point south to Browns Point (near Tacoma), coincidence of variations in the upper and lower layers was poor although the seasonal trend was evident.

"Properties along the lateral section from West Point to Skiff Point were measured during four cruises. In general there was little cross channel variation in all properties. But there was evidence of the plume from the West Point treatment plant producing localized changes near West Point. Localized areas of high nutrient concentrations also were observed in Elliott Bay near the mouths of the East and West Waterways of the Duwamish River, at the mouth of the Puyallup River, and occasionally near Manchester and in Port Madison."

The field program of 1975 was to evaluate the effects of sewage disposal on the balance of nutrients in Puget Sound. The evidence is that the effects are probably negligible in the main basin but there were some local detectable changes. The Southern California Coastal Water Research Project (1975) concluded that the following were not problems when discharged *to* open coastal waters in municipal wastewater:

- nutrients
- dissolved solids including oxygen demanding ones
- detergents
- radioactivity (hospital sources - low level)
- pH, salinity, and temperature differences

Duxbury (1975) evaluated the concentrations of oxygen and phosphate at 10 m for a station off Point Jefferson for the period 1934-73. Point Jefferson station, midchannel in the Sound, is about 8 km north of Seattle. By virtue of Point Jefferson's location, its surface waters are influenced by effluent discharges from all urban areas surrounding the Sound and inside of this point with respect to the ocean. It is also possible that the location may be affected by discharges from urban areas surrounding the Whidbey Basin to the north and east.

During the period August 1933 to May 1967, this station was sampled 287 times, and additional data have been gathered since 1967 at this same location. Early samples were collected only once or twice a year, but after 1935 samples were gathered almost monthly, with a break in the sampling program between 1942 and 1948.

Duxbury notes that the method of measuring inorganic orthophosphate has changed over the years and that changes in methodology may have had an effect on the observed phosphate trend but should not have masked major changes in inorganic phosphate levels.

The single depth, 10 m, was chosen from the Point Jefferson data series as data from this depth should be representative of the seaward-moving surface layer of Puget Sound and thus should reflect human discharges occurring upstream.

Figure 111-90 presents the oxygen saturation and the inorganic phosphate concentrations for 1934-54 and 1951-71 at 10 m for Point Jefferson. The annual cycle in these two variables and their inverse relationship is evident. When sufficient data were available over a given year, the annual averages of these two parameters were calculated and are shown in the figure.

The oxygen highs and phosphate lows correspond to times of high productivity. The oxygen lows and phosphate highs correspond to an inflow of high nutrient low oxygen water in the fall, and a decline in productivity.

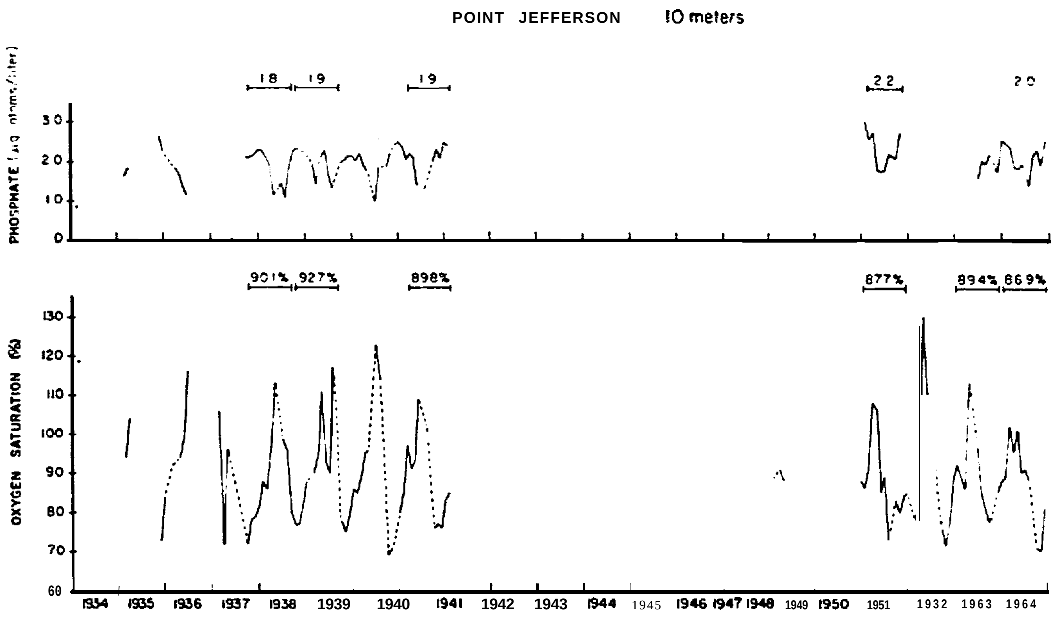
The observed inorganic orthophosphate level does not fall below 1 μg-at/l and thus cannot be considered as limiting phytoplankton growth in the main basin of Puget Sound. Nitrate-nitrogen occasionally does become depleted in specific areas and may sometimes be limiting, but, in general, light exerts a greater control on productivity throughout Puget Sound than do nutrients.

The trends of the available annual averages of the observed inorganic phosphate and dissolved oxygen indicate no continuous increase in phosphate or decrease in dissolved oxygen even though the population of the Puget Sound basin has increased from about 747,000 in 1930 to 1,955,000 in 1970, along with an attendant increase in waste disposal.

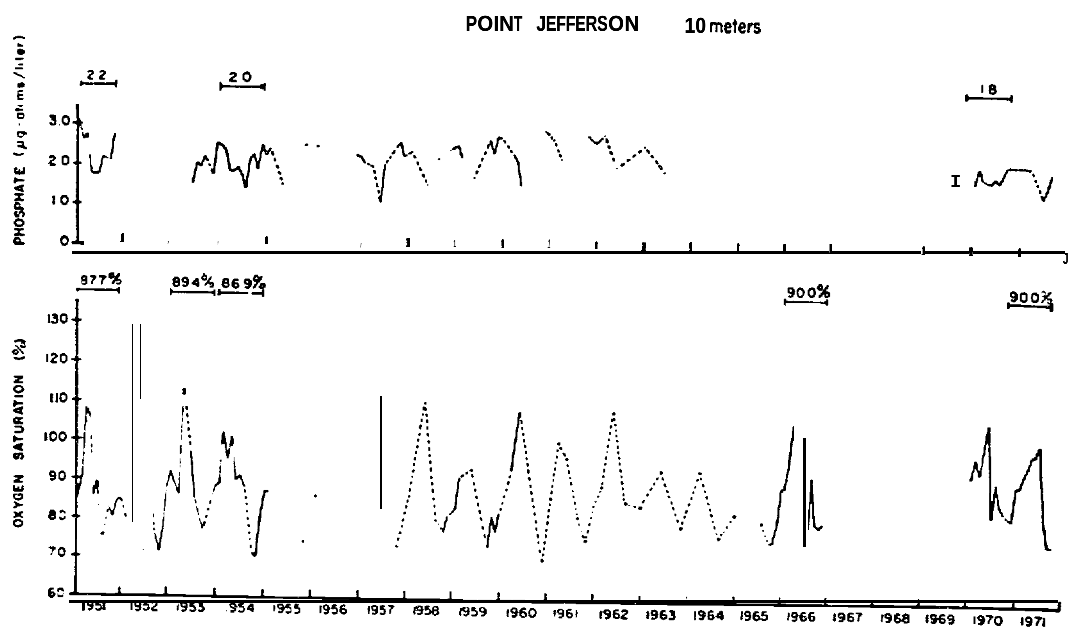
Duxbury concludes that the daily municipal waste discharge of inorganic orthophosphate into Puget Sound is about a twelfth of the mean daily advective outflow of phosphate at Admiralty Inlet. This outflow rate is determined by the average net seaward movement of surface water from the main basin of Puget Sound and its average phosphate content. A comparable influx of phosphate also occurs at depth. Man’s addition is apparently such a small part of the natural advective flux of phosphate that its present influence is easily masked by the larger natural fluxes.

Figure III-90

Observed Values of Inorganic Orthophosphate and Saturation Values of Dissolved Oxygen at 10-m Depth, Point Jefferson Station in Puget Sound[§]



1934-19s4



1951-1974

§ Duxbury, 1975.

iii. Trace Metals. Trace metals, or heavy metals, have been measured in the water column, biota, and sediments of Puget Sound and reported by Schell (1976). Sources of trace metal inputs have been reviewed and totaled by Zafiropoulos (1976). Comprehensive baseline studies of trace heavy metals in biota of Puget Sound were reported by Olsen (1976). for 46 species of biological organisms from the plankton, nekton and benthos. Olsen's study investigated accumulation patterns of trace metals through certain food webs and identified certain organisms that concentrate metals and are useful as indicator species. Huntamer (1976) analyzed more than 50 samples of from S6 to 800 liters of sea-water for both particulate and soluble zinc, copper, lead, nickel, cobalt, cadmium and magnesium for areas in Puget Sound. Crecelius, Bothner and Carpenter (1975) studied the geochemistries of arsenic, antimony, mercury and related elements in sediments in Puget Sound noting that the natural distributions were perturbed by two major human activity sources of trace metals: a copper smelter near Tacoma, Washington that discharges large amounts of arsenic and antimony, and a chlor-alkali plant in Bellingham, Washington that in the recent past discharged significant amounts of mercury, but stopped in 1970. On-going studies are evaluating how the system is responding to cessation of mercury pollution. Bothner (1973) studies some aspects of the geo-chemistry of mercury in Puget Sound. Schell, *et aZ.* (1975) analyzed trace contaminants from the Duwamish River dredge spoils deposited at a dredge spoil dumping site in Elliott Bay. Schell and Nevissi (1976) reported on heavy metals from waste disposal in central Puget Sound. Trace metal studies on lead, cadmium, zinc, copper, mercury and chromium are ongoing at the Patricia Bay Institute of Ocean Sciences under the direction of Dr. Wong.

The following discussion is extracted from Schell (1976), and pertains to intensive heavy metal studies related to sewage discharge, primarily from West Point, Seattle into Puget Sound:

"Recent studies in Puget Sound were designed

1. To investigate the trace metals in the water column, biota and sediments, and

2. To establish techniques and methodology appropriate to the analyses of these samples in order to assure accuracy of the results when dealing with the elements that appear in very low concentrations -- the part per billion range.

"To determine if the distribution of heavy metals could be traced to a source in the discharged sewage, samples were collected near the West Point outfall and at other locations in the central Sound remote from the sewage effluent. To date not all the data are available from which to draw conclusions. However, initial analyses of water samples from the fall and winter period of 1973 indicate that the West Point outfall does not act as a unique source of input of heavy metals into Puget Sound. Around the West Point outfall, trace metals in the water do not appear in high concentrations. At other locations higher concentrations do appear, but these are not considered related to a METRO discharge. However, some organisms near West Point have slightly elevated concentrations of mercury, lead, and zinc. Nonetheless, these concentrations are still below the guidelines recommended by the Environmental Protection Agency, EPA.

"As the terminus of a drainage system, Puget Sound is a collecting point for land discharged materials, and a major source of these materials is the discharge from the metropolitan centers. In the Seattle area the West Point treatment facility is a major service, with Richmond Beach, Carkeek Park, and Alki Point being minor contributors. However, there are other sources present such as industrial wastes; river and surface runoff; storm sewers that carry leacheates and eroded materials from land; and those materials like aerosols that are airborne.

"In the Central Basin of Puget Sound it it possible that there are waste materials discharged by metropolitan centers other than Seattle. For in the net circulation of the Sound, surface waters from further within the Sound traverse the Central Basin as they move seaward. This advective process by which the water in Puget Sound is continually exchanged with the Pacific Ocean is one of two principal mechanisms for removing wastes from the water of which trace metals are a component. The other mechanism is the accumulation of sediments that may incorporate trace metals associated with particulate matter in the water column. Since the fate of trace metals is often determined by the particular physical-chemical state, it is necessary to look at the metals in soluble and particulate form and at the speciation of the metals in conjunction with organic complexes and oxidation states.

"It is of considerable interest to determine the residence time and location of trace metals in the receiving environment. Those that are in the water column may be limited in their stay by the flushing rates of the Sound, while those in sediments may remain for some time unless the sediments are disturbed or reworked by the biota or dredging. When this happens, metals are released for incorporation into the biological food chain. Trace metals in the water column as solubles or particulate matter may also be incorporated into the food chain. Since the presence of trace metals into the food chain enhances the chances of man's contact with these materials, the concentration levels of trace elements in the biota can be significant in determining what steps must be taken to reduce their addition *to* the environment.

"The input of trace metals to the Sound by the METRO plant at West Point was determined by tests of the discharge effluent. These data coupled with precipitation data indicate that there is a positive correlation between the input of trace metals and rainfall. If, however, increasing precipitation does increase the total mass of trace metals delivered to the treatment plant and its eventual discharge, the increase also dilutes the effluent, causing the concentrations of the metals in the effluent to be lower. Monitoring the contribution of trace metals is important not only to determine rates of addition to the environment, but also to detect changes of the concentrations of the elements in question and possibly their sources. When dealing with natural systems, identifying sources of these trace elements becomes very important. For it is quite possible that the natural water sources diverted for domestic use undergo periodic changes in their trace metal content. Thus, some of the trace metal levels noted at sewage treatment plants could be completely natural, and a reduction below these levels would constitute a man-made interference with the natural system -- pollution.

"Sampling the receiving water column for soluble and particulate forms of trace metals involved (1) taking discrete samples at intervals over the column of water at one point in time and (2) time integrated sampling from a single depth using a hose and pumping system. The water samples were filtered to remove particulate with diameters greater than 0.3 µm. The separated particulate materials were treated and analyzed for trace metals, while the filtered water was passed through ion exchange columns to extract soluble trace metals for analyses. Thus, total, soluble, and particulate forms of trace metals were determined. At West Point and Blake Island higher concentrations of lead were found at the surface than at depth; elsewhere the reverse was generally found. Zinc, copper, cadmium and nickel were generally higher in the surface waters than in the deeper water near West Point.

"If the Blake Island sampling site can be assumed to represent the background level of trace metals in the Central Basin of Puget Sound, because of its remoteness, then it is significant that concentrations at Blake Island are generally higher than at West Point where there is a sewage source for trace metals.

"A comparison of concentrations through the Central Basin indicates that there is little geographical variation in trace metal concentrations in the surface waters. Samples from the Duwamish River do show some elevated concentrations of copper and cadmium that could well be attributed to industrial sources.

"The concentration levels of zinc, copper, and nickel as observed in the Sound are slightly lower than the levels observed in the open sea whereas those of lead and cadmium are significantly higher. In the case of lead, it should be remembered that leaded gasoline burned by automobiles forms a major source for this material that may be delivered to the Sound by several routes.

"In these early samples, the apparent lack of a definite and clear geographical pattern relating trace metal concentrations to any particular source reflects the problem of multiple sources and indicates dispersion caused by circulation of Puget Sound waters. Nearly all Puget Sound waters that have contact with the surrounding metropolitan areas must enter the Central Basin as they flow inward at depth and seaward at the surface. This circulation pattern inevitably means the waters of the Central Basin reflect influences from remote sources.

"Trace metals that appear in the water can be incorporated into the biota and further concentrated selectively into body tissues. Once the elements are incorporated in the food chain, the prey/predator roles may pass the materials along and result in concentrating the elements in organs of animals higher up the food chain. Since man is one of the predators in this process, it is important to look carefully at the trace metals and other exotic materials that might affect a seafood customer.

term goal of this research is to generate a predictive capability of the distribution of environmentally stable but potentially toxic organic chemicals among biotic and abiotic ecosystem components, based on fundamental chemical principles and easily measured ecosystem parameters (Dexter and Pavlou, 1976). These studies have emphasized polychlorinated biphenyls (PCB's) as model components for the following reasons: 1) they are ubiquitous in Puget Sound, 2) they have low level detectability, 3) they are environmentally stable, and 4) they represent a series of chemically similar compounds that vary in toxicological and physico-chemical characteristics. Measurements have been made of PCB levels in water, suspended particulate matter, and zooplankton in Puget Sound.

The data for all sample types showed nearly identical spatial distributions of chlorobiphenyl residues within the Sound, with concentrations being highest in the Duwamish River-Elliott Bay region and decreasing to a relatively constant level in the remainder of the Sound. Water concentrations ranged from a high of 40 parts per trillion in the Duwamish to a uniform level of approximately. 2 parts per trillion. Similarly, suspended particulate matter and zooplankton contained from 1.0 to 0.05 ppm (on a dry mass basis) and from 16 to 1.0 ppm (on a liquid mass basis), respectively (Dexter and Pavlou, 1976).

vi. Suspended Particulate. Suspended particulate may be either biogenic or lithogenic in origin. These particles, suspended in seawater play a major role in regulating the chemical forms, distributions, and ultimate deposition of many marine pollutants. Some toxic elements in particulate form are transported to the oceans, where they are desorbed at the freshwater-seawater interface. Other elements (particularly petroleum hydrocarbons) are adsorbed onto the surfaces of suspended particles and are removed to the sediments as the particles settle.

Two studies of the role of particulate matter in transporting toxic pollutants in the marine environment are being carried out by Dr. Richard Feely of the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Lab (PMEL), but they are for the coastal waters around Alaska and for the deep ocean mining environmental study in the eastern tropical North Pacific. The findings of these studies may have some applicability to the Pacific Northwest and its inland waters.

Numerous surface secchi disc readings exist for Puget Sound and its adjacent waters, and possibly this can be correlated to approximate quantities of suspended particulate in the surface waters. As mentioned earlier, the secchi disc reading is a measure of surface turbidity. Measurements of turbidity by light transmissibility have been conducted over submarine waste outfalls in Puget Sound (Environmental Quality Analysts, Inc., 1976). The measurements were relative and were used to identify the depth of the outfall plume. Ongoing studies by Drs. R. E. Burns and E, T. Baker of the University of Washington and PMEL are seeking to distinguish suspended particulate associated with outfall wastes from naturally occurring river inputs and marine detritus both in Puget Sound and on the Outer Continental

Shelf.

c. Biological Oceanography. Controlling factors affecting the biota are 1) available sunlight, 2) available nutrients, 3) oxygen concentrations, and 4] predation. Primary production is that production through photosynthesis that is the foundation of all biological growth in the marine environment. Organisms that photosynthesize are said to be at the producer trophic level, and include attached and floating aquatic plant communities.

Normally, during the winter and spring, nutrients are abundant in the inland waters of Puget Sound, the Strait of Juan de Fuca, and the Strait of Georgia. As more and more sunlight becomes available, a phytoplankton bloom occurs, usually in late April to early May, and oxygen saturation values in Main Basin of Puget Sound may reach as high as 160%. A bloom of zooplankton, "grazers" on the phytoplankton, occurs after the peak of the phytoplankton bloom. A lesser, second phytoplankton bloom may occur in late summer.

Species composition lists of the phytoplankton community have been determined by Thompson and Phifer (1936) (see Table III-47). For the most part, abundance of the various species varies without a discernible pattern. One or more of the species in Table 111-47 may become dominant during bloom periods.

Thalassiosira sp. and *Coscinosira* sp. bloomed briefly in the spring of 1972 with *Chaetoceros* sp. and *Skeletonema* sp. becoming dominant in the summer period. In 1973, *Thalassiosira* sp. dominated the composition in April and May, then *Chaetoceros* sp. in late May and June, and finally *Noctiluca* sp. and *Gymnodinium* sp. dominated from late June through July.

The most extensive bloom yet recorded in the study area was noticed in summer of 1974. *Noctiluca* sp. was the organism blooming, resulting in a characteristic nontoxic red tide. *Noctiluca* sp. is a member of the Dinoflagellata, organisms with characteristics of both animals and plants included in the species composition of the phytoplankton (Table III-47).

i. Primary Productivity. Studies of phytoplankton abundance and productivity are judged by the chlorophyll-a and carbon production. Phytoplankton biomass has been determined historically by Winter, Banse and Anderson (1975) who also found that appreciable amounts of chlorophyll-a were found at depth. For the greater part of the year, the concentration below SO m is between 0.5 and 1.5 mg chl-a/m^3. As a consequence, there is nearly always more pigment in the water column below the euphotic zone than within it (Winter, Banse and Anderson, 1975). The cells at depth were found to be viable, and appear to be advected to depth by turbulence created from tidal cycles at the entrance sill. Figure III-91 presents the chlorophyll-a concentrations for 1966 and 1967 for the months of April and May.

Winter, Banse and Anderson (1975) determined productivity of the phytoplankton in spring months of 1966 and 1967. Their findings (Figure III-92) show that a maximum specific production rate was found to vary from 3 to 4 milligrams carbon per milligram of chlorophyll-a, a rate that they determined was similar to a British Columbia fjord.

Table III-47

Phytoplankton Species Composition of Puget Sound Central Trough[§]

Diatomaceae

Asterionella japonica
Cerataulina Bergonii
Chaetoceros compresses
Chaetoceros debilis
Chaetoceros diadema
Chaetoceros lachiniosus
Chaetoceros pseudocrinitus
Chaetoceros Vanheurckii
Coscinodiscus centralis
Coscinodiscus excentricus
Coscinodiscus radiatus
Concinosira polychorda
Ditylum Brightwelli
Leptocylindrus danicus
Nitzschia seriata
Rhizosolenia hebetata
Rhizosolenia setigera
Skeletonema costatum[†]
Thalassiosira aestivalis[†]
Thalassiosira Nordenskioeldii
Tropidoneis Antarctica
Biddulphia longieruris
Chaetoceros affinis[†]
Chaetoceros crucifer
Chaetoceros decipiens
Chaetoceros eibenii
Chaetoceros lorenzianus
Chaetoceros radicans
Corethron hystrix
Coscinodiscus concinnus
Coscinodiscus Granii
Coscinodiscus Wailesii
Dactyliosolen mediterraneus
Eucampia zoodiacus
Nitzschia closterium
Rhizosolenia fragilissima
Rhizosolenia semispina
Rhizosolenia stolterfothii
Thalassionema nitzschioides
Thalassiosira condensate
Thalassiosira rotula

Dinoflagellata

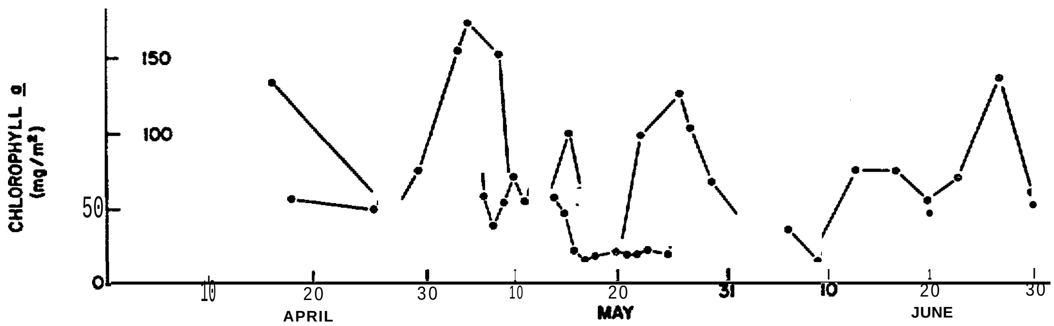
Ceratim fusus
Dinophysis acuminata
Dinophysis ellipsoids
Exuviella perforata
Gymnodinium lunula[†]
Oxytoxum diploconus
Peridinium depressum
Peridinium micrapium
Phalacroma rotundatum
Protoceratium reticulatum
Ceratium tripes
Dinophysis acuta
Dinophysis sphaerica
Goniaulax spinifera
Noctiluca scintillans[§]
Peridinium conicum
Peridinium divergens
Peridinium obtusum
Phaeocystis sp.[†] (Matsuda, pers. comm.)

[§]Thompson and Phifer, 1936.

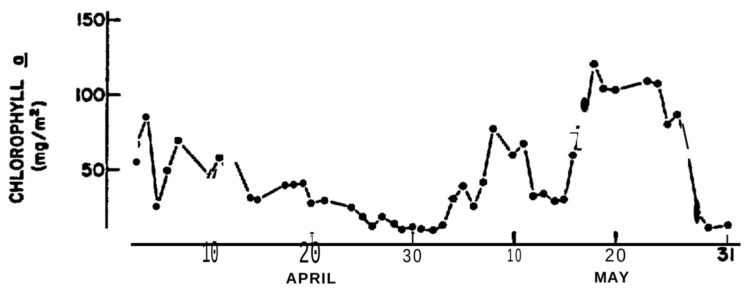
[†]May become dominant during bloom periods.

Figure II I-9 1

Phytoplankton Biomass
Puget Sound Central Trough[§]



	Mean	**Max**	Min	Chlorophyll a mg/m[2]
April	**100**	150	50	
May	75	190	15	
June	72	125	15	



	Mean	**Max**	Min	Chlorophyll a mg/m^{2}[†]
April	40	90	10	
May	60	120	10	

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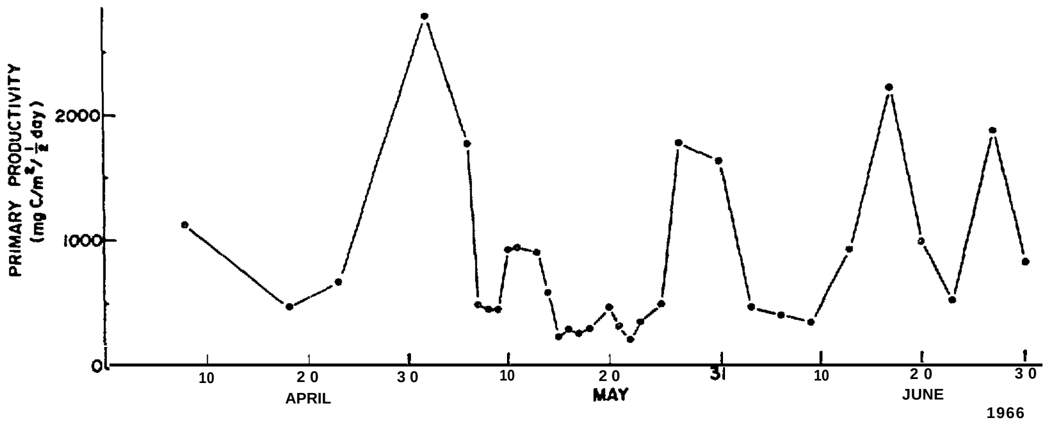
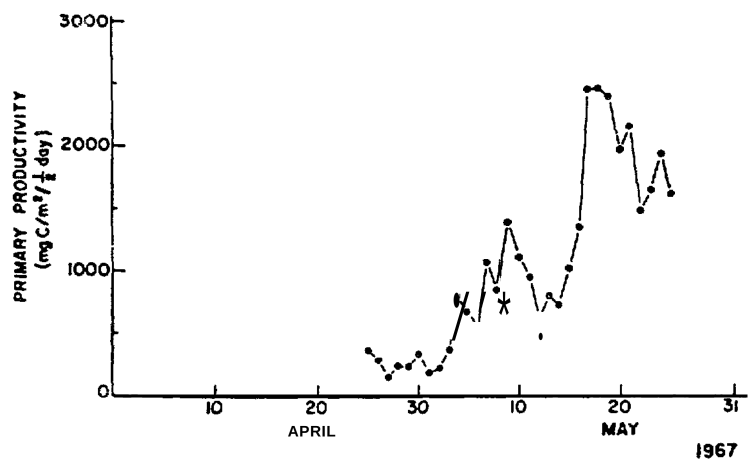
§ **Winter, Banse** and Anderson, 1975.
† **Above 1%** light depth

Figure III-92

Primary Productivity
Puget Sound Central Trough (Carbon Uptake)[$]



	Mean --	Min --	Max	Primary Productivity of Phytoplankton[†] mgC/m²1/2/ddy
April	1200	500	2300	
May	1000	200	2750	
June	1100	300	2200	



	Mean	Min	Max	Primary Productivity of Phytoplankton[†] mgC/m-2 1/2 ddy
May	1200	200	2500	

'Winter, Banse and Anderson, 1975.
†to 1% light depth

Detailed studies of phytoplankton productivity were carried out in the spring of 1975, with daily sampling at a principal station mid-channel off West Point over a three and a half week period (when the bloom normally appeared in the past). Values routinely measured were vertical density distributions to determine stratification and stability, nitrate concentration, chlorophyll-a, tidal range, and primary productivity of carbon (Anderson, 1976).

The daily sampling indicated that at a single location considerable day-to-day variations occurred. Nitrate concentrations did not show marked variability in the near-surface layers. Only in the latter part of May did the near-surface values fall below 20 mg-at N/m^3. A minimum concentration of 12.31 mg-at N/m^3 was obtained on May 19, but this value was not low enough to be considered limiting.

The average observed chlorophyll-a content in the photic zone at the primary station was 1.0 mg/m^3. Chlorophyll-a was increasing in its vertical extent over the photic zone as the study period progressed. On May 11 and 19, 1975, values exceeding 4 mg/m^3 were observed at the surface.

Primary productivity was determined by incubating captive samples of seawater containing phytoplankton. The primary productivity taken over the photic zone ranged from 107 to 1648 mg carbon/m^2/½ day. A half day means half the daylight period, Local Apparent Noon to sunset. Here, high carbon production values are associated with the observed high values of chlorophyll-a. On May 10, 1975, relatively low primary productivity was believed to be related to low insolation values -- there was not sufficient sunlight energy to increase the plant biomass even though there was a large standing stock.

Large day-to-day variations in chlorophyll-a and primary productivity were common, with primary productivity being generally high at the 100% and 50% levels of available solar light. In general, primary productivity determinations varied much more at different depth levels and among observations at each depth than did chlorophyll-a.

This experiment pointed out how the patchiness of organisms, inhomogeneity and motion of the central basin waters, and time variations of observed standing stock as well as of primary production, make evaluation extremely difficult.

Discussion of higher trophic levels -- benthic, pelagic, and intertidal communities -- are presented in Chapter IV., Marine Ecology.

Dr. Carpenter of the University of Washington has begun seasonal samplings of phytoplankton, zooplankton, and neuston at about 40 stations in Puget Sound for hydrocarbon studies, in hope of developing a baseline for hydrocarbon reference. The stations were chosen partly because Dr. Frost, also of the University of Washington, has already made two seasonal collections of zooplankton at many of the stations as a start at defining the geographical and seasonal distribution of zooplankton. Additional stations are closely spaced in the Cherry

Point/Ferndale areas north of Bellingham (southern Strait of Georgia region), and the Anacortes area, because these are the sites of the major refineries in the state.

c. Data Gaps

1. Oregon-Washington-Vancouver Island Coastal Area.

a. Physical. Data gaps are primarily related to circulation. Nearshore circulation has not been studied and surface currents have been inferred from current meters set far enough below the surface to minimize wave effects. The nearshore circulation at the surface, how it responds to winds, sea level changes, etc., must be further investigated to enhance capability of spill trajectory prediction.

b. Chemical. Too little is known about processes of hydrocarbon breakdown and/or transport through bio-geo-chemical pathways in the ecosystem. Critical pathways that pertain to man need to be defined and indicator species determined for monitoring.

c. Biological. More baseline data is needed, along with more specific studies of pollutant biological pathways and pollutant effects.

2. Oregon-Washington Coastal Estuaries.

The main unknown here is how far oil can travel in each estuary, assuming either an offshore spill or a spill within the estuary. Information necessary to assist in this evaluation includes mixing characteristics, extent of salt intrusion, and flushing characteristics.

3. Washington-British Columbia Inland Waters.

Key data gaps are related to spilled oil movement and effects. Since tanker traffic passes through the Strait of Juan de Fuca, and Haro or Rosario Strait (by the San Juan Islands) and into the southern Strait of Georgia, these are the areas for which circulation and biological baseline data are needed most.

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