Summer 1983

Net Shore-drift of Thurston County, Washington

David M. Hatfield Jr.
Western Washington University

MASTER'S THESIS

Name: David Morris Hatfield Jr.

Signature:

Date: 3/2/19

NET SHORE-DRIFT
OF
THURSTON COUNTY, WASHINGTON

A Thesis

Presented to

The Faculty of

Western Washington University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

David M. Hatfield, Jr.

August, 1983

NET SHORE-DRIFT

OF

THURSTON COUNTY, WASHINGTON

by

David M. Hatfield, Jr.

Accepted in Partial Completion

of the Requirements for the Degree

Master of Science

Dean of Graduate School

ADVISORY COMMITTEE

Chairman

ABSTRACT

Geomorphic and sedimentologic variations in coastal landforms were used to determine the direction of net shore-drift and delineate the boundaries of drift cells along 178 kilometers of the southern Puget Sound coast fronting Thurston County, Washington. The net shore-drift indicators used along the Thurston County coast were, in descending order of observed frequency, gradation in mean sediment size, beach width, foreshore offsets at drift obstructions, spit development, bluff morphology, beach slope, diversion of stream mouth outlets, plan view of deltas or intertidal fans, oblique bars, beach pads, and identifiable sediment.

Wind from the south-southwest prevails over Thurston County. Fetch is the major limiting variable in the development of waves along the Thurston County coast. Because of the abundance of open water channels and fetches oriented sub-parallel to the prevailing wind direction, wind-generated waves that approach from the southwest have the greatest influence on net shore-drift direction. The result is that 76 percent of all net shore-drift along the Thurston County coast has a northward vector component and 24 percent has a southward vector component.

Seventy-five drift cells have been identified and described along 52 percent (92 kilometers) of the Thurston County coast. Areas with no appreciable net shore-drift comprise about 42 percent (74 kilometers) of the coast. The remainder of the coast (approximately 12 kilometers) consists of zones of divergent net shore-drift.

Human modification of the Thurston County coast interrupts the process of shore drift and alters net shore-drift patterns. Modified areas include Olympia Harbor and numerous small-boat marinas and oyster farms developed along the coast. Shore defense structures such as bulkheads and groins are reducing or eliminating wave erosion of bluff material as a source of beach sediment available for shore drift.

ACKNOWLEDGEMENTS

I would like to thank my advisory committee, Dr. R. Scott Babcock, Dr. Maurice L. Schwartz, and Dr. Christopher A. Suczek, for their support and advice during the course of this study. Each made many valuable suggestions for improving the manuscript. Special thanks go to Dr. Schwartz; as committee chairman, his time and expertise were sought whenever major questions arose.

I am grateful to Dana Blankenship, Michael Chrzastowski, and Brad Harp for many helpful discussions concerning the subtleties of coastal processes in Puget Sound. I am also grateful to Patty Combs for typing this manuscript and for her friendship and support during my stay at Western.

Lastly, I thank Judith Mosier, who assisted me in every aspect of this study from walking the beaches to the final stages of manuscript preparation.

TABLE OF CONTENTS

ABSTRACT i

ACKNOWLEDGEMENTS iii

LIST OF FIGURES v

LIST OF TABLES vii

INTRODUCTION 1
Purpose and Scope of the Study 1
Background of the Study 2
Previous Investigations 3
Field Methods 6

REGIONAL SETTING 7
Geography 7
Geology 7

CLIMATIC SETTING 10
Wind 11

OCEANOGRAPHIC SETTING 15
Wind-generated Waves 15
Tidal Characteristics 17

PRINCIPLES 20
Coastal Sediment Sources 20
Dynamics of Shore Drift 21
Concept of a Drift Cell 22

INDICATORS OF NET SHORE-DRIFT 27
Indicators Requiring Observation Over Distance 28
Site-specific Indicators 30

PREFACE TO THE NET SHORE-DRIFT DISCUSSION 37

NET SHORE-DRIFT DISCUSSION 43

SUMMARY AND CONCLUSIONS 108

REFERENCES CITED 113

MAP OF NET SHORE-DRIFT, THURSTON COUNTY, WASHINGTON Map Pocket

LIST OF FIGURES

1 Location map of western Washington. 5

2 Wind rose for the Olympia airport. 14

3 Diagram depicting the shore drift process. 23

4 Sketch of a beach pad. 34

5 a-Vertical aerial photograph showing long and narrow beach pads. 35
b-Vertical aerial photograph showing short and wide beach pads. 35

6 Explanation of the symbols used on the net shore-drift map. 38

7 a-Vertical aerial photograph of Steamboat Island and vicinity. 50
b-Oblique aerial photograph of Steamboat Island and vicinity. 50

8 Oblique aerial photograph showing the prograded beach at Hunter Point. 54

9 a-Oblique aerial photograph showing Flapjack Point along the west shore of Eld Inlet. 57
b-Oblique aerial photograph showing spit development and stream diversions at Flapjack Point. 57

10 Vertical aerial photograph of the spit development at Kay Point located along the southwest shore of Eld Inlet. 62

11 Oblique aerial photograph showing a view to the west of the intertidal flat in Mud Bay, southern Eld Inlet. 62

12 a-Vertical aerial photograph showing the cuspate-like shape of the coastal feature at Shell Point. 65
b-Oblique aerial photograph showing a view to the southeast of Shell Point and vicinity. 65

13 Oblique aerial photograph showing spits, beach pads and oblique bars developed along the northeast shore of Eld Inlet. 70

14 Vertical aerial photograph of the spit and wave-cut platform at Cooper Point. 71

15 An oblique aerial view looking to the south at the Olympia Harbor and vicinity. 75

16 Eastward-looking aerial photograph of Gull Harbor showing the terminus area of drift cell 42 and the origin area of drift cells 43 and 44. 78

17 Vertical aerial photograph showing Dofflemyer Point and the terminus area of drift cell 44 along the south shore of Boston Harbor. 80

18 a-View north showing the westward readjustment of boulders and tires along the spit at Burfoot County Park. 82
b-View north showing the erosion of fill emplaced the previous year after one winter storm season. 82

19 a-Vertical aerial view of an ebb tide delta and spit developed in Little Fishtrap. 85
b-Photo of a historical chart showing the pre-development coastline in Little Fishtrap. 85

20 Vertical aerial photograph showing the complex spit developed along the south entrance of Big Fishtrap. 87

21 Oblique aerial photograph showing the wave-cut platform at Dickenson Point. 87

22 a-Vertical aerial photograph shows the plan view geometry of the cuspate spit at Cliff Point. 90
b-Oblique aerial view toward the southwest of the cuspate spit at Cliff Point. 90

23 Vertical aerial photograph of the intertidal flat in South Bay, southern Henderson Inlet. 93

24 Vertical aerial photograph showing the drift pattern and spit development at the terminus area of drift cells 60 and 61. 95

25 Vertical aerial photograph showing spit development in Mill Bight. 99

26 a-Vertical aerial photograph showing the present coastline configuration along DeWolf Bight created by the development of a small-boat marina. 104
b-Photograph of the coastline configuration along DeWolf Bight in 1891. 104

27 Vertical aerial photograph showing an oyster farm developed northwest of Nisqually Head. 106

LIST OF TABLES

1 Summary of the stratigraphic units and glacial materials commonly found in the coastal bluffs of Thurston County. 9

2 Wind velocity and direction data for Olympia Airport. 13

3 Tide parameters for the subordinate tide station at Olympia. 18

4 Abbreviations of the net shore-drift indicators used on the map and Table 5. 39

5 Indicators used to determine the direction of net shore-drift for each drift cell along the Thurston County coast. 40

INTRODUCTION

Purpose and Scope of the Study

With increasing population growth in western Washington, pressure to develop the coastal resources of Puget Sound increases. In order to encourage minimum impact while facilitating maximum use of these resources, effective planning and development along the coast should be based on an understanding of the coastal processes that have shaped and continually modify the coastline we see today.

Shore drift is an important coastal process that influences the Puget Sound coastline. In response to seasonal changes in wave approach, sediment can be transported back and forth parallel to the coast. However, over a long period of time, there will usually be a net transport of sediment in one direction, the net shore-drift direction.

This study documents the direction of long-term net shore-drift along the Thurston County coast utilizing geomorphic and sedimentologic indicators. Seasonal variations in shore drift are not discussed because the long-term net transport direction of sediment is more useful to planners and engineers in managing and developing the coastal zone; nor was an attempt made to measure or predict the rate and volume of sediment transported along the coast. The contribution of information on coastal processes will also aid future scientific studies in the Puget Sound region.

Background of the Study

In the late 1960's the people of Washington State became interested and increasingly active in environmental issues. Among their many concerns were the invaluable water resources and adjacent coastline of the Pacific coast and Puget Sound. In response to these concerns, the Washington State legislature created the Department of Ecology (DOE) in 1970 and ratified the Shoreline Management Act in 1971, which gave the DOE responsibility for carrying out coastal management. In 1972, the United States Congress passed the Coastal Zone Management Act which provided financial incentives for states to initiate programs of their own. Washington State began its Coastal Zone Management Program in 1976. The National Oceanic and Atmospheric Administration (NOAA), under the United States Department of Commerce, awarded grants to administer the program under the guidelines of the Federal Coastal Zone Management Act of 1972. Washington's Coastal Zone Management Program incorporated previously legislated environmental acts into one unified body and gave local governments the primary responsibility to make decisions concerning water resources and coastal management.

In order to make important decisions concerning the coastal zone, a detailed and accurate data base was necessary. In response to this need, the Washington State Department of Ecology published the Coastal Zone Atlas of Washington, one volume each for twelve of fifteen coastal counties. Coastal drift direction was one of the seven sections presented in the Coastal Zone Atlas. After most of the atlases were published the shore drift sections were found to have numerous errors (M. Schwartz, oral communication, 1981). To mitigate the problem the DOE reached an agreement with NOAA's Office of Coastal Zone Management to fund another shore drift study. Supervised by Dr. Maurice L. Schwartz, Professor of Geology at Western Washington University, a study of net shore-drift direction for five coastal counties in southern Puget Sound was conducted. The documentation of net shore-drift direction for the coastline of Thurston County is an effort within the larger regional study to amend some of the shore drift sections of the *Coastal Zone Atlas of Washington*.

Previous Investigations

No previous investigations have documented the long-term net shore-drift along the Thurston County coast using geomorphic and sedimentologic indicators.

The seasonal shore drift of Thurston County and counties along the rest of Puget Sound were mapped using a technique called wave-hindcasting by Norman Associates, Inc., of Redmond, Washington, for the Washington State Department of Ecology's *Coastal Zone Atlas*. Wave-hindcasting is a mathematical modeling procedure which determines the direction of dominant wave approach and resulting shore drift by plotting wave orthogonals using wind data from recording stations.

Applying the wave-hindcasting technique to the crenulated coastline of Puget Sound created errors in net shore-drift direction determinations as reported in several volumes of the *Coastal Zone*

Atlas, including volume eight for Thurston County. There are two main shortcomings in using the wave-hindcasting technique as it has been employed in Puget Sound. First, and most important, fetch (the distance over water wind can blow) was not weighted adequately in the wave modeling calculations. For waters with intricate coastlines, such as are found in the Puget Sound system, fetch becomes more important than the onshore wind resultant in determining the direction of shore drift (Schou, 1945, 1952). Second, wind data (wind velocity, direction, and frequency) from inland recording stations was extrapolated to coastlines many kilometers away. The marine wind patterns over waters within restricted passages might be much different than wind patterns at topographically higher, inland recording stations. Not considering fetch and inappropriately extrapolating wind data resulted in significant discrepancies between the mathematically predicted and the actual net shore-drift directions.

There have been several studies in the Pacific Northwest that support the use of geomorphic and sedimentologic indicators to determine the direction of net shore-drift. This study of Thurston County is based on the methods set forth in those studies. Hunter and others (1979) studied sediment transport along the Alaska Bering seacoast. In the Puget Sound region (Fig. 1), Keuler (1979) conducted a coastal drift study for Skagit County. Ecker and others (1979) and Keuler (1980) studied sediment drift patterns for a portion of Clallam County. The net shore-drift of Whatcom County was documented by Jacobsen (1980), and for King County by Chrzastowski

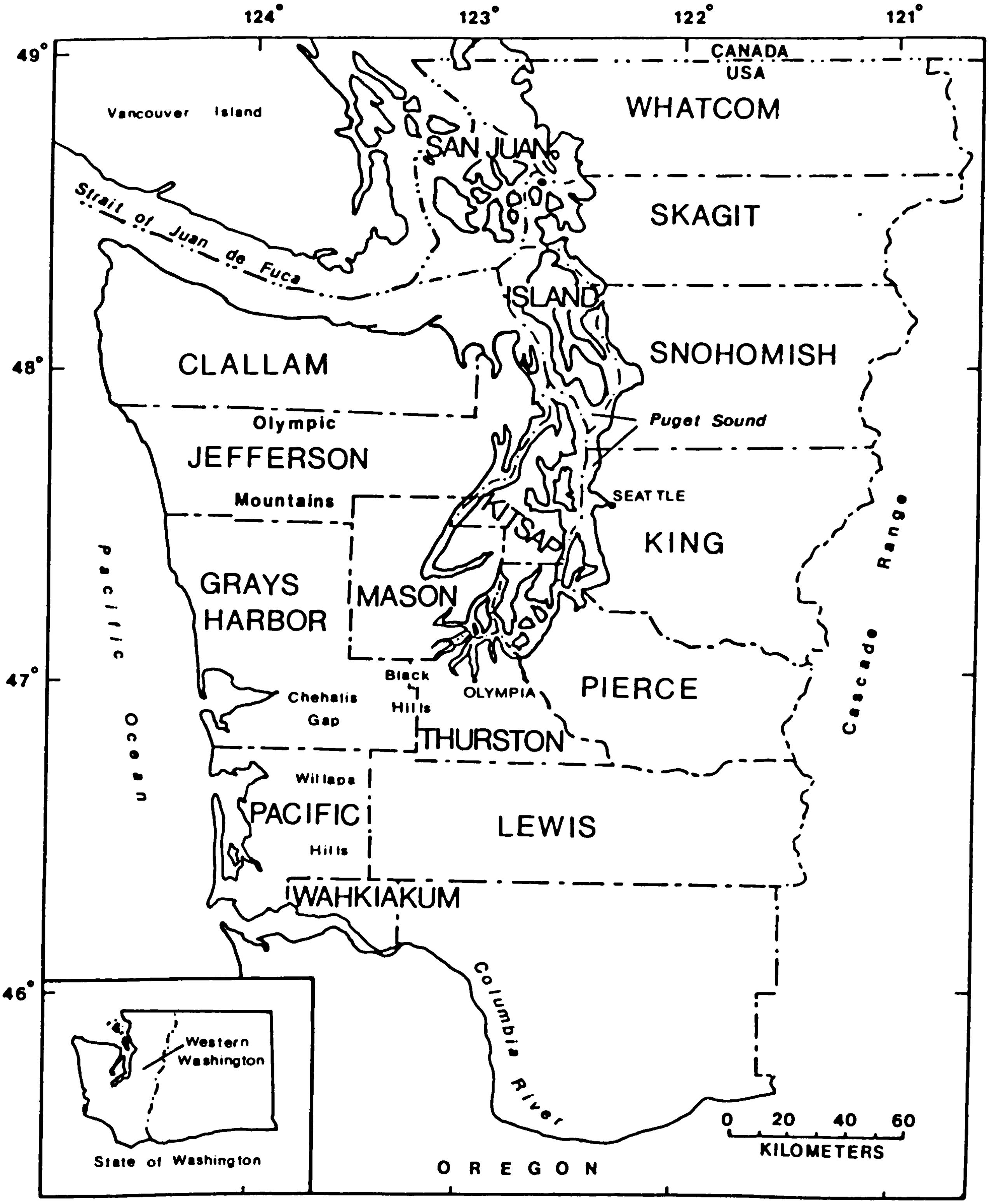

Figure 1. Location map of western Washington showing major physiographic features and fifteen coastal counties (after Chrzastowski, 1982).

(1982). A net shore-drift map of the Port Townsend Quadrangle was prepared by Keuler (1983, in press). The quadrangle includes portions of Clallam, Island, Jefferson, San Juan, Skagit, and Snohomish counties. Net shore-drift patterns are presently being determined for Kitsap County by Taggart (in progress). Mason County by Blankenship (1983), and Pierce County by Harp (1983).

Field Methods

A walking survey was conducted along the Thurston County coast from April to July, 1982. During this period, trends in coastal geomorphology were documented and used to determine the direction of net shore-drift. Observations were recorded in a field notebook and with reference photographs. Aerial photographs were used to locate features and estimate distances, and a pocket transit was used to measure vertical and horizontal angles. Traverses of the coast were made during 8 to 12 day periods of each month that coincided with spring low tides. This allowed free transit along the beach and more importantly provided maximum intertidal exposures.

REGIONAL SETTING

Geography

Thurston County is located in the southern Puget Sound region of western Washington bordering Mason County and Pierce County to the north, Grays Harbor County to the west and Lewis County to the south (Fig. 1). The crenulated coastline of Thurston County is made up of a complex pattern of peninsulas, channels, and embayments with a total coastal length of 178 kilometers (Washington State Department of Natural Resources, 1974). Bathymetric depths of the Puget Sound system surrounding the northern boundary of the county range from 3.0 m to 28.0 m in restricted inlets with maximum depths in main channels of 90.0 m (National Ocean Survey, 1981).

Residential land use dominates the coastline of Thurston County. Approximately 40% of the coastline has been modified by shore defense structures such as bulkheads, rip-rap, and groins (Washington State Department of Ecology, 1980). This modification has altered, and will continue to alter, the natural coastal processes along the coastline, directly affecting the rates of coastal erosion and deposition (Komar, 1976).

Geology

The oldest rocks exposed along the coastline of Thurston County are basaltic and agglomerate igneous rocks of Middle Eocene age, tentatively correlated with the Crescent Formation of the Olympic Peninsula (Globerman, 1980). These igneous rocks are sporadically exposed along the west shore of southern Eld Inlet and are the only exposures of well indurated rock along the Thurston County coast. The remaining exposures along the coast are unconsolidated glacial deposits of Pleistocene age.

During the Pleistocene epoch, the Puget lobe of the Cordilleran ice sheet repeatedly entered the Puget Sound region, and deposited thick sequences of unconsolidated material (Crandell and others, 1958; Easterbrook, 1976; Noble and Wallace, 1966). Most of the sediment exposed in the coastal bluffs along the coast of Thurston County was deposited during the Olympia non-glacial interval and the Vashon Stade of the Fraser Glaciation. The stratigraphic sequence and the types of glacial materials commonly found in the coastal bluffs are summarized in Table 1.

TABLE 1. Summary of the stratigraphic units and glacial materials commonly found in the coastal bluffs of Thurston County (modified from Easterbrook, 1976; Easterbrook and others, 1981; Noble and Wallace, 1966).

FRASER GLACIATION VASHON DRIFT (Upper Pleistocene)	Recessional outwash and lacustrine Loose, stratified pebble to cobble-size gravel, fine to medium sand, locally with lenses of varved silt and clay. Lodgement till Very compact deposits of unsorted pebble to cobble-size gravel firmly encased in a matrix of sandy silt and clay. Advance outwash Loose stratified pebble to cobble-size gravel and sand locally with silt and clay lenses. Colvos Sand Member Loose fine to coarse grained sand locally with subordinate gravel.
OLYMPIA NONGLACIAL INTERVAL (Upper Pleistocene)	Olympia Non-Glacial Sediments (Kitsap Formation of Noble and Wallace, 1966) Horizontally bedded, compact clay, silt and sand, locally with lenses of gravel at base. Commonly contains beds of peat.
UNCONFORMITY	
OLDER GLACIATIONS (Middle to Upper? Pleistocene)	Pre-Fraser undifferentiated glacial drift (Salmon Springs Drift of Noble and Wallace, 1966) Cohesive clay and silt, compact till. Sand through cobble-size gravel, commonly stained by iron oxides.
UNCONFORMITY	
(Middle Eocene)	Crescent Formation Well indurated basalt and agglomerate, exposed only along the west shore of southern Eld Inlet.

CLIMATIC SETTING

The climate of Thurston County is predominantly a mid-latitude west coast marine type, characterized by cool, comparatively dry summers and mild, wet and cloudy winters (Phillips, 1964). This type of climate is shared with the rest of the Puget Sound region.

The climate of the Puget Sound region is affected by the position and intensity of two semi-permanent pressure systems over the north Pacific Ocean (NOAA, 1980a), and by the Cascade and Coastal mountain ranges (Fig. 1). The Hawaiian high pressure area resides in the Puget Sound region from June through September, and the Aleutian low pressure area dominates the remainder of the year. The large amount of precipitation and high winds produced by cyclonic storms are created by the Aleutian low pressure system. The Washington Coast Range, which includes the Olympic Mountains and Willapa Hills, shields the Puget Sound region from the more severe winter storms which move inland from the Pacific Coast. The Cascade Mountain Range is a barrier to higher and lower temperatures observed in eastern Washington.

For the greater Olympia area, the mean summer temperature is 16^{o}C and the mean winter temperature is 4.4^{o}C (NOAA, 1980b). As a result of these mild temperatures, sediment transport via ice does not occur. Mean annual precipitation is 1294 mm, about 85% of which falls during the months of October through April (NOAA, 1980b). Precipitation during these months increases stream discharge and coastal bluff erosion, resulting in an increase of sediment available for transport along the coast.

Wind

The direction, duration, and velocity of surface wind greatly influence the shore drift process. Surface wind for the Thurston County area is controlled by two semi-permanent pressure systems in the north Pacific Ocean. These winds are then modified by regional and local topography. During the late spring and summer months air is circulated in a clockwise direction around a semi-permanent high pressure cell, generating northwesterly winds which enter Puget Sound primarily through the Strait of Juan de Fuca. The flow of surface wind tracks south following the trough of the Puget Sound, eventually crossing Thurston County from a north to northeasterly direction. Early in the fall season, a low pressure cell gradually intensifies and replaces the high pressure cell, pushing it to the south. Air is circulated in a counter-clockwise direction by the low pressure cell which brings winds and storms from a south to southwesterly direction. Winds that reach Thurston County enter the mainland primarily through the Chehalis Gap, which is a narrow topographic corridor south of the Olympic Mountains and north of the Willapa Hills (Fig. 1). Upon reaching the southern Puget Lowland, winds cross Thurston County from a south to southwesterly direction. Locally, the Black Hills affect the wind patterns by curtailing winds from the west.

Occasionally, other wind patterns may occur. Through the course of an average summer, several low pressure storms may bring strong, shortlived southerly winds. In winter months, continental high pressure systems sometimes cross the Cascades from the northeast, generating northeasterly winds and extremely cold mid-continental air.

The pronounced seasonal difference between summer wind conditions (calm) and winter wind conditions (storm) in western Washington is, in part, caused by the exchange back and forth of the two cyclonic pressure systems. Calm summer conditions exist between the months of June through September and winter storm conditions prevail the remaining two thirds of the year (NOAA, 1980b). The result of this annual imbalance is that the prevailing winds (most frequent) and the predominant winds (greatest influence on wave generation) both come from the south to southwest (Table 2). The dominance of south to southwesterly winds is graphically displayed in the wind rose of the Olympia Airport (Fig. 2).

Wind information can be a useful aid in the prediction of net shore-drift direction when weighed against geomorphic evidence, coastline orientation, and fetch considerations. The direction of net shore-drift for much of the Thurston County coast is dictated by the prevailing and predominant wind-generated waves that approach from the south-southwesterly direction.

TABLE 2. Wind velocity and direction data for Olympia Airport 1949-1958 (modified from Pacific Northwest River Basin Commission Meteorology Committee, 1968).

Wind Direction	Mean Velocity (km/hr)	Mean Directional Frequency (%)
N	6.4	5.7
NNE	6.5	5.0
NE	6.3	5.5
ENE	5.8	2.0
E	4.7	1.6
ESE	4.7	1.6
SE	5.1	2.7
SSE	10.1	4.5
S	12.6	11.4
SSW	13.2	16.0
SW	11.9	12.6
WSW	12.3	5.3
W	10.7	2.4
WNW	8.8	1.6
NW	6.5	2.2
NNW	6.5	2.6

Velocity (km/hr)	0-4.8	4.9-11.2	11.3-19.2	19.3-28.9	29.0-38.6	>38.6
Frequency (%)	43.7	28.1	19.4	7.5	1.2	0.2

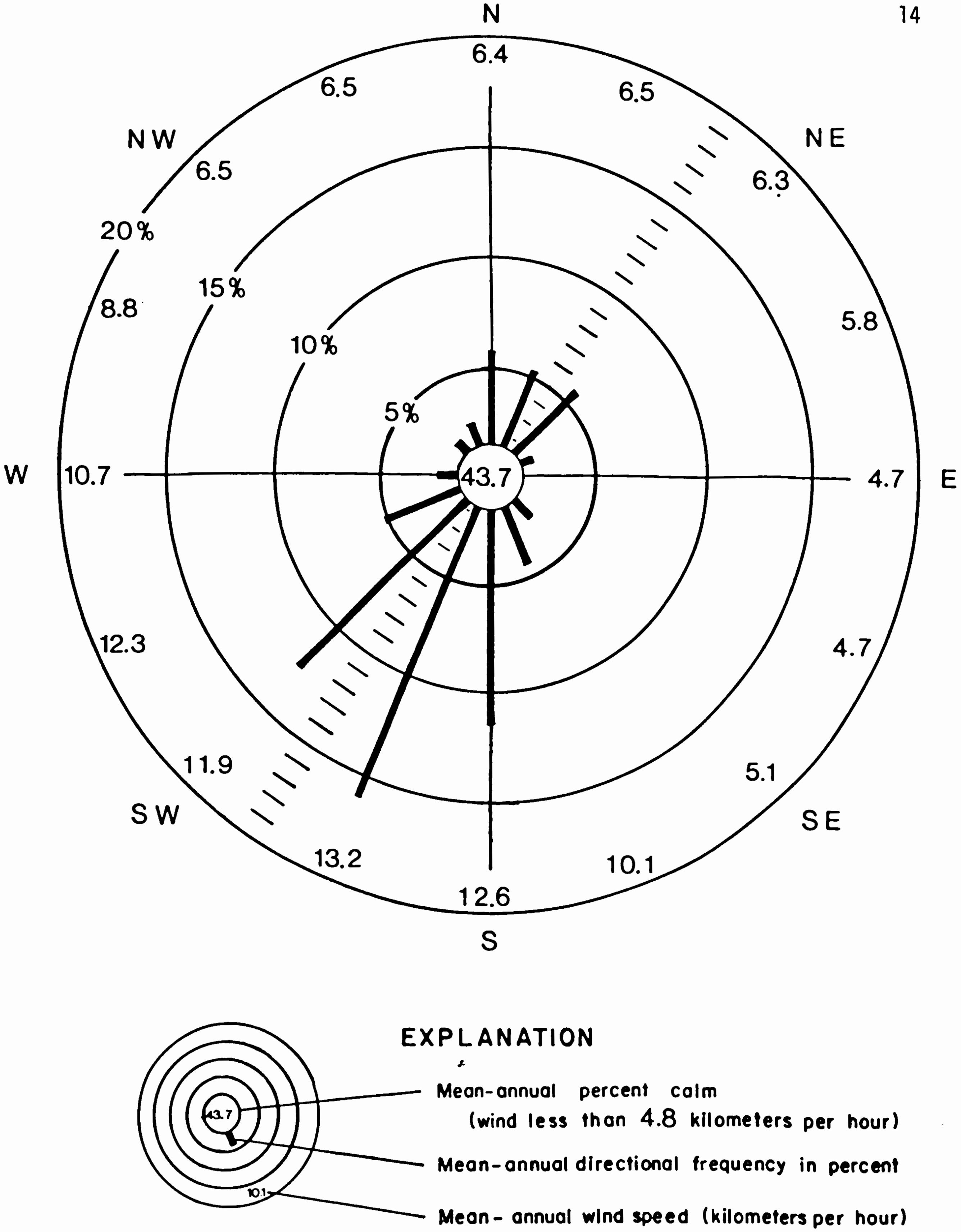

Figure 2. Wind rose for Olympia Airport showing mean-annual percent calm, directional frequency, and speed for a 16 point compass during the ten year period 1949-1958. (Modified from Pacific Northwest River Basin Commission Meteorology Committee, 1968).

OCEANOGRAPHIC SETTING

Two oceanographic factors influence the shore drift and bluff erosion processes in the Puget Sound region; they are wind-generated waves and tidal range. Wind-generated waves provide the energy to erode the bluffs and transport sediment along the shore, and tidal range determines the vertical and horizontal area over which waves may impart energy.

Wind-Generated Waves

Sediment is transported along the shore in response to the oblique approach of wind-generated waves. The energy and resulting transport capability of those waves is dependent on three variables: wind velocity; wind duration; and fetch, which is the distance wind can travel over water. Each variable may limit the height of a wave; yet for Puget Sound, fetch is the dominant limiting variable in the formation of wind-waves (Harris, 1954). The complex coastline pattern of Puget Sound produces short limited fetches of unequal lengths for any given wind direction, and when compared with wind velocity and duration parameters present over the Puget Sound region, fetch becomes the major factor in limiting increases in wave heights.

Schou (1945) and Bird (1969) have also determined fetch to be the major limiting factor in the development of wind-waves for other areas of the world with complex coastlines. For the inner Danish waters, Schou (1945) showed fetch to be of greater geomorphic significance than the prevailing wind direction.

Harris (1954) calculated wave heights for the main channel of Puget Sound using methods described by the United States Navy Hydrographic Office (1951). Based on fetches ≥27.8 km, average wind velocities ≥32 km/hr, and a period of 8 hour wind duration, Harris predicted the maximum wave height for the main channel would be 2.4 meters.

Maximum fetch lengths across Thurston County waters range between 8 and 12 kilometers, with fetch widths between 1 and 3 kilometers. Considering the effect of reduced fetch length and width on wave generation (Saville, 1954), the maximum wave heights produced with Thurston County's fetch parameters would certainly be much less than the 2.4 meters maximum predicted for the main channel of Puget Sound. Using wave forecasting graphs of the United States Army Corps of Engineers (1977), the maximum wave height derived for Thurston County waters would be approximately 0.7 m. This wave height is based upon a 12 km fetch and an average wind velocity of 32 km/hr.

Lower wave heights on Thurston County waters would reduce the potential wave energy available to erode the bluffs and transport sediment along the shore as compared with the wave energy available in the main channel of Puget Sound. Thus, the rates of bluff retreat and shore drift would be predictably less along the Thurston County coastline compared to the bluff retreat and shore drift rates along areas of Puget Sound with longer fetches.

Tidal Characteristics

The tides along the Thurston County coast, as in the rest of Puget Sound, are classified as mixed tides (two high tides and two low tides occur in twenty-four hours, all of unequal height). Tidal data for the study area were gathered at the subordinate tidal station located in the harbor of Olympia, southern Budd Inlet. The primary reference tide station to the Olympia subordinate station is located at the State ferry terminal on Seattle's waterfront. Tidal data for Thurston County are summarized in Table 3.

It can be seen from Table 3 that the tidal range for the body of water surrounding Thurston County is large; and based on the tidal classification system of Davies (1964, 1980), the study area has a macrotidal environment (spring tidal range >4 meters). In a macrotidal environment wave energy is distributed over a large vertical and horizontal area in the course of a tidal cycle (Bird, 1969; Davies, 1980). Thus, the bulk of the wave energy expended on the beach by the breaking waves is dispersed, resulting in a decrease in the rate of long-term bluff retreat (Rosen, 1977) and a decrease in the rate of shore drift as compared to a region with a narrow tidal range.

The tidal ranges for Thurston County waters are slightly different at opposite ends of the county. For instance, the Mean Higher High Water (MHHW) level at Burns Point in Totten Inlet is 0.15 meters higher than the MHHW level along the Nisqually Reach and, in addition, the MHHW level at Burns Point is 1.1 meters higher than the MHHW level at Seattle's reference station (National Ocean Survey,

TABLE 3. Tide parameters for the subordinate tide station at Olympia (after National Ocean Survey, 1982; University of Washington, 1954).

	Height in meters above or below Mean Lower Low Water
Extreme High Water	5.43
Mean Higher High Water (MHHW)	4.39
Mean High Water (MHW)	4.11
Mean Tide Level	2.51
Mean Low Water (MLW)	0.91
Mean Lower Low Water (MLLW)	0.00
Extreme Low Water	-1.43

1982). The increased tidal range for waters of southern Puget Sound is caused by the lateral constriction of the volume of water in the tidal front as it passes through the narrowing passages of Puget Sound. The result is an increase in tidal height the farther south the tidal front proceeds. Thus, bluff erosion and shore drift rates may be slightly less in Totten Inlet compared to the Nisqually Reach, because the tidal range is greater in Totten Inlet. It is doubtful, however, whether the influence tidal range has on bluff erosion and shore drift rates could be isolated from other more dominant rate-determining factors such as fetch and wind-generated waves.

PRINCIPLES

Coastal Sediment Sources

On a worldwide basis, 95% of the sediment delivered to the coast is brought by major rivers (Komar, 1976). However, for the southern Puget Sound region, the coarse-grained, unconsolidated material found in the coastal bluffs is the dominant source of beach sediment, with river sediment only locally dominating beach sediment.

The largest major river that empties into the waters fronting on Thurston County is the Nisqually River, with a mean annual discharge of 42.2 m^3/sec. (maximum discharge up to 582.6 m^3/sec.) (U.S. G. S., 1960), and an estimated mean annual load of 100,000 m^3 of fine-grained sediment (Brundage, 1960). The beaches immediately adjacent to the Nisqually River delta are composed of sand-size particles, reflecting the abundant, proximal sediment supply. With increasing distance away from the delta the beaches become increasingly dominated by coarser sediments. This trend occurs because the majority of sediment transported to Puget Sound by the Nisqually River is entrapped offshore in the deep water basin of the Nisqually Reach. Fine-grained river sediment that is distributed onto the beach near the delta is later transported away from the delta and mixed with a greater proportion of coarse-grained sediment.

With a limited fluvial sediment supply, the beaches of Thurston County are supplied by the only other available source, the coastal bluffs. The coastal bluffs are composed of unconsolidated glacial and non-glacial materials containing sand, granules, pebbles and cobbles with lesser amounts of clay, silt and boulders (Table 1).

Sediment on the beaches beneath coastal bluffs usually reflects the coarsest size fraction of the bluff material because the finest sediment is winnowed away by wave action and deposited offshore. When the bluffs are composed entirely of outwash sand or silt and clay, the adjacent beach usually reflects that fine-grained composition.

Dynamics of Shore Drift

The transport of sediment along the shore is primarily in response to the oblique approach of wind-generated waves. Waves approaching perpendicular to the coast have little or no effect on the transport of sediment in either direction parallel to the shore. Waves that approach the shore at an oblique angle are refracted, tending to become increasingly parallel to the shore. Refraction is generally not complete and the waves intercept the shore at a slight angle.

As waves break along the shore, a surge of water, foam, and sediment called swash is driven up the beach face. The withdrawal of water and sediment down the beach face is called backwash. In this zig-zag fashion sediment is transported along the beach parallel to the shore. This process is called beach drift. Near the shore, a longshore current is generated by variations in the wave breaker height along the length of the beach (Bowen, 1969; Bowen and Inman, 1969) and by waves breaking at an angle to the shoreline (Longuet-Higgins, 1970a, 1970b). The orbital motion of the waves entrains and suspends sediment above the bottom; and, combined with the impetus of the longshore current, sediment is transported parallel to the shore. This process is called longshore drift. Together, beach drift and longshore drift are called shore drift (Johnson, 1919; Schwartz, 1982) (Fig. 3). Other terms used to describe the shore drift process include "longshore drifting" (Bird, 1969), "littoral drift" (Ingle, 1966), and "longshore transport" (King, 1972).

The direction of shore drift can vary on a short term basis in response to daily or seasonal changes in wind-wave approach. Over a period of time sediment may be transported equally back and forth along a stretch of coast so the total or net transport of sediment into and out of an area is essentially zero. If, however, a wave approach predominates along a stretch of coast on a long-term basis, there is a net transport of material in one direction. This process of dominant long-term sediment transport is termed net shore-drift (Schwartz, 1982).

An area of no appreciable net shore-drift may result where shore drift processes are not operating or are eliminated. Such areas may occur where wave energy is very low, as found in an intertidal flat; or where the coast has been artifically modified, such as is found along industrialized areas.

Concept of a Drift Cell

The drift cell concept provides a useful framework to monitor sediment budget cycles in coastal geomorphology (Davies, 1974). A drift cell is a compartment along the coast which acts as a closed or nearly closed system with respect to its sediment source area, zone

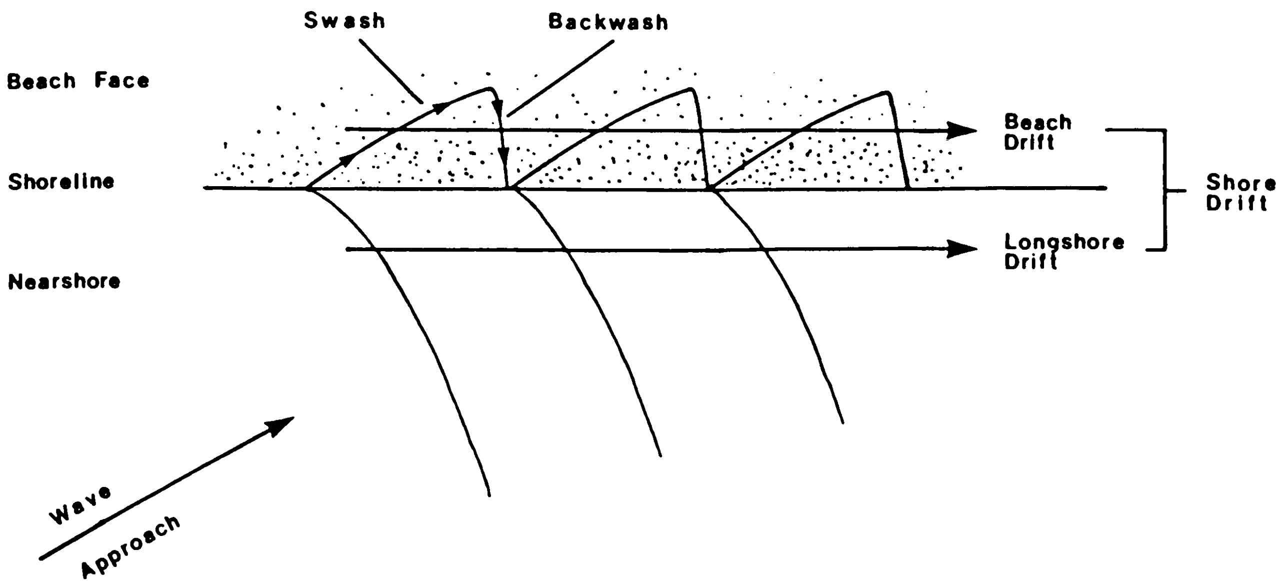

FIGURE 3. Diagram of the shore drift process whereby sediment is transported along the shore.

of transport, net shore-drift direction, and area of sediment deposition. Other terms used to describe such compartments are "drift sectors" (Bauer, 1974; Keuler, 1979; Jacobsen, 1980), "coastal sediment compartments" (Davies, 1974), "longshore transport cell" and "littoral drift cells" (Keuler, 1983).

The origin of a drift cell is a zone of long-term erosion that has generalized boundaries which shift position slightly in response to seasonal wave conditions or man-made alterations of the coast. This zone experiences a net deficit of sediment and as a result the shore in this area retreats at a greater rate than other portions of the coast. The origin is the primary source area for the drift cell sediment budget, and its location is determined by the directional frequency of the highest energy waves with respect to the orientation of the coast.

The origin of a drift cell can usually be recognized by the presence of vertical or near-vertical devegetated bluffs fronted by a wave-cut platform, although these are not a prerequisite. In the southern Puget Sound region, wave-cut platforms are abrasion surfaces characterized by a narrow or absent high-tide beach and by a near-horizontal foreshore profile covered by a thin veneer of well-rounded cobble to pebble-size lag deposits. The abrasion surfaces are commonly, though not always, located at a zone of divergent drift where two opposing wave regimes interface and create two separate drift cells, each diverging from a shared area of origin. Drift cells which originate from an unshared origin are commonly found adjacent to areas with low wave-energy such as along an intertidal flat. Low energy waves develop gradational erosion zones that usually lack vertical, devegetated bluffs and a distinct wave-cut platform. In these cases, shore drift commences where waves develop the energy necessary to transport sediment sizes present along the foreshore.

Sediment is transported along the coast by shore drift processes in the zone of transport, which is located between the drift cell origin and drift cell terminus. Throughout the zone of transport, sediment may be lost, interrupted, or introduced into the sediment budget of a drift cell. Despite the possible exchange of sediment within the zone of transport, the integrity of a drift cell is maintained from the origin through the zone of transport to the terminus.

Sediment is lost from the sediment budget when wave action along the shore winnows out and suspends fine sediment which is then carried offshore and deposited into deeper water. Sediment can also be lost down a submarine gully during the process of longshore drift.

Occasionally shore drift sediment can be interrupted or temporarily detained within the zone of transport. Sediment interruption occurs when waves lose energy while refracting into an indentation in the coastline, such as a small cove. Sediment detainment occurs when sediment is removed from the active part of the transport system and placed in an inactive reservoir, perhaps deposited in the backshore by storm waves.

Sediment may be introduced into the zone of transport along areas within a drift cell that are exposed to high wave-energy.

These areas often resemble the origin of a drift cell in that they usually have vertical, devegetated bluffs fronted by an abrasion surface. They are, however, only erosional areas within the larger drift cell system. Their location, like the origin of a drift cell, is dictated by shoreline orientation with respect to the dominant wave approach. In this way the sediment budget of a drift cell is rejuvenated within the zone of transport.

The terminus of a drift cell is a zone of long-term sediment deposition. Like the origin of a drift cell, the terminus area has generalized boundaries that shift position in response to seasonal wind conditions. The terminus is located where waves lose a significant amount of energy and can no longer support or transport sediment, perhaps while refracting around an abrupt change in shoreline, or as waves attenuate into shoaling water. The presence of a stable accretionary form, such as a spit or prograded beach, and well- vegetated upland slopes characterize the terminus of the drift cell. Occasionally two separate drift cells converge to a common terminus area in response to two converging wave regimes, possibly forming a cuspate spit. If two drift cells converge at a cove, opposing spits may develop from each side of the cove.

INDICATORS OF NET SHORE-DRIFT

The determination of net shore-drift direction through the use of wave-hindcasting techniques (Komar and Inman, 1970) and artificial tracers (Ingle, 1966) has been used successfully along many of the world's coastlines. Application of these techniques to determine net shore-drift direction for the southern Puget Sound coast has, however, proven inadequate because fetch was not weighted adequately in the wave modeling calculations, and wind data were inappropriately extrapolated to coastlines many kilometers away. A growing body of literature supports the use of a field-oriented investigation based upon geomorphic and sedimentologic indicators to determine the direction of net shore-drift along intricate coastlines (Hunter and others, 1979; Keuler, 1979, 1980, 1983; Jacobsen and Schwartz, 1981; and Chrzastowski, 1982). This study is based on and supports the use of methods discussed in these works.

The geomorphic and sedimentologic indicators used in this study to determine the direction of net shore-drift are separated into two categories: indicators which require field observations over considerable distances along the coast to determine variations in geomorphic trends, and indicators which render the direction of net short-drift at a specific site or area. Historical maps, charts, and air photos were used to supplement field interpretations. Historical charts were particularly useful in areas where recent urban development has eliminated geomorphic indicators. Thus, an interpretation of net shore-drift direction was made possible for an area where very few drift indicators exist today.

Observation of a single indicator is not sufficient evidence on which to base a drift direction interpretation. Rather, a case is built for net shore-drift direction based upon numerous supporting geomorphic and sedimentologic indicators in conjunction with secondary interpretive support from historical charts, principal wind/wave approaches, and fetch considerations. The following is a summary of the net shore-drift indicators used in this study of the Thurston County coast.

Indicators Requiring Observation Over Distance

The following group of indicators requires observation throughout the entire length of a drift cell before an overall geomorphic trend is seen. These indicators are best observed where the coastline is fairly straight with few indentations, and where bluff heights and materials are relatively uniform throughout the length of the drift cell. This assures consistent recognizable changes along the coast. Because the coastline of Thurston County is crenulated and the bluffs consist of poorly sorted glacial sediments, minor repetitions of a geomorphic or sedimentologic trend within a drift cell commonly occur.

Gradation in Mean Sediment Size

Mean sediment size decreases in the direction of net shore-drift (Bird, 1969; Davies, 1980). Longshore decreases in sediment size can be the result of various mechanisms including longshore variations in the wave energy level (Bascom, 1951); selective rates of transport, the finer grains out-distancing the coarser grains (Pettijohn and Ridge, 1932; Self, 1977); and surf abrasion of pebbles (Kuenen, 1964). Sediment gradation along the Thurston County coast is often locally ill-defined because poorly sorted glacial material is deposited onto the beach sporadically throughout the length of a drift cell. As a result, minor repetitions in sediment-size gradation are seen, yet when viewed on the larger drift cell scale, a general overall decrease of mean sediment size is observed.

Beach Slope

Published material concerning beach slope shows it to be a function of particle size (Bascom, 1951; Shepard, 1963). A fine-grained beach usually has a low beach slope. Ordinarily the slope of the beach would reduce in a downdrift direction, coincident with sediment size gradation. However, in the Puget Sound region, beach slope tends to increase in the direction of net shore-drift (Keuler, 1979). This seeming contradiction can be explained by looking at drift cell morphology. The origin of a drift cell is a zone of erosion where the beach slope closely approximates the low slope of the thin sediment veneer of coarse lag deposits over a wave-cut platform. Downdrift, the volume or wedge of sediment along the foreshore tends to increase in thickness, and consequently, the slope of the high tide beach increases.

Beach Width

The high tide beach along the upper foreshore tends to widen in the direction of net shore-drift (Keuler, 1979). At the origin of a drift cell the high tide beach is absent or very narrow because the highest energy waves erode and transport sediment away from this area. As the volume or wedge of sediment increases in a downdrift direction the mean higher-high water line is displaced seaward, gradually increasing the width of the high tide beach.

Bluff Morphology

Trends in bluff morphology have been discussed by Emery and Kuhn (1982) for portions of the California coast and by Keuler (1979) for the Skagit County coast, Washington State. In general, for the Puget Sound region, bluff exposures reduce in slope angle in the direction of net shore-drift. At the origin of a drift cell, the high tide beach is absent and waves can attack and maintain near vertical, unvegetated bluff exposures. As the width of the high tide beach increases downdrift, bluff slopes decrease, and vegetation on the bluff slope increases because the high tide beach provides increasingly more protection from wave attack to the bluffs. This trend shows a transference from bluffs dominated by coastal erosion to bluffs dominated by subaerial erosion processes.

Site-Specific Indicators

The following group of indicators gives the direction of net shore-drift at a specific site or area.

Spit Development

Spits accumulate and develop (Meistrell, 1972) in the direction of net shore-drift (Evans, 1942; Bird, 1969) usually at or near the terminus of a drift cell. The refraction of waves around the distal end of a spit may create a localized change in sediment drift direction, possibly forming a recurved spit. Cuspate spits are symmetrical (Zenkovitch, 1959, 1967), often forming at the terminus of two converging drift cells (Bird, 1969).

Foreshore Offsets at Drift Obstructions

Any structure, such as a groin, bulkhead, boatramp, or beach log situated perpendicular to the foreshore will intercept sediment involved in shore drift (Komar, 1976). A vertical and/or horizontal accumulation of sediment occurs on the updrift side of an obstruction coincident with a loss of sediment on the downdrift side. The accumulation and erosion of sediment creates an offset of the foreshore beach. The larger the drift obstruction, the more reliable it is as an indicator of net shore-drift direction (Jacobsen and Schwartz, 1981).

Diversion of Stream Mouth Outlets

The mouth of a stream or lagoon outlet which discharges into a drift cell is diverted in the direction of net shore-drift (Bird, 1969). A stream is diverted when sediment advances into the updrift side of the stream mouth faster than the stream can erode and transport the sediment away. During periods of low stream discharge the stream mouth may be sealed off altogether.

Plan View of Deltas or Intertidal Fans

A delta or intertidal fan that develops across the zone of transport within a drift cell will intercept sediment involved in shore drift. Commonly, the high tide beach along the updrift side is broad and prograded, while the beach along the downdrift side is narrow and rounded (Chrzastowski, 1982). Stream channels of several intertidal fans along the Thurston County coast were concentrated on the downdrift side, diverted across the fan or delta in the direction of net shore-drift.

Identifiable Sediment

Sediment, either natural or artificial, that can be traced along the beach to a known long-term point source is a reliable indicator of net shore-drift (Bird, 1969). Along the Thurston County coast, shells from oyster farms provide a good source of identifiable sediment. The size of the oyster shells and the percentage of shell in the beach sediment both decrease downdrift, with increasing distance from the oyster shell dump.

Oblique Bars

Oblique bars form perpendicular to the predominant wave approach usually along the low tide terrace. They are created by longshore drift processes and trend offshore in a downdrift direction (Guilcher, 1974). Care must be taken when using oblique bars as a drift indicator because bar formation is complex and controversial (Komar, 1976; Schwartz, 1972). Oblique bars are reliable indicators of net shore-drift direction only when they occur in a series of bar sets (Hunter and others, 1979), and when used in conjunction with more dependable drift indicators.

Beach Pads

A geomorphic indicator not discussed in previous studies of Puget Sound shore drift is the beach pad. The term beach pad was used by Tanner (1975) to describe a body of sand generally resembling an obtuse triangle with its base adjacent and parallel to the mainland (Fig. 4). The updrift side of the beach pad tapers slowly and corresponds to the second longest side of an obtuse triangle while the downdrift side of the beach pad corresponds to the shortest side of the triangle. Occasionally a bar may extend from and be parallel with the updrift side of the beach pad. The bar trends obliquely offshore in a downdrift direction.

Beach pads along the Thurston County coast vary in size and shape. Their morphology ranges from long and narrow (Fig. 5a) to short and wide (Fig. 5b). A typical beach pad is characterized by a decrease in sediment size from the updrift side of the pad to the downdrift side of the pad coincident with an increase in the width and slope of the high tide beach. A beach pad is a good example of an accretionary beach form where sediment can be interrupted or detained in transport within a drift cell. It was not determined in this study whether individual beach pads are migrating or stationary

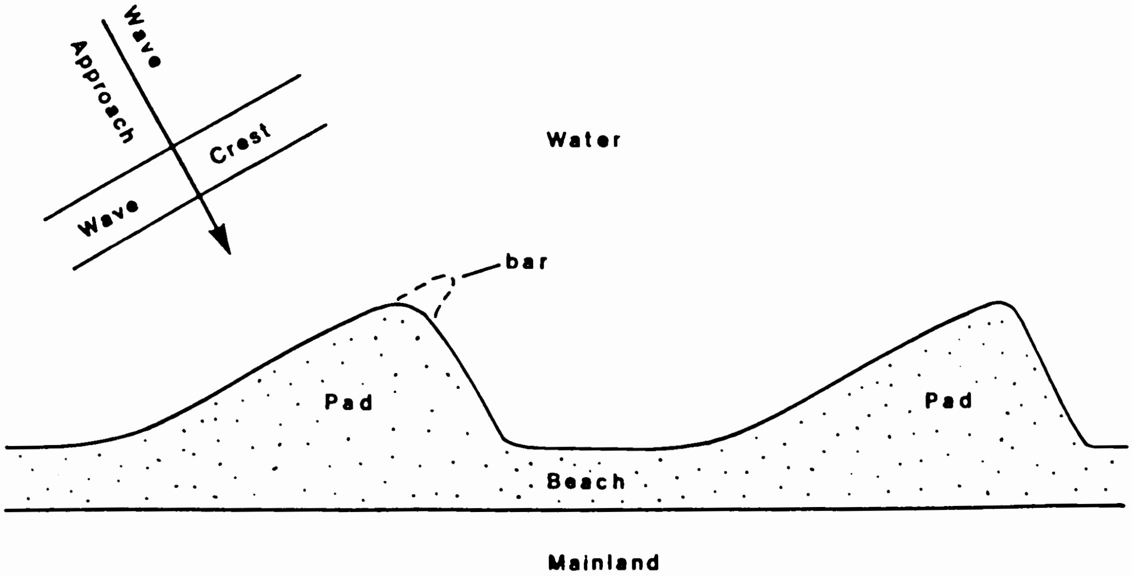

FIGURE 4. Idealized sketch of two beach pads. Net shore-drift is from left to right (after Entsminger, 1982).

FIGURE 5a. Vertical aerial photograph showing long and narrow beach pads located approximately 700 m south of Sandy Point along drift cell 13.

FIGURE 5b. Vertical aerial photograph showing short and wide beach pad located approximately 4 km south of Johnson Point along drift cell 62.

features, nor was it determined how or why the beach sediment is modified into the various beach pad forms.

PREFACE TO THE NET SHORE-DRIFT DISCUSSION

The principles and indicators described in earlier sections were used to identify the direction of net shore-drift and define the boundaries of drift cells along the Thurston County coast. The location of each drift cell and direction of net shore-drift are presented on the map of Thurston County located in the map pocket. Also displayed on the map are the net shore-drift indicators observed along each drift cell. Letter symbols representing the indicators requiring observation over a distance are placed on the map at the first indication of an observable geomorphic or sedimentologic trend. If the geomorphic or sedimentologic trend of an indicator repeats throughout the length of a drift cell a letter symbol is located at the beginning of each repeated sequence. Letter symbols representing the indicators that give a site-specific determination of a net shore-drift direction are also located on the map. Symbols used on the map are explained in Figure 6 and Table 4. Table 4 shows a correspondence between letter abbreviations and indicators described in the text for use with the map and Table 5.

The indicators used to determine drift cell boundaries and drift directions are displayed in Table 5. In this table drift cells are consecutively numbered in vertical columns, and net shore-drift indicators are consecutively letter-abbreviated in the horizontal columns. An X was placed in the matrix when an indicator was used as evidence for a drift direction interpretation. Table 5 is to be used as a quick reference in conjunction with the map. The table does not show the number of times the same type of indicator was encountered along a drift cell (that information is on the map), nor does it give

	Zone of net shore-drift divergence. This is an erosional zone from which sediment is supplied and transported to diverging drift cells.
 75	Direction of net shore-drift, showing boundary and length of drift cell. The line begins at initial indication of net shore-drift and the arrowhead is positioned at or near the drift cell terminus. Number identifies the drift cell for use with the text.
A,E,K	Letters identify the approximate location of indicator(s) used to determine net shore-drift direction.
nansd	Acronym for a zone of "no appreciable net shore-drift".

FIGURE 6. Explanation of symbols used on the map of Thurston County net shore-drift.

TABLE 4. Abbreviations of the net shore-drift indicators used on the map and Table 5.

NET SHORE-DRIFT INDICATORS	ABBREVIATIONS	
<u>Indicators Requiring Observation Over Distance</u>		
Gradation in Mean Sediment Size	A	SED. GRADE
Beach Slope	B	SLOPE
Beach Width	C	WIDTH
Bluff Morphology	D	BLUFF
<u>Site-Specific Indicators</u>		
Spit Development	E	SPIT
Foreshore Offsets at Drift Obstructions	F	DRIFT OBSTR.
Diversion of Stream Mouth Offsets	G	DIVERSION
Plan View of Deltas or Intertidal Fans	H	DELTA/FAN
Identifiable Sediment	I	ID. SED.
Oblique Bars	J	BARS
Beach Pads	K	PADS

TABLE 5. Indicators used to determine the direction of net shore-drift for each drift cell along the Thurston County coast.

INDICATORS OF NET SHORE-DRIFT

Drift Cell	A Sed. Grade	B Slope	C Width	D Bluff	E Spit	F Drift Obst.	G Diversion	H Delta Fan	I I. D. Sed.	J Bars	K Pads
1			x	x	x	x	x				x
2	x				x	x	x				
3	x		x	x	x	x	x		x		
4	x		x	x	x		x				
5	x	x	x	x		x				x	x
6	x		x	x		x	x				
7	x			x	x	x					
8	x				x	x	x				
9	x				x						
10	x				x						
11	x				x						
12	x				x						
13	x	x	x	x	x	x	x			x	x
14				x		x					
15				x		x					
16			x			x					
17			x			x					
18	x	x	x	x		x					
19	x				x						
20	x		x	x	x	x	x				
21			x	x		x					
22	x		x	x	x		x				
23	x	x	x	x	x		x				
24	x	x	x	x	x	x					
25	x			x	x						
26	x				x	x					
27	x		x								
28			x			x					
29					x						
30	x	x	x	x	x	x	x	x	x		
31	x	x	x	x	x	x	x		x		
32	x		x	x	x	x	x	x			
33	x		x	x	x	x					
34	x	x	x	x	x	x	x			x	x
35	x	x	x	x	x	x	x	x			

TABLE 5. Continued.

Drift Cell	Sed. Grade A	Slope B	Width C	Bluff D	Spit E	Drift Obstr. F	Diversion G	Delta Fan H	I. D. Sed. I	Bars J	Pads K
36	x					x					
37		x	x	x		x					
38	x		x	x		x					
39						x	x				
40	x		x		x	x		x			
41	x			x		x					
42	x	x	x	x	x	x	x	x			
43	x	x	x	x	x						
44	x	x	x	x	x	x	x			x	x
45	x	x	x			x					
46	x	x	x	x	x	x					
47	x		x		x	x					
48	x	x	x	x	x	x	x	x			
49	x	x	x	x	x						
50	x	x	x	x	x	x				x	
51	x	x	x	x	x	x	x				
52	x		x	x	x	x					
53			x		x	x					
54	x		x								
55			x	x							
56			x			x					
57	x		x			x					
58	x				x		x				
59	x		x								
60	x				x	x					
61		x	x		x		x				
62	x	x	x	x		x					x
63	x	x	x	x	x	x					
64	x		x			x					
65	x		x	x	x	x	x			x	
66	x		x	x	x						
67	x		x	x	x	x	x				
68	x		x	x		x					
69	x		x	x							
70	x		x	x	x	x					
71	x	x	x	x	x	x	x				
72	x	x	x	x	x	x	x				
73	x		x	x	x		x		x		
74	x		x			x					
75	x	x	x			x					

specific information about the characteristics of individual indicators (vertical displacement measurements of the high tide beach at a drift obstruction or the length measurement of a spit at a drift cell terminus).

A description of each drift cell is presented in the net shore-drift discussion. Each description briefly discusses the indicators used to determine the net shore-drift direction and boundaries of each drift cell as they were observed in the field. Also discussed are selected coastal geomorphic features and areas of no appreciable net shore-drift. The map of Thurston County (located in the map pocket) should be consulted while reading this section.

In reading the net shore-drift discussion the following list of qualifications should be kept in mind:

(1) This study documents the direction of net shore-drift, not seasonal shore drift.

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

(3) Drift cell boundaries may be broad general zones that constantly shift position in response to changes in wave approach.

(4) Not all sediment supplied to a drift cell is necessarily transported to the terminus.

(5) Each indicator is not necessarily observed in every drift cell.

(6) Drift cell patterns described in this text and shown on the map are applicable to the Thurston County coast as of the date of this study. Subsequent modification of the coast could alter drift cell boundaries and net shore-drift direction.

NET SHORE-DRIFT DISCUSSION

Oyster Bay

Oyster Bay is located in the southernmost portion of Totten Inlet. The intertidal flat in Oyster Bay is a vertically accreting, gently inclined, muddy to sandy area exposed during low tide levels. Small meandering streams dissect the intertidal flat and supply fine sand, silt and clay-size sediment. Fine-grained sediment is redistributed across the intertidal flat by tidal currents. A narrow high tide beach, composed of sand and silt, and coastal marshes are sporadically developed along its eastern margin.

Sediment transport along the shore of Oyster Bay is minimal or non-existent because shallow water and short fetches limit wave development. Therefore, Oyster Bay is an area of no appreciable net shore-drift (nansd).

Drift Cell 1

Drift cell 1 originates along the east shore of Oyster Bay, southern Totten Inlet, where prevailing southwesterly waves become large enough to transport sediment to the northeast. The origin is not well defined because wave energies are low. Sediment is directed to Burns Point by prevailing southwesterly waves. At Burns Point northeasterly waves begin to predominate over waves from the southwest and direct sediment south into Burns Cove. This is a good example of a drift cell reversal around a headland.

Drift to the northeast is indicated by beach widening, spit development, and stream diversion to the northeast; sediment accumulated on the southwest side of logs perpendicular to the beach, with maximum vertical displacements of 0.4 m; and a beach pad developed to the north. Net shore-drift to the south into Burns Cove is indicated by an increase in the beach width and a decrease in the slope of the bluffs. Net shore-drift terminates along a spit developed to the south along the west side of Burns Cove.

Drift Cell 2

This drift cell originates at a zone of divergence, where northwesterly waves predominate and direct sediment westward to a terminus area on the south shore of Burns Cove. Bluffs are subdued and there is no indication of a wave-cut platform at the origin of this drift cell. This drift direction is evidenced by sediment prograded on the northeast sides of drift obstructions, such as bulkheads, groins and logs; sediment fining, from pebbles to sand; and spit development to the west. Several streams are diverted to the west by spits. Sediment transport terminates at a 10 m long spit developed northward along the southwest shore of Burns Cove.

Drift Cell 3

Beginning at a divergent zone approximately 1 km northeast of Burns Cove, sediment is directed to the northeast by prevailing and predominant southwesterly waves. Bluffs are subdued and there is no indication of a wave-cut platform at the origin of this drift cell. Net shore-drift to the northeast is evidenced by sediment accumulated on the southwest sides of drift obstructions, such as groins and bulkheads, with maximum vertical offsets of 0.9 m; repeated patterns of bluff slope reduction, beach widening, and sediment fining to the northeast; and spit development to the northeast, often across stream mouths. One such spit is diverting a stream approximately 280 m to the northeast, the longest stream diversion along the Thurston County coast. Net shore-drift terminates at a 45 m long spit composed of pebbles, granules, sand and oyster shell fragments. The oyster shells are from an oyster-farm dump to the south of the spit.

Drift Cell 4

Beginning at a divergent zone located about 200 m west of a small cove, sediment is directed east off a wave-cut platform by prevailing and predominant southwesterly waves. Net shore-drift to the east is evidenced by a decrease in sediment size from cobbles and pebbles to pebbles, granules and sand; widening of the high tide beach to the east; and a change in the bluff morphology from near-vertical, devegetated bluffs at the origin to vegetated, rounded bluffs at the terminus. A small stream is diverted about 15 m to the east by a spit composed of pebbles and sand that is built into the cove.

Drift Cell 5

Drift cell 5 originates at a zone of divergence located about 200 m west of a small cove. Southwesterly waves attack and maintain near-vertical, devegetated bluffs and direct sediment to the northwest off a wave-cut platform cut across glacial outwash. Net shore-drift to the north is indicated by a decrease in bluff slope and an increase in bluff vegetation; a decrease in mean sediment size from cobbles and pebbles to granules and sand; and sediment accreted on the south side of drift logs, with maximum vertical offsets up to 0.3 m. A beach pad is located approximately 400 m west of the small cove at an area locally called Point Reliable. At this location the beach widens and increases slightly in slope, and a bar attached to the seaward end of the beach pad trends offshore in a northerly direction. Net shore-drift terminates along a prograded sand beach locally called Dogfish Point.

Drift Cell 6

Waves that approach along a principal fetch to the northeast direct net shore-drift to the southwest off a wave-cut platform cut across glacial outwash. From headland bluffs at the zone of divergence, net shore-drift toward the southwest is indicated by sediment accumulated on the east side of drift logs and by minor stream diversions to the southwest. Additional evidence of a southwesterly drift direction is a decrease in the size of beach sediment from large pebbles to granules and sand; an increase in the width of the high tide beach; and a change in the bluff morphology from near-vertical, devegetated bluffs at the divergent zone to rounded, well-vegetated bluffs at the terminus. Drift cells 5 and 6 converge and terminate at a prograded beach that has a 9 m wide grassy backshore.

Drift Cell 7

Drift cell 7 begins at a divergent zone located approximately

1 km northwest of Gallagher Cove. Net shore-drift is directed south off a wave-cut platform cut across glacial sediments by predominant waves that approach across a northeasterly fetch. Net shore-drift to the south into Gallagher Cove is evidenced by sediment accumulated on the north side of a drift log with a vertical offset of 0.3 m; a spit developed to the south; a decrease in the bluff slope; and a decrease in sediment size from pebbles to sand and silt. Sediment transport terminates along a broad intertidal flat composed of sand, silt, and clay.

Drift Cell 8

This drift cell originates along a zone of divergent drift northeast of Gallagher Cove. Net shore-drift is directed to the southwest by predominant waves that approach across a fetch to the north as indicated by a decrease in the sediment size from granules over the high tide beach at the origin to silt and clay along a narrow high tide beach at the terminus. Additional indicators of a southerly net shore-drift direction are spit development to the south; diversion of streams to the south; and prograded sediment on the north sides of drift logs, with maximum vertical offsets of 0.4 m. Drift cell 8 terminates along a broad intertidal flat composed of sand, silt, and clay.

Drift Cells 9, 10, 11, and 12

These four drift cells are located about 1.5 km northeast of Gallagher Cove along the east shore of Totten Inlet. Waves that develop across fetches from the north and west impinge on small headlands and create zones of divergent drift. From narrow wave-cut platforms cut across glacial sediments, net shore-drift is directed away from the headland bluffs into each cove as indicated by sediment fining from pebbles to sand and spit development into each cove.

Drift Cell 13

Beginning at a zone of divergence located approximately 1.75 km northeast of Gallagher Cove sediment is transported to the north by prevailing and predominant waves which approach across a fetch to the west-southwest. From a wave-cut platform covered with cobbles adjacent to near-vertical bluffs composed of glacial till, net shore-drift to the north is evidenced by repeated patterns of sediment fining; increases in beach width and slope; decreases in bluff slope to the north; and sediment accumulated on the south side of drift obstructions such as bulkhead stairs, beach logs, groins and a boatramp, with maximum vertical offsets of 0.7 m. Approximately 600 m north of the divergent zone two spits are developing to the north, one across the entrance to a cove and the second an intertidal spit, across the adjacent low tide terrace. The two spits, each about 60 m in length, divert a stream a total of 120 m to the north. The development of two beach pads and a series of oblique bars 800 m south of Sandy Point (Fig. 5a) provide additional evidence of a northerly drift direction.

Sandy Point is connected to Steamboat Island by a prograding submerged bar that is deposited on a ridge of *in situ* glacial sediment (Fig. 7a). Steamboat Island is an island only during high tide levels, the remainder of the time it is connected to the mainland by an exposed bar. Drift cell 13 terminates at a spit developed 200 m to the northwest from the southern end of Steamboat Island.

Drift Cell 14

This drift cell originates in a divergent zone at the northern tip of Steamboat Island. An excellent example of a wave-cut platform, stripped of sediment, is found here accompanied by a devegetated, vertical bluff (Fig. 7b). Net shore-drift is directed to the south by predominant northeasterly waves as indicated by a decrease in bluff steepness to the south and the accumulaton of sediment on the north side of small groins with maximum vertical offsets of 0.1 m. The terminus area lies on the southwest side of Steamboat Island, where sand is accumulated in the lee of a large spit developing from the south (see drift cell 13). Drift cell 14 probably began to develop after the spit from drift cell 13 was large enough to protect the west side of Steamboat Island from the prevailing waves from the southwest.

Drift Cell 15

Beginning along a divergent zone at the northern tip of Steamboat Island, sediment is transported southwest by predominant northwesterly waves to a terminus area on the southeast flank of the island. Sediment accumulated on the north side of a boatramp, with a

FIGURE 7a. Vertical aerial photograph of Steamboat Island and vicinity.

FIGURE 7b. Southwestward aerial view of Steamboat Island and vicinity. Note the exposed wave-cut platform along the north end of Steamboat Island.

maximum vertical offset of 0.1 m, and a decrease in bluff steepness to the south provide evidence for the drift direction interpretation.

Sediment on the east flank of the ridge which separates Sandy Point and Steamboat Island is delivered, for the most part, by drift cell 13. The resulting prograded beach creates a barrier that opposes the southwesterly transport of sediment along drift cell 15. Thus, the terminus area and southern limit of drift cell 15 is determined by the prograded beach developed with sediment delivered by drift cell 13.

Steamboat Island

The drift pattern around Steamboat Island is unique in Thurston County because four separate drift cells converge within the same area. Drift cells 14 and 15 are directed southwest by waves that approach across a northeasterly principal fetch, whereas drift cell 13 is directed to the north by prevailing and predominant southwesterly waves, and drift cell 16 is directed to the northwest by waves that approach across a fetch to the southeast.

Prevailing southwesterly waves influence sediment transport around Steamboat Island as shown by the 200 m long spit developed at the terminus of drift cell 13 and the effect a prograded beach developed with sediment from drift cell 13 has on the terminus of drift cell 15.

Drift Cell 16

Drift cell 16 begins at an ill-defined zone of divergence along the west shore of a small cove located approximately 600 m southeast of Sandy Point. Sediment is directed northwest by waves that approach along a southeasterly fetch as evidenced by accumulations of material on the east side of bulkheads and increases in beach width to the west. Net shore-drift terminates at a prograded beach along the southeast flank of Sandy Point (Fig. 7a).

Drift Cell 17

This short drift cell (about 50 m in length) is a reversal in drift direction to the generally westerly transport of sediment along the shores adjacent to Squaxin Passage. From an ill-defined zone of divergence along the west shore of a small cove, sediment is directed into the cove by predominant waves that approach from the north and northwest and possibly by southeasterly waves as they refract into the cove. Sediment accumulated on the northwest side of a fallen tree, with a maximum vertical offset of 0.3 m, and the widening of the high tide beach toward the southeast are evidence of net shore-drift into the cove.

Drift Cell 18

Beginning at a divergent zone about 300 m east of Sanderson Harbor, net shore-drift travels north and then west, terminating along the east bank of a small cove. Net shore-drift originates along a wave-cut platform which has been cut across unconsolidated sediments exposing vertical, devegetated bluffs. Sediment is transported to the north by predominant southerly waves as evidenced by sediment accreted on the south sides of groins with maximum vertical offsets of 0.9 m, and repeated patterns of sediment fining, bluff slope reduction, beach width and slope increases toward Hunter Point. Examples of intermediate erosional areas are seen along the downdrift ends of coastal indentations from the area of origin to Hunter Point.

As southerly waves refract in a counter-clockwise direction around Hunter Point, they lose energy and deposit a major portion of the entrained sediment along a large prograded beach (Fig. 8). Some sediment, however, appears to continue in a westerly direction past Hunter Point, thus maintaining the integrity of the drift cell. Shore drift is directed to the west by predominant waves that approach across a principal fetch to the southeast. This drift direction is indicated by sediment prograded on the east sides of a bulkhead, drift logs, and a boatramp with maximum vertical displacements of 0.5 m and by beach widening to the west. Net shore-drift terminates at a prograded beach on the east side of a cove.

Drift Cell 19

This short drift cell originates in a zone of divergence 200 m east of Sanderson Harbor. Sediment is directed along the northeastern shore of Sanderson Harbor by predominant southerly waves as indicated by a decrease in the mean sediment size from cobbles, which armor the wave-cut platform, to coarse sand found at the terminus. Net shore-drift terminates along a 10 m long spit developed to the northwest into Sanderson Harbor.

FIGURE 8. Oblique aerial photograph showing the prograded beach at Hunter Point. View is toward the northwest along Squaxin Passage.

Drift Cell 20

Drift cell 20 originates along a zone of drift divergence about 300 m north of Frye Cove. Sediment is directed to the north off a sandy low tide terrace adjacent to near-vertical, devegetated bluffs composed of laminated silts by waves that develop across a fetch to the southeast. Landslides are evident along, and north of, the divergent zone. Sediment accumulated on the south sides of drift logs and groins, increases in the width of the high tide beach, and numerous stream diversions to the north also indicate a northerly net shore-drift direction.

Approximately 1.7 km south of Sanderson Harbor there is a small cove which detains sediment in transport. An erosional zone is found along a headland on the east side of the cove. Much of the sediment brought to the cove is deposited as shown by a prograded beach; however, some material by-passes the cove and continues north. Net shore-drift to the north, past the cove, is indicated by sediment fining from cobbles to sand, bluff slope reduction to the north, beach widening, and sediment accumulated on the south side of a groin and a bulkhead. The terminus of this drift cell is a spit which has developed to the north into Sanderson Harbor.

Drift Cell 21

From a zone of divergence located 300 m north of Frye Cove sediment is transported south, away from eroding near-vertical bluffs fronted by a sandy low tide terrace, by predominant northerly waves. Southerly net shore-drift is indicated by sediment prograded on the north side of a drift log, bluff slope reduction, and beach width increasing to the south. Sediment transport terminates along a broad, sandy, prograded beach developing to the south across the mouth of Frye Cove.

Drift Cell 22

Drift cell 22 originates along a zone of divergence where wave action has developed a wave-cut platform across till. Sediment is directed to the west by waves that approach across a fetch to the northeast as evidenced by sediment fining from cobbles to sand; widening of the high tide beach; and a change in the bluff morphology from near-vertical, devegetated bluffs composed of glacial till at the origin to rounded, vegetated bluffs at the terminus. Additional indicators of net shore-drift direction include the presence of two 9 m long spits which have developed to the west partially across the mouths of two small coves, and stream diversions to the west that result from the spit development. Net shore-drift terminates along a prograded beach developed on the south side of Frye Cove.

Drift Cell 23

This drift cell originates at a zone of divergence about 300 m southeast of Frye Cove and runs southeast to a terminus at Flapjack Point (Fig. 9a). Net shore-drift is directed to the southeast, off a wave-cut platform across till, by predominant waves that approach along a principal fetch to the north as evidenced by an increase in beach width and slope; a decrease in bluff slope; and a decrease in

FIGURE 9a. Oblique aerial photograph shows Flapjack Point along the west shore of Eld Inlet. View is toward the west.

FIGURE 9b. Oblique aerial photograph shows the spit development and stream diversions at Flapjack Point. View is toward the east.

sediment size from cobbles and pebbles at the origin to sand at Flapjack Point. Sediment is deposited along a spit that has developed to the southeast on the north side of Flapjack Point. This spit also diverts a small stream to the east.

Flapjack Point

Flapjack Point is located along the west shore of Eld Inlet, and is formed by the convergence of drift cell 23 from the northwest and drift cell 24 from the southwest (Fig. 9a). Flapjack Point is unusual because a stream outlet bisects and modifies the terminus area of both drift cells.

Along the north shore of Flapjack Point a stream is diverted 30 m to the southeast by a spit developing from the northwest (drift cell 23). Wave refraction in a clockwise direction around the distal end of this spit causes it to recurve. A localized change in sediment drift direction into a lagoon landward of the spit also occurs. Sediment from the southwest (drift cell 24) is deposited along a spit on the south side of the lagoon. The stream is diverted to the north across the low tide terrace after it exits from between the distal end of both spits. A small, narrow cuspate spit is forming to the northeast, on the low tide terrace, off the distal end of the recurved spit (Fig. 9b). Its presence identifies a balance point between the prevailing waves from the south and the waves from the north. Had the stream never existed, Flapjack Point would probably be a cuspate spit. In any event, all three spits developed at Flapjack Point support the drift determinations presented in the drift cell descriptions.

Drift Cell 24

Drift cell 24 originates at a zone of divergent drift approximately 400 m east of Young Cove and continues to the northeast to a terminus area at Flapjack Point (Fig. 9b). Sediment from eroding bluffs composed of glacial outwash is transported off a wave-cut platform to the north by predominant southerly waves, as evidenced by accumulations of sediment on the southwest sides of groins and drift logs, with maximum vertical offsets of 0.5 m; reduction in bluff slope; increases in beach width and slope; and a decrease in mean sediment size from cobbles to sand. Sediment transport terminates at a spit developed on the south side of Flapjack Point.

Drift Cell 25

Beginning at a zone of divergence located 400 m east of Young Cove, sediment is transported west-northwest off a wave-cut platform cut across glacial outwash by prevailing southerly waves into Young Cove. Drift to the west is evidenced by sediment fining from cobbles to pebbles and sand, and a reduction in bluff slope from near-vertical, slumping bluffs to rounded, vegetated bluffs. Sediment transport terminates along a spit developed to the northwest on the north side of the cove.

Drift Cell 26

Beginning at an ill-defined divergent zone approximately 500 m south of Young Cove, sediment is transported to the north by prevailing southerly waves as evidenced by sediment fining to the north from cobbles and pebbles to pebbles, granules and sand, and by accumulations of sediment on the south sides of groins and bulkheads, with maximum vertical offsets of 0.5 m. Sediment transport terminates at a spit developed to the north from the south side of the cove.

Drift Cell 27

This drift cell is reversed in drift direction to the generally northerly transport of sediment in this area. Sediment is directed to the south by predominant waves from the north and perhaps by southeasterly waves that refract counter-clockwise around a small headland into a small cove located approximately 800 m south of Young Cove. Sediment is transported to the south from an ill-defined divergent zone to a prograded beach on the north side of a stream within the cove. A decrease in sediment size from cobbles and pebbles to sand, and an increase in the width of the high tide beach to the south, provides evidence for a southerly drift determination.

Drift Cell 28

This drift cell originates along a broad ill-defined zone of divergence located north of Kay Point. Much of the divergent zone is defended by bulkheads, and as a result wave erosion of the bluffs does not presently contribute sediment to the drift cell sediment budget. Sediment is directed to the north by predominant southerly waves to a small cove 800 m south of Young Cove, where net shore-drift terminates. Drift to the north is evidenced by sediment accumulated on the south sides of drift logs and groins, with maximum vertical offsets of 0.3 m, and by slight beach widening. Sediment transport terminates along the south shore of the cove as southerly waves refract into the cove.

Drift Cell 29

This drift cell originates in a broad zone of ill-defined divergence located north of Kay Point and runs southwest to a terminus at Kay Point (Fig. 10). Evidence for the transport of sediment to the southwest along this short drift cell (100 m) rests mainly on the presence of a spit developed at Kay Point. The presence of grasses and mussels on the north flank of Kay Point indicates a low wave-energy environment and probably minimal shore drift from the north. Mussels and grasses could not survive under high energy wave conditions because they would be continually covered by sediment.

Kay Point

Kay Point (Fig. 10) is a spit, formed by convergent net shore-drift of drift cells 29 and 30. Drift cell 30 is well documented with many indicators that evidence net shore-drift to the north. However, drift cell 29 lacks strong supporting evidence for a drift

FIGURE 10. Vertical aerial photograph shows the spit developed at Kay Point located along the southwest shore of Eld Inlet.

FIGURE 11. Oblique aerial photograph shows a view to the west of the intertidal flat in Mud Bay, southern Eld Inlet. The Black Hills are seen in the distance.

interpretation beyond the fact that a spit has developed at Kay Point.

With minimal sediment supplied from the north (drift cell 29) the majority of sediment deposited at Kay Point probably is delivered from the south (drift cell 30). Sediment from drift cell 30 is deposited at Kay Point as prevailing southerly waves refract in response to a change in the orientation of the coast. This prograding sediment is then modified into a cuspate-like spit by a long-term, balanced interaction between waves that develop across a southerly fetch and waves that develop across a fetch to the north.

Drift Cell 30

Drift cell 30 begins at an area 200 m south of Rocky Point where prevailing southerly waves become large enough to predominant and transport sediment. Net shore-drift to the north and east is indicated by recurring patterns of sediment fining and beach widening to the northeast, increases in beach slope and a decrease in bluff slope to the northeast, and accumulations of sediment against the osuth sides of beach logs and groins, with maximum vertical displacements up to 0.5 m. Outcrops of basaltic bedrock are point sources for identifiable angular basaltic beach fragments. A greater proportion of these basaltic fragments is found north of each outcrop. In addition, several streams are diverted to the north by sediment prograding from the south or, in one case, by a spit 15 m in length. The high tide beach widens along the south side of a delta located 400 m south of Kay Point. Net shore-drift terminates at a spit developed at Kay Point (Fig. 10).

Mud Bay

Mud Bay is an intertidal flat located in the southernmost portion of Eld Inlet (Fig. 11). Sediment transport along the shore of Mud Bay is minimal or non-existent because shallow water and limited fetches limit wave development. Mud Bay is an area of no appreciable net shore-drift (nansd). The eastern shore of southern Eld Inlet south of Shell Point is an area of no appreciable net shore-drift because the Black Hills (seen in Figure 11) curtail winds and wave generation from the southwest.

Shell Point

Shell Point is located along the southeast shore of Eld Inlet. In plan view Shell Point resembles a cuspate spit (Fig. 12a), and one might assume this feature to be the product of two converging drift cells. Careful field observation has shown Shell Point to be a wave-modified remnant of an eroding ridge composed of unconsolidated, poorly sorted glacial sediments, rather than a feature formed by shore drift processes.

Immediately north of Shell Point there is an oyster farm which is continually modifying the foreshore, inhibiting shore drift (Fig. 12b). It has been well documented in this study that net shore-drift north of the oyster farm is to the north (see description of drift cell 31). South of Shell Point there is an area of no appreciable net shore-drift (nansd) as indicated by a lack of geomorphic

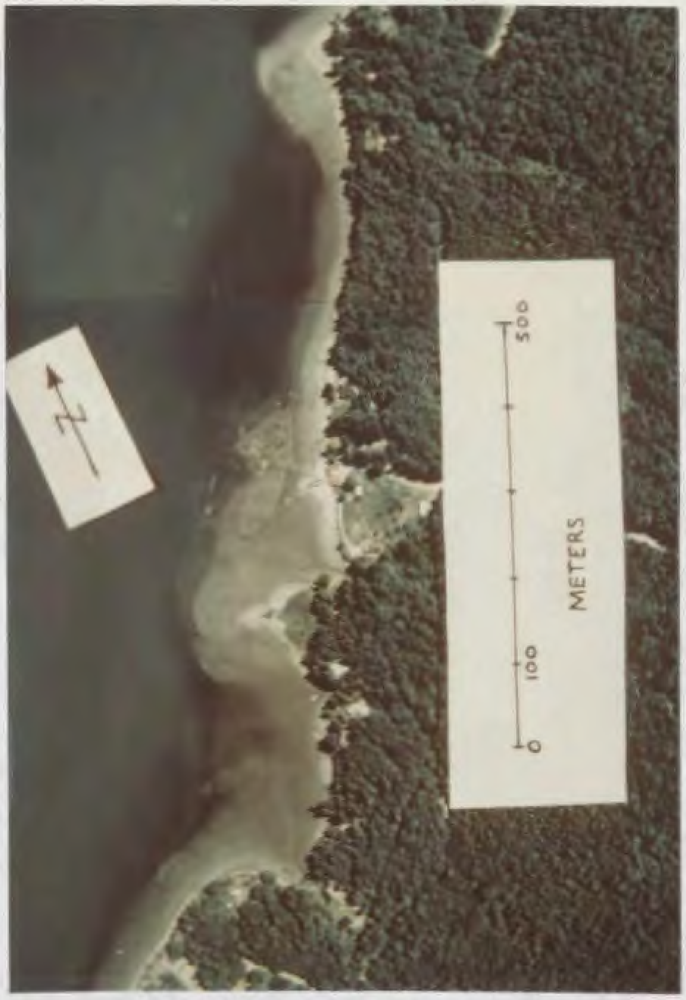

FIGURE 12a. Vertical aerial photograph shows the cuspate-like shape of the coastal feature at Shell Point.

FIGURE 12b. Oblique aerial photograph shows a view to the south-east of Shell Point and vicinity.

indicators and the presence of an intertidal flat composed of silt and clay. Absence of a long-term sediment supply from the north and the south indicates that Shell Point could not be a prograding feature resulting from shore drift processes.

An historical chart (U.S.C.&G.S., 1880) and a topographic quadrangle (U.S.G.S., 1959a) for this area show a ridge south of and parallel with Simmons Creek. Both auger boring and soil pits in the area revealed that the sediment underlying Shell Point is apparently *in situ* and similar to outcrops of *in situ* sediment along the west bank of Simmons Creek. This information suggests that the ridge might once have extended farther into Eld Inlet where Shell Point is located today. Subsequent wave attack and coastal erosion have reduced the overall dimensions of the ridge, planing it off to its present elevation and form.

A lack of fine sediment (silt and clay) in the beach deposits mantling the ridge suggest wave action has redistributed the fine sediment offshore to the intertidal flat adjacent to Shell Point. The remaining beach sediments are lag deposits composed of pebbles, granules, and sand. These lag beach deposits have been reworked into a cuspate-like shape by a balanced interaction between two opposing wave regimes. The presence of a storm berm along the entire south flank and northern distal third of Shell Point suggests southerly waves influence Shell Point to a slightly greater degree than waves which approach from the north. This situation may only have been operating since the development of the oyster farm, the presence of which undoubtedly curtails wave heights approaching from the north.

Drift Cell 31

Drift cell 31 originates at White Point and runs to the northeast to a terminus area in Squaw Cove. Net shore-drift begins when prevailing southerly waves become large enough to transport sediment to the north. The northerly net shore-drift trend is indicated by repeated patterns of sediment fining, increases in beach width and slope, and a reduction in bluff slope morphology to the north, and by accumulations of sediment on the south sides of numerous beach logs, bulkheads, and groins, with maximum vertical offsets of 0.2 m.

Shells from an oyster farm are seen north of the oyster shell dump. A major portion of the shell fragments are deposited along the north side of a small protuberance in the coast, located about 500 m north of White Point. Indicators requiring observation over a distance (A through D) are not expressed north of the coastal protuberance. They are observed again beginning along the north shore of a small cove located about 1 km south of Squaw Point. Approximately 400 m south of Squaw Point is a small lagoon with a 45 m long spit developing to the north across the lagoon entrance. Predominant southwesterly waves refract in a clockwise direction around Squaw Point and create a prograded beach that over-rides a boatramp along the west side of Snyder Cove.

Drift Cell 32

This drift cell originates along the northeast shore of Snyder Cove. Sediment is transported to the northeast by predominant southwesterly waves as evidenced by repeated patterns of sediment fining, beach widening, and bluff slope reduction to the northeast. Accumulations of sediment on the southwest side of bulkheads, with maximum vertical offsets of 0.5 m, spit development to the north across stream mouths, and prograded beach on the southwest side of stream deltas provide additional evidence of drift direction. Approximately 300 m west of Green Cove there is a beach composed of pebbles and sand prograding to the northeast. Sediment which bypasses this area is directed into Green Cove by predominant northerly waves. These waves maintain near-vertical, devegetated bluffs fronted by a stripped wave-cut platform between the prograded beach and the terminus area on the south shore of Green Cove.

Drift Cell 33

This drift cell originates at a divergent zone 200 m north of Green Cove and runs southeast to a terminus area along the north shore of Green Cove. Net shore-drift is directed to the southeast off a wave-cut platform cut across laminated silt by predominant waves that approach from the north and possibly by prevailing southwesterly waves as they refract into Green Cove. A southerly drift direction is evidenced by sediment on the north side of a beach log, and by sediment fining from cobbles to sand, increases in beach width and bluff vegetation, and a decrease in bluff slope to the south. Net shore-drift terminates at a spit developed to the south along the north shore of Green Cove.

Drift Cell 34

Drift Cell 34 originates along a divergent zone located approximately 200 m north of Green Cove. Sediment is transported to the north off a wave-cut platform cut across glacial outwash by prevailing and predominant waves that approach across a fetch to the southwest. Net shore-drift to the north is evidenced by repeated patterns of sediment fining from cobbles to sand, increases in the width and slope of the high tide beach; and changes in bluff morphology from near-vertical, devegetated bluffs composed of gravel and laminated silts at the origin area to rounded, vegetated bluffs at the terminus area. Additional indicators of a northerly drift direction are sediment prograded along the south sides of bulkheads and groins with maximum vertical offsets of 1.0 m; development of spits, beach pads, and oblique bars along the northeastern shore of Eld Inlet (Fig. 13); and the diversion of several streams to the north by spits. Net shore-drift terminates along a spit 250 m in length at Cooper Point (Fig. 14).

Cooper Point

Cooper Point (Fig. 14) is a spit that developed from sediment from the convergence of drift cells 34 and 35. The spit is prograding to the northwest, drift aligned with the wave-maintained bluffs along the northeastern shore south of Cooper Point. Waves approaching Cooper Point from the northeast along an 11 km fetch across Dana Passage together with waves approaching from the southeast along a 10 km fetch across Budd Inlet dominate the

FIGURE 13. Oblique aerial photograph showing spits, beach pads, and oblique bars developed along the northeast shore of Eld Inlet. View is to the northeast.

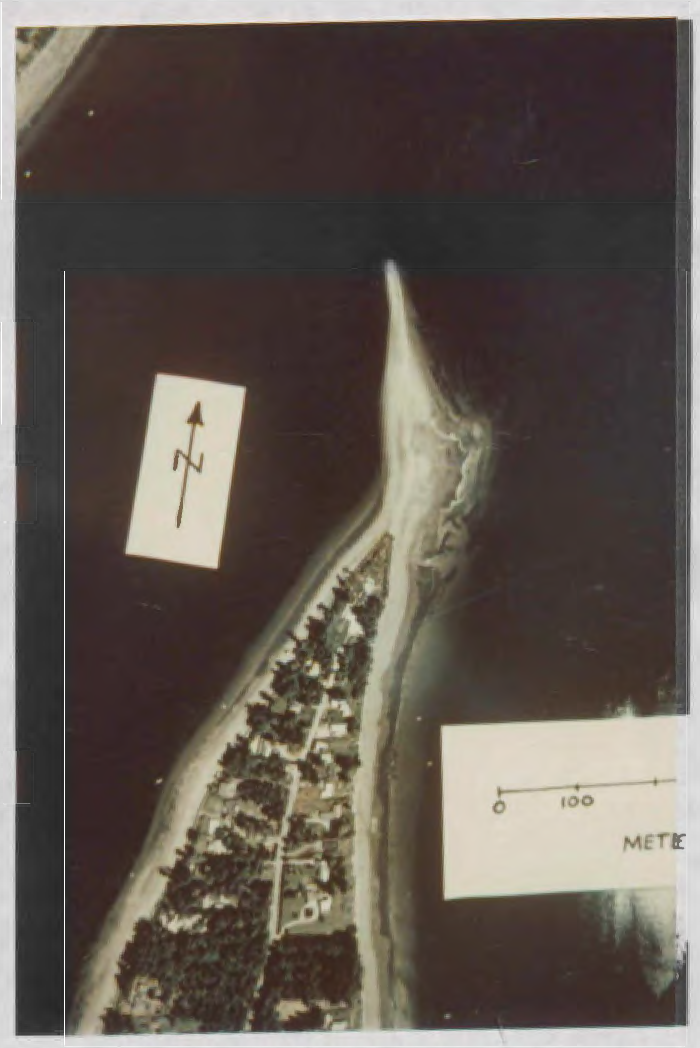

FIGURE 14. Vertical aerial photograph of the spit and wave-cut platform at Cooper Point.

development of, and cause the northwestern orientation of, the spit at Cooper Point. Refraction of the southeasterly waves in a counter-clockwise direciton around a broad wave-cut platform east of the spit may also contribute to the northwesterly orientation of the spit. Influence of the southeast and northeast wave regimes over a prevailing southwesterly wave regime across Eld Inlet is evidenced by bluff retreat along the east shores south of Cooper Point, the presence of a broad wave-cut platform on the east flank of the spit, the northwesterly orientation of spit development, and the existence of longer fetches across eastern waters.

Drift Cell 35

Drift cell 35 originates along an ill-defined zone of divergence located approximately 400 m north of Butler Cove and continues north for 7.7 km to a terminus at Cooper Point. The divergent zone is defended by bulkheads, and as a result bluffs are protected from direct wave attack and no longer supply sediment to the drift cell. Net shore-drift is directed to the north by predominant waves that approach along a fetch to the southeast as evidenced by repeated patterns of sediment fining, beach widening, increasing beach slope and bluff vegetation, and reduced bluff slope exposures to the north. Sediment prograded against the south side of numerous drift obstructions such as groins, bulkheads, bulkhead stairs, and boatramps, with maximum vertical offsets of 0.5 m; a prograded beach on the south side of an intertidal fan in Little Tykle Cove; and a stream diverted to the north by a 45 m long spit called Silver Spit

(U.S.G.S., 1949) provide additional evidence of northerly net shore-drift. As southeasterly waves refract in a counter-clockwise direction into Big Tykle Cove they lose energy and deposit sediment. The resulting prograded beach interrupts sediment in transport. A wave-cut platform fronting eroding headland bluffs is located along the northeastern portion of the cove, aligned perpendicular to and maintained by southeasterly waves. Sediment appears to by-pass Big Tykle Cove and continue north past the erosional zone, thus maintaining the integrity of the drift cell. Net shore-drift terminates along a spit 250 m in length at Cooper Point (Fig. 14).

Drift Cell 36

Sediment is directed to the south into Butler Cove from an ill-defined zone of drift divergence located approximately 400 m north of Butler Cove by predominant waves that approach from the northeast. The divergent zone is defended by bulkheads and, as a result, the bluffs are protected from direct wave attack and no longer supply sediment to the drift cell. The direction of net shore-drift is indicated by a minor accumulation of sediment on the north side of stairs attached to a bulkhead and a decrease in the mean sediment size from pebbles at the divergent zone to granules and sand along a prograded beach on the west shore of Butler Cove.

Drift Cell 37

From a divergent zone east of Butler Cove sediment is directed west and then south into Butler Cove by predominant waves from the northeast. The shore along the divergent zone is wave-straightened, aligned to a northerly predominant wave approach. The low tide terrace at the origin is composed of sand-size material derived from the loose glacial outwash in the adjacent bluffs. Net shore-drift toward Butler Cove is indicated by increases in beach width, slope, and bluff vegetation to the west, coincident with a decrease in bluff slope. In addition, sediment is prograded on the east side of a bulkhead, with 0.5 m of maximum vertical displacement. Sediment transport terminates along a prograded beach on the east shore of Butler Cove.

Drift Cell 38

Drift cell 38 begins at a zone of divergence located about 200 m east of Butler Cove and runs southward to a terminus area about 400 m north of the West Bay Marina. Net shore-drift is directed to the south by predominant waves from the north as indicated by beach widening, bluff slope reduction, a decrease in the mean sediment size from pebbles to granules and sand to the south, and sediment prograded on the north side of drift obstructions such as groins and fallen trees. Sediment transport terminates at a prograded beach composed of sand.

Olympia Harbor

Periodic dredging in southern Budd Inlet and the construction of shore defense structures and harbor facilities have completely altered the coastal zone in Olympia Harbor (Fig. 15). Such

FIGURE 15. An oblique aerial view looking to the south at the Olympia Harbor and vicinity.

modifications eliminate sediment transport along the shore, creating an area of no appreciable net shore-drift.

Drift Cell 39

Drift cell 39 originates along a zone of divergent drift 800 m south of Ellis Cove. The entire divergent zone is defended by bulkheads, and as a result the bluffs are protected from direct wave attack and no longer supply sediment to the drift cell. Sediment is directed south by predominant waves that approach across a northerly fetch as evidenced by prograded material on the north side of groins and by the minor offset of a small stream along the high tide beach. The terminus is an ill-defined area of prograded sand and silt in East Bay of southern Budd Inlet.

Drift Cell 40

Beginning at a zone of divergence approximately 800 m south of Ellis Cove, sediment is transported to the north by predominant southwesterly waves. Net shore-drift to the north is indicated by sediment prograded on the south side of bulkhead steps and on the south side of an intertidal delta. Additional indicators of northerly net shore-drift are beach widening, sediment fining from pebbles to sand, and a 40 m long spit developed north into Ellis Cove.

Drift Cell 41

This drift cell originates along a zone of divergent drift at

Priest Point. From a wave-cut platform covered with cobbles and pebbles, sediment is transported to the east toward Ellis Cove by predominant southwesterly waves as indicated by sediment fining and a reduction of bluff slope to the east, as well as sediment accumulated on the west sides of drift obstructions such as beach logs. Net shore-drift terminates along a prograded beach composed of sand and silt in Ellis Cove.

Drift Cell 42

From a divergent zone located along Priest Point, sediment is transported off a wave-cut platform cut across glacial outwash by prevailing and predominant southwesterly waves. Net shore-drift to the north is evidenced by repeated patterns of sediment fining, beach widening, increases in beach slope, and a decrease in bluff slope to the north. Approximately 2 km north of the divergent zone the high tide beach widens at a stream delta. The stream which enters Budd Inlet here is diverted to the north. Numerous groins, beach logs, and boatramps offset the high tide beach, with a maximum vertical offset of 1.0 m. Sediment transport terminates along a 180 m long spit developed to the north into Gull Harbor (Fig. 16).

Drift Cell 43

This short drift cell originates in a zone of divergent drift about 50 m north of Gull Harbor (Fig. 16). Sediment is transported to the east, off a wave-cut platform cut across glacial sediment, into Gull Harbor by predominant and prevailing southwesterly waves

FIGURE 16. Eastward-looking aerial view of Gull Harbor shows a spit 180 m in length developing north. The spit is the terminus area of drift cell 42. Note bluff morphology north of Gull Harbor. This is the origin area of drift cells 43 and 44.

and possibly by waves which refract in a clockwise direction around the distal end of the spit developed from the south side of Gull Harbor. The direction of net shore-drift is indicated by sediment fining from cobbles to sand; increasing beach slope, beach width, and bluff vegetation; and a decrease in bluff slope. A 22 m long spit developed to the east along the north side of Gull Harbor also supports the drift interpretation.

Drift Cell 44

Drift cell 44 originates along a zone of divergence located about 50 m north of Gull Harbor (Fig. 16). Sediment is transported to the north off a wave-cut platform cut across glacial till by predominant and prevailing waves that approach across a fetch to the southwest. Net shore-drift to the north is evidenced by repeated patterns of sediment fining, increases in the width and slope of the high tide beach, and a reduction in the bluff slope to the north. Accumulation of sediment on the south sides of drift obstructions such as groins, beach logs, and bulkheads, together with spit development and stream diversions to the north, provide additional evidence of a northerly drift direction. Beach pads and oblique bars oriented toward the north at coastal indentations also support the drift direction interpretation. Sediment is directed east into Boston Harbor, around Dofflemyer Point (Fig. 17), by refracting southwesterly waves and by waves that approach across a northerly fetch. This is a good example of a drift cell reversal around a point.

FIGURE 17. Vertical aerial photograph showing Dofflemyer Point and the terminus area of Drift cell 44 along the south shore of Boston Harbor.

Burfoot County Park is located 1.1 km south of Dofflemyer Point along drift cell 44. At the park, a stream is diverted 150 m to the north by a spit after passing through a small embayment. The spit is an accretionary feature with its shore and storm berm drift-aligned to a wave-maintained bluff south of the embayment. The pre-development spit and adjacent foreshore beach were in equilibrium with the base of the bluff face.

A cul de sac connected to a beach access road is built on the spit where it is attached to the bluffs. The cul de sac is defended on the south by a concrete and stone bulkhead and on the west with small boulders and automobile tires. A small prograded beach is developed to the south of the bulkhead. In May, 1982, the boulders and tires were repositioned to the west, farther out onto the foreshore (Fig. 18a).

In March, 1983, after one winter storm season, approximately 1 m of backfill behind the boulders had been removed by wave action (Fig. 18b). The eastward readjustment of the high tide beach and storm berm to an equilibrium profile is illustrated by the eastward shift of driftwood and fill sediment on top of the cul de sac. The modification of the spit at Burfoot County Park is an example of a small engineering project not well suited to local coastal processes.

Drift Cell 45

This drift cell begins along a zone of drift divergence 400 m west of Dover Point. The entire divergent zone is defended by bulkheads, and as a result the bluffs are protected from direct wave

FIGURE 18a. View north showing the westward readjustment of boulders and tires along the spit at Burfoot County Park. Photo taken 5/12/82.

FIGURE 18b. View north showing the erosion of fill emplaced the previous year after one winter storm season. Photo taken 3/30/83.

attack and no longer supply sediment to the drift cell. Sediment is transported to the south off a wave-cut platform cut across glacial till by predominant waves which approach from the north. Net shore-drift to the south is indicated by a fining of sediment from pebbles to sand, an increase in beach slope and width, and accumulation of sediment on the north side of groins. Net shore-drift terminates at a prograded beach along the east shore of Boston Harbor.

Drift Cell 46

Beginning at a divergent zone about 400 m west of Dover Point, net shore-drift is directed to the northeast by prevailing southwesterly waves. From a wave-cut platform cut across glacial till, sediment is directed to the northeast as shown by sediment fining, beach width and slope increases, and accumulations of sediment on the west sides of groins. Waves approaching from the north begin to predominate at Dover Point and direct sediment to the south off a wave-cut platform cut across glacial till into Zangle Cove. This is a good example of a reversal in net shore-drift direction around a headland. A southerly drift direction is evidenced by sediment fining, beach width increases, and a reduction in bluff slope into Zangle Cove. Sediment transport terminates along a spit developed to the south into Zangle Cove.

Drift Cell 47

This drift cell begins along an ill-defined zone of divergence about 400 m northeast of Zangle Cove. Net shore-drift to the southwest is directed by predominant waves from the northeast as indicated by sediment fining and beach widening to the southwest and by accumulations of sediment on the northeast side of drift obstructions. A spit developed to the south along the east side of Zangle Cove is the terminus area.

Drift Cell 48

Drift cell 48 originates along a zone of drift divergence located approximately 400 m northeast of Zangle Cove. Sediment is directed to the northeast off a wave-straightened beach composed of fine sand, silt, and clay by predominant waves that approach across a fetch to the west and southwest. Net shore-drift to the northeast is evidenced by a decrease in sediment size from pebbles to sand, increases in the width and slope of the high tide beach, and changes in the bluff morphology from near-vertical, partially vegetated bluffs at the origin area to rounded, well vegetated bluffs along the terminus area. Additional indicators of a northeasterly drift direction are accumulations of sediment on the south sides of drift obstructions, with maximum vertical offsets of 0.7 m; spit development and stream diversions to the northeast; and sediment prograded on the southwest side of the ebb tide delta at Little Fishtrap (Fig. 19a).

The pre-development coastline of Little Fishtrap (Fig. 19b) had a spit, approximately 110 m in length, developed to the north from the south end of the cove (U.S.C.&G.S., 1876). This suggests the spit-like feature is a relatively recent coastal modification and is

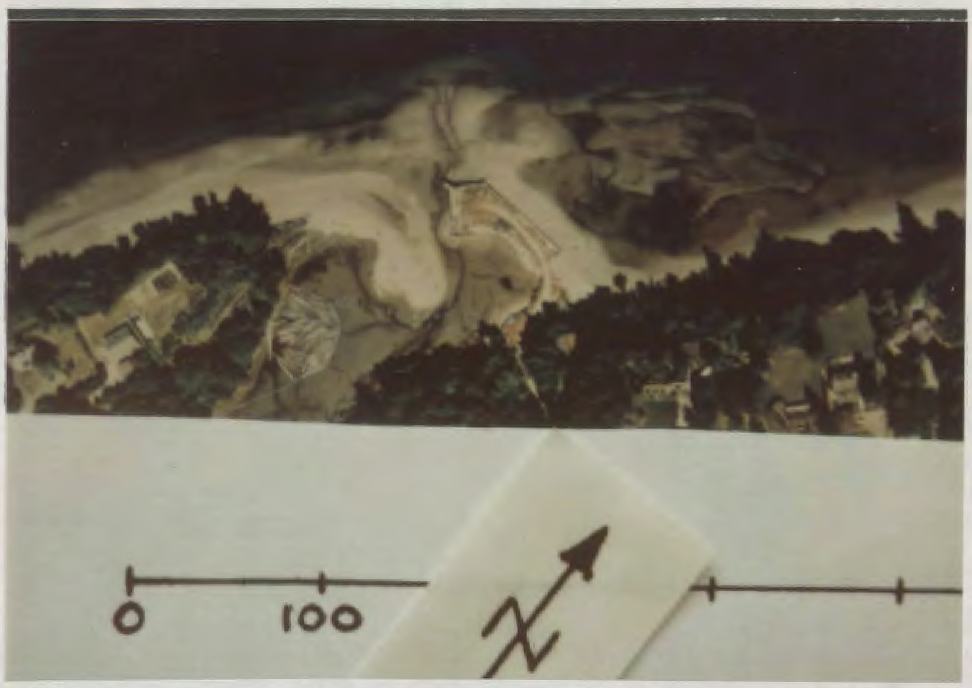

FIGURE 19a. Vertical aerial view of an ebb tide delta and spit developed in Little Fishtrap.

FIGURE 19b. Photo of a historical chart showing the pre-development coastline along Dana Passage (from U.S.C.&G.S., 1876). Little Fishtrap is located in lower left of photo.

not the result of shore drift processes. This historical coastline information reinforces the geomorphic field evidence of northeasterly net shore-drift along Dana Passage.

A complex spit is developed along the south entrance of Big Fishtrap (Fig. 20). Net shore-drift continues past the complex spit and terminates at a 150 m long spit developed to the south along the southwest shore of Big Fishtrap.

Drift Cell 49

This drift cell originates in a zone of divergence about 200 m north of Big Fishtrap (Fig. 20). Bluffs at the origin are near-vertical and devegetated. Net shore-drift is directed to the south off a wave-cut platform cut across glacial outwash by predominant west-southwesterly waves as evidenced by a decrease in sediment size from pebbles to sand, increases in the slope and width of the high tide beach, and a reduction in bluff slope. Net shore-drift terminates along a 60 m long spit developed to the south from the east side of Big Fishtrap.

Drift Cell 50

Beginning in a zone of divergent drift approximately 200 m north of Big Fishtrap, sediment is directed to the northeast off a wave-cut platform cut across glacial outwash by prevailing southwesterly waves as evidenced by sediment accumulated on the south and west sides of groins, bulkheads, and drift logs, with maximum vertical displacement of 0.4 m; sediment fining from pebbles to sand and silt; increases in

FIGURE 20. Vertical aerial photograph showing the complex spit developed along the south entrance of Big Fishtrap.

FIGURE 21. Oblique aerial photograph showing the wave-cut platform at Dickenson Point. View is toward the southwest.

beach slope and width; and a decrease in bluff slope.

Dickenson Point is an eroding headland fronted by a wave-cut platform cut across till that is aligned perpendicular to, and maintained by, waves that approach across a northerly fetch (Fig. 21). Sediment is directed to the southeast as evidenced by sediment fining, increases in beach width, and a reduction in bluff slope. In addition, oblique bars developed on the low tide terrace trend south into a cove southeast of Dickenson Point. Net shore-drift terminates along a 20 m long spit developed to the southeast. Drift cell 50 is an example of a drift cell reversal around a headland.

Drift Cell 51

Sediment is transported to the southwest, off a broad wave-cut platform cut across till, to a terminus on the east side of a cove southeast of Dickenson Point. Directed by predominant northeasterly waves, net shore-drift to the southwest is evidenced by beach widening, sediment fining, bluff slope reduction, and increasing beach slope to the southwest. Several groins have sediment accumulated on the north sides, with maximum vertical offsets of 0.1 m. Sediment transport terminates at a small spit which diverts a small stream to the southwest.

Drift Cell 52

From a zone of divergent drift, sediment is transported to the south off a wave-cut platform cut across till by predominant waves which approach across a principal fetch to the northeast. This drift direction is indicated by repeated patterns of sediment fining, beach widening, and bluff slope reduction to the south, in addition to sediment prograded on the north sides of groins and bulkheads. Net shore-drift terminates at a cuspate spit called Cliff Point (Fig. 22b).

Cliff Point

Cliff Point is a cuspate spit located along the west shore of Henderson Inlet about 1.8 km north of Chapman Bay (Fig. 22a). Cliff Point, like Shell Point (see description of Shell Point), is a wave-modified remnant of an eroding ridge; however, shore drift processes do contribute to the formation of Cliff Point.

The presence of green algae and seaweed on the high tide beach surrounding Cliff Point (Fig. 22b) indicates a low wave energy environment with limited shore drift. If the area had a high wave energy environment, the seaweed would be pulverized by wave action and covered with sediment. Sufficient geomorphic indicators exist to demonstrate net shore-drift from the north (see drift cell 52 description), and net shore-drift from the south (see drift cell 53 description) delivers a limited supply of sediment to Cliff Point.

The topographic map (U.S.G.S., 1959b) of the area shows an east/west-trending ridge due west of, and parallel to, the axis of Cliff Point. This ridge may have extended into Henderson Inlet. Wave attack from the north and south may have reduced the size of the ridge to its present form and elevation, and modified the remaining lag beach sediment into a cuspate spit. The formation and position

FIGURE 22a. Vertical aerial photograph shows the plan view geometry of the cuspate spit at Cliff Point.

FIGURE 22b. Oblique aerial view toward the southwest of the cuspate spit at Cliff Point. Note the algae along the northern flank of Cliff Point.

of the cuspate spit at Cliff Point could therefore be the result of a wave modified ridge that once extended into Henderson Inlet combined with sediment contributed to the spit by shore drift processes.

Drift Cell 53

Drift cell 53 begins along an ill-defined zone of origin approximately 300 m north of a Weyerhauser logging facility and runs northeast to a terminus area at Cliff Point. Sediment is directed to the northeast by southerly waves as evidenced by beach widening, sediment accumulated on the south side of a small groin, with a maximum vertical offset of 0.1 m, and a cuspate spit at Cliff Point (Fig. 22b).

South of drift cell 53 toward Chapman Bay the high tide beach is absent and the low tide terrace is composed of silt and clay. The area is a zone of no appreciable net shore-drift.

Drift Cell 54

This drift cell originates on the north shore of a peninsula which separates Chapman Bay to the north from Woodward Bay to the south. Net shore-drift is directed to the southeast by predominant northerly waves as indicated by beach widening and sediment fining from cobbles to sand. Sediment transport terminates at a prograded beach on the southeast tip of the peninsula.

Drift Cells 55 and 56

These two short drift cells originate from a divergent zone that is wave-aligned to predominant southerly waves. Drift to the east (drift cell 55) off a wave-cut platform cut across silt and clay is indicated by beach widening and a reduction of bluff slope to the east. Drift to the west (drift cell 56) is indicated by beach widening to the west and sediment accumulated against the east side of a rampart leading to a railroad bridge where net shore-drift terminates.

South Bay

South Bay in southern Henderson Inlet is an area of no appreciable net shore-drift. South Bay is an intertidal flat composed of fine sand, silt, and clay. The high tide beach is absent along most of South Bay. The intertidal flat is bordered by coastal marshes, and its gently inclined surface is dissected by small meandering streams (Fig. 23).

Drift Cell 57

Sediment is directed to the south off a narrow high tide beach by predominant waves that approach across a fetch from the north. This drift direction is indicated by sediment accumulated on the north sides of beach logs, with maximum vertical offsets of 0.1 m, beach widening, and a decrease in sediment size from pebbles over a narrow high tide beach to sand and silt at a prograded terminus area.

Drift Cell 58

From a narrow beach covered with pebbles at the origin area, net

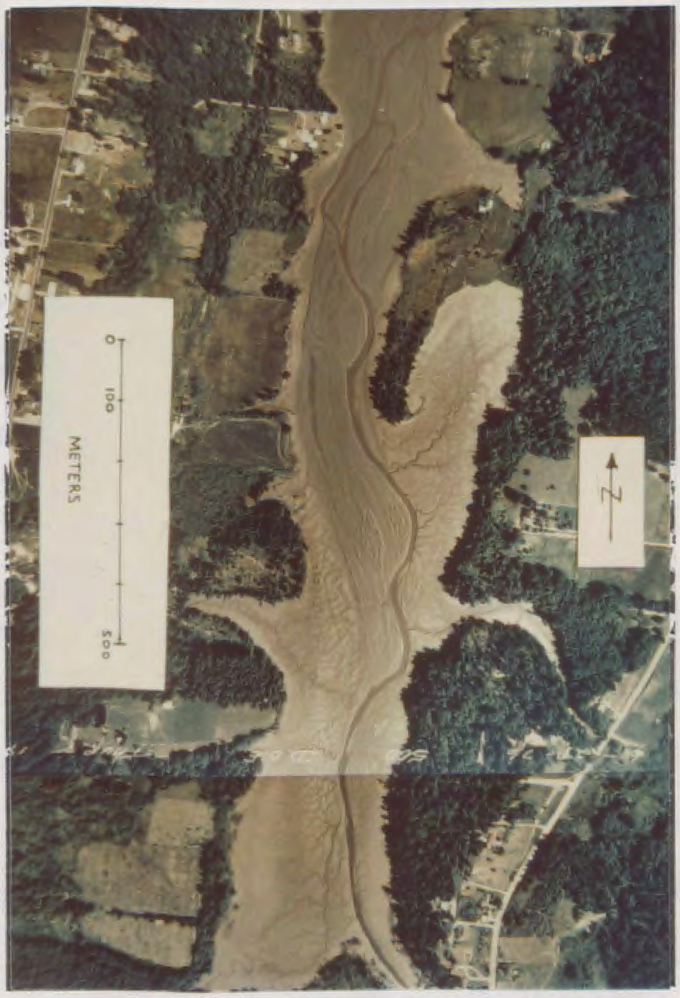

FIGURE 23. Vertical aerial photograph of the intertidal flat in South Bay, southern Henderson Inlet. Note numerous small meandering streams that dissect the intertidal flat.

shore-drift is directed to the north by predominant southwesterly waves. Drift into a small embayment is indicated by a spit developed to the north across a stream mouth. Sediment by-passes the stream mouth and continues into the embayment, as evidenced by another spit of sand and silt developed to the north that also diverts a small stream to the north. Net shore-drift terminates along an intertidal flat at the northernmost portion of the embayment. Some sediment fining is discernible along this drift cell.

Drift Cells 59 and 60

From a common zone of divergent drift sediment is directed to the north off a wave-cut platform cut across glacial sediments by prevailing southwesterly waves. Net shore-drift to the northeast (drift cell 59) is indicated by beach widening and sediment fining from pebbles over the wave-cut platform to fine sand, silt, and clay along a prograding intertidal flat at the terminus. Net shore-drift to the north (drift cell 60) is indicated by sediment accumulated on the south sides of drift obstructions, with maximum vertical offsets of 0.4 m, sediment fining from pebbles to pebbles and sand, and a 15 m long spit (Fig. 24) developed to the north across the mouth of a small cove. Sediment transport ceases at the spit.

Drift Cell 61

Drift cell 61 originates along a broad, ill-defined zone of divergent drift. Sediment is transported to the south by predominant waves that approach across a northerly fetch. This drift direction

FIGURE 24. Vertical aerial photograph showing the drift pattern and spit development at the terminus area of drift cells 60 and 61.

is evidenced by increases in beach slope and width and by the development of a spit 60 m in length to the south across the mouth of a small embayment. The spit diverts a stream to the south. Net shore-drift terminates at the distal end of the spit.

A spit 8 m in length is developed to the north along the landward side of, and attached to, the larger 60 m spit (Fig. 24). Prevailing southwesterly waves predominate on the landward side of the larger spit.

Drift Cell 62

Drift cell 62 originates along a broad, ill-defined zone of divergent net shore-drift. Sediment is transported to the north by predominant waves which approach across a fetch to the southwest. Net shore-drift to the north is indicated by repeated patterns of sediment fining, increases in the width and slope of the high tide beach, and changes in bluff morphology to the north. Approximately 200 m north of the divergent zone, two beach pads have developed, oriented toward the north (Fig. 5b). Numerous beach logs and groins have sediment accumulated on their south sides. Net shore-drift terminates along a sandy prograded beach at Johnson Point.

Drift Cell 63

Predominant southeasterly waves approaching across the Nisqually Reach direct sediment to the north off a wave-cut platform cut across glacial outwash. Net shore-drift to the north is evidenced by a decrease in sediment size from pebbles at the origin to sand at the terminus; increases in the width and slope of the high tide beach; and a change in bluff morphology from steep, devegetated bluffs at the origin to rounded, vegetated bluffs at Johnson Point. Additional indicators of a northerly drift direction are sediment accumulated on the south sides of beach logs, bulkheads and landslide debris, with maximum vertical offsets of 0.3 m, and a 15 m long spit developed to the north partially across the mouth of Poncin Cove. Net shore-drift terminates along a sandy prograded beach at Johnson Point.

Drift Cell 64

Drift Cell 64 originates along a zone of divergent drift located about 300 m north of Baird Cove. Sediment is transported to the south off a wave-cut platform cut across glacial outwash by predominant northerly waves. Net shore-drift to the south is evidenced by sediment fining from pebbles to sand and widening of the high tide beach to the south, and by sediment accumulated on the north side of a bulkhead attached to a small-boat marine facility. The marina is located along the west entrance of Baird Cove. The present terminus of drift cell 64 is at a prograded beach north of the marina. The terminus area before the construction of the marina was along a spit developed to the south on the west side of Baird Cove. The distal end of the relict spit is still visible south of the marina parking lot.

Net shore-drift to the south in drift cell 64 is reversed to the net shore-drift trend along northern Nisqually Reach. Waves from the north predominant and direct sediment to the south, because a headland southeast of Baird Cove creates a wave shadow to waves approaching from the southeast.

Drift Cell 65

Originating along a divergent zone north of Mill Bight, sediment is transported off a wave-cut platform cut across glacial outwash by predominant waves that approach across a fetch to the southeast. Net shore-drift to the north is indicated by repeated patterns of sediment fining, beach widening, and bluff slope reduction to the north. Spit development across cove entrances diverts small streams to the north. Oblique bars and a transverse bar have developed about 700 m north of Mill Bight (Fig. 25), and a bulkhead located about 200 m north of the terminus area has sediment accumulated on its north side.

Net shore-drift is directed to the southwest into Baird Cove by waves that approach across a fetch to the north. Northerly waves predominate because the orientation of Baird Cove shields the east side of the cove from southeasterly waves. Counter-clockwise refraction of southeasterly waves into Baird Cove may also contribute to the reversal of net shore-drift direction in drift cell 65. Net shore-drift terminates along a spit 150 m in length developed to the southwest along the east side of Baird Cove.

Drift Cell 66

Drift cell 66 is a short reversal to the northward trend of net shore-drift in this area. Originating north of Mill Bight, sediment

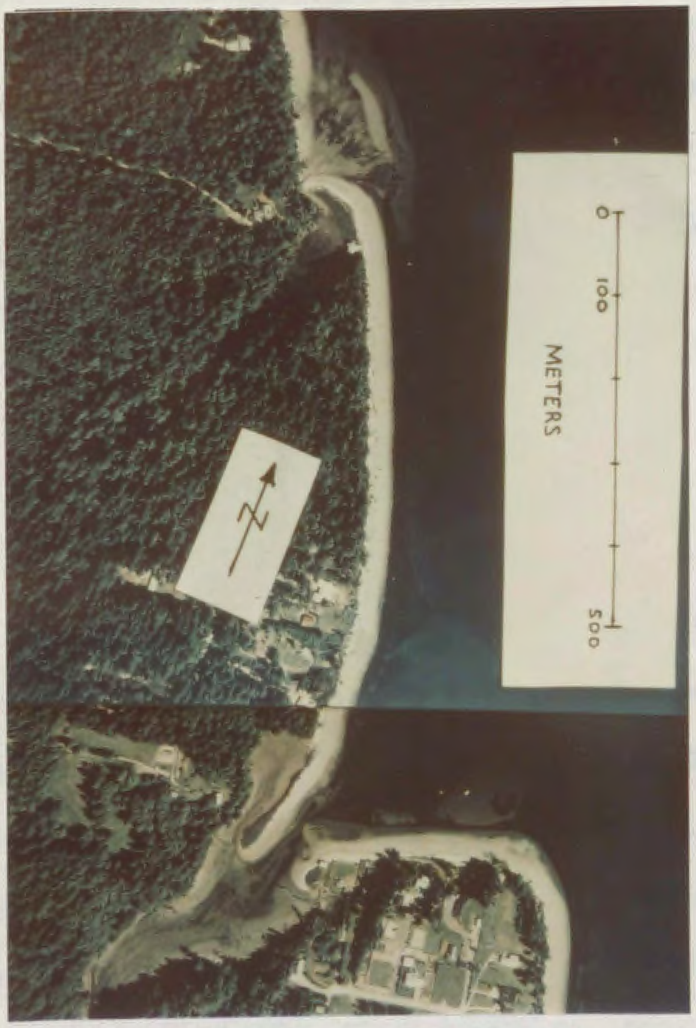

FIGURE 25. Vertical aerial photograph showing spit development in Mill Bight and a transverse bar seaward of a small cove north of Mill Bight.

is directed to the south off a wave-cut platform cut across glacial outwash by predominant waves that approach across a principal fetch to the northeast. Net shore-drift to the south is indicated by a decrease in sediment size from cobbles to sand, an increase in the width of the high tide beach, and a change in bluff morphology from near-vertical, devegetated bluffs along the zone of divergence to rounded, vegetated bluffs at the terminus area. Net shore-drift terminates along a 140 m long spit that has developed to the south along the west side of Mill Bight (Fig. 25).

Drift Cell 67

Drift cell 67 begins in a zone of divergence approximately 1.2 km south of Mill Bight and travels north and west to the terminus area on the north side of Mill Bight. The headland at the divergent zone is actively eroding as evidenced by numerous landslides in the area. Net shore-drift is directed to the north off a wave-cut platform covered with pebbles and cobbles by southerly predominant waves as evidenced by repeated patterns of decreases in the mean sediment size from cobbles to sand, increases in the width of the high tide beach, and a decrease in the slope of the bluffs to the north. North of the divergent zone a 75 m long spit diverts a stream to the north. Accumulation of sediment on the southeast sides of several boatramps and groins, with maximum vertical offsets of 0.3 m, indicate a northerly drift direction.

Net shore-drift is directed west into Mill Bight by waves that approach across a fetch to the north and to the northeast. Northerly waves predominate because the orientation of Mill Bight shields the east side of the cove from southeasterly waves. Counter-clockwise refraction of southeasterly waves into Mill Bight may also contribute to the reversal of net shore-drift direction of this drift cell. Net shore-drift terminates at a 75 m long spit developed to the west from the southeast side of Mill Bight (Fig. 25).

Drift Cell 68

This drift cell originates along a zone of divergent drift about 1.6 km north of Dogfish Bight. Sediment is directed to the south off a wave-cut platform cut across glacial sediments by predominant waves that approach across fetches to the north. Net shore-drift to the south is indicated by a decrease in sediment size from cobbles to sand, an increase in beach width, and a decrease in bluff slope from near-vertical, devegetated bluffs to rounded, vegetated bluffs. Additional evidence of a southerly drift direction is shown by accumulation of sediment on the north side of a groin and a drain culvert, with maximum vertical offsets of 0.8 m. Net shore-drift terminates along a prograded sandy beach in Dogfish Bight.

Drift Cell 69

From a divergent zone at Sand Point, net shore-drift is directed to the north and west by predominant southeasterly waves. Sand Point is actively eroding as evidenced by steep bluffs composed of glacial sediments fronted by a wave-cut platform covered with pebbles and cobbles. A decrease in the sediment size from cobbles to sand, increases in beach width, and a decrease in bluff slope into Dogfish Bight indicate a net shore-drift direction. Net shore-drift terminates along a prograded sand beach in Dogfish Bight.

Drift Cell 70

Beginning at a zone of divergence at Sand Point, net shore-drift is directed south off a wave-cut platform cut across glacial sediments by predominant waves that approach across a fetch to the northeast. This drift direction is evidenced by sediment fining from cobbles and pebbles to sand, increases in beach width, a decrease in bluff slope, and sediment accumulated on the north sides of groins. Net shore-drift terminates along a spit composed of sand developed toward the south from the west side of Big Slough.

Drift Cell 71

This drift cell originates along a zone of divergence north of Butterball Cove. Sediment is directed to the west off a wave-cut platform cut across glacial till by predominant waves that approach across a fetch to the east-southeast. Net shore-drift to the west is indicated by sediment fining from cobbles to sand; increased beach width and slope; and a change in bluff morphology from steep, actively landsliding bluffs at the origin area to rounded, vegetated bluffs in Big Slough. Additional evidence of a westerly net shore-drift direction is shown by the accumulation of sediment on the east sides of drift obstructions, with maximum vertical offsets of 0.2 m. Net shore-drift terminates along a 150 m long spit developed to the west in Big Slough. This spit diverts a small stream to the west.

The spit and lagoon in Big Slough are within the boundaries of Tolmie State Park. The spit in Big Slough has been armored with large pebbles and small cobble-size sediment by the Washington State Park system in order to reduce erosion brought about by increased recreation.

Drift Cell 72

Originating from a zone of divergent drift north of Butterball Cove, sediment is directed to the southeast off a wave-cut platform cut across glacial till by predominant waves that approach across a northerly fetch. Evidence for the transport of sediment to the southeast is shown by repeated patterns of sediment fining, beach width and slope increases, and bluff slope reduction. The bluffs at the origin were near vertical, devegetated, and composed of glacial till and outwash. Net shore-drift to the southeast is evidenced by accumulations of sediment on the northwest sides of beach logs and groins, with maximum vertical offsets of 0.2 m; the development of a 22 m long spit across the mouth of Butterball Cove; and numerous stream diversions across the low tide terrace along DeWolf Bight. Sediment transport terminates along a 60 m long spit developed to the south.

The construction of a small-boat marina about 800 m south of Butterball Cove has modified the outlet of a small stream so that the stream now discharges into Puget Sound on the north side of the cove (Fig. 26a). Prior to the construction of the marina a spit was built

FIGURE 26a. Vertical aerial photograph showing the present coastline configuration created by the development of a small-boat marina. The marina is located within a cove that is located in the lower left corner of this photograph.

FIGURE 26b. Photograph of the coastline configuration along DeWolf Bight in 1891 (from U.S.C. and G.S., 1891). Arrowhead shows position of the cove discussed in text.

to the south from the north side of the cove (U.S.C.&G.S., 1891) possibly diverting the stream to the south (Fig. 26b). This historical information reinforces the geomorphic field evidence of southeasterly net shore-drift along DeWolf Bight.

Drift Cells 73 and 74

Prior to the development of an oyster farm about 900m west of Nisqually Head, drift cells 73 and 74 were one drift cell. At present, drift cell 74 terminates along the east side of the oyster farm, and drift cell 73 originates west of the oyster farm (Fig. 27).

Sediment from eroding near-vertical bluffs and oyster shells from the oyster farm are transported to the west by predominant waves that approach from the east. Net shore-drift along drift cell 73 is evidenced by sediment fining from pebbles and cobbles to pebbles, granules, and sand; beach widening, and a reduction in bluff slope to the west. Transport of sediment and oyster shells terminates along a 45 m long spit developed to the west partially across the mouth of a small cove. The spit diverts a small stream toward the west.

From an ill-defined zone of divergent drift at Nisqually Head, sediment in drift cell 74 is transported to the northwest off a wave-cut platform cut across glacial sediment by northeasterly waves as evidenced by sediment fining from pebbles and cobbles to pebbles, granules, and sand; increase in beach width; and an accumulation of sediment on the southeast side of a bulkhead.

FIGURE 27. Vertical aerial photograph showing an oyster farm developed northwest of Nisqually Head. The oyster farm shell dump inhibits passage of shore drift and creates two separate drift cells.

Drift Cell 75

From an ill-defined zone of divergence located at Nisqually Head, net shore-drift is directed to the south off a wave-cut platform cut across glacial sediment by predominant waves that approach across a northeasterly fetch. Numerous groins with sediment prograded on their north sides, sediment fining from cobbles at the origin to sand along a prograded beach at the terminus, and increases in beach slope and width evidence a southerly net shore-drift direction.

Nisqually Flats

The Nisqually Flats is a very large prograding intertidal delta fed primarily with sediment from the Nisqually River. Numerous coastal marshes have developed along its margins. Shallow water over the delta inhibits wave generation in the area between McAllister Creek and the Nisqually River. As a result, the entire area is a zone of no appreciable net shore-drift.

SUMMARY AND CONCLUSIONS

Thurston County is located in the southern Puget Sound region of western Washington (Fig. 1). The coastline is made up of a complex pattern of peninsulas, channels, and embayments with a total coastal length of 178 kilometers. The area reflects an imprint of the most recent glaciation.

The climate of Thurston County is a mid-latitude west coast marine type, characterized by cool, comparatively dry summers and mild, wet and cloudy winters. Surface wind across the county is controlled primarily by two semi-permanent pressure systems in the northeast Pacific Ocean and secondarily by local topography within the Puget Sound trough. The prevailing (most frequent) and the predominant (greatest influence on wave generation) winds over Thurston County both come from the south to southwesterly direction (Fig. 2).

Wind-generated waves provide the energy to erode the bluffs and transport sediment along the shore. The energy and resulting transport capability of a wave are dependent on three variables: wind velocity; wind duration; and fetch, which is the distance wind can travel over water. Fetch is the dominant limiting variable in the formation of waves along the Thurston County coast, and is of greater geomorphic significance than the prevailing wind direction.

The tides along the Thurston County coast are classified as mixed tides (two high tides and two low tides occur in 24 hours, all of unequal height). The tidal range determines the area over which waves may impart energy. The study area has a macrotidal environment (spring range > 4 m) that causes wave energy expended on the beach by breaking waves to be dispersed over a large horizontal and vertical area in the course of a tidal cycle.

Unconsolidated sediment found in the coastal bluffs in Thurston County is the dominant source of beach sediment, with river sediment only locally dominating beach sediment. Sediment is transported back and forth along the shore by beach drift and longshore drift processes, together called shore drift. Net shore-drift is the net, long-term transport of sediment in one direction in response to a predominant wave approach along the coast.

A drift cell is a compartment along the coast which acts as a closed or nearly closed system with respect to its sediment source area, zone of transport, net shore-drift direction, and area of sediment deposition. The origin of a drift cell is characterized by erosion and experiences a net deficit of sediment on a long-term basis. Throughout the zone of transport, sediment may be lost, interrupted, or introduced into the sediment budget of a drift cell. The terminus of a drift cell is characterized by deposition and experiences a net gain of sediment on a long-term basis.

The direction of net shore-drift and the boundaries of drift cells along the Thurston County coast were documented in a field-oriented investigation based upon geomorphic and sedimentologic indicators. The net shore-drift indicators used in this study were separated into two categories: indicators requiring observation over distance and site-specific indicators. Aerial photographs and historical maps and charts served as supplementary aids to field interpretations of net shore-drift direction. Below is a list of the geomorphic and sedimentologic indicators of net shore-drift used in this study of Thurston County. The first figure to the right of each indicator represents the total number of drift cells in which the indicator was observed (see Table 5). The second figure to the right of each indicator is a percentage that compares the number of drift cells in which the indicator was observed to the total number of drift cells (75) identified along the Thurston County coast.

	Total	Percentage
Indicators Requiring Observation Over Distance		
Gradation in mean sediment size	61	81.3
Beach slope	25	33.3
Beach width	57	76.0
Bluff morphology	46	61.3
Site-Specific Indicators		
Spit development	48	64.0
Foreshore offsets at drift obstructions	54	72.0
Diversion of stream mouth outlets	27	36.0
Plan view of deltas or intertidal fans	6	8.0
Identifiable sediment	4	5.3
Oblique bars	6	8.0
Beach pads	6	8.0

Seventy-five drift cells have been identified along 92 of the 178 kilometers of coast. Therefore, approximately 52 percent of the Thurston County coast experiences active net shore-drift. Drift cells vary in length from 7.7 kilometers (drift cell 35) to 50 meters (drift cells 17 and 55). Areas with no appreciable net shore-drift (nansd) comprise about 42 percent (74 kilometers) of the coast. Most areas of nansd are along intertidal flats that occupy the southern portion of every major inlet in the county and smaller coves adjoining the larger inlets. The remainder of the coast consists of zones of divergent net shore-drift.

Wind-generated waves that approach from the southwest are both prevailing (most frequent) and predominant (greatest influence on shore drift) along most of the Thurston County coast. The predominance of the southwesterly waves is largely dependent upon the abundance of open water channels and fetches oriented sub-parallel to the most frequent and greatest velocity southwesterly wind direction. The result is that 76 percent of all net shore-drift along the Thurston County coast has a northward vector component and 24 percent has a southward vector component.

Possibly one of the most interesting drift cell patterns in the county occurs around Steamboat Island where four separate drift cells converge. Drift cell reversals along the Thurston County coast occur most often at coves. They are usually the product of two processes acting alone or in combination: (1) waves refracting into a cove, and (2) the orientation of the cove allowing another wave regime to predominant. Several cuspate or cuspate-like coastal features are developed along the Thurston County coast. Although they are all similar in plan view, each is distinct in terms of its geomorphology.

Human modification of the coast interrupts the process of shore drift and alters net shore-drift patterns. Modification along the Thurston County coast has, in a few areas, eliminated shore drift altogether, creating man-made areas of no appreciable net shore-drift. In another area, a former drift cell has been divided into two separate, shorter drift cells.

Shore defense structures such as bulkheads and groins are reducing or eliminating wave erosion of the coastal bluffs. At present, approximately 40 percent of the Thurston County coast has been defended by these methods (Washington State D.O.E., 1980). The continued elimination of bluff material as a source of beach sediment may eventually cause the beaches along the Thurston County coast to become narrower. Narrow beaches would provide less protection against wave attack. Thus, paradoxically, the shore defense structures originally designed to eliminate coastal erosion may eventually cause an increase in bluff retreat and coastal erosion along the Thurston County coast.

REFERENCES CITED

Bascom, W. M., 1951, The relationship between sand size and beach-face slope: American Geophysical Union Transactions, v. 32, p. 866-874.

Bauer, W., 1974, The drift sectors of Whatcom County marine shores; their shoreforms and geohydraulic status: Bellingham, Whatcom County Planning Commission, 74 p.

Bird, E. C. F., 1969, Coasts: Cambridge, Mass., M.I.T. Press, 246 p.

Blankenship, D. G., 1983, Net shore-drift of Mason County, Washington: Bellingham, Western Washington University, unpublished M.S. thesis, 172p., 6 maps.

Bowen, A. J., 1969, Rip currents, 1: theoretical investigations: Journal of Geophysical Research, v. 74, p. 5467-5478.

__________ and Inman, D. L., 1969, Rip currents, 2: laboratory and field observations: Journal of Geophysical Research, v. 74, p. 5479-5490.

Brundage, W. L., Jr., 1960, Recent sediments in the Nisqually River delta, Puget Sound region, Washington: Seattle, University of Washington, unpublished M.S. thesis, 178 p.

Crandell, D. R., Mullineaux, D. R., and Waldron, H. H., 1958, Pleistocene sequence in southeast part of the Puget Sound lowland, Washington: American Journal of Science, v. 256, p. 384-397.

Chrzastowski, M. J., 1982, Net shore-drift of King County, Washington: Bellingham, Western Washington University, unpublished M.S. thesis, 153 p., 1 map.

Davies, J. L., 1964, A morphogenic approach to world shorelines: Zeitschrift fur Geomorphologie, v. 8, p. 127-142.

__________ 1974, The coastal sediment compartment: Australian Geographical Studies, v. 12, p. 139-151.

__________ 1980, Geographical Variations in Coastal Development: New York, Hafner Publishing Company, 212 p.

Easterbrook, D. J., 1976, Quaternary geology of the Pacific Northwest, in W. C. Mahaney, ed., Quaternary Stratigraphy of North America: Stroudsburg, Penn., Dowden, Hutchinson and Ross Inc., p. 441-462.

__________, Briggs, N. D., Westgate, J. A., and Gorton, M P., 1981, Age of the Salmon Springs glaciation in Washington: Geology, v. 9, p. 87-93.

Ecker, R. M., Mayer, D. W., and Brown, S. M., 1979, Littoral processes--Sequim Bay and adjacent Strait of Juan de Fuca shoreline: Richland, Wash., Battelle Northwest Laboratories, 114 p.

Emery, K. O., and Kuhn, G. G., 1982, Sea cliffs, their processes, profiles, and classification: Geological Society of America Bulletin, v. 93, p. 644-654.

Entsminger, L. D., 1982, Beach pads, in M. L. Schwartz, ed., Encyclopedia of Beaches and Coastal Environments: Stroudsburg, Penn., Hutchinson Ross Publishing Co., p. 150.

Evans, O. F., 1942, The relationship between the size of wave-formed ripple marks, depth of water, and the size of generating waves: Journal of Sedimentary Petrology, v. 12, p. 31-35.

Globerman, B. R., 1980, Geology, petrology and paleomagnetism of Eocene basalts from the Black Hills, Washington Coast Range: Bellingham, Western Washington University, unpublished M.S. thesis, 373 p.

Guilcher, A., 1974, Studies in coastal geomorphology contributing to coastal engineering: Proceedings 14th Conference of Coastal Engineering, Copenhagen, Denmark, v. 1, p. 1-20.

Harp, B. D., 1983, Net shore-drift of Pierce County, Washington: Bellingham, Western Washington University, unpublished M.S. thesis, in progress.

Harris, R. G., 1954, The surface winds over Puget Sound and the Strait of Juan de Fuca and their oceanographic effects: Seattle, University of Washington, unpublished M.S. thesis, 101 p.

Hunter, R. E., Sallenger, A. H., and Dupre, W. R., 1979, Methods and descriptions of maps showing direction of longshore sediment transport along the Alaskan Bering seacoasts: U. S. Geological Survey, Miscellaneous Field Studies, Map MF-1049, 7 p., 12 sheets.

Ingle, J. C., Jr., 1966, The Movement of Beach Sand: Developments in Sedimentology 5: Amsterdam, Elsevier Publishing Co., 221 p.

Jacobsen, E. E., 1980, Net shore-drift of Whatcom County, Washington: Bellingham, Western Washington University, unpublished M.S. thesis, 76 p., 1 map.

Jacobsen, E. E., and Schwartz, M. L., 1981, The use of geomorphic indicators to determine the direction of net shore-drift: Shore and Beach, v. 49, p. 38-43.

Johnson, D. W., 1919, Shore Processes and Shoreline Development: New York, Hafner Publishing Co., 584 p.

Keuler, R. F., 1979, Coastal zone processes and geomorphology of Skagit County, Washington: Bellingham, Western Washington University, unpublished M.S. thesis, 127 p., 8 maps.

__________ 1980, Net longshore sediment transport, Port Angeles to Sequim Bay: Olympia, Washington Department of Ecology, unpublished report, 10 pl., 1 map.

__________ 1983, Coastal erosion, sediment supply and longshore transport, Port Townsend 1:100,000 quadrangle, Puget Sound region, Washington: U. S. Geological Survey, Miscellaneous Investigations, map I-1198, in press.

King, C. A. M., 1972, Beaches and Coasts: New York, St. Martin's Press, Inc., 570 p.

Komar, P. D., and Inman, D. L., 1970, Longshore sand transport on beaches: Journal of Geophysical Research, v. 75, p. 5914-5927.

Komar, P. D., 1976, Beach Processes and Sedimentation: Englewood Cliffs, N.J., Prentice-Hall, Inc., 429 p.

Kuenen, Ph. H., 1964, Experimental abrasion, 6, surf action: Sedimentology, v. 3, p. 29-43.

Longuet-Higgins, M. S., 1970a, Longshore currents generated by obliquely incident sea waves, 1: Journal of Geophysical Research, v. 75, p. 6778-6789.

_________ 1970b, Longshore currents generated by obliquely incident sea waves, 2: Journal of Geophysical Research, v. 75, p. 6790-6801.

Meistrell, F. J., 1972, The spit platform concept: Laboratory observation of spit development, in M. L. Schwartz, ed., Spits and Bars: Stroudsburg, Penn., Dowden, Hutchinson and Ross, Inc., p. 224-284.

National Ocean Survey, 1981, Nautical Chart 18445, Possession Sound to Olylmpia including Hood Canal, Washington: Washington, D. C., National Ocean Survey, 17th ed., scale, 1:80,000.

_________ 1982, Tide tables west coast of North and South America (including the Hawaiian Islands): Washington, D. C., U. S. Government Printing Office, 231 p.

National Oceanic and Atmospheric Administration, 1980a, Climates of the States: Detroit, Mich.,Gale Research Company, 2 v., 1175 p.

_________ 1980b, Local climatological data, Olympia, Washington: Ashville, N.C., National Climatic Center, 4 p.

Noble, J. B., and Wallace, E. F., 1966, Geology and groundwater resources of Thurston County, Washington: Washington Division of Water Resources, Water Supply Bulletin 10, v. 2, 141 p.

Pacific Northwest River Basin Commission, Meteorology Committee, 1968, Climatological Handbook, Columbia Basin States, Hourly Data, v. 3, Part A: Vancouver, Wash., Pacific Northwest River Basin Commission, 341 p., plus appendix.

Pettijohn, F. J., and Ridge, J. D., 1932, A textural variation series of beach sands from Cedar Point, Ohio: Journal of Sedimentary Petrology, v. 2, p. 76-88.

Phillips, E. L., 1964, Washington climate for these counties: Clark, Cowlitz, Lewis, Skamania, Thurston: Pullman, Washington State University, Agricultural Extension Service, Publication E. M. 2462, 42 p.

Rosen, P., 1977, Increasing shoreline erosion rates with decreasing tidal range in the Virginia Chesapeake Bay: Chesapeake Science, v. 18, p. 383-386.

Saville, T., Jr., 1954, The effect of fetch width on wave generation: Washington, D. C., Beach Erosion Board, U. S. Army Corps of Engineers Technical Memorandum, no. 70, 9 p.

Schou, A., 1945, Det marine forland: Folia Geographica Danica, v. 4, 236 p. (p. 213-224, English summary).

__________ 1952, Direction determining influence of the wind on shoreline simplification and coastal dunes: Proceedings 17th Conference of the International Geographical Union, Washington, D. C., p. 370-373.

Schwartz, M. L., 1972, Introduction, in M. L. Schwartz, ed., Spits and Bars: Stroudsburg, Penn., Dowden, Hutchinson and Ross, Inc., p. 1-2.

__________ 1982, Beach processes, in M. L. Schwartz, ed., Encyclopedia of Beaches and Coastal Environments: Stroudsburg, Penn., Hutchinson Ross Publishing Co., p. 153-156.

Self, R. P., 1977, Longshore variation in beach sands, Nautla area, Veracruz, Mexico: Journal of Sedimentary Petrology, v. 47, p. 1437-1443.

Shepard, F. P., 1963, Submarine Geology: New York, Harper and Row, Inc., 517 p.

Taggart, B., 1983, Net shore-drift of Kitsap County, Washington: Bellingham, Western Washington University, unpublished M.S. thesis, in progress.

Tanner, W. F., 1975, Beach processes, Berrian County, Michigan: Journal of Great Lakes Research, v. 1, p. 171-178.

U. S. Army Corps of Engineers, 1977, Shore Protection Manual: Washington, D. C., U. S. Government Printing Office, 3 vols.

U. S. Coast and Geodetic Survey, 1876, Revised to 1905, 6462, Olympia Harbor, Puget Sound, Washington: scale 1:20,000.

__________ 1880, Topographic survey T-1675, Eld Inlet, Puget Sound, Washington Territory: scale 1:10,000.

__________ 1891, Revised to 1905, 6460, Puget Sound, Seattle to Olympia, Washington: scale 1:80,000.

U. S. Geological Survey, 1949, Olympia quadrangle, Washington: Topographic map, scale 1:62,500.

__________ 1959a, Photorevised 1973, Tumwater quadrangle, Washington: Topographic map, scale 1:24,000.

__________ 1959b, Photorevised 1968, Longbranch quadrangle, Washington: Topographic map, scale 1:24,000.

__________ 1960, Surface water supply for the United States, 1959, Part 12, Pacific slopes basin in Washington and upper Columbia River basin: U. S. Geological Survey Water-Supply Paper 1636, 402 p.

U. S. Navy Hydrographic Office, 1951, Techniques for forecasting wind waves and swell: Washington, D. C., U. S. Navy Hydrographic Office, no. 604, 37 p., 10 pl.

University of Washington, 1954, Puget Sound and approaches, a literature study: Seattle, University of Washington, Department of Oceanography, v. 3, 175 p.

Washington State Department of Ecology, 1980, Coastal Zone Atlas of Washington, Thurston County: Olympia, Department of Ecology, v. 8, 8 p., 18 pl.

Washington State Department of Natural Resources, 1974, Washington Marine Atlas, v. 2, south inland waters: Olympia, Department of Natural Resources, 4 p., 21 pl.

Zenkovitch, V. P., 1959, On the genesis of cuspate spits along lagoon shores: Journal of Geology, v. 67, p. 269-277.

__________ 1967, Processes of Coastal Development: New York, Interscience Publishers, 738 p.