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Net Shore-Drift Along the Pacific Coast of Clallam and Jefferson Counties, Washington

James Mahala
Western Washington University, jimmahala21@gmail.com

NET SHORE-DRIFT ALONG THE PACIFIC COAST OF CLALLAM AND JEFFERSON COUNTIES, WASHINGTON

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ABSTRACT

Geomorphic and sedimentologic indicators of shore drift were used to delineate the boundaries of drift unit cells and their direction of net shore-drift along the 110 km of Pacific coastline of Clallam and Jefferson Counties, Washington. These indicators include changes in bluff morphology, sediment size gradation, beach width and slope, direction of spit progradation and stream mouth diversion, deposition and/or erosion at drift obstructions, identifiable sediment, and nearshore bar orientation. Drift determinations were based on a field oriented approach emphasizing such long-term indicators, supplemented by aerial photography, and literature relevant to the coast.

Wind from the south-southwest prevail and predominate over Western Clallam and Jefferson Counties. This results in a northerly net shore-drift direction dominating along the study area. However, short drift reversals do occur in the wave shadow of headlands, where waves are refracted around nearshore islands and stacks, and where the orientation of the coast differs considerably from the overall trend.

Thirty drift cells, ranging from 0.4 km to over 26 km in length, have been identified and their direction of net shore-drift determined along the Pacific coast of Clallam and Jefferson Counties. The predominant southwesterly wind-generated waves dominate the direction of net shore-drift as evidenced by a northerly drift direction in all but six of the drift unit cells.

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INTRODUCTION

Understanding the coastal processes that shape and continually modify the shoreline is fundamental to any rational planning for use of coastal land. Shore drift is an intrinsic aspect of the coastal processes that directly influence the long-term morphology of a coast. Shore drift is defined as the process by which beach and nearshore sediment is transported parallel to the coast by beach drift and longshore drift. Seasonal variations of shore drift can occur in response to changes in wind and wave approach, but over a long period one direction of sediment transport will usually predominate. This is the direction of net shore-drift.

Short-term studies of net shore-drift, using such methods as artificial tracers or sediment traps, are prone to errors. These techniques record the drift direction only for the period of study, which may reflect a seasonal direction of shore drift, rather than a long-term direction. Drift determinations based on a mathematical modeling procedure, known as wave-hindcasting and the construction of wave orthogonals, are also subject to errors. This method uses wind data from recording stations to determine the direction of dominant wave approach and resulting shore drift by plotting wave orthogonals. On crenulated coastlines, such as Washington's northern Pacific coast, serious mistakes can be made by using this method. Wind data are generally limited along the coast and thus must be extrapolated from inland recording stations, which may not be representative of surface conditions on the coast. In addition, coastal topography and fetch are not adequately considered in the wave modelling calculations.

There have been no previous investigations of net shore-drift along

Washington's northern Pacific coast using geomorphic and sedimentologic indicators. Shore drift has been studied along the southern region of the Pacific coast of Washington by Plopper (1978), Phipps and Smith (1978), and more recently by Schwartz and Bronson (1984), who employed the same methods applied in this study. Hopkins (1971) has investigated the water circulation over the continental shelf off Washington.

The purpose of this study is to delineate the boundaries of drift unit cells and to determine their direction of net shore-drift along the Pacific coast of Clallam and Jefferson Counties, Washington. There was no attempt to measure the rate or volume of sediment transport along this segment of coast. This study is based on a field-oriented approach, which emphasizes long-term geomorphic and sedimentologic indicators of shore drift. These methods have proven to be successful in coastal drift studies in Puget Sound (Keuler, 1980; Jacobsen, 1980; Chrzastowski, 1982; Blankenship, 1983; Harp, 1983; Hatfield, 1983; Taggart, 1984), on the Bering coast of Alaska (Hunter et al., 1979), and more recently on the north coast of Puerto Rico (Morelock et al., 1985) and along a coastal sector of Padre Island, Mexico (Schwartz and Anderson, 1985).

The Pacific coastline of Jefferson and Clallam Counties, Washington, is one of the few remaining undeveloped coastal zones in the contiguous United States. This rugged, but picturesque, wilderness coast has long been recognized for its scenic and recreational value. Because of its value, a 80-km-long coastal strip was added to the Olympic National Park in 1953, although it had been under National Park Service administration for some years prior to that date. This protected coastal sector allows for the study of an undeveloped coast in which natural processes are solely responsible for the present coastal geomorphology.

REGIONAL SETTING

Geography

Clallam and Jefferson Counties are located in the northern Olympic Peninsula of western Washington (Figure 1). The present study area encompasses the Pacific coastline of these two counties (Figure 2), with a total coastal length of approximately 110 kilometers. This coastal sector is bounded on the north by the Strait of Juan De Fuca and to the south by Grays Harbor County.

The crenulated north-northwest-trending coastline of Clallam and Jefferson Counties is characterized by steep sea cliffs, sand-gravel beaches, wave-cut platforms and numerous offshore sea-stacks. Much of the land is undeveloped and under the authority of the Olympic National Park. The Park contains a Pacific coastal strip that stretches 80 kilometers from just above the Ozette Indian Reservation on the north to the border of the Quinalt Indian Reservation on the south. The remaining coastal property within the study area is under the jurisdiction of the Makah, Ozette, Quillayute, Hoh and Quinalt Indian Reservations.

The continental shelf off the Washington coast slopes westward at 3-4.5m/km and varies in width from 35-60 km (Hopkins, 1971). Several major submarine canyons have been incised into the upper continental slope, narrowing the shelf width at their heads. Six rivers and numerous streams discharge into the Pacific Ocean within the study area.

Geology

The tectonic history of the Pacific Northwest has clearly affected the rock formations of the Olympic Peninsula. Numerous workers have suggested that the core rocks of the Olympic Peninsula were formed as a

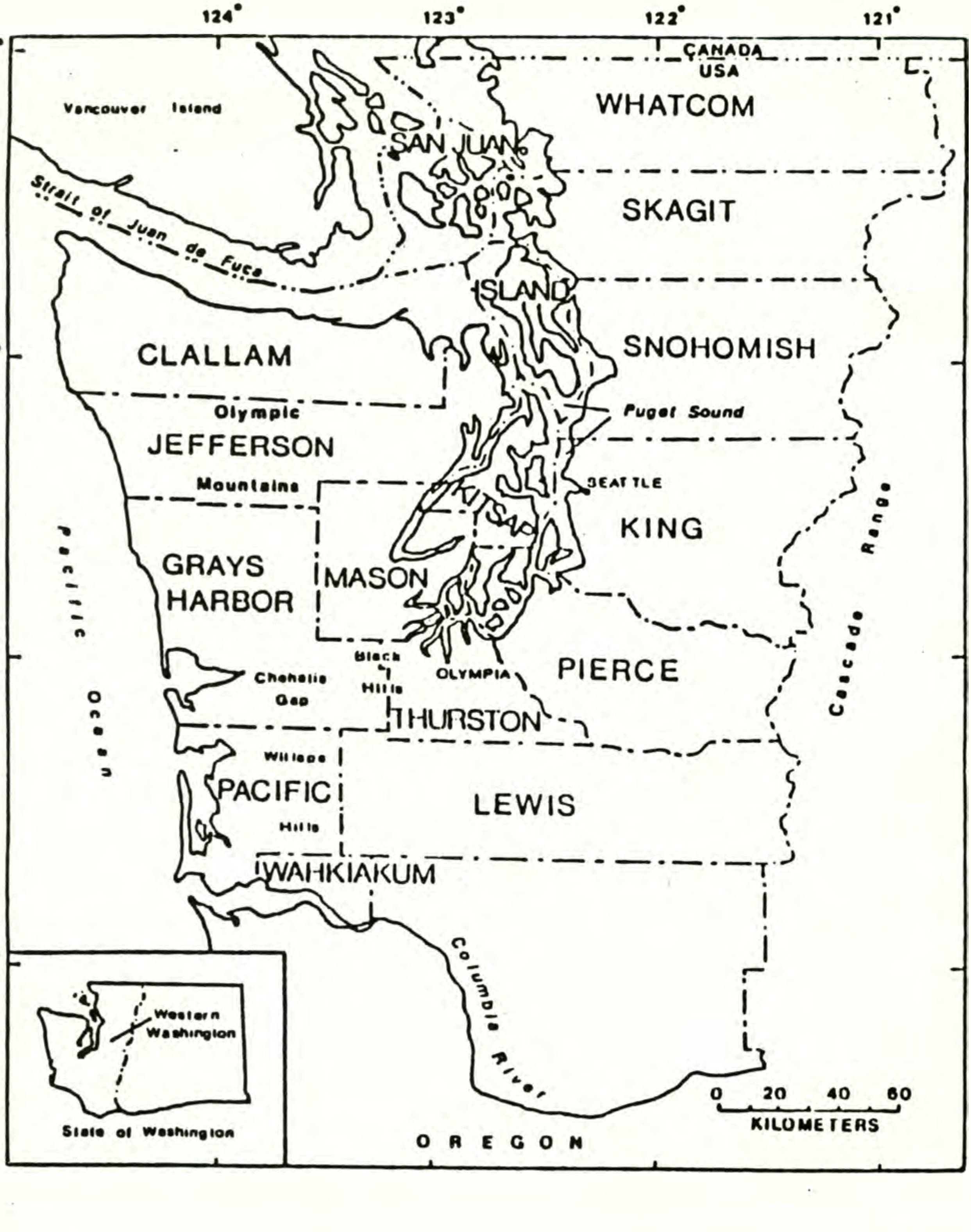

Figure 1. Location map of western Washington (after Chrzastowski, 1982).

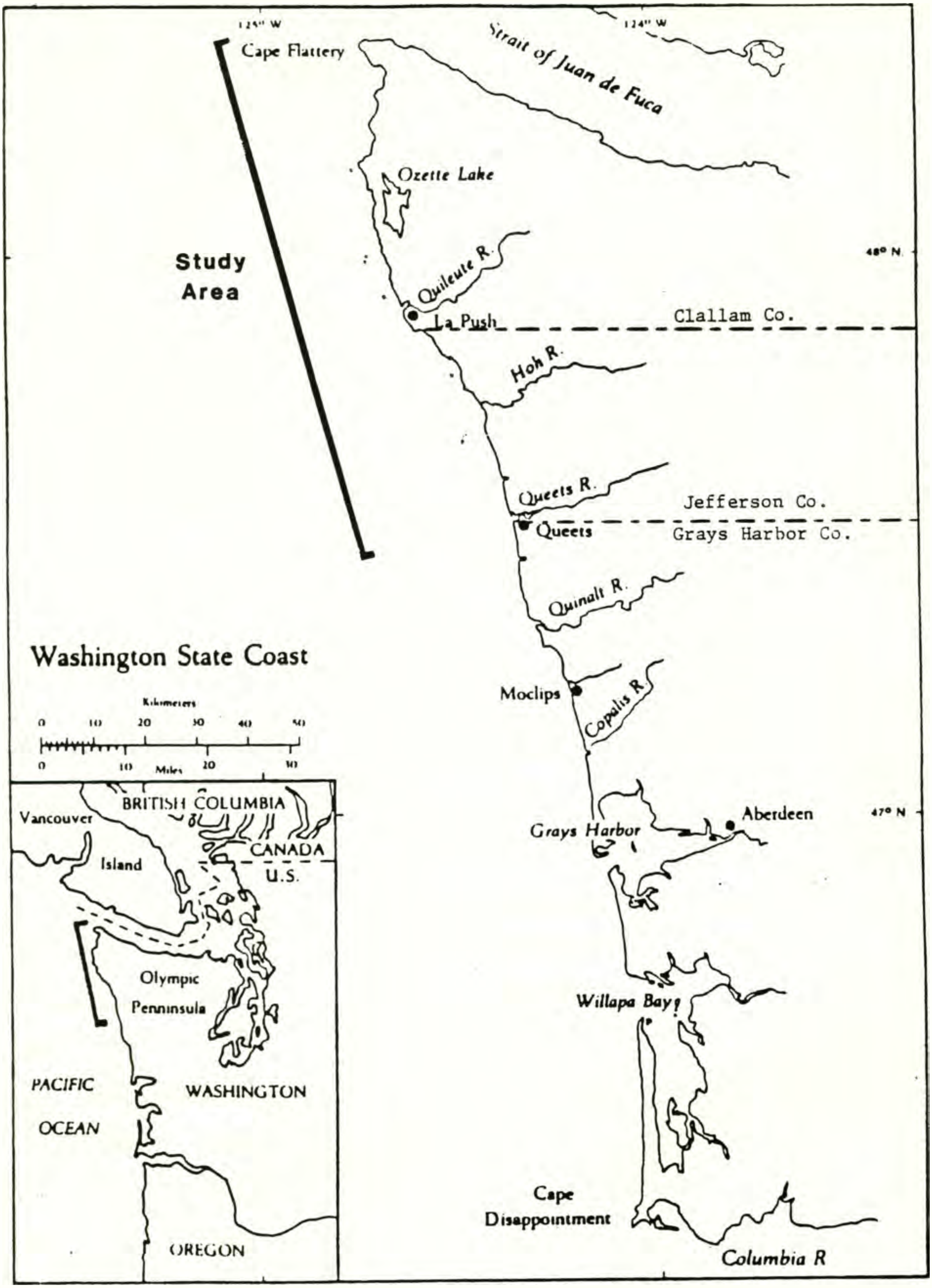

Figure 2. Location map of western Clallam and Jefferson Counties (adapted from Terich and Schwartz, 1981).

result of subduction of oceanic lithosphere, while the overlying sedimentary rock sequences were intensely deformed and accreted to the continental plate (Stewart, 1971; Tabor and Cady, 1978). The presence of oceanic basalt and the overall structural complexity of the rocks lends support to this theory.

The oldest rocks exposed along the coast are those at the Point of the Arches, which are thought to be of at least Jurassic in age (Tabor and Cady, 1978). These plutonic rocks are composed of gabbro and diorite (Table 1). The Crescent Formation consists of volcanic rocks (basalt) with minor siltstone interbeds (Glassley, 1974), and crops out in the study area along wave-cut cliffs at Portage Head and Anderson Point. The Western Olympic lithic assemblege is exposed throughout the study area and is dominantly composed of sandstones with minor granular conglomerates (Tabor and Cady, 1978). Weaver's (1937) Hoh Formation, which is exposed along much of Jefferson County's Pacific coastline, has been reorganized by Rau (1973). Rau has divided the Hoh rocks into two major groups; the Hoh assemblege, and a second group referred to as a "tectonic melange". The Hoh rock assemblege is a group of intensely folded and faulted sandstone, siltstone, and conglomerate sequences. The other major group, tectonic melange, is a chaotic mixture of siltstone, sandstone, and conglomerate set in a relatively weak, unconsolidated matrix of siltstone, sandstone, and claystone.

Most of the bedrock along the Pacific coasts of Clallam and Jefferson Counties is overlain by unconsolidated glacial sediments, composed dominantly of sand and gravel, which were deposited at different times during the Pleistocene. Although four glaciations are recognized in the western Olympic Peninsula (Heusser, 1977), only two major events of deposition are apparent in the stratigraphy along the coast (Rau, 1980).

PERIOD	EPOCH	COASTAL ROCK UNITS AND GEOLOGIC EVENTS
QUATERNARY	Recent	Unconsolidated stream, lake, and beach deposits.
	Pleistocene	No deposits locally
		Silt, sand, and gravel; deposited by streams from glaciers.
		Marine erosion in coastal area
		Gently tilted, semiconsolidated silt, sand, and gravel; deposited by glaciers and streams from glaciers
		Uplift and much stream erosion
TERTIARY	Pliocene	
	Miocene	Uplift and deformation
		HOH ROCK ASSEMBLAGE Sedimentary rock sequences: Steeply tilted and overturned siltstones, sandstones, and conglomerates Tectonic melange rocks: Chaotically mixed blocks of sedimentary and other rock types in a matrix of softer claystone and broken siltstone:
	Oligocene	WESTERN OLYMPIC LITHIC ASSEMBLEGE Sandstone and minor granular conglomerate
	Eocene	CRESCENT FORMATION Badly fractured volcanic rocks interbedded with siltstone beds
	Paleocene	No local rock record
PRE-TERTIARY		Sedimentary rocks and pillow basalt
JURASSIC OR OLDER		Plutonic rocks Massive to gneissic gabbro and diorite

Table 1. Stratigraphic units commonly exposed along western Clallam and Jefferson Counties (adapted from Rau, 1980).

The northern region of the study area was partially occupied by the Juan de Fuca lobe of the Cordilleran glacier complex during Salmon Springs and Fraser glaciations (Crandell, 1965). In addition, alpine glaciers originating in the Olympic Mountains deposited glacial sediment, particularly in and adjacent to the major stream valleys of the Hoh, Quillayute, and Bogachiel Rivers and Goodman Creek (Florer, 1972). After the deposition of the two younger Pleistocene sands and gravels, and probably before much vegetation had developed, windblown sand and silt covered the coastal area of western Jefferson County to a depth of 1 m or more (Rau, 1980).

The geology of the coast is complicated by eustatic, isostatic, and tectonic changes in sea level relative to the mainland. In the late Pleistocene a small eustatic rise in sea-level of about 2 m may have occurred during the Hypsithermal (Danner, 1955). Rau (1980) has found evidence that the coastline was at one time during the Pleistocene farther inland than it is at present. Evidence for this is manifested by the essentially horizontal trace of an elevated wave-cut terrace at the top of many bedrock outcrops in the sea cliffs, stacks, and offshore islands within the study area. This erosional surface lies at approximately 35 m and is located along most of western Jefferson County (Rau, 1980).

South of the Hoh River, in southern Jefferson County, late Pleistocene sand and gravel deposits are exposed in wave-cut cliffs. Here coastal erosion rates have been estimated by comparing old land surveys to those made in recent years. These surveys show that there is an average erosion rate of 1.1 m/year along this coastal sector (Rau, 1973). Thus, Destruction Island, which lies 6 km offshore, would have been a part of the mainland some 6,000 years ago. This high rate of erosion is caused primarily by the susceptability to erosion of sand, gravel, and clay. The tectonic melange of the Hoh Formation, which make up much of this segment of the coast, are also highly erodable. These melange deposits are structurally weak, in part, because of their clay minerals, which expand when wetted by waves and precipitation.

CLIMATIC SETTING

The climate of Clallam and Jefferson Counties is dominated by maritime air brought in from over the North Pacific by prevailing westerly winds. The moderating effects of Pacific Ocean air masses on the climate are shown by wet mild winters and cool dry summers.

The location and intensity of the semi-permanent high and low pressure areas over the North Pacific have a pronounced influence on the climate (National Oceanic and Atmospheric Administration, 1980). During the late spring and summer, the East Pacific high pressure system dominates the weather over Washington's Pacific coast (Figure 3). In the fall and winter, the Aleutian low pressure system is of major importance in controlling the weather. The gale-force winds and heavy precipitation produced by cyclonic storms are generated by the Aleutian low pressure system during the winter season. Annual precipitation ranges from 177.8 to 254 cm along the Pacific coast of Clallam and Jefferson Counties, with approximately 84% of the rainfall occurring between the months of October and April (NOAA, 1980). High precipitation during this time increases stream discharge, surface runoff, and coastal bluff erosion, resulting in an increase of sediment available for transport along the coast.

Temperatures along the Pacific coastlines of Clallam and Jefferson Counties reflect the moderating effect of maritime air. Along the coast, the average maximum temperature in July is near 21^{o} C, and the minimum temperatures in January range from 0^{o} C to 3^{o} C (NOAA, 1980).

Wind

Surface winds generate waves, which directly influence the shore-drift process. The direction, duration, and velocity of surface winds

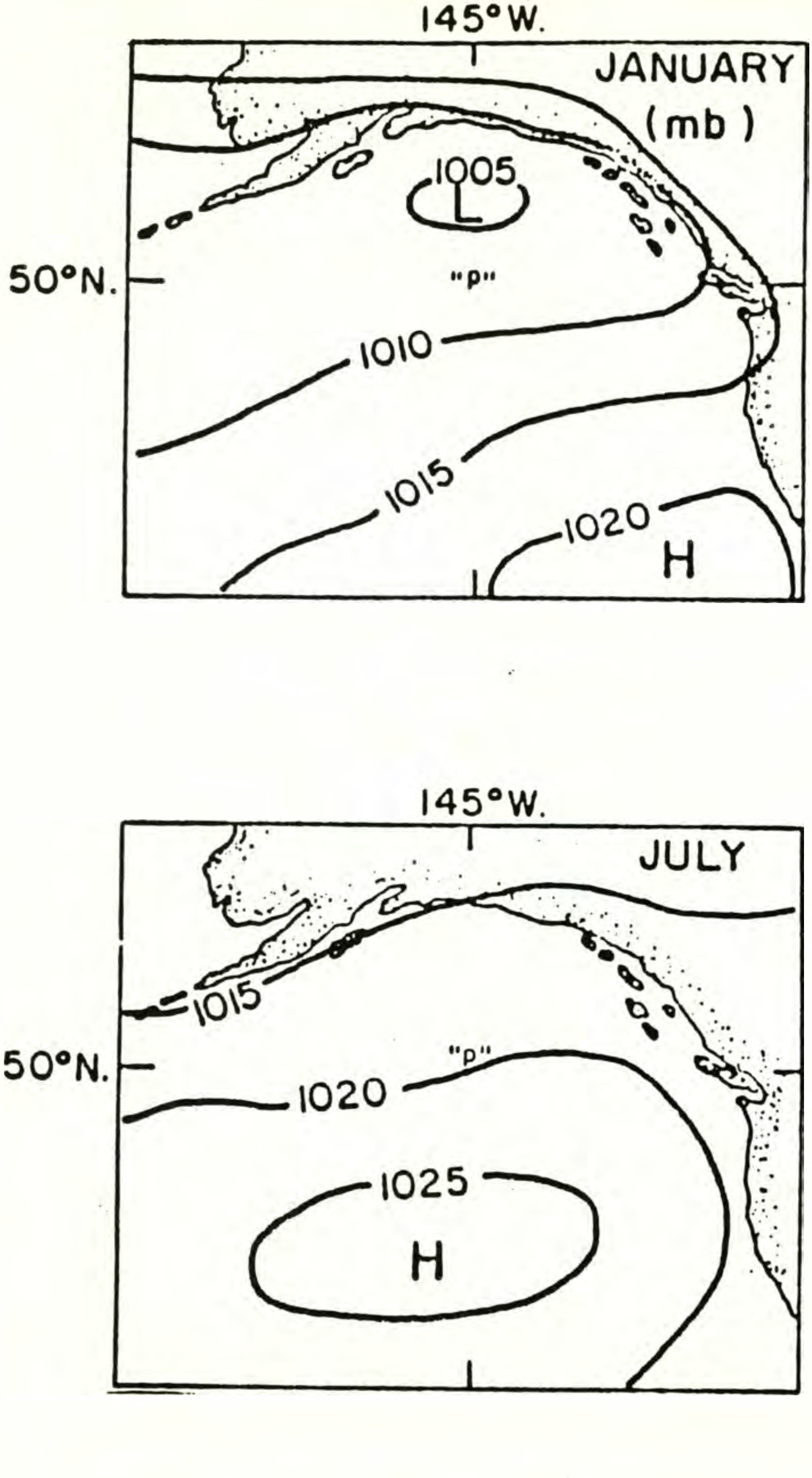

Figure 3. Mean atmospheric pressure systems in the Northeast Pacific (after Hopkins, 1971).

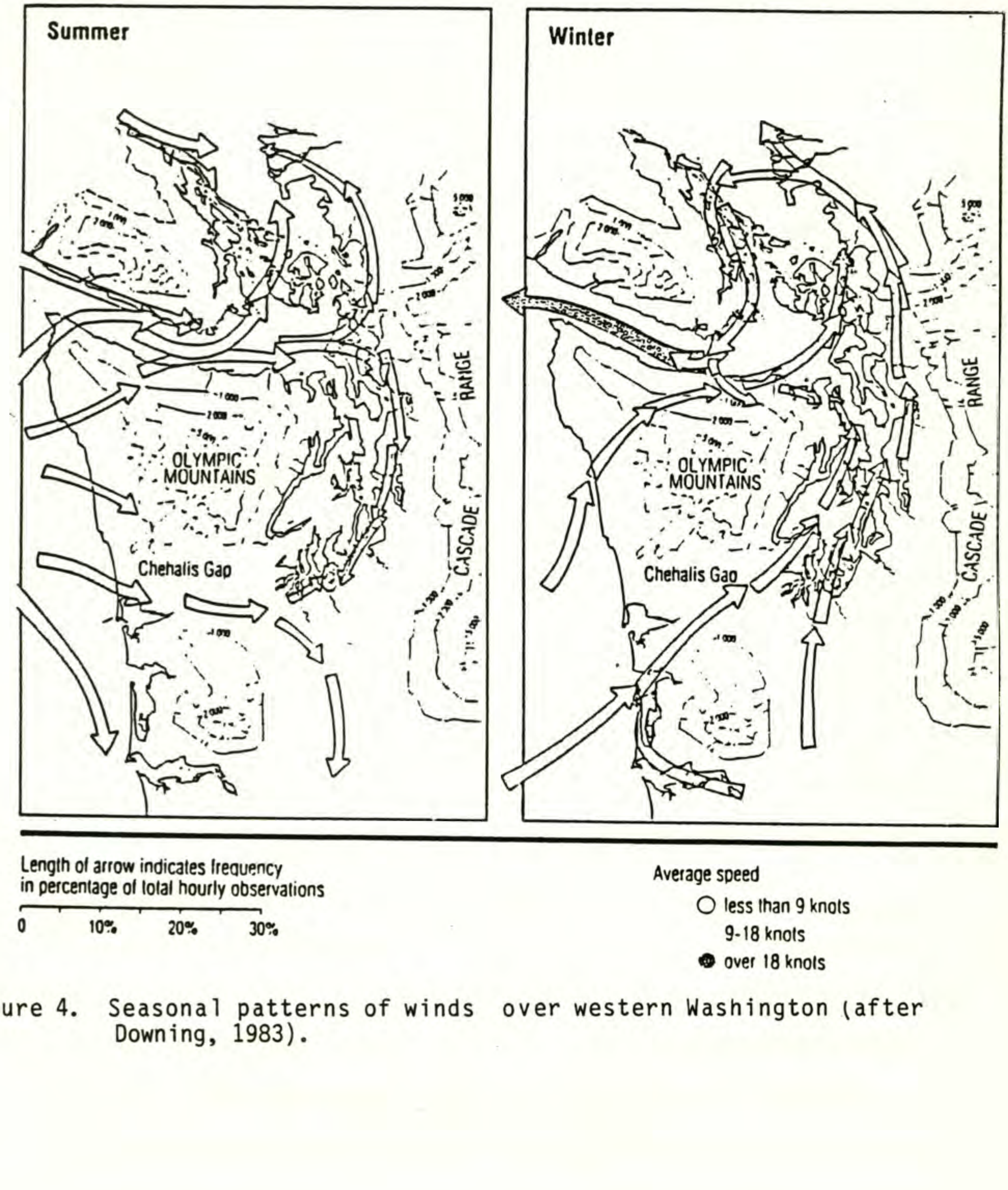

Figure 4. Seasonal patterns of winds over western Washington (after Downing, 1983).

over the Northeast Pacific vary seasonally (Figure 4). These winds are a direct product of the two semi-permanent pressure systems over the north Pacific Ocean.

In the late spring and summer (June to September), a clockwise circulation of air around the East Pacific high pressure system brings a prevailing northwesterly and westerly flow of cool, relatively dry, stable air into the northwest Olympic Peninsula. The high pressure system pushes the Aleutian low pressure system and its related storm activity to the north. In the late fall and winter (October to May), the Aleutian low pressure system gradually intensifies and replaces the high pressure cell, pushing it to the south. During this season, storm systems crossing the Pacific follow a more southerly path, occurring at frequent intervals. The wind-flow pattern is directed counter-clockwise around the low pressure center, resulting in a prevailing flow of air from the southwest. This area receives the full force of storms moving inland from over the ocean; thus heavy precipitation and winds of gale force occur frequently during the winter season. Wind velocities at lower elevations can be expected to reach 144.8 to 160.9 km/hour once in 100 years (NOAA, 1980).

The exchange of location between the two cyclonic pressure systems in the northeast Pacific Ocean is a primary cause of the pronounced seasonal variation in wind conditions found off the northwest Olympic Peninsula. From June through September calm summer conditions exist, while winter storm conditions prevail the remaining two-thirds of the year (NOAA, 1980). The result of this annual exchange is that the prevailing winds (most frequent) are from the northwest during the summer season and from the southwest during the remainder of the year. However, the predominant winds (which have the strongest influence on wave generation) are formed during the winter storm season and are from the southwest.

The predominant southwesterly wind-generated waves dictate much of the net shore-drift direction along the coasts of those parts of Clallam and Jefferson Counties facing the open ocean. However, wind direction may be modified at the shore behind an island, in the lee of a headland, or within an embayment, causing possible drift reversals.

OCEANOGRAPHIC SETTING

The oceanographic parameters that most affect the shore-drift process along the Pacific coast of Washington are wind-generated waves and tidal range. Wind-generated surface waves are the principal source of energy responsible for erosion and transportation of sediment along the shore. The tidal range determines the vertical and horizontal extent to which waves may impart their energy.

Wind-Generated Waves

Shore drift occurs due to the oblique approach of wind-generated waves. The potential energy of wind-generated waves is a function of the wind velocity, wind duration, and the fetch or distance of open water over which the wind can blow unimpeded. Changes in fetch are important up to about 1500 kilometers (Davies, 1980), thus this limiting factor is not significant in beaches facing the open ocean. With fetch being relatively unimportant along much of the northwest Pacific coast of Washington, wind velocity and duration are the primary controls governing the amount of energy available for wave generation in the study area.

Waves originate by the turbulent flow of wind over the water surface, and grow as the result of a pressure contrast that develops between their windward and leeward slopes (Bird, 1969). Waves formed in the zone of generation and that are actively under the influence of the wind are termed "sea waves". As the waves leave the area of formation, they are sorted out by period and thereby become more regular with smooth, rounded crests. Such regular waves are known as "swell". Once the waves enter shallow water, at a depth approximately one-half the deep-water wave length, they interact with the bottom and begin a transformation. May (1982) refers to such waves as "shoaling waves". When waves reach the nearshore zone and enter water approximately as deep as the waves are high, they break on the shore as swash and backwash (Komar, 1976). Though wave period remains constant throughout the wave transformation process, the wave height of the breaking wave is greater than that of the deep-water wave.

The Pacific coast of Clallam and Jefferson Counties lie between the 40^{o} and 60^{o} latitudes which Davies (1980) defines as the storm-wave environment. This environment is characterized by a relatively large number of gale-force winds that generate high energy waves, which tend to dominate transport in the nearshore zone. Swell waves are of background significance.

Tides

Tides are periodic movements of the waters of the oceans induced by the gravitational effects of the sun and moon in relation to the earth (Bird, 1969). The maximal tidal range (spring tide) occurs during new and full moon phases; when earth, sun, and moon are in alignment and have combined gravitational effects (see Figure 5). The minimal tidal range (neap tide) occurs at half moon phases (first and third quarters), when the sun and moon are at right angles to each other in relation to the earth, resulting in gravitational effects minimizing the tidal range. Due to the nearly monthly (28.5 solar days) revolution of the moon about the earth, there are twice-monthly spring and neap tides.

The nature of the tides, diurnal, semi-diurnal, or mixed, depends on the pattern and frequency of occurrence of high and low tides at any one location. Washington's Pacific coast experiences mixed tides, which means

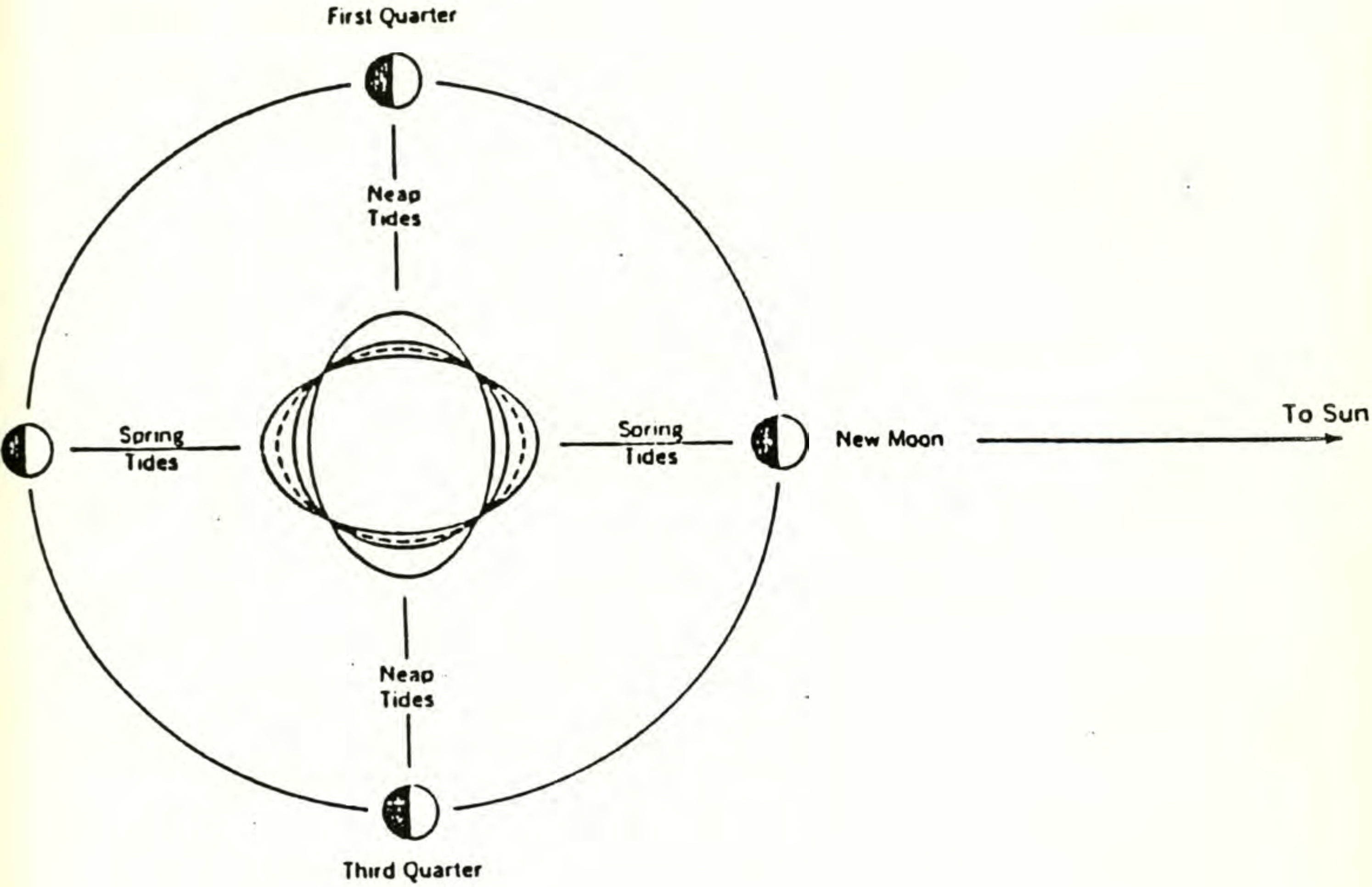

Figure 5. The gravitational attractions produced by the moon and sun combine at times of new and full moon to increase the range of the tides, and counteract each other at first and third quarters to reduce the tidal range (after Wood, 1982).

that there are two highs and two lows during the tidal day, with all of the tides of different heights. This diurnal inequality is caused by the declination of the earth's equatorial plane with respect to the plane of the earth's orbit around the sun and the moon's varying position above and below the plane of the earth's orbit about the sun (Komar, 1976).

The significance of tidal range in coastal development has been widely recognized (Davies, 1980; Rosen, 1977). Tidal range directly limits the extent to which waves may impart their energy. Rosen (1977) found that in areas with a large tidal range, where wave energy is dispersed over a broad inter-tidal zone, there is an overall decrease in coastal erosion. For areas with a small tidal range, wave energy tends to concentrate within a narrower area along the beach profile, resulting in an increase of coastal erosion.

Spring tidal range along Washington's Pacific coast is typically between 3 and 4 m, which is classified as mesotidal by Davies (1980). Mesotidal tides tend to dissipate wave energy across the beach profile, resulting in a widening of shore platforms and beach foreshores.

PRINCIPLES

The following is a brief summary of two important aspects of coastal processes employed in studies of net shore-drift. These aspects are the dynamics of shore drift and the concept of a drift cell.

Dynamics of Shore Drift

As deep water waves approach the shore, they begin to adjust to the bottom contours. This adjustment, known as wave refraction, changes the direction of wave travel with decreasing depth of water so that the crests tend to parallel the bottom contours. Waves that are completely refracted arrive perpendicular to the coast and have little or no effect on the transport of sediment parallel to the shore. However, for most waves, the process of refraction is not complete, and waves arrive at a slight angle to the coastline.

Waves striking the beach at an angle produce an oblique upward rush of swash (sediment and water) succeeded by the return of the backwash down the beach face. This drift pattern carries the swash up the beach at an angle, perpendicular to the breaking wave. The backwash, returning down the beach face under the influence of gravity, carries along the shore with the same force. This pattern results in an arcuate motion, parallel to the coast, of sediment along the foreshore. This type of sediment transport is termed beach drift.

In the nearshore zone, a longshore current is produced by wave action when waves approach at an angle to the shoreline (Longuet-Higgins, 1970a, 1970b). Sediment is transported by the current parallel to the shore in the same direction as the beach drift. This process is known as longshore drift.

The combined action of beach drift and longshore drift is called shore drift (Figure 6). The direction of shore drift can vary on a daily or seasonal basis in response to changes in wind and wave approach. However, for most coastal segments one shore drift direction predominates, resulting in a net transport of sediment in that direction. Thus, net shore-drift is the direction in which the majority of sediment is transported over a long period of time, in spite of any smaller seasonal movement in the opposite direction (Jacobsen and Schwartz, 1981).

Areas of no appreciable net shore-drift may exist along coastal segments where shore drift processes do not take place. This condition may occur due to factors such as a lack of sediment supply, a shore artifically or naturally modified so that it extends out to deep water, or a shore with low wave energy.

Concept of a Drift Cell

An important concept employed in many coastal studies is that of a "drift cell" of sediment transport along the coast. Along rocky or irregular coastlines, sediment transport occurs within discreet compartments, even under conditions of high wave energy, so that movement can usually be measured over a number of kilometers (Jacobsen and Schwartz, 1981). The idealized drift cell consists of three different zones: a zone of sediment supply, a zone of sediment transport, and a zone of sediment accumulation. These zones, like drift cell boundaries, may consist of broad, generalized areas.

The origin of a drift cell may be a zone of fluvial input or long-term erosion which supplies much of the sediment necessary for shore drift. A typical drift-cell origin along Washington's Pacific coastal region would be characterized by a river mouth or by a vertical or near-vertical devegetated bluff or cliff fronted by a wave-cut platform. The

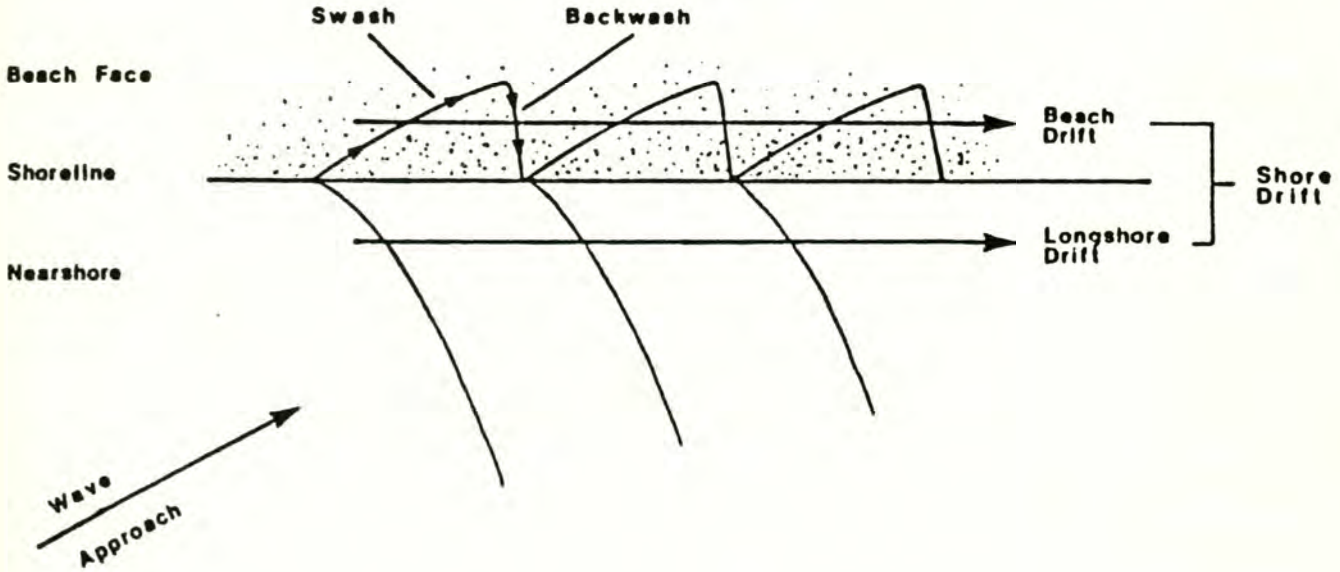

Figure 6. Schematic diagram depicting the shore drift process.

presence of only a narrow or no high-tide beach within this zone permits the continual under-cutting of the bluff, with the material from the bluff supplying much of the sediment for the drift cell. This zone sustains the highest energy waves impinging upon the shore and as a result the coast within this zone retreats at a greater rate than other sections of the coast. In this zone the primary transportable sediment is sand and gravel; while, commonly, cobbles and boulders remain as a lag deposit. A zone of drift divergence results when two drift cells of opposing net shore-drift direction originate from the same zone of sediment supply.

Sediment is moved along the coast by shore-drift processes in the zone of transport, toward the drift cell terminus. Throughout the zone of transport, sediment may be lost, detained, or introduced into the shore-drift system. Sediment is removed from the shore-drift system when wave action agitates and suspends fine sediment, which is then carried offshore and deposited into deeper water. Sediment can be temporarily detained or withdrawn from the active part of the shore-drift system and deposited in a less active site, possibly along the backshore by storm waves. Sediment may be introduced into the zone of transport of a drift cell by input from streams, eroding bluffs, wave-cut platforms, and any local regions exposed to higher-energy waves. Some of this influx of sediment originates from localized erosional areas present within the larger drift- cell system. A fresh input of sediment rejuvenates the sediment budget by increasing the quantity and mean grain size of the sediment.

The terminus of a drift cell is a zone of long-term sediment accumulation. Sediment is deposited at the terminus when wave-energy decreases below the necessary level to sustain movement of sediment of a given size. A typical drift-cell terminus in the study area would be characterized by a well-vegetated upland slope fronted by a stable accretionary landform, such as a prograded beach. Occasionally two drift cells converge at a common terminus, often in response to convergent wave regimes, and form a cuspate spit.

INDICATORS OF NET SHORE-DRIFT

Coastal studies involved in the determination of net shore-drift direction must take into account the variable nature of shore drift. The use of engineering methods such as artificial tracers and sediment traps may only determine short-term or seasonal drift direction. None of these methods fully accounts for all the intricacies of shore drift, especially the possibility that relatively rare, extreme events may be responsible for most of the sediment transport. Along crenulated coastlines, such as Washington's Pacific region, the use of long-term geomorphic and sedimentologic indicators of shore drift tends to be more reliable, because they take into account the many variables involved in net shore-drift. This method has been shown to be highly accurate in coastal studies in Puget Sound (Keuler, 1980; Jacobsen, 1980; Chrzastowski, 1982; Blankenship, 1983; Harp, 1983; Hatfield, 1983; Taggart, 1984) and along the Bering coast of Alaska (Hunter et al., 1979). This technique relies heavily upon a field-orientated investigation, documenting physical evidence.

The following sections deal with the geomorphic and sedimentologic indicators used in this study of net shore-drift along Washington's Pacific coast. These drift indicators are divided into two groups: indicators that require observations over a distance, and indicators for which the direction of net shore-drift can be determined at a specific site. It should be emphasized that the occurrence of a single indicator is not sufficent evidence on which to base a conclusive determination of the direction of net shore-drift. Rather, the combined effects of numerous drift indicators should be used to build a case for a definitive direction of net shore-drift.

Indicators Requiring Observation Over Distance

This category of indicators requires observation throughout the length of a drift cell before the direction of net shore-drift can be determined. The optimum conditions for observing these types of indicators are found along fairly straight coastlines that have a consistent, uniform influx of sediment. When sediment is added from a second source, repetition of these indicators may occur within the drift cell.

Sediment Size Gradation

It has been shown that mean sediment size decreases in the direction of net shore-drift (Bird, 1969; Davies, 1980). This gradation is related to lateral variations in wave energy along a coast (Bird, 1969). In general, as waves move down a coast their energy and competence decreases. As a result coarse sediment, which requires more energy for transport than does finer sediment, is moved only by less frequent, higher-energy waves. Fine sediment can be moved by more frequent, lower-energy waves. Thus, finer sediments tend to out-run the coarser sediments down a coast (Self, 1977; Jacobsen and Schwartz, 1981).

Typically, along Washington's Pacific coast, a drift cell that exhibits this type of gradation in sediment size would start with a beach composed predominantly of boulders and cobbles with lesser amounts of pebbles and sand. Downdrift, the beach would gradually change to a mixture of mostly cobbles with some sand and pebbles, and then to a beach composed of mostly sand with some pebbles (Figure 7). This trend can often be obscured by the input of additional sediment into the drift cell from streams, eroding bluffs, wave-cut platforms, or any local region

A

B

C

Figures 7a, 7b, and 7c. A series of photographs illustrating sediment size gradation through a drift cell. 7a shows a zone of sediment erosion; 7b shows a zone of transport; and 7c shows a zone of sediment accumulation along Drift cell C-1.

exposed to higher-energy waves. As a result, repetitions in sediment size gradation would be observed.

Beach Width

Beaches tend to widen and develop a broader backshore in their downdrift direction (Keuler, 1979; Jacobsen and Schwartz, 1981). This is primarily manifested by the downdrift increase in the abundance of moveable sediment. In most cases, the origin of a drift cell is characterized by a narrow or absent high-tide beach and the lack of a berm. Further downdrift, the volume of sediment gradually increases, causing a seaward displacement of the mean higher high water line. This results in a progressively wider high-tide beach and backshore in the direction of net shore-drift. This trend can be repeated by a fresh influx of sediment; possibly from a landslide, slump, or river, within a drift cell.

Bluff Morphology

This concept, described by Emery and Kuhn (1982) and also by Keuler (1979), has proven to be of great use in the determination of net shore-drift along Washington's Pacific coast. Trends in bluff morphology are directly related to the degree of wave attack at the base of coastal bluffs. At the beginning of a drift cell, bluffs generally show evidence of strong erosion. In this zone, the beach is narrow enough to permit the steady erosion of the bluff base, often producing a notch at the toe due to undercutting. The resulting slope of the bluff is near vertical and devoid of vegetation. Further down the drift cell, in the direction of net shore-drift, the beach gradually widens, providing an increasing degree of protection against wave attack at the base of the bluff. This protection results in the bluff slope becoming less steep and more heavily vegetated in the direction of net shore-drift. The development of a berm and wide backshore at the end of a drift cell offers additional protection for the bluff. Here the bluff slope takes on a more gentle profile and subaerial processes become the dominant type of bluff erosion.

Beach Slope

Beach slope has been found to be a function of particle size (Bascom, 1951; Davies, 1980). Typically, fine-grained beaches have a low beach slope. Thus, as the mean size of sediment generally decreases in the direction of net shore-drift, so does beach slope. However, in glaciated coastal regions, beach slope tends to increase in the downdrift direction (Keuler, 1979). This apparent contradiction can be explained by analyzing drift cell morphology where the shore is composed of glacial debris. At the origin of a drift cell, a wave-cut platform typically fronts a steep bluff or cliff. Within this zone, the low-sloping platform is mantled with a coarse lag deposit. In the direction of the drift-cell terminus, the quantity of beach material gradually increases, forming a large sediment wedge across the foreshore. This results in a progressive increase in mean beach slope in the direction of net shore-drift.

Log-Spiral Beaches

A log-spiral beach, also called a headland-bay beach, can be a reliable long-term indicator of net shore-drift. Yasso (1965, p.702) defines this type of beach "as a beach with a seaward concave plan shape that lies in the lee of a headland". When the predominant waves approach the headland, a wave shadow forms in its lee. This results in wave refraction, and to a lesser extent, diffraction, in the wave shadow. This wave action causes a local reversal in the direction of net shore-drift within the area in the lee of the headland (Jacobsen and Schwartz, 1981). Thus, sediment size and beach slope increase with increasing distance from the headland.

Site Specific Indicators

These indicators of net shore-drift are observable at a specific site.

Spit Development

A spit is a depositional landform consisting of an embankment of sediment attached to the land at one end and terminating in open water at the other end (Evans, 1942). Spits form in response to wave-induced longshore sediment flow and prograde in the direction of net shore-drift (Bird, 1969). Preceding the development of a spit, a submarine platform is built out from the mainland in the direction of net shore-drift (Meistrell, 1972). This period of platform progradation is followed by a period of spit development atop the platform.

Cuspate spits are accumulation landforms that have a distinctive triangular form in plan view, which may be symmetrical or asymmetrical in shape. Symmetrical cuspate spits usually develop where two drift cells converge, as in the lee of offshore islands or stacks. Cuspate spits that are asymmetrical are indicative of unidirectional net shore-drift that continues around the spit from its longest side to its shortest side (Hunter et al., 1979). Spits are one of the most reliable long-term indicators of the direction of net shore-drift.

Object Interruting Shore Drift

Any large object that is securely positioned more or less perpendicular to the shore will act as an impediment to the natural sediment movement involved in shore drift (Komar, 1976). This will result in a pattern of accumulation and erosion of sediment around the object that can be indicative of a net shore-drift direction. Drift obstructions cause sediment to accumulate on the updrift side of the obstacle, while the downdrift side will experience erosion due to sediment starvation (Jacobsen and Schwartz, 1981). This process tends to widen and elevate the beach updrift of the obstacle relative to the downdrift side, which tends to be narrowed and lowered. When applying this technique for the determination of the direction of net shore-drift; the larger and the more permanent the obstacle, the more reliable it is as a long-term drift indicator.

Since man-made obstacles to shore drift are rare along the study sector on Washington's Pacific coast, attention must be given to naturally occurring obstacles. These include protruding drift logs, boulders, and headlands situated more or less perpendicular to the shore.

Stream Diversion

The mouths of streams or rivers that enter into a drift cell are commonly diverted in the direction of net shore-drift (Bird, 1969; Jacobsen and Schwartz, 1981). This process occurs when sediment is transported to the updrift side of a stream faster than the stream can remove it. As a result, sediment accumulates on the updrift bank of the stream, creating a spit-like form which causes the diversion (Figure 8).

Stream or river-mouth diversions range in length from a few meters to several kilometers along Washington's Pacific coast. In some instances,

Figure 8. An example of a stream mouth diversion to the north, located immediately south of Abbey Island.

even very small streams may reflect seasonal variations in shore drift. However, the diversion of larger streams or rivers is always in the direction of net shore drift.

Identifiable Sediment

If a readily identifiable beach sediment can be traced to a known point source, then the direction in which the sediment has drifted may be used as an indicator of net shore-drift (Jacobsen and Schwartz, 1981). The identifiable sediment will be found predominantly downdrift of the source area, with particle size and overall abundance also decreasing in the downdrift direction. The longer the identifiable sediment has been adrift, the more reliable the indicator.

Nearshore Bars

Nearshore bars are generally composed of a sand-pebble mixture and are found in the inter-tidal zone. They form in response to wave action, which results in their orientation being perpendicular to the direction of the predominant wave approach (Greenwood, 1982). The bar will angle away from the shore in the direction of net shore-drift. Thus, nearshore bars can be a useful aid in determining the net shore-drift direction. However, because bar formation is complex and controversial (Greenwood, 1982; Schwartz, 1972), considerable care must be taken when using nearshore bars as a drift indicator.

FIELD METHODS

Documenting evidence of net shore-drift by using geomorphic and sedimentologic indicators of shore drift requires a field-oriented investigation. Thus, information for this report was obtained in a walking survey conducted along the Pacific coast of Clallam and Jefferson Counties between June and September, 1984. In addition, a follow-up investigation was carried out during the winter of 1985 (February). Observations were recorded in a field notebook, with reference photographs taken for future documentation. Aerial photographs were used for particular coastal areas of interest, notably at river mouths, to observe recent changes in morphology. Field traverses were made during tidal stages of +2.0m or lower. This facilitated the observation of geomorphic features over most of the foreshore by providing maximum intertidal exposures.

PREFACE TO THE NET SHORE DRIFT DISCUSSION

The direction of net shore-drift along the Pacific coast of Clallam and Jefferson Counties was determined by using the principles and drift indicators previously described. The location, boundaries, and net shore-driftdirection of each drift cell are illustrated on maps located in the map pocket. Drift cells are numbered consecutively, starting with number one in the south and increasing in number to the north.

A description of each drift cell is presented in the text discussion of net shore-drift. Each description includes the geomorphic and sedimentologic indicators used to determine the net shore-drift direction. Also discussed are selected geomorphic features of the coast and areas of no appreciable net shore-drift. While reading the discussion about net shore-drift, the map pertaining to the area under consideration should be consulted.

As was suggested by Keuler (1980), the reader should be aware of certain considerations when using this type of coastal map:

(1) The maps show the long-term direction of net shore-drift. Seasonal short-term reversals may occur.

(2) Quantifying the volume and rate of sediment transport was not an objective of this study.

(3) Sediment supplied to the drift cell may not necessarily reach the terminus.

(4) Drift-cell boundaries are usually broad zones that may shift in response to changes in wave approach.

(5) The drift cell patterns delinated in this report apply to the Clallam and Jefferson Counties Pacific coastline as of 1984. Subsequent modification of this coastal region could alter drift cell boundaries and

net shore-drift direction.

To assist the reader's visualization and interpretation of the net shore-drift, a beach profile with current nomenclature has been provided in Figure 9.

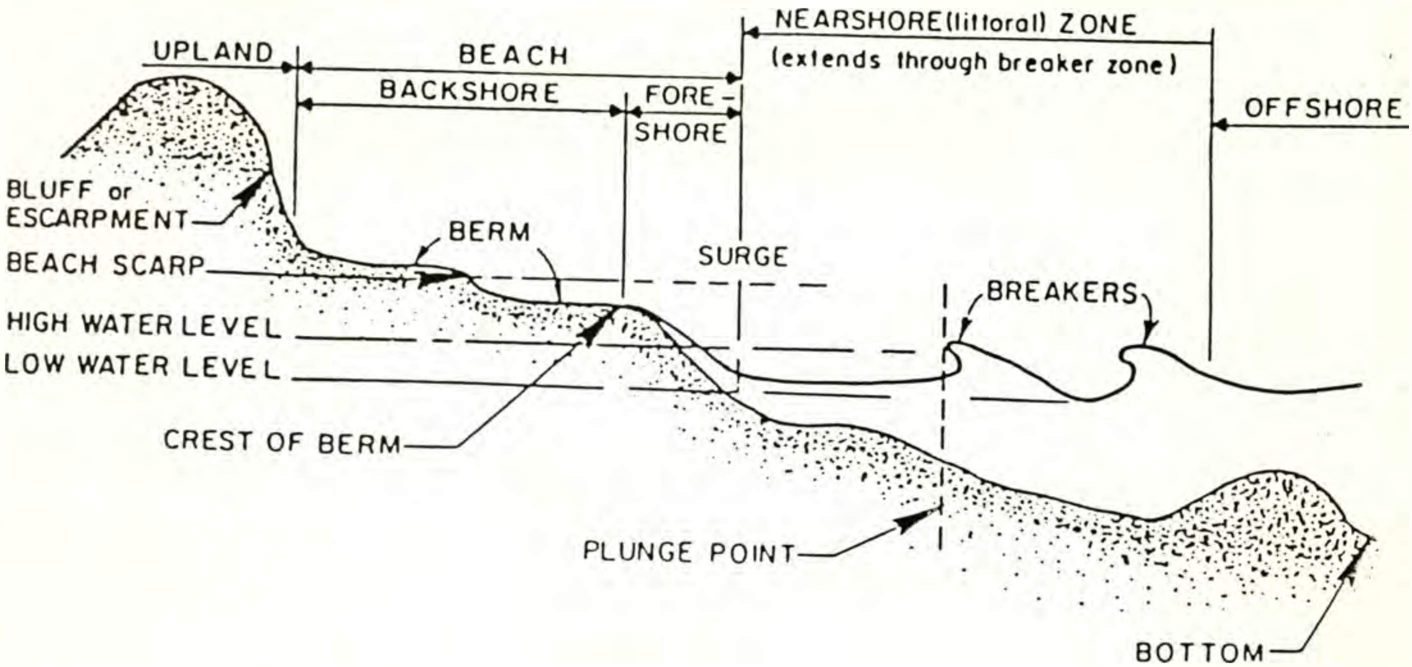

Figure 9. An idealized beach profile showing major geomorphic features (after Harp, 1983).

NET SHORE-DRIFT DISCUSSION

JEFFERSON COUNTY

Drift Cell J-1

This drift segment includes a major middle portion and terminus of a drift cell originating in northern Grays Harbor County (Schwartz and Bronson, 1984). The linearity of this north-northwesterly-trending coastal segment permits unimpeded sediment transport to occur. Some of the sediment is derived from the 10-15 m-high bluffs of glacial outwash and till that back the shore throughout this area (Figure 10). These bluffs are composed of abundant unconsolidated gravel and sand. The beach depositsinthisregionreflect the grain size in the bluff,asthe upper foreshore is predominantly gravel, whereas sand occurs largely in the broad low-tide area. The predominant southwesterly waves produce the northerly net shore-drift observed in this coastal sector. This determination of drift direction is supported by many geomorphic and sedimentologic indicators.

In the southern region of Jefferson County, the Queets River is of particular interest because the position of its mouth has changed so frequently over the years. Presently a sand and gravel spit built in the direction of net shore-drift has caused a significant northward deflection of approximately 2 km. At different times in the past the river has entered the sea at various places through the spit. One channel, possibly the oldest, extended northward about 0.8 km north of the present mouth before reaching the ocean (Rau, 1973).

The presence of a wider backshore and berm north of the Queets River, compared to the area south of the River, indicates that the predominant movement of sediment from the river is to the north. Continuing

Figure 10. Looking southward at a 8 m-high glacial bluff located 0.4 km north of Kalaloch Creek. Glacial bluffs some 8 to 15 m-high back the shore throughout the coastal region south of the Hoh River.

northward, in a region approximately 1.8 km north of Kalaloch Creek, a small headland composed of relatively resistant sandstone, from the Hoh rock assemblege, protrudes across the foreshore enough to act as a partial obstruction to shore drift. This drift obstruction has resulted in sediment accumulation of approximately 1.5 m on the south side of this headland, relative to the north side, which has been narrowed due to erosion. Another headland causing a similar pattern of drift obstruction is located approximately 2 km south of Cedar Creek. Net shore-drift is also indicated by the 75 m northward deflection of the mouth of Cedar Creek. Just north of Cedar Creek, shore drift and fluvial sediment from Cedar Creek combine to form an asymmetrical cuspate spit as waves refract in the lee of Abbey Island. The beach has prograded on the south side of this cuspate spit producing the marked asymmetry, which is indicative of unidirectional net shore-drift that continues on past the island (Hunter et al., 1979). For a distance of nearly 4 km northward, from Abbey Island to the Hoh River, 55 m cliffs composed of glacial outwash and till (Figure 11) are broken by landslides, which feed the shore-drift system. This additional sediment aids in the formation of an 0.6-km-long northward-prograding spit, which results in the diversion of the Hoh River in the northerly direction of net shore-drift. North of the Hoh River, in the direction of the drift cell terminus, sediment has accumulated to form a wide sand beach backed by a well developed berm consisting of abundant driftwood and gravel. Here the beach width and slope gradually increase to the north, further indicating a northerly net shore-drift direction. This drift cell terminates about 1.3 km north of the mouth of the Hoh River at a protruding headland, to the south of which the beach has prograded considerably.

Figure 11. An example of thick, unconsolidated glacial bluffs located along the zone of sediment transport about 1.8 km south of the Hoh River (after Rau, 1973).

Drift Cell J-2

Originating about 0.8 km south of Jefferson Cove along 70 m-high cliffs of Hoh sandstone and conglomerate fronted by a wave-cut platform, this drift cell ends along the northern shore of Jefferson Cove. A northerly direction of net shore-drift is evidenced by an increase in beach width to the north (Figure 12) and by a decrease in sediment size from a lag deposit of cobbles in the south to pebbles and sand at the terminus. Northerly net shore-drift is also indicated by a change in bluff morphology from non-vegetated, vertical cliffs at the origin to a more gently sloped, well vegetated bluff at the drift cell terminus. Sediment transport terminates at a moderately wide low-tide sand beach backed by abundant driftwood and gravel.

Hoh Head and the adjacent coastline to the north and south are characterized by no apparent net shore-drift. The 75 m-high headland, composed of thickly-bedded Hoh sandstone, projects out into the ocean about 1 km from the rest of the coast. This projection results in deep water lying immediately offshore of the headland, which completely impedes shore drift. North of Hoh Head, between two minor headlands, sediment transport is restricted, creating pocket beaches which are also zones of no appreciable net shore-drift.

Drift Cell J-3

This drift cell originates at a 35 m-high headland north of Hoh Head and terminates at the first headland south of Mosquito Creek. Sediment is transported to the north by predominant southwesterly waves, as evidenced by a slight increase in beach width and a decrease in mean sediment size to the north. The low-tide beach near the drift cell terminus is mostly

Figure 12. Looking southward at the beach within Jefferson Cove (Drift cell J-2). Note an increase in the beach width, a reduction in the bluff slope, and an increase in the berm development to the north (after Rau, 1980).

sand with some pebbles, while the high-tide beach is predominantly cobbles and pebbles. This upper-beach sediment is primarily derived from the melange rocks of the Hoh assemblege, which make up the relatively weak, low-sloping bluffs in this area.

Drift Cell J-4

Drift cell J-4 begins approximately 0.8 km south of Mosquito Creek along 30 m-high cliffs of Hoh melange rocks and ends at the mouth of Goodman Creek. Sediment supplied by Mosquito Creek and by cliff erosion is transported north by the predominant southwesterly waves to form a wide low-tide sand beach, extending about 3.6 km to the north. Net shore-drift to the north is indicated by a northerly decrease in mean sediment size and by numerous large pieces of driftwood fallen across the beach showing sediment accumulation on their south side. This drift direction is also indicated by the presence of an asymmetrical tombolo in the lee of a small nearshore island, located approximately 1.2 km south of Goodman Creek. Here the tombolo has developed higher and wider on its south side relative to the north side, which would indicate a northerly net shore-drift direction.

From Goodman Creek northward for about 1.7 km, large outcrops of Hoh sandstone and conglomerate form rugged sea cliffs some 70 m in height. These headlands and associated pocket beaches are characterized by no apparent net shore-drift, due to the presence of deep water directly offshore.

Drift Cell J-5

Drift cell J-5 originates immediately north of the 70 m-high headland of Hoh sandstone and conglomerate at Goodman Creek and terminates at a zone of drift convergence on the south side of Toleak Point. Under the influence of predominant southwesterly winds, this drift cell has a northerly net shore-drift. This drift direction is indicated by an increase in beach width and beach slope to the north, as well as a northerly decrease in bluff slope. Northerly net shore-drift is also indicated by a gradation in mean sediment size from cobbles and pebbles at the origin to a mixture of mostly sand with some pebbles at the drift cell terminus.

Drift Cell J-6

This drift cell originates in a zone of drift divergence along a low-sloping backshore located approximately 1 km north of Toleak Point and terminates on the north side of Toleak Point, which is a cuspate spit. A southerly net shore-drift is evidenced by the gradual increase in beach width and beach slope to the south. This short drift reversal is, in part, related to wave refraction around several islands directly offshore of Toleak Point. These islands form a wave shadow from the predominant southwesterly winds, resulting also in the prevailing northwesterly winds further controlling the net shore-drift direction.

The coastal orientation of this region is largely controlled by differential erosion of selected lithogies. Toleak Point is composed of relatively resistant sandstone from the Hoh assemblege, while the shallow bights to the north and south of Toleak Point are backed by melange rocks of the Hoh assemblege which tend to erode more easily.

Drift Cell J-7

Beginning in a zone of drift divergence along an actively eroding, low-sloping backshore located about 1 km north of Toleak Point, this drift cell ends along the south side of Strawberry Point. Increasing beach width to the north, and the accumulation of 0.2 - 0.4 m of sediment on the south side of several large drift logs and boulders, indicates that net shore-drift is to the north. At the terminus of the drift cell, a tombolo has prograded from Strawberry Point out to an offshore island. To the south of Strawberry Point, the shore is prograding, as evidenced by a wide beach and backshore; while, on the north side of Strawberry Point, the beach is narrow, indicating the origin of a new drift cell.

Drift Cell J-8

The northward net shore-drift of drift cell J-8 originates along the northern side of Strawberry Point tombolo and terminates immediately south of Taylor Point. At the origin, the high-tide beach is narrow with a steep profile and is dominantly composed of cobbles and pebbles. Continuing northward, to a point due east of the stacks known as the Giants Graveyard, sediment size decreases to a beach consisting largely of sand; while the width of the high-tide beach also increases, indicating net shore-drift to the north. Net shore-drift is also evidenced by sediment accumulation on the south side of a small headland, located just north of Scott Creek, that partially protrudes across the foreshore. The northerly direction of sediment transport of this cell is controlled by the predominant southwesterly wind. Net shore-drift terminates at a sand and gravel low-tide beach backed by a well developed berm consisting of driftwood, cobbles, and pebbles.

Taylor Point and the adjacent shore to the north have no apparent net shore-drift. This major headland and its offshore stacks extend into deep water, which results in the blocking of sediment transport. The nearly vertical cliffs reach over 50 m in height and are composed largely of conglomerate and massive sandstone of the Hoh assemblege.

North of Taylor Point a coastal sector, locally known as Third Beach, extends for approximately 1.3 km to the north. This coastal stretch is bounded on the north by a prominent headland, Teahwhit Head, and on the south by Taylor Point. From observations made over a one year period, it has been found that Third Beach is essentially a pocket beach and thus is characterized by no appreciable net shore-drift. That is, sediment is transported back and forth along this coastal sector in response to slight changes in the direction of wave approach. During the summer of 1984, a small stream, located in the center of Third Beach, was diverted about 40 m to the south. A reexamination during the winter of 1985 showed that this stream was diverted approximately 50 m to the north (see Figures 13 and 14). The reversal in the direction of stream mouth diversion, the presence of an equally wide foreshore at the northern and southern ends of Third Beach, and the lack of any other definitive net shore-drift indicators, support the conclusion that this is a pocket beach with no appreciable net shore-drift. This is the only site in the study area where a change of this nature was observed.

The observed stream mouth fluctuation across the foreshore may be, in part, related to seasonal variations in wind-wave approach. The orientation of this coastal sector is also partly responsible for the shifting sediment movement observed along this beach. This northwest-southeast trending coastal segment is nearly perpendicular to the direction of the predominant wave approach, which is from the southwest.

Figure 13. A southward stream diversion along Third Beach during the summer of 1984.

Figure 14. The following winter the stream was diverted to the north. This stream-mouth fluctuation may be related to seasonal variations in wind-wave approach.

This orientation results in the predominant waves striking normal to the shore, so that there is no dominant direction of long-term sediment transport.

Teahwhit Head is a jagged two-pronged headland nearly 35 m in height that projects out from the coast into deep water. The headland, stacks, and associated pocket beaches, are all areas of no apparent net shore-drift. This headland, situated between Second Beach and Third Beach, is composed of massive sandstone from the Hoh assemblege.

Just north of Teahwhit Head, a short coastal stretch located within Jefferson County, constitutes a small portion of a drift cell that terminates along the northern end of Second Beach in Clallam County. For convenience, this drift cell will be discussed in the Clallam County text (see Drift Cell C-1).

CLALLAM COUNTY

Drift Cell C-1

Beginning along 55 m-high cliffs of Hoh sandstone, located at the southern extent of Second Beach in northern Jefferson County, this drift cell has net shore-drift to the north. Sediment size,decreasing from cobbles and pebbles on the south to granules and sand on the north, and increasing beach width to the north, indicate a northerly net shore-drift direction. Bluff morphology also indicates the direction of net shore-drift in the following manner. At the origin, the cliff is at its steepest with little to no vegetation. Progressing northward, the beach widthincreases, providing an increasing degree of protection for the cliff, which becomes less steep and more heavily vegetated. This drift cell terminates along the northern reach of Second Beach where a broad berm has developed, which offers additional protection for the low-sloping bluff (Figure 15).

The headland located between First Beach and Second Beach is locally known as Quateata, and is characterized by no apparent net shore-drift. Like Teahwhit Head, this headland consists of massive sandstone from the Hoh assemblege. Quateata reaches up to 30 m in height and is capped by an excellent example of the eolian deposits (dominantly silt and sand) that blanket much of this coastal region.

Drift Cell C-2

This drift cell originates north of the headland named Quateata and terminates at the northern extent of First Beach, just south of the mouth of the Quillayute River. Northward net shore-drift is indicated by an

Figure 15. Along the northern end of Second Beach a wide berm has developed near the drift cell terminus.

increase in beach width and berm development to the north, and by a small stream that is diverted to the north before it breaks through the berm to discharge across the foreshore. The predominant wind from the southwest controls the northerly net shore-drift direction on this northwest-southeast-trending drift cell.

Drift Cell C-3

This drift cell originates along a low-sloping backshore of alluvium at a zone of drift divergence centered approximately 1 km south of Ellen Creek and terminates at the distal end of a spit built across the mouth of the Quillayute River. Net shore-drift to the south is indicated by the progradation of this spit, which results in the southward deflection of the Quillayute River, and by a decrease in sediment size from cobbles and pebbles on the north to mostly sand at the terminus. Wave refaction of southwesterly storm waves in the lee of these islands is mainly responsible for this short reversal in net shore-drift direction. This coastal sector is shadowed from the predominant southwesterly wind by several nearshore islands, one of which is James Island. Thus, the southerly net shore-drift direction of this drift cell is also affected by the prevailing northwesterly wind.

Drift Cell C-4

This drift cell originates at a zone of drift divergence along a backshore of alluvium located about 1 km south of Ellen Creek and terminates at the headland 2 km north of Ellen Creek. The 200 m northward diversion of Ellen Creek and numerous large drift logs with sediment accumulation on their south sides indicate net shore-drift to the north. A small headland, located approximately 0.9 km north of Ellen Creek, protrudes across the foreshore enough to act as a partial obstruction to shore drift. This results in a prograding beach on its south side, indicating a northward net shore drift direction. The coastal orientation and the predominant southwesterly wind control the northerly net shore-drift in this cell.

Drift Cell C-5

The northward net shore-drift of this drift cell begins along a 50 m-high partially-vegetated headland fronted by an actively eroding backshore composed of boulders and cobbles, located approximately 2 km north of Ellen Creek. This drift cell ends in a prograding beach at the first headland south of Cape Johnson. A general decrease in mean sediment size, an increase in beach width, and a reduction in bluff slope to the north are indicative of a northerly net shore-drift direction. The direction of sediment transport of drift cell C-5 is principally due to the predominant southwesterly wind.

Drift Cell C-6

This drift cell originates immediately south of Cape Johnson along a 15 m-high cliff of sandstone and conglomerate of the Western Olympic lithic assemblege, fronted by a wave-cut platform, and terminates at the north end of the shallow bight south of Cape Johnson. At the origin, the high-tide beach is narrow with a steep profile and is largely composed of boulders and cobbles. Progressing northward, the mean sediment size decreases, while the width of the high-tide beach increases, indicating net shore-drift to the north. The drift direction is also indicated by a reduction in bluff slope from a steep, non-vegetated cliff on the south to a more gently sloped, vegetated bluff on the north. Sediment transport terminates at a prograded beach consisting of abundant granules and pebbles at the northern extent of the bight south of Cape Johnson.

Drift Cell C-7

This short drift cell, beginning at the north side of Cape Johnson along a 60 m-high cliff of sandstone and conglomerate of the Western Olympic assemblege and ending at the headland 0.8 km to the north, has net shore-drift to the north. Sediment transport is directed to the north by predominant southwesterly winds, as is evidenced by an increase in the width of the high-tide beach, and by a decrease in sediment size from boulders and cobbles on the south to pebbles and granules on the north. Net shore-drift is also indicated by a gradual reduction in bluff slope to the north. Net shore-drift terminates at a pebble and granule high-tide beach backed by a wide berm consisting of numerous drift logs and gravel.

Drift Cell C-8

This drift cell originates along 55 m-high cliffs of Western Olympic assemblege sandstone and conglomerate at the headland 0.8 km north of Cape Johnson. Net shore-drift to the north is indicated by repeated patterns of decreasing sediment size, an increase in beach slope, and a decrease in bluff slope to the north. Further evidence indicating net shore-drift to the north is a northward increase in the width of the backshore. The southern region of drift cell C-8 is characterized by a small berm or none at all and no backshore. Progressing northward, toward the drift cell terminus, sediment has accumulated to form a broad, well-developed berm in front of a backshore area. Sediment transport terminates along a prograded sand and granule beach at a protruding headland directly southeast of Jagged Island.

Drift Cell C-9

Originating at a broad zone of drift divergence along a 8 m-high bluff of glacial outwash and till located approximately east-southeast of Jagged Island, this drift cell has a short drift direction reversal to the generally northerly transport of sediment along Washington's Pacific coast. Net shore-drift to the south is evidenced by decreasing sediment size, from cobbles and pebbles on the north to mostly sand on the south, increasing beach width to the south, and a southerly reduction in bluff slope. Due to a slight change in the wind shadow effect, the predominant southwesterly wind is blocked by the headland from influencing this cell, so that sediment transport is controlled by the prevailing northwesterly wind. Drift cell C-9 terminates at a prograded beach on the north side of the headland located southeast of Jagged Island (Figure 16).

Drift Cell C-10

Beginning along a zone of drift divergence centered east-southeast of Jagged Island, this drift cell ends at the headland immediately north of Cedar Creek. A northerly direction of net shore-drift is indicated by repeated patterns of sediment fining to the north, a northerly increase in beach slope, and by the 200 m northward diversion of Cedar Creek. This net shore-drift direction is also evidenced by the buildup of 0.1 - 0.3 m of sediment on the south side of several drift logs. The terminus of this drift cell is a zone of sediment accumulation, as evidenced by the presence of a well developed berm consisting of abundant driftwood, pebbles, granules, and sand. Some of the sediment present at the terminus of the drift cell is supplied, along the zone of sediment transport by wave erosion of semi-consolidated bluffs some 12 m-high composed of glacial outwash and till (Figure 17).

Figure 16. Taken from a headland looking northward, this photograph shows increasing beach width and decreasing sediment size to the south. Drift cell C-9 is a short reversal to the dominantly northerly net shore-drift along the study area.

Figure 17. Along the zone of sediment transport in drift cell C-10, a semi-consolidated glacial bluff feeds the shore drift system.

Drift Cell C-11

This drift cell originates along a 20 m-high cliff of sandstone and conglomerate of the Western Olympic assemblege directly north of Cedar Creek, and terminates at the protruding headland 2 km north of Kayostla Beach. Net shore-drift is directed to the north by predominant southwesterly waves as evidenced by the accumulation of sediment against the south side of toppled trees and drift logs, a northward increase in the width of the berm, and a small stream diverted to the north. The various sizes of beach sediment found along drift cell C-11 are a direct product of the different types of glacial bluffs that back the shore within this coastal sector. Along Kayostla Beach, in the southern region of the drift cell, the low-sloping bluff consists of glacial outwash rich in sand, which results in this sediment size dominating the beach sediment. In the northern region of the drift cell, the 12 m-high bluff is composed dominantly of glacial till, which is reflected in the cobble, pebble, and granule beach deposits.

Drift Cell C-12

Drift cell C-12 begins along the north side of the 40 m-high headland 2.7 km north of Kayostla Beach. This drift cell ends at the northern extent of a small cove known as Yellow Banks along a prograded sand beach. At the origin, a narrow, coarse-grained beach extends for approximately 3 km north of the point of origin. This region is backed by rocks of the Western Olympic assemblege and is clearly undergoing active erosion as evidenced by extensive undercutting of the bluff and by large trees that have toppled across the foreshore. The northerly direction of net shore-drift direction in drift cell C-12 is indicated by a decrease in sediment size from boulders and cobbles on the south to granules and sand on the north, a northerly increase in beach width, and a reduction in bluff slope to the north. Additional evidence for northerly net shore-drift is an inter-tidal bar, located within the cove at Yellow Banks, diverging offshore in a northerly downdrift direction.

Drift Cell C-13

Originating along 35 m-high cliffs of sandstone and conglomerate of the Western Olympic assemblege immediately north of Yellow Banks, this drift cell terminates along the south side of Sand Point. Sediment transport is directed to the north by predominant southwesterly waves as evidenced by numerous geomorphic and sedimentologic indicators. Decreasing sediment size from cobbles and pebbles at the origin to sand with some granules at the terminus; increasing beach width to the north; a change in bluff morphology from a steep, partially-vegetated bluff on the south to a low-sloping, vegetated bluff on the north; all indicate a northerly net shore-drift direction. At the terminus, a symmetrical tombolo has developed as two drift cells converge to form a spit out to a small nearshore island. Net shore-drift terminates at a prograded beach backed by a wide berm on the south side of Sand Point.

Drift Cell C-14

This drift cell, beginning along a low-sloping, actively eroding backshore at a zone of drift divergence located about 1 km north of Sand Point, has net shore-drift to the south. Decreasing sediment size and bluff slope and increasing beach width to the south are indicative of net shore-drift to the south. The sediment transport direction of drift cell C-14 is largely controlled by the prevailing northwesterly wind, due to a wind shadow. This coastal sector is oriented such that waves approaching the coast from the southwest will be refracted around Sand Point. Refraction of southwesterly waves and the prevailing northwesterly wind-generated waves have resulted in this short drift reversal to the south. This drift cell terminates at a prograded beach along the north side of the Sand Point tombolo.

Drift Cell C-15

Drift cell C-15 originates at a zone of drift divergence centered approximately 1 km north of Sand Point, and terminates at the headland east of the rock reef known as Wedding Rocks. Sediment is transported to the north by predominant southwesterly waves as evidenced by sediment accumulation on the south side of drift obstructions (boulders and drift logs) and by an increase in beach width and slope to the north. Net shore-drift terminates along a granule and pebble high-tide beach backed by a well developed berm.

Drift Cell C-16

This drift cell originates along 20 m-high cliffs of Western Olympic assemblege sandstone and conglomerate located due east of Wedding Rocks, and terminates on the south side of a tombolo in the lee of Tskawahyah Island. Net shore-drift to the north is indicated by a decrease in sediment size, an increase in beach width, and a reduction in bluff slope to the north. At the origin, a narrow high-tide beach composed of cobbles and pebbles fronted by a wide wave-cut platform extends for about 1 km to the north. At the drift cell terminus, a beach consisting largely of granules with some sand has prograded out to Tskawahyah Island, forming the south side of a tombolo. The net shore-drift direction of this drift cell is once again controlled by the predominant southwesterly wind.

Drift Cell C-17

This short drift cell begins approximately 0.5 km north of Tskawahyah Island along a low-sloping, eroding backshore at a broad zone of drift divergence and ends along the north side of a tombolo in the lee of Tskawahyah Island. The sediment transport direction of drift cell C-17 is a short reversal to the dominantly northerly direction of net shore-drift along the study area. A southerly net shore-drift direction is indicated by increasing beach width, decreasing bluff slope, and an overall decrease in sediment size to the south. Wave refraction around several offshore islands results in a northwesterly wave approach, causing this short drift reversal.

Drift Cell C-18

Beginning along a low-sloping, actively eroding backshore at a broad zone of drift divergence centered about 0.5 km north of Tskawahyah Island, this drift cell has net shore-drift to the north. This sediment transport direction is indicated by a decrease in sediment size and bluff slope and an increase in beach width to the north. Net shore-drift is also indicated by sediment accumulation on the south side of a small headland which partially protrudes across the foreshore. Drift Cell C-18 terminates in a prograding beach along the south side of the headland immediately south of the Ozette River.

Drift Cell C-19

This drift cell, originating at the mouth of the Ozette River, has net shore-drift to the north. Sediment supplied by the Ozette River and by beach erosion is transported northward by predominant southwesterly wind-generated waves, as evidenced by several geomorphic and sedimentologic indicators. Sediment accumulation on the south side of numerous drift logs, the northward diversion of a small stream, and an increase in beach width to the north are indicative of net shore-drift to the north. A decrease in sediment size from the Ozette River to a location approximately 1.5 km to the north, also indicates a northerly net shore-drift direction. However, from this location northward, beach sediments coarsen due to a fresh influx of gravel from glacial till and outwash deposits, which back the shore throughout the northern region of drift cell C-19. This drift cell terminates along a prograded beach at the onset of a series of rocky headlands due east of the stacks named Father and Son.

The area from the rocky headlands east of the stacks named Father and Son to the Point of the Arches is characterized by no apparent net shore-drift. The nearly vertical cliffs along this coastal sector reach almost 80 m in height and are composed of several relatively resistant rock units. These include a gabbro-diorite unit, which constitutes the oldest rocks exposed along the study area. Other rocks present are sandstone and basalt from an unnamed formation and also a breccia-conglomerate unit which has been correlated with the Lyre Formation. Directly offshore of these prominent headlands, deep water impedes shore drift.

<u>Drift Cell C-20</u>

Drift Cell C-20 begins at a zone of drift divergence located about 1.4 km north of the Point of the Arches. This divergent zone is backed by 25 m-high partially vegetated bluffs of glacial outwash and till which show active signs of erosion. A southerly net shore-drift direction is evidenced by a reduction in bluff slope, an increase in beach width, and a gradation in mean sediment size to the south. This short drift reversal is caused, in part, by refraction of predominant southwesterly waves around several offshore stacks at the Point of the Arches. The orientation of the southern region of Shi Shi Beach is also a factor contributing to the southerly direction of sediment transport of drift cell C-20. This region is shadowed from the predominant southwesterly wind by the Point of the Arches, resulting in the prevailing wind from the northwest controlling the direction of net shore-drift for the drift cell. Net shore-drift terminates at a prograded beach, consisting largely of sand, along the southern end of Shi Shi Beach.

Drift Cell C-21

Originating along 25 m-high bluffs of glacial outwash and till at a zone of drift divergence centered near the mouth of Petroleum Creek, this drift cell terminates approximately 1.8 km to the north at the northern extent of Shi Shi Beach. A northerly increase in beach slope, a vertical accumulation of approximately 0.2 m of sediment on the south side of a large boulder situated across the foreshore, and a decrease in bluff slope to the north indicate a northerly net shore-drift direction. Drift cell C-21 is located far enough north to be unaffected by refraction of predominant southwesterly waves around the Point of the Arches. Thus, the coastal orientation and the predominant southwesterly waves control the northerly sediment transport direction of the drift cell. Sediment transport terminates at a sand and granule prograded beach at the northern end of Shi Shi Beach.

From the headlands at the northern end of Shi Shi Beach to the headland immediately north of Anderson Point, there is no apparent net shore-drift. Portage Head is composed of basalt from the Crescent Formation and has a 0.6 km-long seaward face of bold irregular cliffs over 70 m high. The sea cliffs at Anderson Point are some 75 m in height and also consist of basalt from the Crescent Formation.

Drift Cell C-22

This drift cell begins along 15 m-high basaltic cliffs of the Crescent Formation on the north side of the small headland located 0.3 km north of Anderson Point and ends at the east side of Waatch Point. Sediment is transported to the north by predominant southwesterly waves as evidenced by the significant northward deflection of the Sooes and Waatch Rivers and by repeated patterns of northerly sediment size fining. At the origin, the high-tide beach consists mostly of granules with some pebbles. To the north for approximately 1 km to a tombolo in the lee of a small nearshore island, the width of the high-tide beach increases, while the mean sediment size is reduced largely to sand. North of the Sooes River, the northerly net shore-drift direction continues as indicated by an increase in beach width and by the development of multiple berms along the backshore of Hobuck Beach.

The coastal stretch from the west side of Waatch Point to the northwest corner of Cape Flattery is characterized by no apparent net shore-drift. Steeply dipping sandstones and siltstones compose the 70 m-high sea cliffs in the southern region of Cape Flattery along the Pacific coast. On the northwestern Pacific coast of the Cape, the cliffs consist of a breccia-conglomerate unit and reach up to 80 m in height.

SUMMARY

The crenulated north-northwest-trending Pacific coast of Clallam and Jefferson Counties, Washington, is characterized by rocky headlands separated by sand-gravel beaches with numerous offshore islands and sea-stacks. The effects of Quaternary glacial episodes are clearly evident, as thick coarse-grained glacial deposits reflect the imprint of glaciation.

The surface winds off the northwest Olympic Peninsula are dominated by two semi-permanent pressure centers over the Northeast Pacific Ocean (Figure 3). During the summer, the East Pacific high pressure system directs the surface winds toward the coast from the northwest. Throughout the remainder of the year, the Aleutian low pressure system generates storms, which produce surface winds that approach the coast from the southwest. This seasonal wind pattern results in both the predominant (most effective influence on wave generation) and prevailing (most frequent) winds over Jefferson and Clallam Counties coming from a generally southwesterly direction.

Wind-generated waves are the principal source of energy responsible for erosion and transportation of sediment along the shore. The potential energy of wind-generated waves is a function of three variables: wind velocity, wind duration, and the fetch or distance of open water over which the wind can blow unimpeded. Since changes in fetch are only important up to about 1500 km (Davies, 1980), wind velocity and duration are the primary controls governing the amount of energy available for wave generation in this region.

Washington's Pacific coastal region experiences a mixed tidal regime, which means that there are two highs and two lows during the tidal day, with all of the tides of different heights. The tidal range determines the vertical and horizontal extent to which waves may impart their energy to the coast. Along the study area, spring tidal range is typically between 3-4 m, which is classified as a mesotidal coastal environment. Mesotidal tides tend to dissipate wave energy across a wide beach profile, resulting in a widening of shore platforms and beach foreshores.

Shore drift occurs due to the oblique approach of wind-generated waves. The direction of shore drift can vary on a short-term basis in response to changes in wind-wave appproach. However, over a long period of time, one direction of sediment transport usually predominates; this is the direction of net shore drift.

Along crenulated coastlines, such as Washington's northern Pacific region, sediment transport occurs within discreet compartments along the coast, even under conditions of high wave energy. The idealized drift cell consists of three different zones: a zone of sediment supply, a zone of sediment transport, and a zone of sediment accumulation.

In this study I have delineated the compartmentalization of drift cells and the direction of net shore-drift along the Pacific coast of Clallam and Jefferson Counties, Washington. Drift determinations were based on a field oriented approach, which emphasizes long-term geomorphic and sedimentologic indicators of shore drift. These methods have proven to be more accurate and reliable in determining the direction of net sediment transport than methods using wave hindcasting and the construction of wave orthogonals. Drift studies, using such methods as sediment traps or artifical tracers, only record the drift direction for the period of study and not necessarily the net long-term direction of sediment transport.

Using the methods described in the Principles and Indicators of Net Shore-Drift sections of this report, thirty drift cells have been identified along the 110 km of the Pacific coast of Clallam and Jefferson Counties, Washington. The drift cells vary in length from 0.4 km to a drift cell 26 km-long in Jefferson County (this drift cell originates in northern Grays Harbor County, see Schwartz and Bronson, 1984).

A relationship between the patterns of net shore-drift in the present study area and the direction of predominant wave approach can clearly be made. For coastal regions exposed to the open ocean, the direction of net shore-drift is dominantly to the north. However, wave direction may be modified at the shore behind an island, in the lee of a headland, or within an embayment causing drift reversals. Short reversals in net shore-drift direction also occur in areas that are affected by a wave shadow of the predominant southwesterly waves. In these regions, refraction of predominant waves from the southwest around nearshore islands and stacks contributes to the net shore-drift reversals.

Net shore-drift can be blocked by naturally occurring features, such as prominent headlands, resulting in drift cell termini or areas of no apparent net shore-drift (NANSD). Numerous examples of this condition occur throughout the study area and are generally the product of resistant lithologic units which tend to withstand erosion relative to the surrounding units.

The importance of fully understanding the coastal processes that shape and continually modify the coastline cannot be understated in any rational coastal planning endeavor. Sediment transport along the coast is a system in a state of balance with the surrounding physical regime. Any changes in the intricacies of shore drift will cause the system to adjust until it attains an equilibrium with the new variables. Thus, without a thorough comprehension of the variable nature of shore drift, human modification of the Pacific coastline of Clallam and Jefferson Counties may yield undesireable results.

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