Coastal Zone Processes and Geomorphology of Skagit County, Washington

Ralph Francis Keuler
Western Washington University

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COASTAL ZONE PROCESSES
AND GEOMORPHOLOGY
OF
SKAGIT 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
Ralph F. Keuler
June 1979
MASTER'S THESIS

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Name: Ralph Reuler

Signature: ____________________________

Date: 19 May 2018
COASTAL ZONE PROCESSES
AND GEOMORPHOLOGY
OF
SKAGIT COUNTY, WASHINGTON

by
Ralph F. Keuler

Accepted in Partial Completion
of the Requirements for the Degree
Master of Science

Dean of Graduate School

Advisory Committee

Chairperson
ABSTRACT

Geomorphic mapping of 130 km of marine shoreline in Skagit County reveals repeated morphologic and sedimentologic trends along many segments of the coast. The shoreline segments within which the trends are repeated are the littoral drift cells or shore drift sectors that act as nearly closed systems with respect to longshore sediment transport. The longshore trends include changes in mean grain size of beaches, sediment sorting, foreshore morphology, backshore width and morphology, bluff morphology, and mean beach slope. The last parameter, slope, can be used as an index or surrogate measure of simultaneous changes in the other longshore trends.

The longshore trends, besides being a convenient method to describe the coastal geomorphology, are found to be equally useful as tools to map directions of littoral sediment transport on a net, long-term basis, and, to help define the boundaries of drift sectors. Transport direction and littoral cell boundaries are included on the accompanying maps.

Wave erosion of shore bluffs, as opposed to fluvial delivery, is the primary source of beach sediment. Mean minimum long term erosion rates are 5 cm/yr for unconsolidated bluffs, 0.7 cm/yr for jointed rocks fronted by wave cut platforms, and less than 0.1 cm/year for massive, resistant rock types. Shoreline segments with large, hazardous mass movements are relatively few, but within those segments large slope failures appear to provide a high percentage of the sediment contribution to beaches.
ACKNOWLEDGEMENTS

I would like to thank my committee, Drs. R. S. Babcock, A. K. Lehre, M. L. Schwartz, and T. A. Terich, for their helpful discussions during the course of this study and their valuable suggestions for improving the manuscript. Special recognition of Dr. Schwartz is in order; as committee chairman, more of his time and expertise was sought and always generously given. Robert Schofield, director of the Skagit County Planning Department, helped arrange for partial financial support; that funding is gratefully acknowledged. Discussions with Dr. D. R. Pevear about carbonate cements were most helpful. The support and help of my wife, Margaret, was freely given when needed most, in the final stages of manuscript preparation and revision. Finally, the U.S. Geological Survey, Puget Sound Earth Science Applications Project, particularly Dr. Fred Pessl, deserves special thanks. The Project and Dr. Pessl not only expressed an interest in the study, but provided a job during the writing of the manuscript which allowed confirmation and clarification of many of the ideas expressed herein.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>i</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>ii</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>ix</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>METHODS</td>
<td>2</td>
</tr>
<tr>
<td>PHYSICAL SETTING</td>
<td>4</td>
</tr>
<tr>
<td>OCEANOGRAPHIC ENVIRONMENT</td>
<td>6</td>
</tr>
<tr>
<td>Tidal Characteristics</td>
<td>6</td>
</tr>
<tr>
<td>Winds</td>
<td>7</td>
</tr>
<tr>
<td>Wave Regime</td>
<td>11</td>
</tr>
<tr>
<td>GENERAL FORESHORE MORPHOLOGY</td>
<td>13</td>
</tr>
<tr>
<td>Characteristics of the High-Tide Beach</td>
<td>17</td>
</tr>
<tr>
<td>Characteristics of the Low-Tide Terrace</td>
<td>18</td>
</tr>
<tr>
<td>Characteristics of the Foreshore in Rocky Shoreline Sectors</td>
<td>21</td>
</tr>
<tr>
<td>BEACH SEDIMENTS</td>
<td>23</td>
</tr>
<tr>
<td>Sediment Supply and Longshore Transport</td>
<td>23</td>
</tr>
<tr>
<td>Sediment Transport Competence</td>
<td>28</td>
</tr>
<tr>
<td>Pocket Beaches</td>
<td>28</td>
</tr>
<tr>
<td>Sediment Size and Sorting</td>
<td>29</td>
</tr>
<tr>
<td>Cemented Beach Conglomerate</td>
<td>31</td>
</tr>
<tr>
<td>Occurrence and Description</td>
<td>31</td>
</tr>
<tr>
<td>Origin</td>
<td>32</td>
</tr>
<tr>
<td>Age of Conglomerate Deposition</td>
<td>35</td>
</tr>
</tbody>
</table>
SHORELINE EROSION ................................................................. 38

Methods Used for Determining Modern Erosion Rates ................. 38

Direct Measurement ................................................................. 38

Indirect Methods ................................................................. 40

Late Holocene Shoreline Retreat ................................................ 45

Factors Controlling Shoreline Erosion ........................................... 52

Bluff Material Type ............................................................... 52

Wave Energy ........................................................................... 54

Beach Materials ....................................................................... 55

Erosion Rates ........................................................................... 55

Erosion Rate Data ................................................................. 55

Analysis of Rates ..................................................................... 58

Comparison of Local and Worldwide Erosion Rates ..................... 61

Timing of Erosional Events ....................................................... 62

DETAILED GEOMORPHOLOGY AND SEDIMENTOLOGY OF DRIFT SECTORS ............................................. 63

Longshore Decrease in Mean Particle Size .................................... 65

Longshore Changes in Sediment Sorting ...................................... 71

Occurrence of Abrasion Platform Visible Beneath Beaches .......... 73

Longshore Changes in the Onshore-Offshore Size Distribution of Sediment ....................................................... 74

Longshore Increase in Distinctness of the High-Tide Beach/
Low-Tide Terrace Break in Slope .............................................. 79

Longshore Development of Beach Ridges and Berms, and
Widening of the Backshore ........................................................ 81

Longshore Changes in Unconsolidated Bluff Morphology ............... 82

Longshore Increase in Mean Beach Slope .................................... 88
LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Location map of the study area.</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>Wind rose for Anacortes.</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Typical high-tide beach and low-tide terrace exposed at low tide.</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>High-tide beach and low-tide terrace at north-central Samish Island.</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>High-tide beach and muddy tidal flat at Similk Bay.</td>
<td>19</td>
</tr>
<tr>
<td>6</td>
<td>Ridge-and-runnel topography on northeastern Sinclair Island.</td>
<td>20</td>
</tr>
<tr>
<td>7</td>
<td>Typical wave-cut platform.</td>
<td>22</td>
</tr>
<tr>
<td>8</td>
<td>Cumulative sediment size distribution curves for three northern Puget Sound</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>prograded beaches.</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Beach conglomerate, western Cypress Island.</td>
<td>33</td>
</tr>
<tr>
<td>10</td>
<td>Pelecypod shell in beach conglomerate.</td>
<td>33</td>
</tr>
<tr>
<td>11</td>
<td>Interior of cave, western Cypress Island.</td>
<td>36</td>
</tr>
<tr>
<td>12</td>
<td>Metal plate in beach conglomerate.</td>
<td>37</td>
</tr>
<tr>
<td>13</td>
<td>Iron spike in beach conglomerate.</td>
<td>37</td>
</tr>
<tr>
<td>14</td>
<td>Typical coastal triangulation station.</td>
<td>39</td>
</tr>
<tr>
<td>15</td>
<td>Exposed tree root mass on bluff.</td>
<td>41</td>
</tr>
<tr>
<td>16</td>
<td>Exposed tree root mass on bluff.</td>
<td>42</td>
</tr>
<tr>
<td>17</td>
<td>Boathouse on eroding bank, Guemes Island.</td>
<td>44</td>
</tr>
<tr>
<td>18</td>
<td>Seastack on northwestern Cypress Island.</td>
<td>46</td>
</tr>
<tr>
<td>19</td>
<td>Seastack on northwestern Fidalgo Island.</td>
<td>47</td>
</tr>
<tr>
<td>20</td>
<td>Wave-cut platform and cave on western Cypress Island.</td>
<td>48</td>
</tr>
<tr>
<td>21</td>
<td>Abrasion platform with rampart.</td>
<td>48</td>
</tr>
<tr>
<td>Page</td>
<td>Image Description</td>
<td>Page</td>
</tr>
<tr>
<td>------</td>
<td>-------------------------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>22</td>
<td>Composite eustatic curve.</td>
<td>49</td>
</tr>
<tr>
<td>23</td>
<td>Composite eustatic curve with radiocarbon dates.</td>
<td>51</td>
</tr>
<tr>
<td>24</td>
<td>Lag deposit on Sinclair Island.</td>
<td>53</td>
</tr>
<tr>
<td>25</td>
<td>Bargraph of erosion rates subdivided by bluff material type.</td>
<td>59</td>
</tr>
<tr>
<td>26</td>
<td>Beach sediment, western part of the Shannon Point drift sector.</td>
<td>67</td>
</tr>
<tr>
<td>27</td>
<td>Beach sediment, central part of the Shannon Point drift sector.</td>
<td>68</td>
</tr>
<tr>
<td>28</td>
<td>Beach sediment, central part of the Shannon Point drift sector.</td>
<td>69</td>
</tr>
<tr>
<td>29</td>
<td>Beach sediment at the terminus of the Shannon Point drift sector.</td>
<td>70</td>
</tr>
<tr>
<td>30</td>
<td>Cumulative sediment size distribution curves from three sites on western Cypress Island.</td>
<td>72</td>
</tr>
<tr>
<td>31</td>
<td>Wave-cut platform eroded into till, southern Cypress Island.</td>
<td>75</td>
</tr>
<tr>
<td>32</td>
<td>Wave-cut platform thinly mantled with sand on southern Guemes Island.</td>
<td>76</td>
</tr>
<tr>
<td>33</td>
<td>Photograph showing increasing sediment size down the face of a typical high-tide beach.</td>
<td>77</td>
</tr>
<tr>
<td>34</td>
<td>Upper half of the high-tide beach, southwestern Guemes Island.</td>
<td>77</td>
</tr>
<tr>
<td>35</td>
<td>High-tide beach, southwestern Guemes Island.</td>
<td>78</td>
</tr>
<tr>
<td>36</td>
<td>High-tide beach, south-central Guemes Island.</td>
<td>78</td>
</tr>
<tr>
<td>37</td>
<td>Photograph showing backshore width, southeastern Guemes Island.</td>
<td>83</td>
</tr>
<tr>
<td>38</td>
<td>Backshore and bluff face, southeastern Guemes Island.</td>
<td>83</td>
</tr>
<tr>
<td>39</td>
<td>Backshore and bluff face, south-central Guemes Island.</td>
<td>84</td>
</tr>
<tr>
<td>40</td>
<td>Undercut, vertical bluffs, south Cypress Island drift sector.</td>
<td>86</td>
</tr>
</tbody>
</table>
Photograph showing bluff morphology along the length of the south Cypress Island drift sector.

Small rotational slump in glaciomarine drift on western Cypress Island.

Scalloped bluff morphology developed in outwash materials.

Mass movement developed in glaciofluvial gravels, western Guemes Island.

Diagrammatic map view of amphitheater-type landslide, western Fidalgo Island.

Diagrammatic cross section of amphitheater-type landslide, western Fidalgo Island.

Sketch map of major landslide zone, western Fidalgo Island.

Mouth of an amphitheater-type landslide, western Fidalgo Island.
TABLES

Table | Description | Page
--- | --- | ---
1 | Tidal means and extremes for Seattle and Port Townsend. | 8
2 | Wind velocity and duration at Anacortes. | 9
3 | Computed significant wave heights for typical wind fetch, velocity, and duration in Skagit County waters. | 12
4 | Unconsolidated bluff materials commonly exposed in Skagit County shore bluffs. | 25
5 | Analysis of particles sizes comprising Everson Glaciomarine Drift at Bayview Ridge, Skagit County (from Siegfried, 1978). | 27
6 | Geographic and numeric index to erosion measurement sites. | 56
7 | Comparative summary of erosion rates showing means and standard deviation. | 60
8 | Longshore geomorphic and sedimentologic changes within Skagit County drift sectors. | 64
9 | Comparative summary of beach slope measurements and longshore geomorphic trends within Skagit County drift sectors. | 89
INTRODUCTION

Prior to this study no comprehensive investigation or mapping had been done concerning the geomorphology and physical processes of the Skagit County coastal zone. The only previous investigation, by Schwartz (1971) assessed shoreline erosion at a specific site, Shannon Point, on northwestern Fidalgo Island. Similarly, few systematic assessments of the coastal zone had been conducted anywhere in the Puget Lowland. Since this study began, the Washington Department of Ecology (1978) has begun publishing a Coastal Zone Atlas for each of the inland water counties of western Washington, including Skagit County. That atlas and this study have only one major element in common for Skagit County, a map of littoral sediment transport directions. The Coastal Zone Atlas is a reconnaissance study with maps designed to provide information for county governments; this study focuses in detail on the processes and characteristics of the shorelines. This study contains geomorphic maps which include: bluff height classes, bluff material classes, prograded beaches, occurrence of tidal flats and wave-cut platforms, and major mass movement zones (all maps are located in the Appendix).

The main goals of this study are to describe the geomorphology and sedimentology of the shoreline and to investigate the processes that produce those sediment patterns and morphology. Further goals are to identify areas of bluff instability, map the directions of littoral sediment transport, and identify prograded beaches that are the result of the shore drift.

Initially, the aim was to deal primarily with slope instability
and shoreline geomorphic mapping. It soon became evident that: (1) zones of large, hazardous mass movements were fewer than originally suspected, and (2) that it was difficult to effectively treat the morphology without a clear understanding of the processes shaping the coast we now see. Therefore, the overall goal of this study is not merely to catalog morphologic characteristics of the shorelines through the accompanying maps, but rather to relate the components (e.g., beaches and bluffs) to each other by way of the processes that operate on the various elements.

METHODS

As this study addresses a number of aspects of coastal zone processes and morphology, a variety of study techniques were used. Some of these will be discussed in more detail in later sections. For example, methods of assessing shoreline erosion will be covered in the section that specifically deals with that topic since an understanding of the methods is almost inseparable from an evaluation of the results.

In general, the study approach relied heavily on field study of nearly the entire length of the Skagit County shoreline. This was done either on foot or with a small boat that could be easily put ashore at almost any spot. In addition, air photos were used extensively; these were 1:6000 scale, vertical, true-color photos flown in 1976/77 for the Washington Department of Ecology. The photos were studied both before and after the field visits. Prior to field work they provided a method to locate areas of special interest such as
landslide zones; wide, wave-cut platforms; and prograded beaches. A restudy of photos after field reconnaissance often allowed a clearer understanding of large scale features seen on the ground and often confirmed a hypothesis formed in the field. An example of this was identification of a very large prograded beach (approximately 120 hectares) on northeastern Samish Island; a feature so large that it was difficult to confirm its full extent on the ground.

The field procedure consisted of taking measurements, notes, and photographs of: (1) beach slope, morphology, and sediments; and (2) of bluff materials, morphology, and mass movements. The first item, beach slope, was initially, somewhat unrewarding, but eventually became one of the most useful techniques employed. In measuring slope, the beach is treated as a planar surface even though the majority are concave upward with varying slopes along the profile. A range pole is inserted into the beach at the mean higher high water line, with the top of the pole or other visible marker exactly at eye level. The observer then stands at the mean lower low water level and takes the angle with an optical clinometer. The result is the mean slope of the beach, or the angular difference between the two points. Locating the MHHW line can be somewhat difficult for someone not familiar with local beaches, but only a moderate amount of experience is needed to locate it fairly precisely. Trials indicate that even if it is misjudged by a meter or more the measured angle changes by less than $\frac{1}{2}^\circ$. Repeated measurements of the same site produced results within $\frac{1}{4}^\circ$ of the original, and measurements by two observers were always within $\frac{1}{2}^\circ$. Thus the $\frac{1}{2}^\circ$ error produced by misjudging MHHW level is within the limits of error for the procedure.
Skagit County, located in northwestern Washington (Fig. 1) includes 200 km of marine shoreline, of which 130 km is bordered by beaches (U.S. Army Corps of Engineers, 1971). The balance is low-lying, marshy shoreline fronted by muddy tidal flats; the greatest majority of the latter shoreline is contained within the Skagit River Delta.

The uplands and bluffs bordering the 130 km of beach are composed of a diverse set of geologic materials, both indurated and unconsolidated. Most of the rocks are Jurassic to Cretaceous age belonging to a dismembered ophiolite containing both igneous and sedimentary portions of the original ophiolitic assemblage (Brown, 1977; Gusey, 1978; Whetten, et al., 1978). The igneous suite includes ultramafics, gabbro, pillow basalt, and diorite; the sediments are of deep marine origin, typically graywacke, argillite, and chert. The unconsolidated materials are the product of repeated Pleistocene glaciation of the Puget Lowland. They include interglacial fluvial/lacustrine sand, silt, and clay deposits; proglacial and recessional outwash; till; and glaciomarine drift. The deposits of the late Wisconsinan continental ice advance (locally named the Fraser glaciation) are the most commonly encountered in the coastal bluffs, which are typically 10 to 60 m high (see Easterbrook, 1963 and 1969 for a complete discussion of glaciation and deposits).

The climate in coastal Skagit County is mild, with a mean summer temperature of 16°C, winter mean of 5°C, and mean annual precipitation of 650 mm (Phillips, 1966). There is a pronounced seasonal difference in weather. Winters are dominated by cyclonic storms originating in the northeast Pacific Ocean; these produce over 70% of the yearly precipita-
Figure 1. Location map of the study area.
tion and nearly all of the yearly total of winds higher than 8 m/sec. Summers are dominated by the semi-stationary East Pacific high pressure system which produces mild, anticyclonic circulation.

The topography of the study area is dissected and includes a number of islands (Fig. 1). The channels separating the islands were scoured by glacial ice and are commonly in excess of 60 m deep within a few hundred m of shore. In profile these are seen as mostly submerged U-shaped valleys that have been only slightly modified by Holocene erosion and deposition.

OCEANOGRAPHIC ENVIRONMENT

Tidal Characteristics

The tidal regime of the study area is also that of the entire Puget Sound region, a mixed, semi-diurnal pattern. In this pattern two high tides and two low tides, all of unequal height, are experienced in approximately 24 hours. The higher of the two highs is termed "higher high water," while the lower of the two lows is called "lower low water." The long term means of those highest and lowest tides are abbreviated MHHW and MLLW, respectively (Gary, et al., 1972). Mean lower low water is both the tidal and navigational chart datum for this area.

Davies (1973, p. 51) classified tidal regimes according to the spring tidal range as follows:

- <2 m microtidal
- 2-4 m mesotidal
- >4 m macrotidal
Based on Davies classification, the study area is a mesotidal environment with the southern portion (Skagit Bay) being nearly macrotidal. Table 1 shows tidal means and extremes for the two main Puget Sound reference stations on which tidal parameters for subordinate stations within the study area are based. The Seattle data apply to the area east of Deception Pass, while the Port Townsend station is used for the rest of Skagit County.

The nearly macrotidal environment, the daily tidal inequality, and the generally low wave heights combine to strongly influence the beach and foreshore morphology of Skagit County.

Winds

Wind direction and velocities in the Skagit County area were known only generally prior to 1973. Before that time only a brief regional study by Harris (1954) and data from Whidbey Island Naval Air Station (20 km away) were available. At the latter site a pronounced westerly wind component is experienced due to the topographic influence of the Strait of Juan de Fuca. Since 1973 wind data have been collected in Skagit County by the Northwest Air Pollution Control Authority, but are unpublished. Table 2 is a summary of winds at Anacortes compiled from the NAPCA observations; Figure 2 is a wind rose constructed from the same data. Anacortes winds are thought to be representative of the entire Skagit County coastal zone because the topographic grain of the area is relatively uniform, and the exposures and fetches are similar. Furthermore, Anacortes is approximately in the center of the coastal area, away from special topographic influences like the Strait of Juan de Fuca, as is most of the county.
Table 1.

Tidal Means and Extremes*

<table>
<thead>
<tr>
<th></th>
<th>Seattle</th>
<th></th>
<th>Port Townsend</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>feet (meters)</td>
<td>feet (meters)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>extreme high water</td>
<td>&gt;14.0 (4.27)</td>
<td>&gt;11.0 (3.35)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean higher high water</td>
<td>11.3 (3.45)</td>
<td>8.3 (2.53)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean high water</td>
<td>10.4 (3.17)</td>
<td>7.6 (2.32)</td>
<td></td>
<td></td>
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<tr>
<td>mean tide</td>
<td>6.6 (2.01)</td>
<td>5.0 (1.52)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean lower low water (datum)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>extreme low water</td>
<td>-4.5 (-1.37)</td>
<td>-4.5 (-1.37)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean spring range</td>
<td>12.9 (3.93)</td>
<td>9.3 (2.82)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>extreme range</td>
<td>&gt;18.5 (5.64)</td>
<td>&gt;15.5 (4.73)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Tidal heights are shown in both feet and meters since the former are presently used on U.S. Government tidal publications and charts.

Table 2.

Wind Velocity and Direction
Shell Refinery, Anacortes, 1975-1977*

<table>
<thead>
<tr>
<th>Velocity (mi/hr)</th>
<th>0-2.99</th>
<th>3-6.99</th>
<th>7-11.99</th>
<th>12-17.99</th>
<th>18-23.99</th>
<th>&gt;24</th>
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<td>Velocity %</td>
<td>4.4</td>
<td>38.4</td>
<td>37.2</td>
<td>14.2</td>
<td>5.0</td>
<td>.9</td>
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<table>
<thead>
<tr>
<th>Direction</th>
<th>Direction %</th>
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<tbody>
<tr>
<td>N</td>
<td>5.8</td>
</tr>
<tr>
<td>NNE</td>
<td>7.2</td>
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<td>NE</td>
<td>2.5</td>
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<tr>
<td>ENE</td>
<td>2.7</td>
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<tr>
<td>E</td>
<td>6.1</td>
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<td>ESE</td>
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<td>SE</td>
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<tr>
<td>SSW</td>
<td>3.3</td>
</tr>
<tr>
<td>SW</td>
<td>3.1</td>
</tr>
<tr>
<td>WSW</td>
<td>5.7</td>
</tr>
<tr>
<td>W</td>
<td>7.2</td>
</tr>
<tr>
<td>WNW</td>
<td>5.2</td>
</tr>
<tr>
<td>NW</td>
<td>5.7</td>
</tr>
<tr>
<td>NNW</td>
<td>5.4</td>
</tr>
</tbody>
</table>

*Based on 25,168 hourly observations over the 3 year period.
Courtesy of Northwest Air Pollution Authority, Mt. Vernon, WA.
Figure 2. Wind rose for Anacortes showing frequency, direction, and velocity from which the wind blows. Raw data from NAPCA which is summarized in Table 2.
Of special interest is the high percentage of time that wind velocities are low; winds are under 5.4 m/sec (12 mi/hr) during 80% of the year, and under 8 m/sec (18 mi/hr) 94% of the time. Stronger winds (>8 m/sec) show a distinct clustering in the southeast quadrant of the wind rose, with minor components from the northeast and westerly directions. Well over 50% of all winds stronger than 8 m/sec come from the southeast quadrant. Westerly winds have little oceanographic effect since the north/south topographic grain of the area strongly limits westerly fetch.

Wave Regime

Little wave research has been done in northern Puget Sound waters (J. Downing, oral communication, 1979). One unpublished study (B. C. Research, 1974) was done in Canadian waters on Halibut Bank in southern Georgia Strait. There the fetch of open water is much longer than those prevalent in Skagit County; at that site extreme winds produced waves to a maximum of 2.4 m in height. Wave data given by Terich (1979) for Whatcom County indicates that even in exposed locations significant wave height is almost always under 1.8 m. Similar significant wave heights are derived for Skagit County by using the wave forecast graphs of the U.S. Army Corps of Engineers (1973) and the wind data presented in the preceding section. These wave heights, shown in Table 3, are probably reasonable approximations for the study area.

The usually mild summer winds produce waves that are nearly always less than 0.5 m and often less than 0.25 m in height. Davies (1973, p. 31) observes that winds under 5 m/sec produce waves that are geomorphically insignificant. This area experiences velocities that low about 80% of the time (Table 2).
Table 3.

Significant Wave Heights for Typical Velocity, Fetch, and Duration in Skagit County Waters

<table>
<thead>
<tr>
<th>Velocity: 5.37 m/sec (12 mi/hr)</th>
<th>Fetch (km)</th>
<th>2 hours</th>
<th>6 hours</th>
<th>10 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>.15 meters</td>
<td>.15 meters</td>
<td>.15 meters</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>.24 &quot;</td>
<td>.30 &quot;</td>
<td>.30 &quot;</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>.27 &quot;</td>
<td>.38 &quot;</td>
<td>.38 &quot;</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>.27 &quot;</td>
<td>.46 &quot;</td>
<td>.46 &quot;</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>.27 &quot;</td>
<td>.49 &quot;</td>
<td>.53 &quot;</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Velocity: 8.05 m/sec (18 mi/hr)</th>
<th>Fetch (km)</th>
<th>2 hours</th>
<th>6 hours</th>
<th>10 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>.40 meters</td>
<td>.40 meters</td>
<td>.40 meters</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>.49 &quot;</td>
<td>.52 &quot;</td>
<td>.52 &quot;</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>.55 &quot;</td>
<td>.58 &quot;</td>
<td>.58 &quot;</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>.55 &quot;</td>
<td>.79 &quot;</td>
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</tr>
<tr>
<td>50</td>
<td>.55 &quot;</td>
<td>.91 &quot;</td>
<td>.91 &quot;</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Velocity: 12.97 m/sec (29 mi/hr)</th>
<th>Fetch (km)</th>
<th>2 hours</th>
<th>6 hours</th>
<th>10 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>.64 meters</td>
<td>.64 meters</td>
<td>.64 meters</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>.85 &quot;</td>
<td>.85 &quot;</td>
<td>.85 &quot;</td>
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</tr>
<tr>
<td>15</td>
<td>1.04 &quot;</td>
<td>1.04 &quot;</td>
<td>1.04 &quot;</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>1.07 &quot;</td>
<td>1.34 &quot;</td>
<td>1.34 &quot;</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>1.07 &quot;</td>
<td>1.65 &quot;</td>
<td>1.65 &quot;</td>
<td></td>
</tr>
</tbody>
</table>
The computed significant wave heights in Table 3 do not increase from the 6 to 10 hour duration. The short fetches of open water limit the height of waves generated; that is, beyond a six hour wind duration waves do not become larger due to fetch limitations. Most shore segments in Skagit County have a fetch less than 10 km; even the longer ones are mostly less than 50 km.

GENERAL FORESHORE MORPHOLOGY

The vast majority of beaches in the northern Puget Sound region can be best described as having a "high-tide beach/low-tide terrace" morphology. Komar (1976, p. 297) lists the main elements as: a relatively steep beach face with coarse sediment (the high-tide beach), followed by an abrupt change in slope at the foot of the high-tide beach where a wide low-tide terrace begins (Fig. 3). The terrace is characterized by low slopes and accumulations of poorly sorted fine-grained sediment (sand and silt). Since the high-tide beach is usually composed of dominantly coarse sediment (≤0.5) the morphology seems to occur more often in areas that were glaciated during the Pleistocene (Davies, 1973, p. 109-113 and 119-123). The local occurrence of this morphology, which is not common on a worldwide basis, has been previously unreported. The few shore segments in Skagit County where a distinct break in slope between the two foreshore elements is not obvious are discussed in a subsequent section (pp. 79-81).

The development and maintenance of this particular beach morphology can be attributed to at least three, possibly four, causes, all of which are extant in the Puget Sound region. Inman and Filloux (1960) note that it is most common in regions where the tidal range is large relative
Figure 3. High-tide beach with 8° slope above a sandy, subhorizontal low-tide terrace exposed during a spring low tide.
to predominant wave height; exactly the conditions that exist locally. Mean spring tidal range is nearly 4 m (Table 2) while dominant wave height is less than 0.25-0.5 m during 80% of the year (Table 3).

Bird (1969, p. 105) states the morphology is a reflection of the differing response of shingle and sand to locally generated, short-period storm waves. That is, storm waves tend to move shingle onshore and/or pile it into ridges, while sand is withdrawn to the lower foreshore or nearshore bottom.

Thirdly, a low-tide terrace can be developed by deposition of fines (finer than 2 φ) on the lower foreshore bottom by offshore or longshore transport of suspended sediment supplied by cliff erosion or by nearby streams. This mechanism operates in parts of Skagit County; it is best displayed in the bays adjacent to the Skagit and Samish deltas. There the wave energy is low but tidal currents bring in fine sediment from the adjacent delta.

The fourth possible cause of an extensive low-tide terrace is limited supply of coarse material. Where the beaches are supplied by bluffs of glaciofluvial sand the supply of coarse material is quite limited. This is reflected in a narrow high-tide beach above a wide, sandy low-tide terrace (Fig. 4).

Of the four mechanisms proposed, it appears the wave height/tidal range hypothesis suggested by Inman and Filloux (1960) is the primary control of beach morphology in Skagit County; it is the only one of the four that operates equally on all shoreline segments. While the other three mechanisms do operate, their occurrence is usually limited to specific portions of the study area and mainly serve to modify or accentuate the basic morphology.
Figure 4. Narrow high-tide beach above a very wide (>60 m) low-tide terrace exposed in the right, background. Location: north-central portion of Samish Island (Map C).
Characteristics of the High-Tide Beach

The high-tide beach usually has the coarsest sediment found in the foreshore. Locally, erosion of glacial tills and similar deposits strongly influences the high-tide beach composition. The particle sizes most commonly transported longshore range from 10 to 70, but even a wider range of sizes are commonly found, especially in sizes coarser than 70 which are left as lag deposits. The slope of the high-tide beach varies locally between 3° to 11°, with values between 4° and 9° especially common. The width of the high-tide beach in Skagit County also varies, mainly reflecting the change in slope. Typical widths between MHHW and MLLW level are 20 - 40 m, with the widest associated with the lowest slope.

The width of the backshore or berm deposits (i.e., the distance from MHHW to the cliff foot) also varies, but through a relatively small range of values, typically 1 - 7 m. The area landward of the MHHW level often has substantial accumulations of driftwood and logs. That fact, often taken for granted locally as being "normal" is, in fact, not common on a world-wide basis. It is presently unknown whether drift logs are beneficial, detrimental, or benign with regard to beach stability or erosion. Preliminary study by Terich and Milne (1978) suggests logs may help trap sediment in the backshore and may help somewhat in protection of bluffs from wave attack.

The break in slope between the high-tide beach and the low-tide terrace occurs at approximately MLLW or slightly above in most of the study area; in places it is found as high as the +6-foot tide level.
Characteristics of the Low-Tide Terrace

The presence of fine sand and silt sizes is characteristic of the low-tide terrace in Skagit County. Where abundant sand is available that size class is found on the low-tide terrace (e.g., as shown in Fig. 4), but, where relatively more silt is available the terrace sediment reflects that supply; it is especially noticeable near the Skagit delta. There the tidal flats are accreting vertically and in the process are burying the high-tide beaches so the junction with the coarse upper beach is at a +4 to +6-foot tide level in northern Similk Bay (Fig. 5). Although the overall foreshore morphology appears to be the same, the muddy tidal flat replaces the original low-tide terrace with the junction being displaced to a higher level.

Well defined longshore sand bars are seldom seen on the sandy low-tide terrace. The large tidal range, which shifts the breaker zone laterally over relatively large distances, tends to inhibit development of a barred foreshore. Davies (1973, p. 130-131) notes that the most pronounced bar development is favored by a microtidal environment. Locally, even if a distinct bar did form, the diurnal tidal inequality would tend to destroy it, probably during the next tidal cycle. As a result, the low-tide terrace in this area commonly has a ridge and runnel surface topography (Fig. 6). Both King and Williams (1949) and Komar (1976, p. 298) indicate that the same factors noted as being important in shaping local foreshore morphology also seem to favor the development of ridge and runnel topography. They are: (1) large tidal range, (2) relatively low wave energy, (3) the presence of a nearly horizontal low-tide terrace, and (4) an abundance of sand. It should
Figure 5. Vertically accreting, muddy tidal flat burying a coarse-grained high-tide beach; the mudflat intersects the upper foreshore at about a +6-foot tide level. Location: northern Similk Bay (Map G).
Figure 6. Ridge and runnel topography on the low-tide terrace; here, only partially exposed due to tide level. Location: northeastern shore of Sinclair Island (Map A).
be noted that the term ridge and runnel is used in this report as originally used by King and Williams (1949). Since that time there has been a tendency to also apply it to swash bars which form low in the foreshore and subsequently migrate up the beach during non-storm periods. Orford and Wright (1978) note that the genesis of the two forms of beach topography are probably not the same; they favor the restriction of the term ridge and runnel to the static or very slowly migrating bars on the low-tide terrace as originally used by King and Williams.

Characteristics of the Foreshore in Rocky Shoreline Sectors

The mesotidal to nearly macrotidal regime of Skagit County is not only reflected in the morphology of moveable beaches, but the influence of the tidal range and associated shifting swash-backwash zone is also seen on rocky shorelines. Where rock cliffs are more easily eroded they are fronted by a shore platform. These wave-cut surfaces are nearly planar, slope seaward at $2^\circ$ to $4^\circ$, and in places are over 60 m wide, though widths of less than 40 m are the most typical (Fig. 7). This type of platform morphology is classified by Bird (1969, p. 49) as an intertidal platform. Davies (1973, p. 97) also notes the intertidal platform is most common to regions where the tidal range is large.

Where wide platforms have developed the seaward margin is usually buried in the unconsolidated sediment of the nearshore bottom. There are, however, a few notable exceptions. In at least three instances, an abrupt edge to the platform occurs where the water suddenly deepens.
Figure 7. Typical wave cut platform exposure during spring low tide. Width at this tide level is approximately 35 m. Location: northern tip of Cypress Island (Map A).
These seem to have significant implications for shoreline erosion history and are discussed in detail in the section of this study that deals with erosion (p. 50).

Where rocks are less eroded, either a very narrow platform or notch (<4 m wide) is cut into the vertical rock face, or the vertical cliff face plunges directly into deep water.

A third configuration, seen where the rock is relatively resistant but well jointed, is a scree or talus accumulation at the cliff base. In most instances these accumulations are under water except at low tides. They may cover a narrow, inactive platform, but this is uncertain.

BEACH SEDIMENTS

Sediment Supply and Longshore Transport

Fundamental to any discussion of beach sediment supply and transport is an understanding of the concept of a drift sector. A drift sector is a segment of shoreline that acts as a closed or nearly closed system with respect to longshore transport of littoral sediment. A sector can span a variable length of shoreline from a zone which is contributing sediment to the beach (the beginning) to a zone which is accumulating the transported sediment (the terminus). In Skagit County the termini are prograded beaches, usually in the form of a spit, bayhead beach, or baymouth-barrier beach.

Worldwide, 90-95% of all beach sediment is delivered to the coast by rivers (Komar, 1976, p. 235). The northern Puget Sound area is an exception. Here almost all beach material is derived from erosion of
shore bluffs, particularly those composed of unconsolidated Pleistocene sediments. There are two primary reasons for this reversal of the worldwide pattern: (1) negligible sediment supply from local streams, and (2) a lack of littoral transport of sediment from the mouths of major rivers (e.g., the Skagit) which drain the Cascade Mountains. The small contribution by local streams is due to the relatively low rainfall and runoff in western Skagit County. Mean annual precipitation at Anacortes is 65 cm, while actual evapotranspiration is estimated to be 45-50 cm, leaving only one quarter of the rainfall total available for runoff (Phillips, 1966). Consequently, local streams are small and contribute little sediment to beaches. Furthermore, the sediment these streams deliver to the shore is generally smaller than the particle sizes residing on the high-tide beach. Sediment from the major rivers is not found on even the nearby beaches because the deep, ice-scoured channels, which dissect and embay the coast and isolate a number of islands, preclude long-distance littoral movement of river sediment. Thus, in the absence of a fluvial supply, the beach sediment is derived from the only other source available, the relatively erodible bluffs. Six types of unconsolidated deposits are most often exposed in Skagit County shore bluffs (Table 4). Erosion of these provides the majority of sediment potentially available to beaches. However, there is a large difference between the volume of sediment eroded and the percentage actually retained on the high-tide beach. Since the high-tide beaches are composed predominantly of particles coarser than 1Ø (p. 17), and especially those coarser than 0Ø, any deposit that consists of sizes less than 0Ø will not supply much material to the high-tide beach.
Table 4.

Unconsolidated Bluff Materials Commonly Found in Skagit County

<table>
<thead>
<tr>
<th>Genetic Classification</th>
<th>Named Example(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) fluvial or lacustrine silt/clay</td>
<td>Olympia non-glacial deposits</td>
</tr>
<tr>
<td>(2) fluvial or lacustrine silt/sand</td>
<td>Whidbey Formation interglacial deposits</td>
</tr>
<tr>
<td>(3) glacial outwash sands</td>
<td>Esperance Sand Member of the Vashon Drift</td>
</tr>
<tr>
<td>(4) glaciomarine drift</td>
<td>Everson Glaciomarine Drift</td>
</tr>
<tr>
<td>(5) tills</td>
<td>Vashon Till</td>
</tr>
<tr>
<td>(6) glaciofluvial gravel</td>
<td>Possession Gravel and Vashon recessional outwash</td>
</tr>
</tbody>
</table>
Material categories 1 through 3 (Table 4) do not contain a significant quantity of material coarser than 0Ø. Rather, those deposits are composed of sand and finer material; since those sizes are deposited on the low-tide terrace or in even deeper water, the net sediment gain to the high-tide beach is negligible. Taken in the sequence listed (Table 4), glaciomarine drift is the first material type that supplies a measurable amount of material coarser than 0Ø. The size analysis of glaciomarine drift in Table 5 indicates that as little as 5% of the deposit is coarser than -1Ø. Even if half of the mean sand percentage (representing the coarser sand, 1Ø to -1Ø) is assumed to stay on the high-tide beach the amount of useable material rises to only 16%. Size analysis of an "average" Fraser age basal till would probably yield similar results as glaciomarine drift and till are sometimes visually indistinguishable. In England, Valentin (1954) found only 3% of the eroded volume of Pleistocene deposits could be accounted for in the prograded beaches that resulted from transport of eroded material. Because of the "distillation" process described above, large volumes of sediment are eroded from Skagit County shore bluffs, but well developed beaches capable of protecting the cliffs often do not result.

An excellent example of the effect of supply from various Pleistocene deposits can be seen in a comparison of two drift sectors with similar bluff heights but very different bluff materials. The west-central Cypress Island sector (Map A) is nearly 2.5 km long and is supplied by bluffs of till and glaciomarine drift. Its downdrift accumulation area (Tide Point) has a prograded beach approximately 1 ha in area. In contrast, on the westerly part of the south shore of Guemes
Table 5.

Size Analysis of Everson Glaciomarine Drift
Bayview Ridge, western Skagit County
(data from Siegfried, 1978)

<table>
<thead>
<tr>
<th></th>
<th>&lt;-1Ø (coarse)</th>
<th>-1Ø to 4Ø (sand)</th>
<th>4Ø to 8Ø (silt)</th>
<th>&gt;8Ø (clay)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample #1</td>
<td>6.3%</td>
<td>23.0%</td>
<td>40.1%</td>
<td>30.6%</td>
</tr>
<tr>
<td>2</td>
<td>2.0%</td>
<td>12.6%</td>
<td>72.8%</td>
<td>12.7%</td>
</tr>
<tr>
<td>3</td>
<td>3.4%</td>
<td>37.3%</td>
<td>39.1%</td>
<td>15.4%</td>
</tr>
<tr>
<td>4</td>
<td>1.5%</td>
<td>16.8%</td>
<td>50.4%</td>
<td>31.4%</td>
</tr>
<tr>
<td>5</td>
<td>7.6%</td>
<td>24.6%</td>
<td>56.7%</td>
<td>11.1%</td>
</tr>
</tbody>
</table>

Average of 5 Samples

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>coarse</td>
<td>5.1%</td>
</tr>
<tr>
<td>sand</td>
<td>22.9%</td>
</tr>
<tr>
<td>silt</td>
<td>51.8%</td>
</tr>
<tr>
<td>clay</td>
<td>20.2%</td>
</tr>
</tbody>
</table>

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100.0%</td>
</tr>
</tbody>
</table>
Island (Map B) the drift sector begins at Yellow Bluff (composed to a large degree of glaciofluvial gravel and sand) and extends east for only 0.9 km before reaching the beginning of the prograded beach. Here, the accumulation area is a minimum of 5 ha. The primary difference is that a very high percentage (possibly approaching 100%) of the material eroded from the glaciofluvial gravel will be retained on the high-tide beach.

Sediment Transport Competence

Since prograded beaches are the product of longshore transport, the maximum particle sizes occurring on those beaches are a measure of competence within the associated drift sector. The largest sizes found on prograded beaches in Skagit County are typically -60 to -6.50 (64 to 100 mm). One beach (Strawberry Bay, Cypress Island, Map A), has particles up to 128 mm and slightly larger, but it is exposed to the longest fetch in the study area and is therefore somewhat atypical.

Little is known about the swash velocities and associated breaker heights needed to move sediment in the -60 to -70 range longshore. The one study that attempted such an investigation (Novak, 1972) only addressed onshore-offshore movement and did not include a large range of breaker heights. Therefore, it is difficult to determine if longshore transport of those sizes occurs regularly on Skagit County beaches. The fact that the very coarsest material represents much less than 5% of the prograded volume (visual estimate) suggests that transport occurs very infrequently.

Pocket Beaches

True pocket beaches do not derive sediment from littoral transport. They are confined between headlands where deep water does not permit
transport beyond the bracketing headlands. The sediment particle morphology on pocket beaches within the county seems to be a clear indicator of the lack of longshore contribution. The shingle on those beaches has a high degree of roundness, often high sphericity, and in some cases a polished surface. That morphology and polish is in striking contrast to beaches open to littoral transport and indicates the long-term retention and reworking of sediment. It is particularly well displayed on Rosario Beach (Map F) and is also encountered on southern Sinclair Island, northern Cypress Island (both on Map A), and western Samish Island (Map C).

Sediment Size and Sorting

Figure 8 shows sieve analyses of sediment on three local prograded beaches. They show bimodal size distribution reflecting the presence of both sand and coarser material in the source deposit. In all three cases over 70% of the sediment is coarser than 10 and on two of the beaches 60% is coarser than -1.50. According to Folk (1968), all three would be classified as "poorly sorted" to "very poorly sorted." Most northern Puget Sound beaches have similar size distributions and sorting, and in many cases even poorer sorting.

I believe there are four reasons why local beaches become and remain poorly sorted. First, and most important, are the sediment characteristics inherited from source materials. The size and bimodal sorting of Skagit County beaches seems to reflect the original nature of the glacial source. Folk and Ward (1957), point out that source effects can be found in sediments even after hydraulic transport.
Figure 8. Cumulative curves for three northern Puget Sound prograded beaches. See text for discussion. Data from Spasari (1978).

WB: West Beach, Whidbey Island
RO: Rosario Beach, Fidalgo Island
SH: Ship Harbor, Fidalgo Island
Second, the erosion of coastal bluffs does not provide a "point source" input to the beach drift system as a river mouth does. Rather, erosion provides fresh, unsorted additions along nearly the entire length of a drift sector.

Third, the dissected nature of local shorelines limits drift sector length; nearly all Skagit County sectors are under 7 km. As a result, material in transport does not have an opportunity to sort well before reaching the accumulation area as it might in a very long drift sector (e.g., see Komar, 1976, pp. 352-353).

Finally, the diverse winter/summer wave energy regime and the directional variability of local winds and waves often move beach sediment opposite to the net, long-term direction; this also tends to keep sizes mixed.

Despite overall poor sorting, there are relative changes in sorting through the length of drift sectors. The middle of local sectors are always more poorly sorted than either the beginning or terminus. These longshore changes will be discussed in a subsequent section (pp. 71-73).

Cemented Beach Comglomerate

Occurrence and Description

On Cypress Island (Map A) cemented beach deposits are found on the surface of rock shore platforms. The percentage of the surface covered varies from discontinuous patches to 100% cover of small segments less than 100 m long. Geographically, the greatest concentration is on the southern half of the west shore between Reef Point and Strawberry Bay. Other localized occurrences are on the west side north of Strawberry Bay and north to Tide Point, and along the east side in scattered
patches from Eagle Harbor to the southeastern extremity of the island. There appear to be occurrences in other parts of western Skagit County also.

The deposit is unquestionably cemented beach material since well preserved shells and shell fragments are incorporated into it and the lithology of clasts includes all the rock types present on adjacent patches of uncemented beach (Figs. 9 and 10). The cement reacts vigorously with acid indicating a high CaCO$_3$ content; x-ray diffraction analysis showed the carbonate to be both calcite and aragonite (D. R. Pevear, personal communication, 1978). The texture of the deposits range from incipient and thin coatings to thick, banded crusts.

Origin

Were it not for the local climate the deposit could be called a beachrock as is found in tropical areas. However, true beachrock, which is often attributed to highly evaporative conditions (Stoddart and Cann, 1965), has not been reported in temperate climates. The source of calcium in the carbonate cement and the origin of the conglomerate itself are both somewhat problematic, especially since the shore platforms and cliffs are serpentinite and partially serpentinized peridotite which contain very little calcium. Unless these deposits are a previously unknown type of beachrock formed through evaporation of seawater in a temperate climate (which is unlikely), their origin must be related to the adjacent ultramafic rock. There is evidence, both in the field and in the geologic literature to suggest that this is indeed the case.

Exposures of the conglomerate are limited to foreshores backed by cliffs of ultramafic rock. No occurrences have been found on beaches or
Figure 9. Nearly continuous exposure of beach conglomerate in the upper portion of this beach. Some of the boulders in the middle part are cemented into the substrate others are lying on the surface.

Figure 10. One valve of a pelecypod shell incorporated into cemented beach deposit.
platforms fronting cliffs composed of unconsolidated Quaternary deposits, non-ultramafic rocks, or at stream mouths. Furthermore, euhedral aragonite crystals can occasionally be found growing in vugs in the ultramafic rock cliff faces that have slow water seepage. A white, limey precipitate or "bloom" is often seen on cliff faces above a platform with conglomerate. The bloom is especially apparent where there are freshly exposed joint faces from rockfall; that precipitate, like the conglomerate, reacts vigorously with acid. The occurrence of blooms and conglomerate on platforms seems to be favored along known or inferred fault zones where the rock is more fractured and subject to seepage.

Barnes and O'Neil (1969) and Barnes, et al (1978) report similar cemented gravel in streams draining partially serpentinized ultramafic bodies. They find that cementation occurs where water has a high concentration of CaOH, but not where MgHCO₃ is the dominant constituent. Barnes and O'Neil suggest that CaOH rich water indicates serpentinization occurring under near-surface pressure and temperature conditions. The calcium carbonate species which they find forming cements are highly variable but include both aragonite and calcite, as found on Cypress. They attribute the calcium to selective removal of that ion from pyroxenes in the ultramafic rock during serpentinization. Further study is anticipated to determine if the Barnes and O'Neil findings are applicable to the conglomerate in Skagit County.

Similar sea cliff exposures of ultramafic rock suggests that the conglomerate may also occur on Burrows, Allen, Hope, and Saddlebag Islands. Although field investigation of those islands was limited to boat stops at individual sites, a number of carbonate blooms were noted on cliff faces, strongly suggesting the occurrence of conglomerate there.
Age of Conglomerate Deposition

The rock shore platforms in the county have been mostly or entirely formed during the Holocene (see subsequent section, p. 45); this indicates the conglomerate is no older. An 11 m deep cave on Cypress Island provides further evidence of time of formation. The cave floor is a continuation of the fronting wave-cut platform. Loose gravel lying adjacent to the headwall and abraded rock knobs on the floor indicate that the rock is still being eroded (Fig. 11). Similarly, previously formed conglomerate near the cave mouth has been abraded since it was deposited there. However, at the headwall/floor junction (beneath the cover of gravel tools, Fig. 11) no conglomerate has yet formed. These spatial relations suggest that as the platform is extended by cave enlargement, the mantle of conglomerate also advances. Thus, the conglomerate seen at the cave may well range in age from several thousand years on the fronting platform to quite recent at the head of the cave.

Figures 12 and 13 show pieces of iron that have been incorporated in the conglomerate. It is nearly certain the metal is less than 90 years old (the first occurrence of logging on Cypress) and could easily have been dropped on the beach during the last few years. This suggests conglomerate may be forming at the present time.
Figure 11. An 11 m deep cave with the floor mostly covered by beach conglomerate, except in the middle of the photo where part of the wave-cut platform still protrudes.
Figure 12. Flat metal plate being covered with cemented beach materials. Note especially the lower and left edges where the square edge of the plate is covered. The straight-edge is 15 cm long.

Figure 13. Old-style, square iron spike incorporated into beach conglomerate, southwestern shore of Cypress Island.
SHORELINE EROSION

Methods Used for Determining Modern Erosion Rates

Some of the methods used to assess rates of shoreline retreat in other parts of the world, are not generally applicable to the Puget Sound region. One widely used method is sequential comparison of maps or air photos, particularly where reasonably accurate maps older than 100 years are available (Kaye, 1973). Even where accurate, modern 7½ minute topographic maps are available the procedure is fraught with large potential errors (Coastal Measurement Workshop, 1976). The potential measurement and map plotting errors combined are at least 3 to 10 times larger than the rates of erosion found within the study area. Errors associated with sequential air photo comparison, while somewhat different in origin (Stafford, 1971), produce similar problems. Consequently, a variety of other methods had to be used to assess erosion rates.

Direct Measurement

Direct measurement is possible where records of old ground surveys exist. Resurveying old property lines that extend to the shoreline is one example. Although time and equipment restrictions prevented it in this study, a resurvey along the north and south shores of Samish Island (Map C) would provide useful erosion information. A second direct method makes use of triangulation stations installed by the U.S. Coast and Geodetic Survey in shoreline areas. The markers are located on the beach (Fig. 14) or on the bluff top. When they were originally installed the distance from the marker to the cliff foot (beach installations) or the cliff edge (bluff-top installations) was sometimes recorded. The
Figure 14. Typical location and setting for a U.S. Coast and Geodetic Survey triangulation station. Here mounted in a mostly buried boulder that is 5 m from the colluvial toe of a bluff. Location: Shannon Point, Fidalgo Island (Map D).
stations are reoccupied aperiodically (typically every 5-15 years) and changes in measurements are sometimes noted. To assess erosion one looks for recorded changes in the records or makes a new measurement in the field. Locally, the records are maintained by the National Oceanographic and Atmospheric Administration and by the Washington State Bureau of Maps and Surveys.

Indirect Methods

Since the triangulation stations are not numerous and since many did not have the necessary original measurements noted in permanent records, many are not useable to assess past erosion. Therefore, indirect methods using trees and man-made structures were employed to assess shoreline erosion. It is important to understand that indirect methods yield only minimum erosion rates. However, within some shore segments nothing else is available, thus, knowing a minimum rate is preferable to not being able to make an assessment at all.

One indirect method uses trees growing on the bluff edge that have had part of the root system exposed by cliff retreat. Figures 15 and 16 are two examples of trees used. An erosion rate is computed by dividing the amount of root exposure by the tree's age as determined with an increment borer. Care must be exercised in choosing trees because only a tiny fraction of all bluff-top trees are useable. Trees that are leaning to a large degree or those that have been involved in any kind of mass movement are avoided. Very young trees should not be used because the amount of root exposure may be entirely due to a single, recent storm, and thus not indicative of long-term average rates. Very old trees also cannot be used because they may have been growing for hundreds of years
Figure 15. Undercut tree on low till cliff; the end of the most exposed root is just above the orange flag, 1.8 m from the top edge of the scarp (Lone Tree Point, Map G).
Figure 16. Exposed root mass on top of 20 m high bluff on the south shore of Guemes Island (Map B). The outermost root is over 2 m from the bluff face.
before cliff retreat exposed any part of the root system; if used, the
result would be a minimum rate that is unrealistically low. In all
cases I used trees between 20 and 80 years old. During that time span
one can be reasonably certain that a number of large storms have occurred
so the calculated rate should be fairly representative of a longer term
average; and yet, the trees are not so old that the calculated rate would
be unrepresentatively low. A further confirmation for using a 20 to 80
year time span comes from the work of Horikawa and Sunamura (1970). They
found short-term erosion rates (12 years) to be about twice as high as
a long-term average, but beyond 20 years, calculated rates began to
approach the long-term (80 years) rates. Where I've been able to check
the tree root data against the other methods I find the tree roots
underestimate the rate by about 50%.

A second indirect method, also used on unconsolidated materials,
utilizes man-made structures whose age and position relative to the
original shoreline are known. An example is the boathouse shown in
Figure 17, which was built about a meter back of a low bluff scarp in
1960. In the intervening 18 years the foundation has been undercut by
nearly a meter.

Three of the methods discussed above, bluff-top bench marks, bluff-
top trees, and undercut structures assume parallel cliff retreat. Over
a short time span (i.e., a few years for unconsolidated materials) this
may not hold true. In the longer term however, an actively retreating
sea cliff undergoes parallel retreat by unimpeded basal removal (Young,
1972, p. 125). Many investigators (e.g., Horikawa and Sunamura, 1970)
have assumed parallel retreat, I believe justifiably, when dealing with
longer time spans.
Figure 17. Boathouse with undercut foundation on the south shore of Guemes Island (Map B). Shore recession has been approximately 1.75 m during the past 18 years.
Late Holocene Shoreline Retreat

Indirect methods can also be applied when considering minimum shoreline erosion rates over periods of several thousand years. Erosional remnants on shore platforms have allowed me to establish that most, if not all, of the width of presently visible platforms in Skagit County have been cut during the Holocene. Specifically, the remnants include: sea stacks, ramparts, caves, and lag deposits. Figures 18 through 21 are examples of these features. While features such as stacks and caves are relatively robust, they are entirely too fragile to have withstood overriding by the estimated 1500 meters of ice that occupied the north-central Puget Lowland during the Fraser Glaciation (Crandell, 1965), hence, the conclusion that they are Holocene age erosional remnants. To use these features to compute an erosion rate one has to determine when the sea reached a level high enough to begin modifying the present shorelines. Several lines of evidence suggest this date can be reasonably well constrained to less than 4500-5000 years before present.

The amount and rate of isostatic rebound after deglaciation is not well known for the Puget Trough. Despite that uncertainty there seems to be no evidence for large scale isostatic movement within the lowland during the Late Holocene. Rather, it appears that the process was essentially complete by at least 6000 years BP (Biederman, 1967; Thorson, 1979). Mathews, et al. (1970) suggest completion even earlier, by about 8000 BP. Therefore, the changes in sea level during the Late Holocene are likely to have been almost entirely eustatic. If the change was eustatic, then dated local and regional features related to the change should be consistent with worldwide eustatic curves. Figure 22 is a
Figure 18. Sea stack 37 m from the head of the wave cut platform. Location: northwest shore of Cypress Island (Map A).
Figure 19. Sea stack near Anaco Beach, western Fidalgo Island (Map D). The stack is over 15 m from the present high tide level which reaches the head of the cove in the right background.
Figure 20. Cave 11 m deep eroded into serpentine rock on western Cypress Island (Map A). Note how the wave-cut platform in front continues at the same gradient into the cave to form the floor.

Figure 21. A rampart preserved at the seaward edge of a 55 m wide wave-cut platform, western Cypress Island.
Figure 22. Composite eustatic curve compiled from data of various investigators. The range of the estimates is indicated by the vertical bars. These can be considered as defining an envelope of uncertainty about the mean curve.

DATA FROM:
Jelgersma, 1961, 1966
Shepard, 1963
Scholl, et al, 1969
Neuman, 1969
Bloom, 1970
Horner, 1971
composite, worldwide sea level curve with which local features can be compared to test if they are indeed in accordance with it.

At various places within the Pacific Northwest, freshwater peats are found below present sea level, both in shoreline bogs and exposed on beach faces. In Figure 23 the depths of submergence and the associated radiocarbon dates for submerged peats are superimposed on the composite sea level curve. All seem to be in relatively good agreement with the composite curve. Of special interest is the Portage Inlet site (Victoria, B.C.) of Mathews, et al. (1970); it, and the older peats, indicate that sea level 5500 years ago was still at least several meters below its present position. Work by Schwartz and Grabert (oral communication, 1978) at Blaine, in Whatcom County, indicates that by 4000 B.P. sea level had closely approached that of the present but had not yet built Semiahmoo Spit. This too is consistent with the composite curve. Finally, within the study area, I have found three rock abrasion platforms where the seaward edge terminates abruptly into deeper water at a level 3.5 to 4 m below present high water. This depth seems to indicate the platforms have been cut since sea level has been within approximately 4 m of the present level. Using the bracketing 4000 and 5500 year dates cited above, along with the 3.5 to 4 m platform depth, the composite curve suggests a date of about 4500 to 5000 years B.P. for the beginning of "recent" shoreline modification.

To calculate a long term erosion rate, for instance on a preserved sea stack, the distance from the cliff to the seaward side of the stack is divided by 5000 years; the result is a mean, minimum rate. A similar procedure can be used to arrive at long term erosion rates for unconsolidated bluffs where I've been able to find a very distinct seaward edge
Figure 23. Ages and depths of local and regional freshwater peat deposits that are now submerged.
to the lag deposit of cobbles and boulders left as the cliff retreats landward (Fig. 24). The lag deposit can also be used as an indicator of where the cliff edge was several thousand years ago.

It should be noted that even if a 4000 year starting point were assumed, the long term rates would increase by only 20%, a difference well within the range of uncertainty for indirect methods.

Factors Controlling Shoreline Erosion

Three major factors control the rate of shoreline erosion: bluff material type, wave energy, and beach materials. Each of these factors has often been mentioned in the geologic literature (Jollife, 1979) and their complex interplay is evident along all Skagit County shorelines. However, each of the three primary factors is associated with secondary or modifying controls.

Bluff Material Type

The resistance to erosion displayed by a given material is a primary control on rate of removal. It is intuitively obvious that unconsolidated materials should be more easily eroded than rock. However, even within a given material type there are differences in resistance to erosion; for example, there should be a significant difference in the erodability of a compact, well cemented basal till as compared to an outwash sand. Even within a particular till there are lateral variations in composition and, presumably, resistance to erosion. These differences did not appear in an analysis of erosion rate with respect to material type because the effects of additional variables (beach materials and wave energy) could not be isolated.
Figure 24. Seaward edge of a cobble and boulder lag deposit in front of an eroding till cliff. The distance from the cliff to the laq margin is over 75 m. Location: eastern Sinclair Island (Map A).
In indurated rocks there are many factors that control susceptibility to erosion; complete discussions are available in Yatsu (1966) and Robinson (1977). Robinson has shown that the two processes primarily responsible for rock removal are abrasion and quarrying; the latter is due both to hydraulic cavitation and wedging. Furthermore, he concluded that the effects of abrasion and wedging were more effective than hydraulic quarrying. On shore platforms, where no moveable material was available for use as tools, he found the rate of erosion was very much reduced. Similar conditions are found in Skagit County; that is, the lack of moveable material seems to be correlated with narrow shore platforms and reduced erosion rates.

Wave Energy

Wave energy reaching a shoreline is a second major control on erosion rates. On various sectors of northern Puget Sound shorelines the net wave energy expenditure is highly variable but relatively modest due to the predominance of lower wind speeds (Table 2,3). Even with winds occasionally reaching over 100 km/hour, short fetch distances strongly limit wave height. Since the wind pattern at various shore segments in Skagit County is generally similar, the wave energy reaching shoreline sectors is almost entirely a function of the fetch. However, the wave energy/fetch control is modified by:

(1) Aspect (orientation) of a shoreline sector with respect to predominant wind/wave direction. For instance, the northeastern shore of Samish Bay is exposed to 25 km of open water to the west, but since westerly winds are infrequent the net wave energy received is small.
(2) Aspect of a sector with respect to peak winds. A good example is the northern parts of Sinclair, Guemes, and Cypress Islands. Even though predominant winds are from the southerly and southeasterly directions, infrequent but major storms from the north produce large waves that have a significant effect on those shoreline segments.

(3) The width of intertidal and nearshore shallow platforms and structures that attenuate deep water wave height and energy.

Beach Materials

The third major determinant of erosion rates is beach materials. The importance of the moveable material on rock abrasion platforms noted above is just one example. Rates of erosion of unconsolidated bluffs in Skagit County are, in many instances, controlled to a large degree by the extent to which the cliff is protected by the beach fronting the cliff foot. The ability of a beach to absorb, and generally dissipate wave energy is determined by a large number of factors that are discussed in detail in a subsequent section (pp.81-85). At this point it is sufficient to note that the "health" or material balance of the prism of moveable beach sediment greatly affects the wave energy reaching the bluff toe. That fact has been reported many times; a paper by Kolberg (1974) is just one recent example.

Erosion Rates

Erosion Rate Data

Measured rates of shoreline erosion at sites within Skagit County are shown on Maps A through H, and summarized in Table 6. Each site where a rate could be determined was assigned an index number by
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*Abbreviations: Qcg: cemented outwash and till; Qt: till; Qgd: glaciomarine drift; Qn: nonglacial, unconsolidated sediments.

**Abbreviations: TR: tree root; TS: triangulation station; US: undercut structure; SS: sea stack; AP: abrasion platform width; LD: lag deposit.
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<td>Qn</td>
<td>US</td>
<td>2.1</td>
<td>18</td>
<td>11.9</td>
</tr>
<tr>
<td>49</td>
<td>H</td>
<td>graywacke/argillite</td>
<td>SS</td>
<td>27.4</td>
<td>5000</td>
<td>0.55</td>
</tr>
<tr>
<td>50</td>
<td>H</td>
<td>graywacke/argillite</td>
<td>SS</td>
<td>24.4</td>
<td>5000</td>
<td>0.49</td>
</tr>
</tbody>
</table>
geographic location. The site numbers start at the north part of map segment A and increase consecutively in a clockwise direction through the rest of the map segments. Table 6 also lists: geologic material, method used to determine a rate, amount of landward recession, and the time span involved in rate determination.

Since it is difficult to discern trends from the geographic listing, the rates are grouped by geologic material type in Figure 25. Displayed in this manner, it is obvious that each of the three general material categories has a mean rate that is approximately an order of magnitude different from the adjoining group(s). Table 7 compares the overall averages for all unconsolidated sites and all rock sites. Further, the unconsolidated sites are subdivided into groups where indirect and direct assessment methods were used.

Analysis of Rates

The interplay of the three primary controls on erosion (bluff material, wave energy, and beach materials) leads to a wide scatter in erosion rates at various sites, even within identical materials (e.g., till). Other factors contributing to the large standard deviations are: (1) many of the rates are only minima, and (2) minimum rates and actual rates (from direct methods) are averaged.

Despite the wide range of values, the distinct similarities found within each material category (Fig. 25) indicate that material type does indeed control erosion to a large degree, and may be the most important of the three major controls. This is well displayed when comparing the erosion rates in unconsolidated materials with those in rock (Table 7). Comparison of rates in the two categories of rock
Figure 25. Erosion rates by bluff material type. The left axis is logarithmic. Each material class is approximately an order of magnitude different from the adjacent type.
Table 7.

Comparative Summary of Erosion Rates
(measurements in cm/year)

<table>
<thead>
<tr>
<th>Category</th>
<th>n</th>
<th>$\bar{x}$</th>
<th>s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total, Unconsolidated:</td>
<td>26</td>
<td>4.9</td>
<td>3.4</td>
</tr>
<tr>
<td>Total, Rock:</td>
<td>24</td>
<td>0.59</td>
<td>0.38</td>
</tr>
<tr>
<td>Unconsolidated, Direct Methods:</td>
<td>6</td>
<td>7.6</td>
<td>2.7</td>
</tr>
<tr>
<td>Unconsolidated, Indirect Methods:</td>
<td>20</td>
<td>4.1</td>
<td>3.2</td>
</tr>
<tr>
<td>Jointed Rock with Moveable Tools on Wave Cut Platform</td>
<td>19</td>
<td>0.72</td>
<td>0.31</td>
</tr>
<tr>
<td>Massive Rock, Bare Platform</td>
<td>5</td>
<td>0.08</td>
<td>0.04</td>
</tr>
</tbody>
</table>

$n$: number of observations

$\bar{x}$: mean

$s$: standard deviation
materials also seems to indicate an order of magnitude difference. There may be that great a difference between the least erodable massive rock types (mean .08 cm/year) and the most erodable jointed rocks (mean .72 cm/year), but the lack of data points between the two groups could be misleading. That is, field observations indicate that there are many combinations of joint densities and amounts of moveable material on platforms. This suggests that there could be a continuum of points for erosion rates ranging from near zero to 1 cm/year or higher. Therefore, the distinct grouping of rates for the rock categories shown in Figure 25 may be partly due to the relatively small number of sites where rock erosion rates can be determined with any degree of confidence.

Somewhat similar problems occur when considering erosion rates for unconsolidated materials. As discussed earlier, there are likely to be differences in erodability of various unconsolidated materials. However, no trend is apparent in the measurements taken. The lack of trend is due to the small sample size and because two of the major variable controls, wave energy and beach materials cannot be held constant.

Comparison of Local and Worldwide Erosion Rates

The shoreline erosion rates found in Skagit County are similar, but generally lower, than those reported for similar material types in various parts of the world. This can be attributed to the relatively modest wave energy expenditure locally. For comparison, rock erosion rates reported elsewhere range from 0.2 to 1.0 cm/year (Rudberg, 1967), 0.6 to 2.8 cm/year (Robinson, 1977), and 0.4 to 100 cm/year with a mean of approximately 25 to 30 cm/year (Kirk, 1977). Erosion of unconsolidated
cliffs cited in King, (1972, pp. 472-473) reach upwards of 4 m/year, with most of the values in the 25-30 cm/year range. Foster (1976) reports erosion rates of less than 8 cm/year to 30 cm/year for unconsolidated bluffs in the vicinity of Victoria, British Columbia.

Timing of Erosional Events

Two physical factors, higher than normal high tides and high winds/waves, control the timing of local shoreline erosion. While it is possible to have erosion if only one element is present, significant and measurable erosion becomes certain if both factors occur at the same time. Upon first consideration, these factors would seem to be entirely random. However, analysis of wind patterns and tidal heights indicates there are only a few days in a year when both high velocity winds and tides significantly higher than normal occur together.

Tidal predictions at Anacortes for the period 1976-1978 reveals a consistent year-to-year pattern of about 35 occurrences/year of tides that are 10% higher than MHHW. Nearly all of these occurrences fall on days during the November-January period, with a total of only 6 days, over the entire three years, during the summer months. If attention is further restricted to those tides that are 15% higher than MHHW there are an average of 11/year, all occurring during November-January. Consideration of seasonal wind roses, or even empirical observation, quickly reveals that high winds are very rare during summer months in Skagit County but are quite common during winter. Equally significant is the fact that the very high tides occur in runs of from 4 to 10 consecutive days at a time. The likelihood of experiencing no strong winds during many con-
secutive days in December or January is fairly low given the normal pattern of storm fronts moving onshore from the Pacific. Thus, it is likely that a very high proportion of all shoreline erosion occurs on just a few days per year (during November-January) when the tides and winds are adverse.

**DETAILED GEOMORPHOLOGY AND SEDIMENTOLOGY OF DRIFT SECTORS**

Field investigation and mapping revealed geomorphic and sedimentary characteristics that changed regularly and predictably through the length of drift sectors (Table 8). The longshore trends occur so regularly that they can be used to characterize much of the coastal geomorphology of Skagit County.

In a previous section (pp. 23-24) the concept of a littoral drift sector was discussed. It was noted that sector beginnings are areas of sediment input from an exogenous source (eroding bluffs or streams). In Skagit County sector heads are a part of the littoral system that experiences a net sediment deficit. By comparison, the prograded termini derive sediment from an endogenous source (the rest of the beach system) and have a sediment excess. The causes for longshore morphologic changes within drift sectors (Table 8) become evident when viewed in light of the sediment deficit/excess status outlined above.

Rather than going through a tedious repetition of each of the features listed in Table 8 for the entire 130 km of county shoreline, a description of each of the longshore trends will be given. This will
Table 8.

Longshore Geomorphic and Sedimentologic Changes within Skagit County Drift Sectors*

1. Longshore decrease in mean particle size
2. Longshore changes in sediment sorting
3. Occurrence of abrasion platform visible beneath beaches
4. Longshore changes in the onshore/offshore size distribution of sediment
5. Longshore increase in distinctness of the high-tide beach/low-tide terrace break in slope
6. Longshore development of beach ridges and berms, and widening of the backshore
7. Longshore change in unconsolidated bluff morphology from vertical to angle of repose
8. Longshore increase in mean beach slope

*Unless otherwise specified, all changes listed are found on the high-tide beach.
be illustrated by an example from a specific drift sector, and also a discussion of the cause and how it applies generally to all drift sectors.

Longshore Decrease in Mean Particle Size

This trend is the most dependable of all longshore changes in local drift sectors. No sectors were found where the trend from coarser sediment at the beginning to finer sizes at the terminus was not obvious. Most typically, beaches at the beginning of sectors are predominantly cobbles, boulders, and very coarse gravel, sometimes exclusively the two former size classes. In the central portions of a sector the sediment is a mixture of all sizes available, ranging from boulders through sand. The terminus is typically mixed gravel and sand, with the mean gravel size being often less than 50 mm.

The trend toward decreasing mean particle size in the downdrift direction is most commonly seen as a mixing of the finer material that is in transport, with the resident population of cobbles and boulders. Those very coarse particles are a lag produced by cliff retreat in that segment of the drift sector. The downdrift size reduction is due to two factors which can act singly or in various combinations. The first cause can be a reduction in wave energy input such as that caused by a change in shoreline aspect (orientation) which allows more sheltering from large waves. Alternatively, the energy reduction can be due to a change in nearshore bathymetry which can attenuate incoming waves. Either type of energy reduction results in a reduction of competence to move sediment of larger sizes. The second reason for size decrease
is the tendency for littoral drift systems (not only in Skagit County) to selectively move the finest sizes even though there may be no aspect/energy change along the shoreline. Because the finest sizes can be moved under almost all wave conditions but the coarser transported material only moves during times of high waves, the finest material moves downdrift faster and more often and is concentrated there.

The predominance of boulders and cobbles at sector heads reflects a high rate of removal of finer sizes from that zone, leaving the coarsest particles as a lag deposit. The complete mixture of sizes in mid-sector is due to sediment in transport being mixed with locally eroded additions which contain all sizes available in the bluff. Thus, nearer the terminus, transported sediment is more abundant and tends to mix with and bury the resident cobbles and boulders. The finer suite of sediment of the prograded terminus is due to transport alone since wave attack of bluffs does not occur behind a prograded beach.

The drift sector from Shannon Point to Ship Harbor (Map D) serves well as a specific example of the above changes. Figures 26 through 29 are photos of beach sediment at the mid-tide level through that shoreline segment. In all drift sectors where there is a substantial sediment contribution from eroding tills and glaciomarine drift the basic size decrease shown in the photos is repeated. However, in sectors where the unconsolidated bluffs are primarily glaciofluvial gravels, the predominance of cobbles and boulders at the sector beginning is commonly absent. Rather, the beach is then characterized by very coarse gravel and small cobbles. In the downdrift direction the gravel sizes diminish and sand sizes increase as a proportion of the total sediment population. The
Figure 26. A heavy predominance of cobbles with only minor amounts of gravel found at the mid-tide level near the beginning of the Shannon Point drift sector. The metal rule is 15 cm long.
Figure 27. Beach sediment at the mid-tide level, approximately 1/3 of the distance through the Shannon Point drift sector. The cobble sizes have diminished slightly from that shown in Figure 26 and a matrix of mixed sand and gravel is also present here.
Figure 28. Beach sediment at the mid-tide level, approximately 3/4 of the distance through the Shannon Point drift sector. Predominant sizes visible are coarse to very coarse gravel, occasional cobbles, and mixed sand and finer gravel between and below the coarse gravel at the surface.
Figure 29. Beach sediment on the prograded beach, Ship Harbor, which is the terminus of the Shannon Point drift sector.
southwest Guemes Island sector (Map B) which begins at Yellow Bluff, an exposure of abundant glaciofluvial gravel and sand, displays the second type of mean size reduction through the length of the drift sector.

Longshore Changes in Sediment Sorting

The changes in beach sediment sorting through the length of local drift sectors are closely linked to the size changes described above, but are not exactly parallel. The beginning of sectors tend to be moderately sorted because the smaller sizes have been depleted by longshore transport leaving a fairly uniform coarse lag. The middle portion of a sector has the poorest sorting due to the mixing of the fine to medium sizes in transport with the local lag, plus the fresh, unsorted sediment being added to the beach by bluff erosion at that point. On the prograded beach the sorting again improves because no coarse material is being contributed by erosion, instead, all material on the beach is the result of longshore transport.

Figure 30 shows the cumulative curves for three beaches within one drift sector, western Cypress Island (Map A). Curve C1 is the beginning of the sector; C2 the middle, and C3 the terminus. Because of the very coarse nature of these beaches, sediment sieving was impractical; instead, the pebble counting method (Wolman, 1954) was used. That method tends to underestimate the amount of finer material, especially if the surface is somewhat armored by the winnowing of fines, as many Skagit County beaches are. Therefore, the three beaches on which the pebble counts were done appear to be better sorted than they actually are.
Figure 30. Cumulative curves from pebble counts within the west-central Cypress Island drift sector. See text for discussion.
Nevertheless, the three curves do reflect, qualitatively, my field observations and are representative of the sorting trend in most drift sectors. The sorting trend can also be seen in Figures 26 through 29, used to demonstrate the mean size changes.

Occurrence of Abrasion Platform

Visible Beneath Beaches

Wave-cut platforms are a common feature wherever rocky shorelines are eroding in Skagit County and have been discussed previously (pp. 21-23). However, platforms cut into unconsolidated Quaternary deposits are also occasionally visible. On a retreating, cliffed coast composed of unconsolidated materials it is obvious that the prism of beach materials must be underlain, at some depth, by the platform. However, in Skagit County, it is only at and near the beginning of drift sectors, that the wave-cut surface is commonly visible. At those sites the sediment cover (depth of the beach prism) is so reduced that one only has to turn over or excavate the depth of 2 or 3 layers of cobbles to find the abrasion surface. In some instances shifting of cobbles during storms will expose patches of platform ranging in size from 100 cm$^2$ to several square meters. In other places the cobble mantle is only one particle layer thick and the platform is visible through the interstices of adjacent particles.

These occurrences of visible platform are usually restricted to the zone at the sector beginning due to the coarse lag in that area, and the rapid and constant removal of finer sizes downdrift. Careful searching for exposed platform rarely reveals any beyond approximately 1/3 the distance from the beginning of the sector. This variability in lateral
extent is due to the difference in rate of sediment supply from erosion versus the rate of sediment flux away from the drift sector head. Figures 26, 31, and 32 are three examples of wave-cut platforms visible at the beginnings of different sectors in Skagit County.

**Longshore Changes in the Onshore-Offshore Size Distribution of Sediment**

On most local beaches there is a trend toward coarsening sediment from the MHHW level to the MLLW level (the high-tide beach low-tide terrace junction). This trend is caused by two processes operating simultaneously. First, the lowest portion of the high-tide beach is the plunge zone of higher waves, an area of the foreshore where the most energy is expended, and consequently, has the coarsest sediment. Second, fresh additions of sediment from recent bluff erosion are more likely to reside initially on the upper part of the high-tide beach before getting sorted out in both an offshore-onshore direction and in a longshore direction. Figure 33 is an example of the coarsening trend down the face of the high-tide beach.

Another aspect of this phenomenon is shown in Figures 34 through 36 where the percentage of the high-tide beach face covered by coarser material gradually diminishes through the length of the drift sector. This is caused by the finer sediment in transport concentrating in the upper portions of the high-tide beach near the sector beginnings. Further downdrift, where the transported fraction is more abundant, it covers increasingly wider portions of the high-tide beach face. The trend described applies to the net, long-term condition of the beach.
Figure 31. Wave-cut surface eroded into glacial till near the beginning of the south Cypress Island drift sector (Map A). Note also till debris blocks in upper edge of photo (see discussion, p. 94).
Figure 32. Eroded Whidbey Formation forming the wave-cut surface beneath coarse gravel and sand near the beginning of the southeast Guemes Island drift sector (Map B).
Figure 33. Coarsening particle sizes increasing down the face of the high-tide beach. The sediment in the lower left is at the +2-foot tide level.

Figure 34. Photo near the beginning of the southwest Guemes Island drift sector (Map B). Note how the coarsest sediment covers nearly the whole high-tide beach face.
Figure 35. Photo taken approximately 3/4 of the distance through the southwest Guemes Island drift sector. Note how the coarsest sediment covers only the lowest 1/3 of the high-tide beach.

Figure 36. Near the terminus of the southwest Guemes Island drift sector. Virtually no visible change in sediment size over the whole high-tide beach which is uniformly sand, in other sectors uniformly fine and medium gravel.
In the onshore-offshore direction the appearance can change slightly in summer, particularly on prograded beaches. In summer the zone of maximum energy dissipation is shifted landward because of smaller waves. On prograded beaches the coarsest particles that can be seen are exposed at the mid-tide level. The permanent coarsest population is still usually located at the lowest extremity of the high-tide beach but is often buried by finer material moved up from the low-tide terrace. The overall appearance, then, is a finer upper and lower segment in the high-tide beach, with a coarser strip in the longshore direction, in the middle of the beach. This seasonal change is not found on beaches near sector beginnings since there is not enough fine, moveable sediment to bury whole segments of the cobble beach.

Longshore Increase in Distinctness of the High-tide Beach/Low-tide Terrace Break in Slope

In an earlier section on the general morphology of local beaches, the presence of a fairly distinct and obvious junction between the high-tide beach and low-tide terrace was noted as being characteristic. There is, however, a longshore trend in the sharpness of the junction or angular difference between the slope of the two beach segments. The break in slope is best developed where there is both abundant gravel supplying the high-tide beach, and also abundant sand available for the low-tide terrace. On an overall basis, then, the slope break is best developed where there is enough of a sedimentary prism to have a morphology shaped by littoral processes rather than reflecting the topography of the underlying wave-cut platform. This condition is best met on prograded beaches, hence the sharp break that is obvious in Figure 3.
At drift sector heads the high-tide beach and low-tide terrace often do not exist as distinct elements since the wave-cut platform extends to well below the normal MLLW junction. At these sites one often finds sand mantling the platform and filling the interstices between cobbles only at and below the MLLW level. I consider the sand below that level to be the analog of the low-tide terrace even though it has no topographic expression. A short distance downdrift from the sector head sufficient sediment cover is present on the high-tide beach and enough sand present on the low-tide terrace to allow a distinguishable break in slope to develop. Proceeding down the sector length, the greater availability of transported sediment provides a deeper moveable prism of sediment which steepens the high-tide beach. The result is a constantly increasing angular difference between the two beach segments with an attendant increase in distinctness of the slope break.

There are two exceptions to the general pattern described. In sectors that have an unusually high supply of sand with little coarser material (e.g., from the erosion of sandy outwash deposits) the sediment on both the high-tide beach and on the low-tide terrace is sand. The sedimentologic similarity between the two segments produces a less distinct slope break (even on prograded beaches) than is found at a similar location within other drift sectors. An example is Alexander Beach (Map D); there the prograded baymouth barrier is nearly all sand. Rather than a distinct slope break, the beach is broadly concave upward with gentler slopes lower in the foreshore. The other exception to the general pattern is on the tip of spits. There the high-tide beach merges imperceptibly with the spit platform (Meistrell, 1966) and produces a
similar concave upward profile that changes gradient gradually instead of a sharp break. The three active spits in Skagit County all have this condition at the distal tip.

Longshore Development of Beach Ridges and Berms, and Widening of the Backshore

The downdrift increase in abundance of moveable sediment derived from transport is most clearly manifested in changes in the zone landward of the MHHW level. In that zone two related morphologic changes occur simultaneously toward the terminus of a drift sector. For the purpose of description and explanation these are discussed separately, but both are part of the same process.

The first is the development of a beach ridge or berm. The beginning of nearly all drift sectors is characterized by either no berm or by a small ephemeral swash ridge at the MHHW level. I have informally termed this feature the "summer berm" because it is built and maintained by the low summer waves. The lack of easily moveable resident sediment at sector heads precludes formation of an extensive berm system. Figures 31 and 34 are examples of poor berm development at sector beginnings. Proceeding downdrift, the increasing availability of moveable sediment results in better development of the summer berm. At approximately mid-sector (depending on sediment supply) the beginnings of a "winter berm" begin to appear behind the summer berm. This ridge of sediment is beyond the reach of normal summer waves; its face becomes the active, high-tide swash/backwash zone during winter when the more ephemeral summer berm has been removed by higher winter waves. At a point approximately 3/4 of the distance through the sector the winter
berm becomes almost completely developed and may even have seasonal vegetation on it. Finally, at the prograded terminus, it is very typical to find not only the winter and summer ridge, but a series of unvegetated or partially vegetated beach ridges accumulated behind the active winter berm.

As more sediment is stored in the backshore the MHHW line is displaced laterally seaward. This displacement or widening of the backshore is the second of the two factors alluded to above. At drift sector heads the distance from the MHHW mark to the foot of the cliff is often 3 m or less. At many sector beginnings it is impossible to walk along the base of the cliff when the water is at MHHW or slightly higher. From approximately the ½- to ⅓-way point in the sector the backshore width increases to an average of 3 to 4.5 m. In the downdrift half of sectors the backshore width is typically 4.5 to 7 m. At the prograded terminus the unvegetated portion of the backshore is of variable width, depending on the rate of sediment supply and the rate of vegetative encroachment toward the water, but is almost always greater than 6 to 7 m. Figures 37 through 39 are photos of the southeast Guemes Island drift sector (Map B) that demonstrate increasing backshore width through that sector. They were taken during winter so no summer berm is visible, but the trend toward a wider backshore is obvious.

Longshore Changes in Unconsolidated Bluff Morphology

Longshore changes on the beach produces a parallel change in bluff morphology through the length of drift sectors in Skagit County. At drift sector heads the lack of a protective beach and backshore, and
Figure 37. (above) Near the beginning of the drift sector. The backshore here is 1.5 m wide and decreases to zero at the right edge of the photo.

Figure 38. (right) Backshore width has increased to slightly over 3 m at a point 1/3 of the distance through the drift sector.
Figure 39. Photo taken 3/4 of the way through the sector. The normal MHHW mark is at the small boulder at the right edge of the photo; the previous summer the active swash ridge was built over the boulder, 4 m from the bluff toe.
often higher wave energy, allows enhanced wave attack. The result is bluffs that have a vertical or near vertical profile, often with a notch at the toe due to undercutting.

Downdrift the simple, vertical profile is replaced by a slope-over-wall morphology where the upper slope is at the subaerial angle of repose, or slightly steeper, for the material involved. This slope may be partially or totally vegetated depending on its stability. The lower slope segment, the wall, is a vertical or near vertical wave-maintained scarp that may be partially buried in colluvium in some drift sectors. Temporary burial occurs if the upper slope is too steep to be in equilibrium with the subaerial processes or if active cutting on the wave-maintained scarp continuously keeps the upper segment in an oversteepened condition.

Shortly downdrift from the sector beginning the upper slope is only a small portion of the total bluff height and the lower, vertical wall predominates. Proceeding downdrift the wave-maintained scarp typically comprises less and less of the total bluff height. Near the terminus, where berms are fully developed, bluffs are often fully vegetated, simple, angle-of-repose slopes with little or no wave-cut scarp. The decrease in wave-maintained scarp height, which parallels the increasing backshore width, strongly suggests that increased sediment supply downdrift provides greater bluff protection in the form of a wider backshore. An example of this trend from undercut, simple vertical profile, through slope-over-wall profile, to angle-of-repose profile occurs in the south Cypress Island drift sector (Map A) shown in Figures 40 and 41. Similarly, changing slope morphology along with
Figure 40. Beginning of the south Cypress Drift sector (Map A). Here characterized by undercut, near-vertical bluffs.

Figure 41. Near the terminus of the south Cypress Island drift sector looking west toward the beginning. Figure 40 (above) was taken at the extreme left edge of this photo. Note the gradual trend toward replacement of simple vertical slope by simple angle-of-repose slopes as in the right side of the photo.
changing backshore width can be seen in Figures 38 and 39 used to demonstrate backshore width increase.

The above changes in bluff morphology are less consistent than other longshore changes described in this section. The pattern is most clearly expressed in those sectors where bluff materials and heights are relatively homogeneous throughout. Where bluff height changes rapidly and repeatedly through the sector, or where there is a resistant headland interposed in an otherwise uniform bluff line, morphology can change rapidly. A very non-resistant material (e.g., glaciofluvial sand) at the sector beginning can also modify expected bluff morphology, but does not obliterate the pattern. An example occurs in the eastern Guemes Island drift sector that has its terminus at Sleepy Hollow (Map B). The sector begins in bluffs composed of glaciofluvial sand; its low shear strength does not allow a notch to develop at the cliff toe, but surprisingly, in places the bluffs do stand at angles well in excess of 50°. The normal angle of repose for this material is about 30°. This suggests that even in poorly-cohesive materials the morphologic trend can be maintained if basal removal is rapid enough. Thus, there is almost no correlation between bluff material type and the angle at which it stands. Rather, the bluff angles seem to be almost wholly determined by the relative balance between marine and subaerial processes. It would seem that a composition/angle correlation could be found only in the absence of marine attack.
Longshore Increase in Mean Beach Slope

As alluded to in the Methods section, the recording of beach slopes early in this study was not rewarding. The slopes seemed to bear no relationship to particle size, a common correlation on beaches. Eventually, a trend of increasing slope downdrift in sectors was noted. Specifically, beaches at drift sector beginnings have low slopes of 2-4°; middle portions of sectors show a gradual increase in slope from 4-5° near the beginning to 7° near the terminus. On prograded beaches slopes are almost always greater than 7½°.

Over 120 separate measurements of beach slope and the individual elements comprising the longshore trends discussed in this section showed a close correspondence. The changing mean slope through a sector can be used as an index of the other simultaneous changes. The measurements and correlations are summarized in Table 9.

Two minor exceptions to the beach slope trend are not presented in Table 9 because they rarely occur in Skagit County. The first is beaches that are composed mostly of sand with only minor gravel. Of the 6 beaches of that type, 3 have eroding bluffs behind the beach and 3 are prograded. The sample size is not large enough to establish trends, but it was found that all three eroding areas have beach slopes of less than 4° while the three prograded beaches have slopes greater than 4°. This suggests that the 4° slope may represent a threshold value separating prograded and non-prograded sandy beaches just as the 7½ to 7½° slope seems to be a lower limit for prograded, mixed sand-and-gravel beaches in Skagit County.
<table>
<thead>
<tr>
<th>Mean beach slope</th>
<th>berm development</th>
<th>backshore width</th>
<th>bluff morphology</th>
<th>beach sediment</th>
<th>visibility of wave-cut platform</th>
<th>high-tide beach/low-tide terrace slope break</th>
<th>beach width MHHW to MLLW</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤4°</td>
<td>none</td>
<td>0-2 m</td>
<td>simple vertical or near vertical; no vegetation</td>
<td>predominantly cobbles and boulders</td>
<td>large patches common</td>
<td>often no topographic expression</td>
<td>&gt;45 m</td>
</tr>
<tr>
<td>4 - 5°</td>
<td>none or incipient summer berm</td>
<td>1-3 m</td>
<td>slope over wall with the vertical, wave-maintained scarp predominating</td>
<td></td>
<td>small patches common</td>
<td></td>
<td>34 - 43 m</td>
</tr>
<tr>
<td>5 - 6°</td>
<td>summer berm</td>
<td>2-4 m</td>
<td>slope over wall; angle of repose slope dominates; fully vegetated upper slope</td>
<td></td>
<td>small patches rare</td>
<td></td>
<td>27 - 37 m</td>
</tr>
<tr>
<td>6 - 7°</td>
<td>summer and winter berm</td>
<td>4-7 m</td>
<td>simple angle of repose slope; completely vegetated; may have low wave-maintained scarp of 1-3 m</td>
<td></td>
<td>not seen</td>
<td></td>
<td>24 - 34 m</td>
</tr>
<tr>
<td>≥7 1/2°</td>
<td>summer and winter berm plus 3-7 m of active beach ridges</td>
<td>&gt;6 m</td>
<td>isolated from marine processes, ways less than 100 mm usually &lt;50 mm mixed with sand</td>
<td></td>
<td>almost always never seen</td>
<td></td>
<td>usually very pronounced</td>
</tr>
</tbody>
</table>
The other class of exceptions is the distal tips of spits. There are only three active spits in Skagit County: Kirby Spit (Map C); Weaverling Spit (Map D); and Crandall Spit (Map E). On each of these the headland beach adjacent to the base of the spit has a slope near 7°, a typical value near the sector terminus. At the base of the spit the slope increases to at least 7½° as is the pattern on almost all prograded beaches. But, at the tip of the spit the slopes again decrease to between 4° and 6°. Meistrell (1966), in investigating spit and spit-platform development, noted that the steeper beach slope near the base of the spit and a decreasing slope near the tip is characteristic. Therefore, it would seem the decreasing slopes near the tips in Skagit County are not a local aberration.

No published study has been found that reports results analogous to the drift sector/beach slope trend discovered in Skagit County. Published material on beach slopes (Bascom, 1951; Shepard, 1973, p. 127) notes that slope is a function of particle size, which controls permeability. Relatively impermeable, fine sand beaches slope at 1°; coarser materials have increasing slopes to a maximum of about 24° for highly permeable cobble beaches. The beaches of Skagit County seem to violate those well established principles of size/permeability/slope. Here, there appears to be a reverse correlation, with the coarsest beaches (cobble beaches at sector heads) having the lowest slopes. That correlation does exist (Table 9), but on local beaches the interplay of other factors exerts more control on slope than mean particle size does. Thus, no direct comparison can be made with the previously published values cited above.
The three primary reasons for the unexpected relationship in Skagit County are: (1) sediment supply, (2) tidal range, and (3) sediment sorting.

Sediment supply is the most important control of local beach slopes. Many beaches are poorly supplied and have only a thin sediment cover over the wave-cut platform. This is most easily seen at drift sector beginnings where large patches of platform are exposed. There, sediment is so sparse that the beach surface is parallel to the platform which is only a few centimeters below. Therefore, regardless of the sediment size (in this case very coarse), the 2-4° slope is controlled by the platform, which is to say, the lack of a thick beach deposit. Further downdrift, in the mid-sector area, the platform, though often not visible, still partially controls mean slope. There the lower portions of the high-tide beach are still predominantly cobbles (Fig. 33). If the coarse material is excavated, the platform is commonly found a half meter, or less, below. Since the finer sediment in transport accumulates mainly at the highest portion of the high-tide beach, at the MHHW level, and in the backshore, the wedge of sediment is much thicker there. This increasing thickness of transported sediment gives rise to the progression of higher mean slopes found through the length of sectors. Only on prograded beaches does slope appear to vary in response to mean particle size (permeability) in a manner that resembles published relationships. Those prograded areas with elevated sand content (but not mostly sand) mixed with gravel are close to the 7½ to 7½° minimum for local prograded beaches, whereas, those with a larger mean size and lower sand content are in the 9-10° range. The steepest beach found is at Sleepy Hollow (eastern Guemes Island, Map B); there mean sediment
size is a uniform 60-70 mm coarse gravel and the slope is 11°. However, even these steeper, prograded beaches are not nearly as steep as published values would indicate based on mean grain size and permeability. Thus, there are factors other than sediment supply that also lead to lower slopes.

Davies (1973) notes that on beaches with equivalent wave energies and particle sizes the beach with the larger tidal range will have a lower slope. This effect is manifested in the swash/backwash zone traversing a fairly wide lateral distance during a tidal change (Table 9). The local mesotidal to macrotidal environment thus affects the foreshore profile.

The third factor, particle size sorting, also appears to help produce lower slopes, particularly on prograded beaches where lack of sediment supply is no longer a cause. McLean and Kirk (1969) demonstrated that slope is a function not only of mean grain size, but also of sorting. Their investigation was done on poorly sorted beaches composed of mixed sand and shingle. The beaches of Skagit County and much of the Puget Sound region are the same, that is, derived primarily from erosion of glacial drift materials as are the poorly sorted beaches that McLean and Kirk investigated. The bimodal or polymodal sediment population, with sand as one of the modes, means that the permeability is not being controlled only by the coarse(est) mode. Rather, sand filling the interstices among larger particles leads to reduced permeability and hence, a lower beach slope. As a result, the beach angles found locally, more closely approximate those published by McLean and Kirk (the majority of slopes between 5 and 10°) than those given in standard references.
COASTAL SLOPE STABILITY

A wide variety of slope processes and mass movements are common along all Skagit County shorelines. They range from slow continuous slope processes, through small, individual mass movements, to stretches of coast that form mass movement zones. Although not investigated in this study, slow, continuous processes (soil creep, slope wash, and freeze/thaw weakening) appear responsible for some transport of bluff material to the beach, but are not nearly as significant as direct wave erosion and mass movement. Soil creep is especially effective where the entire bluff toe is a steep, wet, vegetated colluvial fill or landslide debris, as on both the east and west shores of Similk Bay. There, both soil and vegetation are pushing out over the top of the wave-maintained scarp and falling to the beach.

Small Mass Movements

Under the general category of mass movements I have drawn a distinction between small, non-hazardous failures that are ubiquitous on coastal bluffs and go on nearly continuously, and large slope failures that could produce severe economic loss or loss of life. In nearly all cases, small mass movements are minor slope readjustments in response to wave cutting and oversteepening at the base. In comparison, there is an extensive zone of landsliding on western Fidalgo Island that will be discussed in detail below. The variety of mass failure appears to be related to the diverse origins and mechanical properties of the Quaternary bluff-forming materials because sizes and styles of failure are repeated in similar materials and stratigraphic settings throughout the county.
In glaciomarine drift there is a strong tendency for failure to occur through small, shallow rotational slumps. These slumps are usually less than 12 m wide and 5 m deep (Fig. 42). They occur on low bluffs composed entirely or nearly entirely of glaciomarine drift but seldom occur where the drift is thin and only caps another unit (as it often does). Geographically, the largest numbers of these failures are on northeastern Sinclair Island, on western Cypress Island for approximately 1 km either side of Tide Point (both areas on Map A), and on eastern March Point (Map E). Similar small failures are found in low till bluffs, but are not nearly as common as in the glaciomarine unit. The drift is presumably weaker because it has not been overconsolidated by glacial ice and has a lower bulk density (Easterbrook, 1964).

Till is highly overconsolidated and has a comparatively high shear strength. This is displayed by the most common type of mass failure. In seaciffs till often stands at steep angles (60-90°) and becomes notched and undercut by wave attack at the toe. Failure usually takes the form of a slabfall or blockfall with the overhanging segment shearing from the face and disintegrating into blocks on the beach below. An example of this type of undercutting can be seen in Figure 40, and blocks of till debris are seen in Figure 31. Slab failure in till is found in shoreline segments along the south shore of Cypress Island, the east shore of Sinclair Island (both on Map A), the eastern part of Dewey Beach, and both north and south of Kiket Island (all on Map G). A similar style of failure is seen in the massive, silty sand of the Whidbey Formation on the south shore of Guemes Island (Map B).
Figure 42. Small rotational slump in glaciomarine drift on western Cypress Island (Map A). The stumps at the right and left are at the edges of the slump; the headscarp is partly visible in the upper-right-center.
Coarse, granular deposits, such as glaciofluvial gravels, sands, and mixed sand and gravel, fail as discrete wedges or slabs, typically 6-20 m wide that cut back into the bluff top 3-10 m. Since the wedges are semicircular in map view the resulting morphology is a scalloped cliff edge (Fig. 43). Often semicircular cracks and depressions (indicating incipient failure planes) can be found on the bluff top within 5-8 m of the edge. Upon failure the wedges travel all the way to the beach, leaving a vertical scar stripped of vegetation down the bluff face as in Figure 44. The localities most prone to this type of failure are: northern and southwestern Guemes Island (Map B), the western part of the north shore of Samish Island (Map C), western Fidalgo Island (Map F) from just north of Edith Point continuing north for about 1.5 km and the western shore of Similk Bay (Map G). All the above areas are delineated on the maps as landslide zones and are discussed below under the subject of hazards (p. 106).

Major Mass Movements

Occurrence, Morphology, and Stratigraphy

The largest, most hazardous, and most complex failures occur where two dissimilar Quaternary deposits and abundant groundwater occur together, a 2 km stretch from Biz Point to just north of Edith Point on western Fidalgo Island (Map F). The bluffs are up to 100 m high with the upper 2/3 composed of Fraser age outwash sand and gravel, and lower 1/3 of pre-Fraser, non-glacial, laminated silt and clay, possibly Whidbey Formation. In this area there are 7 large bowl or amphitheater-shaped scars representing sites of long continued landsliding. Active landsliding
Figure 43. Scalloped bluff morphology developed in outwash sand and gravel about 0.5 km north of Edith Point (Map F). This mass movement zone continues in the distance at the left edge of the photo; the vertical gaps in bluff-face vegetation indicate failure locations.
Figure 44. A typical failure in glaciofluvial outwash where the failed mass leaves a vertical scar leading to the beach. Location: northwestern Guemes Island (Map B) about 1 km south of Indian Village.
into these amphitheaters is continuing. Amphitheaters range from 100-250 m in diameter, averaging 150 m; average area is over 2 ha. The lowest portion or floor of the bowls lies approximately at the contact of the two stratigraphic units. All have headscarsps in excess of $45^\circ$ which give way to "gentle" $15-20^\circ$ slopes in the bottom of the bowls. The bowls are connected to the beach by narrow chutes less than 15 m wide. Despite the size differences, all 7 have identical overall morphology and stratigraphy. That similarity provides a rare opportunity to observe various stages of activity in each, and from those observations construct a composite model for their initiation and operation. Figures 45 and 46 are diagrammatic sketches based on composite measurements. Additional reasons for detailed investigation of these sites are the large size, the very unusual morphology, and the possible hazard associated with them.

Mode of Operation

Bare, wedge-shaped scars along the upper rims of bowls show that failures originate there. The failed material slides or falls to the bottom of the bowl, breaks up, and becomes a debris slide or flow (depending on how wet it is). At that point the failed mass can take various pathways.

If it is large and has sufficient velocity, it will continue all the way through the chute to the beach. In the process, vegetation, including large trees, will be incorporated into the debris which ultimately forms a semicircular fan on the beach. Amphitheaters that have had debris flows reach the beach during the last few years can be easily spotted in air photos by the presence of several tree trunks lying normal to the shoreline with the butt still imbedded in debris landward of the
Figure 45. Diagrammatic map view of amphitheater-type landslide site (not to scale).

Figure 46. Diagrammatic cross section of amphitheater-type landslide site (not to scale).
MHHW line instead of the usual pattern of drift logs lying parallel to MHHW. During field investigation trees at the chute mouth, as described above, could be seen in front of the amphitheatres labeled number 1, 2, and 4 in Figure 47. If the failure is of insufficient size and/or if the bowl has become heavily vegetated since the last major failure, the debris can become trapped and come to rest as a tongue-shaped lobe in the bowl bottom or as a plug in the narrow chute. In that case the evidence of failure is not easily visible in air photos. In amphitheater number 3 several lobes of debris are visible from inside the bowl; each lobe has young alder trees growing on it, the oldest lobe has trees approximately 20 years old. Eventually, the arrested failures become incorporated in a larger event that again scours the bottom of the bowl and forces its way to the beach. A third pathway for failures is multiple flows (over a period of years) piling on top of each other in the chute. This builds a thickening plug that becomes unstable and evacuates as a separate event, leaving debris lobes and standing vegetation intact in the bottom of the bowl. This occurred 3-5 years ago in amphitheater number 2. The separate chute filling events are indicated by buried organic horizons in landslide debris still remaining on the chute walls.

Age and Origin

The amphitheatres are old features, surely pre-European settlement, and quite probably well in excess of a thousand years old. That judgment is based on the fact that large trees (over 70 cm in diameter) are growing high up on the chute walls and parts of the lower bowls that have not had recent activity. The large trees suggest continued stability, at least in some portions of these features, for long periods of time after they
Figure 47. Sketch map of the Biz Point/Edith Point area. Amphitheater-type landslide sites are numbered from north to south.
were formed. A number of alternative hypotheses for the formation of the amphitheaters were tested. They range from a single catastrophic event (possibly earthquake triggered) where most of the amphitheater we now see was evacuated at once, or alternatively, a large rotational slump that has moved over a long period of time so the downward rotating top surface now forms the bottom of the bowl. Only one hypothesis seems to fulfill all the requirements imposed by stratigraphy, morphology, and known mode of operation. On the seaward-facing bluffs on either side of the narrow chute mouths, the strata are undisturbed and flat lying. That fact rules out a large rotational slump and indicates that the chute has always been a narrow slot through the bluffs. Each of the 7 amphitheaters has a stream exiting to the beach through the chute. The stream maintains a V-shaped morphology in the chute except where the chute is plugged. In chutes that have been recently active the stream incises the V-shape into the bottom of an otherwise U-shaped scar, thus reestablishing the original V-shaped morphology. Recognition of the original nature of the chute and basic V-shaped morphology is the key to understanding the origin of these failures. The chute morphology is highly suggestive of an origin from a steep, V-shaped valley or gully incised into the bluff face. The valley probably originated from a stream that flowed over the bluff top or possibly below a spring that exited the bluff face at the contact between the permeable sandy material and the underlying silt/clay deposit. The lower stratigraphic unit, being more cohesive, would tend to maintain the original V-shaped gully morphology and undisturbed stratigraphy that is still seen in, and adjacent to, the chutes. In the non-cohesive unit above, spring sapping or piping at the contact would initiate failure and headward recession. Once the
topographic form of the bowl started, the process would become even more effective as the enlarging bowl would intercept and concentrate even more groundwater. If the first alternative (a stream from the bluff top) was the origin, then failures in the outwash forming the steep side slopes of the gully could begin the process of bowl formation.

Although most failure occurs in the granular materials above the bowl floor due to increased pore pressures during unusually wet weather or by spring sapping, slumping within the fine-grained unit below may also occur. Stepped topography in the upper parts of the chute and on the bowl floor suggests the treads and risers of the steps may be a series of small rotational slices within the laminated unit. If these are indeed slumps, their movement and withdrawal of support could trigger failure in the overlying material. Steps were visible in amphitheater number 4 during the summer of 1977 following stripping of vegetation and clearing of debris caused by a failure in the winter of 1975/76. The area and thickness of the debris fan (partially visible in Figure 48) show at least 1000 m$^3$ were involved in that failure.

Landslide activity during unusually wet winters is relatively common in the Puget Lowland. The particular stratigraphic setting that produces the Fidalgo Island slides has been found to be very susceptible to failure in inland parts of this region (Tubbs, 1974; Heller, 1978). The failures on Fidalgo Island almost certainly are controlled only by the stratigraphic and groundwater conditions, and are not influenced by marine erosion. The 225 m average distance of the headscarps from the beach indicates the continued activity is unrelated to marine processes.

Although similar amphitheaters are occasionally seen along Puget Sound shorelines, the presence of the narrow chute is unusual. I am
Figure 48. Looking seaward through the chute of amphitheater number 4 (Fig. 47). The lower portions of the bowl floor and the chute are beginning to revegetate 18 months after a major failure. Note the debris fan on the beach in the background.
aware of only two others with identical morphology; both are much smaller, but nicely fit the initiation model developed above. One is in northern Whatcom County, on a shore bluff north of Cherry Point. It developed from a gully receiving water through a culvert from a bluff-top road. The second is on the south shore of the Strait of Juan de Fuca, about 3 km east of Green Point. In that case the water is emerging from a spring at the contact between a laminated silt and overlying outwash sand.

Landslide Hazards

The amphitheaters are currently active and will continue to be active into the foreseeable future. The bowls will continue to regress landward because the headward portions have very steep slopes, and because the failed material rarely comes to rest at the foot of the scarps which might begin to stabilize them as a colluvial toe buttress. Since excess water is at least one of the main triggers for activity, the addition of more water to these slopes is clearly unwise. However, water, in the form of septic effluent, is being added to the ground behind the amphitheaters (Skagit County Planning Dept., oral communication, 1978). The amount of water added by septic systems is not commonly realized. Using data on average per-person water usage (U.S. Dept. of Housing and Urban Development, 1967) and assuming a housing density of 3/acre, computations show a net input of an extra 12 inches of water per acre/year. Since the average runoff in this area is only about 6 inches (17cm) per year (p. 24) the 12 inches (an acre-foot) of added water would be a 200% increase which could exacerbate an already difficult situation.

The hazard in the Biz Point/Edith Point area is that a failure might include a dwelling that is close to the edge of the amphitheater.
I have not been able to determine the rate of enlargement of the amphitheater bowls. However, based on the depth of the scars left by failed wedges in similar outwash materials found in the other landslide areas described earlier, it seems clear that any structure closer than about 10 m from the cliff edge could be severely damaged or tumbled down the cliff. At present, there are a number of houses that are between 10-15 m from the bluff edge. In addition, there are houses built on the narrow fingers of intact bluff top that separate adjacent amphitheaters (Fig. 47).

While the amphitheater zone is clearly the most hazardous area, the zones that have the scalloped bluff morphology developed in Fraser age outwash materials also present some hazard. Accordingly, they are delineated as such on the maps. The same unfavorable combination of stratigraphic units (outwash overlying relatively impermeable deposits) is present in each of the zones delineated. No large amphitheater-type failures have yet developed there, possibly because of less groundwater. It should be noted, however, that all the other zones show what could be the beginnings of small bowls and chutes (Fig. 44). Whether those failures could develop into amphitheaters is speculative but the possibility cannot be ignored. In that regard, the largest and most recent failure (within the last 3 years) on the northwestern shore of Similk Bay (Map G) is directly below a new housing development, begun about 5 years ago, that uses septic systems. That is possibly a coincidence; but the location suggests otherwise.
The beaches at, and north of, the amphitheater-type landslide zone (Map F) have high percentages of sand mixed with the gravel, and the sand percentage increases to the north (downdrift). At Anaco Beach (near the terminus), the littoral sediment becomes nearly all sand. The sand-dominated beaches indicate that there is a substantial sediment input from the sandy, glacial outwash in which the landslides occur. Another indicator is the bluff morphology within that drift sector. The unconsolidated bluffs are nearly all heavily vegetated with only small, wave-maintained scarps at the base, a pattern very different from that seen in other sectors. This too suggests that the landslides provide enough beach sediment to partially protect the bluffs in contrast to the typical pattern of vertical, relatively rapidly eroding bluffs seen at and near the beginnings of most drift sectors. Thus, while the percentage of the total beach sediment budget contributed from the amphitheaters is difficult to quantify, the sedimentologic and morphologic evidence indicates it could be well in excess of 50%.

A somewhat similar situation exists on Guemes Island in the drift sectors north and south of Indian Village (Map B). There the sedimentologic evidence is less clear (more glaciofluvial gravels in the bluffs) and the wave-maintained scarps are higher than those seen on western Fidalgo Island. However, debris cones deposited over wave-maintained scarps (Fig. 44) are common. This indicates that sediment derived from direct wave attack of bluffs is being supplemented by the mass movements.
HUMAN MODIFICATION OF THE SHORELINE

Those parts of Skagit County shoreline that are fronted by beaches show little influence from man-made structures in most area; though, one segment, along the northeastern part of Samish Bay (Map C) below the railroad right-of-way, is heavily rip-rapped. The modifications most often encountered are bulkheads, seawalls, and retaining walls installed by individual property owners. These types of structures are delineated on the maps as "lightly modified." A second type of modification, seen principally along the Skagit Delta (Map H) and the eastern shores of Samish and Padilla Bays (Map C and E), consists of dikes and levees. These areas appear on the maps as "significantly modified shorelines." The dikes were installed (mostly prior to 1900) along the original marsh fringe to prevent salt water inundation during very high tides, allowing use of the land for agriculture. Thus the shoreline in those areas, though in its natural position and retaining some of its natural characteristics, has little of the natural marsh system that originally existed. The areas designated as "heavily modified artificial shores" consist of industrialized zones of docks and artificial fill where the original shoreline no longer exists.

The diking of wetlands and change to agricultural use appears to have produced small changes in the subaerial portion of the Skagit Delta's original boundaries. Bortleson, et al. (1979) have documented these changes, and also what they interpret as small, naturally occurring changes at the subaerial fringe. The changes involve landward recession (on the central part of the delta) of the marsh fringe seaward of the levees; probably because the levees cutoff small distributary channels
and streams that brought in sediment. The natural changes consist of a seaward accretion of some specific areas around the two primary distributary channels at the north and south edges of the delta.

In summary, human modification of the shoreline is pronounced in some parts of Skagit County, primarily in the delta area. Most shoreline segments with coarse beaches, on which this study focuses, are natural or (in a few areas) have been lightly modified.

**DISCUSSION**

**Coastal Erosion**

The most accurate measurement of cliff retreat (unconsolidated materials) is by direct measurement (i.e., triangulation stations) which yields a mean rate of 7.6 cm/year. If the most reliable indirect measurement sites, those man-made structures where the position of both the original shoreline and structure are best known, are included with the direct measurements, the mean increases to 9.5 cm/year. Where tree root measurements can be checked against other methods at nearby sites, the tree root data underestimate rates by about 50%. If that underestimation applies to all the tree root measurements (as presumably it does) then doubling the rates derived from tree roots may not be unreasonable. If this is done, the indirect mean (4.1 cm/year) increases to 8.2 cm/year, a figure reasonably similar to the 7.6 and 9.5 cm/year means noted above. Thus I presume that true mean rates are likely to be in the range of 7-10 cm/year, at least in the more exposed segments of Skagit County.

While analysis of previous erosion to derive rates yields useful long term averages, those mean rates obscure the large amount of temporal
and spatial variability (dependent on tide and wind patterns) discussed on page 62. On a geographic basis, the undercut, vertical bluffs and eroded beaches that occur at drift sector beginnings indicate that the highest erosion rates occur there. Although the evidence for faster erosion there is clear, not enough erosion measurement sites were found along the length of any one sector to conclusively prove this supposition inferred from geomorphic evidence.

Shoreline Modification

Though many areas of the county's shoreline have not been defended by man-made structures, there is at least one shore segment (north-central Samish Island, Map C) where defense structures appear to be exacerbating an erosion problem. There, some shore defenses were built as long ago as the 1930's. As more and more bulkheads have been built through the years, less sediment can be derived from bluffs. At the westerly extremity of the terminal, prograded beach, erosion has been noticed within the last 10 years. This erosion could be a mostly natural occurrence but it is probably also linked to the partial cutoff of the beach sediment source, the bluffs. The northern Puget Sound region shorelines are particularly vulnerable to this type of man-caused (or man-aided) erosion because nearly all beach sediment is derived from bluffs.

Longshore Geomorphic Trends within Drift Sectors

As this report has shown, within Skagit County there are systematic variations in geomorphic and sedimentologic features that can be used
to define the boundaries of drift sectors. Additionally, these variations, which take the form of longshore trends, are a convenient method to summarize the geomorphology along whole segments of shoreline. Thus, it is felt that this approach is a useful way to document processes as indicated by morphology.

Most of the longshore trends found in Skagit County do not appear in the geologic literature. One reason may be that many published studies deal with sandy beaches rather than the coarse-grained systems, as found locally. One aspect of longshore change, decreasing mean grain size in a downdrift direction, has often been referred to in a general way. For example, Morisawa and King (1974) note that the coarsest sediment is found in the zones of highest wave energy, but they do not actually specify decreasing mean size in the downdrift direction. Due to the particular combination of dissected shoreline, sediment supply from bluffs, and wave and tidal regime, the geomorphic trends may apply only locally, rather than to all coarse beach systems. However, they should be applicable through much of the Puget Sound region since the same suite of Quaternary sediments and the same oceanographic factors are found in nearly all areas. It should be emphasized, however, the longshore trends need not be identical in all areas of the region. An example is the description of mean grain size reduction on pages 66 and 71 where one sector beginning is dominated by boulder size material and decreases to gravel at the terminus, while the other sector beginning is mostly very coarse gravel and decreases to sand at the terminus. Even though a longshore trend exists in both cases, no absolute numbers can be used to specify, a priori, the exact change that will be found.
The recognition, fairly early in this study, that increasing mean slope of the high-tide beach is correlated with morphologic changes downdrift (Table 9), especially sediment supply (p. 91), provided an opportunity to make the necessary measurements to document the relationship. In addition to being useful in field mapping, the downdrift beach slope trend provides a rapid method for preliminary mapping of drift sectors and their boundaries, and sediment transport directions by using air photos. The method exploits the fact that, when the tide is out, the low slope beaches at sector beginnings are wider than the steeper beaches in the mid-sector and terminus (Table 9). The difference in width is visible on large scale air photos (e.g., 1:6000 and 1:12,000) and can be measured with an optical micrometer. Thus, preliminary air photo work can reveal those areas with wide, boulder covered beaches that should be field checked as probable sector beginnings. The method is especially useful where two sectors have a common beginning, that is, there is a null zone from which sediment is transported in opposite directions into the respective drift sectors. Examples of this occur at eastern Dewey Beach (Map G) and at Yellow Bluff on Guemes Island (Map B). In a similar manner, the longshore bluff morphology changes can sometimes be used for preliminary air photo mapping of drift sectors.

The beach slope pattern found in Skagit County seems to be at odds with some previously published relationships. However, as previously noted (pp. 90-92) direct comparisons can be misleading. This study has shown that sediment supply, tidal range, and sediment sorting are all exerting an influence on beach slope. The absence of any beach slopes greater than about 7° in any drift sector (except on prograded beaches),
regardless of grain size or percentage of sand or gravel, suggests that sediment supply may be the most important control along most of the sector length. The close correspondence between slope and increasing backshore width and sediment cover in the upper portion of the high-tide beach further supports this hypothesis. Davis (1978) also has noted that size/permeability/slope relationships hold true only on prograded beaches. On prograded beaches, where lack of sediment supply cannot be a cause for relatively low beach slopes, the slope appears to be affected by: sediment sorting, probably the fairly large local tidal amplitude, and possibly the local wave regime. King (1972, pp. 324-330) notes a strong correlation between beach slope and both wave steepness and length. Thus, Skagit County foreshore profiles and morphology appear to be the result of the interplay of at least three variables, and possibly more, in addition to particle size/permeability relationships.

SUMMARY

Unconsolidated bluffs provide nearly all beach sediment through either direct wave erosion or, in a few cases, landslides. Little sediment is contributed from local streams or from major rivers. The types and sizes of mass movements appear to be related to the origin of the deposit in which they are found. The most complex and hazardous mass movements occur where stratigraphic and groundwater variables are combined with material type.

The mean, minimum long-term erosion rate for unconsolidated bluff materials is approximately 5 cm/year. Areas with jointed rocks and
developed wave-cut platforms erode at rates of about 0.7 cm/year, and relatively resistant rock settings recede at rates of less than 0.1 cm/year.

As many of the Quaternary, bluff-forming materials are coarse-grained glacial deposits, the beach sediment strongly reflects the polymodal source characteristics. The lack of appropriate particle sizes for beaches in some of the bluffs, combined with rapid longshore removal of the sizes that are useable, produces littoral transport cells that have a sediment deficit along much of the shoreline length. Thus, most non-prograded beaches in the county are best described as erosional, with a wave-cut substrate only thinly covered by a veneer of mixed sand, gravel, and cobbles.

In conclusion, the coast of Skagit County still displays a pronounced imprint of glaciation which ceased relatively recently. It is seen in the unstraightened, crenulate shoreline in many areas; it is indicated by the U-shaped profile of the ice-scoured channels; it is found in the immature, widening wave-cut platforms; and it is found in the beach sediment supplied from eroding glacial deposits. The complex coastal morphology produces a wide variety of sediment transport directions and a complex facies of littoral sediments within a small geographic area. The littoral transport patterns, although generally in accordance with what one might deduce from a wind rose, are equally determined by localized topographic barriers, restricted fetches, and shoreline aspect. Commonly, these factors produce transport opposite to the direction indicated by the wind rose. Despite the complexities, regular geomorphic trends provide abundant evidence of the processes involved, and can be used to decipher the operation of shoreline systems.
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APPENDIX

Index to Map Segments, Map Key, and Maps
Key for Map Symbols
Explanatory Notes for Map Symbols
Maps
Index to map segments.
### Key for Map Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
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<td>Bluffs composed of unconsolidated materials, more than 10 meters (30 feet) high</td>
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<td>Rock shoreline with abrasion platform</td>
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<td>Plunging rock cliffs, no abrasion platform</td>
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<tr>
<td>········</td>
<td>Bluffs composed of mixed or alternating unconsolidated materials and rock</td>
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<td>Significantly modified shoreline, large shore defense structures</td>
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<tr>
<td>······</td>
<td>Completely modified shoreline, industrialized or filled, original shoreline now nonexistent</td>
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<td>······</td>
<td>Major landslide zones</td>
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<tr>
<td>49</td>
<td>Erosion measurement site</td>
</tr>
<tr>
<td>8.5</td>
<td>Mean minimum erosion rate in centimeters per year</td>
</tr>
</tbody>
</table>
EXPLANATORY NOTES FOR MAP SYMBOLS

A) Where the round symbols (low and high bank, unconsolidated) are used, it may be assumed that a typical mixed sand and gravel beach is also present. If the symbol for a muddy tidal flat is combined with the above, then the mud flat forms what normally would be the low-tide terrace.

B) If used alone, the mud flat symbol indicates a low lying, marshy shoreline with no granular beach; typically found along the Skagit River Delta.

C) The size of the sediment transport direction arrows is a qualitative indicator of the volume of sediment in transport in a drift sector.

D) A diamond (prograded beach) used without transport direction arrows indicates a pocket beach with a prograded profile. The two sizes of diamonds are for convenience of display only.

E) For ease of display the symbols indicating modified shorelines are shown on the seaward side of the symbol which indicates the nature of the bluff and beach. In all cases the defense structures are associated with the terrestrial portion, not out in the middle of the fore-shore as might be implied by the placement of the symbol on the maps.

F) Because of the variability in wave direction and refraction, few, if any, drift sectors have absolute boundaries (beginnings and termini) that are confined to a specific point. Rather, sector beginnings are zones through which the null point fluctuates around some average location. Therefore, on the maps the drift arrows leading away from sector beginnings start where the direction of net, long-term transport can be firmly established from field evidence.
Map B Vendovi and Guemes Island
Map D  Burrows and northern Fidalgo Island
Map F  Allan and western Fidalgo Island
Bluffs composed of unconsolidated materials, less than 10 meters (30 feet) high

Bluffs composed of unconsolidated materials, more than 10 meters (30 feet) high

Rock shoreline with abrasion platform

Plunging rock cliffs, no abrasion platform

Bluffs composed of mixed or alternating unconsolidated materials and rock

Prograded beaches

Fine-grained tidal flats

Direction of net, long-term, sediment transport

Lightly modified shoreline, small shore defense structures

Significantly modified shoreline, large shore defense structures

Completely modified shoreline, industrialized or filled, original shoreline now nonexistent

Major landslide zones

Erosion measurement site

Mean minimum erosion rate in centimeters per year

Figure SK-2. Key for map symbols.

Figure 5. Net shore-drift key.