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Beach Response to Subsidence Following a Cascadia Subduction Zone Earthquake Along the Washington-Oregon Coast

Debra Lee Doyle
Portland State University

THESIS APPROVAL

The abstract and thesis of Debra Lee Doyle for the Master of Science in Geology presented June 13,1996, and accepted by the thesis committee and the department.

COMMITTEE APPROVALS: [redacted]

Curt D. Peterson, Chair

[redacted]

Michael L. Cummings

[redacted]

Richard E. Thoms

[redacted]

John R. Dingler

[redacted]

James R. Pratt
Representative of the Office of Graduate Studies

[redacted]

Marvin H. Beeson, Chair
Department of Geology

****

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ABSTRACT

An abstract of the thesis of Debra Lee Doyle for the Master of Science in Geology presented

Title: Beach Response to Subsidence Following a Cascadia Subduction Zone Earthquake Along the Washington-Oregon Coast

Beach shoreline retreat induced by coseismic subsidence in the Cascadia subduction zone is an important post-earthquake hazard. Sand on a beach acts as a buffer to wave attack, protecting dunes, bluffs and terraces. The loss of sand from a beach could promote critical erosion of the shoreline. This study was initiated in order to estimate the potential amount of post subsidence shoreline retreat on a regional scale in the Central Cascadia Margin. The study area is a 331 km stretch of coastline from Copalis, Washington to Florence, Oregon.

Several erosion models were evaluated, and the Bruun model was selected as the most useful to model shoreline retreat on a regional scale in the Central Cascadia Margin. There are some factors that this model does not address, such as longshore transport of sediment and offshore bottom shape, but for this preliminary study it is useful for estimating regional retreat.

The range of parameter input values for the Bruun model include: the depth of closure (*h*) range from 15 m to 20 m water depth; the cross-shore distance (*L*) range from 846 m to 5975 m; and the estimated subsidence amount (*S*) range from 0 m to 1.5 m.

The minimum to maximum range of post-subsidence shoreline retreat is 142 to 531 m in the Columbia River cell, 56 to 128 m in the Cannon Beach cell, 38 to 149 m in the Tillamook cell, 25 to 91 m in the Pacific City cell, 11 to 126 m in the Lincoln City cell, 30 to 147 m in the Otter Rock cell, 0 to 165 m in the Newport cell, 0 to 76 m in the Waldport cell, and 0 m in the Winchester cell.

Results of the study suggest that many of the beaches in the study area are at risk of beach and personal property loss. Beach communities could limit the amount of potential damage in these areas through coastal zone planning.

BEACH RESPONSE TO SUBSIDENCE FOLLOWING A CASCADIA SUBDUCTION ZONE EARTHQUAKE ALONG THE WASHINGTON-OREGON COAST

by

Debra Lee Doyle

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Beach shoreline retreat is an important post-earthquake hazard resulting from coseismic subsidence in the Cascadia subduction zone. The sand on a beach acts as a buffer to shoreline erosion by dissipating wave energy (Komar and others, 1991; Dean, 1991). Beach sand deposits protect dunes, terraces, and bluffs from wave attack during storms or periods of elevated sea-level. Many studies of potential beach erosion from global and local sea-level rise have been performed during the last several decades (Bruun, 1962; Dean and Maurmeyer, 1983; Dubois, 1977; Hands, 1983). These studies are relevant, but not specific to the long-term, post-seismic erosion that could occur along the Cascadia margin. The goal of this study is to estimate the amount of beach shoreline retreat expected to occur from coseismic coastal subsidence in nine littoral cells of the Central Cascadia margin (Figure 1).

The objectives of this study are (1) review of geologic data verifying beach retreat from prehistoric subsidence events in the Central Cascadia margin, (2) fill in profile data gaps in a regional data base on beach profiles in the study area (Peterson and others, 1994), (3) test the applicability and sensitivity of beach erosion models from coseismic sea-level rise (Komar and

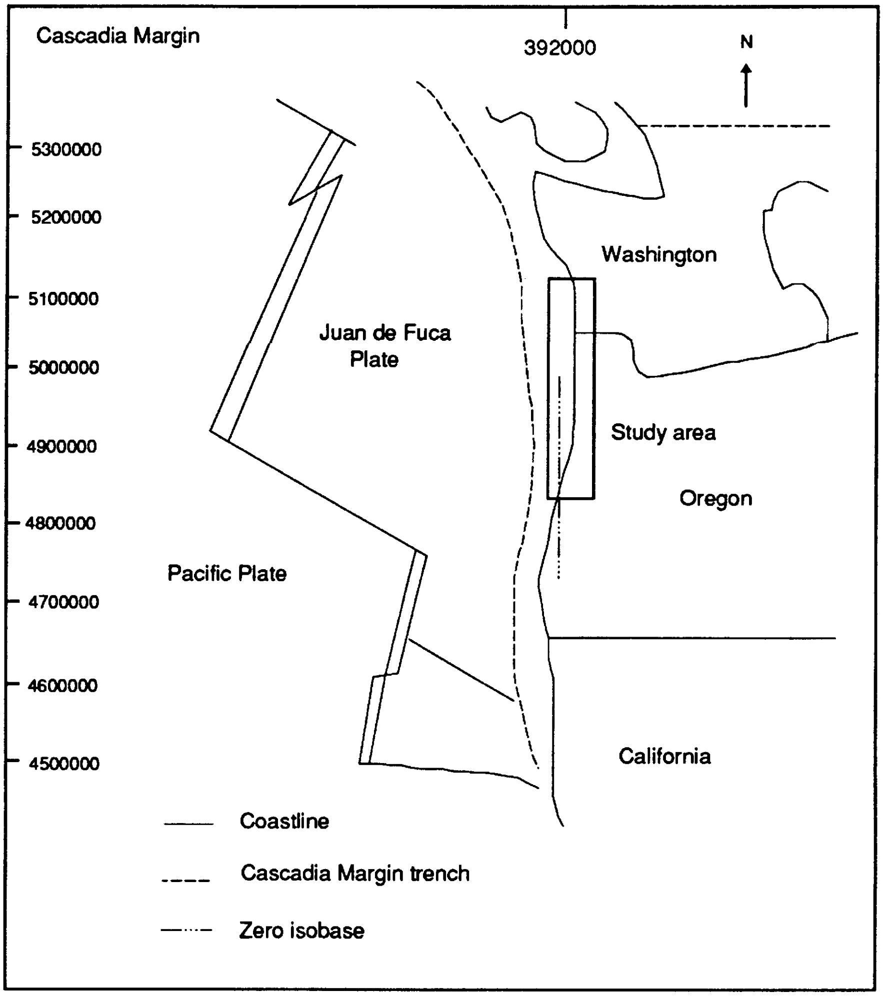

Figure 1. Study area along the Cascadia margin

others, 1991), and (4) estimate the amount of beach retreat resulting from predicted coseismic coastal subsidence in the Central Cascadia margin.

Beaches in the Tillamook and Pacific City cells were surveyed for modern across-shore profiles relative to mean tide level, and the data were entered into the regional data base. Beach profile data, together with other erosion model parameters, were compiled in spreadsheet programs for computation. Several beach erosion models (Bruun, 1962; Dean and Maurmeyer, 1983; Dean, 1991; Dubois, 1975; Edelman, 1968) were evaluated to find the most suitable model for investigating beach response to coseismic coastal subduction in the Cascadia subduction zone.

Results of the study indicate that the amount of shoreline retreat is a function of (1) predicted site-specific coastal subsidence, (2) across-shore profiles of the beach and nearshore region, and (3) the presence or absence of a sea cliff at the back edge of narrow beaches. Using the erosion model of choice (modified Bruun Rule from Komar and others, 1991), estimates of beach retreat were predicted for beaches in the study area.

BACKGROUND

REGIONAL TECTONICS

The Cascadia subduction zone is 1500 km long and extends from the Mendicino Triple Junction off the coast of northern California to Vancouver Island in Canada (Figure 1). It includes the Juan de Fuca, Explorer, Winona, and Gorda oceanic plates. In the past decade, the potential for a great (>8.0 M) Cascadia subduction zone earthquake has generated considerable debate (Heaton and Kanamori, 1984; Acharya, 1992). Strong evidence for several great earthquakes in the past 5,000 years has emerged from the Holocene geologic record in cores from coastal wetlands in bays of British Columbia (Vancouver Island), Washington, Oregon, and northernmost California (Atwater, 1987 and 1992; Darienzo and Peterson, 1990; Clague and Bobrowsky, 1994; Clarke and Carver, 1992). Subsidence due to a megathrust earthquake has been estimated to range from 0.5 to 2 m along the west coast of North America, including British Columbia (Vancouver Island), Southwestern Washington and Northwest Oregon (Atwater, 1987, 1992; Clague and Bobrowsky, 1994; Darienzo and others, 1994). These estimates are based on paleotidal indicators above and below the most recent subsidence event contact in coastal marsh cores (Darienzo and Peterson, 1990).

Estimates of beach retreat from coseismic subsidence is an important aspect of Cascadia earthquake hazard studies to find out how many coastal communities along the Central Cascadia margin would be adversely affected by severe beach erosion. Areas with medium to broad beaches may lose some or all of the beach backshore, while areas with narrow beaches could also experience severe bluff or foredune erosion. The beach (Figure 2) is a natural barrier that protects sea cliffs and dunes from wave attack. Waves break in the nearshore, expending their energy on the beach rather than on the sea cliffs and dunes (Komar, 1976). A beach remains in relative equilibrium by a balance of wave energy, sediment availability, and relative sea-level (Komar, 1976). If a rapid rise in sea-level occurs, that balance is shifted to redistribute sediment offshore (Figure 3). Some segments of the coast, for example the Cannon Beach cell (Figure 9) and the Otter Rock cell (Figure 13), are actively being eroded under current sea-level conditions and very limited sand supply. These cells are backed by sea cliffs and are underlain by shallow wave-cut platforms between 0.5 and 2.5 m below the beach surface. The beach widths range from 164 to 250 m in the Cannon Beach cell, and 68 to 177 m in the Otter Rock cell (Peterson and others, 1994). The results of a rapid sea-level rise on the order of 1 m in these areas could be disastrous: the beaches would be eroded back to the base of the sea cliffs.

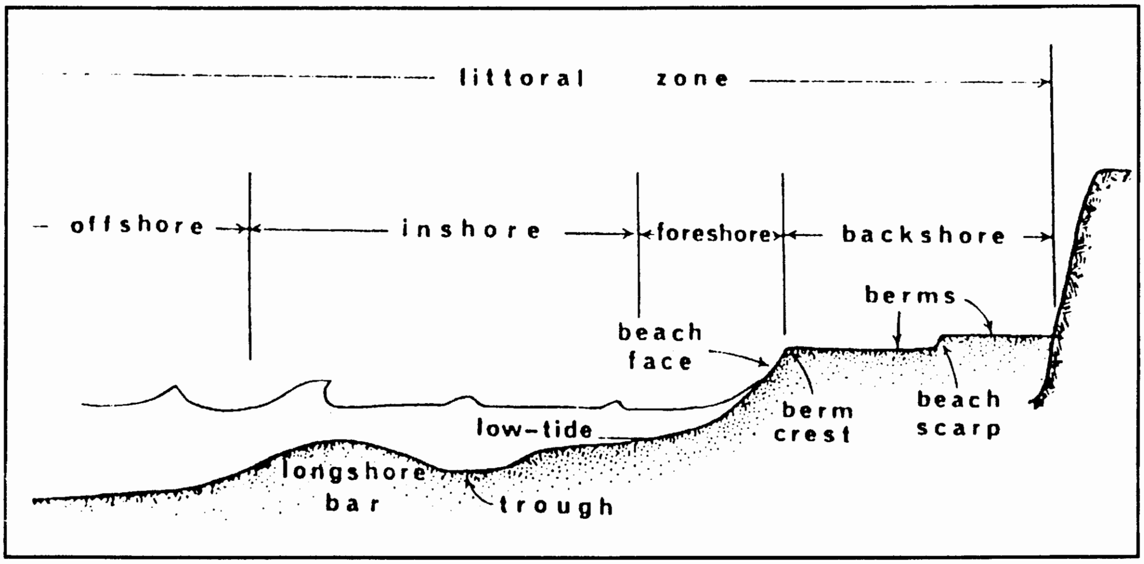

Figure 2. Morphology of a beach profile (Komar, 1976).

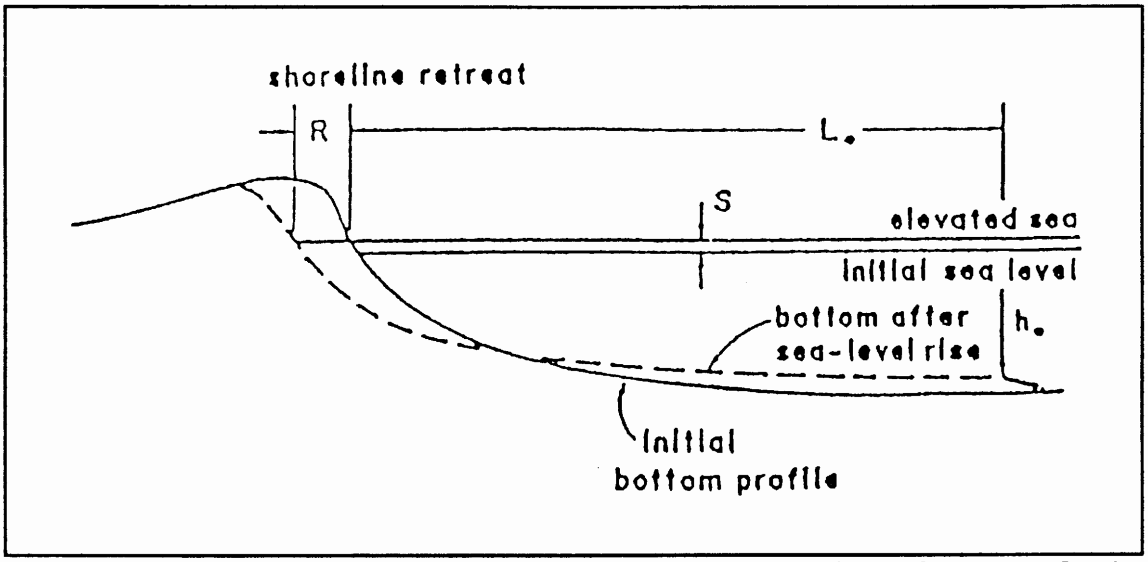

Figure 3. Translation of a beach and nearshore profile after a relative rise in sea-level, where *R* is retreat, *L* is the across-shore distance to water depth *h*, and *S* is amount of sea-level rise (Komar and others, 1991).

The effects of littoral transport on sediment after a rapid rise in sea-level are also important. Eroded sediment could be transported to sinks in bays or around headlands to adjacent littoral cells. For example, sediment loss could occur from longshore transport to the Siletz Bay mouth in the Lincoln City cell (Figure 10) or around Cascade Head to the Pacific City cell (Figure 9) (Peterson and others, 1993). However, most of the Cascadia margin is characterized by small pocket beaches where sand is trapped between headlands. One minor exception to this characterization is the Columbia River cell (163 km long) where net northward littoral drift has been reported (Ballard, 1964; Terich and Schwartz, 1981; Peterson and others, 1991b).

This study will focus on the 331 km coastal area between Copalis, Washington and Florence, Oregon (Figure 1) where regional coseismic subsidence has been verified (Atwater, 1987, 1992; Darienzo and others, 1994; Peterson and others, 1991a). This area was chosen because it reflects the full range of predicted subsidence and contains a wide variety of beach widths and shoreline morphologies (National Shoreline Study, 1971; Peterson and others, 1991b).

EVIDENCE FOR CATASTROPHIC BEACH RETREAT FROM COSEISMIC SUBSIDENCE

Ground Penetrating Radar (GPR) was used by Meyers and others (1996) to detect subsurface sedimentary structures that can be used to infer directions of aggradation or progradation of coastal barriers. One of the areas investigated for beach progradation was

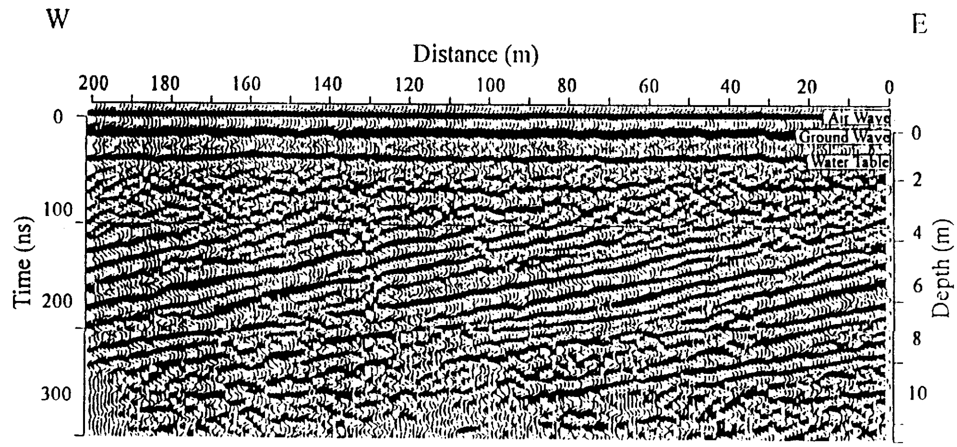

Figure 4. Typical GPR transect of subsurface winter storm beach profile on Willapa barrier showing 1° to 2° dip angle (Meyers and others, 1996).

the Long Beach Peninsula at Willapa Bay, Washington. Figure 4 shows a typical GPR profile from a shore-normal transect. The radar profile shows westward dipping (1°-2°), shingled, inclined reflections that match the dip angle of profiled beach surfaces during the winter storm season (Meyers and others, 1996). They interpret these reflections to be paleostorm beach surfaces.

Within the radar profiles, eight major buried scarps were imaged over longshore distances of 760 m (Figure 5; also see back pocket). The buried scarps start at or near the surface, are concave and dip steeply (up to 7°). They continue down to a depth of 5-6 m and truncate the 1° to 2° slope of the paleobeach reflections (Meyers and others, 1996). The buried scarps were later determined to be beds of unusually high heavy mineral concentrations (see *Results*). Figure 5 illustrates the steeply dipping sedimentary structures underlying the Loomis Lake State

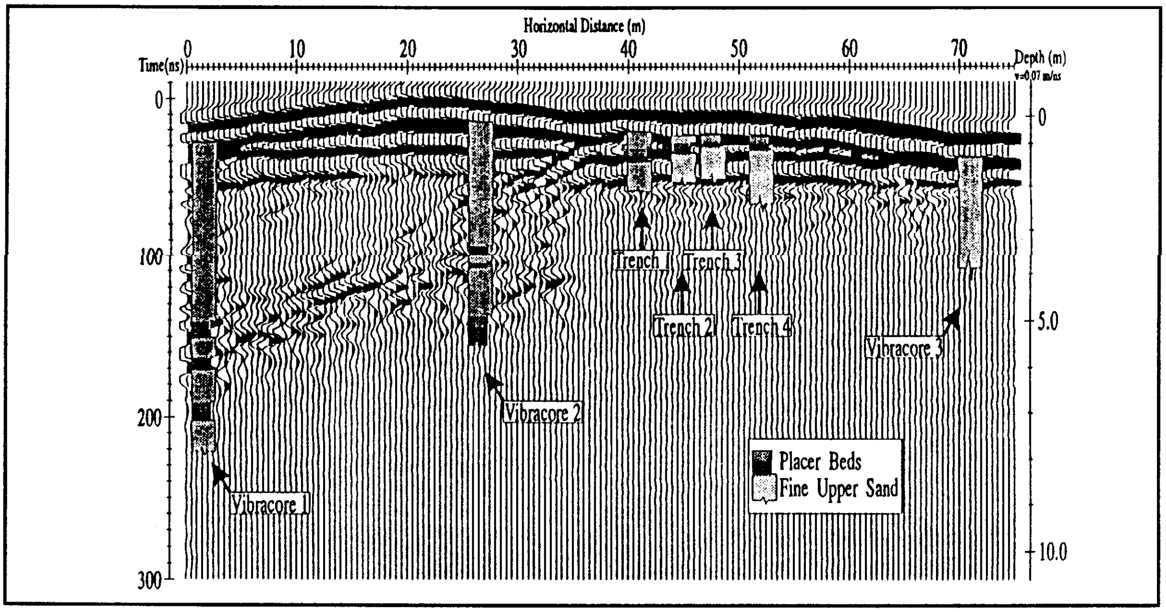

Figure 5. Ground penetrating radar transect along a portion of the 760 m Loomis Lake State Park profile (From Meyers and others, 1996).

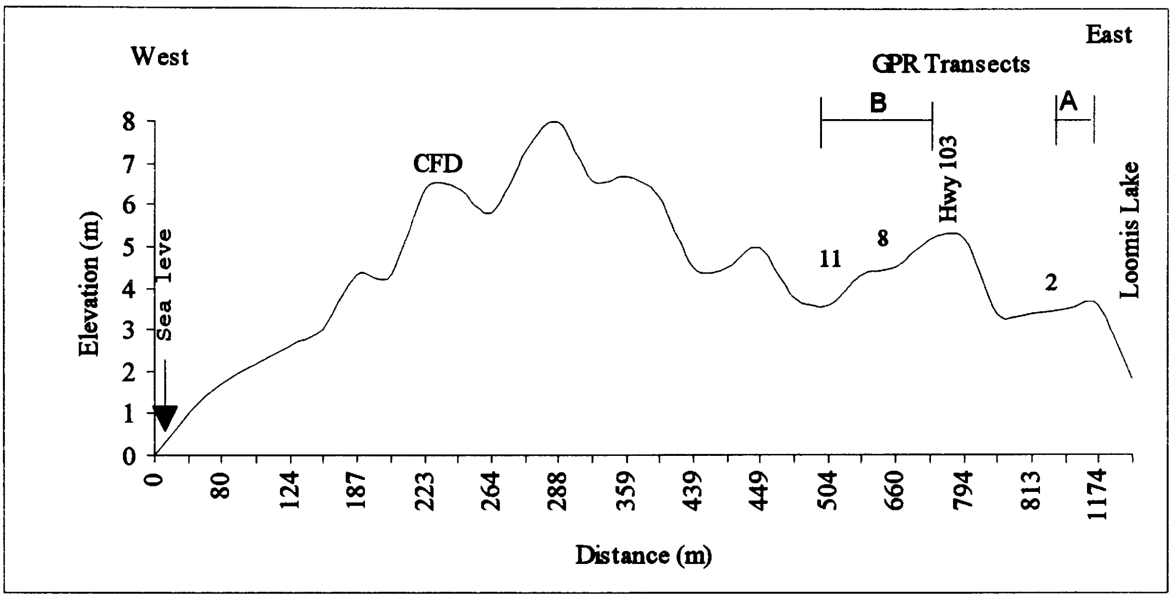

Figure 6. Elevational profile along Loomis Lake State Park access road from MTL (mean tide level) to the western edge of Loomis Lake. Numbers indicate site locations for C-14 dates: 11 (300 RCYBP), 8 (1120 RCYBP) and 2 (2540 RCYBP). CFD = crest of fore dune.

Park access road profile (Figure 6) on the Long Beach Peninsula. Meyers and others (1996) hypothesized that these buried scarps represent catastrophic beach retreat following episodic coseismic subsidence. This hypothesis is further tested in this thesis.

SHORELINE EROSION MODELS

Bruun (1962) proposed the first shoreline retreat rate model based on local sea-level rise (Figure 3). The Bruun rule of erosion assumes a two-dimensional profile in equilibrium with sea-level rise by a landward translation of the shoreline as the upper beach is eroded. The eroded sediment is deposited in the near offshore, elevating the bottom, resulting in a constant water depth in the offshore. Bruun used basic relationships to establish the following equation:

$$R=\frac{L}{B+h}S \tag{1}$$

where R is the shoreline retreat rate due to S, an increase in sea-level, L is the distance from the shoreline to h, which is the water depth of the seaward limit that nearshore sediment exist, which Bruun (1962) determined to be 18 m from previous studies, and B, the vertical elevation of the shore. This relationship is also represented as

$$R = \frac{1}{\tan\theta} S \qquad (2)$$

where $\tan\theta$ is the average slope along the across-shore width L, and is $\approx$ (B+h)/L (Komar and others, 1991). Thus, if $\tan\theta \approx 0.01$ to 0.02, which is common for beach sand, R=50S and 100S in equation (2)(Komar and others, 1991). The model assumes the longshore movement of sediment is negligible, i.e., the longshore transport could be large and this criterion would still apply. Bruun also established the sea-level rise-to-erosion ratio as 1:100. Bruun (1988) reminds workers that the model is a two-dimensional model, even though it is frequently applied to three-dimensional problems.

Edelman (1968) proposed a model for erosion of dunes by storm tides assuming a vertical dune face and uniform dune crest height. Dune erosion was found to be a function of dune height and storm surge level. The sea-level rise is temporary, and resumes its pre-storm surge level quickly after the storm has diminished. This model could be useful for a localized study of dune erosion, but is not suitable for a more regional scope of study.

Dubois (1975) studied the affects of wave conditions and water level increase on two profiles in Lake Michigan. The purpose was to test the Bruun model for predicting shoreline recession due to water level rise when accompanied by wave action. The study upheld the validity of the Bruun model. Dubois (1977) also defined θ (in equation 2) as "the angle of the nearshore slope seaward from breaking waves." Dean and Maurmeyer (1983) point out that θ represents the average slope, as was derived in their paper, and not just the area Dubois suggested.

Dean and Maurmeyer (1983) modified the Bruun rule to account for the landward translation of a barrier island system, where deposition occurs on the barrier island and on the lagoon side of the barrier island. This model includes the complete sediment budget in a system,

$$R = \frac{L}{P(B+h)} S + \frac{(\partial Qs / \partial y)\Delta t}{(B+h)} \quad (3)$$

"...where P is the decimal fraction of eroded material that is compatible with the surf zone sediment" (Dean and Maurmeyer, 1983), with the littoral drift of the longshore gradient given as $(\partial Q_s \ / \ \partial y)$, and Δt as the interval over which the rise in sea-level S occurs. Komar and others (1991) generalized the equation as

$$P(B+h)R = LS + G_B \quad (4)$$

where G_B is the total sediment budget term that includes sediment input from offshore and river systems, sediment loss due to transporting of sediment to the offshore, and aeolian sediment transport inland. The model represents rapid sea-level fluctuation and a short lag time for the profile.

Dean (1991), analyzed natural beach profiles and found a distinct relationship

$$h(y) = Ay^{m} \tag{5}$$

where h is the water depth at a y distance seaward, A is a scalar dependent on sediment characteristics, and m, a shape factor, is found to be 2/3. Equation (5) represents an idealized, unchanging profile without offshore bar effects.

Dean (1982) also evaluated a profile with a sea wall present, and concluded that since sand was prevented from being obtained from the subaerial segment of the profile, there must be a balance of sand volume seaward of the sea wall. The depth at the wall known for the elevated water level is

$$h_w = h_{wo} + S + \Delta h_w \tag{6}$$

where h_w is the final water depth at the sea wall, h_{wo} is initial water depth at the sea wall, S is the amount of sea-level rise, and Δh_w is the change of water depth at the sea wall Dean and Maurmeyer, 1983). This equation (6) may prove useful for very narrow beaches in front of sea cliffs and could also prove useful for a localized study of sea cliff erosion. Equation (5) can be used to evaluate the rest of the profile, landward of the sea wall.

ESTIMATES OF COSEISMIC SUBSIDENCE

Coastal subsidence due to a megathrust earthquake about 300 years ago has been recorded in cores from coastal wetlands in bays of British Columbia (Vancouver Island), Washington, Oregon, and northernmost California (Atwater, 1987 and 1992; Darienzo and Peterson, 1990; Clague and Bobrowsky, 1994; Clarke and Carver, 1992). Estimates of subsidence amount range from 0 to 2 m in the Cascadia margin (Atwater, 1987 and 1992; Clague and Bobrowsky, 1994; Darienzo and others, 1994). These estimates are based on paleotidal indicators above and below the most recent interpreted subsidence event contact in coastal marsh cores. Methods used to restrict the timing of subsidence include radiocarbon dating (Atwater, 1992; Clague and Bobrowsky, 1994; Clarke and Carver, 1992), tree-ring counts of trees killed by subsidence (Yamaguchi and others, 1989), and historical tsunami records in Japan (Satake and others, 1996). Peterson (unpublished data, 1996) has compiled subsidence records and has attempted to formulate the range of likely coseismic subsidence in the Central Cascadia margin. Those estimates of paleosubsidence are based on paleotidal indicators including plant macrofossils, relative peat development, and diatoms. Subsidence estimates are given to the nearest meter 0, 1, and 2 meters, with +/- 0.5 m error bars (Peterson, unpublished data, 1996). Multiple paleotidal indicator sites at some localities allow averaging of subsidence values to better predict estimated subsidence. However, the assumed error (+/- 0.5 m) is retained for these averaged subsidence estimates.

STUDY AREA

To gain a regional perspective on shoreline retreat with respect to coseismic subsidence in the Pacific Northwest, nine littoral cells between Copalis, Washington and Florence, Oregon, were chosen for study (Figure 1). This section of coastline was chosen because of known records of regional coseismic subsidence in the area, and the wide range of beach widths and morphologies (see *Background*). A littoral cell is defined as an area of contained longshore sediment transport (Komar, 1976). Littoral cells are bounded by resistant headlands seaward of the shoreline, smaller protrusions, or shoreline orientation (Peterson and others, 1991a). These protrusions restrict sediment movement to distinct zones of alongshore transport. Data for seven of the nine littoral cells comprising this study have been obtained from the Cascadia Beach-Shoreline Data base (Peterson and others, 1994). The littoral cells of this study (Figure 7) are: (1) the Columbia River cell; (2) the Cannon Beach cell; (3) the Tillamook cell; (4) the Pacific City cell; (5) the Lincoln City cell; (6) the Otter Rock cell; (7) the Newport cell; (8) the Waldport cell; and (9) the Winchester cell.

1. The Columbia River cell, the largest in the study area, extends from Point Grenville at the north (UTM N5239500) (Universal Transect Mercator coordinate system) to Tillamook

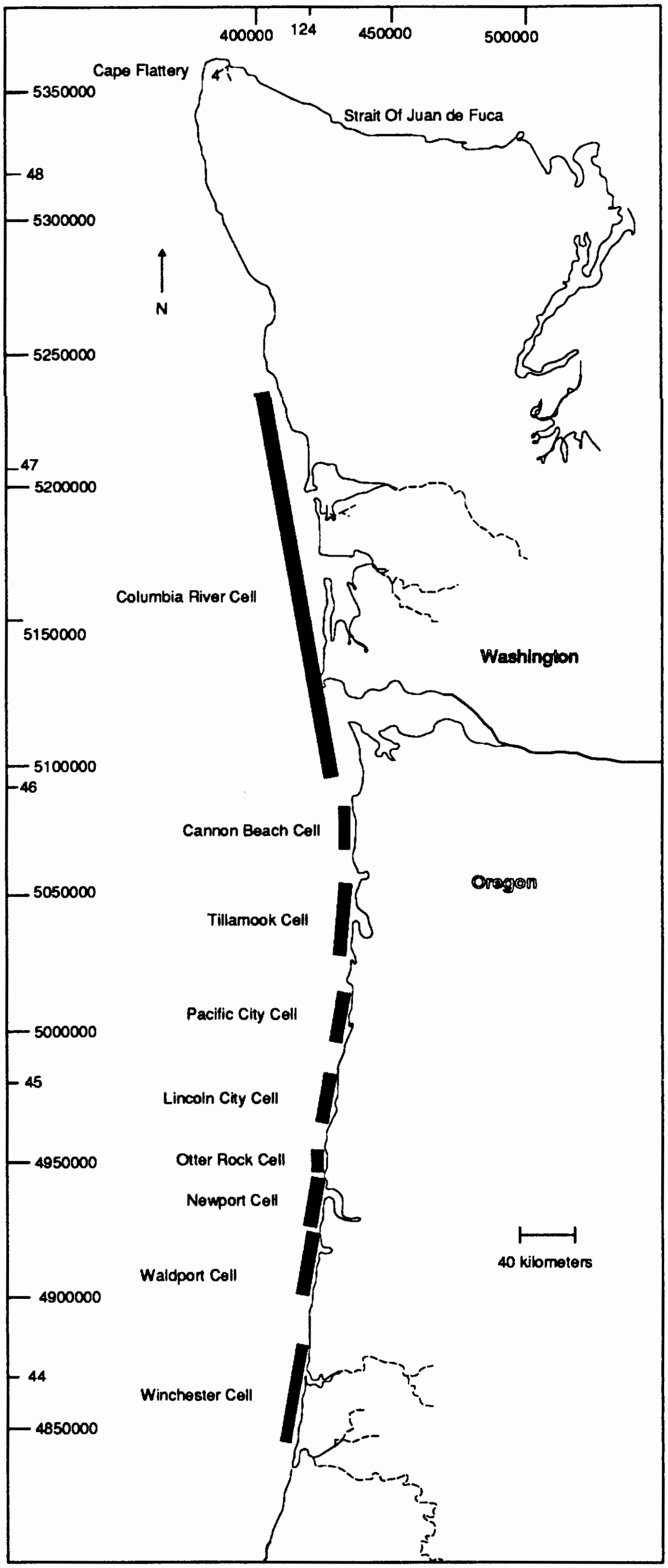

Figure 7. Location of littoral cells studied.

Head at the south (UTM N5090000) (Figure 8). The cell is approximately 163 km in length. Backshore widths range from 75 to 218 m, and the average width is 131 m. Beaches in the Columbia River cell are generally straight, sandy beaches backed by dunes. Prograding beaches characterize the Columbia River cell, unlike the beaches to the north and south of the cell (Ballard, 1964). The largest drainage system in the cell is the Columbia River. Four other lesser drainages are the Chehalis and Hoquiam rivers which enter Gray's Harbor, and the Nasell and Nemah rivers which empty into Willapa Bay. The Columbia River enters the cell approximately 6 km north of the southern cell boundary. Although there is seasonal and/or interannual variation in longshore transport of sediment, there is a net littoral drift of nearshore sediment to the north (National Shoreline Study, 1971). The Long Beach Peninsula is approximately 36 km long and extends northward from the Columbia River to the entrance Willapa Bay. The northernmost 4 km of the spit has little vegetation indicating recent progradation of the shoreline to the north. By comparison there are two spits at the mouth of Gray's Harbor. The spit pointing southward is about 12 km long and the northward pointing spit is about 6 km long. The two bays provide minimal sediment to the system (Ballard, 1964) and are likely to be sediment sinks (Peterson and Phipps, 1992). The entrance to Willapa Bay is

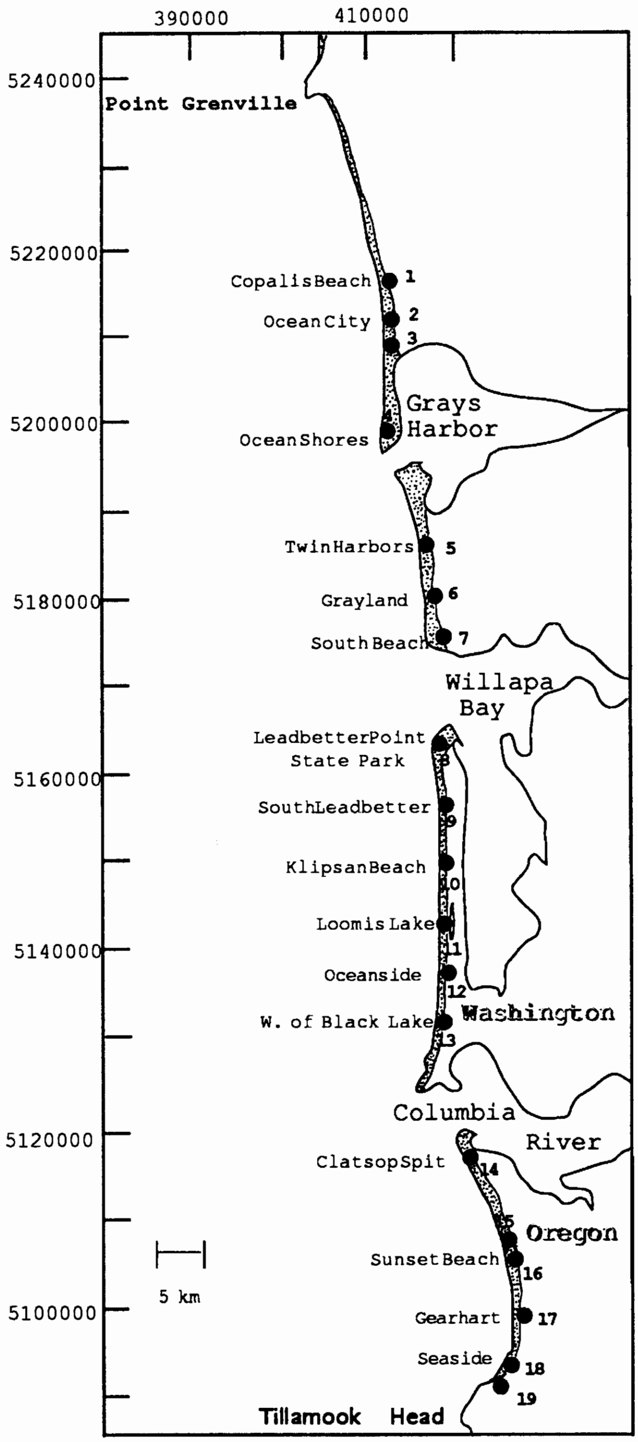

Figure 8. Map of the Columbia River cell. Base from U.S.G.S. 7.5' topographic quadrangles. The solid dots and numbers represent profile locations.

approximately 35 km north of the Columbia River mouth, and Gray's Harbor is about 37 km north of Willapa Bay.

2. The Cannon Beach cell is approximately 20 km in length and extends from Tillamook Head at the north (UTM N5084150) to Cape Falcon to the south (UTM N5069700)(Figure 9). Backshore widths range from 13 to 103 m (Peterson and others, 1994), with an average width of 67 m. With the exception of the northernmost section of the cell (Ecola Point) all of the beaches are backed by sea cliffs. The Ecola Point segment is backed by a small dune-field approximately 1.0 km in alongshore length. Shallow wave-cut platforms in this cell range from 1 to 2.5 m below the surface of the beach (Peterson and others, 1994). Ecola Creek is the main drainage system and enters the beach about 6 km from the north end of the cell. Three smaller streams, Fall Creek, Asbury Creek, and Arch Cape Creek enter the beach in the southern half of the cell. Although there is seasonal and/or interannual variation in longshore transport direction, the net littoral transport of sediment in small pocket beaches of the Oregon coast is zero (Komar, 1976; Peterson and others, 1991b). The beach cliffs in this cell are being eroded, but at low rates (< 10 cm/yr) (National Shoreline Study, 1971).

3. The Tillamook cell is approximately 40 km in length and is bounded by Cape Falcon at the north (UTM N5068500) and Cape

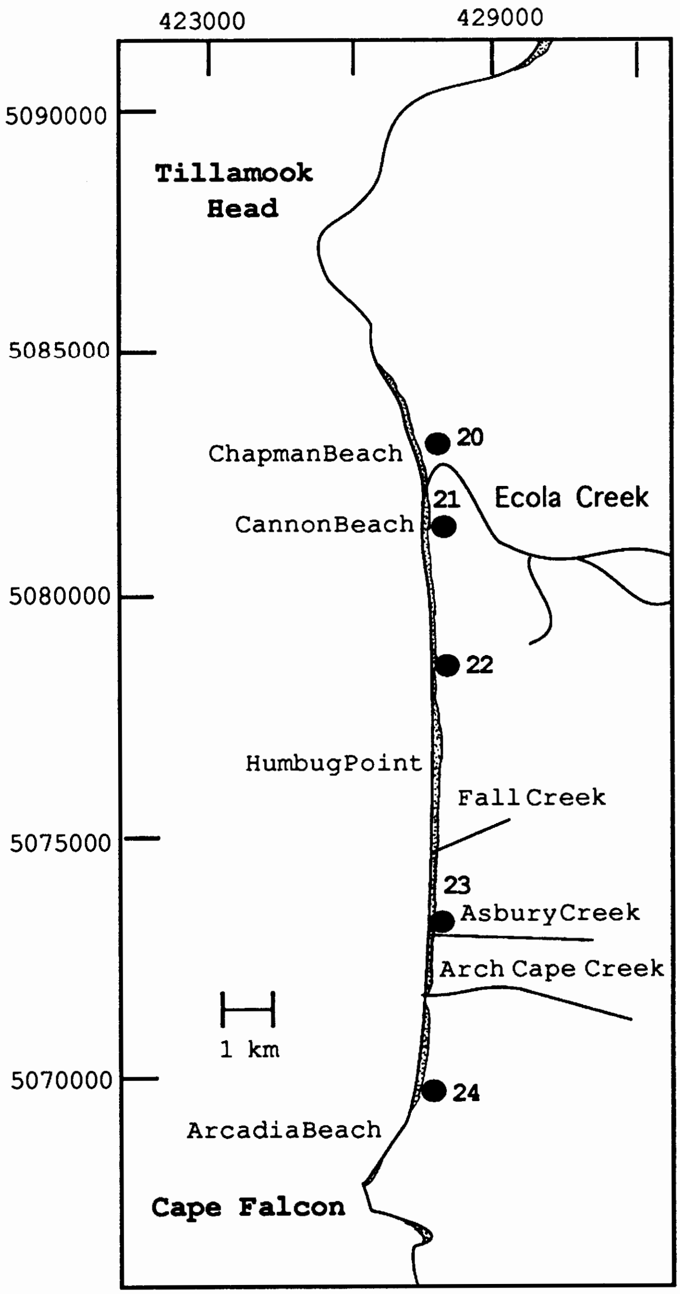

Figure 9. Map of the Cannon Beach cell. Base from U.S.G.S. 7.5' topographic quadrangles. The solid dots and numbers represent profile locations.

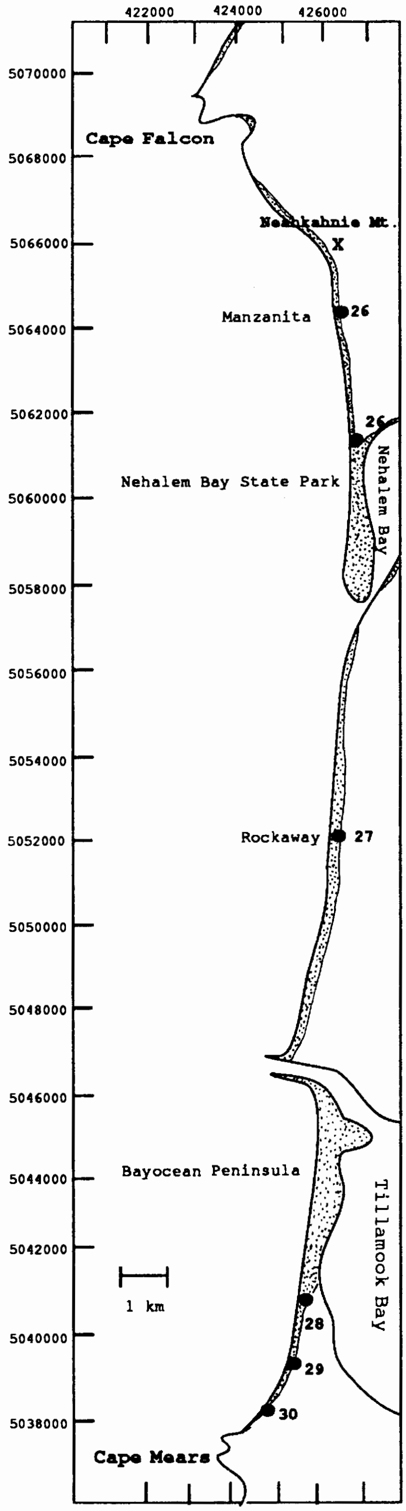

Figure 10. Map of the Tillamook cell. Base from U.S.G.S. 7.5' topographic quadrangles. The solid dots and numbers represent profile locations.

Meares at the south (UTM N5037700)(Figure 10). Backshore widths range from 25 to 71 m with an average width of 51 m. The northernmost section of the cell (approximately 4 km) is backed by a sea cliff, and the southernmost beach (Cape Meares) is composed of cobbles. The remainder of the cell is backed by dunes. The largest drainage systems are the Nehalem River, which empties into Nehalem Bay, and the Kilchis, Wilson, Trask, Miami, and Tillamook Rivers, which empty into Tillamook Bay. Within this cell there appears to be a slight net northward littoral drift, as evidenced by the critical erosion of Bayocean Peninsula at Tillamook Bay (National Shoreline Study, 1971) and dune buildup at the base of Neahkahnie Mountain at Manzanita to the north. The Nehalem Bay spit is about 3.5 km long and points toward the south. That the Nehalem Bay spit and the shoreline between it and Tillamook Bay are not experiencing erosion may also indicate a small net-northward littoral drift of sediment in this cell.

4. The Pacific City cell is approximately 25 km in length and extends from Cape Lookout at the north (UTM N5020800) to Cascade Head at the south (UTM N4991700) (Figure 11). Backshore widths range from 44 to 74 m, with an average of 60 m. The beaches are generally straight, sandy and backed by aeolian dunes. The largest drainage system in the cell is the Nestucca and Little

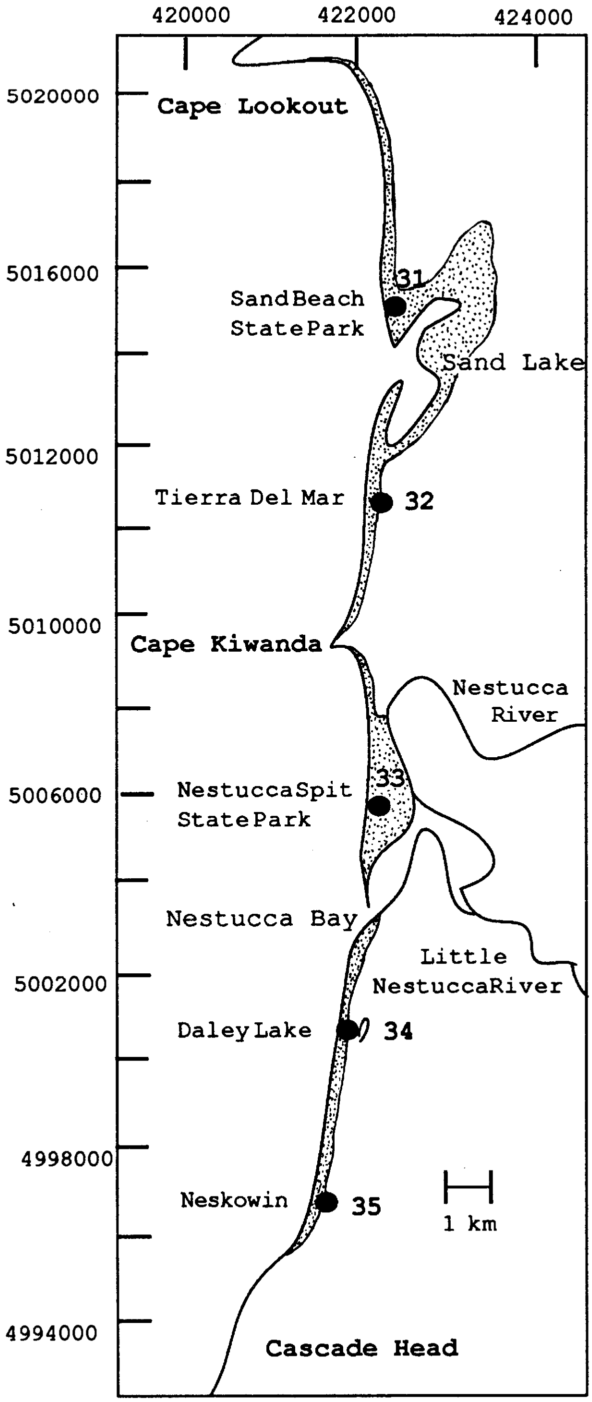

Figure 11. Map of the Pacific City cell. Base from U.S.G.S. 7.5' topographic quadrangles. The solid dots and numbers represent profile locations.

Nestucca Rivers. The Nestucca River enters Nestucca Bay on the north side and the Little Nestucca River enters the bay on the south side. Sand Lake, just south of Cape Lookout, may be a sand sink. That is, an area that 'traps' sediment and prevents migration of sediment out of that area. Northward littoral drift is indicated by the critical erosion in the southern half of the cell near the town of Neskowin, and ending just south of the Daley Lake area, where dunes are accreting (Personal communication, Glen Lyda, October, 1994).

5. The Lincoln City cell is approximately 25 km in length and extends from Roads End (UTM N4966100) at the north to Government Point (UTM N4968500) at the south end (Figure 12). The cell is partially bounded on the north by an unnamed seaward protrusion at the north end of Roads End Beach. Backshore widths range from 23 to 70 m, with an average width of 50 m. All of the beaches in this cell except Siletz Spit are bluff backed. The spit is 4.5 km in length and points toward the north. Shallow wave-cut platforms underlie all of this cell except Siletz Spit. The depth from the surface to the platform ranges from 1 to 2 m (Peterson and others, 1994). The major drainage system is Siletz Bay with one major river, two creeks and a slough. The Siletz River enters the bay on the southeast side, Drift Creek enters from the east and Schooner Creek enters from the northeast. With the exception of Siletz

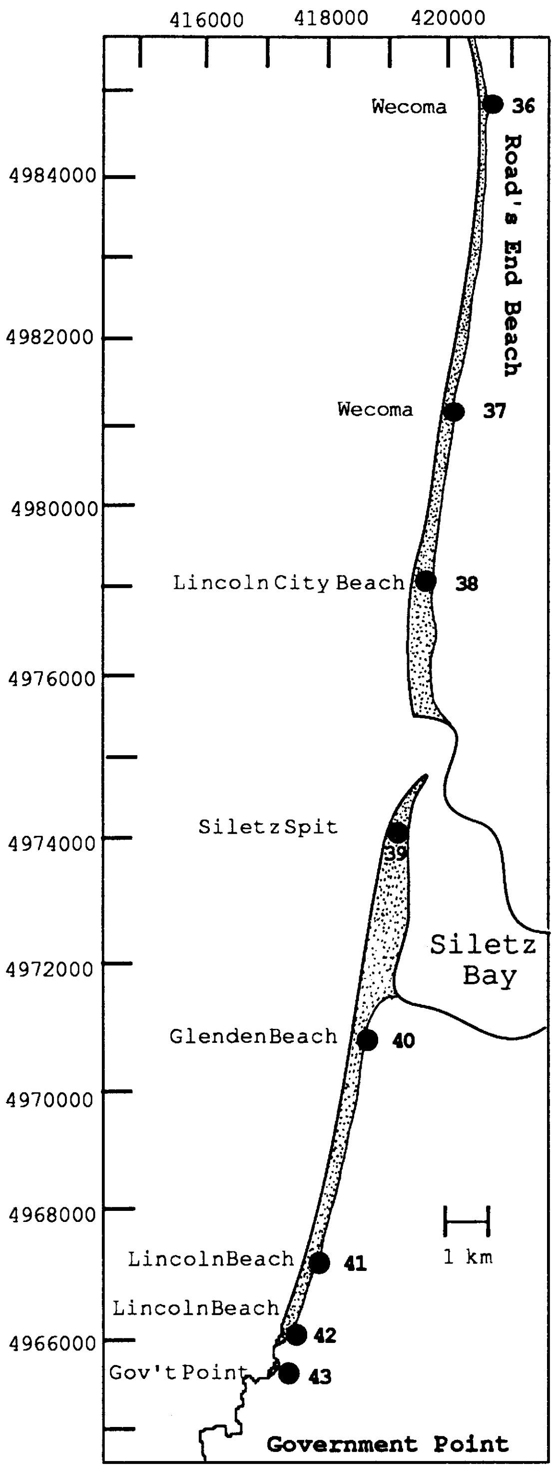

Figure 12. Map of Lincoln City cell. Base from U.S.G.S. 7.5′ topographic quadrangles. The solid dots and numbers represent profile locations.

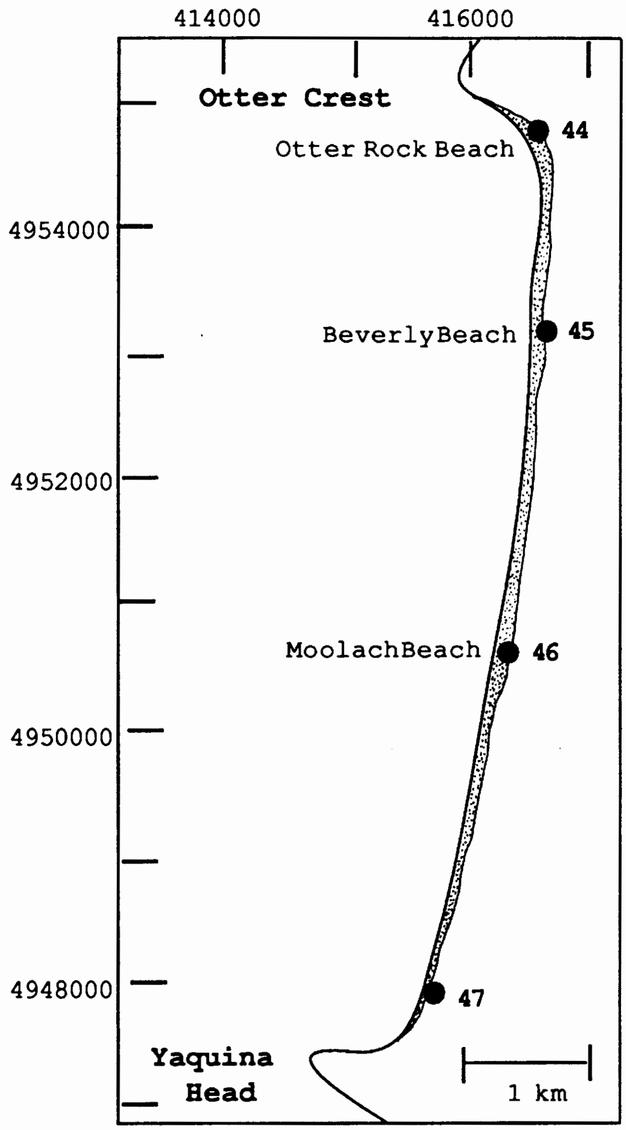

Figure 13. Map of the Otter Rock cell. Base from U.S.G.S. 7.5' topographic quadrangles. The solid dots and numbers represent profile locations.

Spit, which is not eroding at this time, the entire cell is experiencing slight erosion at an average rate of 9 cm/yr (Priest and others, 1993). The Siletz River is probably the principal source of sand to the beach (Komar, 1983).

6. The Otter Rock cell is approximately 8 km in length and extends from Otter Crest at the north (UTM N4955800) to Yaquina Head at the south (UTM N4947500) (Figure 13). Backshore widths range from 23 to 79 m with an average width of 55 m. Sea cliffs run the entire length of the Otter Rock cell. No rivers or streams enter the cell. Shallow wave-cut platforms are from 0.5 to 1.0 m below the surface of the beaches. The entire cell is eroding at an average rate of 33 cm/yr (Priest and others, 1993). There is no indication where the sediment from the beaches is going, as there are no beaches to the north in the Depoe Bay area, and the Newport cell to the south is also experiencing erosion.

7. The Newport cell is approximately 20 km in length and extends from Yaquina Head at the north (UTM N4947100) to Seal Rocks at the south (UTM N4927250) (Figure 14). Seal Rocks is probably not a completely effective southern boundary (Peterson and others, 1990). Backshore widths range from 28 to 93 m, and average 67 m. All of the beaches are bluff backed except the 1 km long south pointing spit at Yaquina Bay. Shallow wave-cut platforms underlie all but the spit areas to a depth of 1.0 to

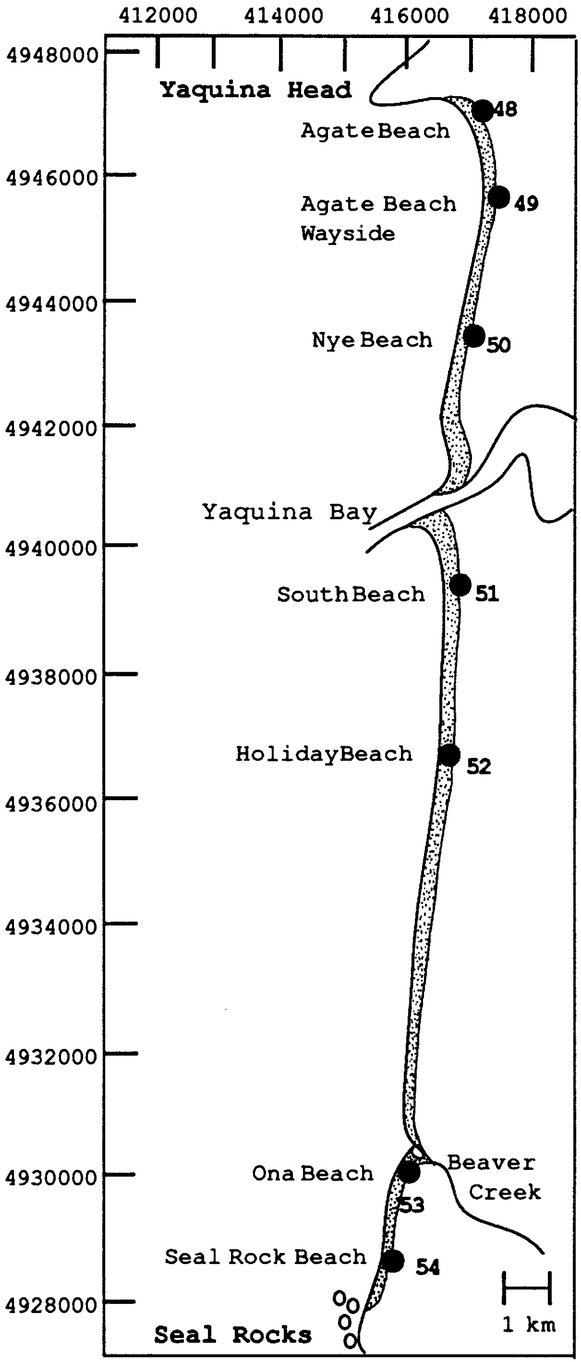

Figure 14. Map of the Newport cell. Base from U.S.G.S. 7.5′ topographic quadrangles. The solid dots and numbers represent profile locations.

1.5 m. The largest drainage system is the Yaquina River in the northern half of the cell. The Yaquina River enters Yaquina Bay from the southeast. Another lesser drainage system is Beaver Creek, which enters the cell at Ona Beach at the southern end of the cell. There are six other minor creeks in the cell. This cell is also experiencing erosion at an average rate of 7 cm/yr (Priest and others,, 1993), and Yaquina Bay has been reported by Kulm and Byrne (1966) as a sand sink.

8. The Waldport cell is approximately 46 km in length and is partially bounded by Seal Rocks at the north (UTM N4927250) and Cape Perpetua at the south (UTM N4905000) (Figure 15). Backshore widths range from 46 to 92 m, averaging 63 m. The entire cell is bluff backed except the 1.5 km long south pointing Alsea Spit. Shallow wave-cut platforms in this cell range from 2 to 4.5 m below the beach surface. Alsea Bay is the major drainage system, with several lesser creeks scattered throughout the cell. The Alsea River enters the bay from the southeast. There is no active erosion of the cell (National Shoreline Study, 1971). The Alsea spit erodes and progrades periodically, and major erosion occurs presumably following climatic anomalies such as the 1982-83 El Niño (Komar, 1986; Peterson and others, 1990; O'Neil, 1987).

9. The Winchester cell is approximately 95 km in length and is partially bounded by Heceta Head at the north (UTM N4887500) and Cape Arago at the south (UTM N4795020) (Figure 7 and Figure

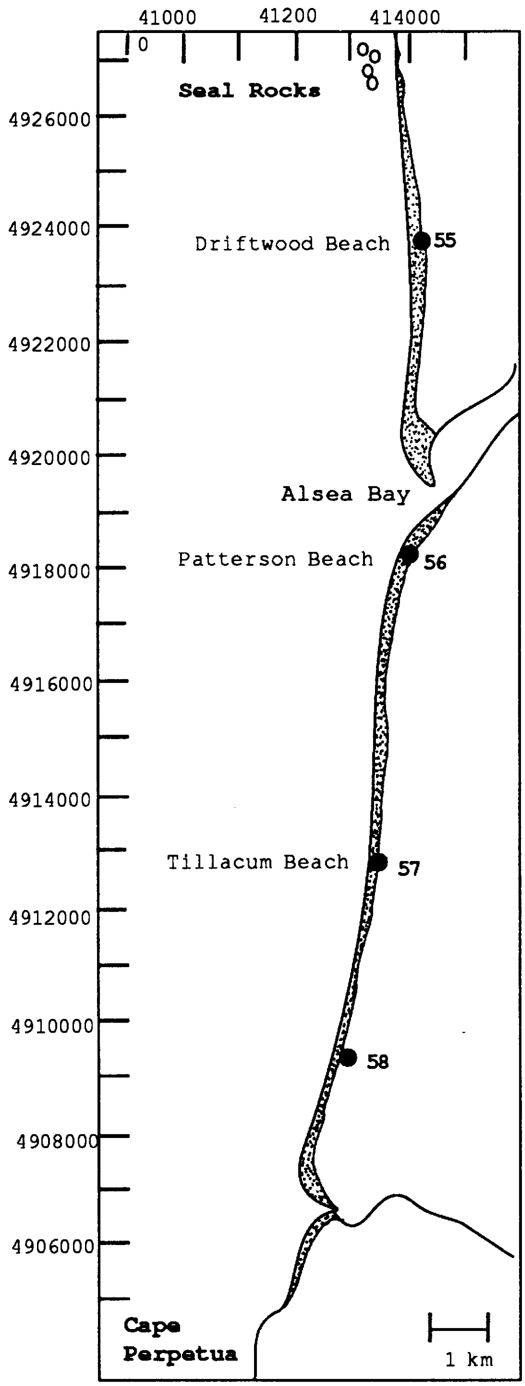

Figure 15. Map of the Waldport cell. Base from U.S.G.S. 7.5' topographic quadrangles. The solid dots and numbers represent profile locations.

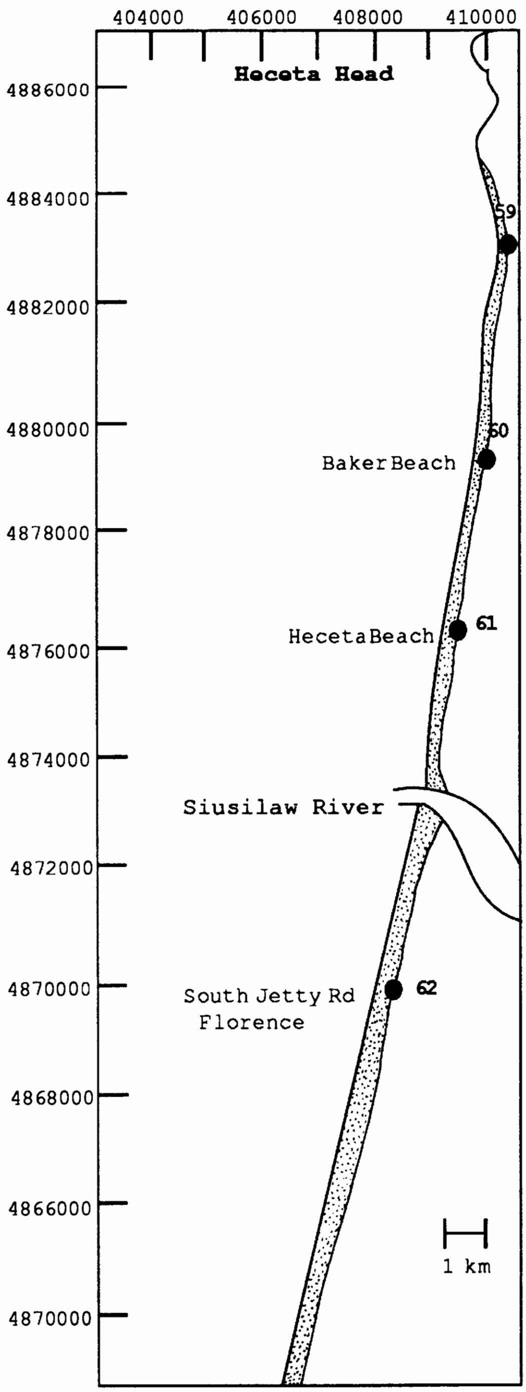

Figure 16. Map of the Winchester cell. Base from U.S.G.S. 7.5' topographic quadrangles. The solid dots and numbers represent profile locations.

16). The southern extent of the study area in this cell is at UTM N4867000, approximately 7 km south of the south jetty for the Siuslaw River. Backshore widths in this portion of the cell range from 47 to 138 m, averaging 103 m. The beaches in this cell are backed by dune-fields. The Umpqua River is the largest drainage system and enters the Winchester cell about 37 km south of the Siuslaw River. Recent mineralogy studies show that the modern beach and dune sands are supplied by recycled Umpqua River sands (Alton and others, 1996).

REGIONAL LITTORAL DRIFT

Longshore currents are generated from the refraction of waves approaching the coast at an angle and are a primary factor of sediment transport (Komar, 1976). Longshore transport of sediment fluctuates seasonally and interannually (Peterson and others, 1991a). Net littoral sediment transport is the difference between the amount of sediment moved in one alongshore direction and the amount moved in the other.

Net transport of sediment along the Oregon coast has been found by Komar and others (1976) to be zero. This is because the rocky headlands of the Oregon coast extend into deep water and are large enough to prevent beach sediment from passing around them (Komar, 1992). Consequently, pocket beaches formed between the headlands are considered littoral cells. The sand within each littoral cell may move to the south or north, but is essentially isolated from the rest of the coast (Komar, 1992). Thus, the long term net movement of sediment along the Oregon coast is zero. Along the southwest Washington coast, stronger winter littoral drift northward and fewer headlands result in a net littoral drift to the north (Ballard, 1964).

DEPTH OF ACROSS-SHORE TRANSPORT

The movement and deposition of sediment from the shore to the offshore area is facilitated by various currents including rip currents and longshore currents. Bruun (1962) found that the maximum depth to which the sediment are transported from the shoreline to the seaward limit on exposed sandy shores of the Pacific California coast was 18 m . That depth contour forms a limit between nearshore and deep-sea littoral drift where the exchange of shore material and offshore bottom material takes place (Bruun, 1962).

An empirical study of depth of nearshore transport closure on the Oregon coast was performed by Peterson and Burris (1993). A compilation of sand size and mineralogy data from shore-normal transects in the Florence and Coos Bay areas of the Umpqua cell (Table 1) indicate a mixing gradient at about the 20 m water depth. There is a discrete mineralogical and size difference between the 18 and 24 m water depth at Florence and deeper than the 18 m water depth at Coos Bay. Although some nearshore sand mixing might occur to the 20 m water depth over long periods, a conservative depth of closure (the depth of water of the seaward limit that nearshore sediment exist) would be 15 m in the study area.

Table 1. Across-shore and inner shelf sample analysis in the Coos Bay and Florence area. (Modified after Peterson and Burris, 1993)

Coos Bay Project			
Site	Depth (m)	Grain Size (mm)	Standard Deviation
CB 5	Bay Mouth	0.26	0.04
CB 2	Bay Mouth	0.24	0.04
E 1	-18 m MSL	0.20	0.04
H 1	-55-60 m	0.16	0.04
H 2	-55-60 m	0.15	0.04
H 4	-55-60 m	0.16	0.03

Siuslaw Project		
Water Depth (m)	Mean Grain Size (mm)	Grain Rounding (Pyroxene)
0 m MSL	0.20	Rounded
-9 m	0.23	Rounded
-12 m	0.20	Rounded
-18 m	0.21	Rounded
-24 m	0.18	Subrounded
-30 m	0.17	Subrounded

CB = Coos Bay (dredging source material)
E = Offshore Target Disposal Site (intermediate water depth)
H = Offshore Target Disposal Site (deep water depth)

METHODS OF INVESTIGATION

To estimate the amount of potential shoreline retreat produced by coseismic subsidence in the Central Cascadia margin, a variety of model inputs are required. These include (1) across-shore beach profile, (2) the depth of closure for across-shore transport, (3) berm or midpoint height, and (4) amount of predicted coseismic subsidence.

Shoreline erosion models were evaluated to determine the appropriate model for the Cascadia margin. Topographic and bathymetric 30'x 60' minute quadrangle maps and nautical charts were used to determine the distance offshore to the 15 m depth contour for model sensitivity analysis.

GEOLOGIC RECORD

Potential beach retreat resulting from coseismic coastal subsidence in the Central Cascadia margin is estimated from prehistoric geologic records (Meyers and others, 1996) and models of beach retreat (Komar and others, 1991) forced by sea-level rise. The geologic records of beach response are examined using Digital Ground Penetrating Radar (GPR) at two sites: Willapa Bay barrier and Siuslaw River barrier (Figure 5 and Figure 18). Subsurface vibra-coring was also used at the Willapa Bay site. These study locations were selected on the basis of 1) extreme differences in predicted subsidence, 2) long, straight coasts with abundant sand supply, and 3) dune-backed beaches.

GPR records were taken at Loomis Lake State Park access road on Willapa Bay barrier and South Jetty Road in Florence. Vibra-coring was performed with 7.5 cm barrels penetrating up to 6.5 m depth.

Six shore-normal GPR surveys were performed by Meyers and others (1996) across the Long Beach Peninsula, Washington. The GPR transect along the Loomis Lake State Park access road (Figure 5 and Figure 6) was used for study. Subsurface vibra-coring and shallow trenching (to one meter) along the transect were performed in areas of predicted scarp structures and where scarp reflections were absent. Three samples of organic material (wood fragments) were collected from vibra-cores that contacted the radar predicted scarps (see *Results*).

MAP ANALYSIS

Topographic 30x60 minute quadrangle maps with bathymetric contours and nautical charts were used to establish the offshore distance to the depth of closure. Topographic 7.5 minute quadrangle maps were used to establish beach shoreline positions in the Tillamook and Pacific City cells. Beach widths for the remaining seven cells were obtained from the regional data base on beach profiles (Peterson and others, 1993). Beach width is the shore-normal distance from the mid-swash zone to an established vegetation line or the base of a sea cliff. Measurements of beach widths and distance offshore at each beach survey site were made from the base maps or charts using a Gerber Scale. Positions of each beach survey site were recorded using the Universal Transect Mercator (UTM) system, based on positioning from topographic 7.5 minute quadrangle maps.

BEACH PROFILING

Shore-normal beach profile surveying was accomplished using a Lietz Set 4 EDM total station and reflecting prisms. The accuracy of the total station was estimated to be within +/- 1.2 cm horizontal distance and +/- 2.5 cm vertical elevation over a 200 m section of the profiles. This was accomplished by moving the total station to a surveyed point along the profile and surveying back to the previous point where the total station had been. This method is called backshooting. The elevation and time that sea-level was measured at the swash zone during surveying was recorded to tie in to NOAA Tide Tables (1994, 1995).

The Loomis Lake State Park access road profile on the Long Beach Peninsula, Washington was surveyed July 21 to 22, 1994. The Florence, Oregon beach profile was surveyed August 21 to 22, 1995.

Beach profile surveying of the Tillamook and Pacific City cells was completed during periods of calm ocean conditions and low tides between June 12 and June 15, 1995. The profiles within the two cells were spaced approximately five kilometers apart and were selected as representative for that section of shoreline. Each beach profile was measured from foredune crests, or the base of sea cliffs if no dunes were present, to mean low water (MLW). The profiling data on the remaining seven littoral cells was garnered from the Cascadia Beach-Shoreline data base (Peterson and others, 1994). Profiles are shown in Appendix A.

DISTANCE FROM TRENCH AND SUBSIDENCE AMOUNTS

Figure 17 (Peterson and Briggs, 1995) depicts the amount of subsidence as a function of distance from the Cascadia trench as estimated for the last Cascadia dislocation (300 years before present). This method correlates with subsidence estimates of 0.5 m and 1.75 m (+/- 0.5 m) along the west coast of North America from Tofino Bay, Vancouver Island, British Columbia, to the Waldport area on the central Oregon coast (Clague and Bobrowsky, 1994; Atwater,

1987 and 1992; Darienzo and Peterson, 1990). These estimates are based on paleotidal indicators above and below the contact of the most recent (300 years before present) subsidence event in coastal marsh cores (Atwater, 1987, and 1992; Darienzo and

Peterson, 1990; Clague and Bobrowsky, 1994; Clarke and Carver, 1992).

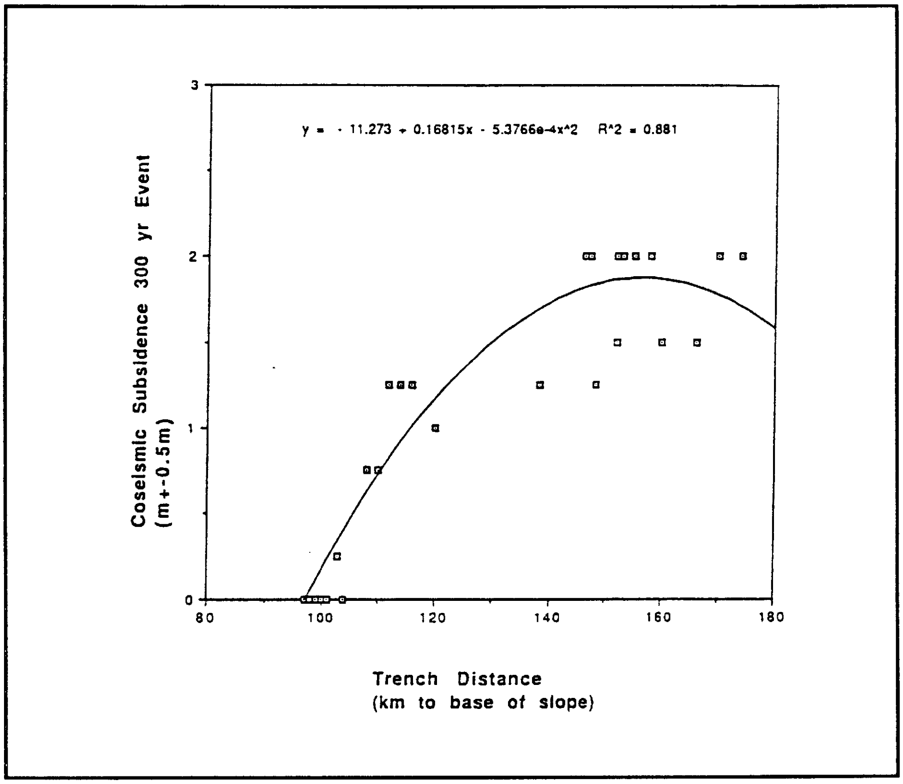

Figure 17. Plot of estimated coseismic coastal subsidence associated with youngest Cascadia earthquake (300 years B.P.) as a function of site distance (due east) from the base of the continental slope (buried trench)(Peterson and Briggs, 1995).

SELECTION OF SHORELINE EROSION MODEL

The first step in estimating the potential hazard of beach erosion from rapid coseismic subsidence is to chose a beach response model. An appropriate model can then be used to estimate the amount of expected shoreline retreat rate for various sites on the Central Cascadia margin. An appropriate model for coseismic subsidence in the Cascadia margin would have to address a sea-level rise that would persist for decades. In addition, the Cascadia margin is dominated by pocket beaches backed by dunes or sea cliffs.

The search for a beach response model of rapid sea-level rise of 1 to 2 m, led first to the Bruun model (1962; see *Background*). The other models investigated for this study were generally derived from profile displacements like those in the Bruun model, but they address a wider range of conditions and beach systems (Edelman, 1968; Dubois, 1975, 1977; Dean and Maurmeyer, 1983; Dean, 1982, 1991).

The Dubois (1975) model was eliminated because the model was created for a lake environment, but the west coast of North America has one of the highest wave energies in the Northern Hemisphere (Peterson and others, 1991b). Scaling effects might present problems in the use of the Dubois model.

In the Edelman dune model the sea-level rise is temporary. It resumes its pre-storm surge level before the profile reaches equilibrium with the higher sea-level conditions. The Edelman model fails the criterion that sea-level height be maintained, so is not a useful model for this study.

The Dean and Maurmeyer (1983) model represents rapid sea-level fluctuation with a short lag time for the profile, and is used for barrier island system retreat. This model is eliminated as a regional model because only about 17 percent of the study area is protected by barrier spits. This model could be of value for localized shoreline retreat studies in areas of the Cascadia Subduction Zone where small barriers are abundant.

The model from Dean (1991) has a useful application for predicting the shape of a beach and its nearshore profile. This model will not be used because nearshore profiling is beyond the scope of this study.

Dean's (1982) sea wall equation (6;) may be useful for very narrow beaches in front of sea cliffs, and equation (5) can be used to evaluate the rest of the profile seaward of the sea wall. Only about 18 percent of the beaches in the study area are backed by sea walls or cliffs fronting narrow beaches. Therefore, this model cannot be widely applied for regional comparisons in the study area and was eliminated.

The Bruun model provides the most suitable approach for a first attempt at estimating potential beach retreat from coseismic subsidence in the Cascadia margin. It is a two-dimensional equilibrium profile model that assumes negligible net longshore transport of sediment and negligible loss of sediment to inshore lagoons. The model also works without regard to the shape of the beach profile. Another aspect of the Bruun model is that response time is assumed to be long. The response time of a profile after coseismic subsidence in the Cascadia margin could be tens of years or longer.

These simplifying assumptions make the Bruun model most effective for this initial regional analysis. Different models might be used in future site-specific studies.

MIDPOINT LOCATION

The berm on a beach is a nearly horizontal, depositional feature and is formed during swell wave conditions that bring sediment onshore (Komar, 1976). Its position on the beach can fluctuate daily with the tides, and seasonally with winter and fair-weather wave attack: the summer berm is farther seaward than the winter berm. The berm is not always possible to locate on fine-grained beaches because the beach usually has a low, constant slope (Komar, 1976). Medium- to coarse-grained beaches have a steeper beach face, and berm development is more distinct. The location of the berm on many of the Washington beaches was not detectable due to the fine grained beach sediment (Pettit, 1990).

The berm location was not noted in the Cascadia Beach-Shoreline Data base (Peterson and others, 1994), so for consistency in determining the distance offshore (L) to the water depth (h) for all of the profiles, a point approximately midway between MTL and the back of the backshore was determined. The backshore of a beach is the area from the base of a foredune or sea cliff, to the berm crest. Backshore sand deposits are an important aspect of the beach that help (1) protect bluffs, (2) provide recreational areas at high tide, and (3) provide a safety buffer for offshore transport of sediment during extreme storm conditions. The midpoint is representative of the backshore elevation and is selected to represent the elevation height (B). The midpoint location of the profile was selected for the elevation height (*B*) because it is representative of the backshore elevation, and retreat of this point represents a loss of the backshore deposits that protect sea cliffs and dunes from wave attack.

The range of midpoint elevations (*B*) for beaches that are in the same general area, are generally within 1 m of the average for that area (Table 2). For example, the midpoint elevations for the beaches north of Gray's Harbor (Ocean Shores to Copalis Beach) range from 2.9 to 3.2 m and average 3 m. The greatest difference from the average is in the Lincoln City cell. The average midpoint elevation is 3.1 m, and the lowest and highest elevations are 2.0 m and 5.0 m, respectively.

Berm locations were noted for the Tillamook and Pacific City cells, and were used to determine the difference between the berm location and the midpoint (Table 3). The midpoint ranges between 3 to 4 m landward of the berm, and 16 to 29 m seaward of the berm. The largest difference between these two points is only 2.3% of

Table 2. Sensitivity of shoreline retreat to changes in midpoint elevation.

CELL	UTM	Retreat B - decrease		B + increas	Midpoint elev. (B)	S	Backshore width
COLUMBIA RIVER CELL		B-0.55		B+0.5			
Copalis Beach	5217950	339	329	320	3.00	1.50	196
Ocean City	5213450	361	350	341	2.90	1.50	178
Ocean City State Park	5209140	326	316	308	3.20	1.50	134
Ocean Shores	5201490	317	307	299	2.90	1.50	169
Twin Harbors Beach	5189900	281	272	265	3.00	1.50	114
Grayland	5184450	267	259	252	2.30	1.50	137
South Beach St. Park	5179950	271	262	255	2.00	1.50	125
Leadbetter Point St. Park	5161230	397	384	372	1.00	1.50	92
6km south of Leadbetter	5155330	305	295	287	2.10	1.50	113
Klipsan Beach	5146300	278	269	262	2.50	1.50	142
Loomis Lake Beach Rd.	5142840	283	275	267	2.80	1.50	83
Oceanside	5140180	271	262	255	2.20	1.50	109
west of Black Lake	5130440	229	222	216	2.30	1.50	91
Clatsop Spit	5117000	374	361	351	1.50	1.50	75
Sunset Beach	5105340	214	207	202	2.30	1.50	143
Sunset Beach	5102260	208	201	196	2.90	1.50	155
Gearhart	5096500	215	209	204	3.70	1.50	218
N. Seaside	5094380	245	237	230	2.20	1.50	115
S. Seaside	5092190	252	244	237	2.20	1.50	102
CANNON BEACH CELL		B-0.8		B+1.2			
Chapman Beach	5083750	93	90	88	3.00	1.25	103
Cannon Beach	5079700	91	88	86	2.20	1.25	72
Humbug Point	5077150	100	96	94	1.50	1.25	73
Arcadia Beach	5073650	105	102	99	1.30	1.25	75
Arcadia Beach	5070000	91	89	86	3.50	1.25	13
TILLAMOOK CELL		B-0.5		B'+1.0			
Manzanita	5063240	161	156	151	1.90	1.00	74
Nehalem Bay St. Park	5059830	152	147	143	2.60	1.00	87
Rockaway	5051000	156	151	147	2.00	1.00	69
Bay Ocean Peninsula #1	5041000	221	214	208	1.60	1.00	50
Bay Ocean Peninsula #2	5039300	213	206	200	1.30	1.00	61
Cape Mears	5038950	201	194	188	0.60	1.00	25
PACIFIC CITY CELL		B-0.4		B+.6			
Sand Beach St. Park	5015300	104	101	98	1.40	1.00	52
Tierra Del Mar	5010650	93	90	87	2.47	1.00	68
Nestucca Spit St. Park	5004700	65	63	61	2.20	1.00	77
Daley Lake	4999350	100	97	94	2.00	1.00	76
Neskowin	4995330	92	90	87	3.00	1.00	42
LINCOLN CITY CELL		B-1.1		B+1.9			
Wecoma	4985000	48	46	45	2.20	0.75	51
Wecoma	4981000	70	68	66	2.00	0.75	59
Lincoln City	4977310	51	49	48	2.10	0.75	36
Siletz Spit	4974080	42	41	40	3.10	0.75	63
Glenden Beach	4969550	34	33	32	4.50	0.75	39
Lincoln Beach	4966500	46	44	43	3.00	0.75	70
Lincoln Beach	4965700	46	45	44	2.70	0.75	23
Government Point	4965460	41	40	39	5.00	0.75	61
OTTER ROCK CELL		B-.4		B+.3			
Otter Rock Beach	4954800	83	81	78	1.40	0.75	79
Beverly Beach	4953150	97	94	91	0.70	0.75	74
Moolach Beach	4950400	99	96	93	1.20	0.75	46
	4947900	116	112	109	1.00	0.75	23
NEWPORT CELL		B-0.8		B+0.8			
Agate Beach	4946950	113	110	107	1.75	0.75	93
Agate Beach St. Wayside	4945550	100	97	94	2.45	0.75	92
Nye Beach	4943300	77	75	73	1.80	0.75	60
South Beach	4939200	106	103	100	2.30	0.75	78
Holiday Beach	4936650	45	43	42	1.40	0.50	69
Ona Beach	4930000	44	42	41	1.50	0.50	48
Seal Rock Beach	4928600	54	52	50	0.90	0.50	28
WALDPORT CELL		B-0.5		B+1.1			
Driftwood Beach	4923880	45	40	42	1.30	0.50	59
Patterson Beach	4918050	0	0	0	2.60	0.00	92
Tillacum Beach	4912680	0	0	0	1.00	0.00	46
	4909300	0	0	0	1.10	0.00	55
WINCHESTER CELL							
	4883320	0	0	0	0.60	0.00	47
Baker Beach	4879490	0	0	0	3.60	0.00	119
Heceta Beach	4876640	0	0	0	2.20	0.00	110
Florence	4870620	0	0	0	2.90	0.00	138

Table 3. Berm versus midpoint location in the Tillamook and Pacific City cells. Distance is from MTL (mean tide level). Negative values for the difference in distances indicates the midpoint is landward of the berm. Negative elevational differences indicate the midpoint is at a lower elevation than the berm. All measurements are in meters.

	Distance			Elevation		
Cell and Site Name	Berm	Midpoint	Difference	Berm	Midpoint	Difference
Tillamook Cell						
Manzanita	42	71	29	2.7	1.9	-0.8
Nehalem Bay St. Pk.	64	61	-3	3.2	3.4	0.2
Rockaway	49	45	-4	2.8	3	0.2
Bay Ocean Peninsula	48	45	-3	1.7	1.9	0.2
Bay Ocean Peninsula	36	52	16	2.7	2	-0.7
Cape Mears	no berm					
Pacific City Cell						
Sand Beach St. Pk.	31	43	12	2.6	2.1	-0.5
Tierra Del Mar	56	64	8	2.6	2.4	-0.2
Nestucca Spit St. Pk.	86	67	-19	1.9	2.1	0.2
Daley Lake	102	63	-39	1.8	2.5	0.7
Neskowin	49	32	-17	2.5	3.1	0.6

the total distance offshore to the 15 m water depth (*h*). The small percentage in differences of berm location relative to the across-shore distance (*L*) does not significantly alter the affect on the retreat distance (Table 2).

MINIMUM WATER DEPTH DETERMINATION

To measure the distance offshore to the 15 m water depth (see *Background*), USGS Topographic 30x60 minute quadrangle maps with 2 m bathymetric contours were used for five of the nine littoral cells (Columbia River, Cannon Beach, Tillamook, Pacific City, and Winchester Cells). NOAA nautical charts were used for the remaining four littoral cells (Lincoln City, Otter Rock, Newport, and Waldport Cells). NOAA nautical chart depths were given in fathoms and converted to meters by the conversion factor of 1 fathom equals 1.8 m. The scale on the topographic maps is

1:100,000 and that of the nautical charts is 1:191,730. The NOAA nautical maps were enlarged 121% to use similar measurement techniques as those used for the USGS topographic maps. For error determination of distance to the 15 m water depth see sensitivity to error below. The nautical charts are referenced with longitude and latitude. To translate longitude and latitude to Universal Transect Mercator (UTM) components, the computer software Plane-PC was used.

Because the maps have different water depth scales and data presentation (spot versus contours) measurement error for water depth was compared at localities that appeared on both the 30x60 topographic maps and the nautical charts (see below). At each site ten measurements were made from the low water line to the 15 m water depth. This is the most conservative depth of assumed across-shore transport in the Pacific Northwest coastal zone (see *Background*). Measurements were then compared between the two map types and an average percentage error was calculated (Table 4).

Where topographic maps and nautical charts displayed both low and high water lines, a point midway between the two lines was used as MTL. The high water line was used as a starting point to measure the offshore distance when the low water line was not shown on the map.

Table 4. Measurement error analysis of across-shore distance to the 15 m water depth at ten locations, 100 m apart.

UTM	Measured Distances (m) NOAA nautical Chart	USGS 30x60 Topographic Map	Percent Difference
Columbia River cell			
5213950	3942	3910	0.8
5213850	3942	3900	1.1
5213750	3776	4100	-7.9
5213650	3868	3750	3.2
5213550	4145	3570	16.1
5213450	3887	4000	-2.8
5213350	4052	3700	9.5
5213250	4052	3710	9.2
5213150	4200	3780	11.1
5213050	3960	3770	5.0
Mean Distance	3982	3819	
		Average % Error	4.5
Pacific City cell			
500520	1105	900	22.8
5005100	1032	950	8.6
5005000	976	950	2.8
5004900	1087	920	18.1
5004800	1105	950	16.3
5004700	1087	1100	-1.2
5004600	921	990	-7.0
5004500	921	850	8.4
5004400	810	830	-2.4
5004300	718	890	-19.3
Mean Distance	976	933	
		Average % Error	4.7

The first locality is Ocean City (UTM N5213450) in the Columbia River cell just north of Gray's Harbor, Washington. The distance offshore to the 15 m water depth was measured at ten places each 100 m apart on both scale maps, five north and five south of Ocean City. The second locality was a one km stretch in the Pacific City cell on the Nestucca Spit. The ten measurements, 100 m apart, were centered at UTM N5004700.

The percentage error between the two map types for the Ocean City site is +/- 4.5%. The Nestucca Spit site error is +/- 4.7%. These percentage errors demonstrate the difficulty of obtaining accurate measurements on small-scale maps. However, this error is acceptable for this initial study.

Another source of error is precision, that is to say, repeatability by the measurer. For this analysis one site each at Ocean City (UTM N5213450) and Nestucca Spit (UTM N5004700) were used as reference points. Each locality was measured ten times on the NOAA nautical charts and the USGS topographic maps, and the standard deviation (SD) was calculated (Table 5).

Measurements made from the NOAA nautical charts has the largest standard deviation at both sites (+/- 13 m for Ocean City, and +/- 67 m for Nestucca Spit). For the USGS topographic maps, the standard deviation at Ocean City is +/- 1 m, while at Nestucca Spit it is zero. The larger errors associated with the

Table 5. Measurement accuracy analysis to the 15 m water depth. Measurements were made at the same site, ten separate times.

UTM Columbia River cell	Measured Distances (m) NOAA nautical Chart	USGS 30x60 Topographic Map	Percent Difference
5213450 - Ocean City	4420	4000	10.5
	4401	4050	8.7
	4401	4002	10.0
	4405	4100	7.4
	4390	4030	8.9
	4400	4005	9.9
	4402	4020	9.5
	4408	4002	10.1
	4390	4001	9.7
	4402	4002	10.0
Standard Deviation	13	1	
		Average % Error	9.5
Pacific City cell			
5004700 - Nestucca	1150	1001	14.9
Spit	1055	1001	5.4
	959	1010	-5.1
	1054	1000	5.4
	1055	1001	5.4
	1055	1001	5.4
	1054	1005	4.9
	1054	1001	5.3
	1150	1001	14.9
	1055	1001	5.4
Standard Deviation	67	0	
		Average % Error	6.2

NOAA charts arise from the fact that the bathymetry data on those charts are designated by a number that indicates a depth in fathoms. To estimate the water depth needed, measurements had to be made between two designated fathom numbers (points). For example, to estimate the 8.3 fathom water depth (15 m), measurements had to be made between the 4 and 9 fathom point locations on the chart. In contrast, the topographic maps are in 2 m water depth contour intervals, and the 15 m water depth location was found half way between the two contour lines. However, these errors are on the order of 0.5 to 26% of the mean offshore distance to the 15 m water depth, with a mean of 6.1%, and so are considered acceptable for this initial study.

Because measurement and accuracy error were low on the USGS topographic maps, all measurements for the rest of the study were made using the USGS topographic maps.

RESULTS

GROUND PENETRATING RADAR

Possible evidence for beach retreat from past coseismic subsidence events in the Cascadia margin has been found by Meyers and others (1996). This evidence comes from buried scarps in the barrier spit of Willapa Bay (see *Background*). In this section the geologic evidence for catastrophic beach retreat is presented. This evidence is contrasted with profiles from Florence, Oregon where no episodic subsidence is recorded in coastal marsh deposits (Briggs, 1994).

One cross-barrier GPR transect that imaged the buried scarps in the Willapa barrier (Meyers and others, 1996;(Figure 5; also see back pocket) was run along the Loomis Lake State Park access road. An elevation profile is shown for that transect (Figure 6). The profile is 1.2 km long, and spans the distance from the western edge of Loomis Lake to mean tide level of the Pacific Ocean. At locations along the transect determined to contain the buried scarps, vibra-core and shallow trenching located concentrated beds of heavy minerals at depths from 2.6 to 5.3 m predicted by GPR (Meyers and others, 1996) (Figure 5). The heavy mineral beds are dominated by magnetite, ilmenite, and other iron-bearing minerals that form the conductance-contrast reflections in the GPR records (Meyers and others, 1996). The heavy mineral beds vary in thickness from 0.2 cm to 1.70 m, have erosional bases, and grade upward into quartz-rich sand (Table 6 and Appendix B). The beds commonly contain 85-90% heavy minerals and 10-15% light minerals. The present beach sand is composed of 93% light minerals and 7% heavy minerals (Li and Komar, 1992).

Along the length of the Loomis Lake State Park access road profile (Figure 6) there are many dunes and hollows. Three of the vibra-core sites contained wood fragments that were later dated at 300 (+/- 70), 1110 (+/- 60), and 2540 (+/- 60) radiocarbon years before present. These sites are noted in Figure 6 by the site numbers where the material was found. The youngest date (300 RCYBP) is the farthest west along the profile (site 11), the middle date (1110 RCYBP) is from site 8, and the oldest date (2540 RCYBP) is farthest east, i.e., near Loomis Lake (site 2).

The buried scarps represent episodic erosion in an otherwise progradational barrier system. The scarps and related heavy mineral beds are interpreted to be the products of shoreface scouring and lag development. Possible processes that could cause the shoreface retreat include unusually large storm waves, tsunamis, or a wave-dominated subsided coast.

Many large storms have affected the Long Beach Peninsula in the past 300 years. Because there is no evidence of buried scarps in beach sediment younger than 300 years (Meyers and others,

Table 6. Percent heavy and light minerals in vibra-core and trenches.

Site	Core	Trench	Depth (m)	% Light Minerals	% Heavy Minerals	p = placer deposits
1	1		3.80	75	25	p
			4.60	9	91	p
			4.80	23	77	p
			4.90	2	98	p
			5.05	22	88	p
			5.30	11	89	p
1	2		5.50	27	73	p
			5.80	10	90	p
			6.20	92	8	
			6.47	82	18	
2	3		2.60	84	16	
			3.18	19	81	p
			3.50	67	33	
3		1	0.20	74	26	
			0.40	24	76	p
			0.70	82	18	
4		2	0.08	77	23	
			0.18	68	32	
			0.35	92	8	
5		3	0.10	31	69	p
			0.26	65	35	
6		4	0.10	27	73	p
			0.25	68	32	
7	4		2.77	78	22	
			4.00	79	21	
			4.15	17	84	p
8	5		2.10	73	23	
			2.80	57	43	
8	8		3.50	67	33	
			4.25	7	93	p
			4.50	81	20	
9	6		1.00	64	36	
			2.00	70	30	
			2.30	58	42	
			2.50	54	46	
			3.20	62	38	
10	7		2.45	69	31	
			2.80	33	67	p
			3.00	28	72	p
			3.50	15	84	p
10	9		2.15	71	29	
			3.90	3	97	p
			4.30	62	38	
			4.70	79	21	
11	10		2.64	13	87	p
			2.80	30	70	p
			3.90	63	37	

1996), it is thought that large storms are not the principal cause of the anomalous buried scarps.

Tsunamis have struck the coast of Washington in the recent past (Atwater, 1987, 1992). Tsunamis can blanket coastal lowland areas under a mantle of sand. However, they might not generate the number of waves needed to strongly alter the geomorphology of the shoreline over tens of kilometers of longshore distance. An empirical test of tsunami origin of buried scarps is discussed below under the section on the Florence GPR line.

The remaining process for the formation of the anomalous buried scarps is a subsided coast impacted by normal and storm wave activity. Coastal subsidence has been reported from British Columbia to Northernmost California (Atwater, 1987, 1992; Clague and Bobrowsky, 1994; Clarke and Carver, 1992; Darienzo and Peterson, 1990). After coseismic subsidence of 1 to 2 m, the ocean waves should attack the newly submerged beach front, winnowing the light minerals from the heavy minerals. The light minerals are carried offshore by wave action, whereas the heavy minerals are left on the beach as a lag deposit. These lag deposits form the heavy mineral beds found in the buried scarps.

To test the earthquake hypothesis of subsidence-related beach erosion, another GPR profile was run over a shore-normal transect at South Jetty Road in Florence, Oregon. This study area was chosen based on evidence of no coseismic subsidence during the last several thousand years (Nelson, 1992; Briggs, 1994).

Figures 18 and 19 show the underlying structure of the South Jetty Road transect. Figure 20 shows the elevation profile along which the GPR transect was made. The subsurface GPR reflectors sharply contrast with those found on the Willapa barrier (Figure 20). For example, the Florence reflectors are less steeply dipping than those in the Willapa barrier. And secondly, there are no apparent buried scarps in the Florence transect. The gradually dipping reflector in Figure 19 might represent a shore-normal channel or interdune hollow.

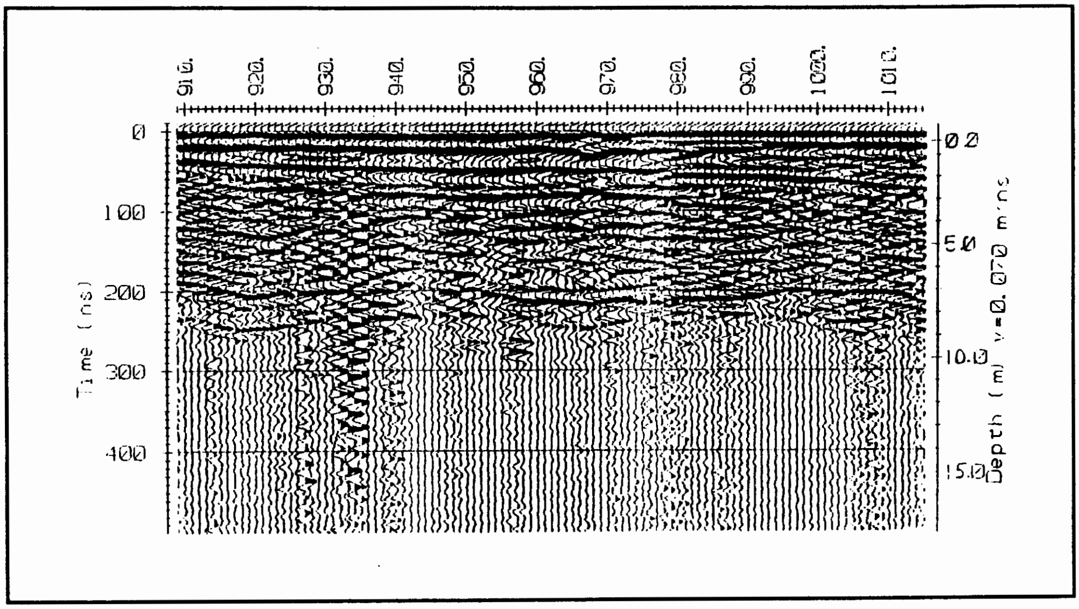

Figure 18. Ground penetrating radar transect (A) along 105 m of the South Jetty Road elevational profile, Florence, Oregon. (From Meyers and others, 1996).

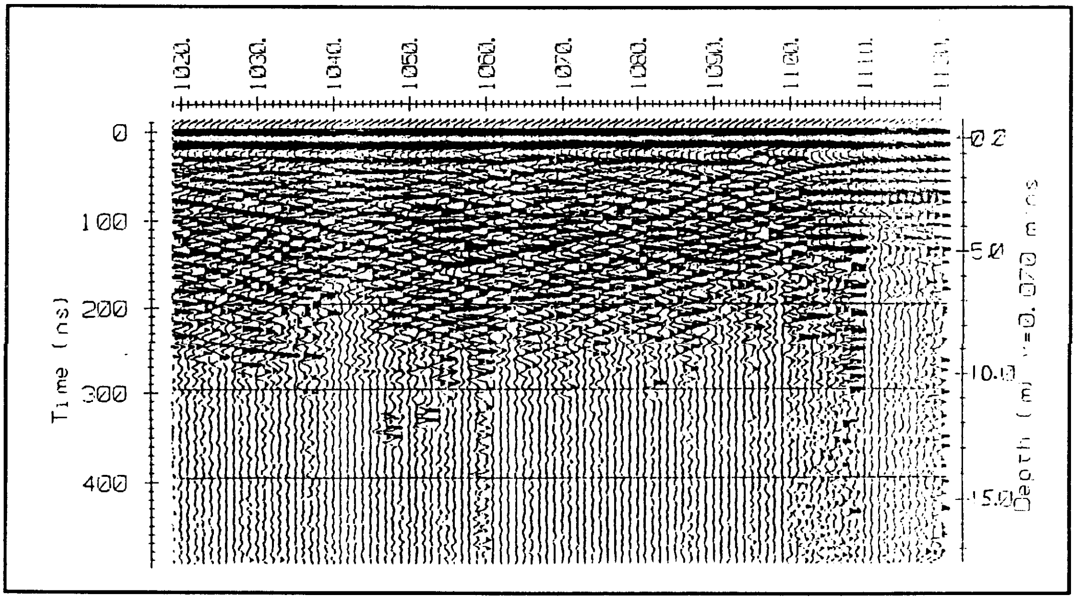

Figure 19. Ground penetrating radar transect (B) showing a reflector that could be a shore-normal channel or an interdune hollow, Florence, Oregon (Meyers and others, 1996).

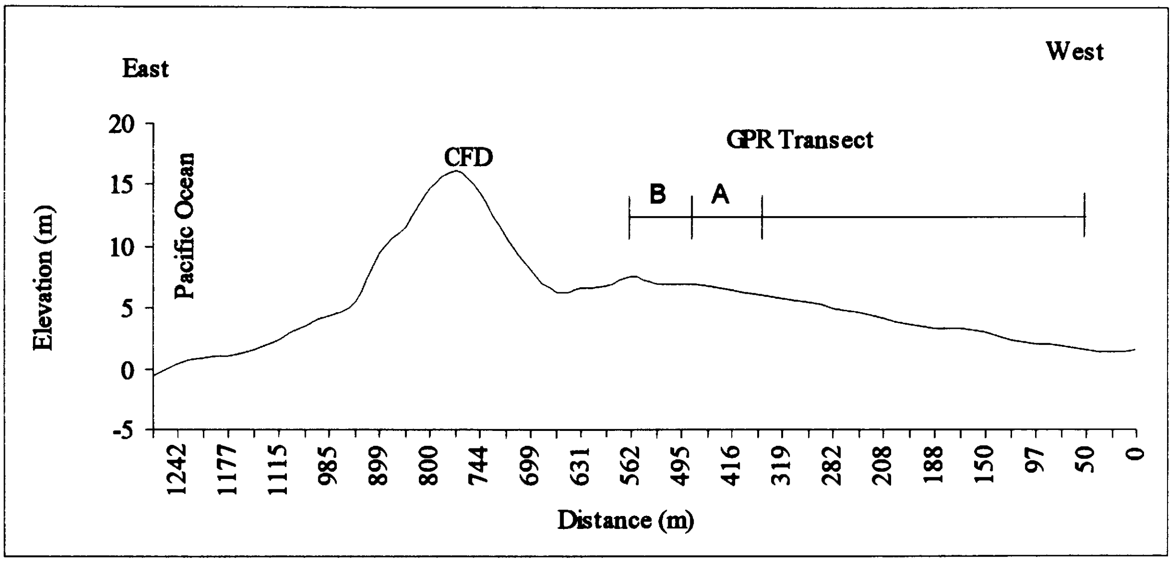

Figure 20. Elevational profile along South Jetty Road, Florence, Oregon. Transect A refers to Figure 18; Transect B refers to Figure 19.

Although this area (Florence) is comparable to the Long Beach Peninsula in terms of morphology, abundant sand supply, wave energy and tsunami inundation, it lacks the evidence of episodic, rapid accretion and catastrophic retreat found in southwest Washington.

CARBON-14 DATES

Three wood fragments found at three vibracore sites in the Long Beach transect(Figure 6; also see *Appendix B* for location of wood fragments in cores) were dated by Carbon-14 analysis and yielded dates of 300, 1120, and 2540 (+/- 60 years before present)(Table 7). The ages of the wood fragments increase eastward. A comparison of the dates from this study with other

Table 7. Radiocarbon dates of wood fragments from magnetite beds.

Location of Samples	Material Dated	Lab No.	Age (RCYBP)
Site 11, 259 m W. of Hwy 103, alley opposite Loomis Lake Rd.	Wood fragment	Beta-79506	300 +/- 70
Site 8, 89 m W. of Hwy 103, alley opposite Loomis Lake Rd.	Wood fragment	Beta-79505	1110 +/- 60
Site 2, 147 m W. of Loomis Lake,	Wood fragment	Beta-79504	2540 +/- 60

published data reveals possible agreement between the younger two radiocarbon dates and the last two or three subsidence events in

Washington (Table 8). Possible explanations for the lack of additional buried scarps associated with subsidence events reported for the period between 1,100 and 2,400 RCYBP are (1) the event was minor (< 1 m) and subsequent erosion of the scarps was complete, and/ or (2) the scarp was missed near the highway (Figure 6) where the GPR transect was not run.

Table 8. Comparison of radiocarbon dates related to past subsidence events.

Data Source	Ages (RCYBP) of Subsidence Events							
	1	2	3	4	5	6	7	8
This Study	300	1120	-----	2540	-----	-----	-----	-----
Meyers and others (1996)	300	1120	*1800	2540	*3400	4250	*5000	*5800
Darienzo and Peterson (1995)	480, 680	800-1370	2000-2200	-----	-----	-----	-----	-----
Atwater (1995)	300	900-1300	1400-1900	-----	-----	-----	-----	-----
Atwater and Yamaguchi (1991)	300	-----	1700	-----	3100	-----	-----	-----
Darienzo and Peterson (1990)	300-500	1000-1300	1400-1800	-----	3000-3300	-----	-----	-----

*Extrapolated dates by Meyers and others (1996)

BRUUN MODEL SENSITIVITY TO CHANGING PARAMETER VALUES

The Bruun model has been selected to represent regional shoreline retreat in the Central Cascadia margin (see *Background*). The Bruun model is represented by the equation

$$R=\frac{L}{B+h}S \tag{1}$$

where *R* is the shoreline retreat distance due to *S*, an increase in sea-level, *L* is the distance from the shoreline to *h*, which is the water depth of the seaward limit that nearshore sediment exist, and *B* is the vertical elevation of the berm or midpoint of the beach. Testing the sensitivity of the retreat distance to each variable is important in understanding possible errors in predicting beach retreat from assumed parameters of coastal subsidence, offshore closure depth and backshore elevation.

Model Sensitivity to Different Subsidence Amounts (S)

Estimated subsidence (S) directly affects the amount of sea-level rise. Table 9, Table 10, and Table 11 show the effect different subsidence amounts have on retreat. As predicted by the Bruun model (see *Background*), the retreat distance is approximately equal to 150 to 200xS (see Figure 21). For example, at Copalis Beach in the Columbia River cell, the retreat distances (*R*) for 1.0, 1.5, and 2.0 m of subsidence (*S*) are 219, 329, and 438 m respectively. For a 2 m rise in sea-level, the retreat distance increased by 200 m relative to the 1 m subsidence estimate. As expected, the predicted retreat is very sensitive to assumed amounts of subsidence. Subsidence is estimated to the nearest meter for the 300 year event. However, greater differences in actual subsidence might occur between different earthquakes for a given coastal area (Peterson, unpublished data, 1996). For this

Table 9. Estimated retreat using minimum subsidence amounts. All parameters in meters.

CELL	UTM	Retreat (R)	Subsidence (S)	Present Backshore width
COLUMBIA RIVER CELL				
Copalis Beach	5217950	200	1.00	196
Ocean City	5213450	189	1.00	178
Ocean City State Park	5209140	194	1.00	134
Ocean Shores	5201490	284	1.00	169
Twin Harbors Beach	5189900	132	1.00	114
Grayland	5184450	109	1.00	137
South Beach St. Park	5179950	135	1.00	125
Leadbetter Point St. Park	5161230	190	1.00	92
6km south of Leadbetter	5155330	146	1.00	113
Klipsan Beach	5146300	127	1.00	142
Loomis Lake Beach Rd.	5142840	119	1.00	83
Oceanside	5140180	140	1.00	109
west of Black Lake	5130440	111	1.00	91
Clatsop Spit	5117000	215	1.00	75
Sunset Beach	5105340	134	1.00	143
Sunset Beach	5102260	123	1.00	155
Gearhart	5096500	117	1.00	218
N. Seaside	5094380	125	1.00	115
S. Seaside	5092190	144	1.00	102
CANNON BEACH CELL				
Chapman Beach	5083750	38	0.50	103
Cannon Beach	5079700	43	0.50	72
Humbug Point	5077150	44	0.50	73
Arcadia Beach	5073650	47	0.50	75
Arcadia Beach	5070000	40	0.50	13
TILLAMOOK CELL				
Manzanita	5063240	41	0.50	65
Nehalem Bay St. Park	5059830	43	0.50	44
Rockaway	5051000	34	0.50	32
Bay Ocean Peninsula #1	5041000	54	0.50	37
Bay Ocean Peninsula #2	5039300	47	0.50	35
Cape Mears	5038950	41	0.50	22
PACIFIC CITY CELL				
Sand Beach St. Park	5015300	35	0.50	26
Tierra Del Mar	5010650	31	0.50	57
Nestucca Spit St. Park	5004700	34	0.50	49
Daley Lake	4999350	29	0.50	37
Neskowin	4995330	27	0.50	14
LINCOLN CITY CELL				
Wecoma	4985000	16	0.25	51
Wecoma	4981000	12	0.25	59
Lincoln City	4977310	14	0.25	36
Siletz Spit	4974080	11	0.25	63
Glenden Beach	4969550	8	0.25	39
Lincoln Beach	4966500	12	0.25	70
Lincoln Beach	4965700	15	0.25	23
Government Point	4965460	10	0.25	61
OTTER ROCK CELL				
Otter Rock Beach	4954800	25	0.25	79
Beverly Beach	4953150	19	0.25	74
Moolach Beach	4950400	9	0.25	46
	4947900	42	0.25	23
NEWPORT CELL				
Agate Beach	4946950	32	0.25	93
Agate Beach St. Wayside	4945550	38	0.25	92
Nye Beach	4943300	31	0.25	60
South Beach	4939200	36	0.25	78
Holiday Beach	4936650	35	0.25	69
Ona Beach	4930000	19	0.25	48
Seal Rock Beach	4928600	37	0.25	28
WALDPORT CELL				
Driftwood Beach	4923880	0	0.00	59
Patterson Beach	4918050	0	0.00	92
Tillacum Beach	4912680	0	0.00	46
	4909300	0	0.00	55
WINCHESTER CELL				
	4883320	0	0.00	47
Baker Beach	4879490	0	0.00	119
Heceta Beach	4876640	0	0.00	110
Florence	4870620	0	0.00	138

Table 10. Estimated retreat using determined subsidence amounts. All parameters in meters.

CELL	UTM	Retreat (R)	Subsidence (S)	Present Backshore width
COLUMBIA RIVER CELL				
Copalis Beach	5217950	351	1.50	196
Ocean City	5213450	340	1.50	178
Ocean City State Park	5209140	360	1.50	134
Ocean Shores	5201490	354	1.50	169
Twin Harbors Beach	5189900	280	1.50	114
Grayland	5184450	268	1.50	137
South Beach St. Park	5179950	262	1.50	125
Leadbetter Point St. Park	5161230	384	1.50	92
6km south of Leadbetter	5155330	295	1.50	113
Klipsan Beach	5146300	269	1.50	142
Loomis Lake Beach Rd.	5142840	273	1.50	83
Oceanside	5140180	301	1.50	109
west of Black Lake	5130440	242	1.50	91
Clatsop Spit	5117000	361	1.50	75
Sunset Beach	5105340	207	1.50	143
Sunset Beach	5102260	201	1.50	155
Gearhart	5096500	209	1.50	218
N. Seaside	5094380	237	1.50	115
S. Seaside	5092190	244	1.50	102
CANNON BEACH CELL				
Chapman Beach	5083750	72	1.25	103
Cannon Beach	5079700	71	1.25	72
Humbug Point	5077150	77	1.25	73
Arcadia Beach	5073650	81	1.25	75
Arcadia Beach	5070000	71	1.25	13
TILLAMOOK CELL				
Manzanita	5063240	78	1.00	65
Nehalem Bay St. Park	5059830	73	1.00	44
Rockaway	5051000	72	1.00	32
Bay Ocean Peninsula #1	5041000	105	1.00	37
Bay Ocean Peninsula #2	5039300	99	1.00	35
Cape Mears	5038950	91	1.00	22
PACIFIC CITY CELL				
Sand Beach St. Park	5015300	58	1.00	26
Tierra Del Mar	5010650	53	1.00	57
Nestucca Spit St. Park	5004700	63	1.00	49
Daley Lake	4999350	48	1.00	37
Neskowin	4995330	52	1.00	14
LINCOLN CITY CELL				
Wecoma	4985000	46	0.75	51
Wecoma	4981000	82	0.75	59
Lincoln City	4977310	49	0.75	36
Siletz Spit	4974080	42	0.75	63
Glenden Beach	4969550	33	0.75	39
Lincoln Beach	4966500	50	0.75	70
Lincoln Beach	4965700	51	0.75	23
Government Point	4965460	40	0.75	61
OTTER ROCK CELL				
Otter Rock Beach	4954800	86	0.75	79
Beverly Beach	4953150	99	0.75	74
Moolach Beach	4950400	103	0.75	46
	4947900	104	0.75	23
NEWPORT CELL				
Agate Beach	4946950	77	0.50	93
Agate Beach St. Wayside	4945550	90	0.50	92
Nye Beach	4943300	83	0.50	60
South Beach	4939200	109	0.50	78
Holiday Beach	4936650	55	0.50	69
Ona Beach	4930000	51	0.50	48
Seal Rock Beach	4928600	57	0.50	28
WALDPORT CELL				
Driftwood Beach	4923880	0	0.00	59
Patterson Beach	4918050	0	0.00	92
Tillacum Beach	4912680	0	0.00	46
	4909300	0	0.00	55
WINCHESTER CELL				
	4883320	0	0.00	47
Baker Beach	4879490	0	0.00	119
Heceta Beach	4876640	0	0.00	110
Florence	4870620	0	0.00	138

Table 11. Estimated retreat using maximum subsidence amounts. All parameters in meters.

CELL	UTM	Retreat (R)	Subsidence (S)	Present Backshore width
COLUMBIA RIVER CELL				
Copalis Beach	5217950	472	2.00	196
Ocean City	5213450	483	2.00	178
Ocean City State Park	5209140	450	2.00	134
Ocean Shores	5201490	456	2.00	169
Twin Harbors Beach	5189900	418	2.00	114
Grayland	5184450	399	2.00	137
South Beach St. Park	5179950	406	2.00	125
Leadbetter Point St. Park	5161230	523	2.00	92
6km south of Leadbetter	5155330	417	2.00	113
Klipsan Beach	5146300	430	2.00	142
Loomis Lake Beach Rd.	5142840	341	2.00	83
Oceanside	5140180	417	2.00	109
west of Black Lake	5130440	446	2.00	91
Clatsop Spit	5117000	556	2.00	75
Sunset Beach	5105340	318	2.00	143
Sunset Beach	5102260	310	2.00	155
Gearhart	5096500	308	2.00	218
N. Seaside	5094380	335	2.00	115
S. Seaside	5092190	333	2.00	102
CANNON BEACH CELL				
Chapman Beach	5083750	114	1.75	103
Cannon Beach	5079700	110	1.75	72
Humbug Point	5077150	111	1.75	73
Arcadia Beach	5073650	114	1.75	75
Arcadia Beach	5070000	109	1.75	13
TILLAMOOK CELL				
Manzanita	5063240	106	1.50	65
Nehalem Bay St. Park	5059830	105	1.50	44
Rockaway	5051000	93	1.50	32
Bay Ocean Peninsula #1	5041000	156	1.50	37
Bay Ocean Peninsula #2	5039300	149	1.50	35
Cape Mears	5038950	137	1.50	22
PACIFIC CITY CELL				
Sand Beach St. Park	5015300	95	1.50	26
Tierra Del Mar	5010650	95	1.50	57
Nestucca Spit St. Park	5004700	88	1.50	49
Daley Lake	4999350	71	1.50	37
Neskowin	4995330	78	1.50	14
LINCOLN CITY CELL				
Wecoma	4985000	95	1.25	51
Wecoma	4981000	132	1.25	59
Lincoln City	4977310	84	1.25	36
Siletz Spit	4974080	82	1.25	63
Glenden Beach	4969550	62	1.25	39
Lincoln Beach	4966500	92	1.25	70
Lincoln Beach	4965700	81	1.25	23
Government Point	4965460	67	1.25	61
OTTER ROCK CELL				
Otter Rock Beach	4954800	142	1.25	79
Beverly Beach	4953150	146	1.25	74
Moolach Beach	4950400	147	1.25	46
	4947900	154	1.25	23
NEWPORT CELL				
Agate Beach	4946950	161	1.00	93
Agate Beach St. Wayside	4945550	131	1.00	92
Nye Beach	4943300	158	1.00	60
South Beach	4939200	166	1.00	78
Holiday Beach	4936650	172	1.00	69
Ona Beach	4930000	103	1.00	48
Seal Rock Beach	4928600	101	1.00	28
WALDPORT CELL				
Driftwood Beach	4923880	79	0.50	59
Patterson Beach	4918050	84	0.50	92
Tillacum Beach	4912680	80	0.50	46
	4909300	80	0.50	55
WINCHESTER CELL				
	4883320	0	0.00	47
Baker Beach	4879490	0	0.00	119
Heceta Beach	4876640	0	0.00	110
Florence	4870620	0	0.00	138

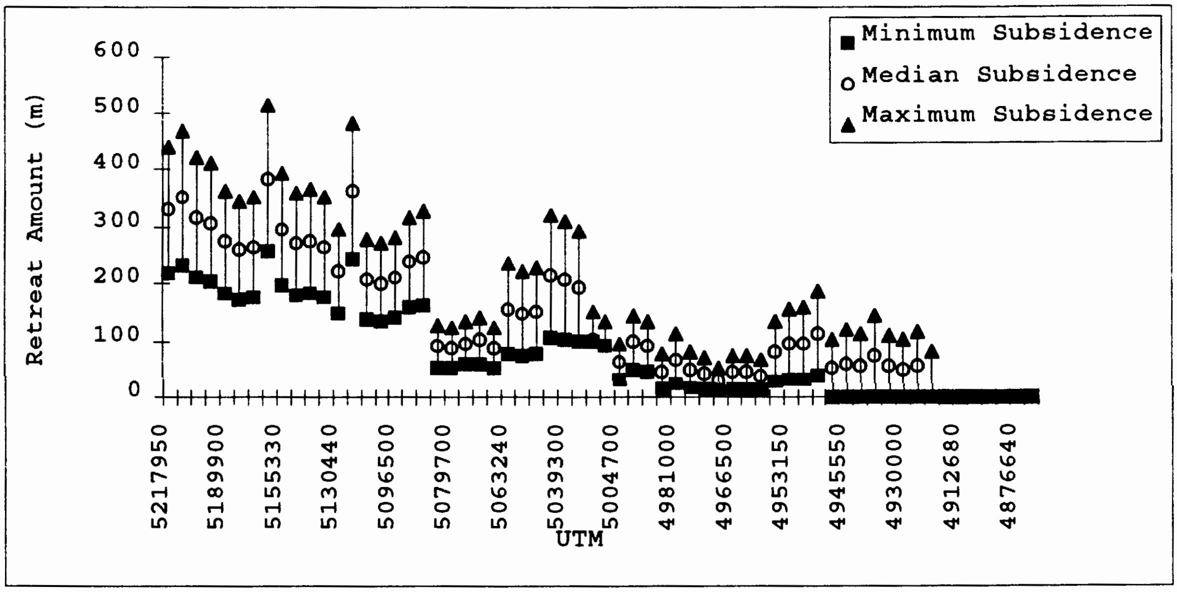

Figure 21. Retreat distance as a function of minimum, determined and maximum subsidence.

study, the upper range of estimated subsidence from multiple earthquake records are used. These values are either the same as, or about 0.5 m more than, the 300 year event.

Model Sensitivity to Different Values for the Cross-Shore Distance (L) and Water Depth (h)

The cross-shore distance (L) is measured from the berm or beach midpoint, to the chosen water depth of closure (h). Many of the beaches in the study area lack well-defined summer berms, so a midpoint is used instead. This midpoint is taken halfway between mean tide level (0m, MTL) and the back edge of the backshore (see *Methods*). As previously noted, variability in L occurs both from natural variation in beach inner shelf morphology and error measurements.

Three water depths (h) to which the across-shore measurement is made, are shown in Table 12. These values were chosen early in the study for sensitivity analysis. The minimum and medial values (10 and 15 m water depths) have since been determined to be too low (see *Background*). In the northern section of the Columbia River cell, the retreat distance ranged from 117 to 216 m for the 10 m water depth, 262 to 360 for the 15 m water depth, and 385 to 484 m for the 20 m water depth. The retreat distances from the 10 to 15 m water depth (*h*)have larger increases (1.2 to 2.3 times more) than from the 15 to 20 m depth (1.2 to 1.5 times more; Table 12 and Figure 22).

In the Newport cell, the retreat distance ranged from 1 to 74 m for the 10 m water depth, 76 to 109 for the 15 m water depth, and 28 to 93 m for the 20 m water depth. All of the beaches have a larger retreat distance for the 15 m water depth (*h*) than with the 10 m water depth. Four of the beaches profiled in this cell have larger retreat distances for the 15 m water depth than with the 20 m depth (Figure 22). The change in *L* from the 15 to 20 m water depth was small relative to the change in *B+h* (berm + water depth) resulting in less retreat distance with the 20 m water depth.

For the profiled beaches tested, eight have less retreat distance with the 20 m water depth than with the 15 m depth. There is a greater increase in retreat distance from the 10 to 15 m

Table 12. Sensitivity of retreat (*R*) with different across-shore distances (*L*) to water depth (*h*).

		10 m water depth			15 m water depth			20 m water depth		
CELL	UTM	L	L/h	R	L	L/h	R	L	L/h	R
COLUMBIA RIVER CELL										
Copalis Beach	5217950	2594	259	216	4214	281	351	5668	283	472
Ocean City	5213450	2434	243	204	4054	270	340	5774	289	484
Ocean City State Park	5209140	2554	255	211	4364	291	360	5444	272	449
Ocean Shores	5201490	3668	367	307	4228	282	354	5218	261	437
Twin Harbors Beach	5189900	1710	171	143	3360	224	280	4810	241	401
Grayland	5184450	1344	134	117	3094	206	268	4444	222	385
South Beach St. Park	5179950	1617	162	143	2967	198	262	4467	223	394
Leadbetter Point St. Par	5161230	2092	209	196	4092	273	384	5492	275	515
6km south of Leadbetter	5155330	1763	176	155	3363	224	295	4613	231	405
Klipsan Beach	5146300	1582	158	136	3142	209	269	4842	242	415
Loomis Lake Beach Rd.	5142840	1526	153	129	3236	216	273	3886	194	328
Oceanside	5140180	1709	171	149	3449	230	301	4629	231	404
west of Black Lake	5130440	1361	136	118	2791	186	242	4971	249	431
Clatsop Spit	5117000	2475	247	225	3975	265	361	5975	299	543
Sunset Beach	5105340	1643	164	142	2393	160	207	3543	177	307
Sunset Beach	5102260	1585	158	133	2405	160	201	3555	178	298
Gearhart	5096500	1605	161	129	2605	174	209	3655	183	293
N. Seaside	5094380	1525	153	133	2715	181	237	3715	186	324
S. Seaside	5092190	1752	175	153	2802	187	244	3702	185	323
CANNON BEACH CELL										
Chapman Beach	5083750	903	90	63	1303	87	90	1753	88	122
Cannon Beach	5079700	972	97	71	1222	81	89	1622	81	118
Humbug Point	5077150	923	92	70	1273	85	96	1593	80	121
Arcadia Beach	5073650	975	98	75	1325	88	102	1625	81	125
Arcadia Beach	5070000	993	99	67	1313	88	89	1713	86	116
TILLAMOOK CELL										
Manzanita	5063240	974	97	58	1324	88	78	1544	77	91
Nehalem Bay St. Park	5059830	1087	109	62	1287	86	73	1577	79	90
Rockaway	5051000	819	82	48	1219	81	72	1369	68	81
Bay Ocean Peninsula	5041000	1250	125	75	1750	117	105	2250	112	136
Bay Ocean Peninsula	5039300	1061	106	65	1611	107	99	2111	106	130
Cape Meare	5038950	875	88	56	1425	95	91	1875	94	120
PACIFIC CITY CELL										
Sand Beach St. Park	5015300	802	80	49	952	63	58	1352	68	82
Tierra Del Mar	5010650	768	77	44	918	61	53	1418	71	81
Nestucca Spit St. Park	5004700	827	83	48	1077	72	63	1307	65	76
Daley Lake	4999350	692	69	41	812	54	48	1042	52	61
Neskowin	4995330	692	69	38	942	63	52	1192	60	66
LINCOLN CITY CELL										
Wecoma	4985000	771	77	34	1051	70	46	1681	84	73
Wecoma	4981000	599	60	26	1859	124	82	2319	116	102
Lincoln City	4977310	666	67	29	1113	74	49	1486	74	65
Siletz Spit	4974080	603	60	25	1005	67	42	1513	76	63
Glenden Beach	4969550	489	49	19	846	56	33	1209	60	46
Lincoln Beach	4966500	610	61	25	1210	81	50	1690	84	70
Lincoln Beach	4965700	743	74	31	1193	80	51	1473	74	62
Government Point	4965460	601	60	23	1061	71	40	1331	67	50
OTTER ROCK CELL										
Otter Rock Beach	4954800	1159	116	53	1879	125	86	2429	121	111
Beverly Beach	4953150	794	79	38	2064	138	99	2424	121	116
Moolach Beach	4950400	410	41	19	2220	148	103	2490	125	115
	4947900	1856	186	87	2226	148	104	2586	129	121
NEWPORT CELL										
Agate Beach	4946950	1365	136	61	1725	115	77	2805	140	126
Agate Beach St. Wayside	4945550	1721	172	74	2091	139	90	2351	118	101
Nye Beach	4943300	1329	133	59	1859	124	83	2759	138	123
South Beach	4939200	1618	162	70	2518	168	109	2968	148	129
Holiday Beach	4936650	1459	146	44	1789	119	55	3689	184	112
Ona Beach	4930000	779	78	24	1679	112	51	2219	111	67
Seal Rock Beach	4928600	1478	148	46	1828	122	57	2108	105	66
WALDPORT CELL										
Driftwood Beach	4923880	509	51	14	1059	71	30	1689	84	48
Patterson Beach	4918050	1442	144	0	1892	126	0	1892	95	0
Tillacum Beach	4912680	766	77	0	1676	112	0	1676	84	0
	4909300	775	77	0	1401	93	0	1685	84	0
WINCHESTER CELL										
	4883320	692	69	0	992	66	0	1512	76	0
Baker Beach	4879490	569	57	0	1019	68	0	1379	69	0
Heceta Beach	4876640	740	74	0	1110	74	0	1560	78	0
Florence	4870620	499	50	0	1188	79	0	1588	79	0

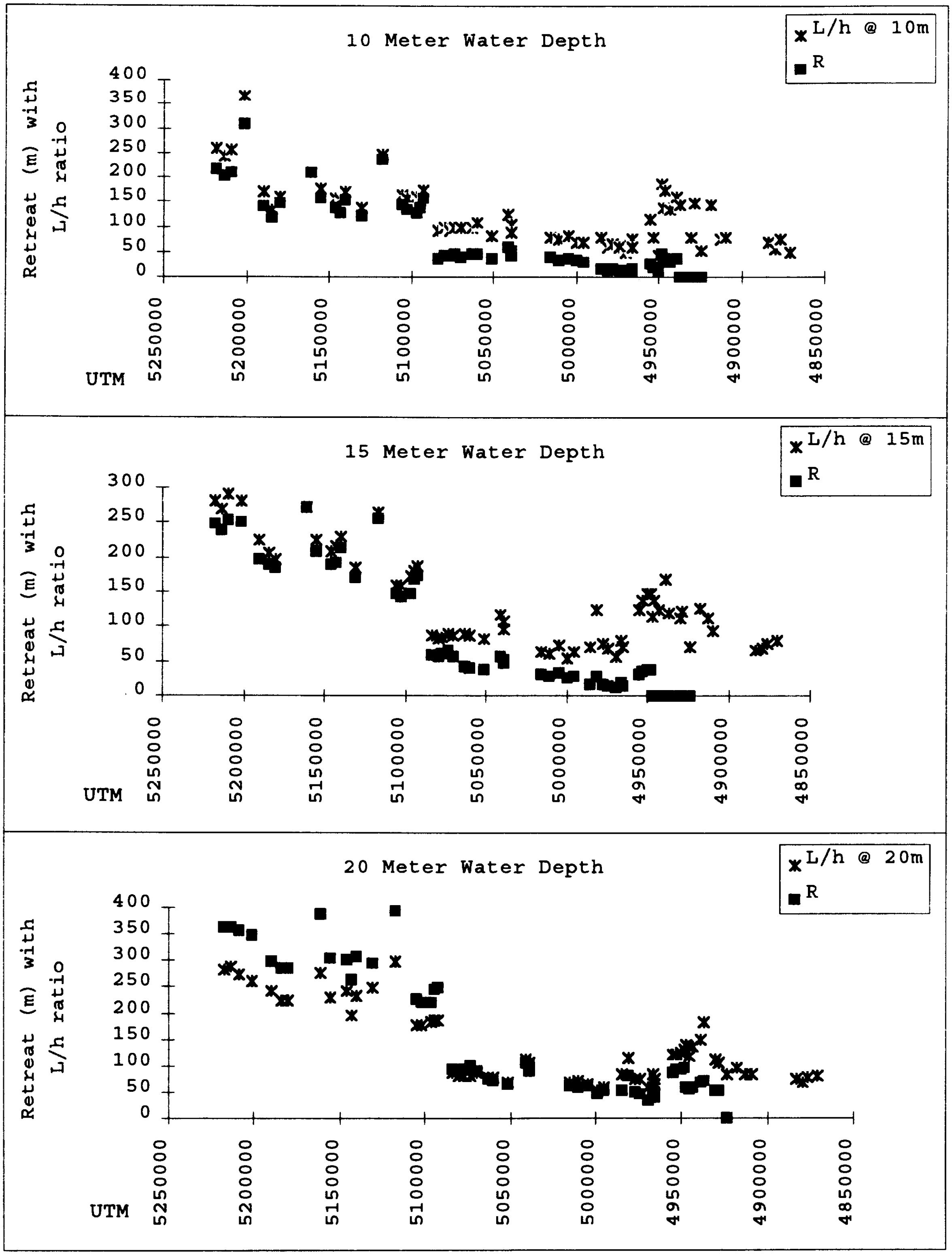

Figure 22. Sensitivity of retreat (*R*) to different across-shore distances (*L*) and water depths (*h*).

water depth for 39 of the 54 beaches (72%). The indication is that with greater depth the ratio of L/h becomes smaller.

A depth of closure at 10 m is not a reasonable parameter, as sediment migrates out to depths of 15 to 20 m (Hall and others, 1985). Therefore, the model will be tested for retreat response to minimum, medial, and maximum parameters, including the 15, 17.5, and 20 m water depths.

Predicted Retreat Distances

The estimated retreat distances using minimum, medial, and maximum parameters are listed in Table 13, Table 14 and Table 15. The retreat distances, based on 15, 17.5, and 20 m water depths for the study area, are graphically shown in Figure 23. For the Winchester cell, no subsidence is estimated (Table 13, 14 and 15), therefore there should be little or no beach loss associated with Cascadia earthquakes. The Waldport cell shows shoreline retreat only if the maximum values are used, but may still retain beach frontage. Of the 62 beaches profiled, 54 profiles could be affected by coseismic subsidence with minimum, and medial value inputs, and 58 profiles are affected by subsidence when maximum value inputs are used. The areas affected by shoreline retreat are addressed below.

With minimum values (Table 13), the retreat distance is greater than the backshore width for 22 out of 54 beaches (41%), which would result in total loss of the backshore. Most of the greater retreat distances occur in the Columbia River cell (18 of the 22 beaches profiled).

The medial values (Table 14) produced beach retreat greater than the backshore width for 48 out of 54 beaches (89%). This is a 45% increase from the minimum values in the number of beaches that are predicted to experience greater retreat than the backshore beach width. These retreat distances encompass the entire Columbia River, Tillamook, and Otter Rock cells. Some of the beaches in the remaining littoral cells retain some backshore width.

The maximum values (Table 15) predict retreat distances greater than the backshore width for 54 of the 58 beaches that could be affected by coseismic subsidence. Although the retreat distance for these beaches is greater than their present backshore widths (some as high as 400 m more retreat), existing sea cliffs or large dunes will probably restrict the actual amount of retreat (see *Study Area*). The four beaches that retain some of their backshore are in the Waldport cell. Maps of the beaches profiled in the study area with the minimum, medial and maximum retreat distances are in Appendix C.

Table 13. Retreat sensitivity to minimum values for all parameters in the Bruun model. All parameters in meters.

CELL	UTM	Retreat (R)	Cross-shore Distance (L)	Midpoint (B)	Subsidence (S)	MTL to 15 m depth (h)	Present Back-shore width
COLUMBIA RIVER CELL							
Copalis Beach	5217950	248	4214	2.00	1.00	3970	196
Ocean City	5213450	240	4054	1.90	1.00	3970	178
Ocean City State Park	5209140	254	4364	2.20	1.00	4160	134
Ocean Shores	5201490	250	4228	1.90	1.00	4160	169
Twin Harbors Beach	5189900	198	3360	2.00	1.00	3150	114
Grayland	5184450	190	3094	1.30	1.00	2850	137
South Beach St. Park	5179950	185	2967	1.00	1.00	2850	125
Leadbetter Point St. Park	5161230	273	4092	0.00	1.00	4000	92
6km south of Leadbetter	5155330	209	3363	1.10	1.00	3250	113
Klipsan Beach	5146300	190	3142	1.50	1.00	3000	142
Loomis Lake Beach Rd.	5142840	193	3236	1.80	1.00	3150	83
Oceanside	5140180	213	3449	1.20	1.00	3340	109
west of Black Lake	5130440	171	2791	1.30	1.00	2700	91
Clatsop Spit	5117000	256	3975	0.50	1.00	3900	75
Sunset Beach	5105340	147	2393	1.30	1.00	2250	143
Sunset Beach	5102260	142	2405	1.90	1.00	2250	155
Gearhart	5096500	147	2605	2.70	1.00	2500	218
N. Seaside	5094380	168	2715	1.20	1.00	2600	115
S. Seaside	5092190	173	2802	1.20	1.00	2700	102
CANNON BEACH CELL							
Chapman Beach	5083750	38	1303	2.00	0.50	1200	103
Cannon Beach	5079700	38	1222	1.20	0.50	1150	72
Humbug Point	5077150	41	1273	0.50	0.50	1200	73
Arcadia Beach	5073650	43	1325	0.30	0.50	1250	75
Arcadia Beach	5070000	38	1313	2.50	0.50	1300	13
TILLAMOOK CELL							
Manzanita	5063240	42	1324	0.90	0.50	1250	71
Nehalem Bay St. Park	5059830	39	1287	1.60	0.50	1200	44
Rockaway	5051000	38	1219	1.00	0.50	1150	65
Bay Ocean Peninsula	5041000	56	1750	0.60	0.50	1700	45
Bay Ocean Peninsula	5039300	53	1611	0.30	0.50	1550	57
Cape Meares	5038950	48	1425	0.00	0.50	1400	25
PACIFIC CITY CELL							
Sand Beach St. Park	5015300	31	952	0.40	0.50	900	49
Tierra Del Mar	5010650	28	918	1.47	0.50	850	68
Nestucca Spit St. Park	5004700	33	1077	1.20	0.50	1000	74
Daley Lake	4999350	25	812	1.00	0.50	770	63
Neskowin	4995330	28	942	2.00	0.50	900	44
LINCOLN CITY CELL							
Wecoma	4985000	16	1051	1.20	0.25	1000	51
Wecoma	4981000	29	1859	1.00	0.25	1800	59
Lincoln City	4977310	17	1113	1.20	0.25	1077	36
Siletz Spit	4974080	14	1005	3.10	0.25	943	63
Glenden Beach	4969550	11	846	3.50	0.25	808	39
Lincoln Beach	4966500	18	1210	2.00	0.25	1140	70
Lincoln Beach	4965700	18	1193	1.70	0.25	1170	23
Government Point	4965460	14	1061	4.00	0.25	1000	61
OTTER ROCK CELL							
Otter Rock Beach	4954800	30	1879	0.40	0.25	1800	79
Beverly Beach	4953150	34	2064	0.00	0.25	1990	74
Moolach Beach	4950400	37	2220	0.20	0.25	2170	46
	4947900	37	2226	0.00	0.25	2170	23
NEWPORT CELL							
Agate Beach	4946950	27	1725	0.75	0.25	1630	93
Agate Beach St. Wayside	4945550	32	2091	1.45	0.25	2000	92
Nye Beach	4943300	29	1859	0.80	0.25	1800	60
South Beach	4939200	39	2518	1.30	0.25	2440	78
Holiday Beach	4936650	29	1789	0.40	0.25	1720	69
Ona Beach	4930000	27	1679	0.50	0.25	1630	48
Seal Rock Beach	4928600	0	1828	0.00	0.25	1800	28
WALDPORT CELL							
Driftwood Beach	4923880	0	1059	0.30	0.00	1000	59
Patterson Beach	4918050	0	1892	1.60	0.00	1800	92
Tillacum Beach	4912680	0	1676	0.00	0.00	1630	46
	4909300	0	1401	0.10	0.00	1347	55
WINCHESTER CELL							
	4883320	0	992	0.00	0.00	930	47
Baker Beach	4879490	0	1019	2.60	0.00	900	119
Heceta Beach	4876640	0	1110	1.20	0.00	1000	110
Florence	4870620	0	1188	1.90	0.00	1050	138

Table 14. Retreat sensitivity to medial values for all parameters in the Bruun model. All parameters in meters.

CELL	UTM	Retreat (R)	Cross-shore Distance (L)	Midpoint (B)	Subsidence (S)	TL to 17.5 depth (h)	Present Back-shore width
COLUMBIA RIVER CELL							
Copalis Beach	5217950	362	4941	3.00	1.50	4697	196
Ocean City	5213450	361	4914	2.90	1.50	4830	178
Ocean City State Park	5209140	355	4904	3.20	1.50	4700	134
Ocean Shores	5201490	347	4723	2.90	1.50	4655	169
Twin Harbors Beach	5189900	299	4085	3.00	1.50	3875	114
Grayland	5184450	286	3769	2.30	1.50	3525	137
South Beach St. Park	5179950	286	3717	2.00	1.50	3600	125
Leadbetter Point St. Park	5161230	389	4792	1.00	1.50	4700	92
6km south of Leadbetter	5155330	305	3988	2.10	1.50	3875	113
Klipsan Beach	5146300	299	3992	2.50	1.50	3850	142
Loomis Lake Beach Rd.	5142840	263	3561	2.80	1.50	3475	83
Oceanside	5140180	308	4039	2.20	1.50	3930	109
west of Black Lake	5130440	294	3881	2.30	1.50	3790	91
Clatsop Spit	5117000	393	4975	1.50	1.50	4900	75
Sunset Beach	5105340	225	2968	2.30	1.50	2825	143
Sunset Beach	5102260	219	2980	2.90	1.50	2825	155
Gearhart	5096500	221	3130	3.70	1.50	3025	218
N. Seaside	5094380	245	3215	2.20	1.50	3100	115
S. Seaside	5092190	248	3252	2.20	1.50	3150	102
CANNON BEACH CELL							
Chapman Beach	5083750	75	1528	3.00	1.00	1425	103
Cannon Beach	5079700	72	1422	2.20	1.00	1350	72
Humbug Point	5077150	76	1435	1.50	1.00	1363	73
Arcadia Beach	5073650	78	1475	1.30	1.00	1400	75
Arcadia Beach	5070000	72	1513	3.50	1.00	1500	13
TILLAMOOK CELL							
Manzanita	5063240	74	1434	1.90	1.00	1360	71
Nehalem Bay St. Park	5059830	71	1432	2.60	1.00	1345	44
Rockaway	5051000	66	1294	2.00	1.00	1225	65
Bay Ocean Peninsula	5041000	105	2000	1.60	1.00	1950	45
Bay Ocean Peninsula	5039300	99	1861	1.30	1.00	1800	57
Cape Meare	5038950	91	1650	0.60	1.00	1625	25
PACIFIC CITY CELL							
Sand Beach St. Park	5015300	61	1152	1.40	1.00	1100	49
Tierra Del Mar	5010650	58	1168	2.47	1.00	1100	68
Nestucca Spit St. Park	5004700	61	1192	2.20	1.00	1115	74
Daley Lake	4999350	48	927	2.00	1.00	885	63
Neskowin	4995330	52	1067	3.00	1.00	1025	44
LINCOLN CITY CELL							
Wecoma	4985000	52	1366	2.20	0.75	1315	51
Wecoma	4981000	80	2089	2.00	0.75	2030	59
Lincoln City	4977310	50	1300	2.10	0.75	1264	36
Siletz Spit	4974080	46	1259	3.10	0.75	1197	63
Glenden Beach	4969550	35	1028	4.50	0.75	989	39
Lincoln Beach	4966500	53	1450	3.00	0.75	1380	70
Lincoln Beach	4965700	49	1333	2.70	0.75	1310	23
Government Point	4965460	40	1196	5.00	0.75	1135	61
OTTER ROCK CELL							
Otter Rock Beach	4954800	85	2154	1.40	0.75	2075	79
Beverly Beach	4953150	92	2244	0.70	0.75	2170	74
Moolach Beach	4950400	94	2355	1.20	0.75	2305	46
	4947900	98	2406	1.00	0.75	2350	23
NEWPORT CELL							
Agate Beach	4946950	88	2265	1.75	0.75	2170	93
Agate Beach St. Wayside	4945550	84	2221	2.45	0.75	2130	92
Nye Beach	4943300	90	2309	1.80	0.75	2250	60
South Beach	4939200	104	2743	2.30	0.75	2665	78
Holiday Beach	4936650	109	2739	1.40	0.75	2670	69
Ona Beach	4930000	77	1949	1.50	0.75	1900	48
Seal Rock Beach	4928600	80	1968	0.90	0.75	1940	28
WALDPORT CELL							
Driftwood Beach	4923880	0	2004	1.30	0.00	1945	59
Patterson Beach	4918050	0	1780	2.60	0.00	1688	92
Tillacum Beach	4912680	0	1535	1.00	0.00	1489	46
	4909300	0	1553	1.10	0.00	1499	55
WINCHESTER CELL							
	4883320	0	1252	0.60	0.00	1190	47
Baker Beach	4879490	0	1199	3.60	0.00	1080	119
Heceta Beach	4876640	0	1335	2.20	0.00	1225	110
Florence	4870620	0	1388	2.90	0.00	1250	138

Table 15. Retreat sensitivity to maximum values for all parameters in the Bruun model. All parameters in meters.

CELL	UTM	Retreat (R)	Cross-shore Distance (L)	Midpoint (B)	Subsidence (S)	MTL to 20 m depth (h)	Present Back-shore width
COLUMBIA RIVER CELL							
Copalis Beach	5217950	472	5668	4.00	2.00	5424	196
Ocean City	5213450	483	5774	3.90	2.00	5690	178
Ocean City State Park	5209140	450	5444	4.20	2.00	5240	134
Ocean Shores	5201490	437	5218	3.90	2.00	5150	169
Twin Harbors Beach	5189900	401	4810	4.00	2.00	4600	114
Grayland	5184450	381	4444	3.30	2.00	4200	137
South Beach St. Park	5179950	388	4467	3.00	2.00	4350	125
Leadbetter Point St. Park	5161230	499	5492	2.00	2.00	5400	92
6km south of Leadbetter	5155330	399	4613	3.10	2.00	4500	113
Klipsan Beach	5146300	412	4842	3.50	2.00	4700	142
Loomis Lake Beach Rd.	5142840	327	3886	3.80	2.00	3800	83
Oceanside	5140180	399	4629	3.20	2.00	4520	109
west of Black Lake	5130440	427	4971	3.30	2.00	4880	91
Clatsop Spit	5117000	531	5975	2.50	2.00	5900	75
Sunset Beach	5105340	304	3543	3.30	2.00	3400	143
Sunset Beach	5102260	297	3555	3.90	2.00	3400	155
Gearhart	5096500	296	3655	4.70	2.00	3550	218
N. Seaside	5094380	320	3715	3.20	2.00	3600	115
S. Seaside	5092190	319	3702	3.20	2.00	3600	102
CANNON BEACH CELL							
Chapman Beach	5083750	110	1753	4.00	1.50	1650	103
Cannon Beach	5079700	105	1622	3.20	1.50	1550	72
Humbug Point	5077150	107	1598	2.50	1.50	1525	73
Arcadia Beach	5073650	109	1625	2.30	1.50	1550	75
Arcadia Beach	5070000	105	1713	4.50	1.50	1700	13
TILLAMOOK CELL							
Manzanita	5063240	101	1544	2.90	1.50	1470	71
Nehalem Bay St. Park	5059830	100	1577	3.60	1.50	1490	44
Rockaway	5051000	89	1369	3.00	1.50	1300	65
Bay Ocean Peninsula	5041000	149	2250	2.60	1.50	2200	45
Bay Ocean Peninsula	5039300	142	2111	2.30	1.50	2050	57
Cape Mears	5038950	130	1875	1.60	1.50	1850	25
PACIFIC CITY CELL							
Sand Beach St. Park	5015300	91	1352	2.40	1.50	1300	49
Tierra Del Mar	5010650	91	1418	3.47	1.50	1350	68
Nestucca Spit St. Park	5004700	85	1307	3.20	1.50	1230	74
Daley Lake	4999350	68	1042	3.00	1.50	1000	63
Neskowin	4995330	75	1192	4.00	1.50	1150	44
LINCOLN CITY CELL							
Wecoma	4985000	91	1681	3.20	1.25	1630	51
Wecoma	4981000	126	2319	3.00	1.25	2260	59
Lincoln City	4977310	80	1486	3.10	1.25	1450	36
Siletz Spit	4974080	78	1513	4.10	1.25	1450	63
Glenden Beach	4969550	59	1209	5.50	1.25	1170	39
Lincoln Beach	4966500	88	1690	4.00	1.25	1620	70
Lincoln Beach	4965700	78	1473	3.70	1.25	1450	23
Government Point	4965460	64	1331	6.00	1.25	1270	61
OTTER ROCK CELL							
Otter Rock Beach	4954800	136	2429	2.40	1.25	2350	79
Beverly Beach	4953150	140	2424	1.70	1.25	2350	74
Moolach Beach	4950400	140	2490	2.20	1.25	2440	46
	4947900	147	2586	2.00	1.25	2530	23
NEWPORT CELL							
Agate Beach	4946950	154	2805	2.75	1.25	2710	93
Agate Beach St. Wayside	4945550	125	2351	3.45	1.25	2260	92
Nye Beach	4943300	151	2759	2.80	1.25	2700	60
South Beach	4939200	159	2968	3.30	1.25	2890	78
Holiday Beach	4936650	206	3689	2.40	1.25	3620	69
Ona Beach	4930000	123	2219	2.50	1.25	2170	48
Seal Rock Beach	4928600	120	2108	1.90	1.25	2080	28
WALDPORT CELL							
Driftwood Beach	4923880	38	1689	2.30	0.50	1630	59
Patterson Beach	4918050	40	1892	3.60	0.50	1800	92
Tillacum Beach	4912680	38	1676	2.00	0.50	1630	46
	4909300	38	1685	2.10	0.50	1630	55
WINCHESTER CELL							
	4883320	0	1512	1.60	0.00	1450	47
Baker Beach	4879490	0	1379	4.60	0.00	1260	119
Heceta Beach	4876640	0	1560	3.20	0.00	1450	110
Florence	4870620	0	1588	3.90	0.00	1450	138

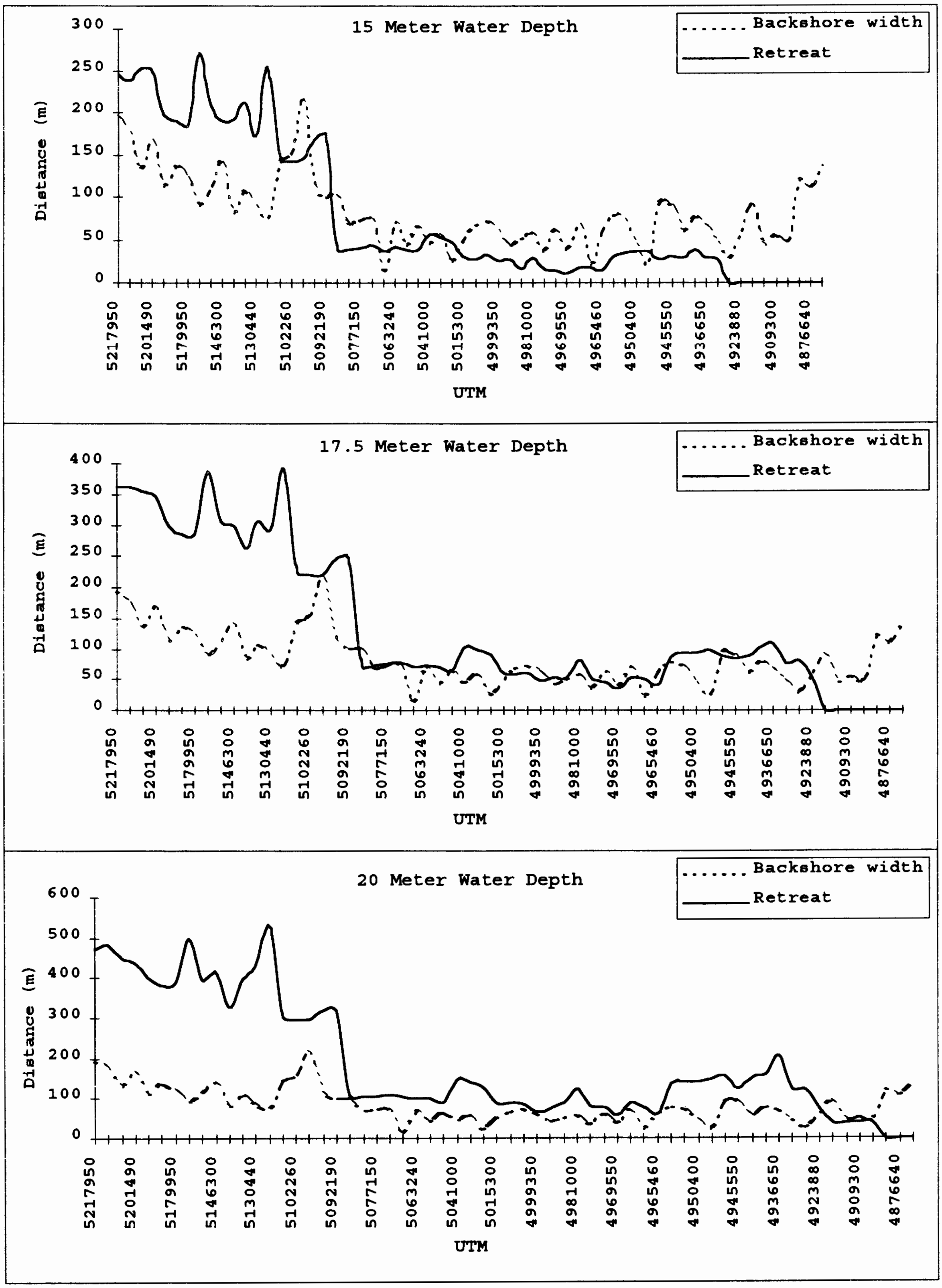

Figure 23. Retreat distances for 15 m, 17.5 m, and 20 m water depths.

DISCUSSION

COSEISMIC SUBSIDENCE

The range of coseismic subsidence for this study have been estimated from the 300-year event and may not be representative of other Cascadian earthquakes, which could have produced more-or-less subsidence. However, the assumed error (+/- 0.5 m) of subsidence probably captures the largest amount of potential subsidence (Peterson, personal communication, April, 1996) and therefore serves as a useful hazard index.

The 300 year event is not well represented in the western end of Yaquina Bay (Newport cell) (Peterson and Priest, 1995). The indication is that the western end of Yaquina Bay may have been within or very near the zero-isobase zone at the time of the 300 year event. Because earlier coseismic subsidence events of 0.5 to 1.0 m are recorded for the same area in the bay, and the position of the zero-isobase zone is thought to shift from earthquake to earthquake (Peterson and Priest, 1995), the average subsidence amount (0.75 m) for these earlier events has been used for the Newport cell.

GROUND PENETRATING RADAR

The appearance of buried scarps amongst strongly dipping reflectors (5-7°) in the Willapa barrier indicate a rapidly accreting beach face between episodes of catastrophic retreat

(Figure 5). In contrast, the Florence transect (Figure 18) shows very slow progradation relative to vertical accretion (horizontal reflectors) without any apparent catastrophic retreat events (no buried scarps). The slow progradation is puzzling because of the abundant supply of sediment to this littoral cell from the Umpqua and Siuslaw Rivers. It may indicate strong littoral drift and no sea-level changes. Vibra-coring and radiocarbon dating of the subsurface deposits at Florence are needed to confirm the origin and age of the horizontal reflectors in the beach profile.

VARIABILITY OF COASTAL RETREAT

Sensitivity of beach face retreat to different parameter values of the Bruun model suggest that some parameters affect the retreat distance by a greater degree than others. For example, the across-shore distance (L) greatly affects the retreat distance, but the water depth (h) value modifies its intensity. Relative sea-level rise (R), however, has a direct affect on the retreat distance. The difference between one and two meters of relative sea-level rise doubles the amount of retreat (see Figure 20). In general, areas further from the Cascadian trench have greater estimated subsidence and experience greater retreat distances.

Variability of coastal retreat in different areas can be affected by a combination of large subsidence and narrow beaches. Beaches backed by sea cliffs or sea walls that are estimated to have retreat distances greater than their backshore widths will not only lose most or all of the backshore, but will have to contend with erosion of the cliffs, bluffs, or sea walls. For example, four of the five beaches in the Cannon Beach cell, the entire Otter Rock cell, and six of the seven beaches profiled in the Newport cell are backed by sea cliffs. Of those beaches, all of the Cannon Beach cell and Otter Rock cell beaches could experience greater retreat distance than the backshore width. In the Newport cell, four of the six beaches backed by sea cliffs experience greater retreat distance than the backshore width.

Another factor that could modify the retreat distance are dune-field backed beaches. Many of the beaches in the study area are backed by dune-fields that range from 10 m to more than 500 m wide (Peterson and others, 1991a). These dune-fields can provide an erosional buffer to shoreline retreat and modify the lateral extent of the estimated retreat distance. However, construction on the foredunes will reverse the mitigating effects of the dunes as buffers because it increases the potential for erosion.

The nearshore bottom profile also affects the retreat distance. The depth of closure for a low-gradient profile is farther offshore than a steeply dipping bottom profile, resulting in a greater retreat distance because the L/h ratio is larger than that for a steeply dipping profile. The Dean (1991) model for predicting the shape of a nearshore profile would provide valuable information toward predicting retreat distances.

The depth of closure for any given shoreline is not agreed upon by the scientific community because of variability in wave energy and bottom profiles at any given location. For the purpose of this study, a depth of closure of 17.5 m (+/- 2.5 m) was chosen as a medial value for this preliminary retreat study. This is possibly a conservative value, but the duration of post-seismic subsidence is not well constrained. The greatest effects of beach retreat might only last a few decades. Therefore, deeper depths of closure from very infrequent storms might not be appropriate.

OTHER EROSIONAL EVENTS

Other natural erosional events that occur along the Central Cascadia margin include erosion caused by global sea-level rise, rip currents, and large winter storm events. Global warming over the next century is expected to produce about 0.4 m of sea-level rise on the west coast of North America (Titus and others, 1985). Although not insignificant, global sea-level rise is a slow process compared to the relative sea-level rise following coseismic subsidence. The estimated erosion resulting from subsidence is far greater than that from global sea-level rise.

Rip currents, a cell like, nearshore circulation system within the breaker zone, transport sand offshore and hollow out embayments (Komar, 1983). This process produces a rhythmic shoreline of cusps and bays. Some embayments can become quite large, and may cut back through the beach, encroaching on properties. Although very little direct erosion of property is caused by the embayments, they allow waves to break very close to shore and produce greater runup, which in turn causes more erosion of the beach (Komar, 1983).

Large storm events can cause major local erosion, such as the 1972-73 winter storm that caused up to 30 m of fore dune retreat in a three week period along a 350 m stretch of Siletz Spit (Komar, 1983). Three homes that were threatened by erosion, ended up on promontories on the beach. They were protected on three sides with riprap and survived, while one house and many empty lots were lost to the erosion of the dune. Continued erosion of the fore dune was halted only after riprap was installed to protect utility lines and the access road (Komar, 1983). The amount of shoreline retreat estimated to occur due to coseismic subsidence is substantially more than large storm events have produced in the past.

Regional erosional events, such as an El Niño, erodes large volumes of sand from one section of a littoral cell and deposits it at another location. On the Oregon coast, the 1982-83 El Niño eroded sand in the southern end of littoral cells and deposited the sand at the northern end of the cells (Komar and others, 1989;

Peterson and others, 1990). Along Netarts Spit, severe erosion resulted in the loss of the beach as a buffer to wave action leaving the sea cliffs immediately north of Cape Lookout vulnerable to wave induced erosion. The displaced beach sand is believed to have been moved into Netarts Bay (Komar and others, 1989).

The 1982-83 El Niño also affected a seven km stretch in the southern half of the Waldport cell (Peterson and others, 1990). Erosion of the sand on wave-cut platforms resulted in 92 to 190 m of shoreline retreat, leaving the platforms exposed. The severest erosion occurred at the southernmost location (190 m) and decreased to the northern location (92 m). The eroded sediment was deposited in the north end of the littoral cell, where fore dune accretion occurred.

For the erosion that occurred on Netarts Spit and the wave-cut platforms by the 1982-83 El Niño event, the recovery time was approximately four years, when equilibrium was reestablished between the beach and the nearshore (Komar and others, 1989; Peterson and others, 1990). The recovery time after coseismic subsidence is not known, but could potentially last tens of years or more.

Major storms commonly hit the coast in October and November but rarely result in property loss because there is enough beach berm to act as a buffer (Komar, 1983). Based on the 300 year event, estimated retreat along the Washington and Oregon coast could result in extensive property loss.

LIMITATIONS OF STUDY

Some aspects of coastal processes were not addressed in this study, but are important to understanding the dynamic coastline of the Pacific Northwest. Longshore transport of sediment, estuary sand sinks, dune and sea cliff sand sources are some of the coastal processes that could influence shoreline retreat and are discussed below.

Longshore Movement of Sediment

The Bruun model was useful for this study to estimate regional shoreline retreat from the central Washington coast to the central Oregon coast, but it does no address the longshore movement of sediment which is an important aspect of coastal processes.

The Columbia River cell, which comprises the central to southern half of the Washington coast and the northernmost portion of the Oregon coast, has a net northward movement of sediment (Komar, 1992). These beaches are accreting, with the highest rates of accretion nearest the Columbia River, decreasing to the north to Copalis Head. North of this point the beaches are eroding.

Although net longshore transport of sediment along the Oregon coast is zero (see *Study Area*), there is movement within littoral cells. In the Tillamook cell there is a slight net northward movement of sediment. In the southern half of the cell, erosion is occurring on Bay Ocean Peninsula, while in the northern section of the cell dune buildup is occurring at the base of Neahkahnie Mountain. The Pacific City cell is also experiencing a similar pattern of southern erosion and northern dune buildup due to northward littoral drift. Net and interannual littoral drift could locally increase or decrease beach retreat from coseismic subsidence.

Subsidence Effects on Bays

Beach sand loss can occur in bays such as Yaquina Bay in the Newport cell. These bays are called sand sinks by Kulm and Byrne (1966). The source of shore sediment deposited in Yaquina Bay comes from erosion of sea cliffs north of the bay and dune sands blown in by winds from the south and southwest (Kulm and Byrne, 1966). How coseismic subsidence would affect sediment dispersal patterns in bays and estuaries would be important to navigation and the shellfish industry, as well as to predicting beach retreat from coseismic subsidence.

Dunes and Sea Cliffs

The study also does not address the hazard of dune erosion due to retreat induced by coseismic subsidence. There are many beaches in the study area that are backed by dune-fields. For example, all of the Columbia River cell is backed by dune-fields and all of the beaches profiled will have a greater retreat distance than the backshore beach width (using determined values for subsidence in the Bruun equation). Dune erosion as a function of shoreline retreat could result in an increase in the amount of sediment added to the system. As the base of the dune erodes, collapse of the upper portion of the dune would add more sediment to the system than from a non-dune backed beach.

Beaches backed by sea cliffs face a similar hazard, but instead of a dune-field buffer, the sea cliff will be vulnerable to wave attack and erosion. Of the beaches backed by sea cliffs, 17 out of 24 beaches (71%) in the study area will experience greater retreat than their backshore widths (using medial values in the Bruun equation). The accelerated landward migration of eroding sea cliffs could have a devastating effect on many developments along the central Cascadian margin.

RECOMMENDATIONS FOR FURTHER STUDY

Through the course of this project, it became apparent that there were several factors that could not be addressed. These important aspects to understanding the impact of coseismic subsidence on the Pacific Northwest are listed below.

(1) Nearshore bottom profiling is an important aspect in determining retreat distances and could also aid in determining the depth of closure for a particular location. The model for predicting the shape of the nearshore profile (Dean, 1991) could be applied to the results of nearshore profiling.

(2) A three-dimensional model that accounts for littoral drift, designed specifically for the high-energy environment of the Cascadia margin, would greatly enhance the ability to predict coseismic shoreline retreat.

(3) Site-specific modeling is needed for areas that are backed by sea cliffs or sea walls, and bays protected by barriers and spits. Dean's (1982) sea-wall equation could be used to better understand the impact shoreline retreat would have on localities in the Cannon Beach, Lincoln City, Otter Rock, Newport, and Waldport cells that are backed by sea cliffs. The Dean and Maurmeyer (1983) model for barrier-island retreat could be applied to areas such as the bay barriers at Tillamook Bay, Nestucca Bay, Siletz Bay, and Alsea Bay.

(4) A regional shoreline hazards analysis would be useful for planning and coastal zone management, especially in areas that are at risk of losing entire backshores and are backed by sea cliffs.

CONCLUSIONS

Subsidence amount, across-shore distance, and water depth are all important factors in predicting shoreline retreat caused by a Cascadian subduction zone earthquake. Many other factors contribute to the accuracy of estimating shoreline retreat, such as beach morphology, including the shape of the nearshore bottom and the presence or absence of dune-fields or sea cliffs. Longshore sediment transport is an important aspect in coastal processes and should be accounted for when modeling shoreline retreat. This preliminary study on the regional affects of coseismic subsidence on shoreline retreat has uncovered areas that need to be addressed. These include (1) nearshore bottom profiling, (2) a three-dimensional model that accounts for littoral drift, and (3) site specific modeling for areas that are backed by sea cliffs or sea walls, and bays protected by barriers and spits.

There appears to be a trend of greater retreat to the north, which corresponds with a greater distance from the Cascadia trench and with estimated subsidence found in the geologic record. Many of the beaches profiled are potentially at risk of losing all their sand as well as private property behind the existing beach.

Communities could circumvent some of the loss in the event of a megathrust earthquake through coastal zoning and planning.

Each littoral cell should be addressed individually, and each beach segment within the cell should also be studied on its own merits. Within one cell there may be dune backed beaches and beaches backed by sea cliffs or sea walls. Each of these beach types comes with its own sets of potential problems and attributes.

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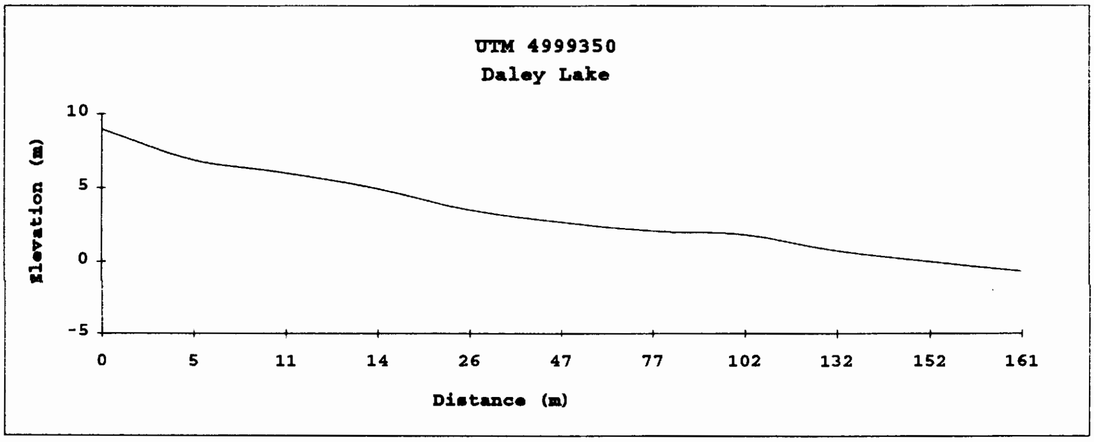
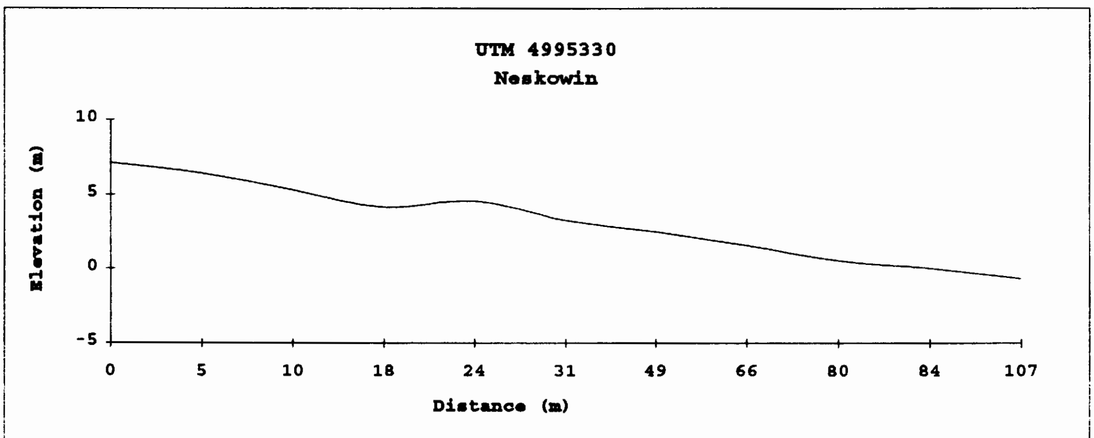
APPENDIX A

PROFILES OF BEACHES IN THE TILLAMOOK AND PACIFIC CITY CELLS
JUNE 12-15, 1996

PACIFIC CITY CELL con"t





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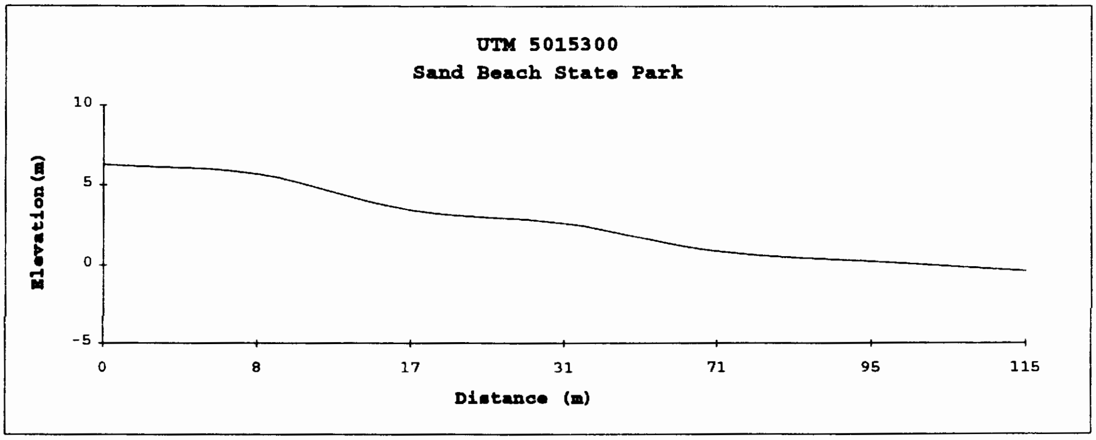

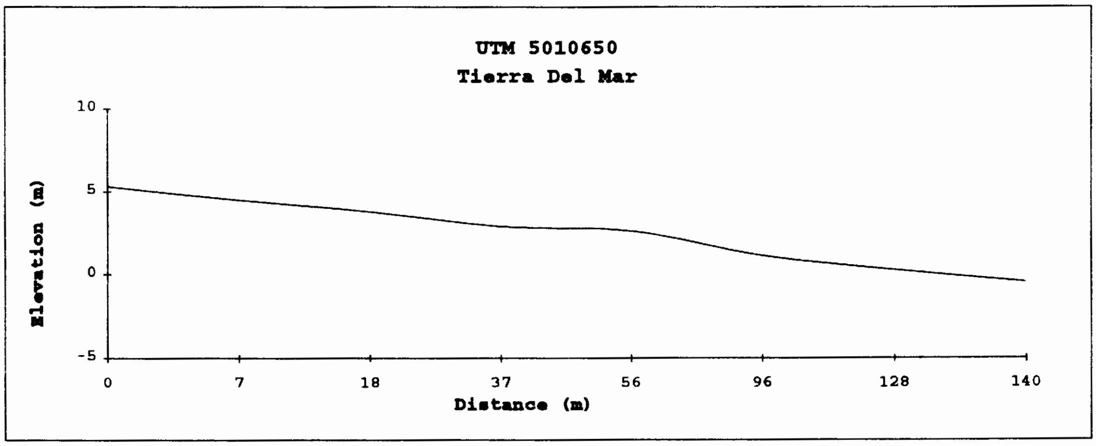

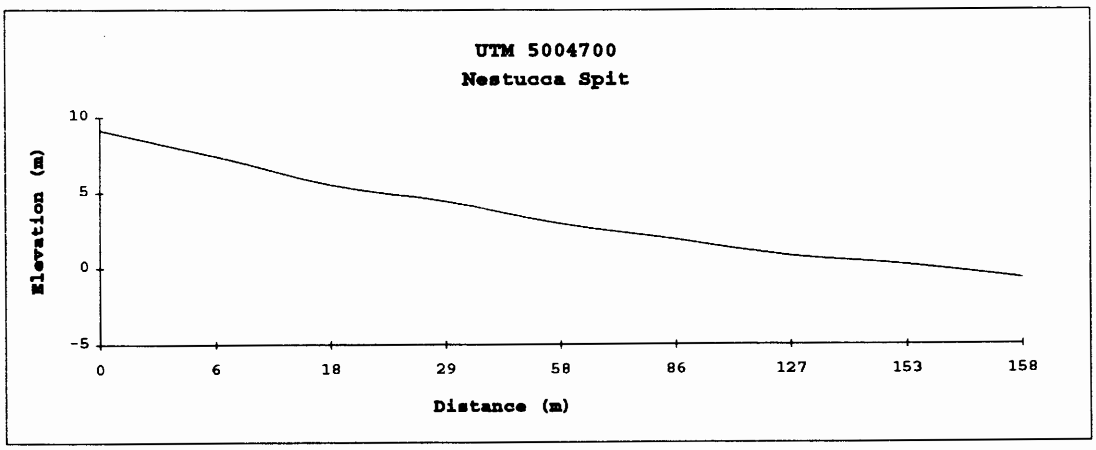

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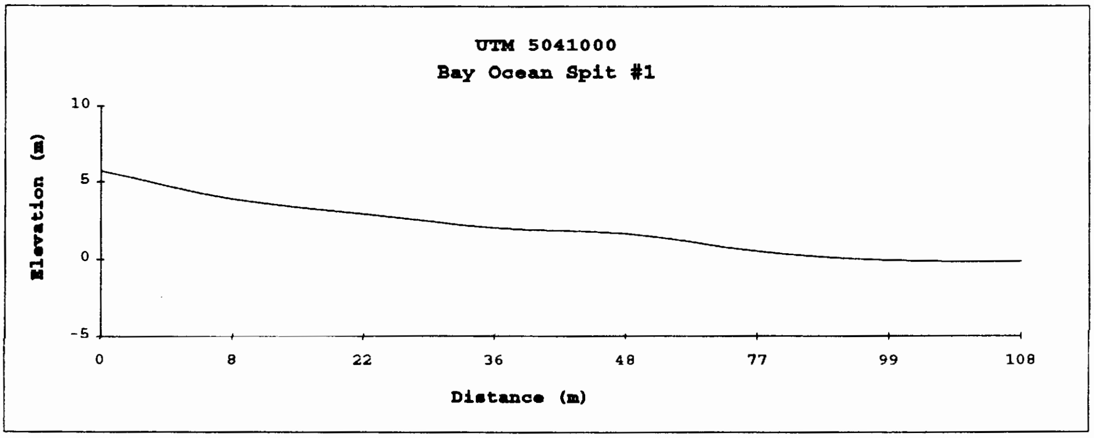

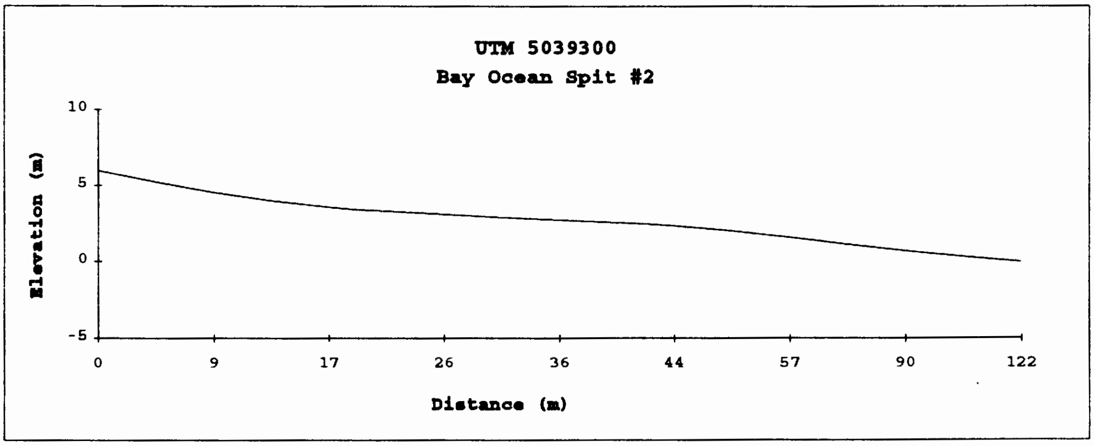

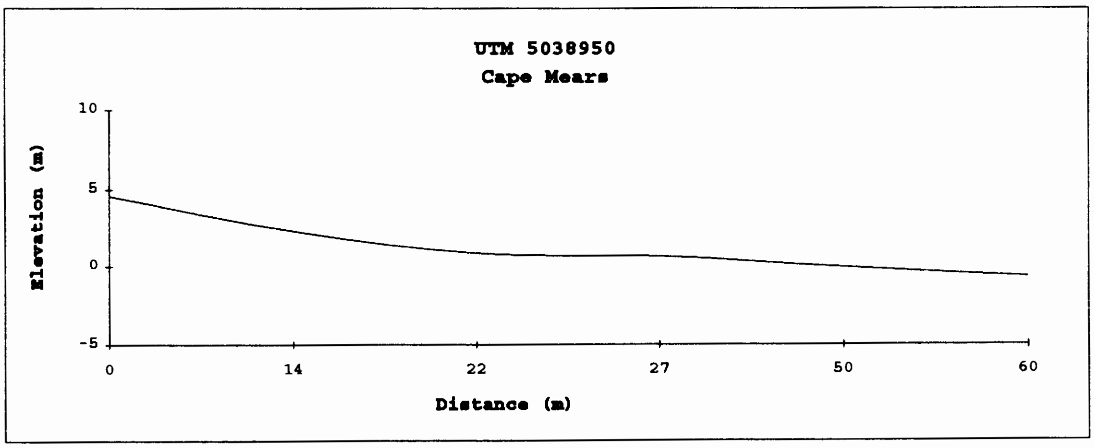

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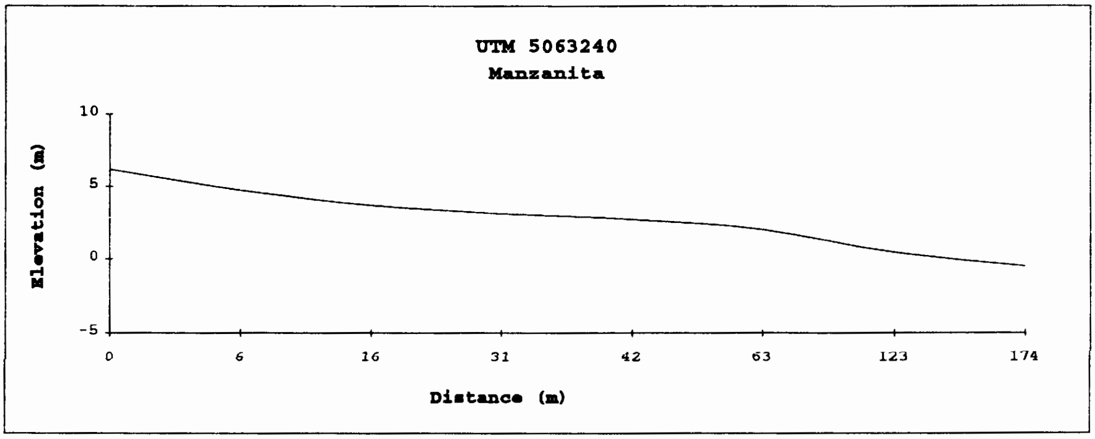
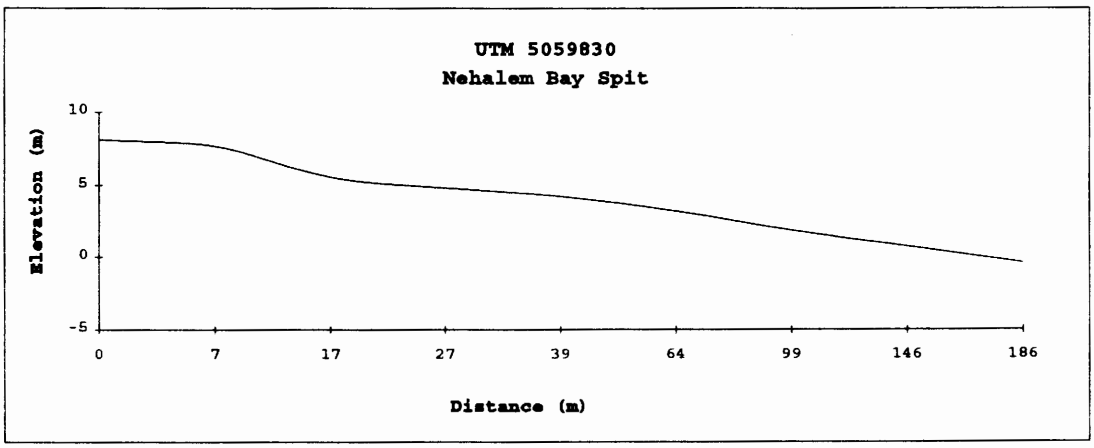
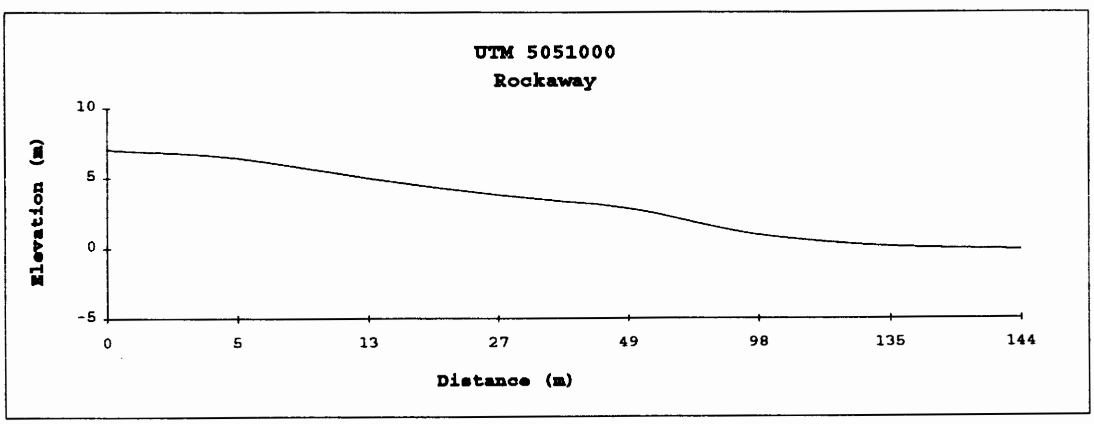




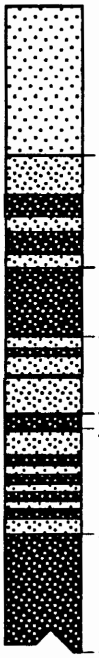


APPENDIX B

FIELD DATA CORE LOGS

Site 1
Core 1

The top of the cores contained an average of 3 - 6 cm of soil, underlain by clean, medium sand.



3.8 meters subsurface

40 cm disturbed core. Medium-fine sand; 10% heavy minerals.

4.2

30 cm light tan, medium-fine sand. 15% heavy mineral concentration; disturbed core with 5 cm blocks of undisturbed core containing heavy mineral laminations. Gradational bottom contact.

4.5

20 cm dense placer sand. 80% heavy minerals; bioturbated lamination. ? macronities. Sharp bottom contact.

4.67

22 cm light tan, medium to fine sand; 20% heavy minerals; well defined heavy mineral laminations; bioturbated gradual lower contact.

4.89 4 cm dense placer layer; 80-90% heavy minerals; sharp lower

4.93 contact with verticle burrows extending down into lower unit approximately 1 cm deep, filled with black placer sand.

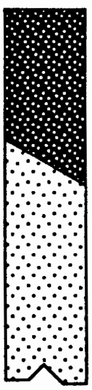
7 cm gradational finely laminated heavy and light minerals; heavy mineral laminations increase in abundance down unit.

5.2

30 cm dense placer sand; 70% heavy minerals, ?macronities; very bioturbated.

5.5 (EOC)

Site 1
Core 2



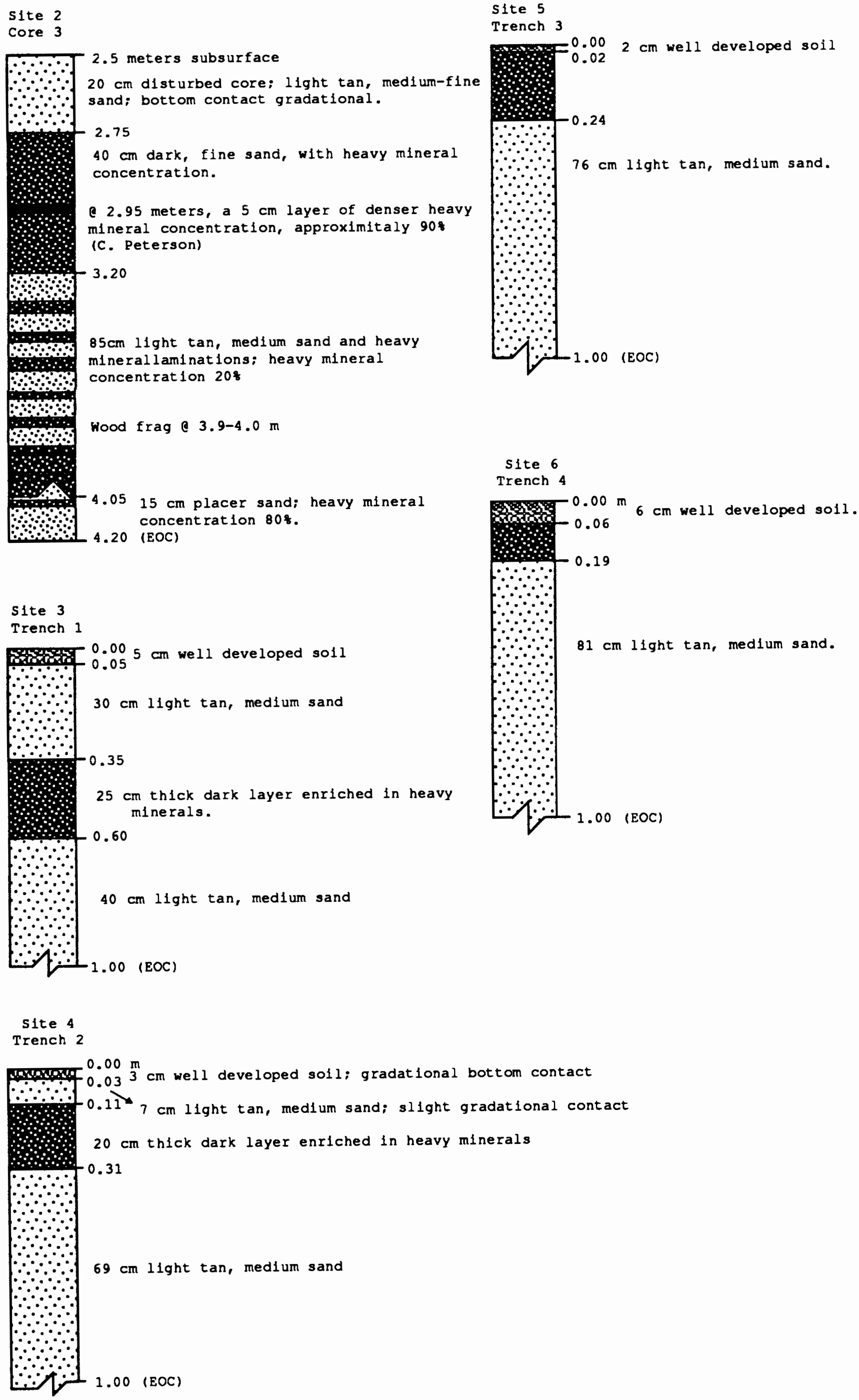
5.5 meters subsurface

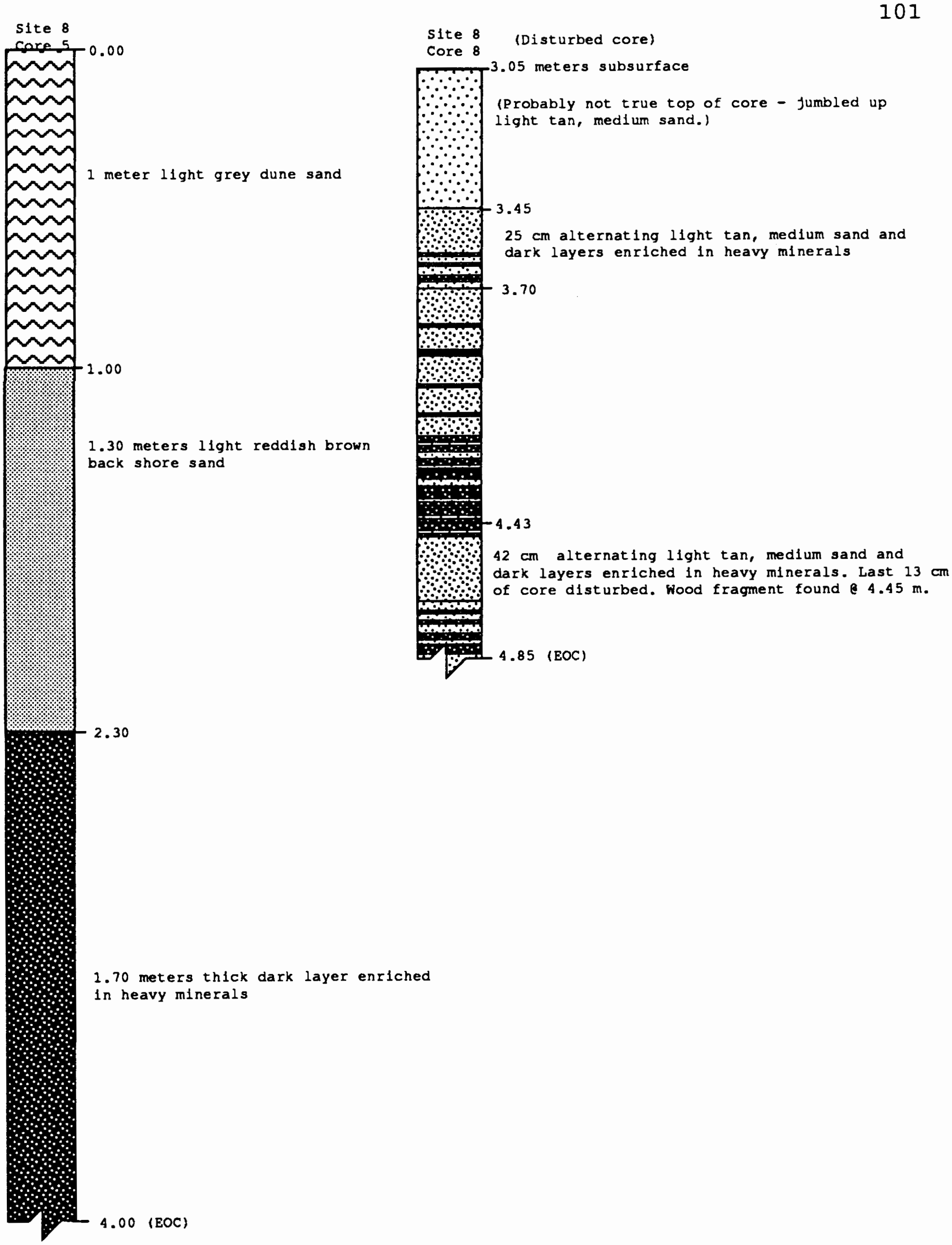
40 cm of disturbed core. Medium to medium-fine clean placer sand. Coasrsest lights up to 200 microns. 20 - 30% heavy minerals. Gradual lower contact down to 5.75 meters, where light minerals are trace to minor amounts, with 70 - 80% heavy minerals.

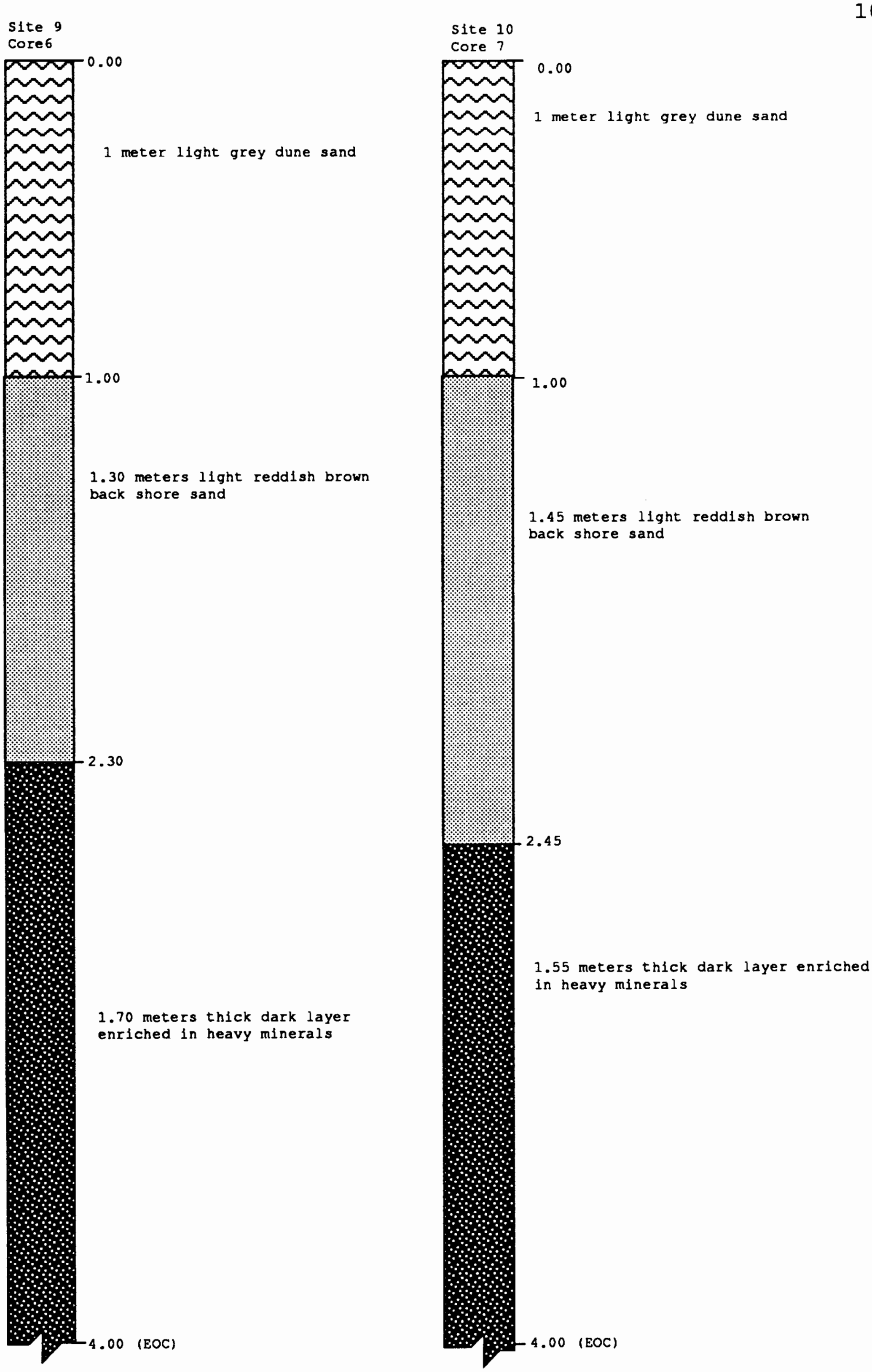
5.9

127 cm. light tan,medium sands. Sharp, sloped, non-intruded (erosional) contact. No burrowing evident. Contact from 5.8 - 6.0 meters.

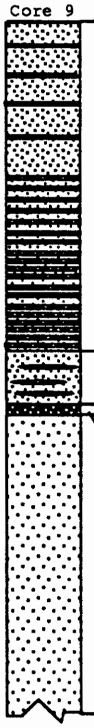
6.47m (core catcher)
EOC


Site 2
Core 3
2.5 meters subsurface
20 cm disturbed core; light tan, medium-fine sand; bottom contact gradational.
2.75
40 cm dark, fine sand, with heavy mineral concentration.
@ 2.95 meters, a 5 cm layer of denser heavy mineral concentration, approximitaly 90%
(C. Peterson)
3.20
85cm light tan, medium sand and heavy minerallaminations; heavy mineral concentration 20%
Wood frag @ 3.9-4.0 m
4.05
15 cm placer sand; heavy mineral concentration 80%.
4.20 (EOC)
Site 3
Trench 1
0.00
5 cm well developed soil
0.05
30 cm light tan, medium sand
0.35
25 cm thick dark layer enriched in heavy minerals.
0.60
40 cm light tan, medium sand
1.00 (EOC)
Site 4
Trench 2
0.00 m
3 cm well developed soil; gradational bottom contact
0.03
0.11
7 cm light tan, medium sand; slight gradational contact
20 cm thick dark layer enriched in heavy minerals
0.31
69 cm light tan, medium sand
1.00 (EOC)
Site 5
Trench 3
0.00
0.02
2 cm well developed soil
0.24
76 cm light tan, medium sand.
1.00 (EOC)
Site 6
Trench 4
0.00 m
6 cm well developed soil.
0.06
0.19
81 cm light tan, medium sand.
1.00 (EOC)


Site 8
Core 5
0.00
1 meter light grey dune sand
1.00
1.30 meters light reddish brown
back shore sand
2.30
1.70 meters thick dark layer enriched
in heavy minerals
4.00 (EOC)
Site 8
Core 8
(Disturbed core)
3.05 meters subsurface
(Probably not true top of core - jumbled up
light tan, medium sand.)
3.45
25 cm alternating light tan, medium sand and
dark layers enriched in heavy minerals
3.70
4.43
42 cm alternating light tan, medium sand and
dark layers enriched in heavy minerals. Last 13 cm
of core disturbed. Wood fragment found @ 4.45 m.
4.85 (EOC)


Site 9
Core6
0.00
1 meter light grey dune sand
1.00
1.30 meters light reddish brown
back shore sand
2.30
1.70 meters thick dark layer
enriched in heavy minerals
4.00 (EOC)
Site 10
Core 7
0.00
1 meter light grey dune sand
1.00
1.45 meters light reddish brown
back shore sand
2.45
1.55 meters thick dark layer enriched
in heavy minerals
4.00 (EOC)

Site 10
Core 9



3.43 meters subsurface

82 cm of alternating light tan, medium sand and dark layers enriched in heavy minerals. The bottom 42 cm very heavily concentrated in heavy minerals.

27 cm light tan, medium sand with stringers of heavy minerals

4.25

4.42

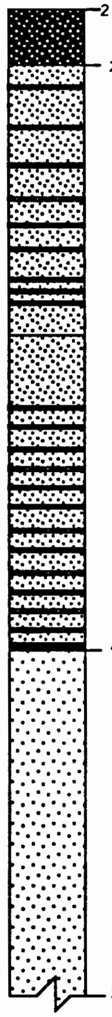
4.47

3 cm concentration of heavy minerals

78 cm light tan, medium sand

5.25 (EOC)

Site 11
Core 10



2.40 meters subsurface

15 cm laminated placer deposit

2.55

72 cm of alternating light tan, medium sand and dark layers enriched in heavy minerals; heavy minerals thinning upward.

83 cm alternating light tan, medium sands and dark sand layers enriched in heavy minerals. At base of unit, an approximate 2 cm thick concentration of heavy mineral concentration.

4.10

90 cm light tan, medium sand; area of little or no placer/heavy mineral concentration.

5.00 (EOC)

Soil

Light grey dune sand

Light tan, medium grain sand

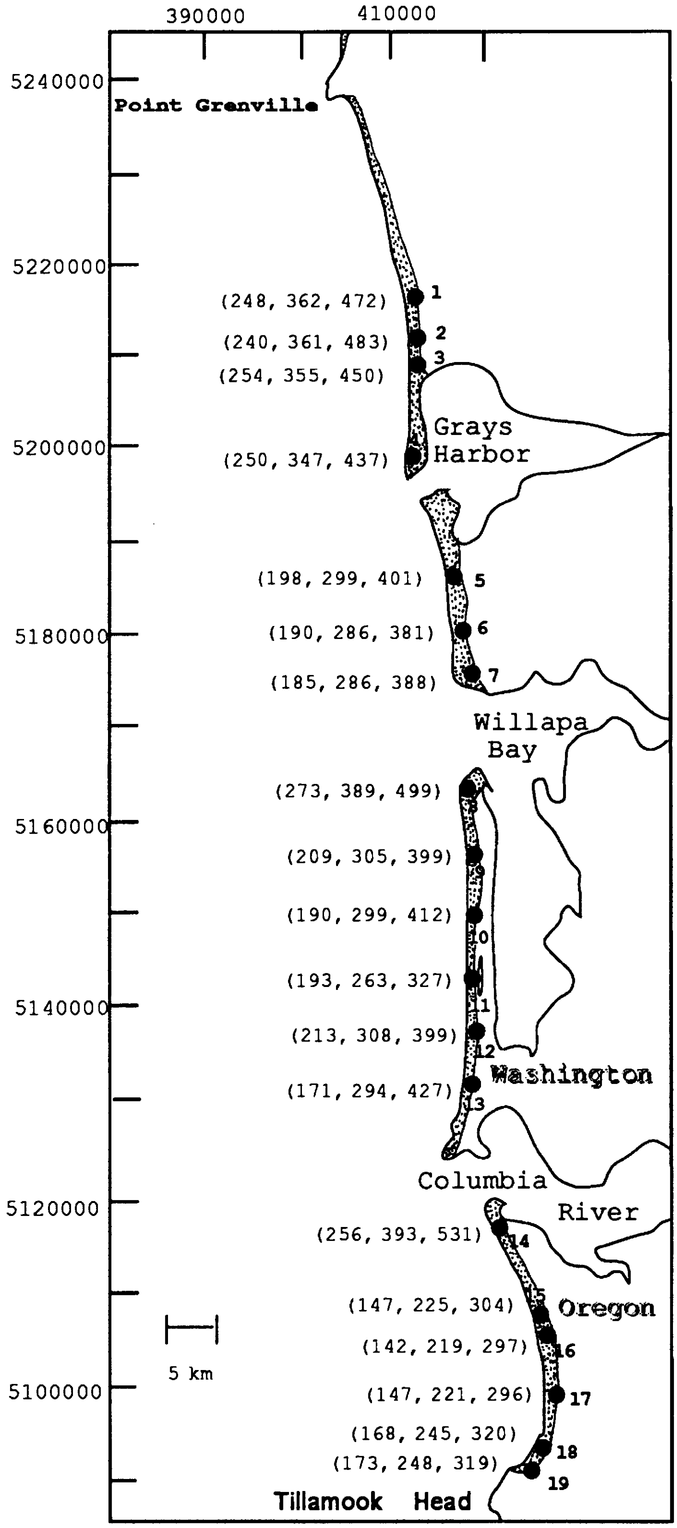
Light reddish brown back shore sand

Laminated dark/light sand

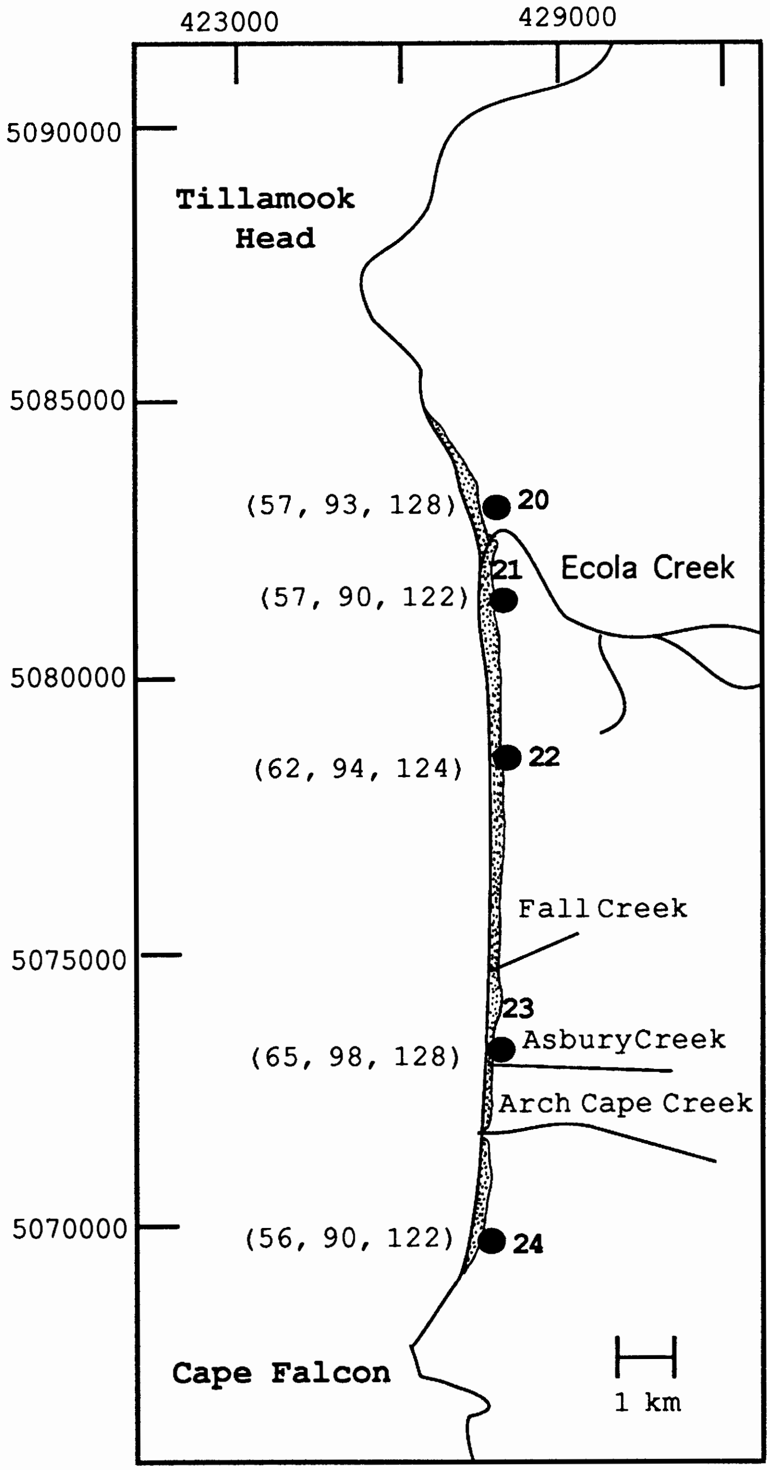
Fine grain dark sand

APPENDIX C

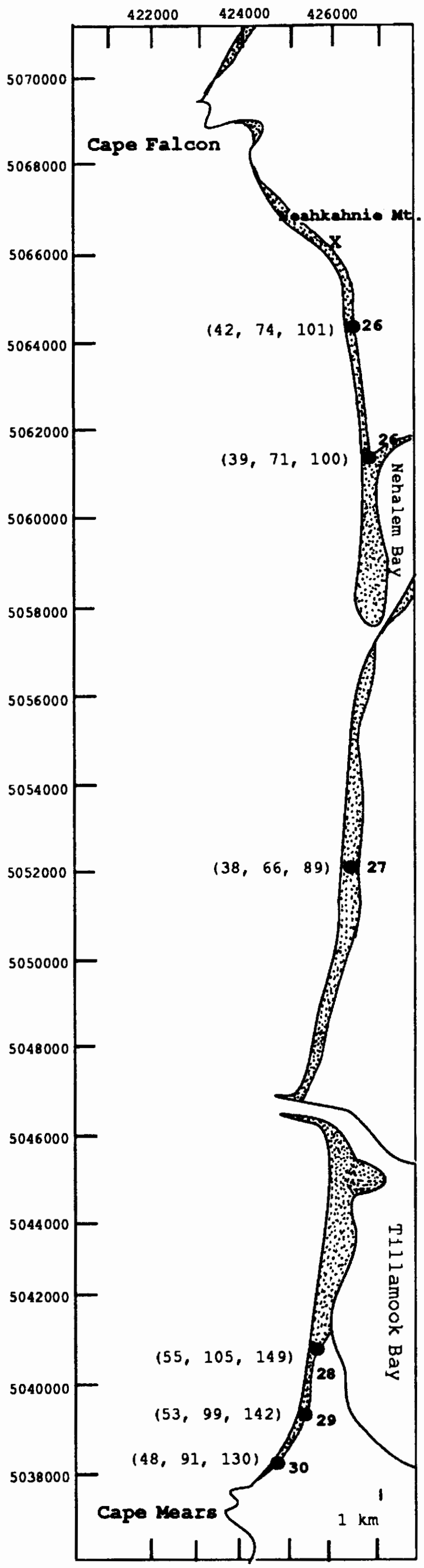
MINIMUM, MEDIAL AND MAXIMUM RETREAT FOR EACH PROFILE



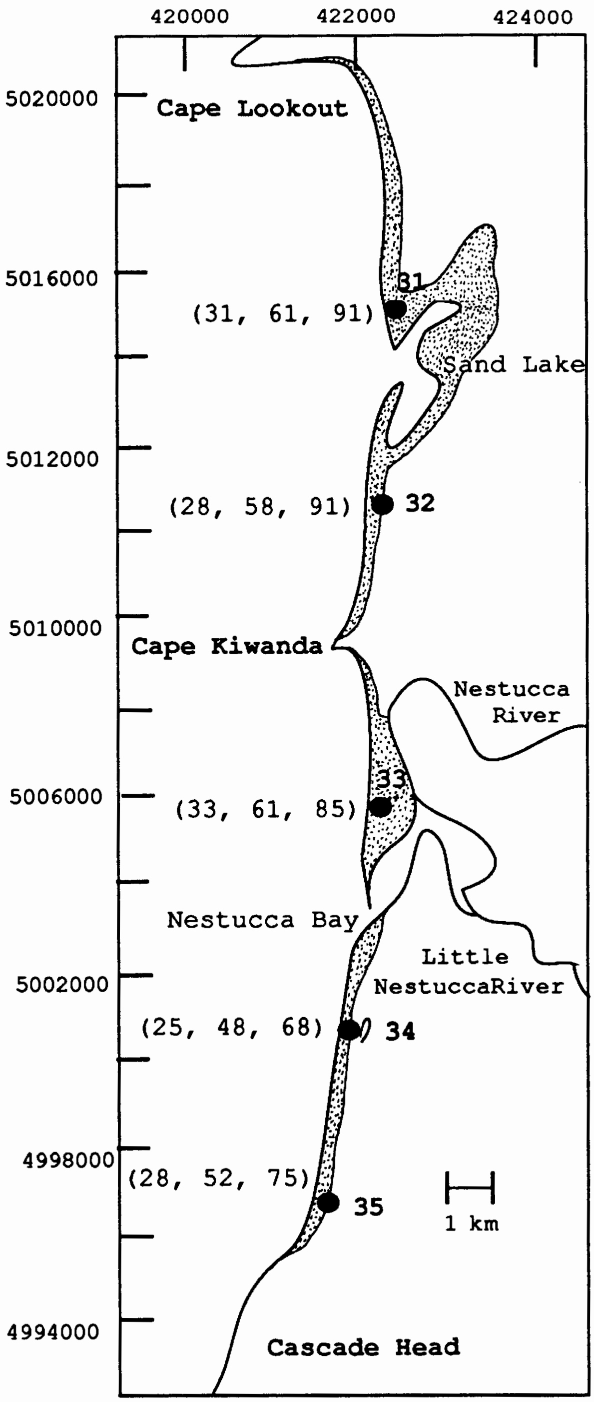
Columbia River Cell showing minimum, medium, and maximum retreat amounts.



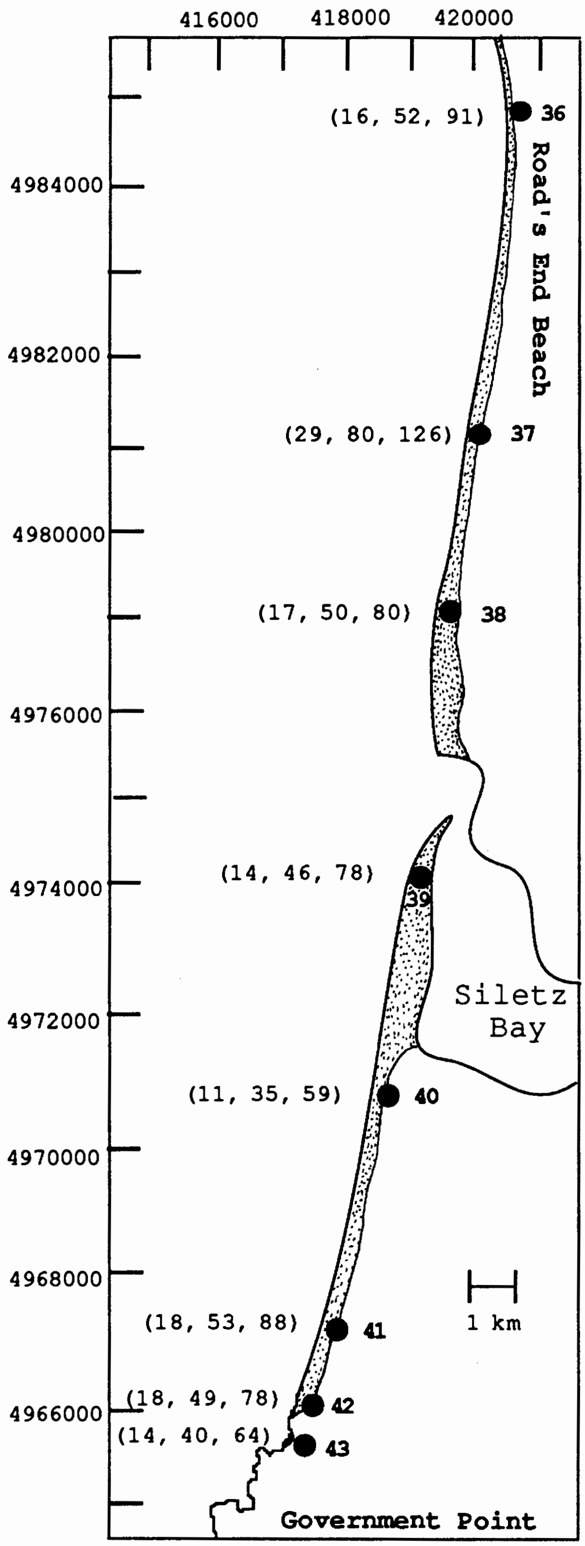
Cannon Beach Cell showing minimum, medium, and maximum retreat amounts.



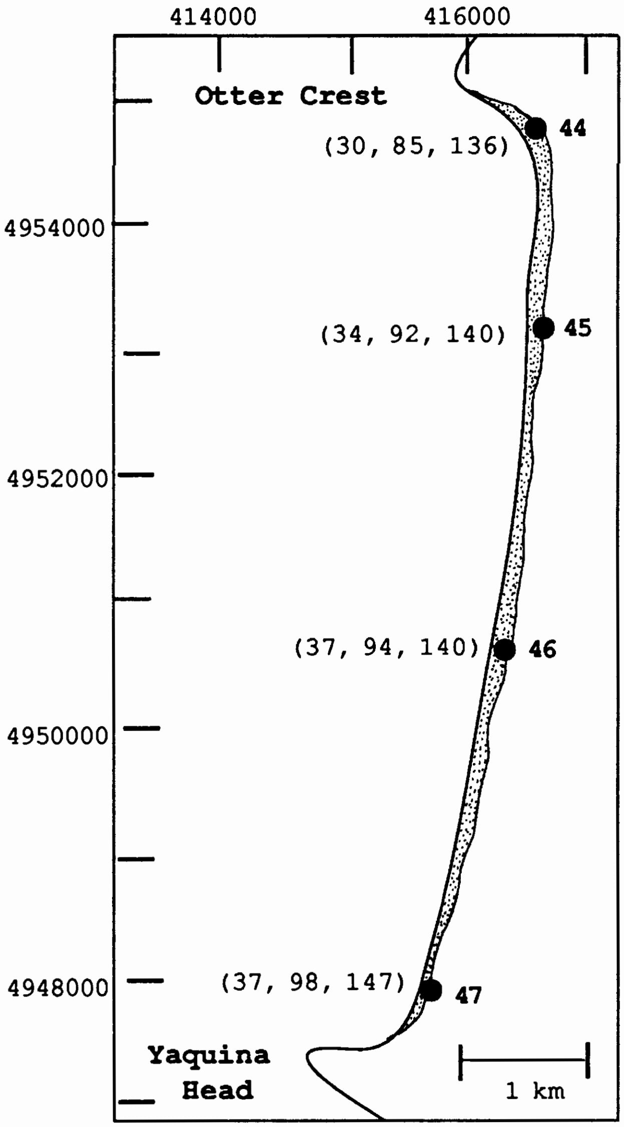
Tillamook Cell showing minimum, medium, and maximum retreat amounts.



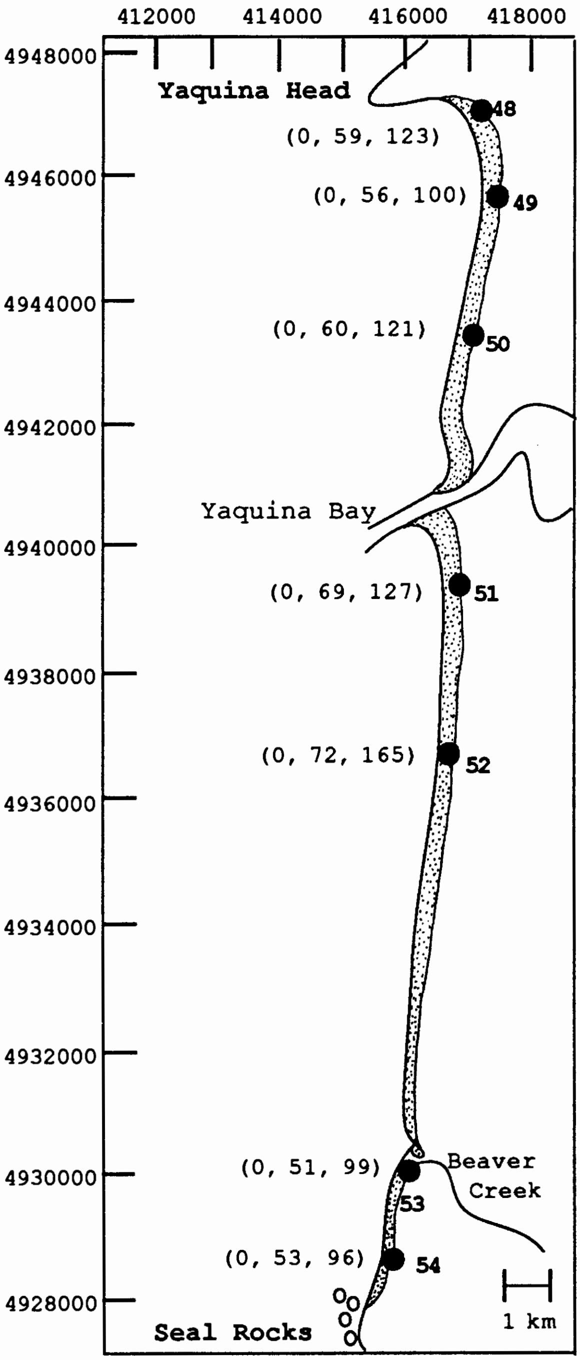
Pacific City Cell showing minimum, medium, and maximum retreat amounts.



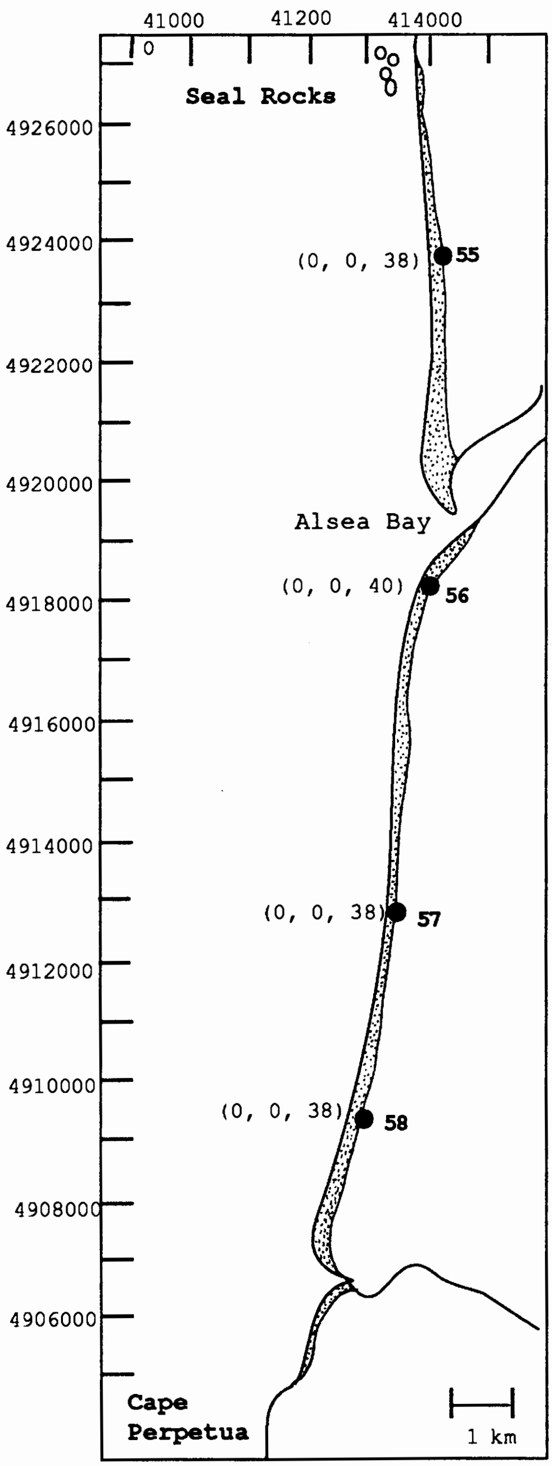
Lincoln City Cell showing minimum, medium, and maximum retreat amounts.



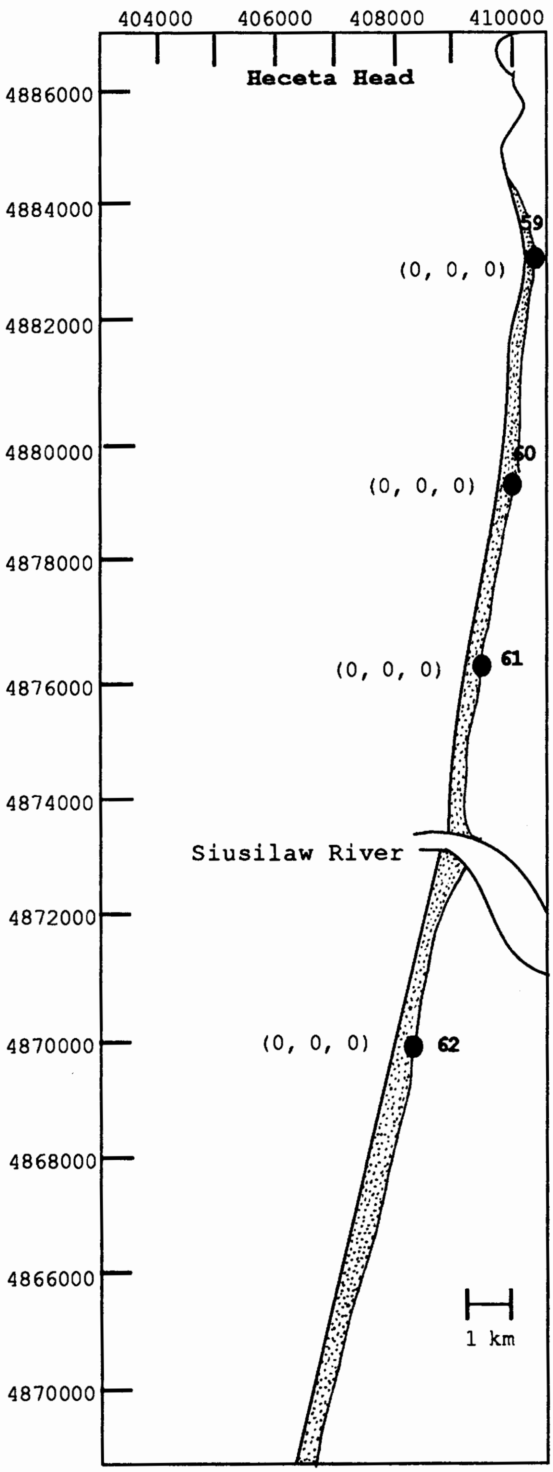
Otter Rock Cell showing minimum, medium, and maximum retreat amounts.



Newport Cell showing minimum, medium, and maximum retreat amounts.



Waldport Cell showing minimum, medium, and maximum retreat amounts.



Winchester Cell showing minimum,
medium, and maximum retreat amounts.