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# *Slope Regression Study*
# *The Capes Property*
# *Oceanside, Oregon*

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*Prepared for*
*The Capes Homeowners Association c/o*
*Williams Merrick Dalley & O'Leary, P.C.*
*and The Miller Law Firm*

*January 20, 2000*
*J-5754-02*

**THE CAPES HOMEOWNERS ASSOCIATION**
**SLOPE REGRESSION STUDY**
**OCEANSIDE, OREGON**

Prepared for
The Capes Homeowner's Association
c/o Williams Merrick Dalley & O'Leary, P.C. and The Miller Law Firm

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# SUMMARY

The site soil and slope conditions, setbacks, and remediation recommendations are provided in this report by Hart Crowser. Key design items are summarized below, and are discussed in greater detail in the following sections of this report.

- Site conditions are generally categorized into beach bluff frontage, the headwall area, and the main slide block. Slide movement at the beach bluff areas is of a dune slip category in that if five feet are eroded at the base, five feet of sand will slide in to replace it. Movement at the headwall is in direct response to movement of the main block in that if, the main block moves, the headwall sands slide into the void left behind. Movement of the main block is generally translational (horizontal) and responds directly and immediately to wave activity and erosion at beach level.

- Projections of future slide movement were evaluated by study of aerial photos, topographic maps, the history of El Nino occurrences, and review of climatological data on past and future climatic cycles.

- Setbacks regarding current and projected future movement were estimated taking into account soil types, slide types, normal erosion cycles, extreme climatic events. Setbacks and building life spans took into account all of the above factors and transition zones and marginal building areas were discussed individually.

- Upper slope remediations were discussed and included conventional retaining walls, tied back shotcrete structures, and driven piles with tieback anchors and lagging. Cost estimates were provided using year 2000 dollars.

- Utilities were evaluated and recommendations made for mitigation of future damage to sanitary sewer systems and storm systems.

- Both the South Stairs and North Stairs were evaluated and the conclusion was that the South Stairs should be considered temporary, or long-term maintenance should be anticipated. The North Stairs should not be rebuilt at this time, or in the near future.

The preceding summary is intended for introductory and reference use only. Full understanding of the recommendations, should be made by reading the entire contents of this report.

## THE CAPES HOMEOWNERS ASSOCIATION
## SLOPE REGRESSION STUDY
## OCEANSIDE, OREGON

## INTRODUCTION

Previous engineering studies have been performed in order to assess the possibility of mitigating the landslide (referred to in this document as the main slide block) at the Capes Development between Oceanside and Netarts, Oregon. At this time, mitigation of the slide appears to have sufficient physical, monetary, and political roadblocks that the idea has been all but abandoned.

The purpose of our current work is to utilize existing data to provide an assessment of the existing slope conditions at the Capes Development, and make projections of future slope erosion conditions, attempting to take into account potential changes in climatic cycles. The scope of past services has included numerous surface reconnaissances, 20 subsurface explorations (12 borings and 8 CPT's), review of previous surface and subsurface explorations by ourselves and others, study of aerial photographs, and review of slope stability information previously prepared for the project. This report has been prepared for exclusive use by the Capes Homeowner's Association and their agents, in accordance with generally accepted geologic and geotechnical engineering practices.

## SITE DESCRIPTION

The site is located on the Oregon Coast in Tillamook County, approximately halfway between the towns of Netarts and Oceanside. The outlet of Netarts Bay is just south of the development. The site covers about 76 acres between the Netarts-Oceanside highway to the east, the Pacific Ocean to the west, Fall Creek to the south, and the Sea Haven/Avalon Subdivision to the north. The area of our study consists mainly of the coastal portions of Phases I, II, and III of the Capes Development, primarily at the crest of the slope above the beach (upper slope) and the area east and south of the main slide block.

The development as platted is laid out using a lot numbering system; however, the actual street addresses are different from the lot numbers. In addition, most of the buildings are two-unit townhouses, with each unit having its own lot number and street number. For example, Lots 201 and 202 would contain one building with street addresses of 2710 and 2730. For the purposes of this report, we will use lot numbers only (Figure 2). The units along the slope crests were built generally using a 10 foot setback from the crest of the slope. Currently, although the major slide area is located in the northern portion of the development, bluff erosion and retreat is occurring throughout the beach front portions of the property.

The ground east and south of the main slide block originally consisted of a series of north-south (to slightly northeast to southwest) trending ridges and valleys formed by ancient sand dune formation. This can be observed by the trend of Fall Creek, the ridges containing Promontory and Fall Creek Drive, and the canyon housing the detention facility and the upper landing of the south stairs. The surface soil throughout the site is dune sand.

East of, and adjacent to the main slide block is a steep slope ranging from El. [El. = elevation in feet above Mean Sea Level (MSL)] 60 to 80 to about El. 160 to 200. The height of this slope is greatest (130 vertical feet) near the center of the slide mass, tapering to about 120 feet high near the north and south edges of the zone of movement. This slope will be referred to as the landslide "headwall" in this report. The dimensions of the slide, extending from the seaward side of the slide mass to the top of the headwall described above, is approximately 1,300 feet north to south and 500 to 600 feet east to west. The area east of the headwall is nearly flat at El. 200 in the northern third and slopes moderately downward toward the south, reaching about El. 160 slightly south of the active portion of the slide.

## *Recent Site History*

Prior to site development, an open pit about 50 feet deep was located in the approximate area of the open space between The Capes Drive and The Capes Loop designated as Tract "A". The pit became a landfill and was apparently filled with a variety of materials including household garbage and other waste materials. Thus far, no movement has been observed that would establish a connection between the landfill and the slide area. Also existing prior to development, was a series of natural drainages or "lineations" crossing the site in approximately a S. 20°-30° W. trend. The only obvious remaining lineation is the ravine south of Phase I which contains a play area and detention pond. The others have been modified or obscured by site grading.

Prior to the severe winters of 1995-1996 and 1996-1997, the base of the slide block transitioned seaward into a sand dune that extended several hundred feet to the west. During and after the winter of 1995-1996, the toe of the dune began to erode and retreat toward the east. In addition, the effects of the 1997-1998 El Nino caused the tidal outlet to Netarts Bay to move northward in front of the Capes Development. This probably further accelerated the erosion process. In December 1997, a landslide scarp appeared in the mid-slope area south of the stairs in the central part of the main slide block. In January 1998, the movement began to accelerate and portions of the stairs were damaged and had to be removed. Around February 20, 1998, minor surface cracks were noticed at the top of the slope behind Lots 34 and 35. Within slightly more than one week the scarp had increased in height by approximately five feet and by the last week in March 1998, the scarp was about 30 feet high. The landslide scarp throughout most of January and February was estimated to lengthen 4 to 6 inches/day, gradually slowing to about one inch per day. Sliding continued through the fall and winter of 1998-1999.

During the storms of March and early April 1999, slide movement accelerated and a series of here-to unnoticed "jolts" were reported by some of the residents on the property. After investigating nearby quarry activities and checking earthquake activity in the Pacific Northwest we finally determined that the jolts seemed to be related to storm wave activity, but were not a result of pounding breakers. They seemed to occur during quiet periods after storms and in our opinion, were probably caused by sand sloughing into open cracks at the base of the headwall, created by slide movement following the storms.

## GEOLOGY

The bedrock unit underlying the site consists of siltstones, sandstones, and basaltic inclusions of the Miocene age Astoria Formation and Columbia River Basalt (Figure 2, Regional Geology). Regionally, the bedding planes are thought to dip about 12° seaward. However, on-site measurements indicate a variety of northwest-trending strikes (parallel to sub-parallel to the shoreline) and easterly dips (mainly east to northeast at 7° to 25°). A series of three thrust faults has been mapped at the rock outcrop north of the mouth of Fall Creek (United States Geologic Survey-Wells, Snavely, and Niem, 1992 GSA Cordilleran Section Annual Meeting). The interpretation of the faulting does not appear to relate to geologic conditions that affect the landslide activity.

It appears that in the vicinity of the main slide block, the area below Lots 138-140, and seaward of the mouth of Fall Creek, a clayey residual soil appears to be located on the bedrock surface. The residual soil was subsequently covered by estuarine or back-dune lagoonal clays with interbedded organic-rich, tree rooted paleosols, alluvial sands, and conglomerates.

The soils directly above the clays appear to consist of consolidated sands, which may be elevated beach sands, partially cemented dune sand, or less likely, Pleistocene Terrace Deposits. Above the consolidated sands are unconsolidated dune sands placed by aeolian processes (wind deposition). The major source of sand for the dunes was probably the expanded beach area exposed during the last Ice Age.

## *Site Geologic Setting*

The following descriptions and interpretations are based upon a series of surface geologic reconnaissances and mapping performed by Hart Crowser, along with the interpretations of 12 mud rotary borings and eight Cone Penetrometer Tests (CPT's). Locations of the borings and CPT's are shown on the attached Site Plan, Figure 3. Four interpretive cross-sections through the slide mass are presented as Figures 4 through 7.

The Capes project is primarily founded upon Holocene age sand dunes which overlie consolidated sands at depths of 50+/- feet below the ground surface on the upper slope. In the lower foredune area, the young dune sand appears to directly overlie clay or basaltic talus deposits. The clay and talus deposits are inferred to have been placed in a paleovalley now buried beneath the sand dunes.

The paleovalley is probably of Pleistocene age and the most recent valley fill materials are thought to be Holocene in age, about 2,000 years before present (bp). Apparently, during the last Ice Age the sea level was about 400 feet lower than today and the combined width of the coastal plain and beach was as much as 25 miles westward of the present coastline (Scheidegger, 1971). As sea level rose near the end of the last Ice Age, alluvial deposition continued in the paleovalley. Strong westerly winds formed massive dunes that migrated eastward covering rocky shorelines and filling stream valleys. As the dunes blocked stream outlets, inland lakes were formed. The overrunning by the dunes and inundation by the lakes killed the forests and vegetation in the valley and on surrounding higher ground. In the upstream environment, prior to inundation by the dunes, still water deposits of clay and silt buried the vegetation and formed distinctive organic deposits. Prior to, and at the time of the valley filling, stream activity was probably still occurring, resulting in deposits of sand and gravel below, within, and on top of the lake clays, particularly at the valley margins. A series of radiocarbon age dating tests were performed on woody samples gathered independently by Hart Crowser and DOGAMI derived from tree stumps within the clays buried beneath the dune sands. The ages were very consistent at about 40,000 to 45,000 years BP (before present).

Eventually the dunes entirely buried the paleovalley under as much as 200+ feet of sand. As the ice sheet melted, sea level rose and the shoreline retreated to approximately the current location. It is unclear when the landslide first started but the assumption can be made that when the dune had eroded sufficiently to expose the lake clays, an unstable condition occurred, probably several hundred years ago. It appears that the sliding is cyclic, depending upon whether the base of the slope is protected by a foredune, or whether severe weather patterns erode the dune. The current slide movements appear to have been initiated by foredune erosion as a result of winter storms during the 1995 to 2000 time period.

## LANDSLIDE OBSERVATIONS OF MAIN SLIDE BLOCK

### *General*

The majority of the slide block ranges from El. 50 to El. 80. The slide block is tilted slightly toward the south, with a depressed linear feature near the toe of the headwall slope. Open ground cracks and scarps resulting from the past two years of slope movement are present throughout the slide block.

The beach front area south of the main slide block is mostly comprised of 1.5H:1V (one and one-half horizontal to one vertical) beach bluffs. The bluffs are subject to shoreline retreat as evidenced by periodic disappearance and reappearance of vegetation on the slopes above the main slide block and the beach, evident on aerial topography spanning the past 60 years. Two areas appearing to be landslide topography are evident; one in the area of Lots 27-32 (which was filled during development), and the other in the vicinity of Lots 137-140 on Fall Creek Drive.

At the base of the main slide block along the beach, a steep 20- to 30-foot-high sand face is present, consisting of dune sand overlying exposed layers of clay, sand and gravelly sand, basaltic talus, peat, and zones of heavy concentrations of brush and tree stumps. In the southern two-thirds of the exposure along the beach, the clays and organic layers are up to 19 feet thick. Along the northern third of the dune face near beach level, a clayey boulder talus deposit lies directly above the dark gray clay. In plan dimension, the main slide block measures approximately 800 feet north to south and 300 feet east to west. Based upon visual observations and subsurface explorations, it is our opinion that the entire mass has been active for probably several hundred years, is currently moving, and will continue to move.

It is believed that the majority of the slide movement is translational (horizontally sliding) as opposed to a classical circular failure. This is based on the site and soil geometry, and presence of numerous extension (tension) cracks across the width of the slide mass. Both horizontal translation (block) and circular failure modes were analyzed previously with regard to potential solutions for stopping the slide movement.

**Slide Character.** The area affected by ground movement (including the headwall) measures about 1,300 feet north to south, by about 500 feet east to west. The slide appears to be occurring in the Holocene clay deposits described above. The clays are not a consistent unit throughout the entire slide mass. They contain layers of silt and sand, and near paleovalley margins or near the center of old stream channels there exists some gravels. Talus from erosion of valley margins and headlands are also intermingled with the clays. As the foredune was eroded away, buried stumps, tree roots, and highly organic layers of brush were exposed on the beach. The slide block toe was exposed at beach level during the most severe erosion (February 1998) and has remained visible since that time. The slide toe was observed to be directly overlying a very soft plastic clay, which is deemed to be a portion of the slide plane. A Hart Crowser representative has repeatedly observed active bulging and cracking in the sand at the clay contact during tidal retreat, indicating active movement. In addition, Hart Crowser personnel made several minor excavations beneath the clay and found that it appeared to be thrusting up over the beach sand at about a 14° angle. The nominal northeastward dip of the clay deposits at the base of the dune (slide mass) is close to 14° throughout the length of the slide toe.

### *Slide Movement*

In examining the regional trend of topographic highs and lows in the vicinity, it appears that a general trend of geologic features is toward the southwest at about S 20° - 30° W. This includes the trend of Fall Creek, O'Hara Creek, Rice Creek, and other drainages as they cross the Pleistocene Terrace Deposits. If this has been the case throughout the Wisconsin Ice Age, then the trend of the paleovalley beneath the slide mass may have continued the same direction.

Our general observations are that the slopes on the north side of the site are moving more slowly and to a lesser degree of severity than those on the south. The slip faces on the slopes all measure approximately 45° from the horizontal, except those along the slopes below Lots 33-38, which measure closer to 60° from the horizontal. It appears that the base of the slide is adjacent to, or on the slope of the basaltic bedrock at the north end. The southern most limit of the slide appears to be below the toe of the slope directly downslope from the aforementioned units.

In simplistic terms, the observable slope failures are entirely within the sand dunes, which react to undercutting, either by wave erosion or by movement of the main slide block away from the base of the headwall. The mode of failure appears to be tensional along the north and central parts of the headwall slope above the slide block; i.e., as the slide moves seaward, sand on the slope face slides downward to the west and southwest to "fill the void." At the same time, the materials on the slide block also slide downward "to fill the void," but in this case toward the east and northeast. This would imply that the eastern most margin of the slide block is at, or beneath, the toe of the headwall slope. Talus is exposed in the headwall at approximately El. 100, perhaps the northeastern most extent of slide block.

In measuring the trend of the steep headwall scarp on the south slope, it follows a fairly straight line trending about S. 15° W., then turns abruptly to about S. 30° W. where it intersects the beach. The tensional features on the northeastern part of the slope above the slide block trend in a N. 75° W. direction, almost 90° from the steepest and most active slide area.

Based upon the above observations, the axis, and possible direction of greatest slide movement, is estimated to be in the range of S. 20° - 30° W. Based on these observations, it appears that the units on the south side of the slide area are more at risk than those to the north because the slide is moving parallel to the slope contours and beneath the slope itself.

## BEACH BLUFF EROSION

The areas of the beach bluff not affected by the main slide block to the north, or the smaller one below Lots 137-140, are affected by a different form of erosion. Much of the shoreline area in Oregon is affected by beach bluff retreat. The causes are many and include: normal erosion due to rising sea level (in millimeters per year), El Nino or La Nina related climatic cycles, sinking of the Oregon land mass, storm surges from wind and storm generated waves, tsunami waves generated by earthquakes, jetty construction, and landsliding. Also, many materials erode at different rates; some very slowly such as hard basaltic flows, and others quite rapidly such as sand dunes and sandy terrace deposits. The potential number of factors involved in shoreline retreat makes it difficult to predict from locality to locality, and a variety of methods have been dealt with in the literature. Setbacks will be discussed in a subsequent section.

## PROJECTIONS OF FUTURE MOVEMENT

Our primary task in preparation of this report is to provide estimates of future movement based upon data currently available. We have prepared a series of two maps (Figures 2 & 2a) containing two lines drawn above the crest of the slope along the entire north-south extent of the property. The first (western most) line represents the 1.5H:1V (Factor of Safety 1.0) zone of "imminent failure", and the second (eastern most) line represents the 2H:1V (Factor of Safety 1.5) "reasonable setback for planning purposes."

Imminent failure is a term used in this document for the natural angle of repose of dune sand, approximately 1.5H:1V, or 32 to 33 degrees from the horizontal. If a slope is undercut or steepened to a greater angle, the slope will fail or "lay back" to that angle. Also, the phrase "reasonable setback for planning purposes" as used in this document, refers to the farthest possible eastward headwall and beach bluff retreat if the current erosional and climatic conditions are maintained throughout the life of the structures, including a Factor of Safety.

A series of Cross Sections (A-A' through P-P') were used to calculate the lines, and are presented as Figures 4 through 19.

### *Methodology*

In order to derive the setback lines a variety of factors were taken into consideration. They include, but are not necessarily limited to:

- Study of aerial photographs from 1939 through 1999
- Study of topographic mapping from 1939, 1991, 1998, and 1999
- Review of El Nino and La Nina effects over approximately 450 years
- Review of Climatological events over the past 100 years
- Review of subsurface, site-specific, soil and geologic data generated on this project

#### ***Study of Aerial Photographs***

For this report, we reviewed aerial photography between 1939 and 1999, examining the entire beach front zone and main slide block for the purpose of

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establishing historical erosion patterns. The dates of the photos and a summary of observations follows:

| | |
|---|---|
| 1939 | Observable recent landslide in main slide block area. No vegetation on slide mass or north half of headwall. 3 drainages above main slide block trending about S.20°W. and running into scarp area at Lots 75-76, 51-58, and 27-32. Fresh slide onto beach N. of basalt knob below Lots 78-81. Dump pit is obvious. Existing dike blocking ravine below detention pond was in place at this time; most likely an access road from the Co. Rd. to the dump. Erosion all the way to beach level at S. stairs area. Scarps in Lots 140-142 area. |
| 7/6/53 | Very poor resolution in area of main slide block. Vegetation on headwall, except for slide area around Lots 51-58. Uncertain of slide base/beach line. No vegetation north of the South Stairs. Slip surface at Lot 135. |
| 9/24/64 | Nearly all vegetation on headwall has slid from area of Lot 38 and north. Dune well established and far out on beach. Almost no vegetation below Lots 15-30. Fairly recent scarps below Lots 140-142; vegetation is primarily trees. |
| 6/28/67 | Dump pit filled, apparently by cutting down ridges at crest of beach-facing slopes. Fresh slide masses below Lots 35-39. Dune on beach appears to be eroding. Fresh slip surface north of the South Stairs. Vegetation on bluff below Lots 16-24 appears to be sparse grass only; no trees or bushes. |
| 7/14/70 | Scarps paralleling contours on headwall slopes (almost same pattern as 1998 scarps), diving off seaward at the south side of the slide mass in area of Lots 35-39 and below Lots 30-32. Scarps in trees below Lots 140-142. |
| 5/23/82 | Apparent slump in area of Lots 28-32; fresh sand from slope crest to beach level. Fresh slips near Lot 35. Dune on beach very evident. |
| 1983 | Dune field on beach completely gone. Fresh erosion at north side of main slide block below Lots 78-81. Fresh scarps paralleling contours on headwall (same as 1998) and below Lots 28-32 paralleling slope trend. Fresh scarp north of the South Stairs. Not much vegetation below Lots 16-24. Erosion scarps evident below Lot 140. Slump in area of Lots 28-32. |
| 6/2/86 | Dune on beach nearly re-established. Scarp north of the South Stairs |

overgrown. Scarps on headwall still evident.

1989 No vegetation on Lots 51-58 and Lots 27-32. Recent slide movement?

7/29/91 Dune on beach well established. Scarps in headwall still evident. Scarps near beach level below Lot 140 still visible. Brush & grass below Lots 15-30 taking hold.

3/27/94 Dune on beach very high and well-established, but contains no vegetation. Scarps in headwall not visible. More brush growing below Lots 15-30.

The conditions reflected by the 1998 and 1999 photos have been described in great detail throughout this document.

In summary, the scarps on the headwall have been historically visible; erosion in now filled areas below Lots 27-32 and 51-58 was ongoing throughout the time period covered; the slide below Lots 78-81 appears to be above a rock outcrop and may be shallow slip face movement; erosion and scarps below Lots 138-140 has been ongoing throughout the time of our examination, however no massive slides occurred and mature trees still dominate the vegetation; the dunes on the beach are transient and were absent in photos from 1939, 1967, 1983, and 1998.

## ***Study of Topographic Mapping***

Hart Crowser made comparisons of Topographic profiles in the main slide block area for the years 1939, 1991, 1998, and 1999. The purpose of the comparisons was to attempt to determine the amount of slide movement and shoreline retreat that had occurred at that time. Representative profiles of Cross Section areas A-A' and D-D' are attached as Figures 20 and 21.

Cross Section A-A' is located in the most active slide area, but since the slide movement is nearly perpendicular to the section shown, slope regression between 1939 and 1999 only appears to be on the order of 10 feet. However, the crest of the slope appears to have undergone at least two episodes of filling so total apparent retreat is on the order of 20+ feet. The toe of the slope appears to have retreated on the order of 80-90 feet from 1939 to 1999 (no beach dune was present for either year). Most of that apparent regression was removal of extensive amounts of slide debris from the beach resulting from the 1939 slide.

Cross Section D-D' is located near the center of the main slide block and is probably more representative of actual slide movement. Although some construction-related filling occurred in this area, the regression of the slope face still appears to be on the order of 25 feet from 1939 through 1999. The toe of the slope in this area also indicates a regression on the order of 90 feet, again probably due in part to the removal of the 1939 slide debris from the beach. Of significance is the down-dropping of the soil block at the base of the headwall/main slide block contact; the vertical displacement in this area is on the order of 30 feet in apparent response to soil sloughing into scarp areas to fill the voids caused by horizontal slide block movement. Vertical movement since January 1998 has probably been on the order of 10 feet. Horizontal movement of the main block at the base of the stair landing has been on the order of 15 feet since Feb 1998.

The Aerial Photo interpretation indicated ongoing erosion in the areas of Lots 137-140, but very little actual beach bluff retreat. Topographic mapping of this area was not available from 1939, and the Spencer Gross mapping of 1998 and 1999 stopped around the area of the South stairs. The long standing presence of trees on the hillsides is indicative of past stability, but not necessarily future stability.

## ***Review of El Nino Activity***

El Nino is a climatic activity that has been occurring throughout recorded history. It can have effects on weather world wide, but is most noticeable in the northern South America region and adjacent Pacific Ocean waters. Severe weather patterns in Oregon, Washington, and California have been linked to El Nino generated Pacific storms, and sometimes the effects of one event can carry over for several years.

During "normal" equatorial climatic occurrences, the Trade Winds blow east-to-west on a fairly constant basis. The resultant is that surface friction created by the winds cause a "mounding" of warm sea water in the West Pacific, with a measurable west to east slope. An El Nino occurs when the Trade Winds cease to blow, in effect releasing the water built up in the Western Pacific and allowing it to flow "downhill" in a wave from west to east toward northern South America. In addition, the Coriolis effects of the earth's rotation confine the wave to the equatorial region, not allowing it to spread north and south. The wave of released water has been measured on the order of two feet in height as it moves through the equatorial islands. As the wave of warm water hits the equatorial region around northern Peru, it splits north and south and makes its way along the coastline.

Some of the results of the El Nino are: warming of coastal waters, elevation of sea levels along the coast, destruction of fisheries, warm water species brought into coastal waters, and the triggering of severe climatic events, particularly the "Pineapple Express" storms generated in the South Pacific that bring high storm waves and extreme rainfall. The storms result in severe beach erosion and shoreline retreat in the southern parts of Littoral Cells, and very high accumulation of sand in the northern parts of Littoral Cells.

Over the past 100 years 17 El Nino events have occurred which could be classified as "moderate," or "strong" to "very strong." Severe erosion on the Oregon coast can be correlated with several of the events, but careful records of erosion were not kept prior to about 1970. The severe erosion observed in the aerial photographs examined correlate with 1939, 1982-83, and 1997-98 El Nino events. Erosion was also noted in the 1967 and 1970 photos, but did not necessarily correlate with El Nino activity.

For those wishing more in-depth information on El Nino we are attaching, as Appendix A, five pertinent articles that relate to El Ninos worldwide, historical occurrences over the past four and one-half centuries, and El Ninos in the Pacific Northwest with emphasis on the 1982-1983 and 1997-1998 events.

### ***Climatological Events***

As part of our work on this project, we were asked to address the probability of severe erosion continuing at its present rate. The Oregon State Climatologist, Mr. George H. Taylor has written an article entitled "Long-Term Wet-Dry Cycles in Oregon" March 1999. In general, he refers to wet and dry "cycles" that generally span about 20 to 25 years. His general conclusion is that we have just emerged from a dry cycle and since 1996 we have entered a wet cycle that, if history holds true, may last at least 20 years.

The article connects a global "Conveyor Belt" of oceanic currents that has a direct correlation to climatic cycles. The correlations include: Atlantic Hurricanes, average global precipitation, El Nino events, and Precipitation in the Pacific Northwest. The changes do not necessarily affect the warm seasons, only the cool months. The conclusion is that if the predictions are accurate (and he thinks that they are), we can look forward to frequent floods, no droughts, about 75% of the years will be wetter than normal, and overall temperatures will be relatively cool.

We are attaching Mr. Taylor's article in Appendix B.

In a January 20, 2000, article in the Associated Press, La Nina is discussed as perhaps being a portion of a global event that could result in wetter, stormier weather in the Pacific Northwest over the next 30 years.

The basis for the discussion is satellite data that reveals a warming trend in the North, West, and South Pacific Ocean over the past 18 months, while cooler water is wedged up against the Pacific Northwest (our current La Nina event). This temperature change phenomenon is referred to as the Pacific Decadal Oscillation, which refers to temperature shifts that occur every 20 to 30 years, favoring either El Nino, or La Nina. The last 20 years have been El Nino dominated and the projected climate shift would probably favor the La Nina. The overall result would be that the Southwestern US would be drier and the Pacific Northwest would be more stormy.

In actuality, it would likely be ten years before meteorologists could confidently know that a global (or at least Pacific Ocean) shift in climate has actually occurred, as opposed to an isolated, short-term event..

We are unable to attach a copy of the article because of an Associated Press Copyright that prevents the material from being "published, broadcast, rewritten, or redistributed."

## SETBACKS

In order to aid in determining which units are in immediate jeopardy from those not affected by slope movement, it was necessary to establish a set of criteria to be used for this project. The erosion rate of dune backed beaches has been studied extensively by the Oregon State University College of Oceanography, DOGAMI, the US Army Corps of Engineers, and independent researchers. Because of the variables involved, there is no one method or formula that is considered definitive or more reliable than all the others. Without hundreds of years of direct observation and measurement, most predictions are educated guesses. Seemingly, one of the most consistent methods of calculating retreat in areas of sand dunes and marine terrace deposits is to use the 1.5H:1V slope (from the bluff-beach contact) as a Factor of Safety of 1.0, and the 2H:1V slope as a Factor of Safety of 1.5 (also representing the setback line) for a 100 year planning period. This represents an annual bluff retreat rate of approximately 0.5 feet per year in dune sands in this area.

### *Establishing Setbacks Behind Slide Block*

In order to establish a reasonable setback from the slide area, it was necessary to derive an estimate as to the boundaries of the slide block. Using boring and slope inclinometer information from B-4 through B-7 and B-10, we determined that the plane of failure was close to El. 10 and was fairly flat. Using the same information, we also determined that the slide block extended at least to the base of the headwall slope.

To further define the slide limits, we utilized boring and inclinometer information from B-8 and B-9, both drilled on the headwall slope above the main slide block, but below the open scarps on the face of the headwall slope. Both of these borings encountered a rock surface significantly higher in elevation (approximately El. 70) than the slide plane, but neither boring encountered evidence of deep-seated sliding. Ultimately, the slopes moved and deflected the inclinometer casing. Measurement between the open scarps and the deflection points on the inclinometers confirmed a failure plane within the dune sand at approximately 45 degrees from the horizontal. Projection of the failure plane within the dune sand to the estimated slide plane beneath the main block allowed us to estimate the margin of the active slide block.

After establishing the estimated slide margins, we projected a 1.5H:1V (Factor of Safety 1.0) line upward from the margins beneath the headwall slope face and intersecting the ground surface. We then projected a 2H:1V (Factor of Safety 1.5) line upward from the margins beneath the headwall slope face and intersecting the ground surface. These are the two lines that appear above the slide block on Figure 2. Cross-sections A-A' through D-D' show the planes of projection and estimated slide margins

We used a similar method to establish the setback lines in the area of Lots 138-140 on Figure 2a.

The area in the northern portion of the headwall above the main slide block was treated in a slightly different manner. An outcrop of clayey, basaltic talus is exposed in the headwall

### *Establishing Setbacks Behind Beach Bluffs*

Although there is a lack of boring and inclinometer data behind the beach bluffs, we observed no evidence that slope movement was occurring from sources other than wave erosion and gravity, with the exception of the slide in the area of

Lots 137-140. With this in mind, we projected a 1.5H:1V (Factor of Safety 1.0) line upward from the plane of intersection between the slope face and the beach level. In general, this line intersected the ground surface near the slope crests, further substantiating the angle of repose of the dune sand.

We then projected a 2H:1V (Factor of Safety 1.5) line upward from the same point to an intersection with the ground surface. This line represents a reasonable setback line for planning purposes. Cross-sections E-E′ through J-J′ were used to generate the lines between Lots 15 and 26, and sections K-K′ through P-P′ were used for Lots 133 to 143.

### *Establishing Setbacks in Transition Zone*

The area beneath Lots 27 to 32 represents a transition area from landslide-induced retreat, to beach bluff erosion retreat. Because the criteria for establishing the setback lines is different, when attempting to connect lines drawn south-to-north through the transition zone with those drawn north-to-south through the same area, they do not exactly match. We chose the most conservative line because the precise location of the slide margin at beach level is not known. Based upon historical aerial photo data, the location of the slide margin may vary as much as 100 feet north-to-south at beach level.

## MARGINAL BUILDING LOCATIONS

As can be observed on Figure 2, several of the buildings (and lots) are bisected by the 1.5H:1V line "of imminent failure," particularly 31-32 (possibly 29-30), 51-52, and 71-72. Based upon our observations and researching events over the past 60 years, we are fairly confident that these lines are representative of future occurrences. Buildings adjacent to these listed above, but behind the 1.5H:1V line can be remediated to prolong their livability. Possible remediation structures include underpinning and/or retaining structures.

We reiterate that the 2H:1V setback line is approximately the limit that the slides will regress to if the present climatic cycle continues unchanged.

The lots discussed in this section are in zones of relatively different geologic processes and failure mechanisms as explained below:

**Lots 31-32.** The building constructed on these lots is at the margin of maximum severity between seaward movement and ground shearing from the main slide block, and normal shoreline retreat processes. Although these properties could be shored up, underpinned, or have retaining walls built, the proximity to a zone of severe movement and what appears to be a historically active landslide feature makes them subject to short-term damage. Lots 29-30 are positioned behind the 1.5H:1V line, but are still within the old landslide zone. We feel that these lots are more vulnerable than those to the south, but less so than those to the north.

**Lots 51-52.** This building (occupying two lots) has the 1.5H:1V line running through it, but due to its relative distance from the main slide block and direct shoreline erosion, we feel that the encroachment of the slide scarp will be relatively slow in comparison to Lots 31-32. Additional time could be gained by construction of a retaining wall and/or underpinning the foundations, but ultimately the building will most likely be a loss.

**Lots 71-72.** Our 1.5H:1V setback line on Figure 2 places approximately the southern one-third of the building within the zone of "imminent failure." As previously explained, the presence of the "talus" outcrop below Lots 73-74 limits the amount of severe movement that is anticipated east of its southern most exposed margin. The scarp shown on the map beneath Lots 72-73 does not appear to have shifted noticeably from the ones observed in the historical aerial photos researched for this project. It appears that the damage to this building will stem from gradual laying back of the sand to its natural angle of repose and shallow (approximately four to five feet parallel to the slope face) slip surface slide movement. This structure could have an extended period of usage by utilizing underpinning of the foundations and periodic replacement of sand and planting vegetation below the scarp directly downslope.

## UPPER SLOPE LANDSLIDE REMEDIES AND LOCATIONS

The majority of the houses along the beach bluff area can have life spans that could approach design lives of the structures (provided normal erosion cycles prevail in the future) by utilizing underpinning and/or retaining structures.

Prices quoted herein are from a single source contractor and single source structural engineer. Actual costs would have to be negotiated with the contractor and engineer of the homeowner's choice, and would have to be based upon dollars at the time of construction; i.e., if no work is done for 10 years, prices for the year 2010 would prevail. Costs quoted do not include engineering or permitting.

### *Underpinning*

The original soils reports prepared for the development in 1982 and 1991 recommended deepened foundations or driven piles for buildings located seaward of the 2H:1V setback line for protection against future erosion. Most of the slide front or beach front structures fall into this category. At this point, the most logical way to protect the structures is to derive vertical support from piles or piers. For estimating purposes, we are assuming that the piles or piers would be approximately 20 feet long and would derive lateral support from sand buttressing or retaining structures. In our opinion, if lengths beyond 20 feet are required, the structures are in imminent danger and should probably be removed.

Each underpinning system would need to be designed by a structural engineer in order to determine spacing, which is a function of building weight and load distribution. For estimating purposes, each vertical member would cost approximately $900.00 to $1,000.00 installed. Total cost would depend upon volume; i.e., installing only four or five piers would probably run over $1,000.00 each, whereas 20 piers would probably run closer to $900.00 each, or about $18,000.00. The costs do not include engineering, permitting, or removing and replacing deck structures, which would probably be necessary for construction of the underpinning system.

### *Retaining Structures*

In areas where slide front and ocean front structures are not threatened by deep-seated slide movement, but by gradual slope regression, retaining structures can prolong their useful lives. In order to maintain the maximum usage of the back yard areas and provide a comfort zone buffer, the most logical locations for these structures is along the existing slope crests.

The retaining walls explored consist of: conventional concrete cantilever, shotcrete walls with tieback anchors, and driven pile and concrete lagging structures with tieback anchors.

**Concrete Cantilever Walls.** These structures are probably best suited for structures close to, but not necessarily in the zone of imminent danger. Roughly speaking, this would include Lots 73-81. We did not include lots 53-56 because the fill within the old landslide scarp and the scarp itself are unknown quantities.

Roughly speaking, this type of wall can be constructed for approximately $15.00

per square foot, for a wall up to eight feet high and about 80 feet long; total cost estimate would be about $9,600.00. The costs on a smaller wall would dramatically increase the unit price; i.e., an eight foot high wall only 20 feet long could cost as much as $20.00 per square foot or around $3,200.00.

**Shotcrete Walls.** These structures would be useful in areas of fairly aggressive slope retreat such as in front of Lots 37-56 above the main slide block, or those that front the beach bluff such as lots 16–28. This system would involve emplacing tieback anchors a maximum of 40 feet long into the slope or scarp face, and using gunite or shotcrete as a slope facing to tie everything together. To be effective, the wall face should be about 20 to 25 feet high and the tieback anchors should be on approximately six foot centers. Because of the tendency for the sand to erode from beneath the wall as the slopes regress, a wedge of sand, probably 8 to 10 feet high should be placed along the base of the entire wall so that as the slopes settle from beneath the wall the sand wedge will slide down the face and help to keep sand from running from beneath the wall. Periodic replacement of the sand would be a long-term maintenance issue until the wall becomes totally undercut and begins to fail. At this point the structures should be removed.

As described, the shotcrete and tieback system would cost approximately $1,400.00 per anchor. For example, a wall with three vertical rows of tieback anchors 60 feet long would require about 33 anchors and cost about $46,200.00. As stated for previous walls, a very small wall would have a substantially higher per anchor cost.

**Driven Pile and Lagging Walls.** These structures are probably the most expensive of the wall alternatives, but will be more functional and probably have a longer life span than the concrete cantilever and shotcrete alternatives. We would envision that this structure would be effective for usage in the areas listed above as "Marginal Building Locations" that may allow the structure to last the full design life.

The wall would consist of driven steel H-piles approximately 40 feet long, on six foot centers, with concrete panels dropped into the channels to retain the soil. Concrete was chosen over wood for discussion and costing purposes, for reasons outlined below. Depending upon the location of the lot, at the time of construction the piles would probably only stick out of the ground a few feet. As the panels are installed between the H-beams, the sand could be excavated from beneath the downhill side to allow the panels to be installed deeper. The final exposed wall face would probably be eight to ten feet high.

In addition to the piles and lagging, the wall would have to be restrained with tieback anchors approximately 30 feet long. The tieback system should consist of steel "walers" spanning between, and welded to the H-piles. Tieback anchors would be installed and tied to the walers at about the central point between the H-piles. The concrete panels have an advantage over wooden beams for lagging because, due to their weight, as sand erodes from beneath the wall or sliding in front of the wall undermines it, the panels will "knife" into the sand and settle into the void space. This will cut down on long-term maintenance and repairs and the sand wedge in front of the wall is not as necessary as it would be for shotcrete structures.

For estimating purposes, we have assumed a 120-foot long wall, 14 or 16 inch wide H-piles 40 feet in length on six-foot centers, 30-foot long tieback anchors (with walers) with a capacity of 24 kips ultimate strength each, and concrete panels for lagging material. The costs have been consolidated into a per pile figure that includes these items, but not engineering and permitting costs. As stated the cost would be approximately $6,000.00 per pile (for 21 piles), or about $126,000.00.

## SEWER LINE BETWEEN LOTS 57 AND 69

As stated previously, the 2H:1V setback line on Figure 2 represents the extreme case if the present erosional and climatic cycles continue as they have for the past few years, throughout the life of the development. If this were the case the sewer line in the area of Lots 75-69 through the Lot 56-57 area would be destroyed, along with every front row lot, leaving only a few houses in service.

We do not feel that this will ultimately be the case; a more likely scenario would be that a portion of the sewer line between Lots 57 and 69 could be damaged under "normal" regression and erosion conditions. Depending upon the climatic cycles, the existing system could remain functional for another 10 to 15 years. We estimate that eventually about 250 feet of sewer line would need to be repaired or re-routed. In order to insure that repairs are only handled one time, we would anticipate that the sewage would be collected near the end of Capes Drive in the Lot 72-74 area, and pumped around the hazard zone to the existing sewer in the Lot 55-56 area and allowed to drain by gravity to the main pump station in the Capes Drive-Capes Loop common area.

An alternative to installation of a new pump station and sewer system would be to use one of the stabilization measures discussed for the houses, such as the tied back H-pile and concrete panel retaining system. This system could be slightly modified and installed such that it would be covered and not visible in the near future. The base of the wall should be installed at least five feet below the sewer pipe invert.

This alternative would allow the existing sewer to remain in place without disruption from construction activities. Once the erosion begins to approach the wall system, a sand wedge can be maintained on the slide block side of the wall to keep lateral stress down and prevent undermining. We estimate that the life of this alternative could approach that of the development.

A less expensive alternative would be to collect the sewage in a manhole near Lot 70 and pump it through a near-surface, high strength conduit to the next manhole near Lot 57. This system may need long-term maintenance or repairs, but would probably remain viable for many years. A plumbing code variance may be needed to install the line at, or near the ground surface.

## STORM WATER ISSUES

### *Detention Pond Area*

We have stated previously that it does not appear that storm water entering the pond contributes significantly to the main slide block movement, and we are still of the same opinion. The slide has been moving for, most likely, hundreds or thousands of years. The "dam" across the canyon was in place prior to our oldest aerial photos (1939) and prior to the most current cycle of slide movement that began in December 1997.

Observations of site drainage over the past two years indicates that virtually all of the rainfall on the site percolates into the ground before it reaches the slopes or beach level. Prior to development, the rainfall on the site probably percolated into the ground in a similar manner as today without noticeable effects on ground movement. The primary difference today is that with nearly all of the storm water from roofs and pavements being routed to the detention pond area, it tends to fill rapidly and could be a hazard if anyone were to fall into, or get trapped in the pond when it is nearly full. At the least, a fence or barrier should be placed around the pond for safety reasons.

We understand that water from The Cottages percolates directly into the ground in the ravine before reaching the pond. The global stability of the area is most likely not affected by whether the water from this area enters the ground at the pond location or prior to reaching it. On a localized basis, the water velocity and concentration should be slowed and dissipated to prevent surface erosion that could ultimately affect localized stability.

### *Storm Drainage*

**Streets.** Although we are not overly concerned about the detention pond area being used as a dispersion or percolation basin, we still feel that it is prudent to keep from concentrating water directly onto the main slide block. It is our opinion that the storm drains from Lot 55 and to the south should be permanently closed off and the water routed to the detention pond.

The lot and street drainage that runs toward the catch basins around Lots 76-77, and into the north drain line is currently being piped down a steep sandy slope, across the main slide block, into a manhole, and onto a riprap velocity dissipation structure, and finally to the beach. Over the past two years this drain has broken or pulled apart several times and caused deep gullying and erosion, mostly confined to the lower part of the slope.

It is our opinion that the water should not be allowed to flow into the slide mass, especially in concentration. Several types of drain pipe or drainage systems could be designed to cross the slide area, but in our opinion they would require heavy maintenance, and would probably fail one or more times over the course of the development life.

It is our opinion that the water should be routed away from the slide area and into the detention basin. This would entail design and construction of a collection and pumping facility. Design of this facility and preparation of construction estimates should be performed by a qualified civil engineer with expertise in this area.

**Roof Drains.** Our opinion of the roof drainage is similar to that of the street drainage; runoff should not be concentrated onto the main slide block area. As designed, the roof drainage from Phases I and II emptied into a conduit in the back yards of the bluff frontage lots. After the slide damaged the roof drain conduit, the water was intercepted and re-routed south of Lot 51. As erosion progresses over the years, this conduit will probably cease to function along much of the bluff crest.

If our projections are reasonably accurate, five or six of the buildings will be gone in the next few years. If the wet climatic cycle continues unabated for 20 years, most of the slide front and bluff front buildings will also be removed or shored up. Regardless, the water issue should be addressed immediately with the assumption that the drainage system will remain active for many years. The drainage system selected should be capable of servicing structures from Lots 55-56 through Lots 15-16 along Capes Drive, Capes Loop, and Capes Point.

An alternative to construction of a regional storm drain would be to supply each building with a small reservoir and sump pump to direct roof drainage to the street. The size of the reservoir and pump would need to be determined by a qualified civil engineer. A major drawback to this system would be the need for power to run the pump. Since most of the units are not occupied throughout the year, a power outage or pump failure could disable the system for long periods of time.

It is our opinion that a new drain line should be installed on the street side of the units at a depth that will allow gravity drainage of the roof drains into it. This would insure that the system works year around and would be intact for the life of the development.

Most of Fall Creek Drive is still undeveloped, but similar considerations for roof drainage should be observed; i.e., not dumping roof or street drainage onto the slopes above the beach or canyons. Historical evidence of slope movement in this area has been previously noted in this report and should not be exacerbated.

## BEACH ACCESS

### *South Stairs*

Over the past several years the base of the south stairs has been alternately built to beach level, buried by sand dune building, exposed by wave erosion, and damaged by wave erosion. Very few structures built on the Oregon coast within the zone of storm wave activity have a chance for survival. It should be anticipated that that portion of the South Stairs in the zone of storm wave activity will be subjected to frequent damage and high levels of maintenance. Although it is beyond the scope of our expertise, we anticipate that the HOA could be subject to future liability if an injury occurs on a damaged stair landing.

During our historical aerial photo review, we noted in several instances that a landslide has been intermittently active immediately adjacent to the north side of the South Stairs (Figure 2). If the current severe storm cycle continues, this slide could be re-activated and damage the stairs in areas other than at beach level.

It is our opinion that with close monitoring and adequate warnings, the stairs can still be usable for partial beach access. If the current climatic cycle continues unabated, the stairs may be unusable in just a few years. If the dune building process recurs in the next few years then the stairs may be used for beach access until the next severe El Nino event or prolonged storm cycle.

## North Stairs

At this point, the upper two landings of the North Stairs are still fully intact. The lower set of stairs and landing on the main slide block are in place, but severely damaged. During the course of the current landslide cycle, as evidenced on the aerial photos of February 1998 and September 1999, the mid-slope scarp has moved approximately 30 to 40 feet parallel to the slope face, and the bottom stair landing has moved horizontally approximately 10 feet toward the west. It must be remembered that by the time the February 1998 photo was taken, the stairs were already severely damaged and two sections totaling approximately 40 feet horizontally, had already been removed.

If the current erosion and climatic cycle continue, this slope will continue to move on a regular, measurable basis. Even after the movement of the main slide block ceases, the slopes will continue to shift, lay back, and adjust for several years to come.

In our opinion, the North Stairs should not be re-built as long as the present erosion cycle continues. The rebuilding and usage of the stairs could present a safety hazard and potentially incur liability in the event of an injury. If the current severe erosion cycle ends and dune stabilization occurs in the future, the stairs could be reconstructed with the understanding that they should be considered a temporary structure, subject to removal if a new erosion cycle commences.

We appreciate the opportunity to continue to be of service to you on this project. If you have any questions, please contact the undersigned.

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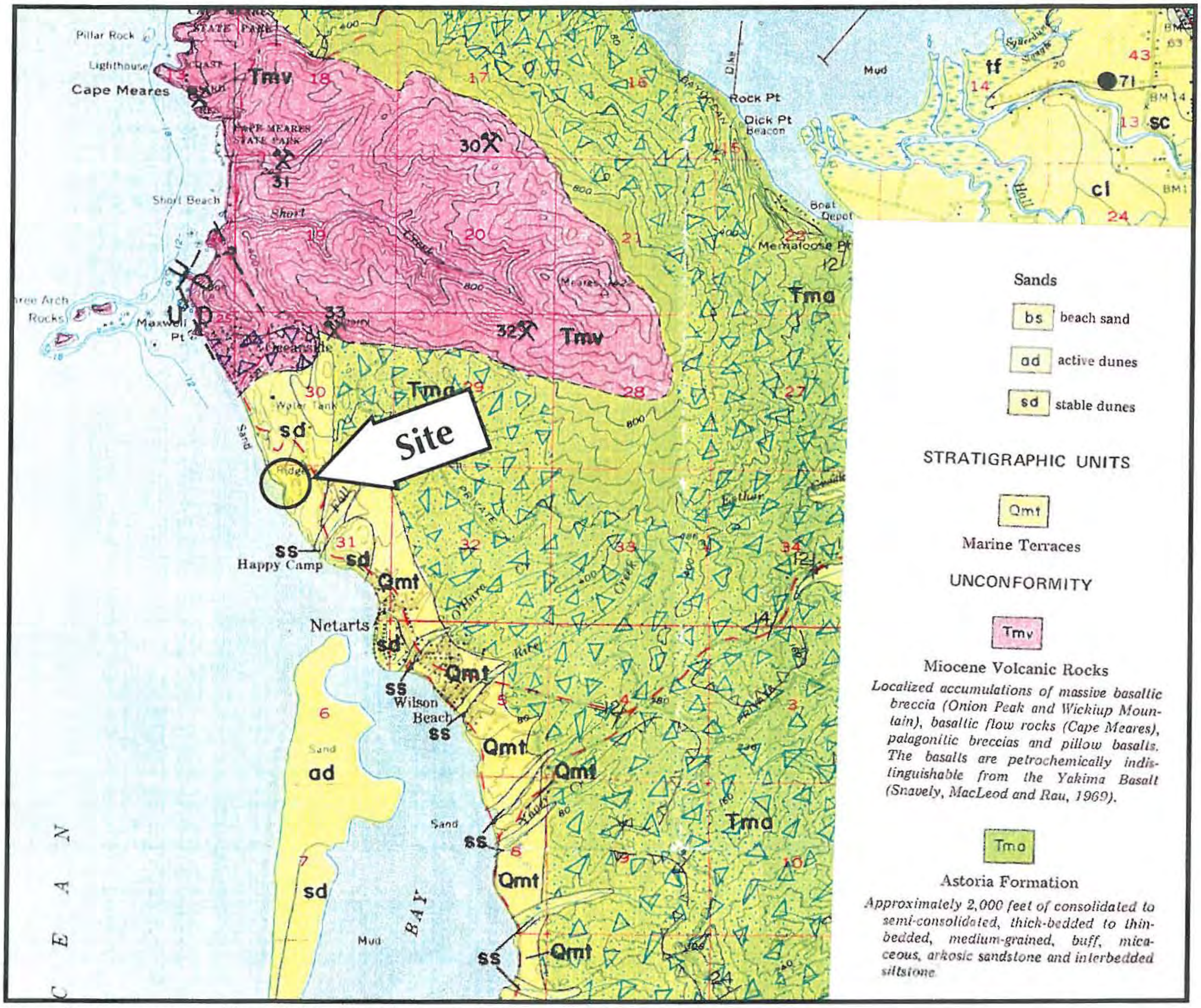
# Site Location Map
## The Capes
## Oceanside, Oregon




**Note:** Base map prepared from DOGAMI Bulletin 74, 1972.


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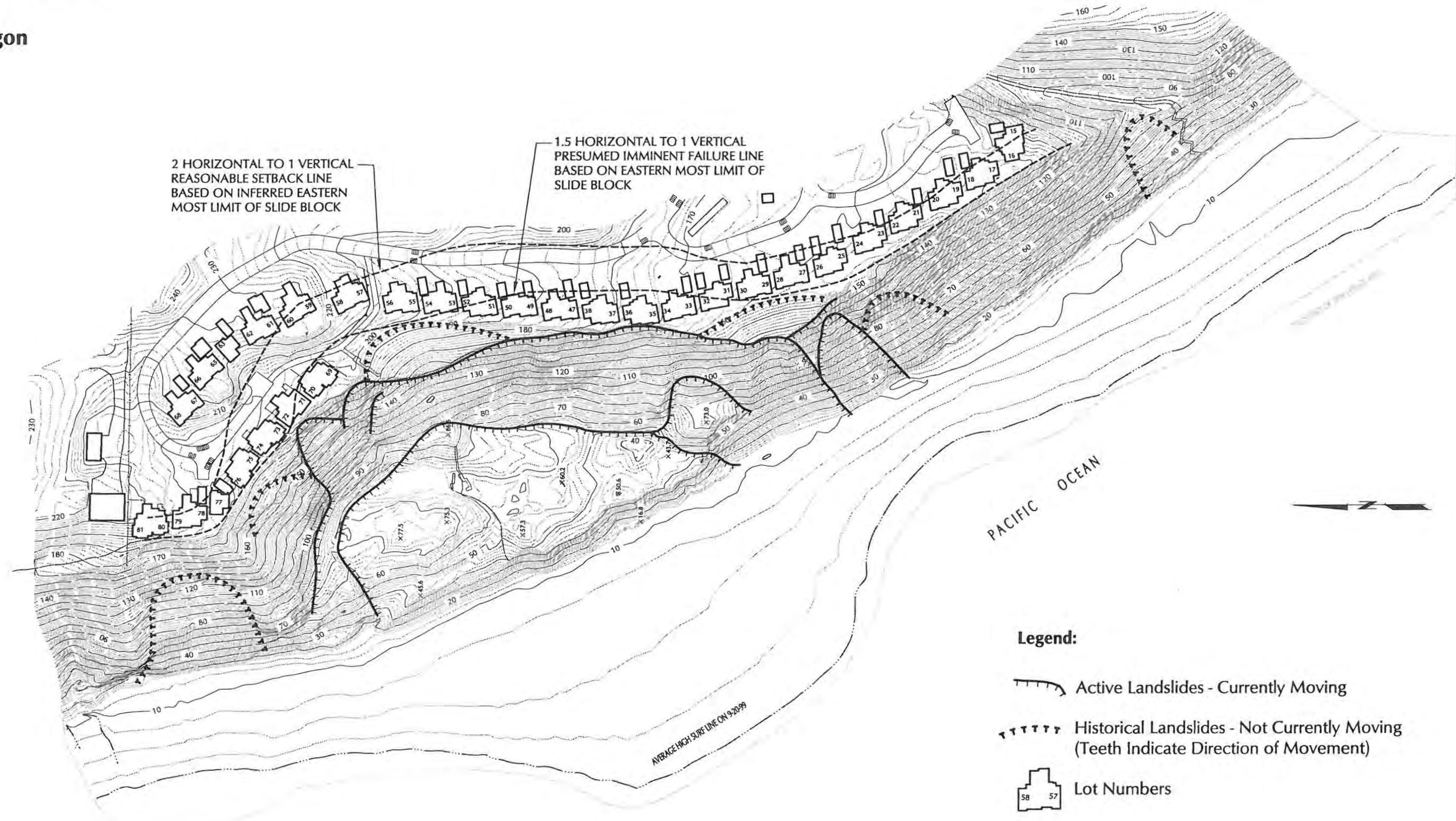
Figure 1

# Landslide Plan - 2000

## The Capes
## Oceanside, Oregon




**Legend:**

Active Landslides - Currently Moving

Historical Landslides - Not Currently Moving (Teeth Indicate Direction of Movement)

Lot Numbers

0 200 400

Approximate Scale in Feet

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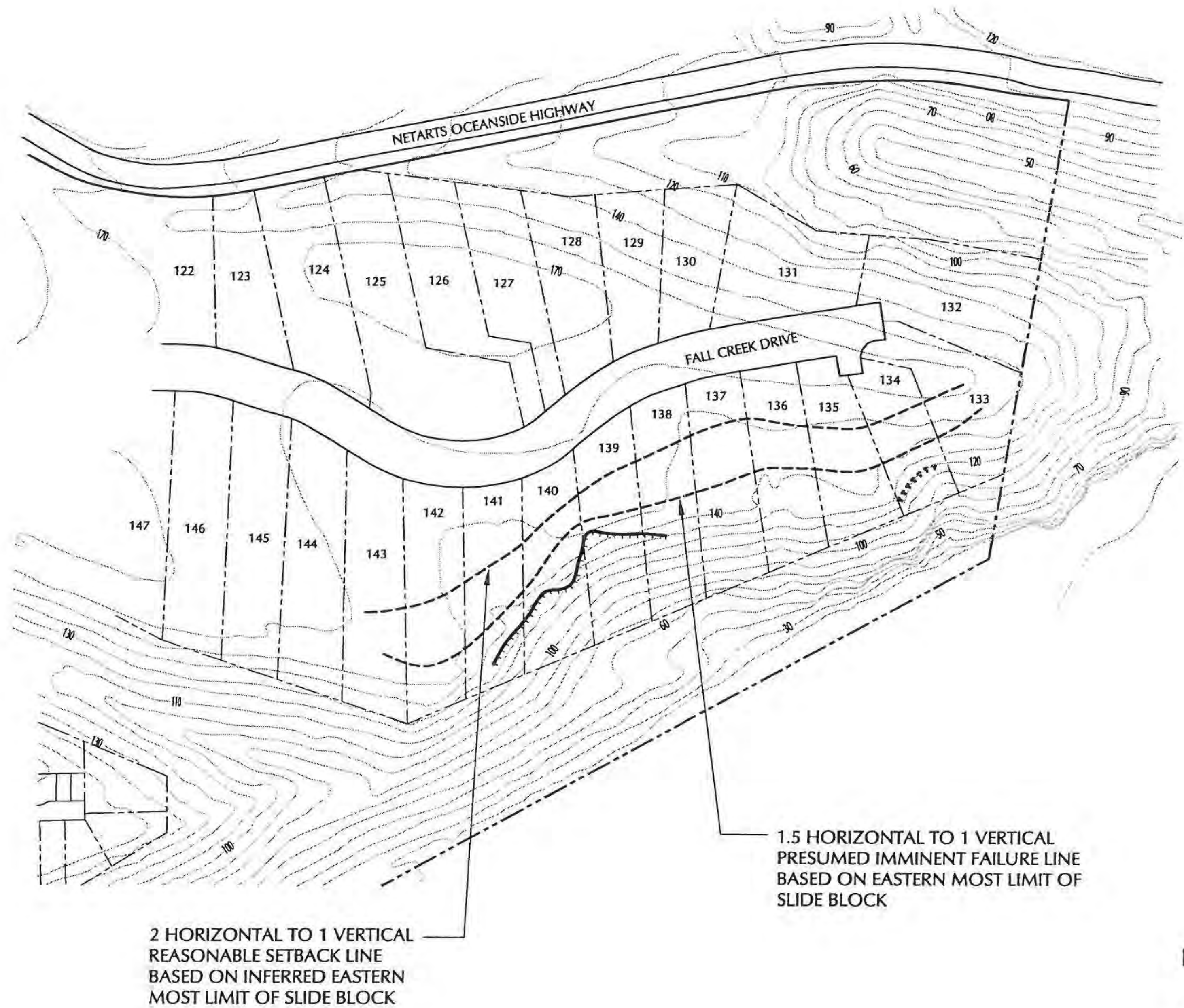
Figure 2

## Landslide Plan - 2000

**The Capes**

**Oceanside, Oregon**




**Legend:**

Active Landslides - Currently Moving

Historical Landslides - Not Currently Moving (Teeth Indicate Direction of Movement)

123 Lot Number and Lines

0 200 400

Approximate Scale in Feet

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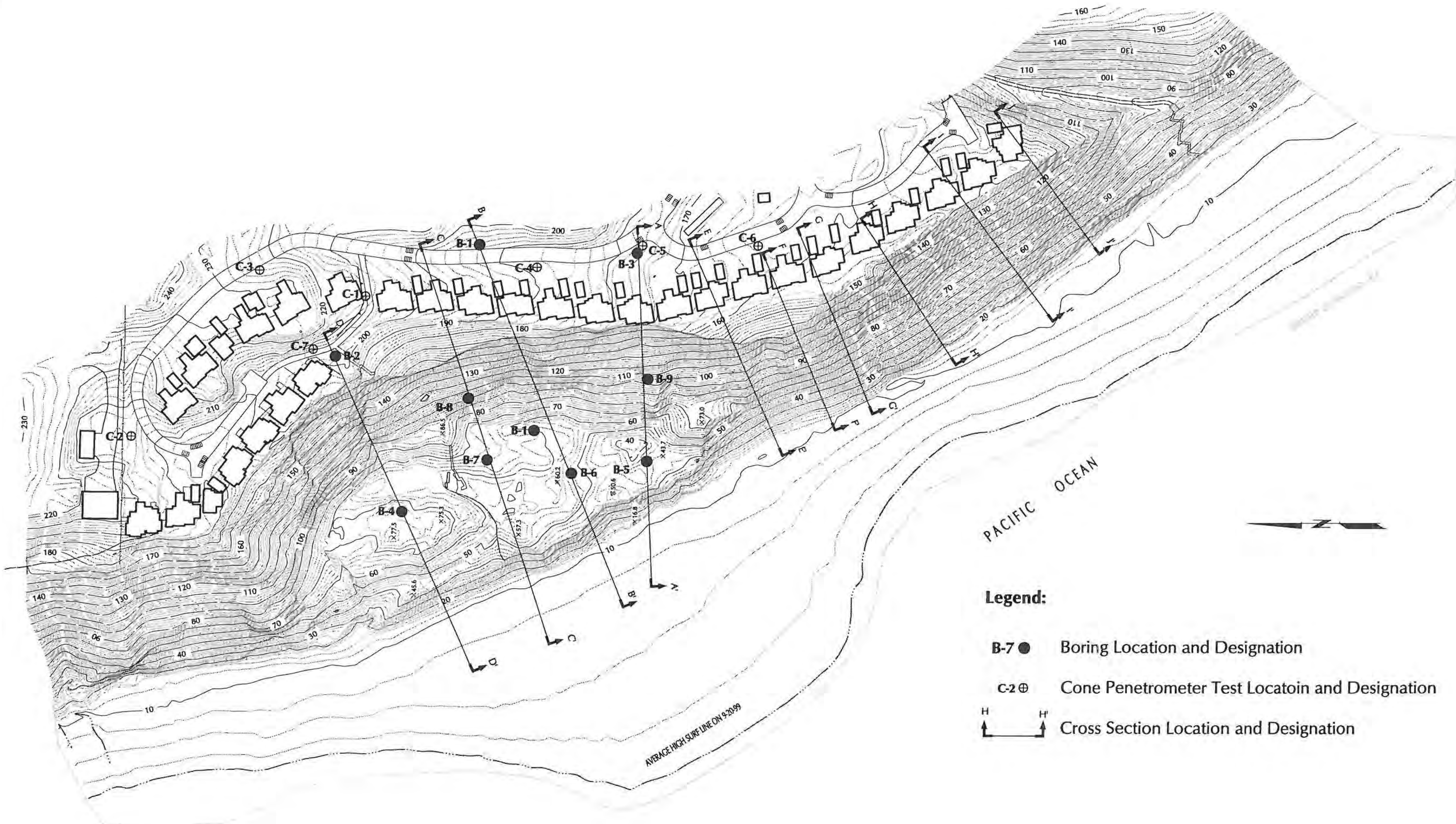
Figure 2a

# Site Plan - 1999

**The Capes**

**Oceanside, Oregon**




**Legend:**

| | |
|---|---|
| B-7 ● | Boring Location and Designation |
| C-2 ⊕ | Cone Penetrometer Test Locatoin and Designation |
| H —— H' | Cross Section Location and Designation |

0 200 400

Approximate Scale in Feet

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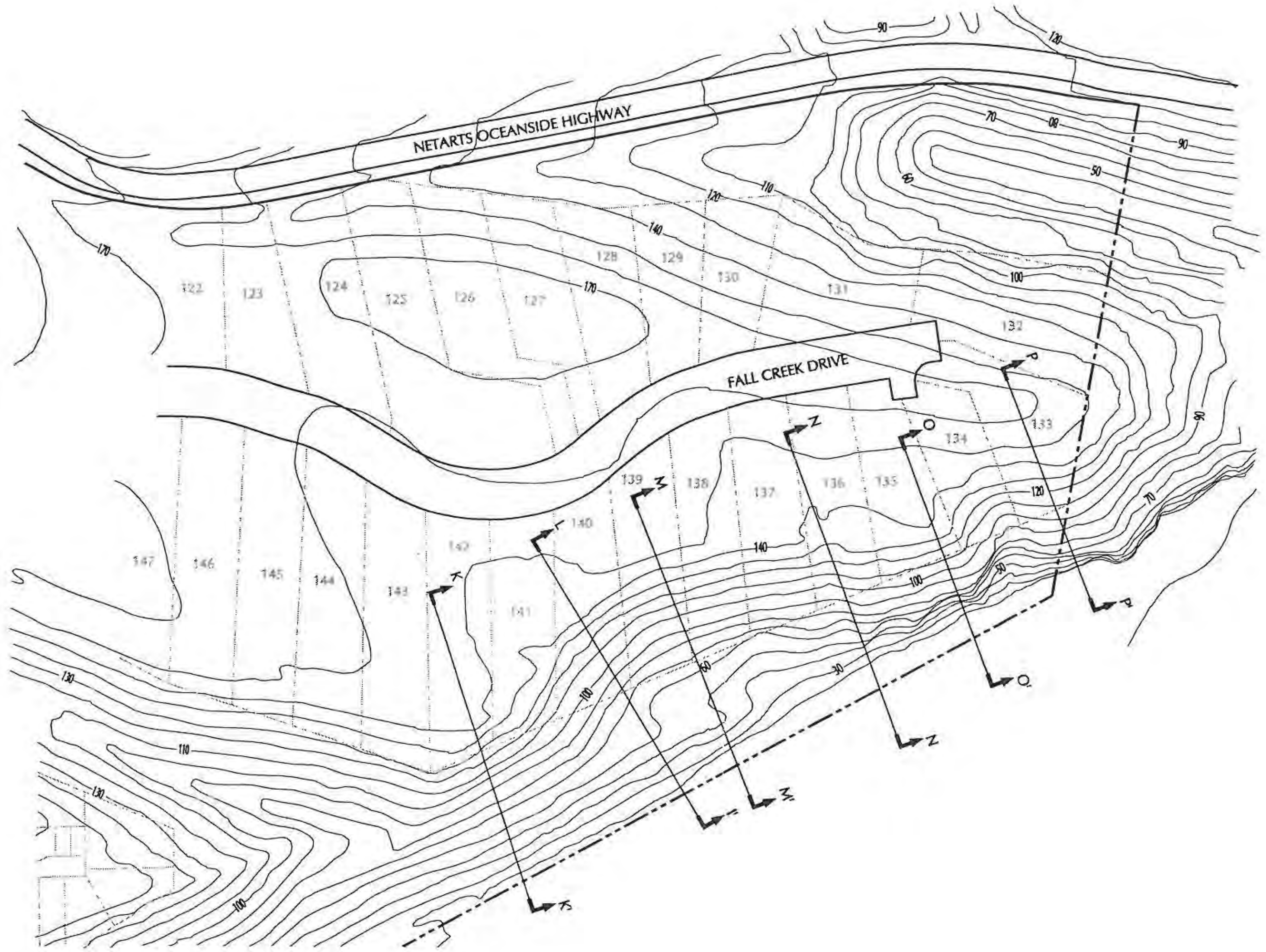
**Figure 3**

# Site Plan - 1999

**The Capes**

**Oceanside, Oregon**




**Legend:**

K K' Cross Section Location and Designation

123 Lot Number and Lines

0 200 400

Approximate Scale in Feet

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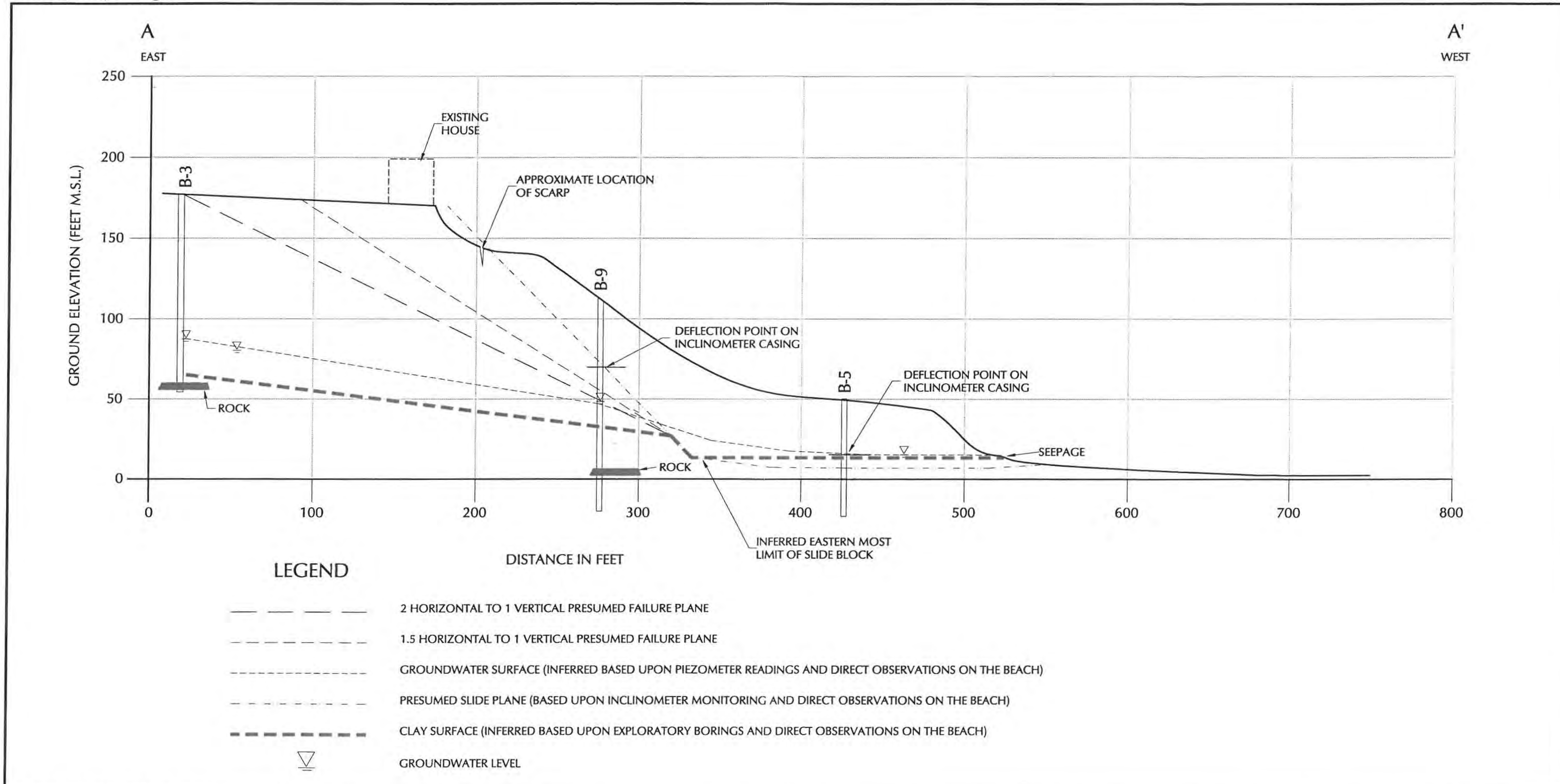
**Figure 3a**

# Cross Section A-A'

## The Capes
## Oceanside, Oregon




**Note**: Based on topography by Spencer and Gross, 1998.

0 60 120
Approximate Scale in Feet

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Figure 4

# Cross Section B-B'

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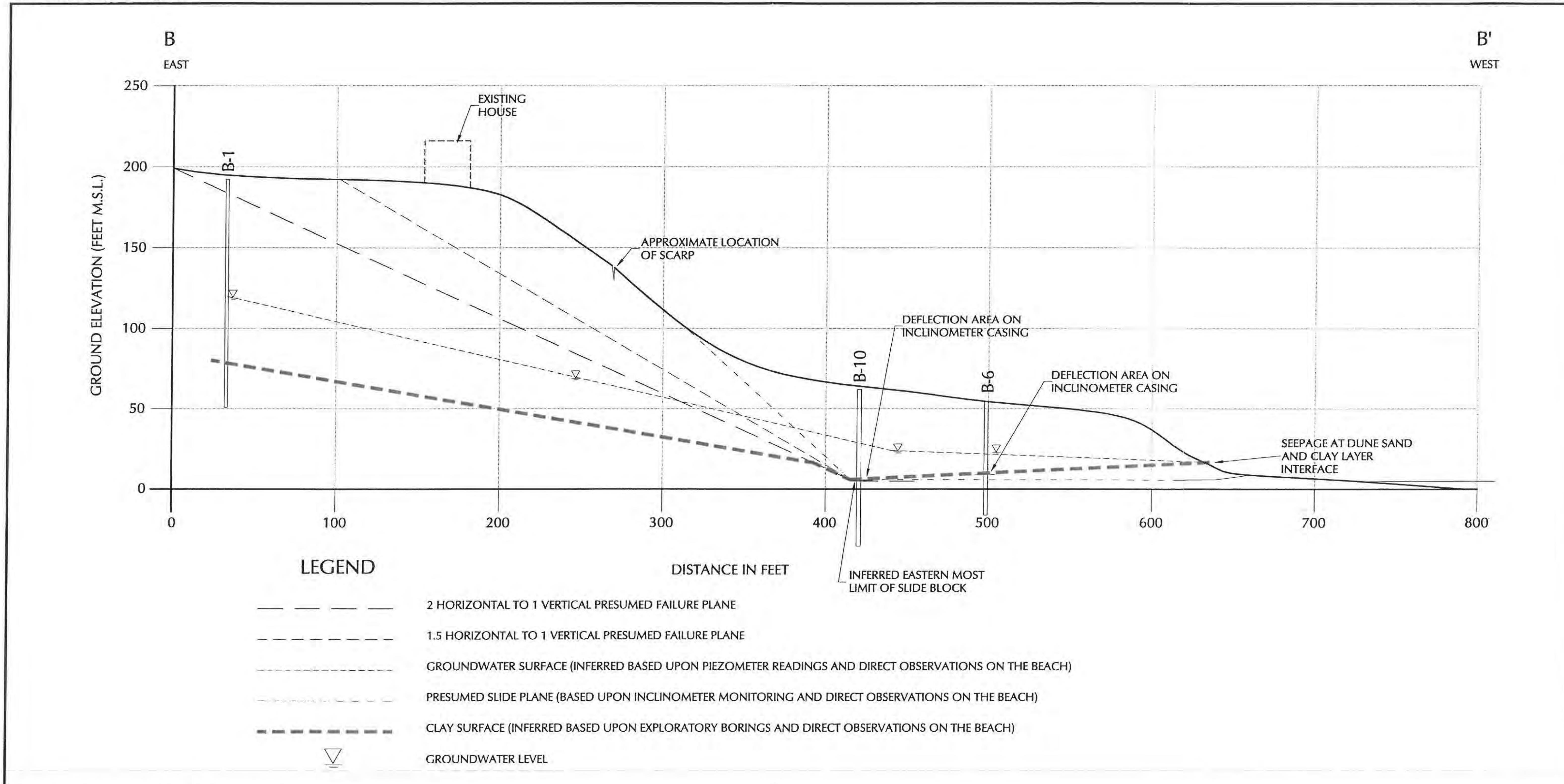
## Oceanside, Oregon




**Note**: Based on topography by Spencer and Gross, 1998.

0 60 120

Approximate Scale in Feet

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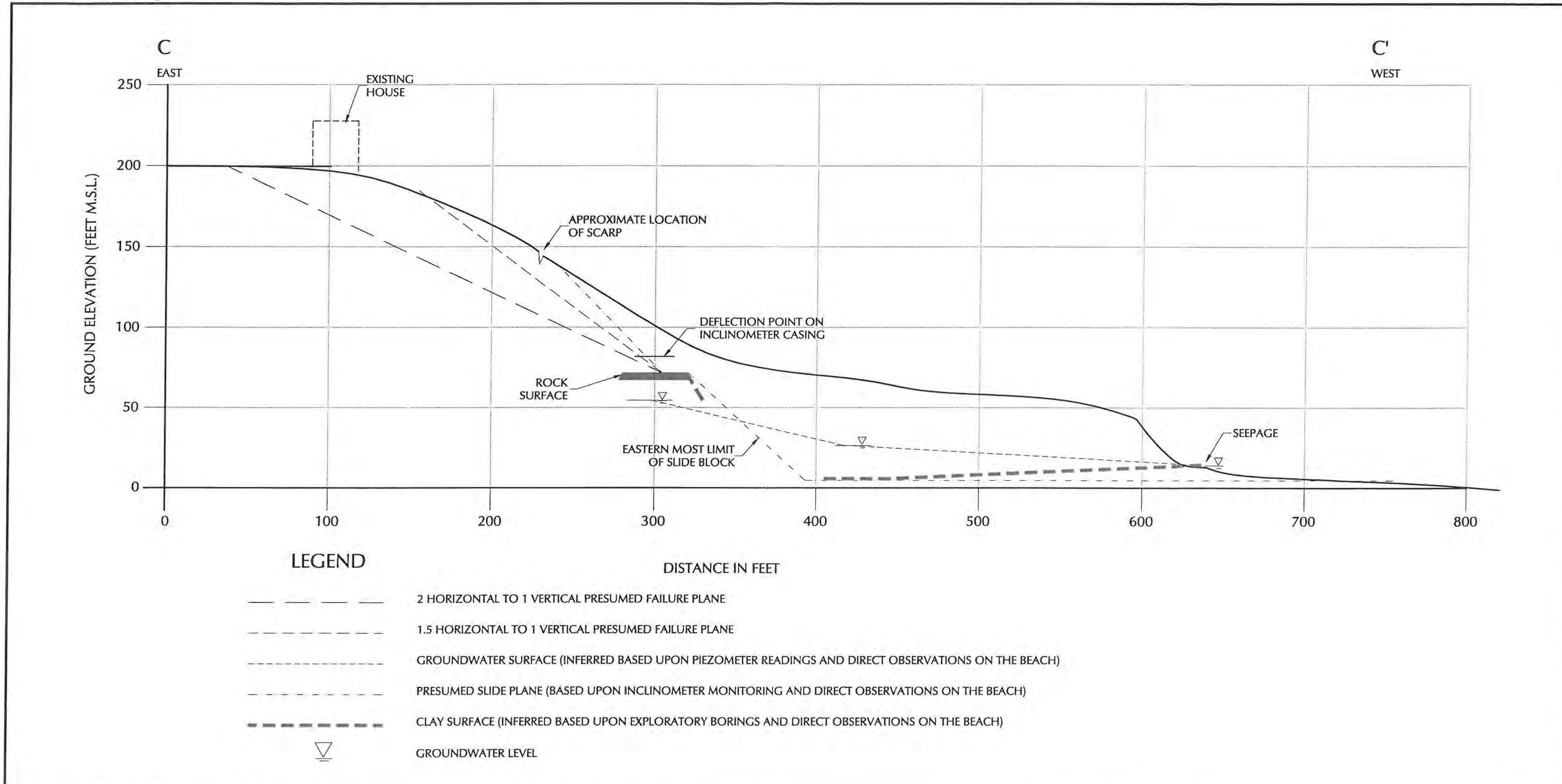
**Figure 5**

# Cross Section C-C'

## The Capes

## Oceanside, Oregon




**Note**: Based on topography by Spencer and Gross, 1998.

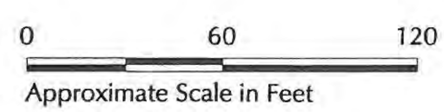



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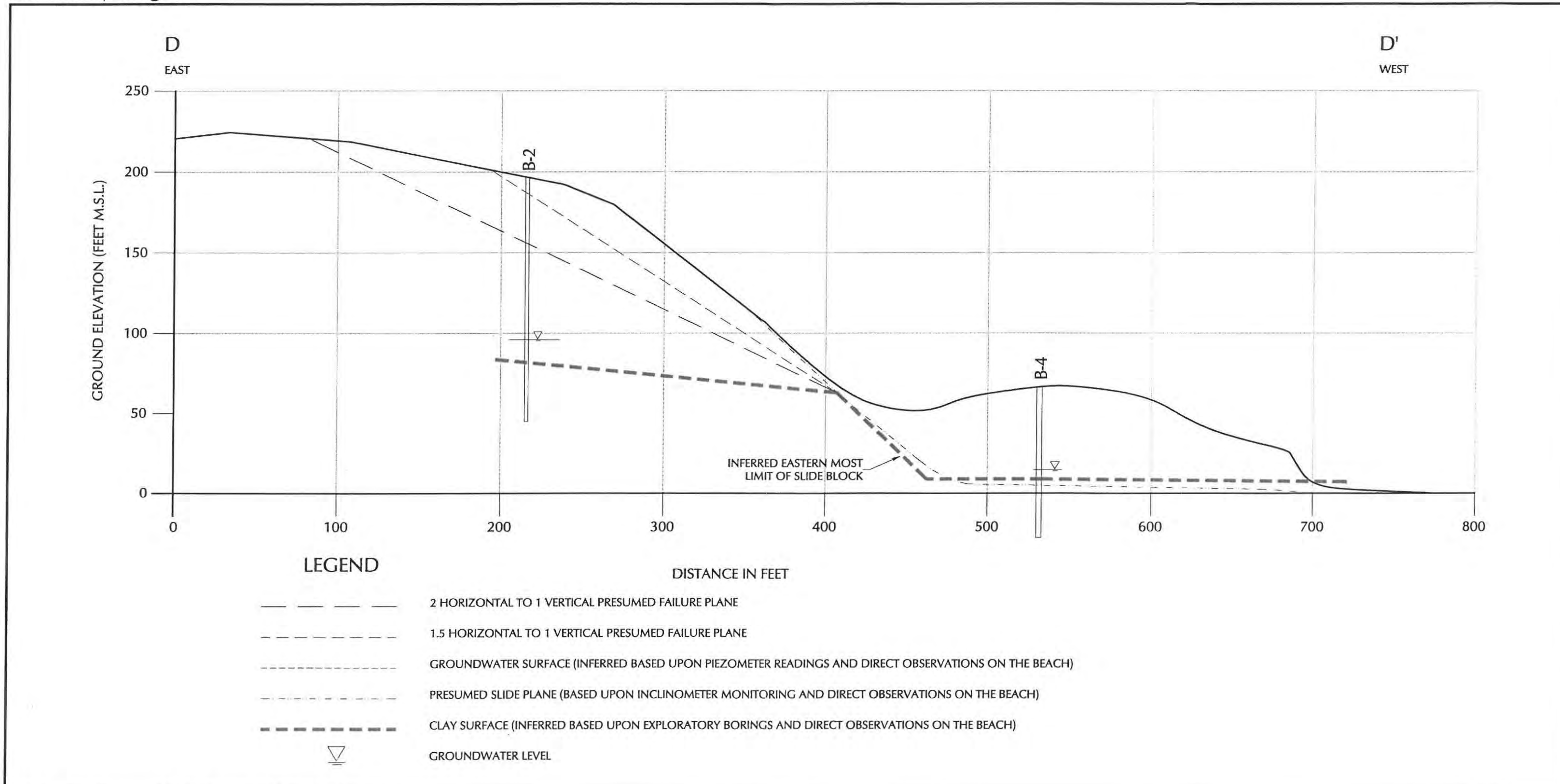
Figure 6

# Cross Section D-D'
**The Capes**
**Oceanside, Oregon**




**Note**: Based on topography by Spencer and Gross, 1998.

0 60 120
Approximate Scale in Feet

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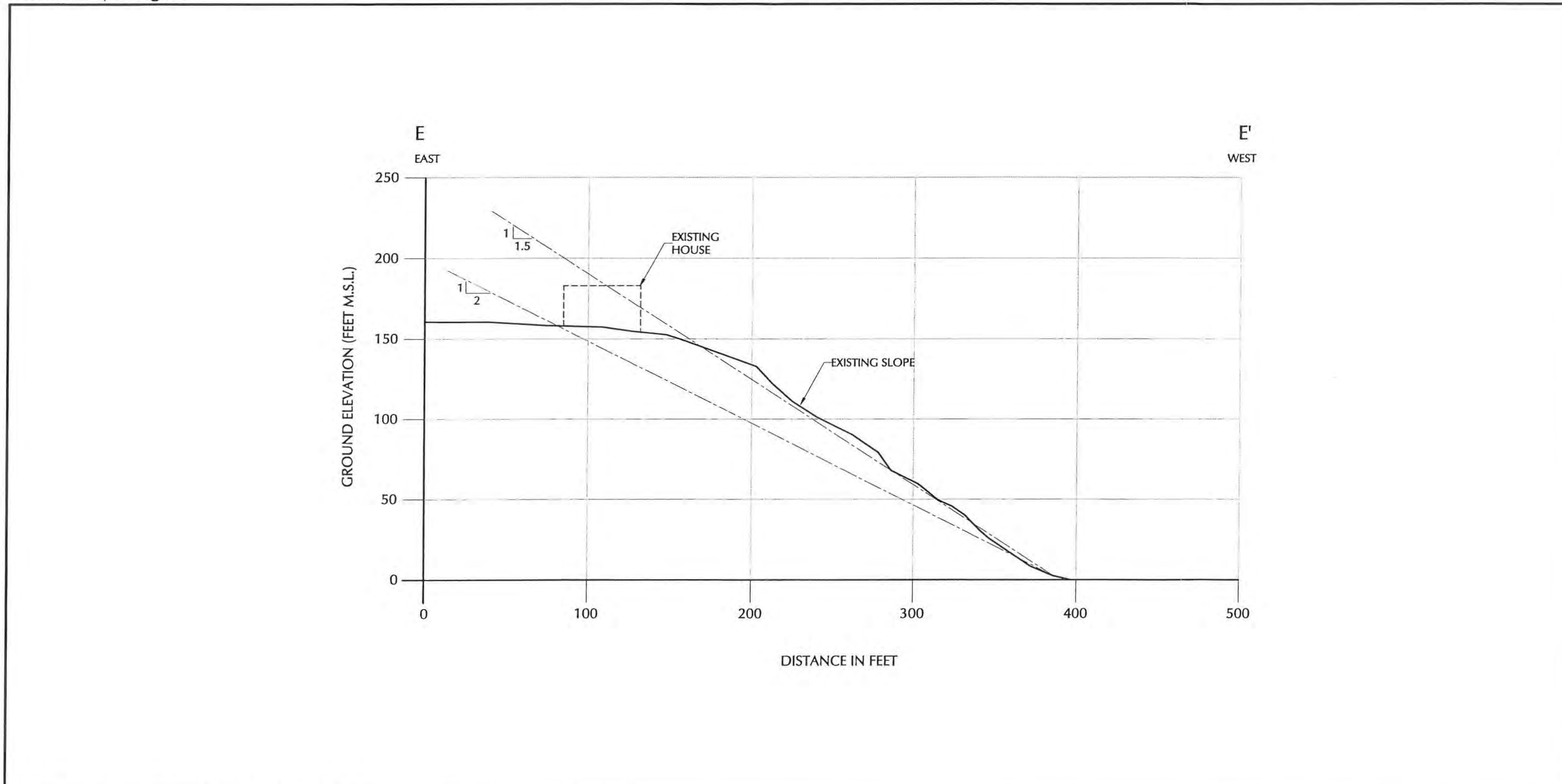
Figure 7

# Cross Section E-E'

## The Capes
## Oceanside, Oregon




**Note**: Based on topography by Spencer and Gross, 1998.

0 60 120

Approximate Scale in Feet

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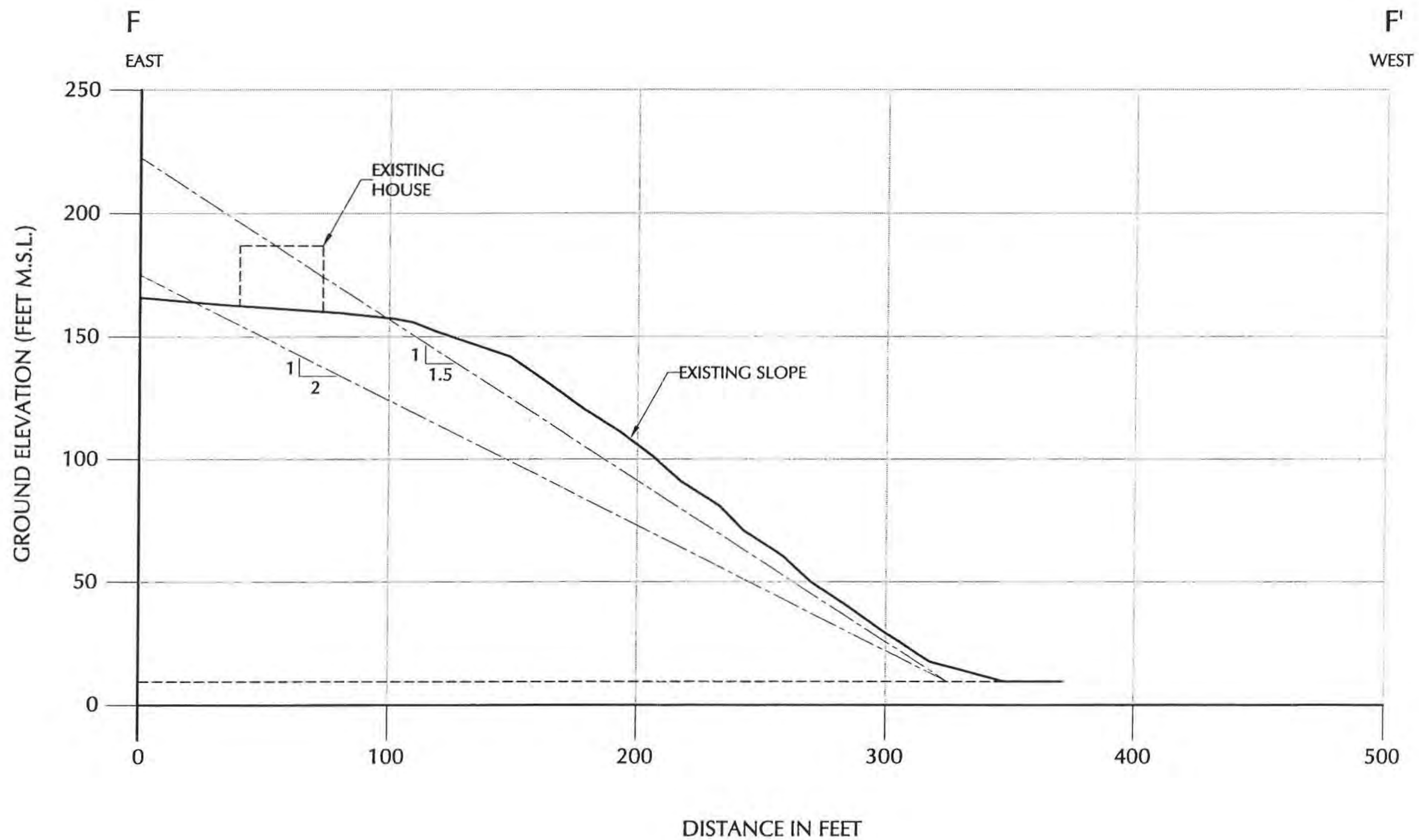
**Figure 8**

# Cross Section F-F'
## The Capes
## Oceanside, Oregon




**Note**: Based on topography by Spencer and Gross, 1998.

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0 60 120
Approximate Scale in Feet

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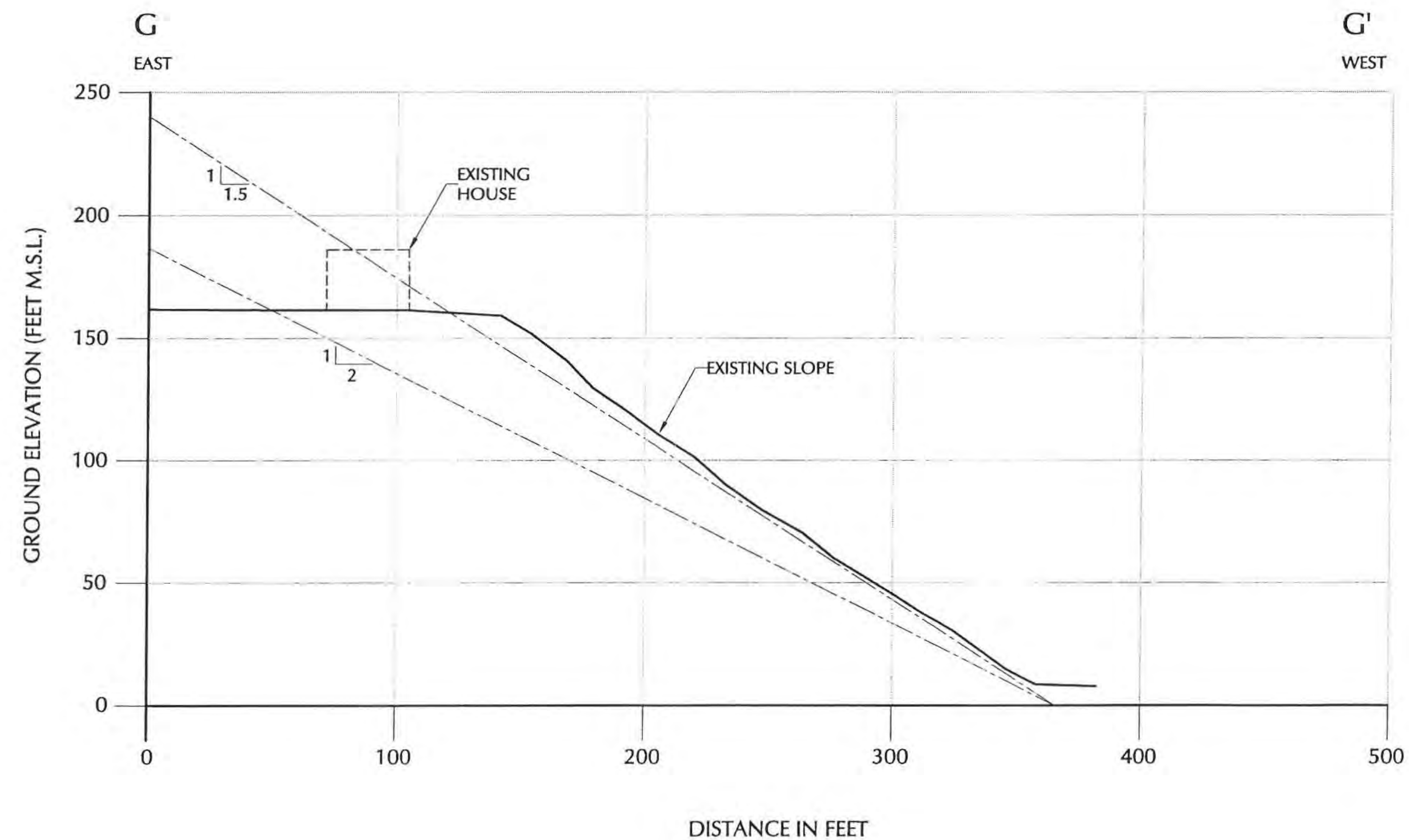
Figure 9

# Cross Section G-G'

**The Capes**

**Oceanside, Oregon**




**Note**: Based on topography by Spencer and Gross, 1998.

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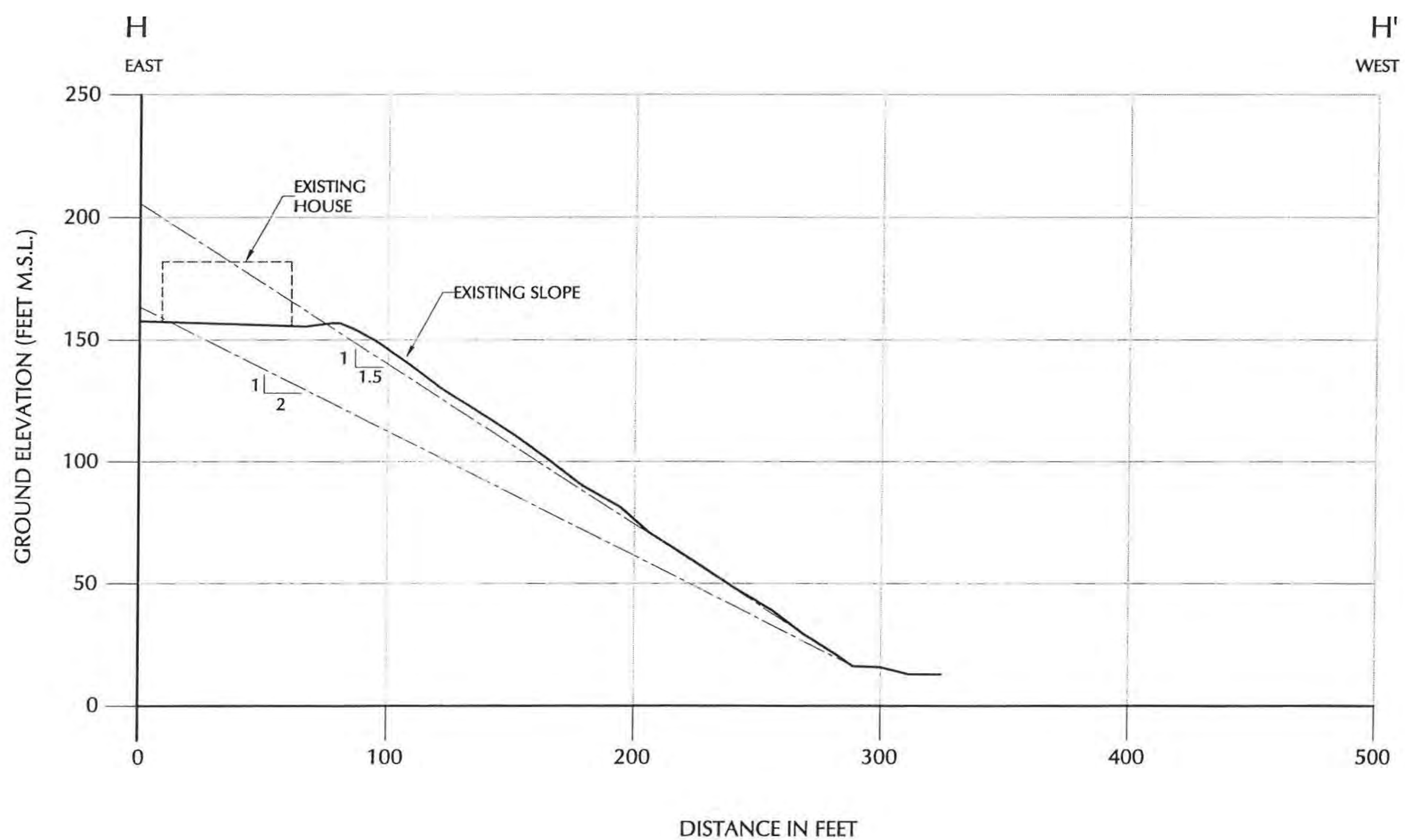
Figure 10

# Cross Section H-H'

**The Capes**

**Oceanside, Oregon**




**Note**: Based on topography by Spencer and Gross, 1998.

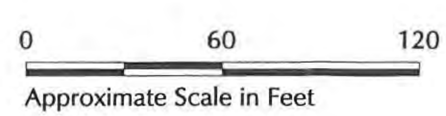



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Figure 11

# Cross Section I-I'
## The Capes
## Oceanside, Oregon

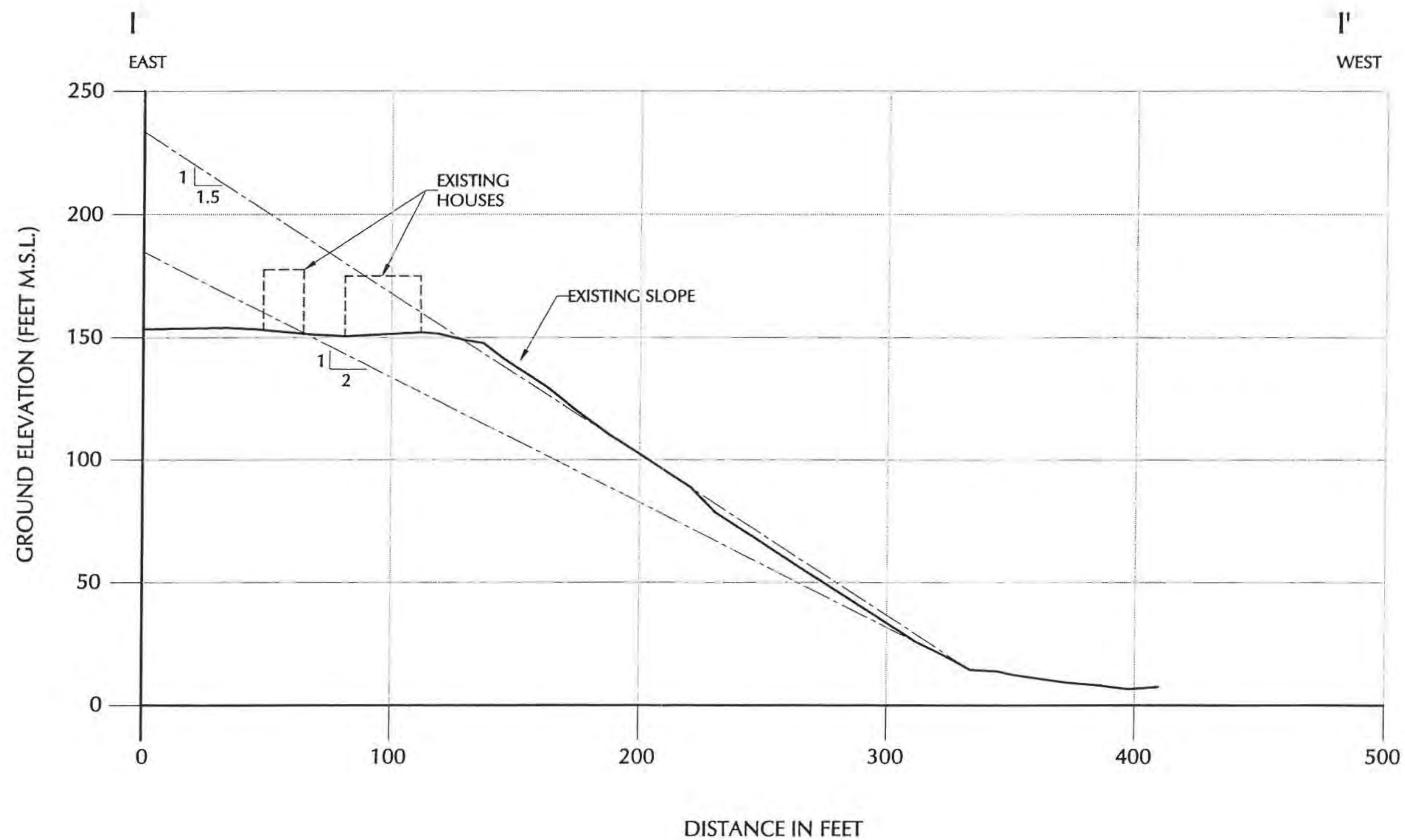


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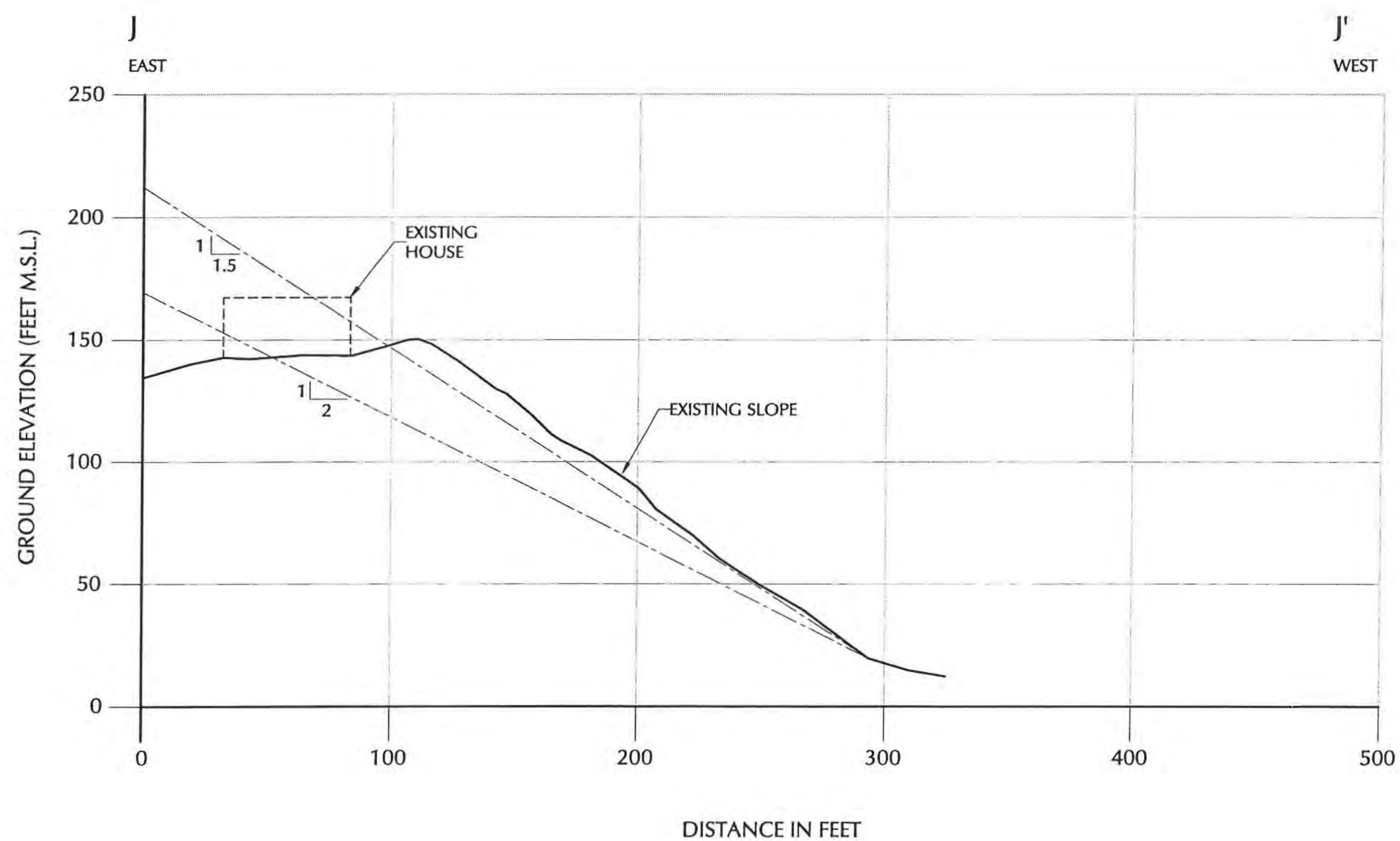
Figure 12

# Cross Section J-J'

**The Capes**

**Oceanside, Oregon**




**Note**: Based on topography by Spencer and Gross, 1998.

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Approximate Scale in Feet

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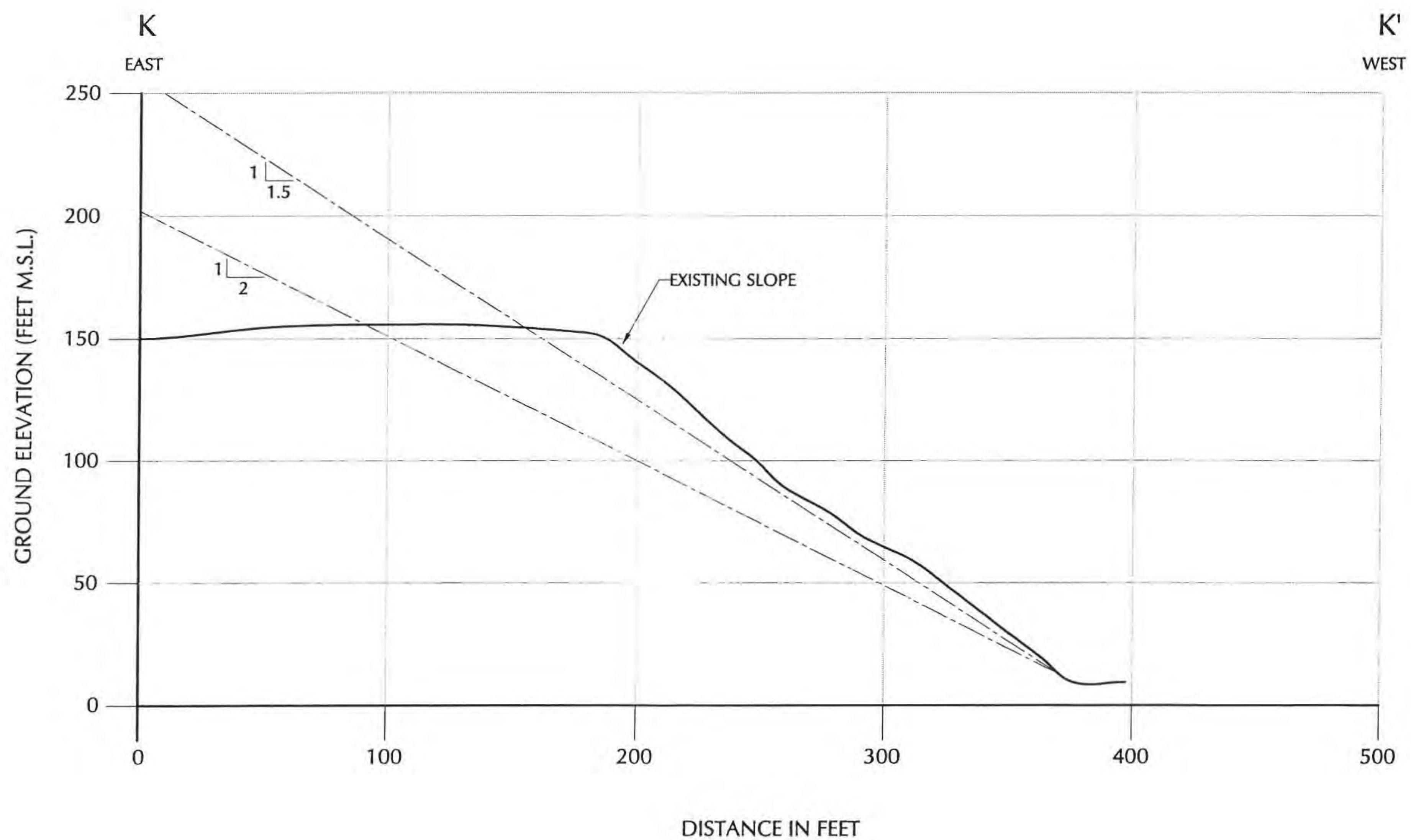
Figure 13

# Cross Section K-K'

## The Capes

## Oceanside, Oregon




**Note**: Based on topography by Spencer and Gross, 1998.

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Approximate Scale in Feet

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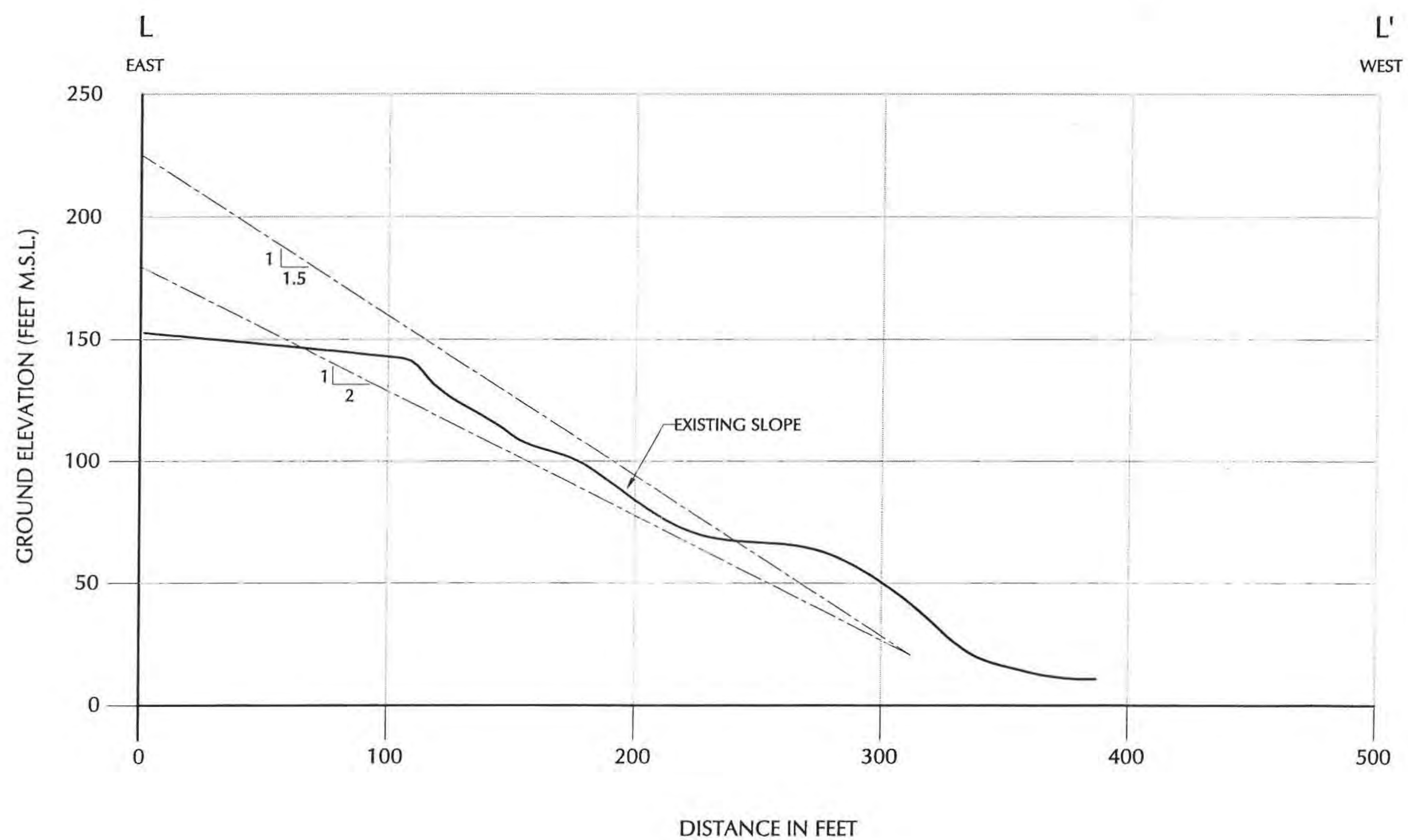
# Cross Section L-L'

## The Capes

## Oceanside, Oregon

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Approximate Scale in Feet

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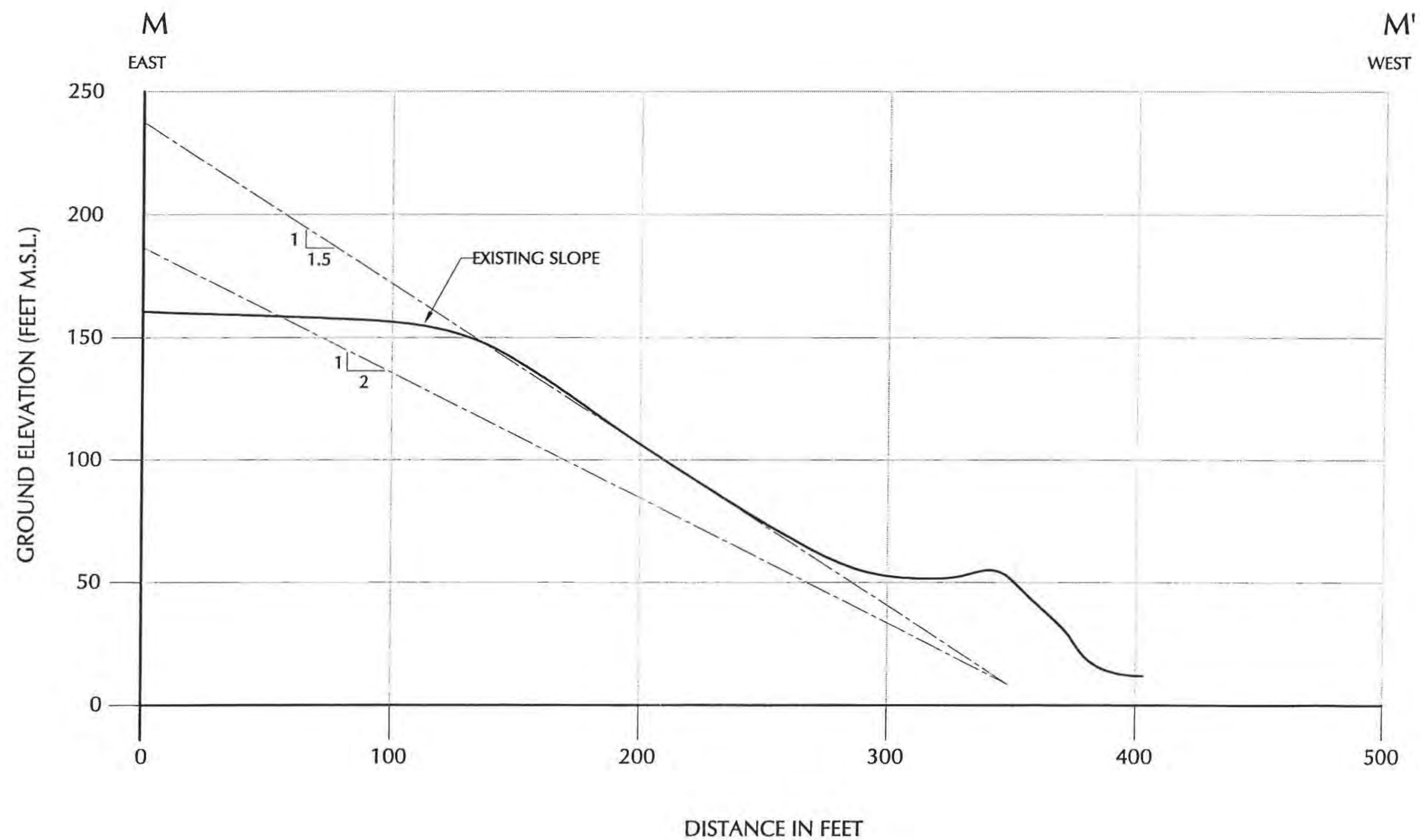
Figure 15

# Cross Section M-M'
## The Capes
## Oceanside, Oregon




**Note**: Based on topography by Spencer and Gross, 1998.

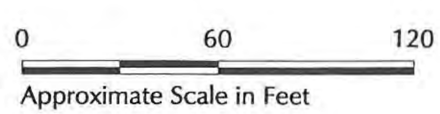



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Figure 16

# Cross Section N-N'

**The Capes**

**Oceanside, Oregon**

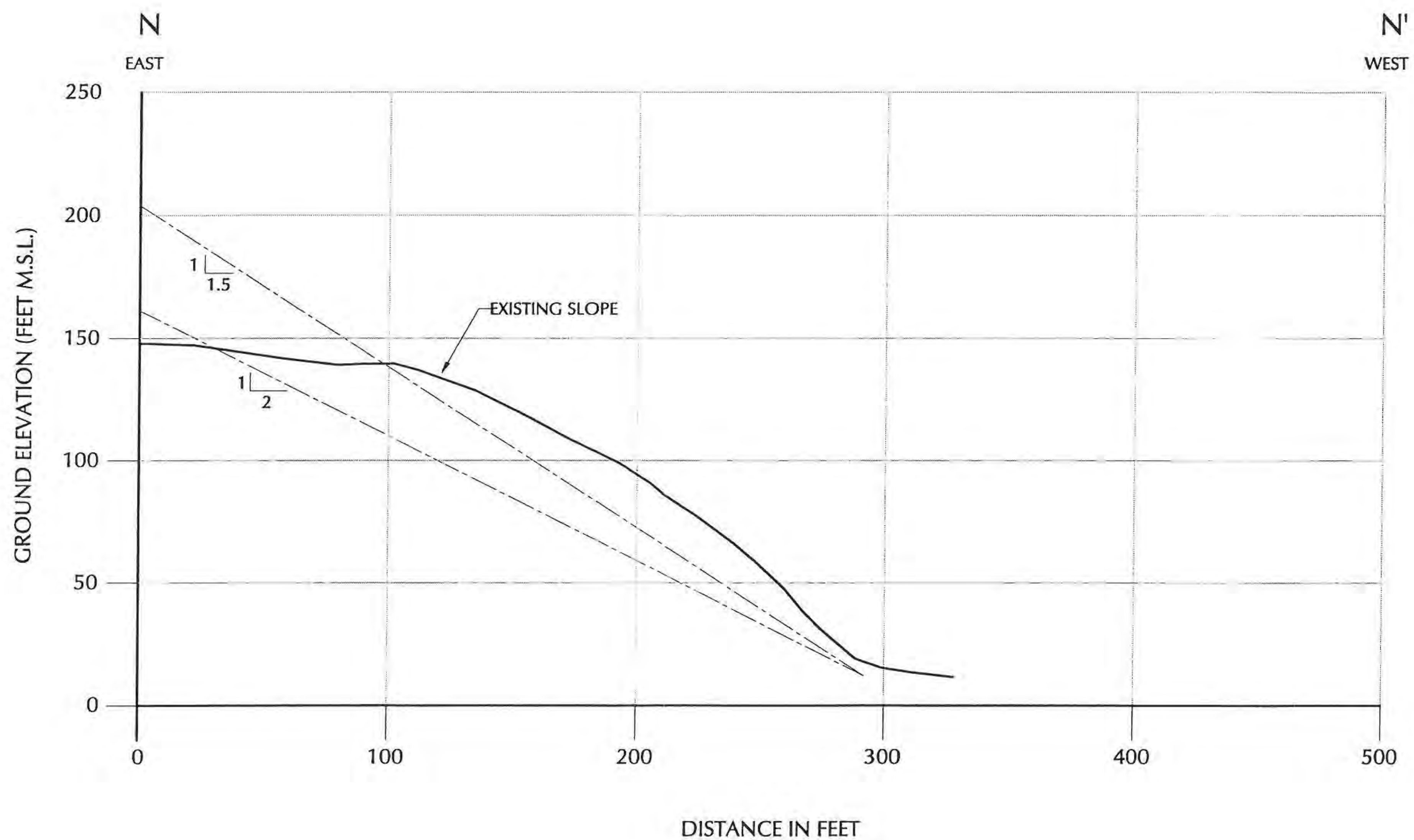


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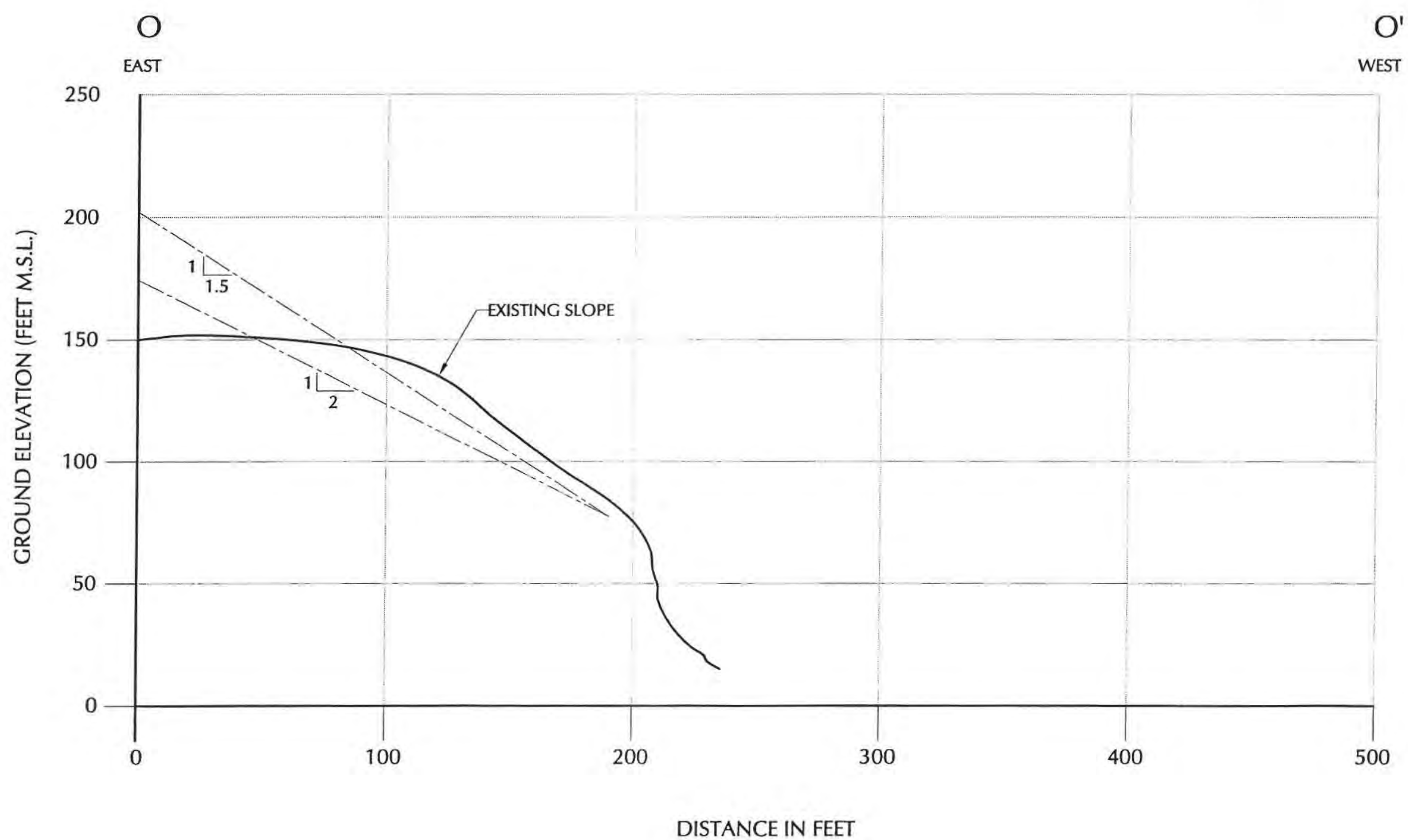
**Figure 17**

# Cross Section O-O'

## The Capes
## Oceanside, Oregon




**Note**: Based on topography by Spencer and Gross, 1998.

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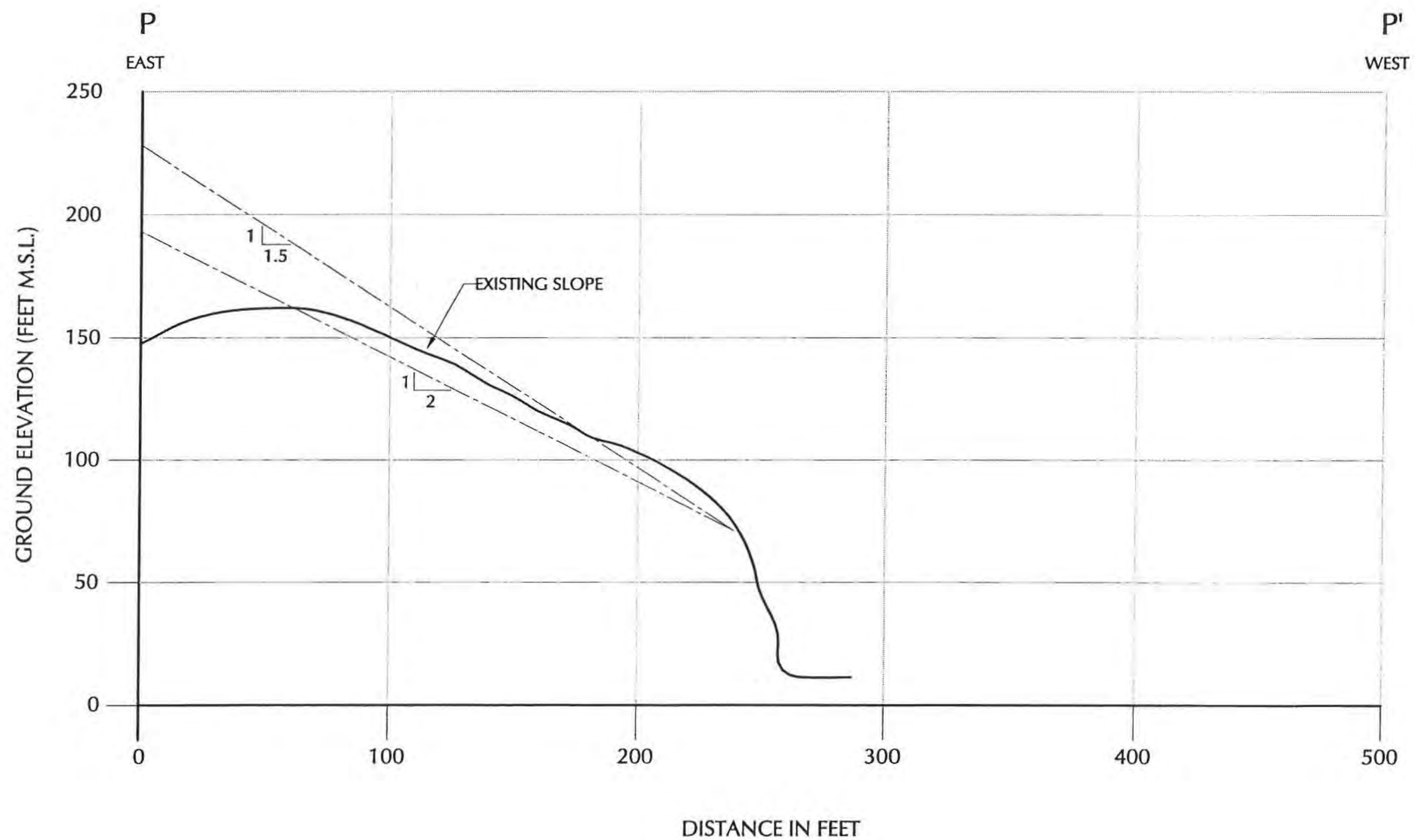
**Figure 18**

# Cross Section P-P'
## The Capes
## Oceanside, Oregon




**Note**: Based on topography by Spencer and Gross, 1998.

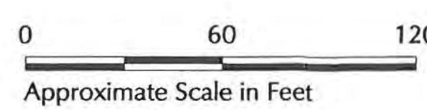



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**Figure 19**

Cross Section A-A′ History
The Capes
Oceanside, Oregon

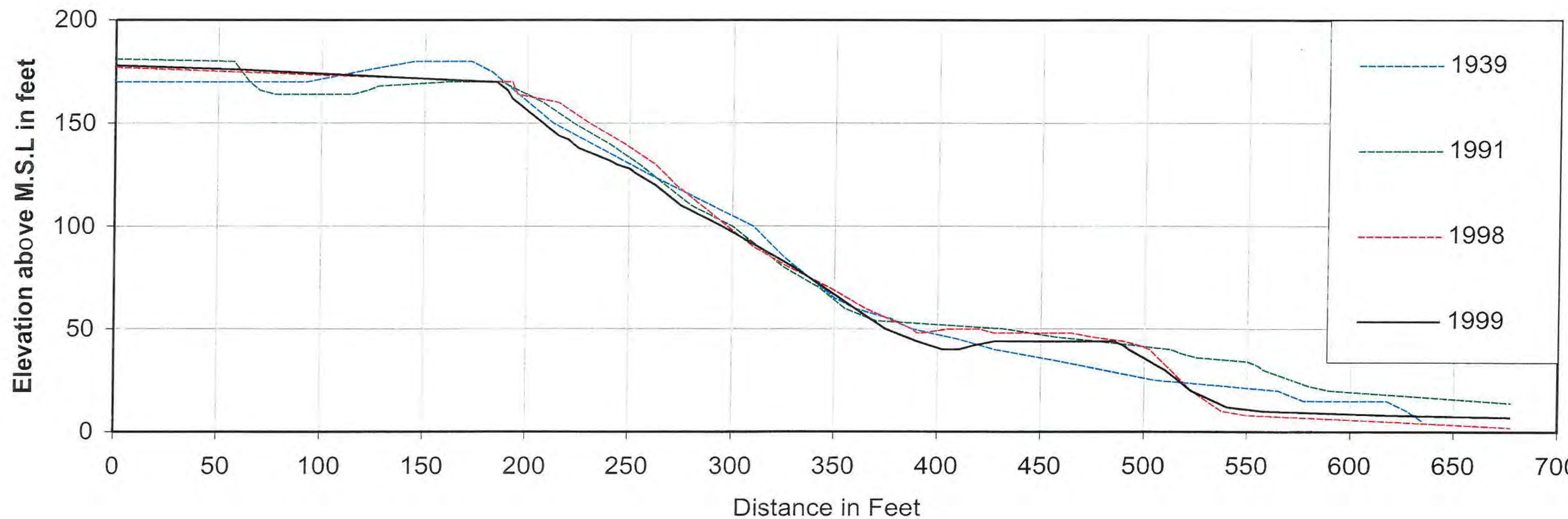


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Figure 20

# Cross Section D-D′ History
The Capes
Oceanside, Oregon

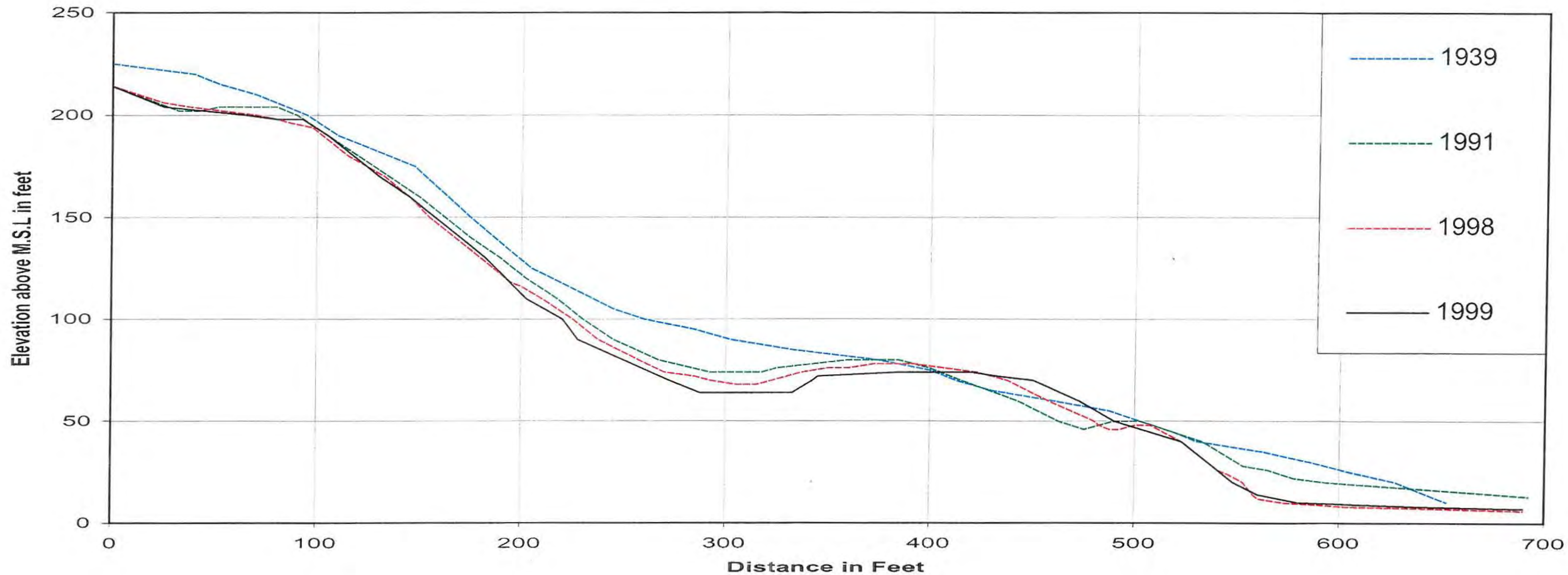


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Figure 21

# APPENDIX A
# FIVE EL NINO ARTICLES

# The 1982-83 El Niño and Erosion on the Coast of Oregon

BY PAUL D. KOMAR
*College of Oceanography*
*Oregon State University*
*Corvallis, Oregon*

## INTRODUCTION

EROSION along the west coast of the United States was unusually severe during the winter of 1982-83. Most news-media attention was focused on the loss of homes in southern California, on the houses at Malibu Beach owned by movie stars. During the same period there were unusual weather phenomona throughout the world; draughts in Australia, and floods in the United States and the Peruvian desert. These diverse natural occurences were attributed collectively to El Niño, a disturbance of the meteorological and oceanographic conditions in the Pacific Ocean [see the series of review articles in the Summer 1984 issue of *Oceanus* (v. 27, n. 2)].

Although not as major as the erosion experienced in California, beach erosion and property losses were also widespread on the coast of Oregon. The impact has not been confined to the 1982-83 period of maximum El Niño, however, as significant erosion is still continuing on Alsea Spit on the central-Oregon coast. The purpose of this paper is to report on the unusual processes and patterns of Oregon-coast erosion which resulted from the 1982-83 El Niño.

## EL NIÑO AND THE RISE IN SEA LEVEL

As recently as a decade ago, El Niño events were thought to be limited to the coastal waters of Peru where upwelling normally brings cold nutrient-rich water to the surface, supporting an abundant fishery. Every few years, however, this upwelling system breaks down and the cold water is replaced by warm water depleated in nutrients, leading to a whole-scale decline of the fishery. This breakdown most often occured during the Christmas season, and so was referred to by the Peruvians as El Niño (the child). Thought to be only a local oceanographic phenomenon, a decade ago there was little reason to associate El Niño with beach erosion on the west coast of North America.

It was thought that the onset of El Niño was caused by the cessation of the local coastal winds which produce upwelling off Peru. This view changed when Wyrtki[16] demonstrated that these local winds do not necessarily diminish during an El Niño. He showed that it is instead the breakdown of the equatorial trade-wind system in the central and western Pacific that triggers an El Niño, far away from the Peruvian coastal waters where its chief impact is felt. Wyrtki concluded that during normal periods of strong southeast trades, there is a sea-level setup in the western equatorial Pacific with an overall west to east downward slope of the sea surface along the equator. When the trade winds subsequently relax, the potential energy of this sloping water surface is released, and it is this release that produces the variety of observations associated with El Niño. Accumulated warm water in the western Pacific propagates eastward along the equator, "flooding" the Peru coastal waters when it reaches South America, destroying the fishery.

Associated with this warm water movement eastward along the equator is a wave-like bulge in the sea level. The Coriolis force both to the north and the south of the equator acts to confine the wave to the equatorial zone, preventing its dissipation by expansion to the north and south. The eastward progress of this sea-level wave can be monitored at tide gauges on equatorial islands.[17,18] These tide-gauge records typically reveal sea-level rises up to 50 cm, influencing the water level at a given island for up to six months. The crest of the sea-level wave takes about two months to pass across the width of the equatorial Pacific.

Upon arrival at the coast South America, the sea-level wave splits with one portion moving south along the coast of Peru and Chile while the other portion travels north to eventually raise sea level along the west coast of Mexico and the United States. The movement of the sea-level wave along the coast is trapped by the inclination of the continental shelf and slope, being held there by refraction over the slope and by the Coriolis force. Although some energy will be progressively lost as the wave moves away from the equator, the Coriolis force increases at higher latitudes causing the wave to hug the coast more tightly so that its height at the coastline is maintained or can even increase. The north and south progressions of these coastally-trapped sea-level waves resulting from El Niño have been documented by Enfield and Allen[3] who analyzed a 25-year time series (1950-1974) of monthly-averaged sea level anomalies measured on tide gauges from Yakutat, Alaska, to Valparaiso, Chile. Analyses of the series of gauges along Mexico and the U.S. demostrated that the northward-moving wave travels at a rate of about 75 km/day and so reaches California and Oregon within months following its inception at the equator.

Figure 1 shows the monthly-mean sea levels at Newport, Oregon, for the 1982-83 El Niño period, analyzed by Huyer et al[5]. Sea level reached a maximum in February 1983, nearly 60 cm higher than the level in May 1982, nine months earlier. The thin solid line in the figure is the ten-year means for the seasonal variations in sea level measured at Newport, and the dashed lines give the previous maxima and minima for that period. For the most part those curves reflect the normal seasonal cycle of sea level produced by parallel variations in the atmospheric pressure (the inverse barometer effect) and in the water temperature, the water levels being lower during the summer months of upwelling when the water is colder and hence denser.[1] Winds and currents also contribute to the normal seasonal cycle of sea level. It is readily apparent in Figure 1 that the 1982-83 sea levels were exceptional, reaching some 10 to 20 cm higher than previous maxima, about 35 cm above the normal winter level. This unusually high sea level can be attributed to the combined effects of a sea level "wave" as documented by Enfield and Allen[3] during previous El Niños, to the exceptionally low atmospheric pressures and perhaps to high winds associated with storms. Similar extreme sea levels occured along the coast of California during the 1982-83 El Niño, and have been analyzed by Flick and Cayan.[4]

These abnormally high sea levels along the west coast of the United States during the 1982-83 El Niño certainly have been a significant factor in the resulting beach erosion and property losses in both Oregon and California. The extent of its impact is unclear, however, since there were other El Niño related factors which also contributed to the erosion.

## OREGON WAVE CONDITIONS DURING EL NINÕ

Wave conditions on the Oregon coast during the 1982-83 El Niño period were also exceptional. For a number of years we have been measuring waves at Newport on a daily basis, employing a microseismometer which is calibrated to yield a significant wave height and period.[2,11,10] These measurements have been utilized in a number of past studies of Oregon coast erosion.[7,8,10]

Figure 2 shows the daily measured waves from August 1982 through April 1983. It is apparent that there were several storms which generated high-energy

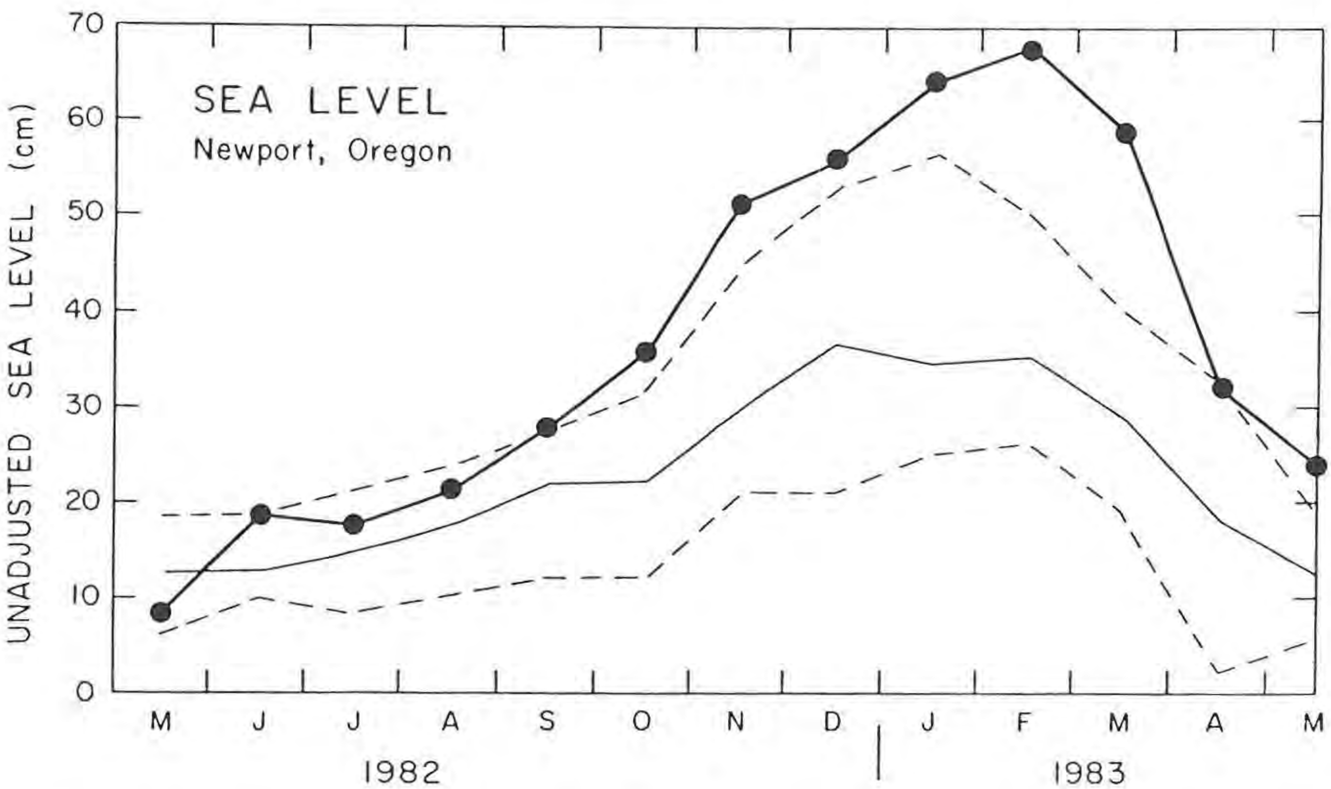


Fig. 1 Monthly average sea levels, the 1982/83 values (heavy curve) generally exceeding the mean and maximum ranges measured in previous years.[5]

waves, three achieving breaker heights on the order of 7 meters. Breakers of this magnitude are rare on the Oregon coast, there on average being one such occurence about every two years. Associated with such high-energy storm waves during previous years have been major episodes of beach erosion and property losses. It is therefore not surprising that extensive erosion occured during the winter of 1982-83 under three such storms. Note also that these storms struck the Oregon coast at the same time when sea level was approaching a maximum, Figure 1, these two factors acting together. The third important factor was high Spring tide levels. High tides during the December 1982 storm reached +11.0 ft (+3.4 m) MLLW, 58 cm higher than the predicted level. The tides during the January 1983 storm were even more impressive, reaching +12.4 ft (+3.8 m), 85 cm higher than predicted. This pattern continued during the February 1983 storm, high tides up to +10.3 ft (+3.1 m) being measured, 43 cm above the predicted level. All of these tide levels are usually high for the coast of Oregon, +9 ft (+2.7 m) being a representative Spring tide, so that tide levels during the strongest storms undoubtedly must have played an important role in the resulting erosion.

Also of considerable importance to Oregon, and to California, was that during this El Niño period the storm systems generating these waves were further south than during normal winters. Their passage through California directly accounts for the extensive erosion along the coast of that state.[13] The impact on the Oregon coast was both unusual and complex. The coast of Oregon consists of a series of beaches separated by major headlands or extensive stretches of rocky shoreline. The result is a segmented coastline with the stretches of beaches in essence forming pockets between the headlands even though the shoreline may be many kilometers in length. In the absence of significant sediment sources, each of these pocket beaches must have an essentially zero net littoral drift when averaged over a number of years. The existence of a near-zero net drift is also indicted by the response of the shoreline to jetty construction.[9]

Normally the summer waves approach from the northwest while the winter waves arrive from the southwest, so there is likely some seasonal reversal in sand transport directions superimposed on the otherwise zero net movement. The magnitudes of this reversing sand transport are likely small since during normal years there are no discernable seasonal patterns of shoreline erosion or advancement that can be attributed to such a reversal. The orientations of the shorelines must be such that in the long term the southward summer movement of sand cancels the northward movement during the winter months. With the exception of immediately adjacent to the Columbia River, there are no long-term trends in the shoreline changes on the Oregon coast which suggest the existence of a net littoral drift.

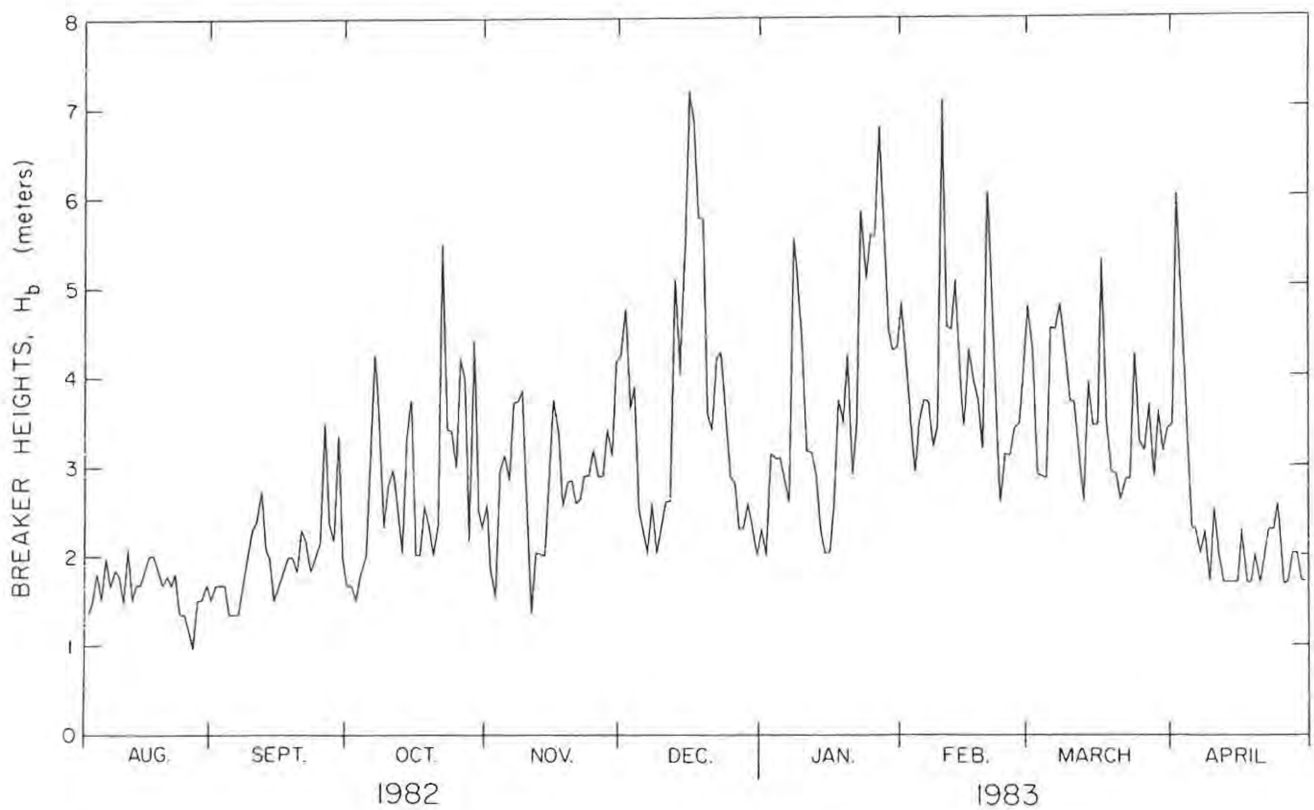


Fig. 2 Breaker heights (significant wave heights) measured at Newport, Oregon, during the 1982-83 El Niño period.

This equilibrium condition was upset during the 1982-83 El Niño year. Although we lack measurements of wave-approach angles, the southward displacement of the storm systems plus the higher energies of the waves themselves resulted in an unusually high northward drift of sand along the Oregon beaches. As diagrammed in Figure 3, the resulting effect is one of sand erosion at the south end of each beach segment with deposition at the north. This can be viewed as the reorientation of the pocket beach to face the waves arriving from the southwest, or as any one headland acting like a groin so that it blocks sand on its south and causes erosion to its immediate north. The actual response of many beaches was more complex than indicated by this generalized pattern. Due to the high storm waves, all beaches tended to erode into "storm" or "winter" profiles (Komar, p. 289).[6] However, superimposed on that shore-normal beach cycle was the longshore movement of sand. The general result was that erosion tended to be more severe along the southerly portions of each beach segment, that is, to the north of the headlands. In contrast, at the northern ends immediately south of the headlands the erosion was comparatively mild or even resulted in some shoreline buildout. Although we lack quantitative information as to the actual quantities involved in this longshore sand movement during 1982-83, general observations suggest that on some beaches it was considerable. I fortunately live in Otter Rock at the north end of the beach that extends from Yaquina Head north to Cape Foulweather (see Fig. 3, and also the cover photo of Shore & Beach, Oct. 1985). I observed that during 1982-83 when so much erosion was occuring elsewhere, considerable sand accumulated on our beach, more than at any time during my 15 years familiarity with the area. Beach sand covered a number of tide pools that clearly had been existent for many years. At the same time, sand dissappeared at the southern end of this beach immediately north of Yaquina Head. Contiuing this pattern, considerable quantities of sand accumulated to the south side of this headland at Agate Beach, Figure 3, forming an extensive tract of dunes as well as building out the shoreline.

Initially the considerable spatial variability of erosion suffered along the Oregon coast during 1982-83 offered an enigma, but this longshore shift of sand to the north does much to explain the observed patterns. The beaches still have not returned to their more normal conditions, and it may be a number of years before the sand accumulated at the north ends of the beach segments returns to the depleted southern ends. In the meantime the south portions will remain more susceptible to property losses during winter storms, the depleted beaches being unable to offer their normal buffering protection from ocean-wave attack. Fortunately, the subsequent two winters since 1982-83 El Niño have been unusually mild with respect to storm-wave intensity.

## ALSEA SPIT EROSION

One of the major areas of erosion during the 1982-83, and continuing up to the present, is that on Alsea Spit on the central-Oregon coast (Fig. 4). The erosion experienced there can also be attributed directly to the unusual El Niño conditions, particularly the northward longshore movement of sand.

The 1982 aerial photograph of Figure 4 shows Alsea Spit during its early stages of development, after the streets had been installed but before the construction of many houses. This photograph also illustrates the

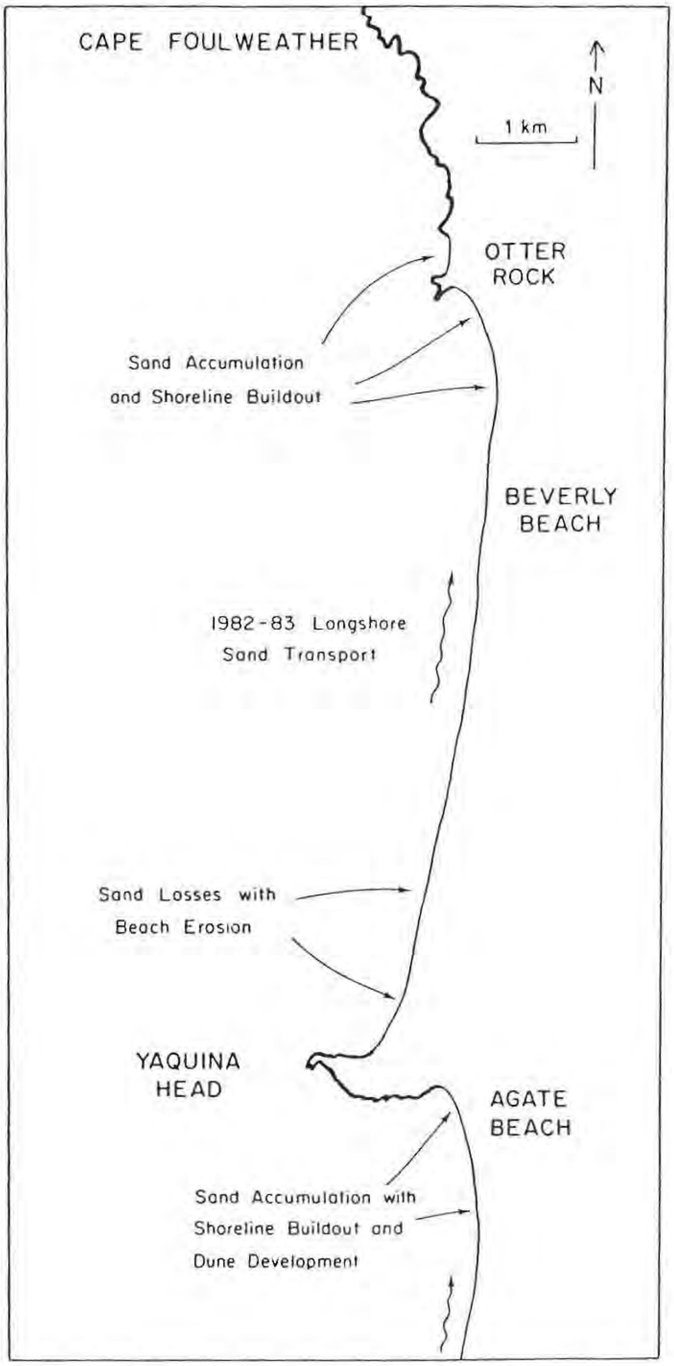


**Fig. 3 The patterns of beach erosion and sand accumulation along a typical pocket beach on the central Oregon coast.**

normal configuration of the spit and inlet, with a narrow mouth to the far south pushed against the mainland. There was little change in this morphology until its disruption by the 1982-83 El Niño.

During normal periods the channel continues directly seaward beyond the inlet mouth (Fig. 4), but in the 1982-83 El Niño year this channel was deflected well to the north. As seen in Figure 5, there was no migration of the inlet mouth itself, the channel deflection taking place in the shallow offshore. Also apparent in this photograph is the underwater bar covered with breaking waves extending from the south. It was the northward growth of this bar that diverted the channel from its normal course, the bar growth occurring as a result of the northward sand transport during El Niño.

The erosion experienced on Alsea Spit during the last three years can be directly attributed to this northward deflection of the channel. The earliest property losses on the spit were during the winter of 1982-83, and occured on its ocean side well to the north of the inlet (Fig. 6). The focus of this erosion was directly landward of where the channel turned seaward around the end of the northward-extending offshore bar. Erosion there appeared to be caused both by the over-

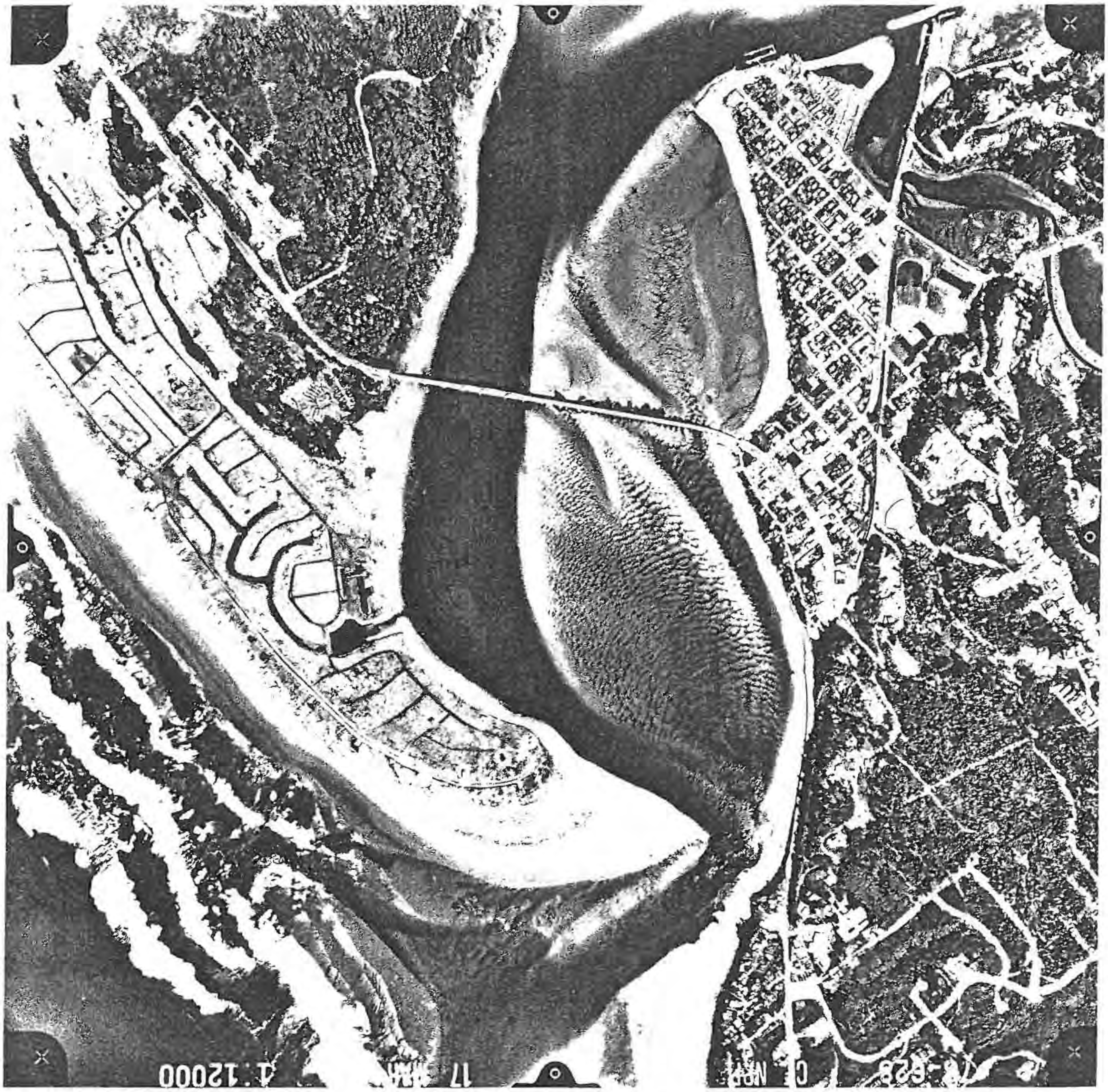

Fig. 4 A 1978 aerial photograph of Alsea Spit during its early stages of development, also showing the inlet with its normal morphology.

steepened beach profile leading into the deep channel and by direct wave attack, the waves not being broken by an offshore bar and so retaining their full energy until breaking directly against the coastal property. Most of the lots in the eroding section were still empty, and so only four homes were in danger of being lost. Placement of riprap initially offered protection, but the adjacent empty lots were left defenseless and so the riprap fronting the homes was flanked, eroding along the sides of the homes and leaving them on promentories extending out onto the beach (Fig.6). Three of the four threatened homes were eventually saved, but the house in Figure 6 was burned down before succumbing to erosion.

The erosion depicted in Figure 6 was initiated during the El Niño winter of 1982-83 with the northward deflection of the offshore channel, but has continued up to the present with additional losses of property. In subsequent years the seaward channel opening has slowly migrated southward towards its more-normal position. The photograph of Figure 5 was obtained during July 1985, by which time significant migration had already occured from the most-northerly position of the opening during the winter of 1982-83. With this slow southward movement of the opening, the focus of maximum erosion on the spit similarly shifted southward. Then in September 1985 there was an abrupt increase in the rate of erosion as the focus was now on the unvegetated, low-lying tip of the spit seen in Figures 4 and 5. Within a month, this tongue-extension of Alsea Spit completely eroded away leaving a broad inlet opening. At the same time the deep water of the offshore channel shifted landward, directly eroding the vegetated and developed portion of the spit where it curves inward toward the inlet. Seven houses are threatened by this erosion, particularly one home adjacent to an empty lot that was initially left unprotected (Fig. 7). This renewed erosion is continuing so that the ultimate fate of these homes is uncertain. The September erosion occured during a period of modest waves and tide levels, and there is the potential for increased spit erosion during upcoming higher tides and winter storms. Another concern is the increased potential for flooding of the low-lying areas of the town of Waldport on the south bank of the estuary (Fig.4). Waldport has experienced frequent flooding in the past, and the increased opening of the inlet due to spit erosion raises the probability for a significant storm surge that would give rise to unusually high flood levels.

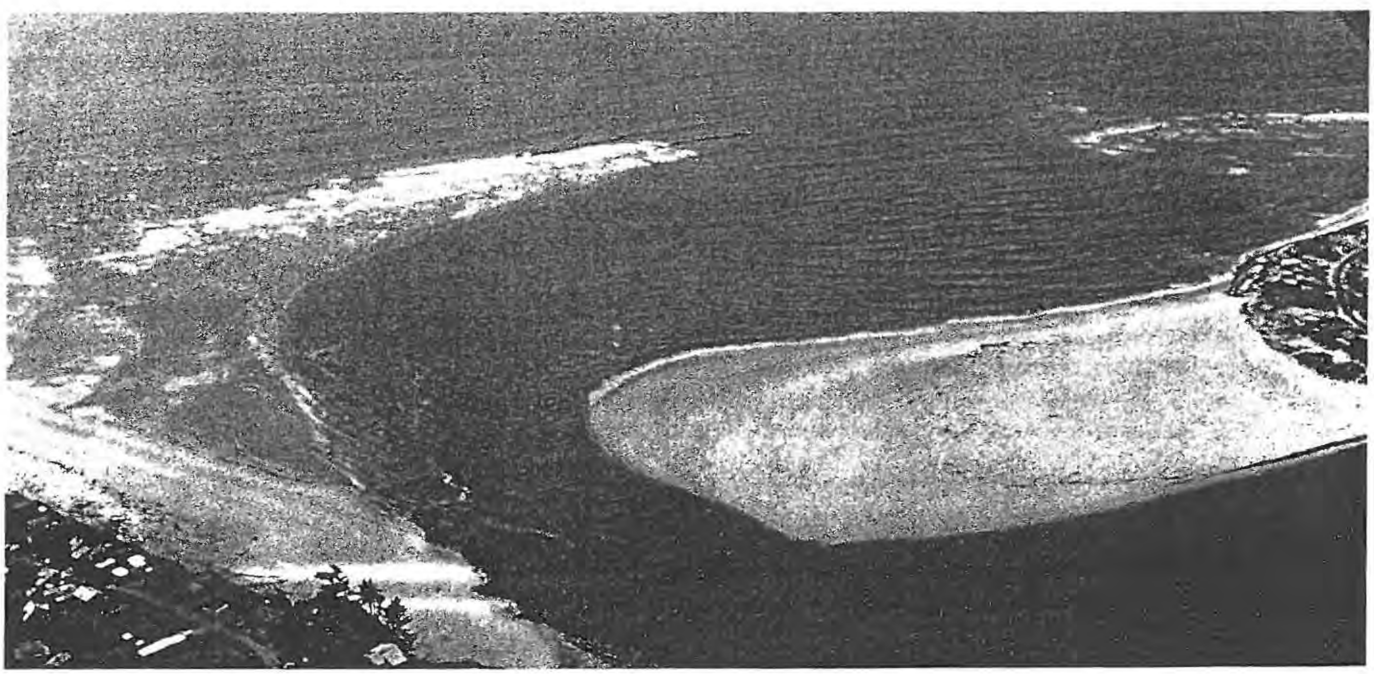

**Fig. 5. The deflection ofthe channel leading into Alsea Bay by the northward growth of the longshore bar in response to El Niño related storms to the south. (July 1985 photo by C. Peterson.)**

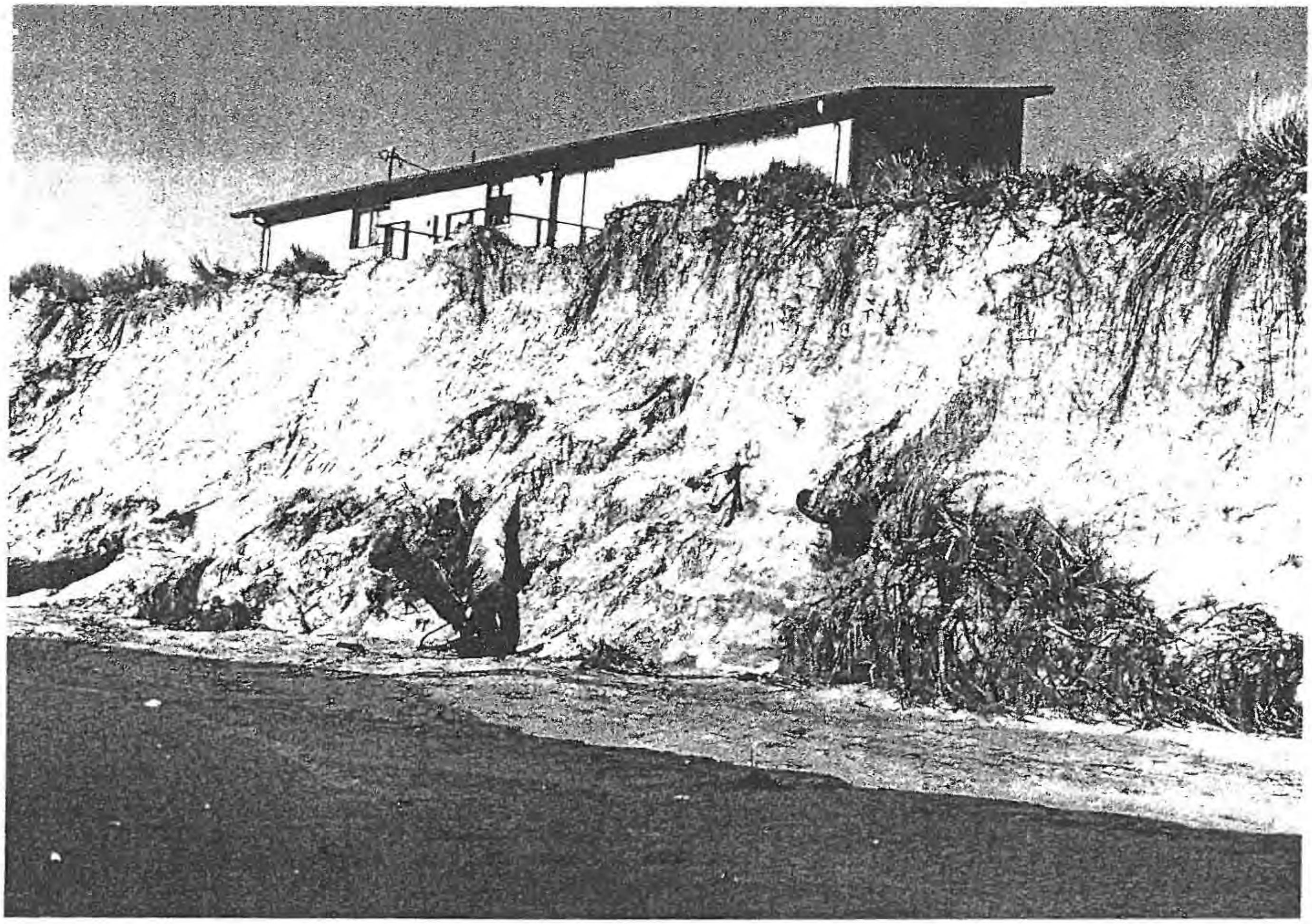

Fig. 6 The area of maximum erosion on Alsea Spit during the 1982-83 El Niño period, continuing into the winter of 1983-84. The upper photo was obtained during the early stages of erosion just prior to riprap placement, the lower photo showing the same house later threatened on its side due to the lack of protection of the adjacent lot.

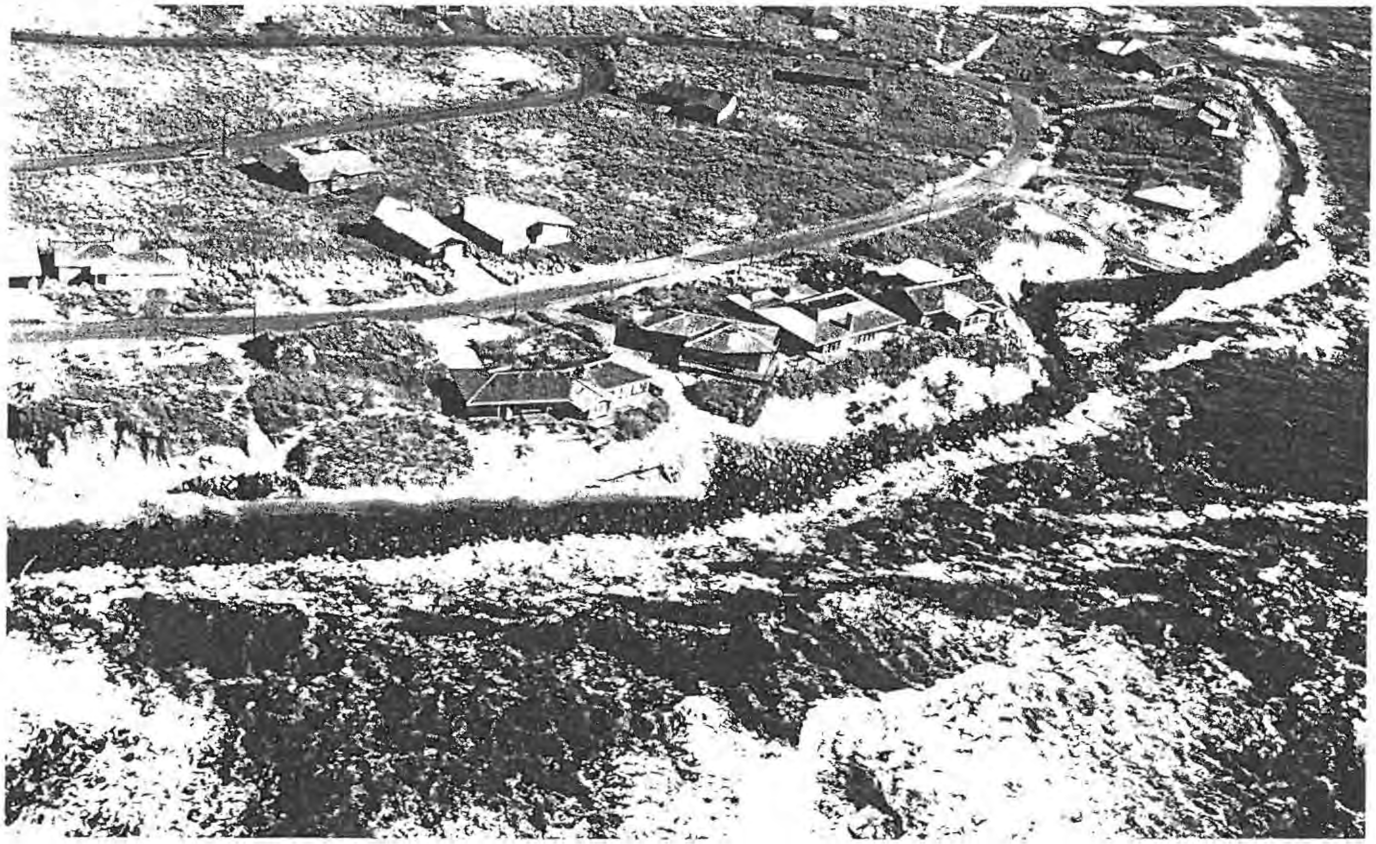

Fig. 7. Erosion on Alsea Spit that has been most active since about August 1985 and continues to threaten a number of homes.

## EL NINŌ AND PREVIOUS EPISODES OF EROSION

The importance of El Niño to the 1982-83 Oregon-coast erosion raises the question of whether previous El Niño events played a similar role. Although not truely periodic, El Niños occur some 20 to 25 times per century. Quinn et al.[12] have investigated the historic occurences and classified them according to their intensity. Table 1 lists the El Niño events since 1900 assessed as "moderate" or "strong."

In recent years much of the Oregon-coast erosion has centered on Siletz Spit.[8, 10] The two major erosion periods there were the winters of 1972-73 and 1976, corresponding to El Niño years (Table 1). On the other hand, serious erosion took place during 1978 leading to the breaching of Nestucca Spit,[7] an episode that did not occur during an El Niño. Unfortunately, little is known about Oregon coast erosion prior to 1970, at which time Sea Grant began to sponsor studies of its cause. Aerial photographs are available back to 1939 which indicate earlier erosion events, but their exact timing is uncertain. Stembridge[14] (Table 8) compiled newspaper accounts of the early occurences of erosion, but these show no correspondence with the El Niño years listed in Table 1. These newspaper accounts typically report on erosion of rather local extent, altough a few events represented coastwide problems. Most of that reported erosion was to sea cliffs of marine terraces where the major coastal communities are found. The Oregon sandpits would have been the most sensitive indicators of erosional responses to past El Niños, but unfortunately their histories prior to 1970 are poorly documented. For the most part the sandpits were not developed until the late 1960's and 1970's, so any earlier erosion there went unnoticed. The one exception was Bayocean Spit which was developed early in the century,[15] but its erosion was in response to jetty construction and little of the community on the spit survived past the 1930's.

**TABLE 1.**
**Occurrences of El Niños (Quinn et al., 1987)[12]**

| | | | |
|---|---|---|---|
| 1982-83 | strong | 1929-30 | medium |
| 1976 | medium | 1925-26 | strong |
| 1972-73 | strong | 1918-19 | strong |
| 1965 | medium | 1914 | medium |
| 1957-58 | strong | 1911-12 | strong |
| 1953 | medium | 1905 | medium |
| 1941 | strong | 1902 | medium |
| 1939 | medium | 1899-1900 | strong |

Although the positive correlation between El Niño and erosion on Siletz Spit during 1972-73 and 1976 suggests a cause and effect, those earlier erosion events differed in their processes from that which occured during 1982-83. Very important to both the 1972-73 and 1976 erosion was the development of strong rip currents which cut into the beach, hollowing out embayments which reached back to the foredunes upon which homes were built. These became the focal points of property losses during storms. Such embayments did not develop during the 1982-83 El Niño year, and Siletz Spit suffered no property erosion. In all likelihood the northward longshore movement of sand on the beach prevented rip currents from developing stable postions which permits them to cut deep embayments into the beach. Although such rip-current embayments were very important to earlier episodes of erosion on Siletz Spit, the actual times of erosion were governed by high storm-wave energies with breaker heights in excess of 7 meters. It is possible that these unusual stroms were related to the 1972-73 and 1976 El Niños, just as were the storms of 1982-83. This is indicated by the study of Seymour et al.[13] who found in a time series from 1900 to 1984 a strong statistical correlation between large wave events in southern California and El Niño periods. However, the 1972-73 and 1976 storms passed through Oregon, not being displaced to the south as during 1982-83. For that reason, there was no strong northward sand transport during the earlier El Niño events, and the coastal response differed markedly from that during 1982- 83 when such sand movements played an important role in producing erosion.

## SUMMARY

The 1982-83 El Niño produced considerable erosion along the coast of Oregon as well as in southern California. The main contributing factors were exceptionally high sea levels, storms which generated unusually-intense wave conditions, and the northward transport of sand along Oregon beaches. This northward movement of sand was caused by the southward displacement of the storm paths during the El Niño, and is unusual for the Oregon beaches where near-zero net littoral sand transports normally prevail. This northward sand movement was particularly important in governing the locations of beach erosion, being greatest to the north sides of headlands while sand accumulated to their south sides (the headlands acting much like groins). Particularly severe erosion has occured on Alsea Spit where the northward sand transport deflected the inlet, erosion that still continues in direct consequence of the 1982-83 El Niño even though three years have passed.

It is unclear as to the extent of the role played by previous El Niños in Oregon-coast erosion. The 1972-73 and 1976 erosion episodes on Siletz Spit occured during El Niños, and the high storm-wave energies important to that erosion were likely associated with the El Niños. On the other hand, there was no accompanying northward sand transport, rip-current embayments instead playing a major role in focusing the erosion. From this it appears that El Niños can be a factor in causing Oregon coast erosion, principally by the higher wave energies and perhaps increased sea levels that accompany this phenomenon. But it is also clear that the 1982-83 El Niño was a highly exceptional event, and the erosion response to more typical El Niños will not be nearly so great as experienced during this past occurence.


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# El Niño Occurrences Over the Past Four and a Half Centuries

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Applicable publications, involving five languages, have been reviewed to obtain information on El Niños that occurred over the past four and a half centuries. Since this information refers strictly to El Niño occurrences, a regional manifestation of the large-scale (El Niño–Southern Oscillation (ENSO)) event, it is based primarily on evidence obtained from the west coast region of northern South America and its adjacent Pacific Ocean waters. Authored lists of events were not acceptable without referenced valid information sources. It was desirable to have cross-correlated reports from independent sources. Relative strengths of events are based on such considerations as wind and current effects on travel times of ancient sailing ships, degree of physical damage and destruction, amounts of rainfall and flooding, mass mortality of endemic marine organisms and guano birds, extent of invasion by tropical nekton, rises in sea temperatures and sea levels, affects on coastal fisheries and fish meal production, etc. Emphasis is placed on strong and very strong events. For example, the 1940–1941, 1957–1958, and 1972–1973 events fall into the strong category, whereas the 1891, 1925–1926 and 1982–1983 events are considered very strong. Over our period of study, 47 El Niño events were placed in the strong or very strong categories. Over the period 1800–present, we noted 32 El Niño events of moderate or near moderate intensity. Weak events are not included here. The approach used here caused us to revise many of our earlier evaluations concerning event occurrences and intensities. Our tropical Pacific thickness analyses and cumulative plots of Southern Oscillation index anomalies over the southeast Pacific trade wind zone showed additional evidence as to the unusual strength of the 1982–1983 event. Also, in our investigation we noted several periods of long-term (near decadal or longer) climatic change.

## 1. INTRODUCTION

Our investigation of El Niño activity lies within the historical realm from the time that the earliest Spanish explorers and conquistadores entered upon the South American scene in the early 1500s to the present. Penetrations into earlier periods of time are being carried on by archaeologists and those studying ice cores, sediment cores, tree rings, cadmium variability in corals, paleontological data, and other sources of proxy information relating to climatic change.

Some of the earliest evidence of very strong El Niño events was presented by *Nials et al.* [1979]. In their study of the rise and fall of early irrigation systems in the Moche Valley on the north coast of Peru, they discovered an El Niño catastrophe of extreme proportions. They called this ancient cataclysm the "Chimu flood." They found evidence that this flood of unusually large magnitude occurred early in the Chimu dynasty, within a century of the year 1100 A.D. In their opinion a very conservative estimate would indicate that flood waters at least 2–4 times the size of the unusual 1925 floods occurred then. They also stated that there appeared to be evidence in the Moche Valley of another large flood that occurred about 500 B.C. Their concern regarding the rapid rise in coastal population, and the disaster an inundation of Chimu extent could cause, is certainly a well-founded disquietude, especially since the strong and very strong events continue to recur.

Our study through the first three centuries was primarily limited to the contents of available literature, most of which was in Spanish, English, German, and French, and some in Dutch. However, over the past century and a half, meteorological, hydrological, and oceanographic data became increasingly more available for augmentation of the authored reports. The earliest part of our investigation depended upon reports emanating from the early Spanish explorations and military penetrations into northwestern South America. The historians, ship captains and navigators, and clergy that accompanied the conquistadors were valuable sources of information. The clergy, through their wide travels and access to the records of the missions that they established, soon became excellent informants on geophysical phenomena that occurred during the early years of the Spanish occupation. However, violent earthquakes, volcanic eruptions, and their consequences usually took precedence in their reports. Religious superstition abounded in those early years, and the more ominous occurrences were often attributed to offenses against God. As time progressed, the reports from historians, explorers, pirates, geographers, hydrologists, engineers, marine biologists, botanists, meteorologists, oceanographers, and expeditions on land and sea (conducted by universities, governmental fishery interests, etc.) became increasingly important sources of information.

This investigation is directed toward the El Niño which is a regional manifestation of the large-scale (El Niño-Southern Oscillation (ENSO)) event; and, occurrences are primarily based on evidence of significant climatic changes over the ordinarily dry west coast region of northern South America and its adjacent Pacific Ocean waters. Although the El Niño generally reflects an intensity near that of the related large-scale equatorial Pacific event (ENSO), this is not always the case, and at times, we find a significant divergence in intensity between them.

Although this research is still under way, we have now reached a point where we can provide some useful information to the climatic research community on the stronger events with a reasonable degree of confidence. In Table 1 we show



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TABLE 1. (continued)

| El Niño Event | Event Strength | Confidence Rating | Information Sources |
|---|---|---|---|
| 1844–1845 | S+ | 5 | *Spruce* [1864], *Eguiguren* [1894], *Labarthe* [1914], *Portocarrero* [1926], and *Taulis* [1934] |
| 1864 | S | 5 | *Spruce* [1864], *Eguiguren* [1864], and *Taulis* [1934] |
| 1871 | S+ | 5 | *Hutchinson* [1873], *Eguiguren* [1894], *Tizon y Bueno* [1907], *Sievers* [1914], *Labarthe* [1914], *Bachmann* [1921], *Portocarrero* [1926], and *Gaudron* [1925] |
| 1877–1878 | VS | 5 | *Eguiguren* [1894], *Palma* [1894], *Melo* [1913], *Sievers* [1914], *Labarthe* [1914], *Bachmann* [1921], *Portocarrero* [1926], *Murphy* [1926], *Taulis* [1934], and *Kiladis and Diaz* [1986] |
| 1884 | S+ | 5 | *Eguiguren* [1894], *Sievers* [1914], *Labarthe* [1914], *Bachmann* [1921], *Murphy* [1925], and *Portocarrero* [1926] |
| 1891 | VS | 5 | *Carranza* [1891], *Eguiguren* [1894], *Fuchs* [1907], *Labarthe* [1914], *Sievers* [1914], *Bachmann* [1921], *Zegarra* [1926], *Murphy* [1926], *Portocarreo* [1926], *Nials et al.* [1979], and *Taulis* [1934] |
| 1899–1900 | S | 5 | *Labarthe* [1914], *Bachmann* [1921], *Murphy* [1923], *Portocarrero* [1926], *Hutchinson* [1950], *Taulis* [1934], and *El Comercio* (February 10, 1899) |
| 1911–1912 | S | 4 | *Forbes* [1914], *Labarthe* [1914], *Bowman* [1916], *Lavalle y Garcia* 1917], *Balen* [1925], *Portocarrero* [1926], *Vogt* [1940], *Hutchinson* [1950], and *Schweigger* [1961] |
| 1917 | S | 5 | *Lavalle y Garcia* [1917], *Murphy* [1923], *Balen* [1925], *Portocarrero* [1926], *Petersen* [1935], *Hutchinson* [1950], and *Schweigger* [1961] |
| 1925–1926 | VS | 5 | *Murphy* [1926], *Zegarra* [1926], *Berry* [1927], *Petersen* [1935], *Vogt* [1940], *Mears* [1944], *Hutchinson* [1950], *Rudolph* [1953], *Nials et al.* [1979], and *Mugica* [1983] |
| 1932 | S | 5 | *Petersen* [1935], *Sheppard* [1933], *Vogt* [1940], *Mears* [1944], *Hutchinson* [1950], *Rudolph* [1953], and *Mugica* [1983] |
| 1940–1941 | S | 5 | *Lobell* [1942], *Mears* [1944], *Hutchinson* [1950], *Sears* [1954], *Schweigger* [1961], *Wooster* [1960], *Mugica* [1983], and *Quinn and Zopf* [1984] |
| 1957–1958 | S | 5 | *Wooster* [1960], *Schweigger* [1961], *Bjerknes* [1966]; *Idyll* [1973], *Miller and Laurs* [1975], *Caviedes* [1975], and *Mugica* [1983] |
| 1972-1973 | S | 5 | *Idyll* [1973], *Wooster and Guillen* [1974], *Miller and Laurs* [1975], *Ramage* [1975], *Caviedes* [1975], *Nials et al.* [1979], and *Mugica* [1983] |
| 1982–1983 | VS | 5 | *Mugica* [1983], *Rasmusson and Hall* [1983], *Rasmusson and Wallace* [1983], *Quiroz* [1983], *Smith* [1983], *Canby* [1984], *Woodman* [1984], *Quinn and Neal* [1984], and *Caviedes* [1984] |

S, strong; VS, very strong. See text for more information on confidence rating.

the strong and very strong events that occurred between 1525 and the present. In Table 2 we show events of moderate intensity that occurred between 1806 and the present. From 1800 on, more data (e.g., hydrological reports, sea surface temperatures, air temperatures, rainfall, barometric pressures) were available. The weak events are not included here. It is expected that events of the intensities noted in Tables 1 and 2 would have significant effects on sea life, bird life, plant life, coastal facilities, man, etc. The reference dates that appear in Tables 1 and 2 are those of original manuscripts or first editions of resulting publications, so the reader can be aware of the time between event occurrence and the author's report on it.

This multilanguage approach provided a reasonably thor-

TABLE 1. El Niño Events of Strong and Very Strong Intensities, Their Confidence Ratings, and Information Sources

| El Niño Event | Event Strength | Confidence Rating | Information Sources |
|---|---|---|---|
| 1525–1526 | S | 3 | *Xeres* [1534] |
| 1531–1532 | S | 4 | *Xeres* [1534] and *Prescott* [1892] |
| 1539–1541 | M/S | 3 | *Montesinos* [1642] and *Cobo* [1653] |
| 1552 | S | 4 | *Palma* [1894] and *Moreno* [1804] |
| 1567–1568 | S+ | 5 | *Oliva* [1631], *Cobo* [1639], *Labarthe* [1914], and *Portocarrero* [1926] |
| 1574 | S | 4 | *Garcia Rosell* [1903] |
| 1578 | VS | 5 | *Acosta* [1590], *Cobo* [1639, 1653], *Labarthe* [1914], *Portocarrero* [1926], and *Garcia Rosell* [1903] |
| 1591–1592 | S | 2 | *Martinez y Vela* [1702] |
| 1607 | S | 5 | *Cobo* [1639], *Alcedo y Herrera* [1740], *Palma* [1894], *Labarthe* [1914], *Portocarrero* [1926], and *Taulis* [1934] |
| 1614 | S | 5 | *Cobo* [1653], *Labarthe* [1914], and *Portocarrero* [1926] |
| 1618–1619 | S | 4 | *Vasquez de Espinosa* [1629], *Cobo* [1653], and *Taulis* [1934] |
| 1624 | S+ | 4 | *Cobo* [1653], *Labarthe* [1914], and *Portocarrero* [1926] |
| 1634 | S | 4 | *Palma* [1894] and *Puente* [1885] |
| 1652 | S+ | 4 | *Cobo* [1653], *Labarthe* [1914], and *Portocarrero* [1926] |
| 1660 | S | 3 | *Labarthe* [1914] and *Portocarrero* [1926] |
| 1671 | S | 3 | *Labarthe* [1914] and *Portocarrero* [1926] |
| 1681 | S | 3 | *Rocha* [1681] |
| 1687–1688 | S+ | 4 | *Juan and Ulloa* [1748], *Melo* [1913], *Unanue* [1806], *Remy* [1931], and *Taulis* [1934] |
| 1696 | S | 3 | *Palma* [1894] |
| 1701 | S+ | 4 | *Feijoo de Sosa* [1763], *Bueno* [1763], *Haenke* [1790], *Paz Soldan* [1862], *Palma* [1894], *Labarthe* [1914], *Portocarrero* [1926], and *Nials et al.* [1979] |
| 1707–1708 | S | 3 | *Cooke* [1712] and *Alcedo y Herrera* [1740] |
| 1714–1715 | S | 4 | *Gentil* [1728], *Labarthe* [1914], and *Portocarrero* [1926] |
| 1720 | S+ | 4 | *Shelvocke* [1726], Feijoo de Sosa [1763], *Bueno* [1763], *Alcedo* [1786–1789], *Haenke* [1790], *Paz Soldan* [1862], *Palma* [1894], *Labarthe* [1914], *Bachmann* [1921], *Portocarrero* [1926], and *Nials et al.* [1979] |
| 1728 | VS | 5 | *Feijoo de Sosa* [1763], *Bueno* [1763], *Alcedo* [1786–1789], *Paz Soldan* [1862], *Spruce* [1864], *Eguiguren* [1894], *Palma* [1894], *Labarthe* [1914], *Portocarrero* [1926], and *Nials et al.* [1979] |
| 1747 | S | 5 | *Feijoo de Sosa* [1763], *Llano Zapata* [1748], *Moreno* [1804], *Palma* [1894], *Labarthe* [1914], *Portocarrero* [1926], *Nials et al.* [1979], and *Taulis* [1934] |
| 1761 | S | 5 | *Bueno* [1763], *Alcedo* [1786–1789], *Haenke* [1790], *Labarthe* [1914], *Portocarrero* [1926], and *Ruschenberger* [1834] |
| 1775 | S | 4 | *Labarthe* [1914], *Portocarrero* [1926], and *Puente* [1885] |
| 1785–1786 | S | 4 | *Labarthe* [1914], *Portocarrero* [1926], and *Estrada Icaza* [1977] |
| 1791 | VS | 5 | *Unanue* [1806], *Ruschenberger* [1834], *Paz Soldan* [1862], *Spruce* [1864], *Hutchinson* [1873], *Eguiguren* [1894], *Labarthe* [1914], *Bachmann* [1921], and *Portocarrero* [1926] |
| 1803–1804 | S+ | 5 | *Moreno* [1804], *Unanue* [1806], *Stevenson* [1829], *Paz Soldan* [1862], *Spruce* [1864], *Eguiguren* [1894], *Palma* [1894], *Labarthe* [1914], *Portocarrero* [1926], and *Petersen* [1935] |
| 1814 | S | 4 | *Spruce* [1864] and *Eguiguren* [1894] |
| 1828 | VS | 5 | *Ruschenberger* [1834], *Paz Soldan* [1862], *Spruce* [1864], *Hutchinson* [1873], *Eguiguren* [1894], *Sievers* [1914], *Labarthe* [1914], *Bachmann* [1921], *Portocarrero* [1926], and *Taulis* [1934] |

TABLE 2. El Niño Events of Moderate and Near-Moderate Intensities, Their Confidence Ratings, and Information Sources

| El Niño Event | Event Strength | Confidence Rating | Information Sources |
|---|---|---|---|
| 1806–1807 | M | 3 | *Stevenson* [1829], *Remy* [1931], and *Unanue* [1815] |
| 1812 | M | 4 | *Palma* [1894] and *Gonzalez* [1913] |
| 1817 | M+ | 5 | *Eguiguren* [1894], *Labarthe* [1914], *Portocarrero* [1926], and *Taulis* [1934] |
| 1819 | M+ | 4 | *Eguiguren* [1894] and *Taulis* [1934] |
| 1821 | M | 5 | *Eguiguren* [1894], *Fuchs* [1925], *Remy* [1931], and *Taulis* [1934] |
| 1824 | M | 5 | *Spruce* [1864], *Basadre* [1884], and *Eguiguren* [1894] |
| 1832 | M | 5 | *Spruce* [1864], and *Eguiguren* [1894] |
| 1837 | M | 5 | *Eguiguren* [1894], *Labarthe* [1914], *Portocarrero* [1926], and *Taulis* [1934] |
| 1850 | M | 5 | *Eguiguren* [1894], *Fuchs* [1925], and *Taulis* [1934] |
| 1854 | W/M | 4 | *Spruce* [1864], *Eguiguren* [1894], and *Taulis* [1934] |
| 1857–1858 | M+ | 5 | *Eguiguren* [1894], *Labarthe* [1914], *Portocarrero* [1926], *Gaudron* [1925], *Zegarra* [1926], and *Taulis* [1934] |
| 1860 | M | 4 | *Labarthe* [1914], *Portocarrero* [1926], and *Taulis* [1934] |
| 1866 | M | 4 | *Eguiguren* [1894], *Labarthe* [1914], *Bachmann* [1921], and *Portocarrero* [1926] |
| 1867–1868 | M | 4 | *El Comercio* (January 10, 1872), *Raimondi* [1897], *Taulis* [1934], and *Eguiguren* [1894] |
| 1874 | M | 4 | *Bravo* [1903], *La Patria* (February 9, 1874), and *Bachmann* [1921] |
| 1880 | M | 4 | *Eguiguren* [1894], *Puls* [1895], and *Taulis* [1934] |
| 1887–1889 | W/M | 5 | *Eguiguren* [1894], *Labarthe* [1914], *Portocarrero* [1926], and *Taulis* [1934] |
| 1896–1897 | M+ | 4 | *Bravo* [1903], *El Comercio* (February 3, 1897, and February 22, 1897), and *Bachmann* [1921] |
| 1902 | M+ | 4 | *El Comercio* (February 17, 1902), *Bachmann* [1921], and *Taulis* [1934] |
| 1905 | W/M | 4 | *Bachmann* [1921], and *Taulis* [1934] |
| 1907 | M | 3 | *Remy* [1931], and *Paz Soldan* [1908] |
| 1914 | M+ | 5 | *Labarthe* [1914], *Portocarrero* [1926], *Petersen* [1935], *Taulis* [1934], and *Schweigger* [1961] |
| 1918–1919 | W/M | 5 | *Murphy* [1923], *Portocarrero* [1926], *Vogt* [1940], *Hutchinson* [1950], and *Taulis* [1934] |
| 1923 | M | 5 | *Lavalle y Garcia* [1924], *Balen* [1925], *Zegarra* [1926], *Gunther* [1936], *Hutchinson* [1950], and *Schweiggar* [1961] |
| 1930–1931 | W/M | 5 | *Petersen* [1935], *Hutchinson* [1950], *Schweigger* [1961], *Miller and Laurs* [1975], and *Woodman* [1984] |
| 1939 | M+ | 5 | *Vogt [1940]*, *Schweigger* [1940], *Mears* [1944], *Hutchinson* [1950], *Sears* [1954], *Mugica* [1983], and *Woodman* [1984] |
| 1943 | M+ | 5 | *Schweigger* [1961], *Miller and Laurs* [1975], *Caviedes* [1975], *Mugica* [1983], and *Woodman* [1984] |
| 1951 | W/M | 5 | *Garcia Mendez* [1953], *Schweigger* [1961], *Wooster and Guillen* [1974], and *Miller and Laurs* [1975] |
| 1953 | M+ | 5 | *Rudolph* [1953], *Sears* [1954], *Wooster and Jennings* [1955], *Merriman* [1955], *Avila* [1953], *Schweigger* [1961], *Mugica* [1983], and *Woodman* [1984] |
| 1965 | M+ | 5 | *Guillen* [1967, 1971], *Stevenson et al.* [1970], *Wooster and Guillen* [1974], *Miller and Laurs* [1975], *Caviedes* [1975], *Mugica* [1983], and *Woodman* [1984] |
| 1976 | M | 5 | *Quinn* [1977, 1980], *Smith* [1983], *Ceres* [1981], *Mugica* [1983], *Rasmusson and Hall* [1983], *Quinn and Neal* [1983], and *Woodman* [1984] |
| 1987 | M | 4 | Based on SSTs being very close to SCOR criteria, Peruvian fishery catch has been greatly reduced, and rainfall has been relatively high at Piura Airport (as provided by R. Mugica, Universidad Piura, Piura, Peru). |

M, moderate; W/M, near moderate. See text for more information on confidence rating.

ough information base for evaluating event occurrences and their intensities. We were particularly interested in obtaining better statistics on the frequency of occurrence of El Niño in the stronger categories. We were also interested in knowing in what way the unusual very strong El Niño differs from its counterparts in the lesser intensities. The large number of information sources covered by our search provided some insight into the peculiarities of many of these events as they evolved. In the course of this research we also noted some significant long-term (near decadel or longer) climatic changes. They were evidenced by persistent thermal changes and by more frequent and/or stronger El Niño occurrences.

The following sections refer to types of evidence used for detecting and evaluating El Niño occurrences; the strong and very strong El Niño occurrences, including a discussion of deviations from past listings; the moderate El Niños, including a discussion of deviations from past listing; a discussion concerning the very strong El Niño; the long-term climatic changes noted during our investigation; and a general discussion concerning the investigation and its findings.

## 2. EVIDENCE RELATING TO EL NIÑO OCCURRENCES AND CONFIDENCE THEREIN

In our search of the literature we looked for occurrences of the following nature over the northern Peruvian coastal region and its adjacent waters: (1) significant variations in travel times by sailing vessels between ports along the coast of Peru (e.g., large increases in northward travel time and decreases in southward travel time because of southward coastal currents and/or winds), (2) data from ship logs (pirates, privateers, explorers, etc.) noting unusual sea and weather conditions, sensing unusual sea and air temperatures, sighting displaced continental vegetation, noting displaced marine fauna, etc., (3) presence of aguaje (red tide), (4) penetration of abnormally warm waters farther south than usual along the coast of Peru during southern hemisphere summer and/or fall, (5) abnormally high air temperatures in the coastal cities of northern Peru, (6) thunderstorms, heavy rainfall, and/or flood conditions, (7) destruction of buildings, houses, and sometimes whole cities in the coastal zone by river inundations and flood waters, (8) obstructions to travel as the result of destruction of bridges, roadways, and/or railroad facilities by hydrological forces, (9) destruction of agricultural crops, (10) significant rises in sea temperatures and sea levels, (11) southward invasions of tropical nekton, (12) mass mortality of endemic marine sea life, (13) death and/or departure of guano birds, and (14) reduction in coastal fishery and fish meal production. Of course, one must determine whether or not the changes noted fit into the pattern of an El Niño development. For example, the increase in river discharge may be misleading unless the precipitation that causes it also occurs over the ordinarily dry coastal region. Negative evidence is very useful: as in the case of travelers, armed forces, or explorers who visit the vulnerable region and note nothing but the extreme drought conditions that prevail between events during their sojourn. Visitors tend to believe that the conditions that occur while they are in an area are always that way, and since the dry conditions between events are much more extensive timewise than the wet event conditions, many reports of the past indicate that it never rains over this northwestern Peruvian coastal region.

The *Scientific Committee on Oceanic Research* (SCOR) *Working Group 55* [1983] definition of El Niño is as follows: El Niño is the appearance of anomalously warm water along the coast of Ecuador and Peru as far south as Lima (12°S), during which a normalized sea surface temperature (SST) anomaly exceeding one standard deviation occurs for at least four consecutive months at three or more of five coastal stations (Talara, Puerto Chicama, Chimbote, Isla Don Martin, and Callao). The data used at that time gave the monthly mean SST and the standard deviation computed over the period 1956–1981 for each month for each coastal station. This definition identifies El Niños for 1957–1958, 1965, 1972–1973, and 1976. It establishes a minimum level for events of moderate intensity and eliminates the weaker events. However, it still does not provide any criteria for determining the strength of an event (i.e., moderate, strong, very strong), although one would expect the stronger events to be associated with higher coastal SSTs. In determining intensity, we also find it essential to include a consideration of meteorological, hydrological, and other oceanic characteristics associated with the El Niño developments, as well as related environmental destruction in coastal communities, ecological consequences (with regard to sea life, guano birds, etc.), and industrial costs (brought about by, for example, a loss in northwestern Peruvian oil production, reduction and/or drastic changes in fishery output, etc.) to the nation. It is assumed that the stronger the event, the greater the amount of damage, destruction, and cost to the nation. Obviously, with the types of information available over our long record (as indicated at the beginning of this section), the intensity determinations must be essentially subjective.

Accepting the above El Niño identifications, based on the use of the SCOR coastal SST criteria, we believe that most investigators would agree that the 1957–1958 and 1972–1973 El Niños were strong and the 1965 and 1976 El Niños were moderate in intensity. By considering the overall effects of the 1965 and 1976 El Niños as described by their information sources in Table 2 and the overall effects of the 1957–1958 and 1972–1973 El Niños as described by their information sources in Table 1, we have some rough models with which we can compare the information obtained for the other events in our long chronology to determine whether they meet moderate or strong classification levels. We also believe that most investigators would concur in a very strong classification for the 1982–1983 El Niño. The information sources on this event, as well as those for the unusual 1891 and 1925–1926 events, provide an excellent model with which to compare information on events that may meet criteria for the very strong intensity.

One might wonder what would cause us to put an S+ on an event as far back as the 1567–1568 El Niño. However, in addition to the information provided by the other sources, which exhibits particularly strong activity, *Oliva* [1631] reports that Padre Geronimo Ruiz Portillo and his six companions had a surprisingly successful trip from the Port of Panama to Lima in 26 days, a trip which usually took 6 months. (They arrived in Callao on March 25, 1568.) An accomplishment such as this in a sailing vessel would indicate the presence of highly favorable winds and currents during their journey southward.

In determining whether or not and when a particular El Niño occurred, we refer to all the applicable reports that we can find and cross-check them as to time of occurrence and compatibility. With regard to determining event intensity, we check the reports for degree of activity and through comparison with the aforementioned rough models arrive at an estimate of event strength. The very strong events show extreme amounts of rainfall, flood waters, and destruction, and coastal SSTs usually reach values of 7°–12°C above normal during some months of the southern hemisphere summer and fall seasons. The strong events, in addition to showing large amounts of rainfall and coastal flooding and significant reports of destruction, exhibit coastal SSTs in the 3°–5°C above normal range during several months of the southern hemisphere summer and fall seasons. The moderate events in addition to showing above normal rainfall, some flooding, and small amounts of destruction, generally show coastal SSTs in the 2°–3°C above normal range for several months during the southern hemisphere summer and fall seasons. In all three categories the effects on coastal fisheries are highly damaging. Based on the short (1957–1987) SST and air temperature records that we had available for the San Juan (15°23'S) coastal station, we noted that only the strong and very strong El Niños penetrated this far south.

The confidence ratings in Tables 1 and 2 run from 2 through 5. We eliminated those with a rating of 1 since they were merely listed by an author, without any source reference or informational basis, and one of our goals was to eliminate unsubstantiated events. The other ratings are as follows: 2, event based on limited circumstantial evidence, 3, additional references desired to firm up the time of occurrence or intensity; 4, occurrence time and intensity information is generally satisfactory, but we would like additional references as to areal extent; 5, the existing occurrence and intensity information is considered to be satisfactory.

## 3. STRONG AND VERY STRONG EL NIÑOS

Table 1 lists the strong/very strong events, confidence ratings for our determinations, and information sources that we used for our determinations. We show events with strong (S), quite strong (S+), and very strong (VS) strength ratings. With regard to the S+ events from 1567–1568 through 1720, additional information may result in a VS rating for one or more of them. With respect to the contents of Table 1, where we have added events over earlier years that do not conflict with published reports, we submit our references for justification. However, in those cases where we do not accept events listed by other authors, or we upgrade or downgrade a strength categorization, we hereby submit our justification. More detail is provided concerning the first three events since data concerning the 1525 to early 1526 case have just recently been noted; for the 1531–1532 event there were several prior inquiries, some of which were in disagreement with our findings; and for the 1539–1541 case, additional information led to an alteration of earlier findings.

The earliest indication of a possible El Niño was during 1525 to early 1526. Pizarro, after many setbacks following his departure southward from Panama in November 1524, remained at the San Juan River while one ship under Captain Almagro returned to Panama to obtain reinforcements and supplies, and the other ship under the Pilot Ruiz was sent farther south to discover good land [*Xeres*, 1534]. After the ships returned and they were aware of a more inviting region to the south, the two ships set out for the newly discovered land. However, navigation was difficult, since "They had constant northerly winds, with heavy squalls, and storms of thunder and lightning" [*Xeres*, 1534], and they were detained so long that they ran out of supplies and had to go ashore to replenish them. (The ships at this time reached the Bay of San Mateo.) These weather conditions would indicate that they had been on the north side of the intertropical convergence zone off the coast of Ecuador. Later, after receiving some additional support, Pizarro sailed from the island of Gorgona southward to the Gulf of Guayaquil in 20 days. He landed on the island of Santa Clara, crossed over to Tumbez, and then explored the Peruvian coast as far south as the Santa River [*Xeres*, 1534]. Based on available intinerary data, it appears that the travel from the island of Gorgona to the Santa River was accomplished during the latter part of 1526.

Prior to reading the eyewitness report of Pizarro's Secretary, Francisco Xeres [*Xeres*, 1534], we tended to agree with the opinion that no El Niño occurred during Pizarro's conquest. However, based on the following information, it is now our opinion that there was an El Niño during 1531 to early 1532.

1. Favorable winds and currents occurred in early 1531, which allowed a rapid 13-day transit from Panama to the Bay of San Mateo (a trip which had previously taken Pizarro about 2 years to complete) [*Xeres*, 1534].

2. Heavy rainfall was encountered on the island of Puna (in the Bay of Guayaquil) apparently during the late 1531 to early 1532 southern hemisphere summer which caused Pizarro to remain there ("for, he could not have advanced in the rains without serious detriment" [*Xeres*, 1534]).

3. Later, while they were at Tumbez (circa early 1532), it was mentioned that "the river had increased in size and could not be forded" [*Xeres*, 1534].

4. On September 24th 1532, Pizzaro departed San Miguel and struck out toward the camp of the Inca [*Prescott*, 1892]. After crossing the smooth waters of the Piura, the little army continued to advance over a level district intersected by streams that descended from the neighboring cordilleras [*Prescott*, 1892]. (If this was truly the Piura River that he crossed in late September, conditions were very unusual for this time of year, since the Piura River ordinarily dries up from July through December unless there has been an El Niño.)

5. By late October they had reached the valley of Cinto through which it was reported that a large, swift river in a very swollen stage flowed [*Xeres*, 1534]. (*Lorente* [1861] identifies the river as the La Leche; *Raimondi* [1876] believes that it was the Lambayeque River.)

Although we need additional information on the situation, it appears that the activity for 1539–1541 might be similar to that for the more recent 1939–1941 situation, consequently the strength is reported as M/S and the confidence level as 3. *Montesinos* [1642] reports the death of more than 30,000 Indians in Cuzco in 1539 due to starvation. Droughts commonly occur in Cuzco (southeast Peru) when the El Niño sets in over northwestern Peru. *Montesinos* [1642] also reports that the Marquis of Cuzco encountered thunderstorms and extraordinary hail on his trip from Cuzco to Lima in 1540. (S. E. Antunez included a report on the occurrence of aguaje on July 12, 1540.) *Cobo* [1653] reports heavy rainfall in Lima in 1541 which caused water to flow through the streets of Lima.

We did not accept the 1726 case of *Juan and Ulloa* [1748] which was referenced in several later publications. *Feijoo de Sosa* [1763], who made a careful investigation of the events that occurred over the northwest coastal region of Peru in the early 1700s, states that what Juan and Ulloa reported for 1726 was what actually occurred in 1728. Other chronologies [*e.g.*, *Hamilton and Garcia*, 1986] support this viewpoint, and no original information sources report a 1726 event.

The list of very heavy rainfall years over the coastal desert of northern Peru by *Hamilton and Garcia* [1986], with the exception of the 1763 and 1770 years taken from *Frijlinck* [1925], was verified and had previously been covered by *Eguiguren* [1894] and/or his references. There is absolutely no reference or evidence for heavy northern Peruvian rainfall given by *Frijlinck* [1925] for the 1763 and 1770 years or any other of the early years in his chronology. *Hamilton and Garcia* [1986, p. 1356] in the following statement admit that they cannot substantiate the addition of those years:

> The lack of any corroboration of Frijlinck's reports is unfortunate, but it was decided to tentatively include 1763 and 1770 in the present list of probable ENSO years.

Unfortunately, after the spurious 1763 and 1770 years were listed throughout the Hamilton and Garcia paper alongside the other substantiated heavy rainfall years, they tended to acquire a state of legitimacy in the mind of the reader. Since *Quinn et al.* [1978] and others have referred to the chronology of *Frijlinck* [1925], it is time we set the record straight. In our opinion Frijlinck used *Eguiguren's* [1894] information in constructing the legitimate part of his early rainfall chronology. Frijlinck's heavy rainfall years between 1791 and 1890 (1791, 1804, 1814, 1828, 1845, 1864, 1871, 1877 + 1878, 1884) do not differ one iota from *Eguiguren's* [1894] 100-year record of class −4 (extraordinary year) rainfall years. Of course, if Frijlinck had acknowledged the use of *Eguiguren's* [1894] class 4 rainfall estimates, he would then be obliged to refer to the source of his 1763 and 1770 heavy rainfall years. Instead, he does not show sources for any of his heavy rainfall years. Although Eguiguren uses the Feijoo de Sosa reference for heavy rainfall years, he somehow overlooks the 1747 listing therein. The fact that Frijlinck also misses the 1747 rainfall year is another indication that he used Eguiguren's material. Our opinion that Frijlinck used the Bruckner cycle and its harmonics to fill his 1728–1791 gap is based on the 35-, 7-, 21-year spread between 1728, 1763, 1770, and 1791. Much of Frijlinck's paper is devoted to a discussion of the Bruckner, sunspot, and Easton cycles in relation to climatic changes. He even downgrades some years of his acquired rainfall chronology that do not fit his views by placing parentheses around them and ignoring them in one of his discussions of intervals between heavy rainfall years.

*Berlage* [1957, p. 25], after referring to *Eguiguren* [1894], *Frijlinck* [1925], and eighteenth century witnesses and correspondents (none of which are named), lists the Peru heavy rain years as occurring every 7 years between 1728 and 1798. The only years of our record that agree with those of Berlage are 1728 and 1791, the original departure points that Frijlinck and Berlage obtained from *Eguiguren* [1894] for eighteenth century events.

With regard to the gap between 1747 and 1791, we listed and provided references for strong El Niños in 1761, 1775, and 1785–1786 in our Table 1. Also, during our search we noted some evidence for activity of lesser intensity (perhaps moderate) in 1750, 1778–1779, and 1783. However, the search has not revealed any evidence for heavy rainfall, or any other hydrological activity, which might be associated with an El Niño occurrence for either 1763 or 1770.

We rated the 1917 event as strong based on the strong hydrological effects reported by *Portocarrero* [1926] and the effects on the fishery and guano birds, as reported by *Lavalle y Garcia* [1917] and other authors. This differs considerably from the weak rating given by *Quinn et al.* [1978]. However, here it was rated strictly as a regional (El Niño) event, whereas Quinn et al. rated it on an overall basis and the effects were insignificant on the large-scale (ENSO) level. The situation was reversed in the case of the 1918–1919 event in that it only showed a weak to moderate strength as an El Niño, yet on the large-scale (ENSO) basis, it appeared to be strong, as indicated by *Quinn et al.* [1978].

The last point of departure lies with the 1932 case, which we upgraded here to the strong level as an El Niño. The rainfall and other information of *Petersen* [1935] and the hydrological data of *Mugica* [1983] endorse this rating, as do the other references. The weak rating of Quinn et al. was based on the fact that as a large-scale (ENSO) event, it was not significant.

In general, the shortest time between onsets of strong/very strong El Niño events is about 6–7 years, but we did note a few 4- to 5-year intervals. On the long-term average these events set in about 9.9 years apart. This average is based on onset to onset values for S, S+, and VS events for 1525–1982. Of course, the time between onsets of such events may be as much as 14–20 years.

## 4. El Niños of Moderate Intensity

We included El Niños of moderate intensity since they too can at times have profound effects on the coastal environment, its fisheries, and bird life. Table 2 lists the El Niños of moderate (M, M+) and near-moderate (W/M) intensity. The weak (W) events were not included since they do not have a substantial effect on the coastal environment or its fisheries and they do not meet the SCOR SST criteria (see section 2). Events below the strong intensity are more difficult to evaluate; therefore, at this time we limited our period of reference to 1800–present, when more information was available. Many of the evaluations differ from those of *Quinn et al.* [1978]. But, as in the case of Table 1, most differences result from the fact that here we consider each event strictly on its El Niño aspect, whereas Quinn et al. also considered the large-scale (ENSO) aspects. We have already discussed the upgrading of the 1917 and 1932 events to the strong level and the downgrading of the 1918–1919 event to the near-moderate level in section 3. Another change was the downgrading of the 1905 event to a near-moderate (W/M) level here. It is expected that if the 1905 event was evaluated just on its equatorial Pacific and other larger-scale effects, it would have been considered a strong event. The 1923 and 1943 events were raised from a weak intensity by Quinn et al. to the moderate level here, based on the evidence of their activity on the regional (El Niño) scale which the references adequately support.

Based on the period 1803–1987, the average time between onsets of near moderate or stronger El Niños is about 3.8 years. However, long-term climatic changes may cause significant variations in this frequency.

## 5. The Very Strong El Niño

The very strong events occur too infrequently to provide any useful frequency statistics. If we accept the designated occurrences of Table 1 from 1728 on, the separations range from 14 to 63 years. The 1982–1983 event was exceptionally strong on both the regional (El Niño) and large scales. It gave scientists the first opportunity to observe an event of this magnitude using modern meteorological and oceanographic facilities. What happened prior to, during, and following this unusual event has been well documented in newsletters, bulletins, workshop proceedings, conference proceedings, and a large number of articles in recognized journals. They attest well to its nature, intensity, and areal extent. What stood out to us

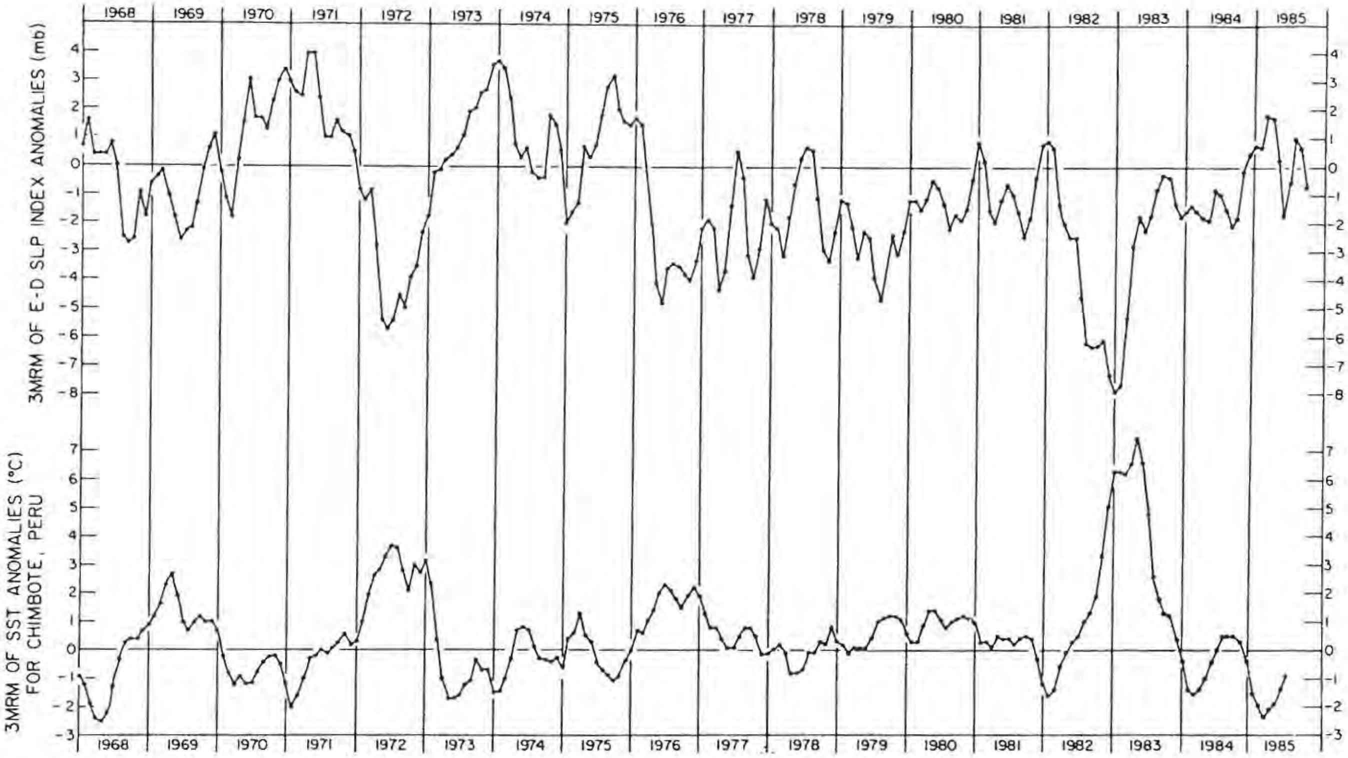


Fig. 1. Three-month running mean plot of anomalies of the difference in sea level atmospheric pressure (mbar) between Easter Island (27°10′S, 109°26′W) and Darwin, Australia (12°26′S, 130°52′E), and 3-month running mean plot of sea surface temperature anomalies (°C) for Chimbote, Peru (09°10′S, 78°31′W).

was the generally synchronous nature of the atmospheric and oceanic changes as the event evolved and ran its course. A few of our plots that show this high degree of compatibility over the tropical Pacific are included here. Figure 1 shows the close relationship between the Easter-Darwin Southern Oscillation index anomalies and the Chimbote sea surface temperature anomalies. In Figure 2, note how closely the 200–850 mbar atmospheric thickness anomaly trends relate to one another at stations over both the northeast and southeast trade wind zones. The thickness changes reflect the effects of the underlying sea surface temperature changes on the overlying atmosphere. Figure 3 shows plots of the integrated anomalies for the Tahiti-Darwin pressure index and Tahiti pressure, the Hao-Darwin pressure index and Hao pressure, and the Totegegie-Darwin pressure index and Totegegie pressure. They illustrate the long-term climatic change and its consistency over the critical southeast trade wind zone. The long-term climatic change and use of the integrated anomaly trends were discussed by *Quinn and Zopf* [1984]. It is noteworthy that both cores of the Southern Oscillation are actively involved in this long-term change (Figure 3), and this too contributes to the unprecedented strength of the 1982–1983 ENSO.

In our opinion all very strong events and most strong events will show similar intensities for both the larger-scale (ENSO) development and its regional (El Niño) manifestation. The rawinsonde data, as represented in thickness anomaly plots, can be used to evaluate the large-scale atmospheric changes in much the same manner as the STD data are used to evaluate the upper oceanic changes associated with the ENSOs.

The cumulative index and index component anomaly plots are particularly useful for identifying and evaluating the long-term changes that may affect an event. In the case of the unusual 1982–1983 event the long-term input appears to be quite significant.

## 6. LONG-TERM CLIMATIC CHANGES

In the course of this investigation we also noted some extended periods of time (near-decadel or longer), over this four and a half century record, when the amount and/or strength of El Niño activity and its resulting effects appeared to represent significant long-term climatic changes. These changes, such as the recent one represented in Figure 3, are so insidious that it would be difficult to note them over the historical past except through gross changes in activity and its resulting effects. Some of the periods of this nature which we have noted are as follows.

The period 1607–1624 may be one of significant climatic change, but we must find much more evidence before we make a decision in this regard. The period 1701–1728 was definitely one of unusually strong activity, as the record in Table 1 and its references will substantiate. *Eguiguren* [1894] summarizes some of the information that he accumulated on this period.

The period 1812–1832 was unusually active. In addition to the strong and very strong events listed in Table 1, there were moderate strength events in 1812, 1817, 1819, 1821, 1824, and 1832. The frequency of activity over this time span was very unusual.

From 1864 through 1891 the El Niño activity was unusually strong and frequent, as Tables 1 and 2 indicate. *Eguiguren* [1894] comments on the frequency of rainfall, as evidenced in his table of rainfall categories, and then further states:

> But let us do away with the table and all the historical citations and we shall still find ourselves in the presence of this fact: the

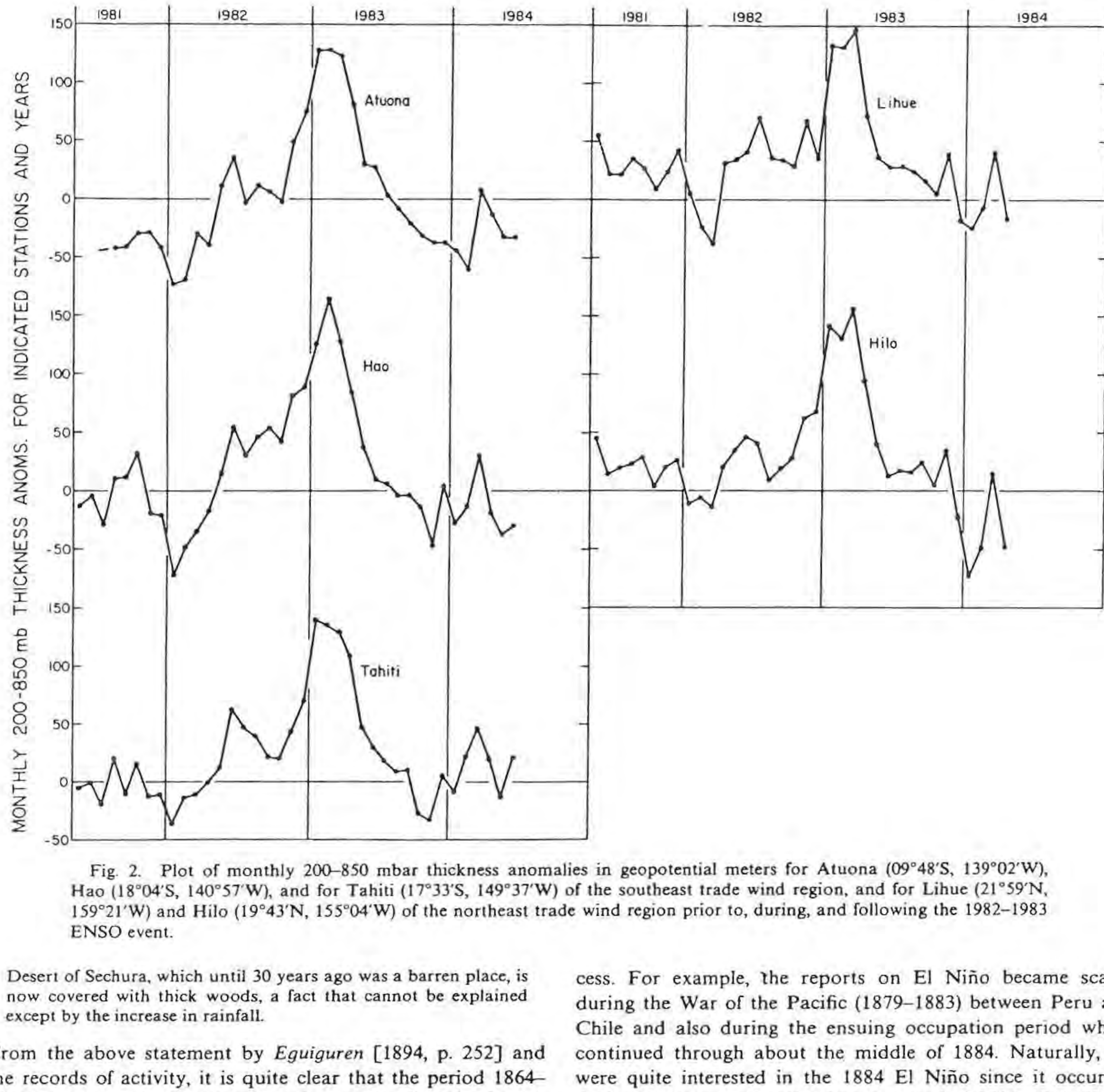


Fig. 2. Plot of monthly 200–850 mbar thickness anomalies in geopotential meters for Atuona (09°48'S, 139°02'W), Hao (18°04'S, 140°57'W), and for Tahiti (17°33'S, 149°37'W) of the southeast trade wind region, and for Lihue (21°59'N, 159°21'W) and Hilo (19°43'N, 155°04'W) of the northeast trade wind region prior to, during, and following the 1982–1983 ENSO event.

> Desert of Sechura, which until 30 years ago was a barren place, is now covered with thick woods, a fact that cannot be explained except by the increase in rainfall.

From the above statement by *Eguiguren* [1894, p. 252] and the records of activity, it is quite clear that the period 1864–1891 was one reflecting a strong long-term climatic change. Was this increased activity at this time related to emergence from the Little Ice Age? (Although several authors place the beginning of the Little Ice Age between the late 1500s and 1600 and the end during the latter few decades of the 1800s, *Sellers* [1965] places its bounds at 1500–1900 but also mentions the later worldwide warming as starting in 1880.)

Another period of unusual activity was 1925–1932. During this period the rainfall and sea surface temperatures were on the average unusually high. *Peterson* [1935, p. 125] discusses this period in some detail and states as follows:

> We conclude with reference to the coastal province of Tumbes that the eight year period, 1925–1932, has been a period of abundant rains, that is an essentially wet or oceanic period.

The recent period of climatic change as represented in Figure 3 is discussed by *Quinn and Neal* [1984].

## 7. DISCUSSION

Various changes occurred during our historical investigation period that disturbed the information-gathering process. For example, the reports on El Niño became scarce during the War of the Pacific (1879–1883) between Peru and Chile and also during the ensuing occupation period which continued through about the middle of 1884. Naturally, we were quite interested in the 1884 El Niño since it occurred during the strong climatic change period of 1864–1891. However, the following quote from *Murphy* [1925, pp. 169–170] was noted:

> During the Chilean occupation of northern Peru, after the War of the Pacific, so vast a quantity of dead fish was cast on the beach near Eten during the prevalence of an aguaje that the whole region became insufferable. The Chilean troops occupying Chiclayo had to be ordered out to bury the decomposing fish in a trench which extended from Eten to Pimental (10 geographical miles).

This confirmed our views on the great strength of the 1884 El Niño, which on its larger scale aspect (the ENSO) caused the heaviest rainfall ever at San Diego and Los Angeles in 1884.

The recurrent nature of rainfall at various intervals over the generally dry northwest coastal region of Peru led some investigators to a belief in cyclic activity based on the intervals they witnessed over the span of time that they were on the scene. By the end of the nineteenth century, when the Bruckner cycle became a prominent climatic consideration, investigators often tried to fit their recurrent patterns of activity to harmonics of this cycle. To do this, some were tempted to downgrade cer-

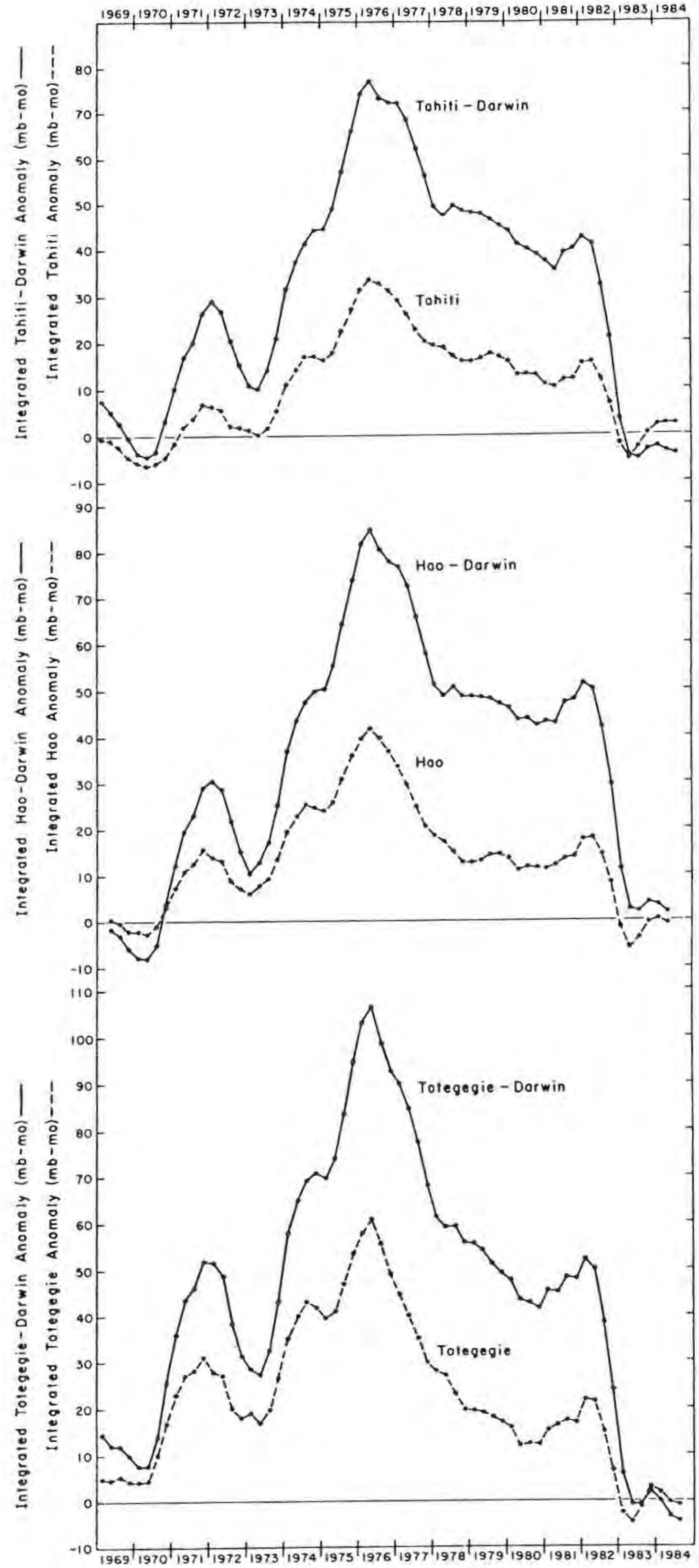


Fig. 3. Integrated anomalies in millibar-months for Tahiti-Darwin and Tahiti, for Hao-Darwin and Hao, and for Totegegie-Darwin and Totegegie (23°06'S, 134°52'W). In all cases, quarterly average figures are entered.

tain events, upgrade others, and at times to assume the existence of events at harmonic intervals over large gaps in a record. (According to *Fairbridge* [1987] the Bruckner cycle is an ill-defined cycle of about 35 years which was first noticed by Sir Francis Bacon in 1625 from evidence of an alternation of cool-damp and warm-dry periods in Holland. It was rediscovered in 1890 by E. Bruckner, who regarded it as a worldwide phenomenon. A cycle of 33–37 years (in the mean) has been found in many meteorological and allied phenomena, including tree rings and long rainfall records, but its length is quite variable (from 15 to 50 years), and this may be caused by the interference of cycles of different length [*Huschke*, 1959]. It is doubtful whether the Bruckner cycle has any reality but instead results from statistical smoothing.)

The average period of 3.8 years between El Niños, which was arrived at by considering all events (moderate, strong, and very strong) over the 1803–1987 record, compares quite favorably with the quasi-period for the ENSO as noted in the recent theoretical studies of *Cane and Zebiak* [1985] and *Cane* [1986].

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# Erosion of Netarts Spit, Oregon: Continued Impacts of the 1982-83 El Niño

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## INTRODUCTION

THE 1982-83 EL NIÑO WAS AN UNUSUALLY INTENSE atmospheric and oceanic phenomenon that produced severe erosion along much of the Pacific coast of the United States. the main contributing factors in causing that erosion were exceptionally high local water levels, and a series of storms that generated intense wave conditions. These processes and their impacts on the Oregon coast have been documented in an earlier paper.[5] During the 1982-83 period of that El Niño, and during the subsequent two years, the principal erosion on the Oregon coast took place along Alsea Spit. In addition to high sea levels and storm-wave conditions, the erosion of that spit was caused by the northward migration of the inlet to Alsea Bay in response to the southwest approach of storm waves. Since that time, the inlet has shifted back to its normal position, and the beach fronting the spit has recovered; the erosion problems on Alsea Spit have effectively ceased. However, impacts from the 1982-83 El Niño still persist on the Oregon coast, even though several years have passed. The present paper reports on the erosion of Netarts Spit, a contributing factor of which is the long-term disequilibrium produced by that unusual El Niño. Erosion of Netarts Spit represents a serious problem in that Cape Lookout State Park at the southern end of the spit is a popular recreation site, with the lost lands including picnic and campground areas.

## SETTING AND EROSION OF NETARTS SPIT

Netarts Spit is located on the northern half of the Oregon coast, about 100 km south of the Columbia River. The spit itself is 6 km in length, forming most of the stretch of shore between the large Cape Lookout to the south and Cape Meares to the north (Fig. 1). There is a sand beach fronting the sea cliff north of the spit, extending from the Netarts Bay inlet to Cape Meares. The pocket between Cape Meares and Maxwell Point is dominated by a high-tide cobble ridge, but with a sandy foreshore in the lower portions of the beach profile. Maxwell Point projects outward only across the inner part of the surf zone, but together with the offshore shoal area of Three Arch Rocks (Fig. 1), it is effective in blocking southward movements of cobbles derived from Cape Meares. However, Maxwell Point does not obstruct longshore sand movements.

Studies of beach-sand mineralogies and grain rounding indicate that major rocky headlands on the Oregon coast such as Capes Lookout and Meares extend into sufficiently deep water to isolate the individual beach compartments or cells.[2] Each cell is in effect a pocket beach, even though some are many kilometers in total length. Within any pocket beach there are seasonal reversals in the directions of longshore sand movements as waves reach the coast from different storms, but when averaged over a number of years the net sand transport is essentially zero. The existence of zero net longshore sand movements within the Oregon beach cells is further established by the patterns of sand accumulations in response to jetty construction.[7]

Being one of the smallest cells on the Oregon coast, the cell between Cape Lookout and Cape Meares (Fig. 1) particularly illustrates this pocket-beach nature of the Oregon shoreline and the resulting zero net-sand movement. The principal feature within this cell is Netarts Spit (Fig. 2; see also photo on the cover). This spit together with its dunes represents a large quantity of sand, yet there is a lack of significant local sediment sources within this isolated pocket beach. Cliff erosion south of the spit and in the Oceanside area may have contributed some sand to the beach, but the quantities were small. No rivers enter Netarts Bay, only a few minor streams; the total watershed draining into Netarts Bay amounts to only 34 km$^2$.

A study of the mineralogy of the sand forming Netarts Spit also demonstrates that much of it could not have had a local source.[2] Particularly revealing is that the sand contains heavy minerals which could only have been derived from metamorphic rocks found in the Klamath Mountains of southern Oregon and northern California. The many headlands of the Oregon coast preclude present-day longshore movements of sand along the beaches between the Klamaths and Netarts Spit. However, during periods of glacial advances and the resulting lowered sea-levels, a northward movement of sand would not have been obstructed by headlands. At that time sands derived from rivers draining the Klamath Mountains mixed with sands from the Coast

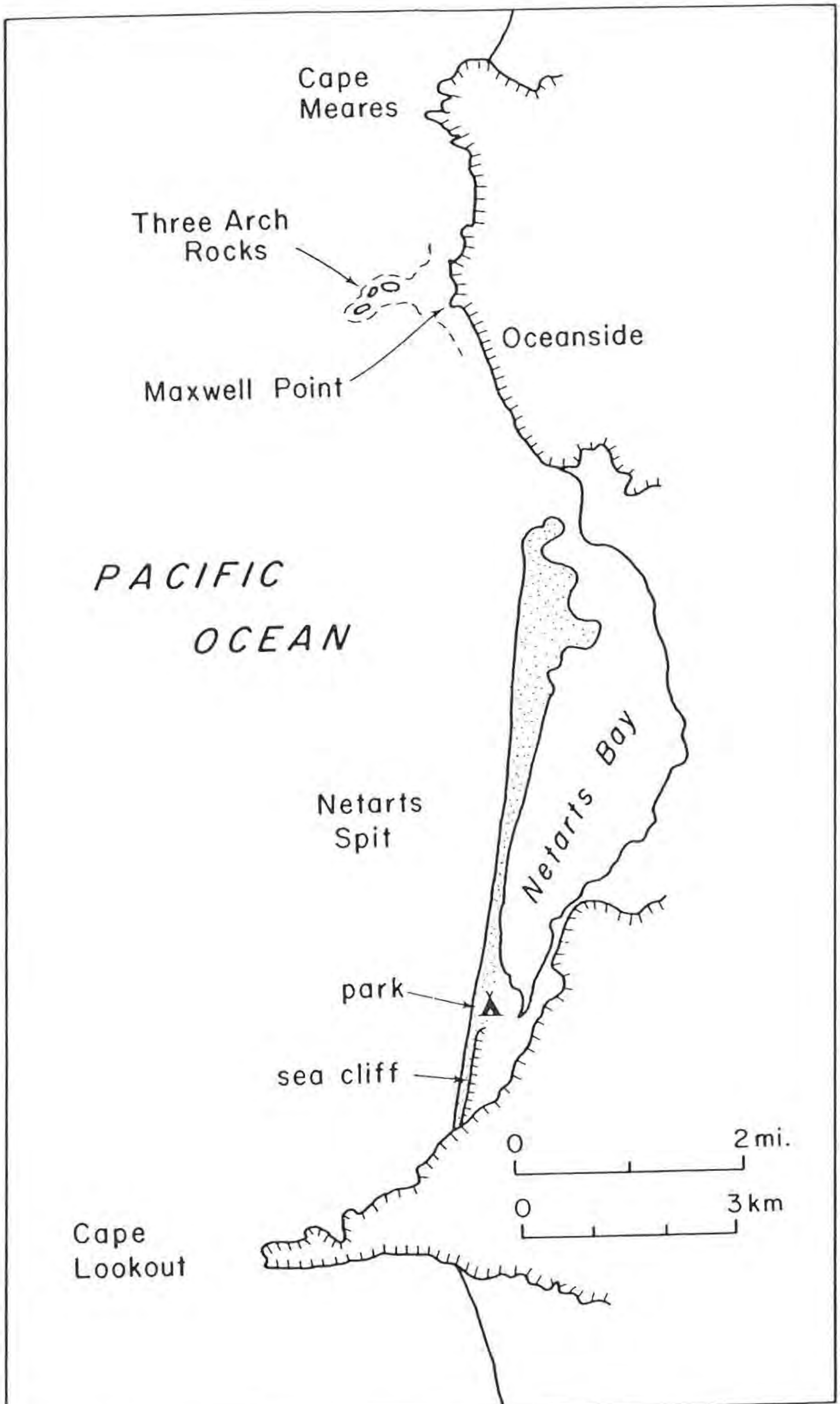


**Fig. 1 Netarts Spit on the northern Oregon coast, contained within the littoral cell bounded on the north by Cape Meares and on the south by Cape Lookout. Cape Lookout State Park is located at the south end of the spit**

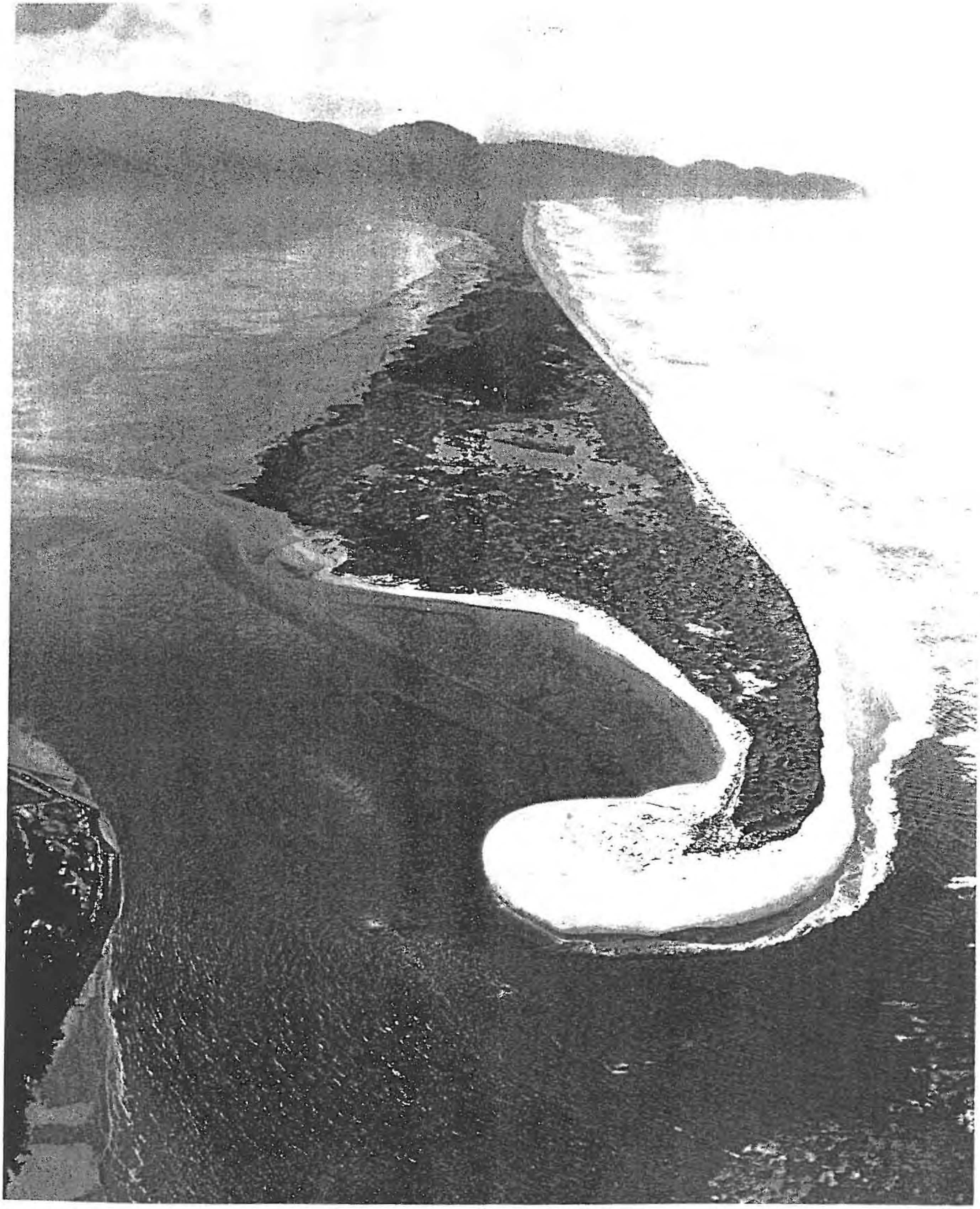

Fig. 2 Oblique aerial of Netarts Spit and the inlet to Netarts Bay [March 10, 1978; Oregon State Highway Dept. photo A682-23]

Range and from the Columbia River. The patterns of mineral changes along the coast indicate that there was a northward net longshore movement of sand along that ancient shoreline.[2,8].

With the subsequent melting of glaciers and rise in sea level, the beaches of the Northwest coast migrated landward. Although the exact timing is uncertain, several thousand years ago these landward-moving beaches became segmented by the headlands which are composed of sufficiently resistant rock that their slow erosion did not keep pace with the rising sea and migrating shores. The seaward projections of the headlands have increased with time, as did their efficiencies in preventing along-coast exchanges of sand between the shoreline cells of the Oregon coast. It is apparent from this history that the sand mass which now comprises Netarts Spit has little to do with local sources. Furthermore, the existence of Netarts Bay and the length of the Spit are due to the geometry of the land topography backing this particular cell. Similarly, the longshore extension of the spit toward the north has little significance, and in particular does not imply a northward net transport of sand along this beach. This is further confirmed by the next cell to the north, that between Cape Meares and Cape Falcon, which contains two sand spits pointing in opposite directions.

The recent erosion of the seaward edge of Netarts Spit has revealed that the sand of the spit and beach overlies bay muds and marsh deposits. This is common evidence for landward migrations of barrier islands on other coastlines, and demonstrates that Netarts Spit has undergone a similar migration. However, the migration of Netarts Spit was probably restricted primarily to the stage of rapidly rising sea levels prior to about five thousand years ago; it appears to have been minor during the past century. The presence of very old dunes along most of the spit length indicates that washovers have not occurred, at least in those areas. It is known that washovers did take place during the 1930s in the narrowest portion of the spit where there were no high dunes[3]; that area of washovers can be seen in the 1931 photograph of Figure 3. Photographs taken in 1948 reveal that this narrow portion of the spit was still a zone of low active dunes. The planting of European beach grass on Netarts Spit, begun in 1951 and continued through the 1970s, raised dune elevations, especially those in particularly low-lying areas. This has contributed to the spit's resistance to washovers and potential breaching. Another contributing factor to the rarity of washovers on Netarts and other sand spits along the Northwest coast is the tectonic rise of this area. Although the absolute (eustatic) level of the sea continues to rise (estimated[1,4] at 1.5 to 2.3 mm/yr), the coasts of Oregon and Washington are undergoing tectonic uplift such that the net effect appears to be local lowering or nearly stationary sea level. Therefore, a landward migration of Netarts Spit is not presently required as a response to increasing sea levels.

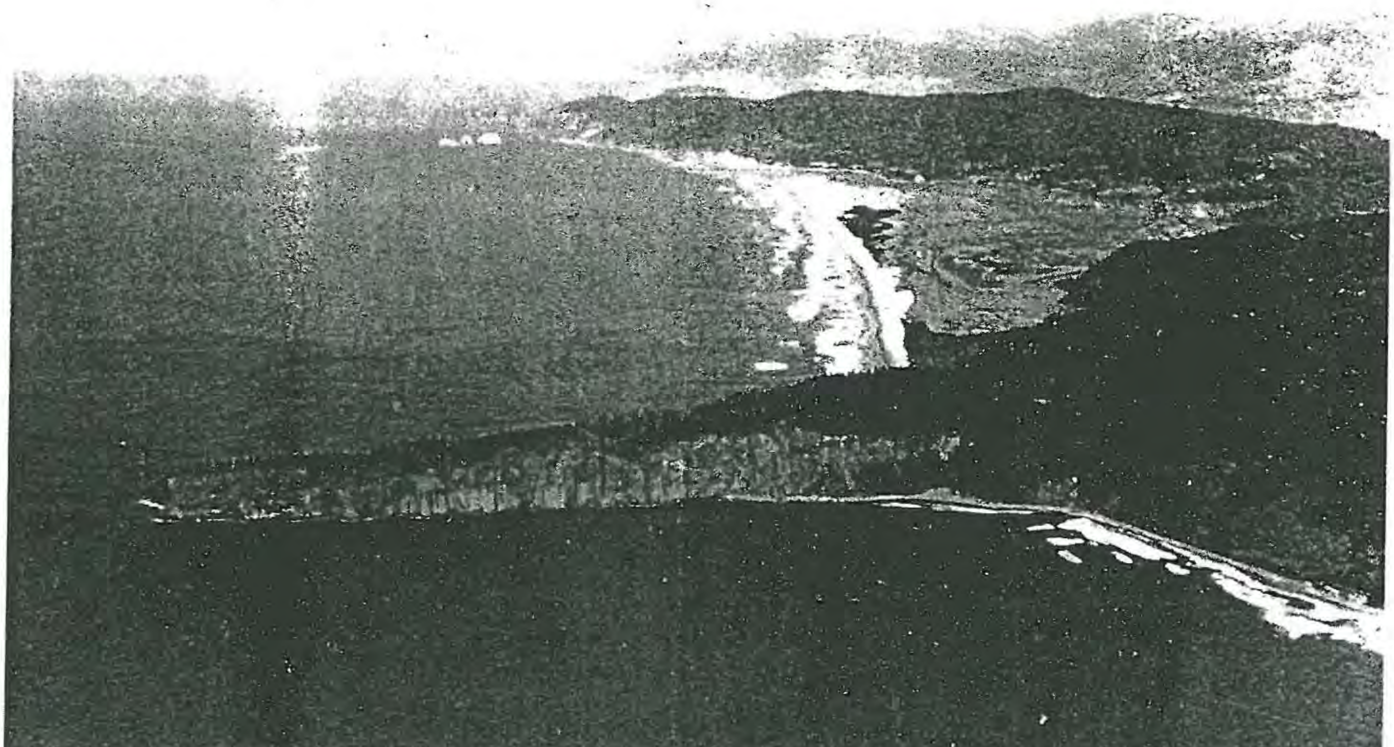

**Fig. 3 Oblique aerial photo taken during 1931, showing Cape Lookout and Netarts Spit with washovers [Brubaker Aerial Surveys, Portland, Oregon].**

Historic changes of Netarts Spit have been small, an its overall configuration is much the same as observed in its first survey a century ago. Prior to the problems initiated by the 1982-83 El Niño, there had been minimal erosion of the spit and its fronting beach. Vertical and oblique aerial photographs of the spit covering the past 50 years show that the dunes were vegetated, even on their slopes immediately backing the beach. In some photographs there are indications that dune erosion had taken place, but this affected only their seaward edges and cut them back by only a couple of meters. The photographs further reveal that rip-current embayments played a role in causing that limited dune erosion[6] Due to the longshore extent of the rip-current embayments, the erosion typically affected only some 200 to 500 meters of dune length rather than extending the full length of the spit.

In the late 1960s a 500-meter long timber bulkhead was built at the back of the beach in the park area to the immediate south of the spit (Fig. 4). Its construction was not a response to wave-erosion problems, but due instead to people walking on the dune face, leading to the loss of dune grasses and a renewal of aeolian activity and slumping. The bulkhead consisted of horizontal logs held in place by vertical I-beams, with its end protected by riprap composed of basalt rocks.

There had been minimal erosion on Netarts Spit for the past half-century. In the summer months there was an extremely wide sandy beach which attracted vacationers to Cape Lookout State Park. There conditions changed with the arrival of El Niño during the winter of 1982-83.

## THE EL NIÑO IMPACT ON NETARTS SPIT

As recently as a decade ago, El Niño events were thought to be limited to the coastal waters of Peru where every few years an incursion of warm water causes a mass killing of fish. This limited view changed as we came to appreciate that an El Niño involves a number of interrelated oceanic and atmospheric processes. Among these are the cessation of the trade winds in the equatorial Pacific, the release of a wave-like bulge of water that raises sea levels along the west coasts of North and South America, and shifts and intensifications of storm systems over the Pacific. The importance of these processes to coastal erosion became evident during the 1982-83 El Niño due to the extraordinary intensity of that particular event.

One important aspect of the 1982-83 El Niño was that the major storms crossed the U.S. coast much further south than usual.[5] This accounts for its major impact on the beaches of southern California. The southward displacement of the storms was also important to the Oregon coast in that the generated waves approached the beaches with larger than usual breaker angles from the southwest, and this produced a northward transport of sand along our shores. The result was that during the 1982-83 El Niño, sand was displaced northward within the individual littoral cells on the Oregon coast; sand eroded from the south ends of beach segments and deposited at the north ends. This can be viewed as a reorientation of each pocket beach to face the waves arriving from the southwest, or as any one headland acting like a jetty so that it blocks sand on its south and causes erosion to its immediate north. In subsequent years the sand that was displaced northward in the cells has slowly returned to the south restoring the pocket beaches of the cell to their long-term equilibrium orientations.

Being one of the smallest beach cells on the Oregon coast, the pocket beach within the Netarts cell would have undergone a marked reorientation. This depleted the beach of sand to the immediate north of Cape Lookout, evident in aerial photographs taken during and immediately following the 1982-83 El Niño period. The reduced buffering ability of this beach at the south end of the cell resulted in rapid erosion of the low-lying sea cliffs north of Cape Lookout, also apparent in the aerial photographs. In contrast to the basaltic headland, those cliffs are not particularly resistant to erosion, consisting of a mixture of alluvium, old forest soils, and ancient massive landslide deposits. There was a little concern about the erosion losses at that stage since this area of cliffs is undeveloped.

The first set of aerial photographs taken after the El Niño were obtained on January 31, 1984. These reveal that the beach progressively decreased in width toward the south, and there still was little if any sand on the beach north from Cape Lookout to the park. The beach was particularly narrow toward the northern end of the log bulkhead due to a major rip-current embayment. The next set of aerial photos (June 12, 1986) shows no unusual signs of erosion and no rip-current embayments. The beach still narrows toward the south, but by that stage a significant amount of sand had returned to the beach immediately north of Cape Lookout.

Except for the local effects of rip currents creating embayments in the shoreline (discussed below), the overall width of the beach is now essentially uniform along the full length of the Netarts cell. A sand beach exists to the immediate north of Cape Lookout, and there is no unusual accumulation of sand to the south of Cape Meares. This indicates that the shoreline has returned to its pre-El Niño quasi-equilibrium orientation. However, of particular significance is that the beach appears to be depleted in sand in comparison with its size prior to the 1982-83 El Niño. This is indicated by extensive areas of gravels on the beach and rock outcrops in the shallow offshore, features that were covered by beach sand prior to the 1982-83 El Niño. Unfortunately, profiles of the beach were not obtained before the El Niño, so that we are unable to

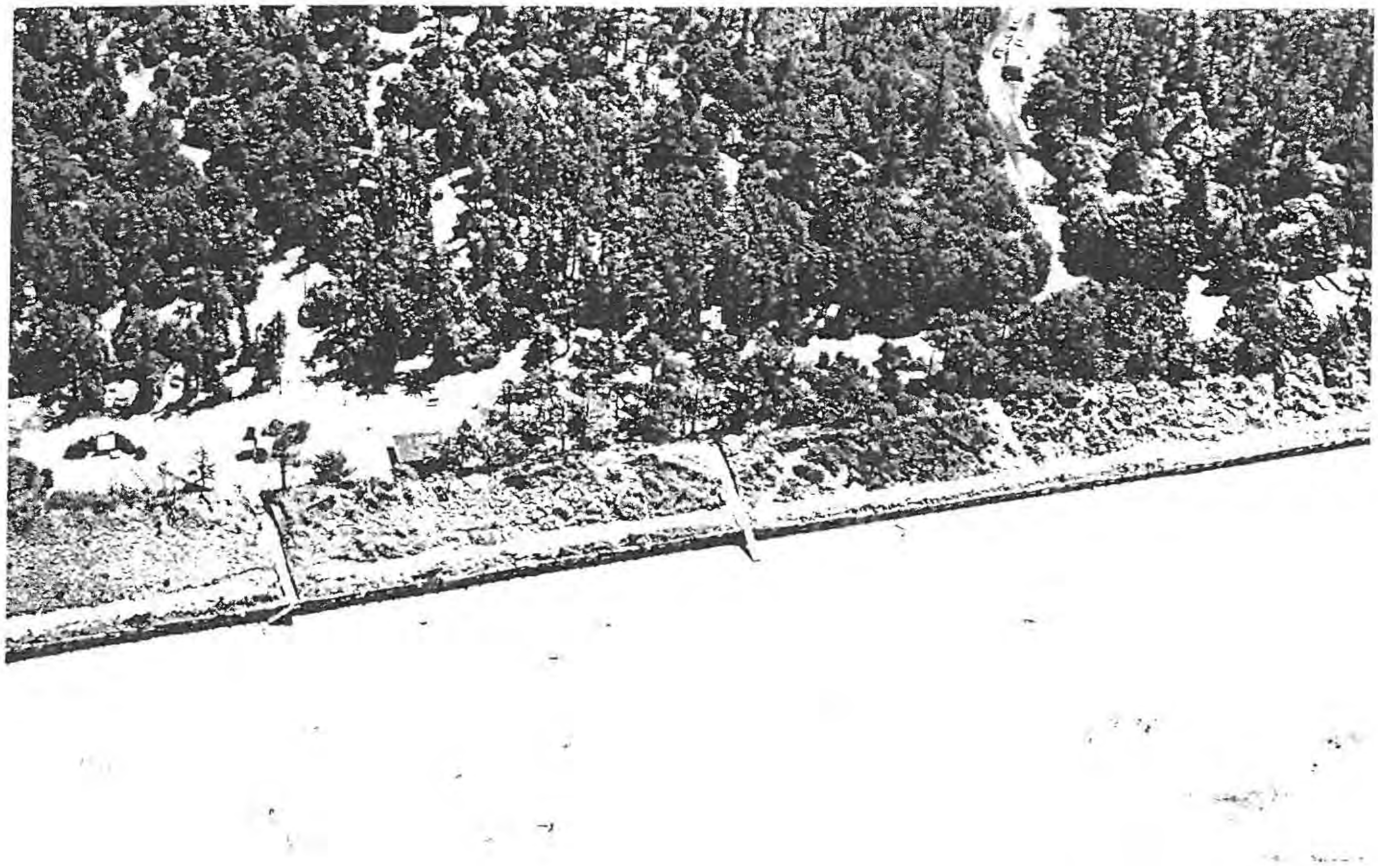

**Fig. 4 The log bulkhead along the parklands on Netarts Spit prior to its destruction by recent erosion [*upper* - July 21, 1975; Oregon State Highway Dept. photo A615-42; *lower* - July 25, 1975; P.D. Komar].**

assess quantitatively the volumes of sand lost from the nearshore.

There are two potential routes for sand losses from the beach. One would be to the offshore, the extreme wave conditions possibly having moved the sand to sufficiently deep water that it has been unable to move back onshore and return to the beach. This cannot be documented due to insufficiently accurate bathymetry in the offshore. However, other beaches on the Oregon coast have not suffered a permanent loss of sand that might have resulted had transport to the deep-water of the offshore been substantial. It is unlikely that the sand loss from the beach fronting Netarts Spit was directly to the offshore. The more probable route for beach-sand losses was into Netarts Bay. Sand moving northward along the beach fronting Netarts Spit during the El Niño storms would have encountered the broad tidal inlet. Caught up in the tidal flows, some sand would have been swept into the bay. The park manager at Cape Lookout State Park observed a growth of the sand shoals during the 1982-83 El Niño. We have examined the available aerial photographs in an attempt to further substantiate this, but we were unable to do so with confidence due to the photographs having been taken at different tidal stages.

The depletion of sand on the beach following the 1982-83 El Niño reduced its capacity to act as a buffer between storm waves and park properties on Netarts Spit. Because of this, there has been an epidemic of erosion problems in recent years. The October 1984 photograph of Figure 5 shows the bulkhead under direct attack by storm waves; a considerable deterioration of the wall has already taken place, with the beginning of erosion losses of the dunes. However, the structure was still intact over most of its length.

Each subsequent winter has brought additional erosion to Cape Lookout State Park. Failure of the bulkhead became more serious during storms in early 1987, with significant erosion of the dunes and parklands backing the beach. The losses accelerated during the winter of 1987-88 when a major rip current was once again positioned offshore from the wall. The first storm of the fall destroyed a major section of the bulkhead, and the waves cut away at the dunes. During the winter and spring, the rip current slowly migrated northward with a parallel migration of the zone of maximum erosion impact. The destruction of what remained of the wall has also progressively shifted northward. By spring there was little sand on this section of the beach; the profile instead consisted of a steep cobble beachface (Fig. 6). The I-beams were all that remained of most of the bulkhead, emerging from what is now the middle of the beach. A detailed survey conducted on June 4, 1988 showed a distinct low in the topography which represents the rip embayment at that stage in the erosion. Dune-bluff retreat distances then amounted to about 20 to 25 meters beyond the former position of the bulkhead. Nearly 400 meters of the south end of the structure had been lost.

It is apparent that the presence of rip currents off-

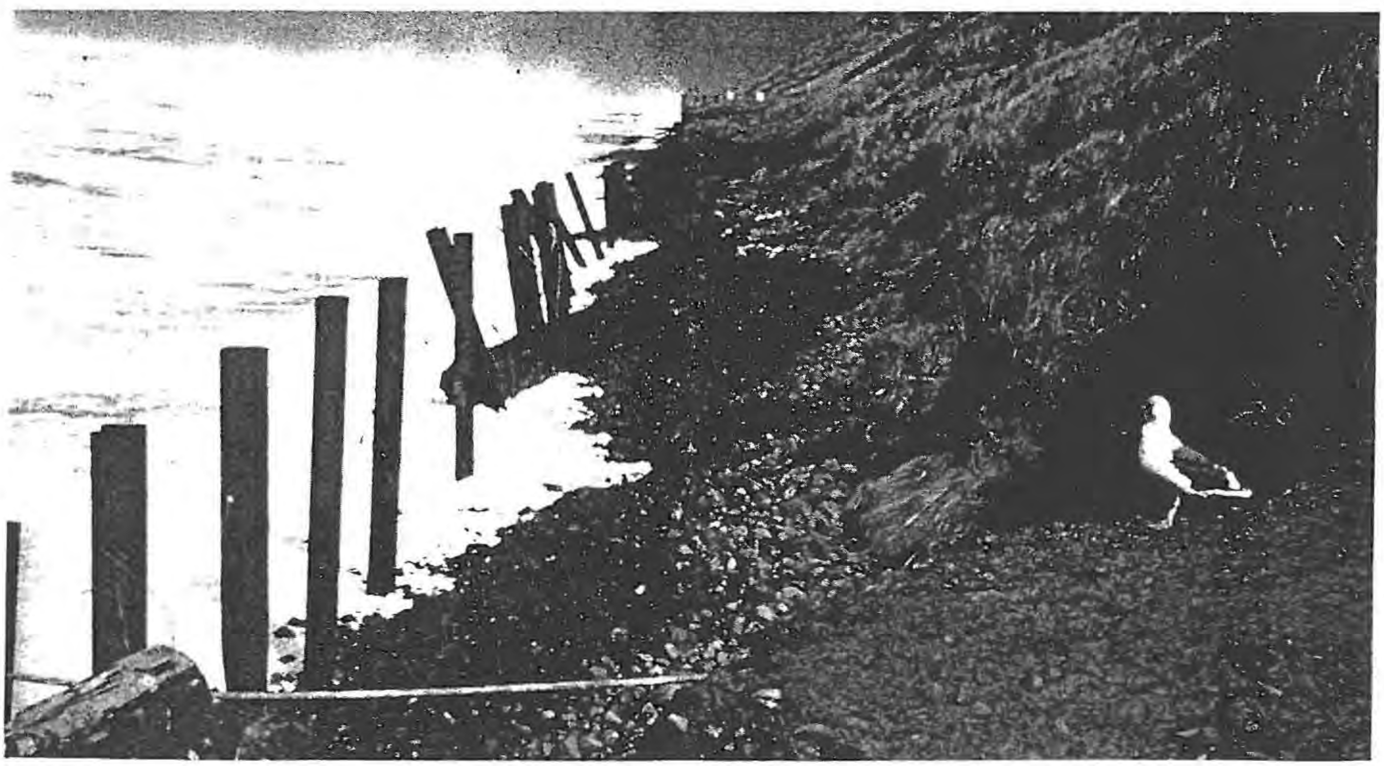

**Fig. 5 Partial destruction of the bulkhead and the initiation of dune erosion during October 1984 [J.W. Good].**

shore from the park during the winters of 1984-85 and again during 1987-88 was a major factor in causing the erosion. However, a more basic cause is the general depletion of sand on the beach following the 1982-83 El Niño. Prior to that El Niño the beach had a sufficient width that when a rip-current embayments did form, their erosion impact on the spit was minor, limited to a couple of meters of dune retreat. There is no evidence to suggest that rip-current embayments are larger now than before the 1982-83 El Niño. But now the embayments can quickly cut through the weakened beach and have a greater erosion impact on the dunes and parklands of the spit.

In view of this weakened condition of the beach to act as a buffer from wave attack, there is concern that the erosion may shift to other areas of Netarts Spit in future winters. It is likely that the positioning of rip currents is a random process, so that their locations will change from year to year. Next winter the focus of erosion might not be in the park area, but instead toward the central or northern end of the spit. There could be serious erosion in the zone where the spit is narrowest, with the potential for a complete breaching of the spit. This is of concern since Netarts Bay contains many acres of protected wetlands and has the highest diversity of clam species of any Oregon estuary.

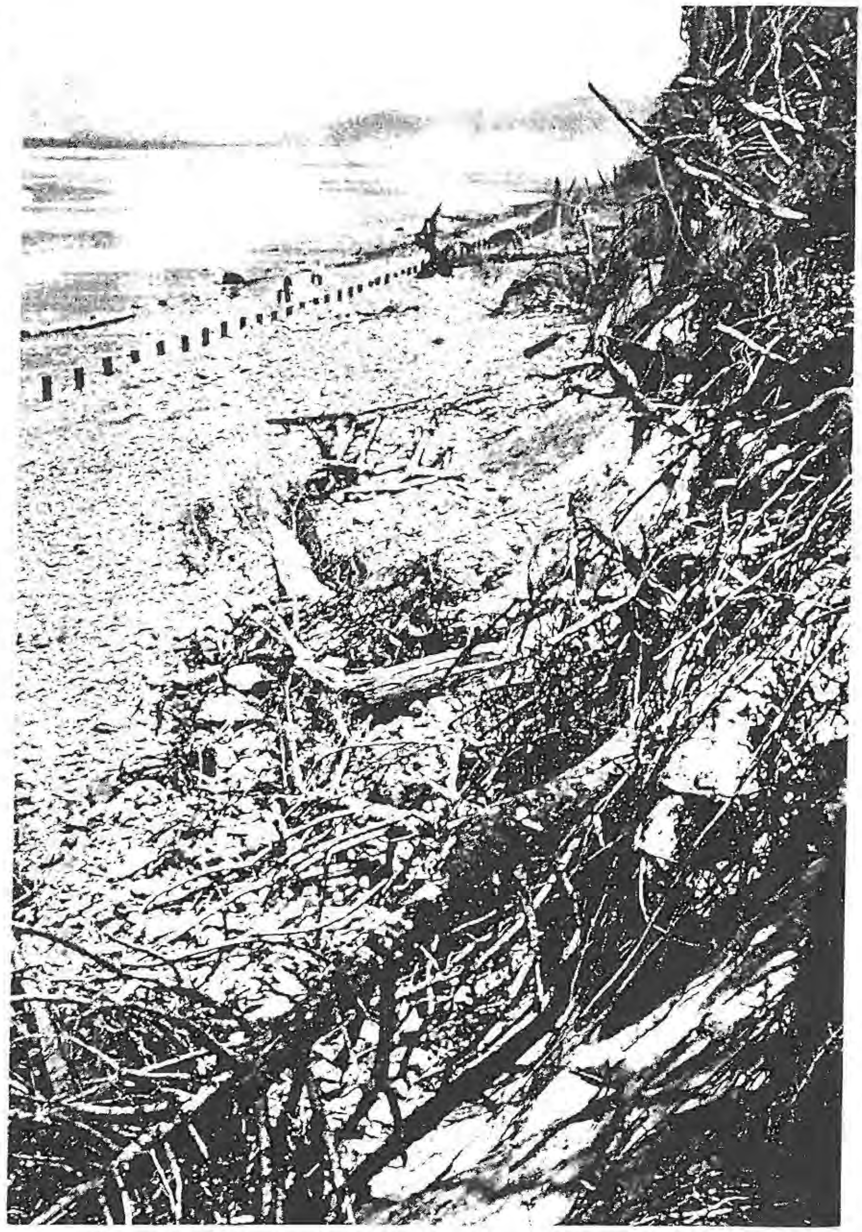

**Fig. 6 Recent Erosion of the beach and dunes fronting the parklands on Netarts Spit (June 4, 1988). The vertical beams, many of them cut off, were supports for the now destroyed bulkhead (Fig. 4).**

## POSSIBLE CORRECTIVE MEASURES

Potential measures to deal with the erosion of Netarts Spit have had to address two issues: (1) the significant losses of recreational lands in Cape Lookout State Park, and (2) the longer-term potential for erosion in other areas of the spit due to depleted volumes of beach sand. In view of the severity and rate of the erosion in Cape Lookout State Park, with an immediate threat to campground facilities, its was first necessary to focus on this aspect of the problem. The State Parks and Recreation Division has been evaluating the possibility of placing a riprap revetment at the base of the bluff in the immediate area of greatest losses. However, indications are that this solution to the erosion problem will not be implemented. The cost of the revetment would be some three times greater than the facilities it is designed to protect, so it would be more cost effective to move the seaward-most portions of the campground. There is also a general concern about the placement of structures of this type in state parks, and in particular within Cape Lookout State Park and the adjacent Netarts Spit which is designated as a Research Natural Preserve. There is also the possibility that the park may not experience additional erosion problems for several years, given that the erosion depends in large part on the occurrence of an exceptional rip current in that immediate area. Furthermore, construction of the revetment in the park would do nothing to secure the integrity of the rest of Netarts Spit.

An alternative approach would be beach nourishment, the placement of substantial quantities of compatible sand on the beach in order to advance the shoreline seaward. This approach would attempt to restore the beach-sand volumes to those found prior to the 1982-83 El Niño, and thereby re-establish the buffering capacity of the beach. If successful, this would eliminate or greatly reduce the necessity for constructing engineering structures along Netarts Spit. It would also have the benefit of fully restoring the recreational uses of the beach. Beach nourishment has not been attempted previously on the Oregon coast. The use of beach nourishment on Netarts Spit has a higher probability of success than generally experienced on the east coast of the United States where long, unbounded shorelines exist. As discussed earlier, the Netarts cell is a closed system between Capes Lookout and Meares, so there will be no losses due to longshore sand movements (as is the case on the east coast). One potential source of sand that could be used in such a nourishment project would be from dredging sandy shoals within Netarts Bay. This would in effect return sand to the beach which had been swept into the bay, some of it during the 1982-83 El Niño. An associated positive effect would be the restoration of the bay itself, which has undergone considerable shoaling even prior to the 1982-83 El Niño. However, this would have to be balanced against probable negative impacts of dredging operations in the bay. There are other potential sources of sand for nourishment of Netarts Spit. The routine dredging of the entrance to Tillamook Bay or the Columbia River by the Corps of Engineers likely obtains sand that is compatible in composition and grain sizes to the sand found on Netarts Spit. The Oregon State Parks and Recreation Division is presently examining whether a beach-nourishment scheme would be a viable option to solve the long-term erosion problems on Netarts Spit.

## SUMMARY

After many years with minimal erosion problems, Netarts Spit has become an area of major beach losses during the last five winters. This erosion is critical in that the chief impact has been at Cape Lookout State Park, a popular recreation site. The inception of this erosion has been attributed to the lingering effects of the 1982-83 El Niño. It appears that during the El Niño years, sand was transported northward along the beach fronting Netarts Spit and was then swept into Netarts Bay. This has permanently removed sand from the nearshore zone, and has left the beach-sand volume in a depleted condition. As a result, the beach no longer offers the same degree of buffering protection of the parklands from wave-erosion processes as it did prior to the 1982-83 El Niño. Potential solutions to the erosion problem have considered: (1) the placement of a small-scale riprap revetment in the area of the park that has suffered severe erosion, and (2) a beach nourishment project to restore the beach as a buffer between the developed parklands and storm waves. In that the area is designated as a Research Natural Preserve, it is unlikely that a revetment will be installed. Furthermore, such a revetment would only serve as local protection rather than as a general solution to the problem. Instead the use of beach nourishment is being given more consideration since this approach is compatible with maintaining the site in a natural condition, it would restore the recreational uses of the beach, and nourishment would act to protect the entire length of the spit.

## ACKNOWLEDGEMENTS

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# The 1997-98 El Niño and Erosion on the Oregon Coast

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WE FIRST BECAME AWARE of the importance of El Niño to coastal erosion in the Pacific Northwest — the shores of Oregon and Washington — during the extreme 1982-83 event.[5,6,9,10] The realization that El Niño can bring havoc to our coast has been strongly reinforced by the 1997-98 occurrence. Beach and property erosion has been severe at a number of sites along the Oregon coast, recurring in areas that previously had suffered during the 1982-83 El Niño. The objective of this paper is to briefly examine the coastal processes enhanced by El Niño that are important in producing erosion along the Oregon coast. While measurements during the ongoing El Niño are still being collected and analyzed, it is evident that the processes are remarkably similar to those experienced during 1982-83. The main focus of this paper will be a description of the erosional "hot spots" experienced during the 1997-98 El Niño along the Oregon coast. The examples presented will serve to illustrate how El Niño processes combine to yield unusually severe beach erosion and property losses.

## PROCESSES OF COASTAL EROSION

Most occurrences of coastal erosion involve one or more of the following processes:

- *storm-generated waves*
- high predicted tides
- *elevated water levels above the predicted tidal elevation*
- an increase in relative sea level due to glacial melting plus land-level change
- *erosion of embayments by rip currents*
- *alongshore movement of beach sediment*
- *jetty or breakwater disruption of beach sand movement*
- *migrations of tidal inlets and river mouths*

The processes that are enhanced during an El Niño and result in increased erosion along the Oregon coast are given in italics. Important is that not only are the intensities of these processes enhanced during an El Niño, they generally reinforce one another to maximize their erosional impacts.

### Enhanced sea levels

Particularly unusual during an El Niño are the processes that locally alter mean water levels in the ocean. They become readily apparent when we compare predicted tides, those found in tide tables, with the measured tides that are actually experienced. During both the 1982-83 and 1997-98 El Niño years, tides on the Oregon coast were typically 1 to 2 feet higher than predicted. The elevated water levels tended to drown out the beaches, and were extremely important at times of high tides since the water was able to reach sea cliffs and foredunes, allowing waves to attack and erode coastal properties.

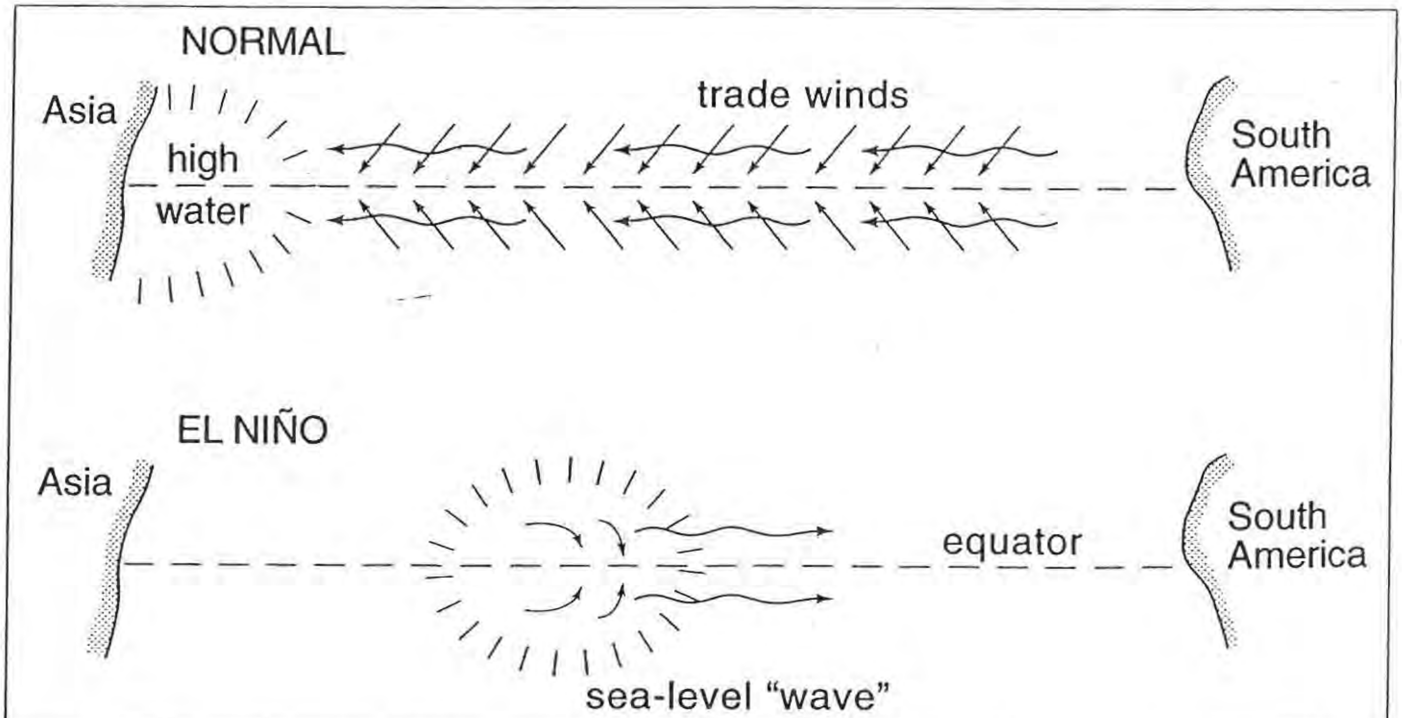


**Figure 1.** The shift in Trade Winds and ocean currents along the equator in the Pacific Ocean during a normal year (upper) versus an El Niño year (lower). The cessation of the Trade Winds during an El Niño produces a sea-level "wave" that travels eastward along the equator.

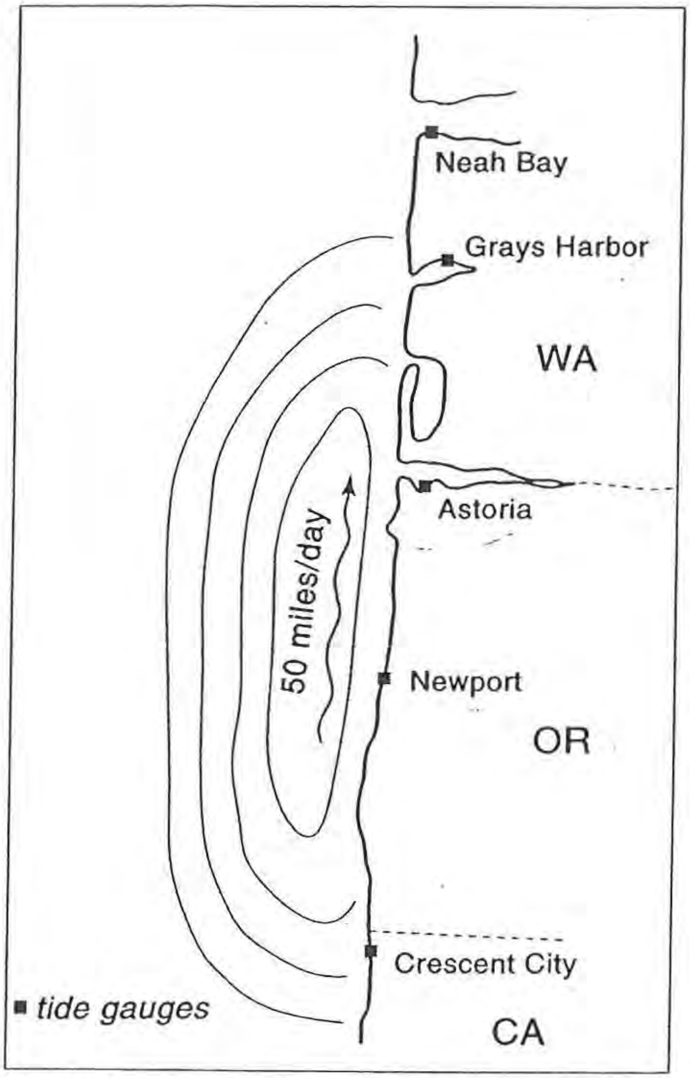


Figure 2. Schematic depiction of the sea-level wave moving northward along the Oregon coast, measured by the series of tide gauges.

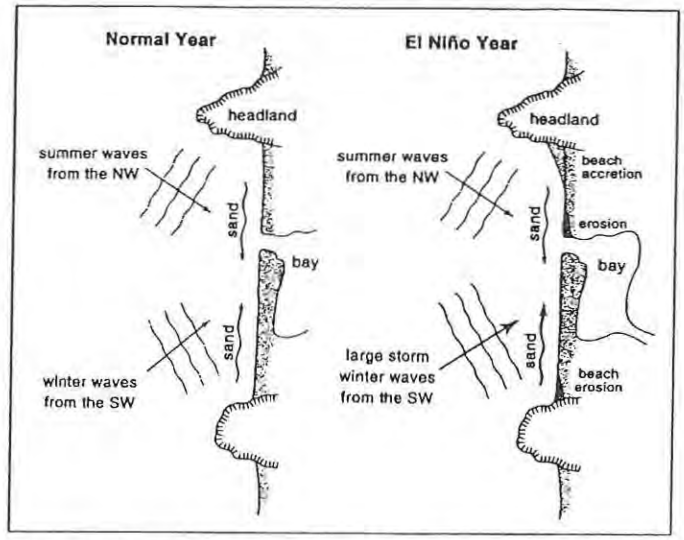


Figure 3. Alongshore movement of beach sand within littoral cells on the Oregon coast due to the seasonal shift in wave directions. During normal years (left) there is an approximate balance of north and south sand movements, but in an El Niño year (right) the strong storm waves from the southwest cause large amounts of sand to move to the north, causing "hot spot" erosion areas.

Part of this elevated water level on the Oregon coast owes its inception to changes in processes acting along the Earth's equator during an El Niño. Historically, the first recognized impacts of an El Niño were dramatic changes in water temperatures and fisheries off the coast of Peru. Upwelling normally brings deep ocean water to the surface, much as it does off Oregon. The cold water, high in nutrients, has made the Peruvian fisheries one of the richest in the world. However, during an El Niño this system breaks down and the water becomes warm; fish and sea birds die en mass. Such an event usually develops during the Christmas season — hence its name, El Niño or "The Child".

It once was thought that the onset of an El Niño off Peru was caused by the cessation of local coastal winds which produce upwelling. This view changed when the physical oceanographer Klaus Wyrtki demonstrated that these local winds do not necessarily diminish during an El Niño.[13] Instead, he found that the breakdown of the equatorial Trade Winds in the central and western Pacific trigger an El Niño, far away from the Peruvian coastal waters where its chief impact is felt. The process is illustrated schematically in Figure 1, contrasting a normal period with an El Niño year. During normal years the Trade Winds blow toward the equator but with a component directed to the west, and generate ocean currents that flow toward the west parallel to the equator. The stress of the wind on the water and the westward flow of currents combine to produce an elevated water level in the western Pacific, centered in the area where the equator intersects the coast of Asia. The same effect is obtained when blowing steadily across a cup of coffee — the surface of the coffee becomes highest on the side of the cup away from you. If you stop blowing, the coffee surges back and runs up your side of the cup. The process is similar in the ocean when the Trade Winds stop blowing during an El Niño year; this condition is depicted in the lower half of Figure 1. The slope of the water surface is released, and this results in the eastward flow of warm water along the equator toward the coast of Peru where it kills fish not adapted to warm temperatures.

Associated with this warm water movement eastward along the equator is a wave-like bulge in sea level, also depicted in the lower diagram of Figure 1. The eastward progress of the sea-level wave has been monitored by Wyrtki through analyses of tide gauges located on islands near the equator.[14,15] Data from a tide gauge can be averaged to remove the tidal fluctuations, yielding a measure of the mean level of the sea during that time interval. The analyses by Wyrtki clearly demonstrated the eastward movement of sea-level waves during El Niño events, affecting in turn tide gauges from west to east on the series of equatorial islands.

With its arrival on the coast of South America, the sea-level wave splits, and the separated parts respectively move north and south along the coast. Analyses of tide-gauge records along the full length of the west coasts of North and South America have demonstrated that the sea-level waves can travel as far north as Alaska.[1] The passage of a sea-level wave along the Oregon coast is depicted schematically in Figure 2, which also shows the locations of tide gauges used to monitor its movement.

The increased elevations in mean sea level along the Oregon coast during an El Niño are only partly due to a sea-level wave originating at the equator. Other factors include changes in water temperatures along the coast, and the development of a northward flowing current. During normal years, upwelling occurs in the summer along the Oregon coast, and this produces colder and more dense water than in the winter. The result is that monthly mean sea levels tend to be higher during the winter when the water is warm and less dense. During an El Niño the water is unusually warm, and this contributes to the elevated water levels along the coast. There is also a reversal in current directions from winter to summer. During the winter the current flows toward the north, and the rotation of the Earth (the Coriolis effect) deflects the current to the right, that is, toward the coast, elevating still further the level of the sea along the shoreline. These processes tend to occur every year, causing sea levels along the Northwest coast to be higher during the winter than in the summer. But in an El Niño year these processes are more intense, with the water during the winter being warmer than usual and the northward current stronger. So these factors add to the sea-level wave moving northward from the equator to produce extreme water levels during an El Niño winter.

Reinard Flick and colleagues at the Scripps Institution of Oceanography have analyzed the extreme sea levels on the coast of California produced by El Niño events.[2,3] Similar analyses have been undertaken of monthly-averaged sea levels along the Oregon coast.[4,5,6] During the 1982-83 E Niño, sea levels on the Oregon coast were truly exceptional, reaching some 8 to 16 inches higher than previous winter maxima, about 14 inches above the average winter level. Similar results are found for the 1997-98 El Niño. During January and February 1998 the measured sea levels were again 14 to 16 inches above the average winter level.

The water-level increase during an El Niño year along the Oregon coast is seen to be substantial, making the measured tides persistently higher than predicted. This elevated water level is extremely important in producing coastal erosion during an El Niño. Beaches along the Oregon coast typically have slopes of about 1-in-50, so an increase in water level of 15 inches as experienced during the 1997-98 El Niño winter shifts the shoreline landward by about 60 feet, drowning out most beaches at high tide. This moves the shoreline to the base of the sea cliff or foredunes, and permits the direct attack of waves against coastal properties, in large part accounting for the extreme erosion during an El Niño.

## El Niño storm waves

Coastal property erosion usually occurs when storm waves combine with elevated water levels, and this is especially true during an El Niño when these processes are intensified and reinforce one another. During an El Niño the high-altitude jet stream in the atmosphere becomes narrow and strong, and spins off cyclonic storms over the Pacific that are more intense than usual. The jet stream is also shifted further south, so the storms cross the North American coast in southern California rather than passing over the Northwest. These storm systems are important to the generation of high-energy waves, and in an El Niño year with the shift of storms to the south, communities such as Malibu Beach in southern California have a taste of wave energies to which they are not accustomed.

Richard Seymour and colleagues have undertaken detailed analyses of El Niño storm systems and generated waves, with their focus being primarily on the coast of California.[11,12] Wave conditions along the Northwest coast also are intensified during an El Niño year. Daily measurements on the Oregon coast during the 1982-83 event demonstrated the occurrence of several storms that generated high-energy waves during January and February 1983, simultaneous with the occurrence of the highest water levels.[5] The 1997-98 El Niño has seen a repeat of high wave conditions on the Oregon coast. The first major storm of the winter occurred on 14 November 1997, when deep-water significant wave heights reached 16 feet. The first substantial property erosion of the El Niño winter occurred during a storm on December 13-14 ; although the wave conditions were comparable to those on November 14, the tides were higher and the beaches had been cut back during the ensuing month, allowing the waves to more directly attack sea cliffs and foredunes. Storm wave activity significantly increased in January and continued through February. During those two months, twelve storms generated waves having deep-water significant wave heights in excess of 20 feet. Far and away the largest occurred on January 17, when the deep-water significant wave height reached 30 feet; they would have grown to some 35 to 40 feet in height when they traveled to the nearshore and broke on Northwest beaches.

While there has been an overall intensification of wave energies along the Northwest coast during both the 1982-83 and 1997-98 El Niño years, compared with normal years, the intensification is more in the frequency of storm-wave occurrence than in the absolute extreme sizes of the generated waves. The 30-foot waves on 17 January 1998 have an expected return interval of about 10 to 20 years, so are somewhat exceptional, while the 20 to 25-foot storm waves have return periods of roughly 1 year, which means that we experience waves having those heights essentially every winter. The difference is that we have seen more storm wave occurrences having 20 to 25-foot heights during the El Niño winters than in normal years. Higher waves can occur along the Oregon coast during normal years, in part because the paths of storms bring them directly across our shores. While extreme waves are generated by El Niño storms[11,12], their impacts are felt more directly in southern California than on the Northwest coast of Oregon and Washington.

## Longshore movement of beach sand

An important aspect of the El Niño storms and generated waves to Oregon coast erosion is the southerly shift of the storm systems, with their passage over California. The result of this shift is that the storm waves approach the Oregon coast more frequently from the far southwest quadrant compared with normal years. This produces an abnormal northward movement of sand along our beaches, which exerts a strong control on the locations of "hot spot" erosion.

Important to this control is the fact that the Oregon coast is divided naturally into a series of littoral cells, stretches of beach isolated by large rocky headlands.[6] The stretch of beach may range from only a couple of miles to as long as 50 miles in the case of the Coos Bay littoral cell that extends from Cape Arago in the south to Cape Perpetua at its northern end. There is little or no exchange of beach sand around the bounding headlands (shown by differences in beach sand grain sizes and mineralogies), so the stretch of beach within a littoral cell is largely isolated and self contained.

A schematic depiction of a littoral cell is diagrammed in Figure 3, contrasting the wave directions and alongshore sand

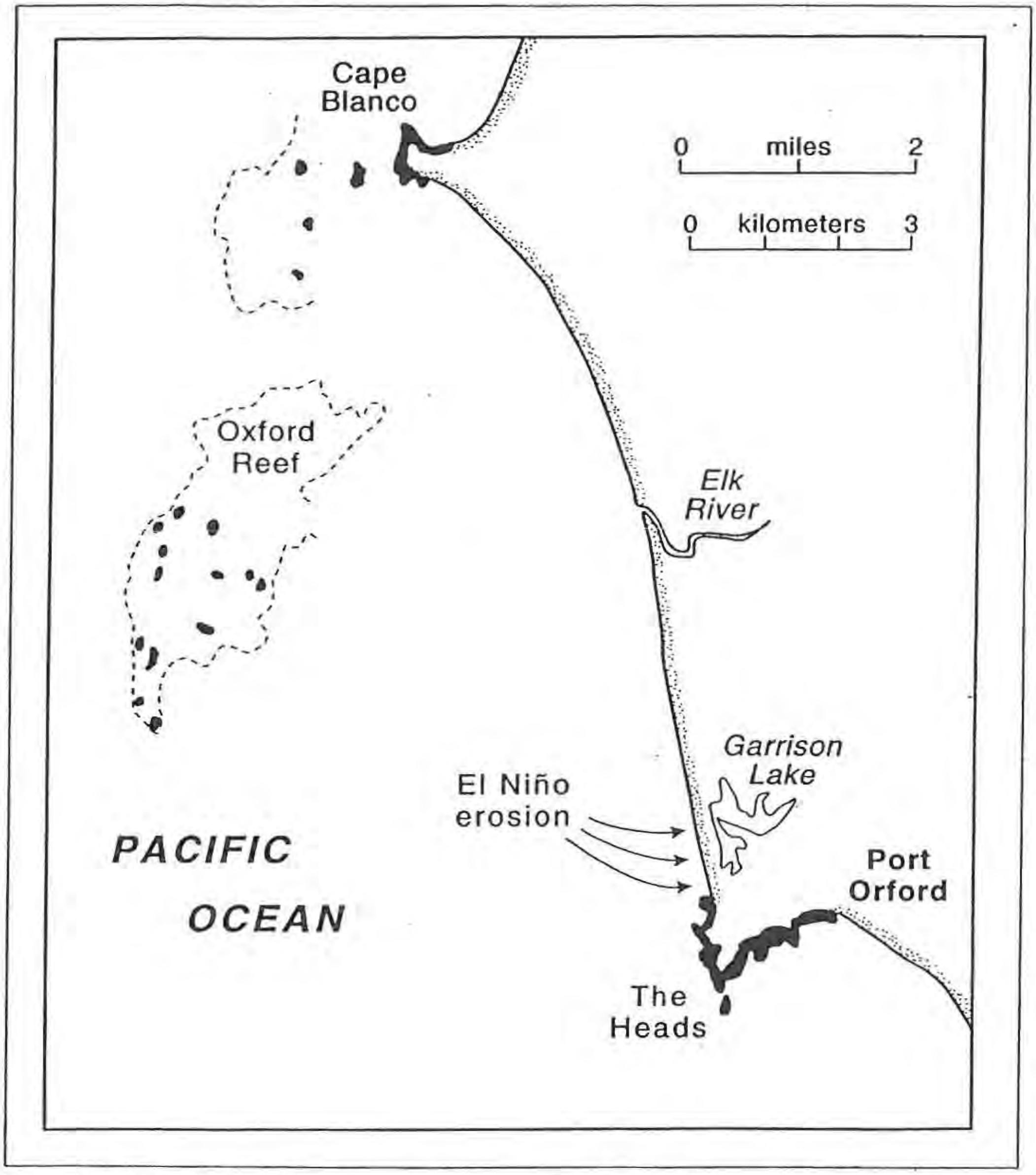


**Figure 4. Erosion at Port Orford occurred at the south end of the littoral cell that extends from The Heads to Cape Blanco.**

movement during normal years (left) with an El Niño year (right). In a normal year the summer waves dominantly approach the coast from the northwest, causing sand to move southward along beaches, while the winter waves arrive from the southwest and move sand back toward the north. Over the span of several normal years there is an equilibrium balance, with approximately equal amounts of sand moving north and south. This equilibrium was seen in shoreline changes that occurred when jetties were constructed along the coast early in the century, with a symmetrical pattern of shoreline change north and south of the jetties.[6]

In contrast to the equal north and south movements of sand during a normal year, in an El Niño event (Figure 3, right) more sand moves toward the north under the frequent storm waves arriving from the southwest. One result is that sand is systematically moved from the south ends of the littoral cells, producing erosion there, while sand accumulates at the north ends so the beaches widen. Jetties on inlets can have much the same effect as a headland. During an El Niño with the enhanced sand movement toward the north, the jetties block this drift resulting in beach sand accumulation to the south of the jetties while enhanced erosion occurs to the immediate north. This pattern may be obscured in part by the seasonal cross-shore movement of sand along the beach profile. During the winter the high waves erode sand from the dry part of the beach and transport it to offshore bars, while low waves of the summer reverse this process.[6,7] Thus the actual response of the beach (net erosion or accretion) at a specific site depends on the combined effects of the alongshore movement of sand related to the El Niño, and the cross-shore movement associated with the seasonal cycle of beach profile change.

Natural inlets to bays and estuaries on the Oregon coast, those uncontrolled by jetties, tend to migrate to the north during an El Niño due to the stronger northward movement of beach sand. This can result in beach and property erosion to the immediate north of an inlet, as depicted in Figure 3 (right). This shift is temporary, with the inlets tending to migrate back toward the south during subsequent normal years.

## EROSION HOT SPOTS DURING THE 1997-98 EL NIÑO

In the preceding section it was seen that a number of processes are involved in producing enhanced coastal erosion during an El Niño. While the increased sea level and wave energies act to produce greater erosion along the full length of the coast, the alongshore movement of beach sand and deflection of inlets yields "hot spots" where the erosion is greatest (Fig. 3). In this section we examine several erosional hot spots that occurred along the Oregon coast during the 1997-98 El Niño, and attempt to understand their development in light of the processes described above.

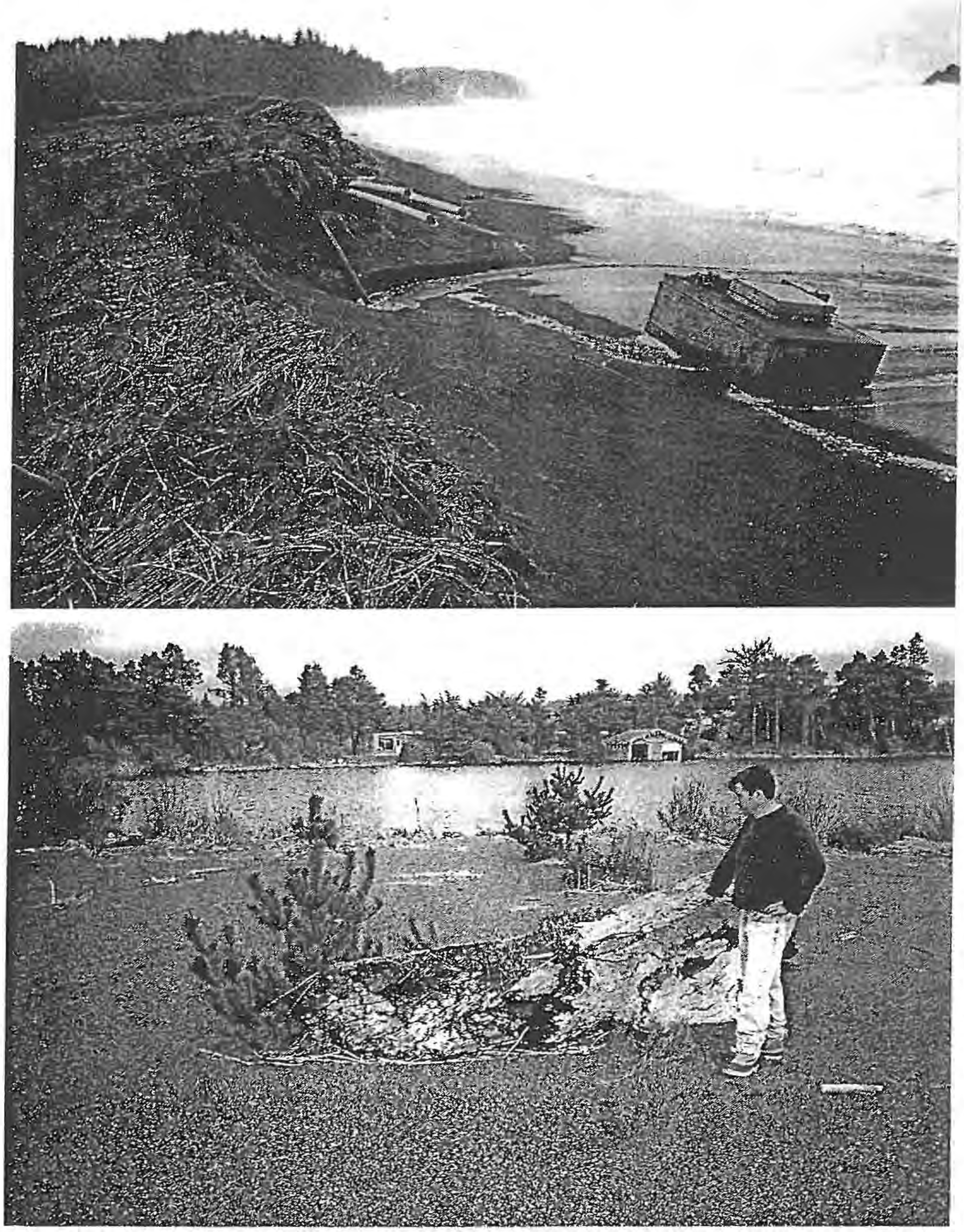

Figure 5. The erosion at Port Orford during the 1997-98 El Niño destroyed the drain field of the sewage treatment plant (upper), and has carried beach sand into Garrison Lake (lower), the city's chief fresh water supply.

occurred at the south end of the littoral cell, fitting the pattern of El Niño impacts with storm waves arriving from the southwest and moving beach sand alongshore toward the north.

The eroding shore is centered on the narrow beach/dune barrier that separates the ocean from Garrison Lake. The beach is composed of coarse sand with some gravel, and is steep and has a narrow surf zone. This type of beach erodes very rapidly when attacked by storm waves that break directly on the beach face close to shore.[6,7] Prior to the El Niño erosion, extensive dunes had accumulated in this area and the City of Port Orford had installed the drainage field for its sewage treatment system within the dunes. Erosion this winter has all but eliminated the dune field and destroyed most of the drain field. The threat now is that continued erosion may break through the beach/dune barrier into Garrison Lake. This lake is the principal source of fresh water for the community, and there are a number of homes built along its shore that may be adversely affected by a breach. The combined elevated mean water levels and runup of storm waves from El Niño have frequently washed over the barrier into the Lake. This overwash process has eroded sand from the beach and carried it over the top of the barrier and into the Lake (Figure 5, lower). This has had a positive effect by building up the elevation of the barrier, making it less likely that the erosion will break through and create an inlet connecting the ocean with Garrison Lake. There is still a critical area at the south end of the barrier, where the erosion is cutting back the dunes and forming a nearly vertical scarp (Figure 6). Although there has been frequent washovers of ocean water in this area, this has not carried sand to build up the elevation of the barrier as has occurred further to the north. The barrier at the south end is now very narrow, so there is the possibility that it could break through into the Lake. The City has placed a ridge of gravel and cobbles along the top of the barrier to prevent further washover, which at this stage could develop into a breach of the barrier, forming an inlet.

## Port Orford

The erosion at Port Orford during the 1997-98 winter illustrates several factors that are important in an El Niño year. Port Orford is a small community on the southern Oregon coast, with the center of the city situated immediately south of a headland known as The Heads (Figure 4). However, the community extends to the north of The Heads, and it is this area that has been experiencing severe erosion. This stretch of beach comprises a littoral cell that extends north to Cape Blanco, Figure 4, a distance of about 8 miles. The erosion, shown in Figure 5,

Figure 6. The El Niño erosion is now threatening to break through the beach/dune barrier and wash into Garrison Lake, prevented by the placement of a gravel ridge.

If dune erosion continues, the gravel and cobbles will slough off onto the eroding dune scarp and upper beach, where its presence should provide some temporary protection from continued wave attack, hopefully being a sufficient defense until the impacts of the 1997-98 El Niño end.

### Alsea Spit

One of the main areas of erosion during the 1982-83 El Niño took place along Alsea Spit on the central Oregon coast.[5,6] The primary factor important to erosion was the northward migration of the inlet to Alsea Bay. Inlet migration combined with the elevated water levels and storm waves to completely erode away the beach along nearly the full length of the spit. The waves and currents then begin to cut back the foredunes, where a number of homes had been constructed. One house was lost, while the others were saved by the placement of riprap at the base of the eroding dunes.

In the years subsequent to the 1982-83 El Niño, the return of lower water levels and less severe wave conditions has allowed the beach to recover along Alsea Spit. The beach has become very wide, and onshore winds have blown sand into the dunes so they had fully recovered from the El Niño erosion. Eventually the riprap revetment was covered by the accumulating dune sand, and apparently forgotten. Development began once again, and a number of new homes were build on the spit. Unfortunately, some were constructed atop and across the now buried revetment, seaward of this line of defense, in the area where erosion had occurred only a decade earlier.

The return of El Niño during the winter of 1997-98 has brought about a recurrence of erosion problems on Alsea Spit. Older homes landward from the line of riprap placed in 1982-83 are likely safe from the renewed attack, but the newly constructed homes that extend seaward from the riprap line are now in danger. It is possible that another line of riprap will have to be installed to protect those homes.

### Cape Lookout State Park

Another area of significant erosion during the 1982-83 El Niño occurred at Cape Lookout State Park on Netarts Spit (Figures 7 and 8).[6,9,10] This park is located at the south end of the Oceanside littoral cell, so again much of its erosion can be attributed to the northward transport of sand by the approach of high storm waves from the southwest during the El Niño, moving sand toward the north. During 1982-83, much of the sand disappeared from the beach, apparently carried into Netarts Bay, so the reduced sand volumes on the beach within this littoral cell now make it more susceptible to attack by waves, in normal years and well as during an El Niño. Another factor in the erosion during the 1982-83 El Niño was the presence of a large rip current flowing seaward from the area of the park, carrying sand offshore and contributing to the local erosion. Erosion in the park partially destroyed an old log seawall, and then eroded away the high ridge of dune sand that had sheltered the park development.

Erosion of Cape Lookout State Park during the 1997-98 El Niño year, Figure 8, has essentially picked up where the 1982-83 event left off. The last remnants of the log seawall are rapidly disappearing, leaving the tall iron beams extending vertically from the beach that had been used to support the logs (the beams remaining after the 1982-83 erosion have been cut off by State Parks). Additional dune erosion has occurred, and the public bathrooms were in danger of being undermined by waves until a line of riprap was placed for protection (Figure 8). High water elevations have combined with storm wave runup to wash over into the park lands, depositing a large amount of beach sand in the campground. Such extensive washovers did not occur during the 1982-83 El Niño.

### The Capes

Most dramatic and newsworthy has been erosion during the 1997-98 El Niño at The Capes, a development of expensive condominiums recently built on the high bluff to the immediate north of the inlet to Netarts Bay (Figure 9). The site is centered within the Oceanside littoral cell, Figure 7, about 6 miles north of Cape Lookout State Park. The Capes erosion is not only dramatic in its potential economic impacts for the home owners, but also due to the number of coastal hazards involved.

Being immediately north of the inlet to Netarts Bay, the northward migration of the inlet during the 1997-98 El Niño winter has acted to erode the fronting beach and has created deepened water directly offshore. Normally the low sloping beaches in this littoral cell cause the waves to break well offshore so most of their energy is dissipated before they runup on

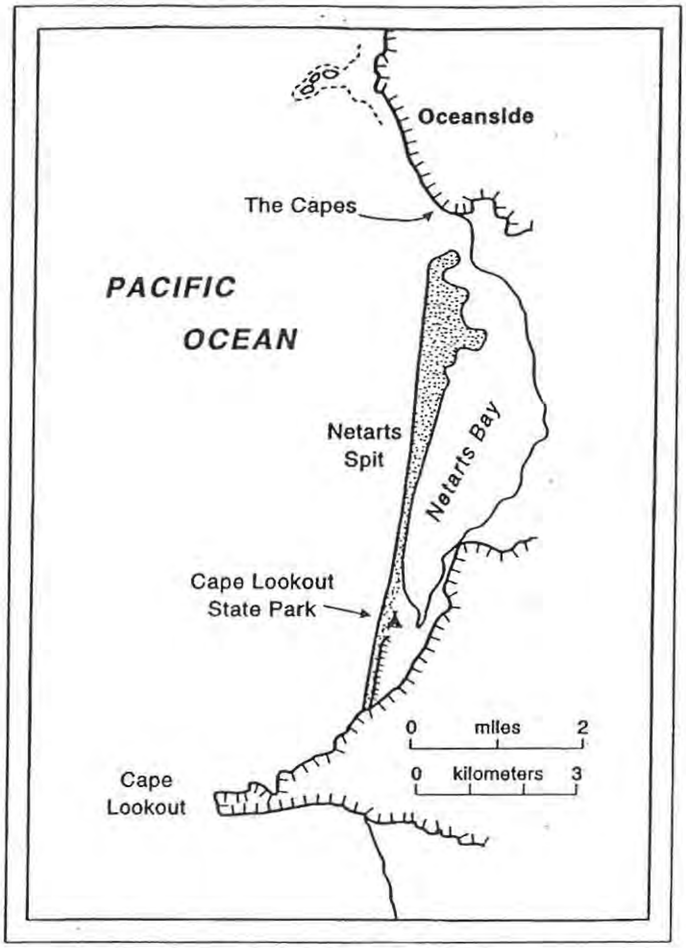


**Figure 7. The Oceanside Littoral Cell, where El Niño erosion has centered on Cape Lookout State Park and at The Capes development.**

the beach face at the shore. With the creation of deeper water due to the migration of the inlet, the waves can now travel closer to shore before breaking, with less loss of energy. The runup of the stronger waves now combines with the elevated mean water levels associated with the El Niño, allowing the runup to reach the toe of the high bluff below The Capes. The resulting toe erosion has made the bluff unstable, and slippage of the land now poses the immediate threat to the front line of condominiums (Figure 9). Unfortunately, the condominiums had been constructed with only a 10-foot setback distance, insufficient considering the potential for erosion and instability of the site, so many of the homes were immediately placed in danger.

The development site is located atop an old massive landslide. The lower portion, now exposed by the toe erosion, consists of a layer of mud that is extremely mobile; rather than participating in rotational slippage typical of many landslides, this mud appears to be squeezed out like toothpaste by the weight of the overlying material. This overlying material is sand of old dunes deposited atop the bluff, sand that has minimal internal strength so it tends to cascade down slope, much like the loose sand of an active modern dune. Thus, only part of the problems at The Capes can be attributed to the occurrence of an El Niño and its erosion processes. There were the pre-existing hazardous conditions of the development having been constructed on a landslide, the upper part of which consists of dune sand. The present instability and movement of the landslide can, however, be attributed to the erosional impacts of the 1997-98 El Niño, which have cut away the toe of the landslide.

## CONCLUSIONS

The Northwest coast now has experienced two major El Niño events, that in 1982-83 and again in 1997-98. Both resulted in substantial beach erosion and impacts to coastal properties. Although data are still being collected and analyzed from the recent event, the evidence thus far is that the processes are very similar to those which occurred during the 1982-83 El Niño. Important to coastal erosion are the elevated water levels that cause tides to be 1 to 1.5 feet higher than predicted, the generation of high energy waves by more frequent storms, and the fact that the waves approach the coast more from the southwest, causing a northward movement of sand that redistributes beach sand volumes along the coast and causes inlets to migrate to the north. It is the combination of these processes and the fact that they reinforce one another that accounts for "hot spot" erosion areas along the Oregon coast, such as at The Capes.

At the time of this writing (May 1998), El Niño is continuing, but looks to be decreasing and will likely

**Figure 8. The erosion of Cape Lookout State Park on Netarts Spit, which has cut back the large coastal dunes and is now eroding the campground. The last vestiges of the log seawall are seen in the background.**

Figure 9. The Capes is a recent development of expensive condominiums, located on the edge of an old massive landslide (upper). Erosion of the toe of the slide during the 1997-98 El Niño has caused it to become unstable with slippage threatening the first line of homes (lower).

soon come to an end. Water temperatures and sea levels in the equatorial Pacific are returning to normal conditions. The same can be expected off the Northwest coast. Wave energies along the coast abruptly declined at the end of February, following the usual pattern of decreasing wave conditions in the summer. The eroded beaches have noticeably began to rebuild. So additional property erosion is unlikely, at least through the summer. But we may not have seen the last of the impacts that can be attributed to the 1997-98 El Niño. Following the 1982-83 event, significant erosion took place during subsequent winters, continuing in areas that had eroded during the El Niño winter.[6,9,10] The processes directly associated with El Niño had ceased (unusually high water levels, etc.), but the beaches were unable to fully recover during the following summer. Sand that had shifted far offshore to deep water did not completely return to the dry beach, and sand moved alongshore to the north within the littoral cells did not all shift back to the south. So with the return of high storm waves the following winter, many beaches were still depleted in sand and were not able to adequately buffer coastal properties, so erosion began once more. In fact, it was 2 to 3 years before the beaches fully recovered, and the lingering impacts of the 1982-83 El Niño finally ended. It remains to be seen whether history repeats itself, and whether or not we have seen the last of the 1997-98 El Niño impacts on the Oregon coast.

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# El Niño and Coastal Erosion in the Pacific Northwest

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## INTRODUCTION

El Niño/Southern Oscillation (ENSO) has a profound effect on the Earth's weather and climate, and on ocean processes including water temperatures, currents, mean sea level and wave generation. The accompanying paper by Taylor (1998) focuses on changes in weather and climate in the Pacific Northwest, while the present paper deals with the oceanic processes that are important in causing beach and property erosion. We became particularly aware of the importance of El Niño to coastal erosion in the Northwest during the extreme 1982-83 event (Komar 1986, 1997; Komar et al., 1988; Komar and Good, 1989), and this awareness has been reinforced by the 1997-98 El Niño. There has been much news coverage of the El Niño produced erosion along the coast of California (together with accounts of floods and landslides). Beach and property erosion also has been severe in the Pacific Northwest, having occurred at numerous sites along the coast. The main objective of this paper is to examine the atmospheric and oceanic processes produced by El Niño that are important in causing erosion. Most of the discussion of the processes will center on the 1982-83 event, since data collected from that period have been thoroughly analyzed. While measurements of the processes during the ongoing 1997-98 El Niño are still being collected, it is evident that the processes important to coastal erosion are very similar to those experienced in 1982-83. The paper will end with a brief account of erosional "hot spots" experienced during the 1997-98 El Niño along the Oregon coast, serving to illustrate how these processes combine to produce beach erosion and property losses.

## PROCESSES OF COASTAL EROSION

Most occurrences of coastal erosion involve one or more of the following processes or factors:

*storm-generated waves
high predicted tides
*elevated water levels above the predicted tidal elevation
an increase in relative sea level due to glacial melting plus land-level change
*erosion of embayments by rip currents

*alongshore movement of beach sediment

*jetty or breakwater disruption of beach sand movement

*migrations of tidal inlets and river mouths

The processes and factors that are enhanced during an El Niño are designated by an asterisk (*). The greatly increased erosional impacts along the west coast of the U.S. during an El Niño are accounted for by the increased intensities of these processes and by the fact that they generally reinforce one another to maximize their impacts. These important processes and factors are briefly recounted here.

## Enhanced sea levels

Particularly unusual during an El Niño are the processes that locally alter mean water levels in the ocean. They become readily apparent when we compare predicted tides, those found in tide tables, with the measured tides that are actually experienced. During both the 1982-83 and 1997-98 El Niño years, tides were typically on the order of 1.5 feet higher than predicted. The elevated water levels tended to drown out the beaches, and were extremely important at times of high tides since the water was able to reach sea cliffs and foredunes, allowing waves to attack and erode coastal properties.

Part of this elevated water level on the Northwest coast owes its inception to changes in processes acting along the Earth's equator during an El Niño. Historically, the first recognized impacts of an El Niño were dramatic changes in water temperatures and fisheries off the coast of Peru. Upwelling normally brings deep ocean water to the surface, much as it does off Oregon and Washington. The cold water, high in nutrients, has made the Peruvian fisheries one of the richest in the world. However, during an El Niño this system breaks down and the water becomes warm; fish and sea birds die en mass. Such an event usually develops during the Christmas season — hence its name, El Niño or "The Child".

It once was thought that the onset of an El Niño off Peru was caused by the cessation of local coastal winds which produce upwelling. This view changed when the physical oceanographer Klaus Wyrtki demonstrated that these local winds do not necessarily diminish during an El Niño (Wyrtki, 1975). Instead, he found that the breakdown of the equatorial Trade Winds in the central and western Pacific trigger an El Niño, far away from the Peruvian coastal waters where its chief impact is felt. The process is illustrated schematically in Figure 1, contrasting a normal period with an El Niño year. During normal years, the Trade Winds blow toward the equator but with a component directed toward the west, and generate ocean currents that flow toward the west parallel to the equator. The stress of the wind on the water and the westward flow of currents combine to produce an elevated water level in the western Pacific, centered in the area where the equator intersects the coast of Asia. The same effect is obtained when blowing steadily across a cup of coffee — the surface of the coffee becomes highest on the side of the cup away from you. If you stop blowing, the coffee surges back and runs up your side of the cup. The process is similar in the ocean when the Trade Winds stop blowing during an El Niño year; this condition is depicted in the lower half of Figure 1. The potential energy of the sloping water surface is released, and it is this release that produces the eastward flow of warm water along the equator toward the coast of Peru where it kills fish not adapted to warm temperatures.

Associated with this warm water movement eastward along the equator is a wave-like bulge in sea level, also depicted in the lower diagram of Figure 1. The eastward progress of the sea-level wave has been monitored at tide gauges located on islands near the equator. Data from a tide gauge can be averaged to remove the tidal fluctuations, yielding a measure of the mean level of the sea during that time interval. Such analyses have been undertaken by Wyrtki to demonstrate the eastward movement of sea-level waves during El Niño events (Wyrtki, 1977, 1984). Figure 2 shows the results for the 1982-83 El Niño. From this series one can easily see the passage of the released sea-level wave as it traveled eastward across the Pacific, affecting in turn tide gauges on a series of equatorial islands. Sea level at Rabaul in the western Pacific reached a peak in March or April 1982 and then begin to drop. The crest passed Fanning Island south of Hawaii in late August, Santa Cruz in the Galapagos at the end of the year, and reached Callao on the coast of Peru in January 1983.

With its arrival on the coast of South America, the sea-level wave splits, and the separated parts respectively move north and south along the coast. Analyses of tide-gauge records along the full length of the west coasts of North and South America have demonstrated that the sea-level waves can travel as far north as Alaska (Enfield and Allen, 1980). The wave travels at a rate of about 50 miles per day, so quickly reaches California and Oregon. The passage of the sea-level wave along the Oregon coast is depicted in Figure 3, which also shows the locations of tide gauges used to monitor its movement. Figure 4 gives the monthly mean sea levels measured by the tide gauge in Yaquina Bay, Oregon, during the 1982-83 El Niño, contrasting the levels with more normal years (Huyer et al., 1983) — as in the analyses of Wyrtki, the tide-gauge record has been averaged to remove the tides, leaving the net difference between the predicted and measured tides for the month. During the 1982-83 El Niño, sea level reached a maximum during February 1983, nearly 24 inches higher than the mean water surface in May 1982, nine months earlier. The thin solid line in the figure follows the ten-year averages for the seasonal variations, and the dashed lines give the previous maxima and minima measured at Newport.

The increased elevations in mean sea level along the Northwest coast during an El Niño are only in part due to a sea-level wave originating at the equator. Other factors include changes in water temperatures along the coast, and the development of a northward flowing current. The curves in Figure 4 in part reflect the normal seasonal cycle of sea level produced by parallel variations in water temperatures, which are colder during the summer than in the winter due to the occurrence of upwelling in the summer. The thermal expansion of the warm water of the winter raises water levels along the coast, while the cold dense water of the summer depresses the level. There is also a reversal in current directions from winter to summer. During the winter the current flows toward the north, and the rotation of the Earth (the Coriolis effect) deflects the current toward the right, that is, toward the coast, elevating the level of the sea along the shoreline. These processes tend to occur every year, causing sea levels along the Northwest coast to be higher during the winter than in the summer. But in an El Niño year these processes are more intense with the water during the winter being warmer than usual and the northward current stronger. So these factors add to the sea-level wave moving northward from the equator to produce the observed extreme water levels during an El Niño winter.

It is seen in Figure 4 that the 1982-83 sea levels were truly exceptional, reaching some 8 to 16 inches higher than previous winter maxima, about 14 inches above the average winter level. Similar analyses are underway for the 1997-98 El Niño. During January and February 1998 the measured sea levels were again 14 to 16 inches above the average winter level, indicating that water levels during this El Niño reached higher elevations than occurred during the 1982-83 event.

The water-level increase during an El Niño year along the Northwest coast is seen to be substantial, making the measured tides significantly higher than predicted (both high and low tides are elevated). For example, in the 1982-83 El Niño year, during a January 1983 storm the highest spring tides of the month reached +12.4 feet MLLW, 34 inches higher than the predicted tide (elevated by both the El Niño processes and by the strong onshore winds of the storm). During a February storm, high tides of +10.3 feet were measured, 17 inches above the predicted level. All of these tides are exceptional for the Oregon coast where a spring tide level of +9.0 feet MLLW is fairly representative (Komar, 1997). This elevated water level is extremely important in producing coastal erosion during an El Niño. Beaches along the Oregon coast typically have a slope of about 1-in-50, so an increase in water level of 17 to 34 inches as experienced during the 1982-83 El Niño winter shifts the shoreline landward by about 70 to 140 feet, drowning out most beaches at high tide. This moves the shoreline to the base of the sea cliff or foredunes, and permits the direct attack of waves against coastal properties, in large part accounting for the extreme erosion during an El Niño.

## El Niño storm waves

Coastal property erosion usually occurs when storm waves combine with elevated water levels, and this is especially true during an El Niño when these processes are intensified and reinforce one another. During an El Niño the high-altitude jet stream in the atmosphere becomes narrow and strong, and spins off cyclonic storms over the Pacific that are more intense than usual. The jet stream is also shifted further south than normal, so the storms cross the North American coast in southern California rather than passing over the Northwest. These storm system are important to the generation of high-energy waves, and in an El Niño year with the shift of storms to the south communities such as Malibu Beach in southern California have a taste of wave energies to which they are not accustomed.

Wave conditions along the Northwest coast are also intensified during an El Niño year (Komar, 1986). Daily measurements obtained during the 1982-83 event demonstrated the occurrence of several storms that generated high-energy waves, three having produced deep-water significant wave heights on the order of 20 to 25 feet [the "significant wave height" is the average of the highest one third of the waves]. The strongest storms occurred during January and February 1983, simultaneous with the occurrence of the highest water levels (Fig. 4). With this combination it is understandable that extensive erosion took place during the El Niño winter of 1982-83.

There also has been an intensification of wave conditions along the Northwest coast during the 1997-98 El Niño. The first major storm of the winter occurred on 14 November 1997; when deep-water significant wave heights reached 16 feet. The first substantial property erosion of the El Niño winter occurred during a storm on December 13-14 ; although the wave conditions were comparable to those on November 14, the tides were higher and the beaches had been cut back during the ensuing month, allowing the waves to attack sea cliffs and dunes. Storm wave activity significantly increased in January and continued through February. During those two months, twelve storms generated waves having deep-water significant wave heights in excess of 20 feet. Far and away the largest occurred on January 17, when the deep-water significant wave height reached 30 feet; they would have grown to some 35 to 40 feet in height when they traveled to the nearshore and broke on Northwest beaches.

While there has been an overall intensification of wave energies along the Northwest coast during both the 1982-83 and 1997-98 El Niño years, compared with normal years, the intensification is more in the form of the frequency of storm-wave occurrences than in the absolute extreme sizes of the generated waves. The 30-foot waves on 17 January 1998 have an expected return interval of about 10 to 20 years, so are exceptional, while the 20 to 25-foot storm waves have return periods of roughly 1 year, which means that we experience waves with those heights essentially every winter. The difference is that we have seen more storm wave occurrences having 20 to 25-foot heights during the El Niño winters than in normal years. Higher waves can occur along the Northwest coast during normal years, in part because the paths of storms bring them directly across our shores. While extreme waves are generated by El Niño storms (Seymour et al., 1985), their impacts are felt more directly in southern California than on the Northwest coast.

## Longshore movement of beach sand

An important aspect of the El Niño storms and generated waves to coastal erosion in the Northwest is the southerly shift of the storm systems. The result of this shift is that the storm waves approach the Northwest coast more frequently from the far southwest quadrant compared with normal years. This results in the northward movement of sand along Northwest beaches, which exerts a strong control on the alongcoast centers of "hot spot" erosion.

Important to this control is the fact that the Oregon coast is divided naturally into a series of littoral cells, stretches of beach isolated by large rocky headlands (Komar, 1997). The stretch of beach may range from only a couple of miles to as long as 50 miles in the case of the Coos Bay littoral cell that extends from Cape Arago in the south to Cape Perpetua at its northern end. There is little or no exchange of beach sand around the bounding headlands (shown by differences in beach sand grain sizes and mineralogies), so the stretch of beach within a littoral cell is largely isolated and self contained.

A schematic depiction of a littoral cell is diagrammed in Figure 5, contrasting the wave directions and alongshore sand movements during normal years (left) with El Niño years (right). In a normal year the summer waves dominantly approach the coast from the northwest, causing sand to move southward along the beaches, while the winter waves arrive from the southwest and move sand back toward the north. Over the span of several normal years there is an equilibrium balance, with approximately equal amounts of sand moving north and south. This equilibrium was seen in the shoreline changes that occurred when jetties were constructed along the coast early in the century (Komar, 1997), with a symmetrical pattern of shoreline change north and south of the jetties. In contrast to the equal north and south movements of sand in a normal year, during an El Niño event (Figure 5, right) more sand moves toward the north under the more frequent storm waves arriving from the southwest. One effect is that sand is systematically moved from the south ends of the littoral cells, producing erosion there, while sand accumulates at the north ends so the beaches widen.

Jetties on inlets can have much the same effect as a headland. During an El Niño year with the enhanced sand movement toward the north, the jetties block this drift resulting in beach accretion to the south of the jetties while erosion occurs to the immediate north. This patterns may be obscured in part by the seasonal cross-shore movement of sand along the beach profile. During the winter the high waves erode sand from the dry part of the beach and transport it to offshore bars, while low waves of the summer reverse this process (Komar, 1998). Thus the actual response of the beach (net erosion or accretion) at a specific site depends on the combined effects of the alongshore movement of sand related to the El Niño, and the cross-shore movement associated with the seasonal cycle of beach profile change.

Natural inlets to bays and estuaries on the Northwest coast, those uncontrolled by jetties, tend to migrate toward the north during an El Niño due to the stronger northward movement of beach sand. This can result in beach and property erosion to the immediate north of inlets, as depicted in Figure 5 (right). This shift is temporary, with the inlets tending to migrate back toward the south during subsequent normal years.

## OCCURRENCES OF EROSION DURING THE 1997-98 EL NIÑO

In the preceding section it was seen that a number of processes are involved in producing enhanced coastal erosion during an El Niño. In this section we will examine several erosional "hot spots" that occurred along the Oregon coast during the 1997-98 El Niño, and attempt to understand their development in light of the processes described above.

### Port Orford

The erosion at Port Orford during the 1997-98 winter illustrates several factors that are important in an El Niño year. Port Orford is a small community on the southern Oregon coast, with the center of the city situated immediately south of a headland known as The Heads. However, the community extends to the north of The Heads, and it is this area that has been experiencing severe erosion. This stretch of beach comprises a littoral cell that extends north to Cape Blanco, a distance of about 8 miles. The erosion, shown in Figure 6, occurring at the south end of the littoral cell, fits the normal pattern of El Niño impacts with storm waves arriving from the southwest, moving the beach sand alongshore toward the north.

The eroding shore is centered on the narrow beach/dune barrier that separates the ocean from Garrison Lake. The beach is composed of coarse sand with some gravel, and is steep and has a narrow surf zone. This type of beach erodes very rapidly when attacked by storm waves that break directly on the beach face close to shore (Komar, 1997). Prior to the El Niño erosion, extensive dunes had accumulated in this area and the City of Port Orford had installed the drainage field for its sewage treatment system within the dunes. Erosion this winter has all but eliminated the dune field and destroyed most of the drain field. The threat now is that continued erosion may break through the beach/dune barrier into Garrison Lake. This lake is the principal source of fresh water for the community, and there are a number of homes built along its shore that may be adversely affected by a breach. The combined elevated mean water levels and runup of storm waves from El Niño have frequently washed over the barrier into the Lake. This overwash process has eroded sand from the beach and carried it over the top of the barrier and into the Lake. This has had a positive effect of building up the elevation of the barrier, making it less likely that the erosion will break through and create an inlet connecting the ocean with Garrison Lake. There is still a critical area at the south end of the barrier, where the erosion is cutting back the dunes and forming a nearly vertical scarp. Although there has been frequent washovers of ocean water in this area, this has not carried sand to build up the elevation of the barrier as has occurred further to the north. The barrier at the south end is now very narrow, so there is the possibility that it could break through into the Lake. The City has placed a ridge of gravel and cobbles along the top of the barrier to prevent further washover, which at this stage could develop into a breach of the barrier, forming an inlet. If dune erosion continues, the gravel and cobbles will slough off onto the eroding dune scarp and upper beach, where its presence should provide some temporary protection from continued wave attack, hopefully being a sufficient defense until the impacts of the 1997-98 El Niño end.

## Alsea Spit

One of the main areas of erosion during the 1982-83 El Niño took place along Alsea Spit on the central Oregon coast (Komar, 1986, 1997; Komar and Good, 1989). The primary factor important to erosion was the northward migration of the inlet to Alsea Bay. Inlet migration combined with the elevated water levels and storm waves to completely erode away the beach along nearly the full length of the spit. The waves and currents then begin to cut back the foredunes, where a number of homes had been constructed. One house was lost, while the others were saved by the placement of riprap at the base of the eroding dunes.

In the years subsequent to the 1982-83 El Niño, the return of lower water levels and less severe wave conditions has allowed the beach to recover along Alsea Spit. The beach has become very wide, and onshore winds have blown sand into the dunes so they had fully recovered from the El Niño erosion. Eventually the riprap revetment was covered by the accumulating dune sand, and apparently forgotten. Development began once again, and a number of new homes were build on the spit. Unfortunately, some were constructed atop and across the now buried revetment, seaward of this line of defense, in the area where erosion had occurred only a decade earlier.

The return of El Niño during the winter of 1997-98 has brought about a recurrence of erosion processes and problems on Alsea Spit. Older homes landward from the line of riprap placed in 1982-83 are likely safe from the renewed attack, but the newly constructed homes that extend seaward from the riprap line are now in danger. It is possible that another line of riprap will have to be installed to protect those homes.

## Cape Lookout State Park

Another area of significant erosion during the 1982-83 El Niño occurred at Cape Lookout State Park on Netarts Spit (Komar, 1997; Komar et al., 1988; Komar and Good, 1989). This park is located at the south end of the Oceanside littoral cell, so again much of its erosion can be attributed to the northward transport of sand by the approach of high storm waves from the southwest during the El Niño, moving sand toward the north. Much of this sand has disappeared from the beach, apparently carried into Netarts Bay, so the reduced sand volumes on the beach along this littoral cell now make it more susceptible to attack by waves, during normal years and well as in an El Niño. Another factor in the erosion during the 1982-83 El Niño was the presence of a large rip current flowing seaward from the area of the park, carrying sand offshore and contributing to the local erosion. Erosion in the park partially destroyed an old log seawall, and then eroded away the high ridge of dune sand that had sheltered the park development.

Erosion of Cape Lookout State Park during the 1997-98 El Niño year, Figure 7, has essentially picked up where the 1982-83 event left off. The last remnants of the log seawall are rapidly disappearing, leaving the tall iron beams extending vertically from the beach that had been used to support the logs (the beams remaining after the 1982-83 erosion have been cut off by State Parks). Additional dune erosion has occurred, and the public bathrooms were in danger of being undermined by waves until a line of riprap was placed for protection (Figure 7). High water elevations have combined with storm wave runup to wash over into the park lands, depositing a large amount of beach sand in the campground. Such extensive washovers did not occur during the 1982-83 El Niño.

## The Capes

Most dramatic and newsworthy has been erosion during the 1997-98 El Niño at The Capes, a development consisting of expensive condominiums recently built on the high bluff to the immediate north of the inlet to Netarts Bay (Figure 8). The site is centered within the Oceanside littoral cell, about 6 miles north of Cape Lookout State Park. The Capes erosion is not only dramatic in its potential economic impacts for the home owners, but also due to the number of coastal hazards involved.

Being immediately north of the inlet to Netarts Bay, the northward migration of the inlet during the 1997-98 El Niño winter has acted to erode the fronting beach and has created deepened water directly offshore. Normally the low sloping beaches in this littoral cell cause the waves to break well offshore so most of their energy is dissipated before they runup on the beach face at the shore (Komar, 1997). With the creation of deeper water due to the migration of the inlet, the waves can now travel closer to shore before breaking, with less loss of energy. The runup of the stronger waves now combines with the elevated mean water levels associated with the El Niño, allowing the runup to reach the toe of the high bluff below The Capes. The resulting toe erosion has made the bluff unstable, and slippage of the land now poses the immediate threat to the front line of condominiums (Figure 8). Unfortunately, the condominiums had been constructed with only a 10-foot setback distance, insufficient considering the potential for erosion and instability of the site, so many of the homes have immediately been placed in danger.

The development site is located atop an old massive landslide. The lower portion, now exposed by the toe erosion, consists of a layer of mud that is extremely mobile; rather than participating in rotational slippage typical of many landslides, this mud appears to be squeezed out like toothpaste by the weight of the overlying material. This overlying material is sand of old dunes deposited atop the bluff, sand that has minimal internal strength so it tends to cascade down slope, much like the loose sand of an active modern dune. Thus, only part of the problems at The Capes can be attributed to the occurrence of an El Niño and its erosion processes. There were the pre-existing hazardous conditions of the development having been constructed on a landslide, the upper part of which consists of dune sand. The present instability and movement of the landslide can, however, be attributed to the erosional impacts of the 1997-98 El Niño, which have cut away the toe of the landslide.

## CONCLUSIONS

The Northwest coast now has experienced two major El Niño events, that in 1982-83 and again in 1997-98. Both have resulted in substantial beach erosion and impacts to coastal properties. Although data are still being collected and analyzed from the recent event, the evidence thus far is that the processes are very similar to those which occurred during the 1982-83 El Niño. Important to coastal erosion are the elevated water levels that cause tides to be 1 to 1.5 feet higher than predicted, the generation of high energy waves by more frequent storms, and the fact that the waves approach the coast more from the southwest, causing a northward movement of sand that redistributes beach sand volumes along the coast and causes inlets to migrate toward the north. It is the combination of these processes and the fact that they reinforce one another, that accounts for "hot spot" erosion areas along the Oregon coast such as at The Capes.

At the time of this writing (April 1998), El Niño is continuing but it looks like it is decreasing and will likely soon come to an end. Water temperatures and sea levels in the equatorial Pacific are returning to more normal levels. The same can be expected off the Northwest coast. As discussed above, wave energies along the coast abruptly declined at the end of February, following the usual pattern of decreasing wave conditions in the summer (Komar, 1997). The eroded beaches have noticeably began to rebuild. So additional property erosion is unlikely, at least through the summer. But we may not have seen the last of the impacts that can be attributed to the 1997-98 El Niño. Following the 1982-83 event, significant erosion took place during subsequent winters, returning to the areas that had eroded during the El Niño winter. The processes directly associated with El Niño had ceased (unusually high water levels, etc.), but the beaches were unable to fully recover during the following summer. Sand shifted far offshore to deep water did not completely return to the dry beach, and sand moved alongshore to the north within the littoral cells did not all shift back to the south. So when the next winter returned with its high storm waves, the beaches still depleted in sand were not able to adequately buffer coastal properties, so that erosion began once more. It was 2 to 3 years before the beaches finally recovered, and the lingering impacts of the 1982-83 El Niño finally ended. It remains to be seen whether history repeats itself, and whether or not we have seen the last of the 1997-98 El Niño.

## ACKNOWLEDGMENTS

I wish to thank Dr. John Marra, Prof. William McDougal, Dr. Peter Ruggiero and Mr. John Stanley, who are involved in investigations of El Niño erosion problems with me, or have provided me with wave and water-level data. I am grateful for their assistance.

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## FIGURE CAPTIONS

Figure 1: The shift in Trade Winds and ocean currents along the equator in the Pacific Ocean during a normal year (upper) versus an El Niño year (lower). The cessation of the Trade Winds during an El Niño produces a sea-level "wave" that travels eastward along the equator.

Figure 2: Sea-level waves measured on tide gauges of islands located along the length of the equator during the 1982-83 El Niño. [after Wyrtki (1984)]

Figure 3: Schematic depiction of the sea-level wave moving northward along the Oregon coast, measured by the series of tide gauges.

Figure 4: Monthly averaged sea levels measured on the tide gauge in Yaquina Bay, with the 1982-83 El Niño extreme levels compared with previous years. [after Huyer et al. (1983)]

Figure 5: Alongshore movement of beach sand within littoral cells on the Oregon coast due to the seasonal shift in directions of waves approaching the coast. During normal years (upper) there is an approximate balance of north and south sand movements, but in an El Niño year the strong storm waves from the southwest cause large amounts of sand to move to the north, causing "hot spot" erosion as shown.

Figure 6: The erosion at Port Orford during the 1997-98 El Niño, north of The Heads. The erosion has destroyed the drain field of the sewage treatment plant (upper), and is now threatening to break through the beach/dune barrier and wash into Garrison Lake, prevented by the placement of gravel ridge (lower).

Figure 7: The recent erosion of Cape Lookout State Park on Netarts Spit, which has cut back the large coastal dunes and is now eroding the campground.

Figure 8: The Capes is a recent development of expensive condominiums, located on the edge of an old massive landslide (upper). Erosion of the toe of the slide during the 1997-98 El Niño has caused it to become unstable with slippage threatening the first line of homes (lower).

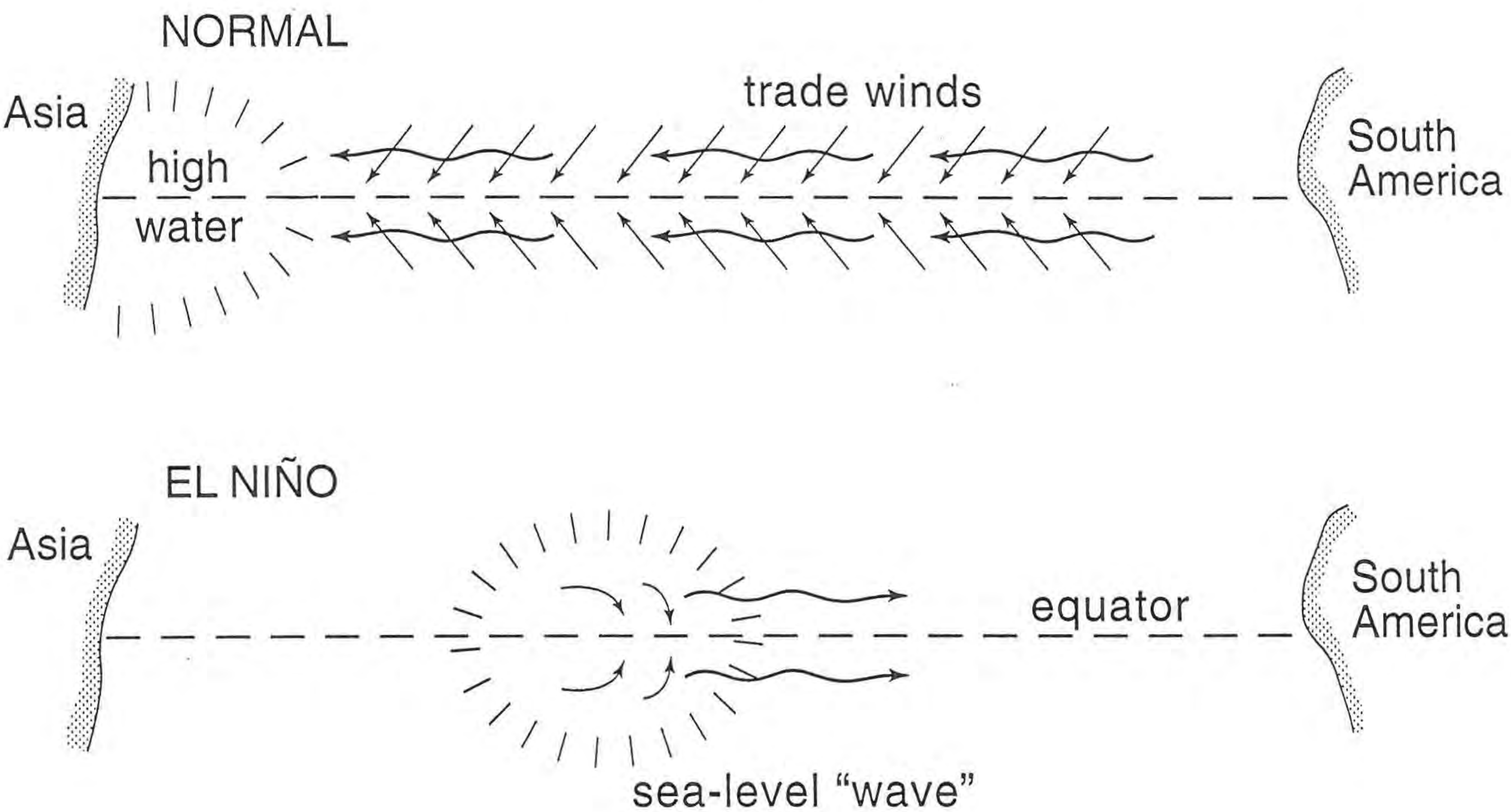
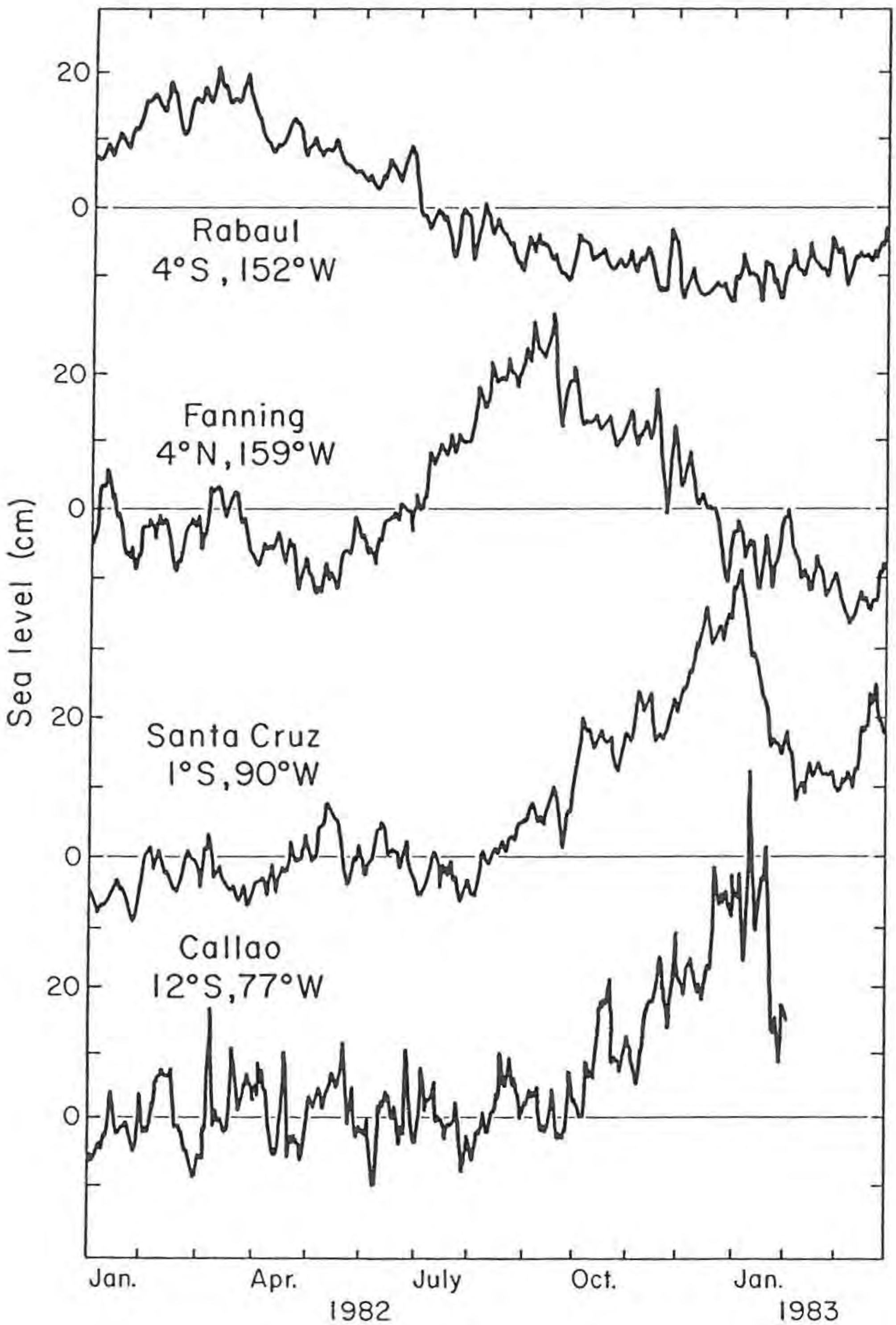
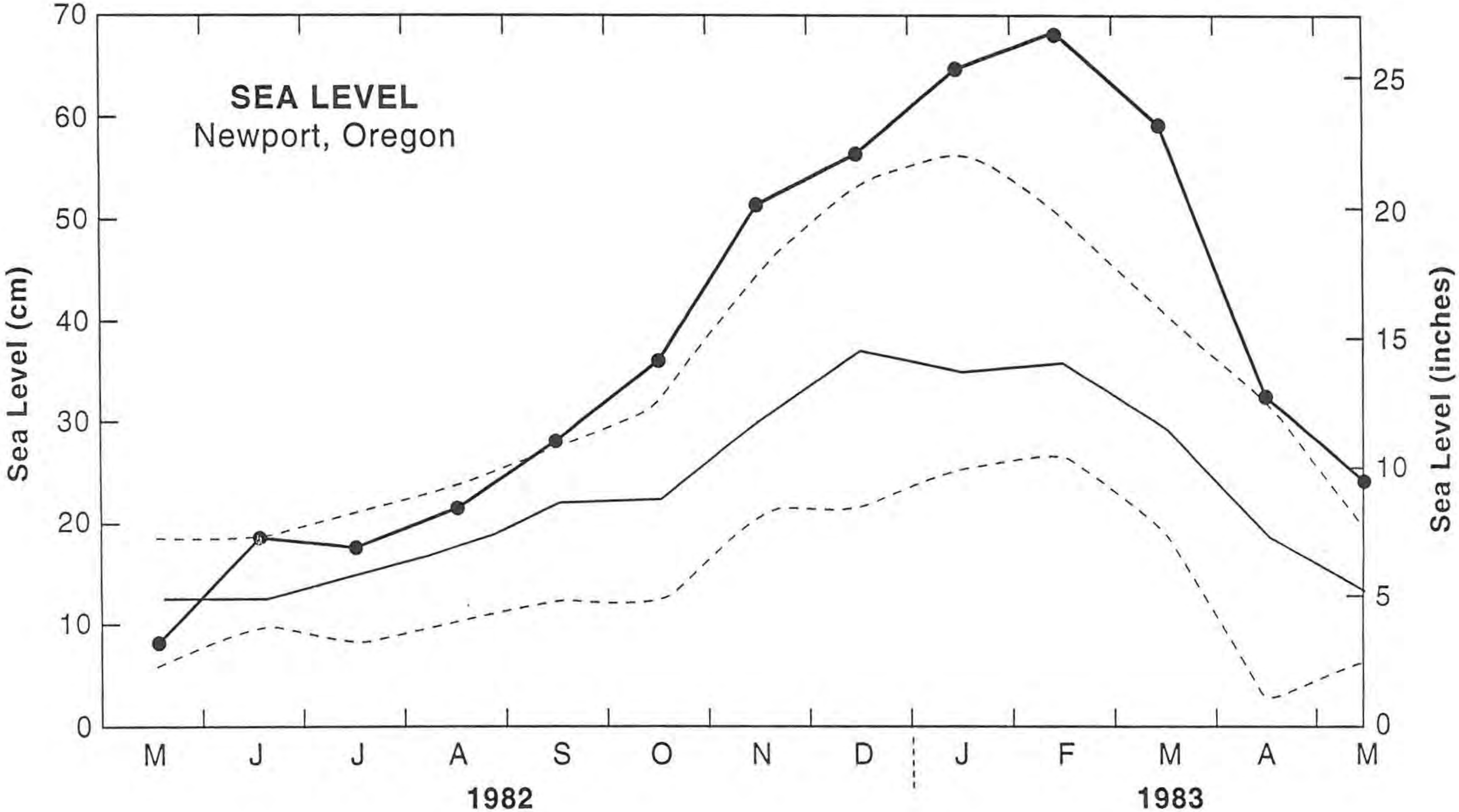

NORMAL
Asia
high
water
trade winds
South
America
EL NIÑO
Asia
equator
South
America
sea-level "wave"

Figure 1

Figure 2



Sea level (cm)
20
0
Rabaul
4°S, 152°W
20
Fanning
4°N, 159°W
0
20
Santa Cruz
1°S, 90°W
0
Callao
12°S, 77°W
20
0
Jan.
Apr.
July
Oct.
Jan.
1982
1983



SEA LEVEL
Newport, Oregon
Sea Level (cm)
Sea Level (inches)
70
60
50
40
30
20
10
0
25
20
15
10
5
0
M
J
J
A
S
O
N
D
J
F
M
A
M
1982
1983


Figure 3

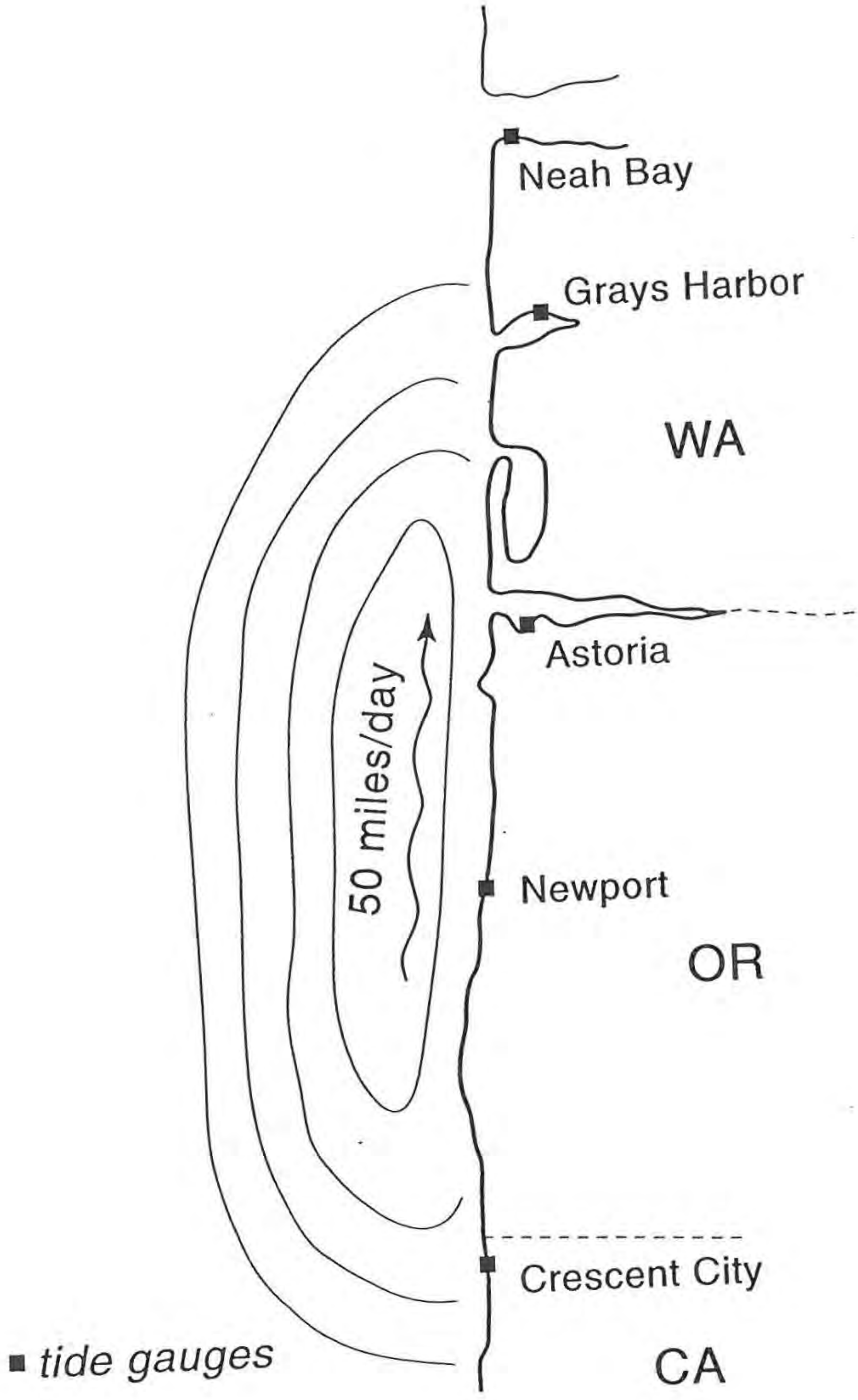
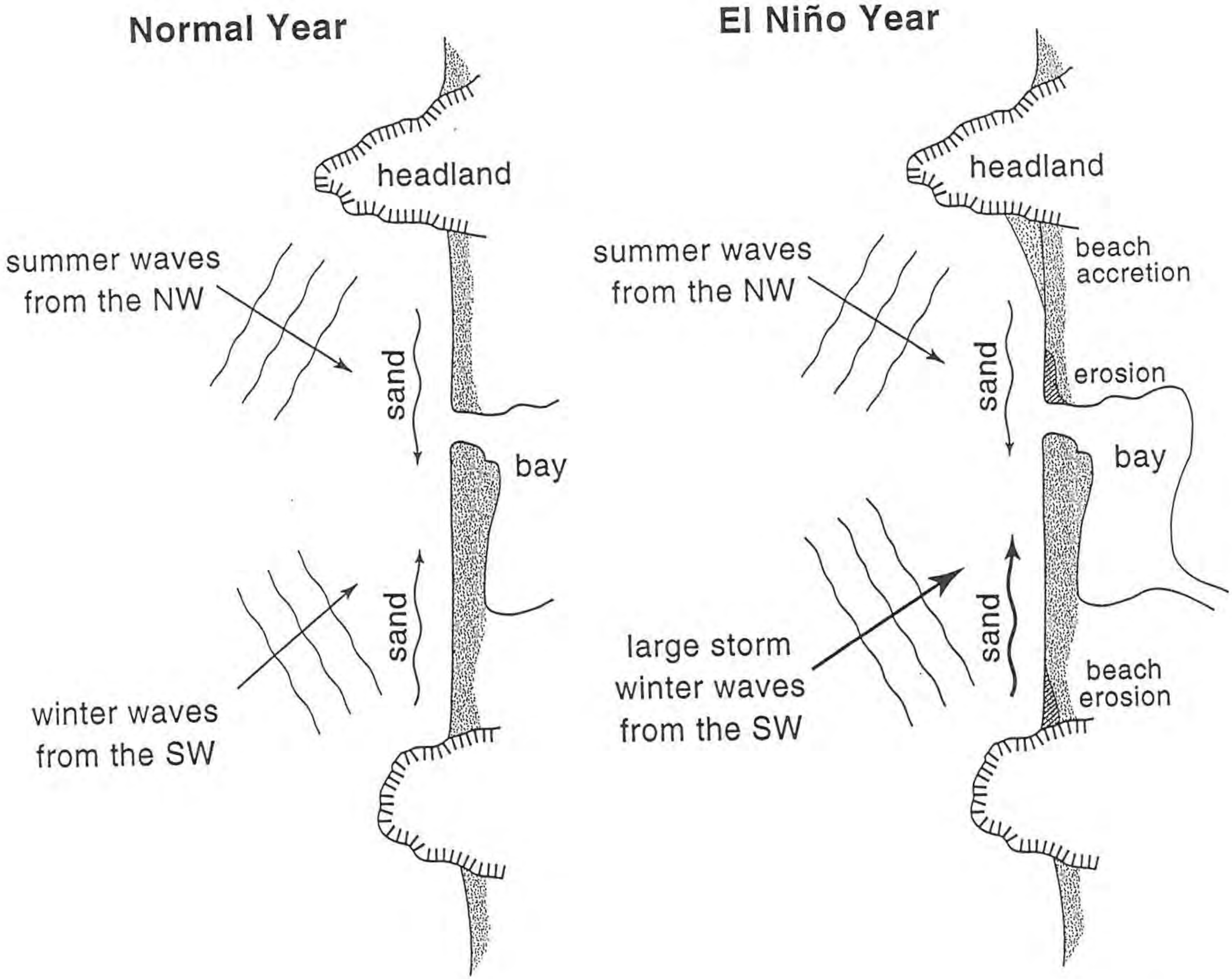
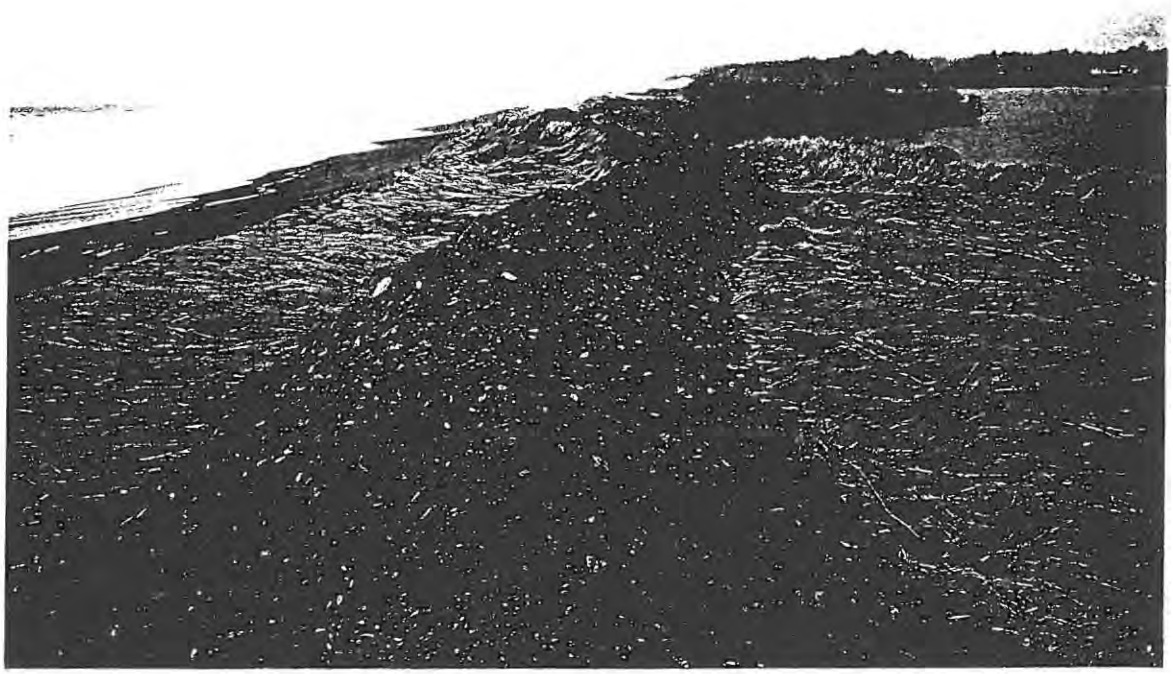
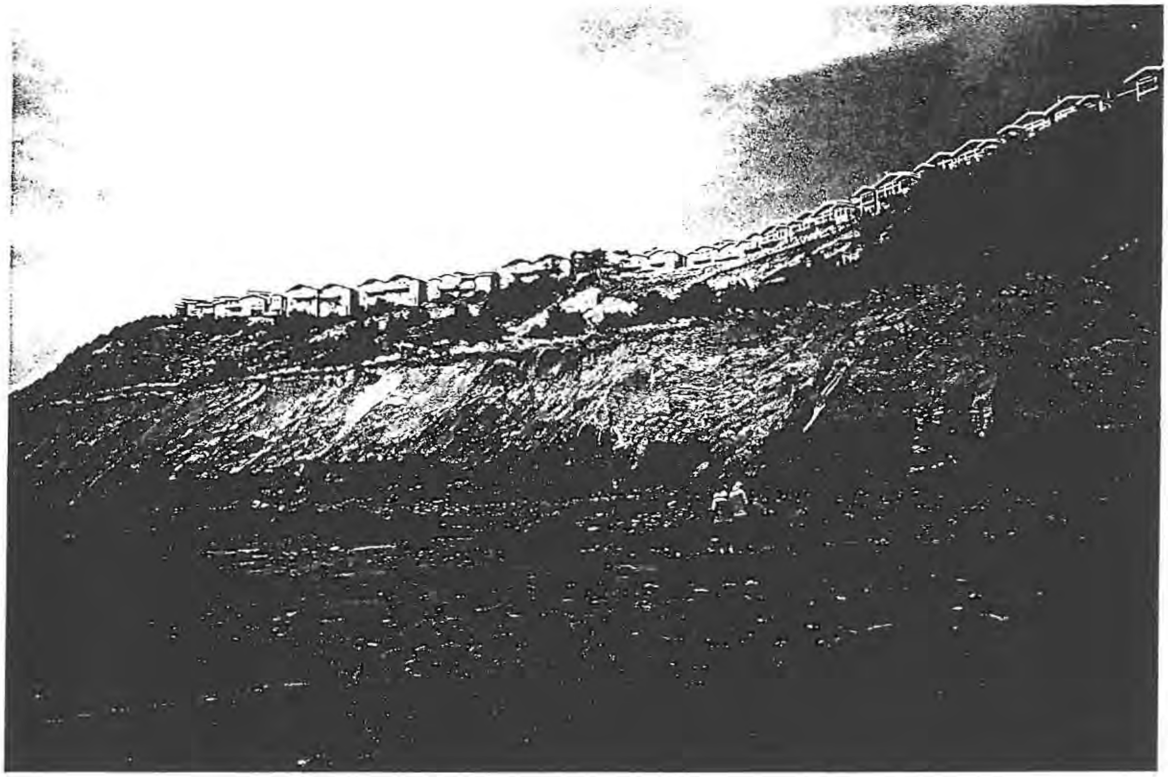

Neah Bay
Grays Harbor
WA
Astoria
50 miles/day
Newport
OR
Crescent City
CA
tide gauges

Figure 4


Normal Year
headland
summer waves
from the NW
sand
bay
sand
winter waves
from the SW
El Niño Year
headland
summer waves
from the NW
beach
accretion
sand
erosion
bay
large storm
winter waves
from the SW
sand
beach
erosion





# APPENDIX B
# CLIMATOLOGY

# Long-Term Wet-Dry Cycles in Oregon

**George H. Taylor**

**March, 1999**

Reliable weather and climate information for Oregon extend back about 100 years. During that time, there have been about an equal number of wet years and dry years. We find, however, that during some periods there is a preponderance of wetter than average years while in others there are mostly dry years. These wet and dry "cycles" generally span 20-25 years. The dry years tend to be warm (due to reduced cloudiness, most likely) and the wet years cool.

Figure 1 shows Water Year precipitation (Oct. - Sept.) for the Oregon Coast Division (Zone 1) since 1896. Notice the dry (and warm) periods from about 1920-1945 and 1975-1994, and the wet periods before and after. The last four years have been quite wet. Figure 2 shows Portland precipitation since 1920. The wet/dry periods are similar, coinciding almost exactly with those on the coast. Are the recent wet years a harbinger of things to come? Have we reentered a wet cycle?

### The Global "Conveyor Belt"

Several years ago I heard a talk by Dr. William Gray (see Gray and Landsea, 1993) that described an exciting new finding based on the work of an oceanographer, Wallace Broeker. Broeker (1991) suggested that there is a global-scale current, operating on a time scale of several decades, which affects worldwide weather patterns. Broeker used data from ice cores to postulate that changes in this current may have been a primary triggering mechanism for the last ice age. Gray and Landsea, however, were more interested in our era. Gray has received acclaim for his work in predicting Atlantic hurricanes, with significant success.

The "conveyor belt" involves transport of warm ocean water from the Pacific through the Indian Ocean and into the Atlantic. In the north Atlantic, this warm water (now very saline due to evaporation during the journey), encounters cold water coming down from the north. The warm water cools quickly, and sinks (due to greater density). This sets up a sub-surface countercurrent which transports the cool water back to the Indian and Pacific oceans. Figure 3 illustrates the warm and cold currents associated with an active conveyor cycle.

In looking back over the last 100 years, Gray and Landsea identified four distinct periods, two when the conveyor belt was very active, two when it was quite inactive. They also found several important atmospheric phenomena which correlate quite well with the strength of the conveyor; we have added precipitation in the Northwest to the table (Figure 4). Note also that global temperatures seem to correspond to the active-inactive phases as well. This should not surprise us, since the tropical Pacific is the largest terrestrial heat source to the atmosphere; when the Pacific warms, so does the atmosphere. And during El Niño events, the Pacific temperatures (taken overall) warm significantly. Thus the warmup during El Niño-dominated inactive periods.

Gray and Landsea suggest that we may be entering a period of strong conveyor belt activity again. Consider how the four major indicators have changed over the last several years:

1. Atlantic Hurricanes. After the quietest 4-year period of the last 50 years during 1991-94, 1995 had the largest number of hurricanes since storms were first named in the early 1950s. 1996 and 1998 were active years, and 1997 was about average. The latest four-year period is the busiest on record.

2. Sahel precipitation. The last four years have seen near-average precipitation after many years of sever drought.

3. El Niños. Following a 20-year period with only one La Niña, three of the last four years have seen La Niña conditions in the Pacific.

4. Precipitation in the Northwest. Following the very dry 1975-94 period, which saw two significant statewide droughts and 10 consecutive dry years, we are now completing the fifth consecutive above-average year.

**Predictions**

The signs are there. All indications are that the Conveyor Belt has switched back to "active" again, portending a mostly wet regime for the next 20 years or so. If history repeats itself, we can expect:

- frequent floods
- no droughts
- about 75% of all years wetter than average
- relatively cool

Note that the above predictions apply to the cool season only. Summers do not necessarily reflect those trends. Our usual warm, dry, beautiful Northwest summers will still be here.

**Technical note: Atlantic Hurricanes and Portland Precipitation**

Since the number of Atlantic hurricanes seems to correspond to precipitation in the Northwest, we decided to plot both types of data together to see how well they correlate. As can be seen in Figure 5, there is a very strong correlation indeed. Active hurricane years are almost always followed by wetter than average winter conditions in Portland, and inactive years by dry winters. This graph not only validates the Conveyor Belt concept, it suggest that hurricane frequency can be used effectively to predict Portland precipitation the following winter.

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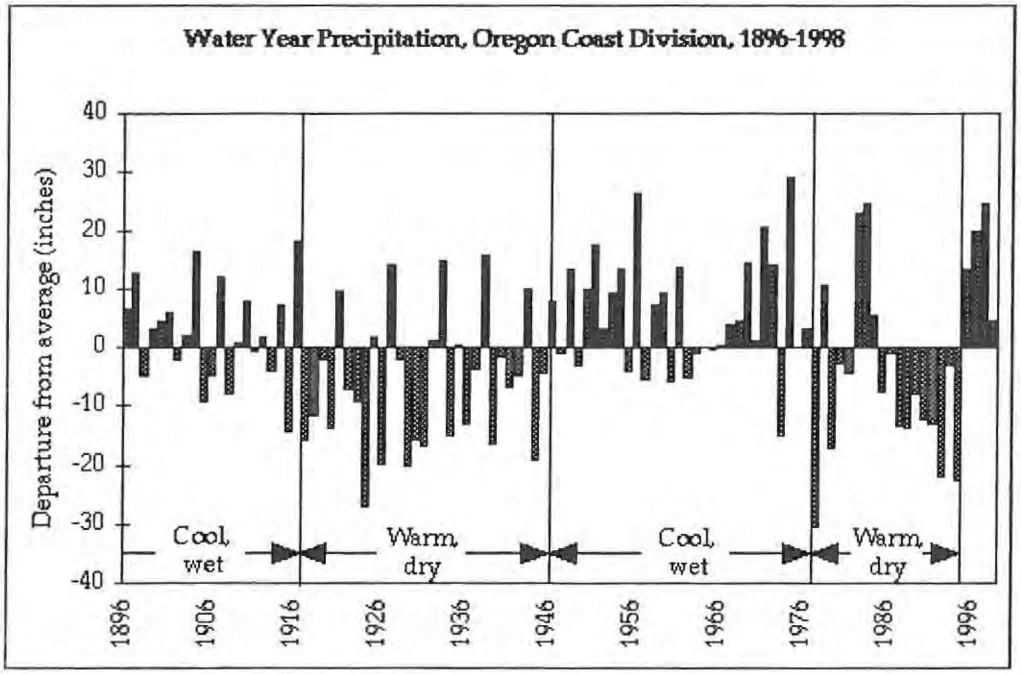
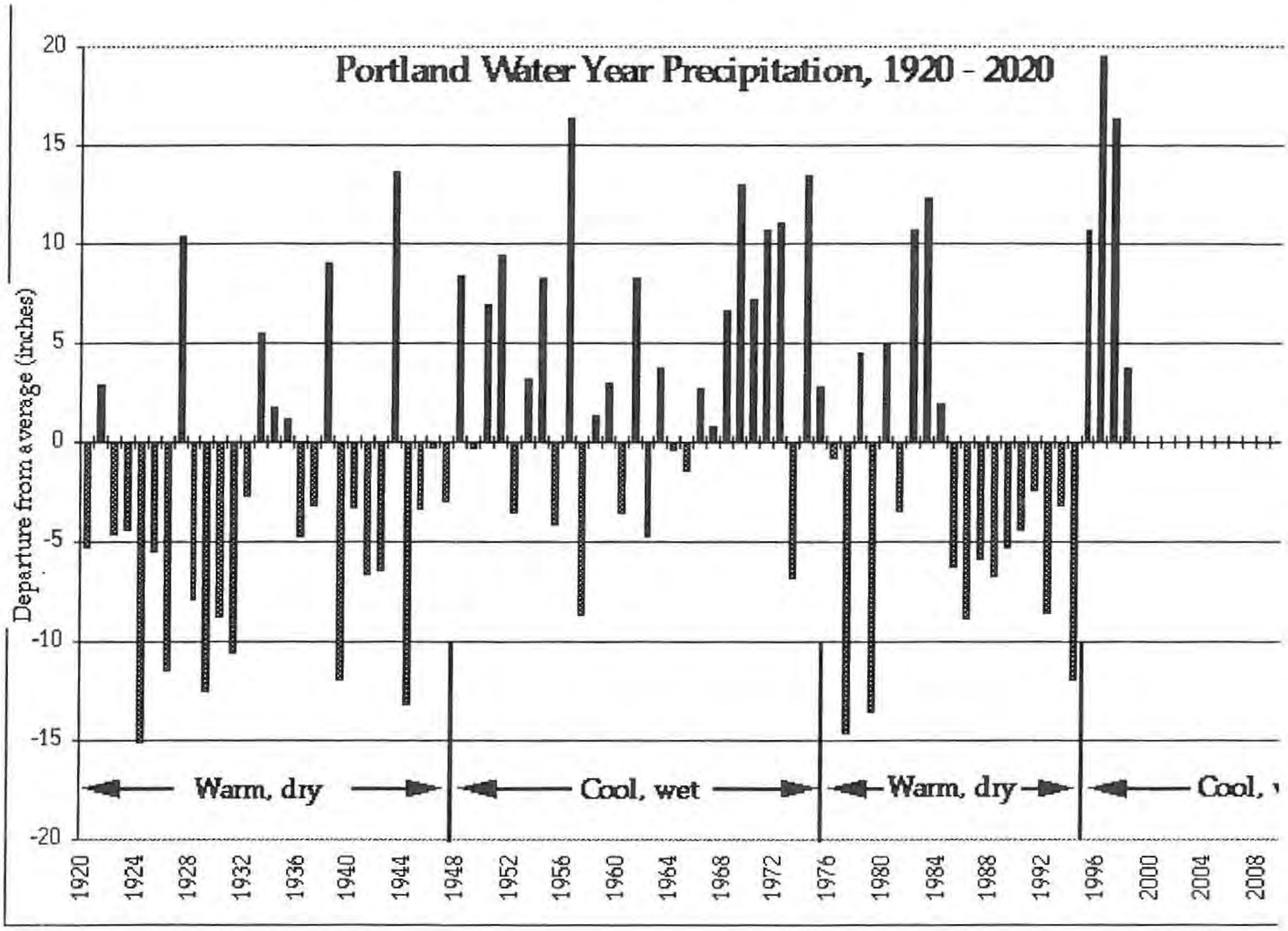
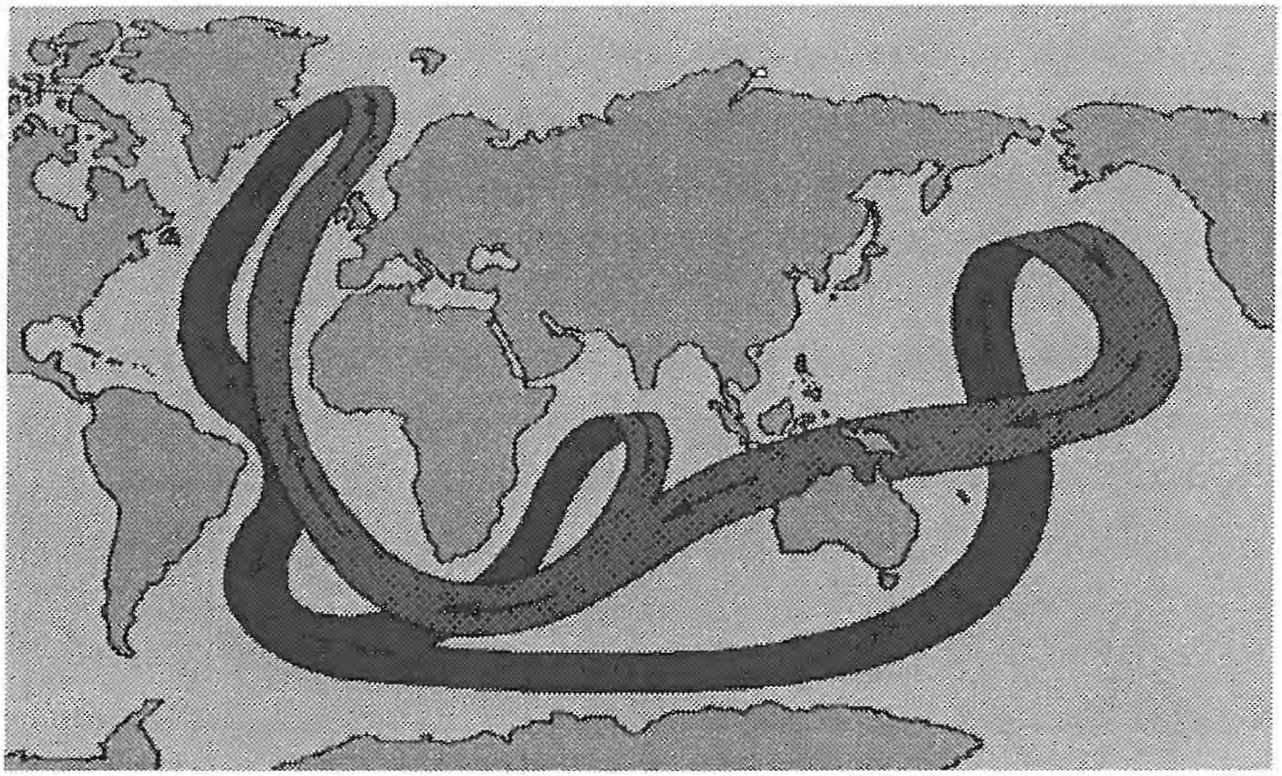
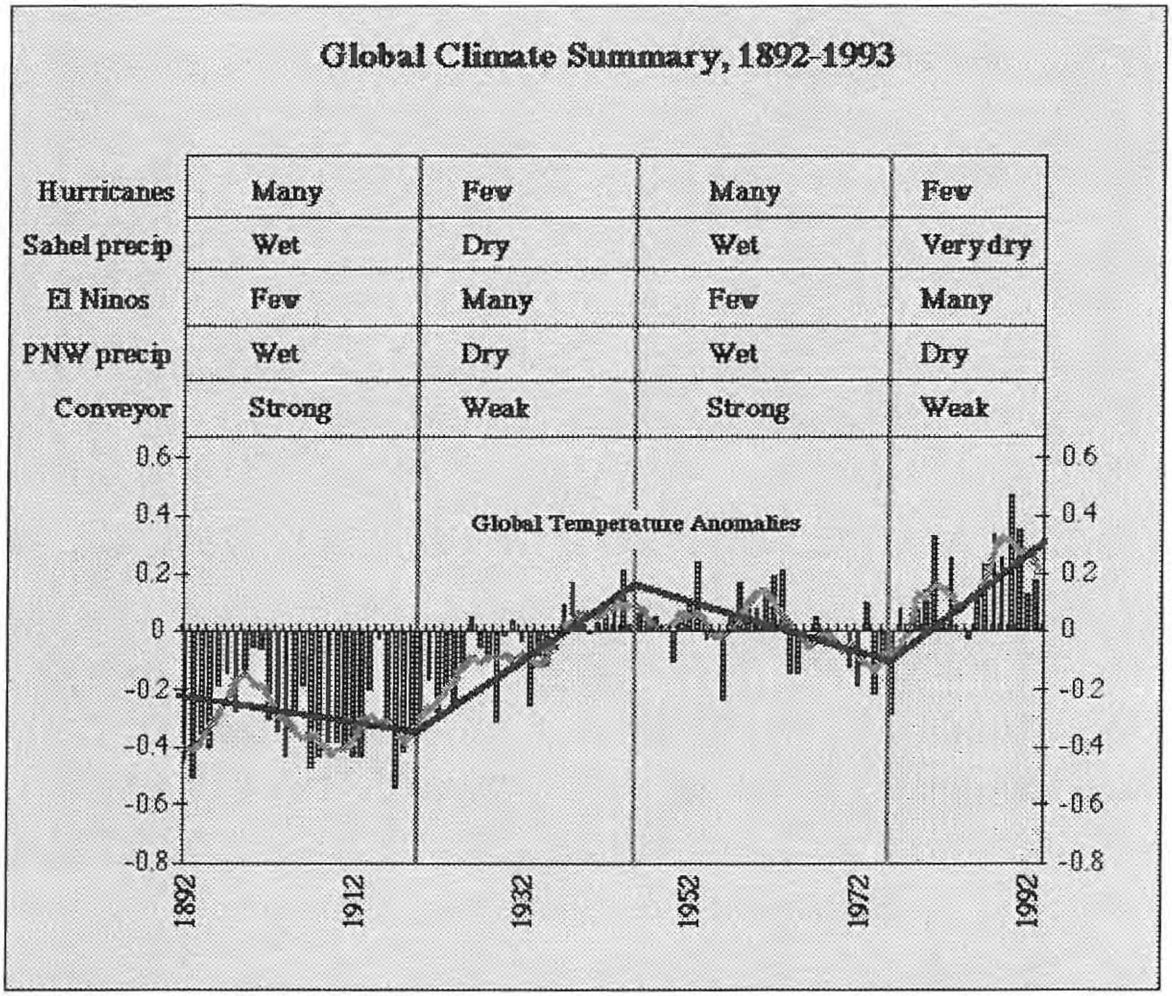

Water Year Precipitation, Oregon Coast Division, 1896-1998
Departure from average (inches)
40
30
20
10
0
-10
-20
-30
-40
Cool, wet
Warm, dry
Cool, wet
Warm, dry
1896
1906
1916
1926
1936
1946
1956
1966
1976
1986
1996

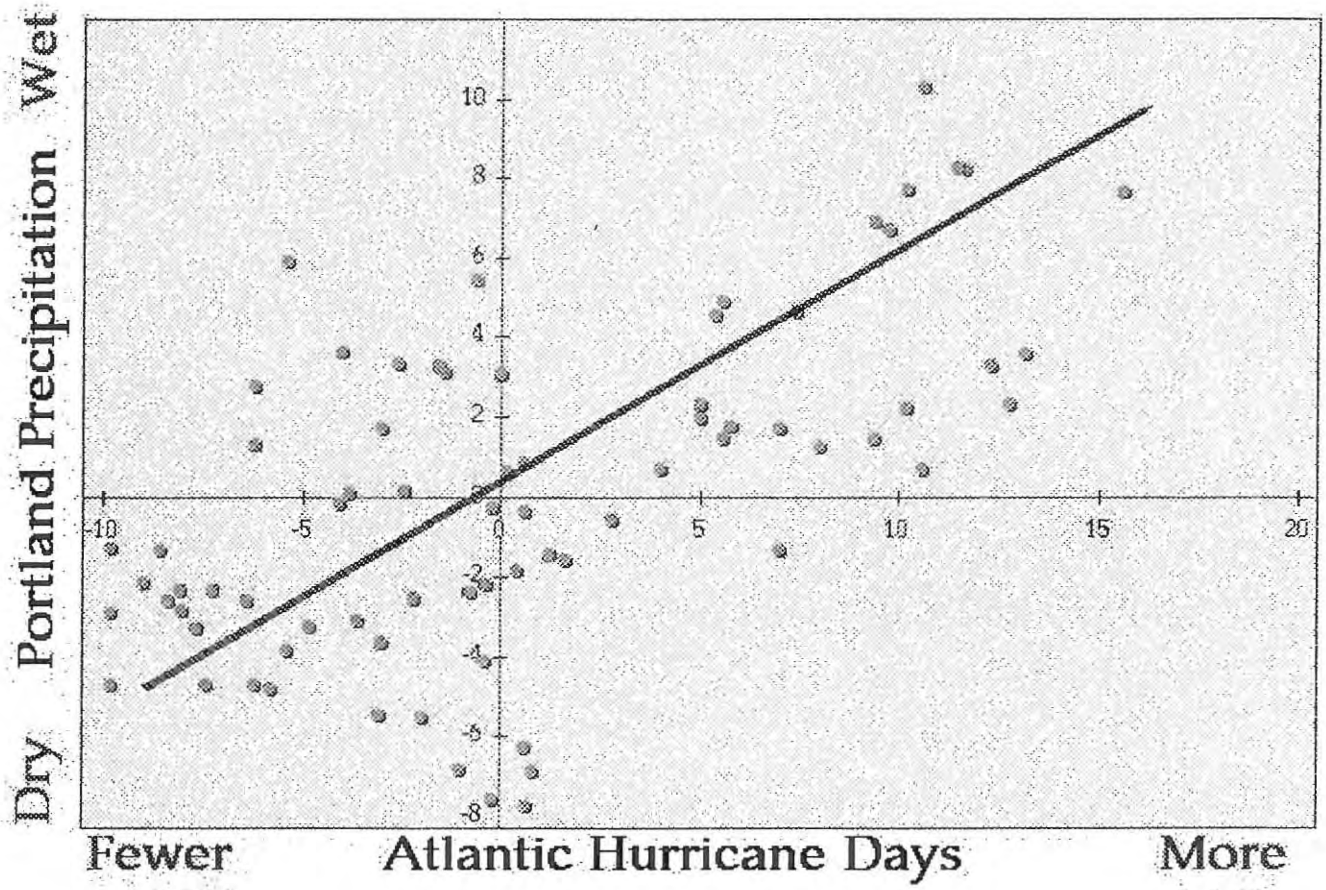

Portland Water Year Precipitation, 1920 - 2020
Departure from average (inches)
20
15
10
5
0
-5
-10
-15
-20
Warm, dry
Cool, wet
Warm, dry
Cool, 
1920
1924
1928
1932
1936
1940
1944
1948
1952
1956
1960
1964
1968
1972
1976
1980
1984
1988
1992
1996
2000
2004
2008

# The Oceanic "Conveyor Belt"



Oregon Climate Service


Global Climate Summary, 1892-1993
Hurricanes
Sahel precip
El Ninos
PNW precip
Conveyor
Many
Wet
Few
Wet
Strong
Few
Dry
Many
Dry
Weak
Many
Wet
Few
Wet
Strong
Few
Very dry
Many
Dry
Weak
Global Temperature Anomalies
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
1892
1912
1932
1952
1972
1992


Wet
Portland Precipitation
Dry
10
8
6
4
2
0
-2
-4
-6
-8
-10
-5
0
5
10
15
20
Fewer
Atlantic Hurricane Days
More