Ocean processes and hazards along the Oregon coast

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INTRODUCTION

Early explorers of the Oregon coast (Figure 1) were impressed by the tremendous variety of its scenery. Today, visitors can still appreciate those same qualities. The low rolling mountains of the Coast Range serve as a backdrop for most of the length of its ocean shore. In the south, the Klamath Mountains extend to the coast, and the edge of the land is characterized by high cliffs being slowly cut away by ocean waves. The most resistant rocks persist as sea stacks scattered in the offshore. Sand and gravel are able to accumulate only in sheltered areas where they form small pocket beaches within the otherwise rocky landscape.

The more extensive stretches of beach are found in the lower lying parts of the coast. The longest continuous beach extends from Coos Bay northward to Heceta Head near Florence, a total shoreline length of some 60 mi. This beach is backed by the impressive Oregon Dunes, the largest complex of coastal dunes in the United States. Along the northern half of the coast there is an interplay between sandy beaches and rocky shores. Massive headlands jut out into deep water, their black volcanic rocks resisting the onslaught of even the largest storm waves. Between these headlands are stretches of sandy shoreline whose lengths are governed by the spacings between the headlands. Portions of these beaches form the ocean shores of sand spits such as Siletz, Netarts, Nehalem, and Bayocean. Landward from the spits are bays or estuaries of rivers that drain the Coast Range.

The first western explorers and settlers were attracted to the Oregon coast by the potential richness of its natural resources. Earliest were the traders who obtained pelts of ocean otter and beaver from the Indians. Later came prospectors who sought gold in the beach sands and coastal mountains but in many cases were content to settle down and "mine" the fertile farm lands found along the river margins. Others turned to fishing, supporting themselves by harvesting the abundant Dungeness crab, salmon, and other fish in the coastal waters. Also important to the early economy of the coast were the vast tracts of cedar and sitka spruce, a significance that continues to the present.

In contrast, today the most important "commodity" for the Northwest coast economy is the vacation visitor. Vacationers arrive in thousands during the summer months, but in spite of their numbers it is still possible to leave coastal Highway 101 and find the seclusion of a lonely beach or the stillness of a trail through the forest.

However, there is cause for concern that the qualities of the Oregon coast we cherish are being lost. Like most coastal areas,

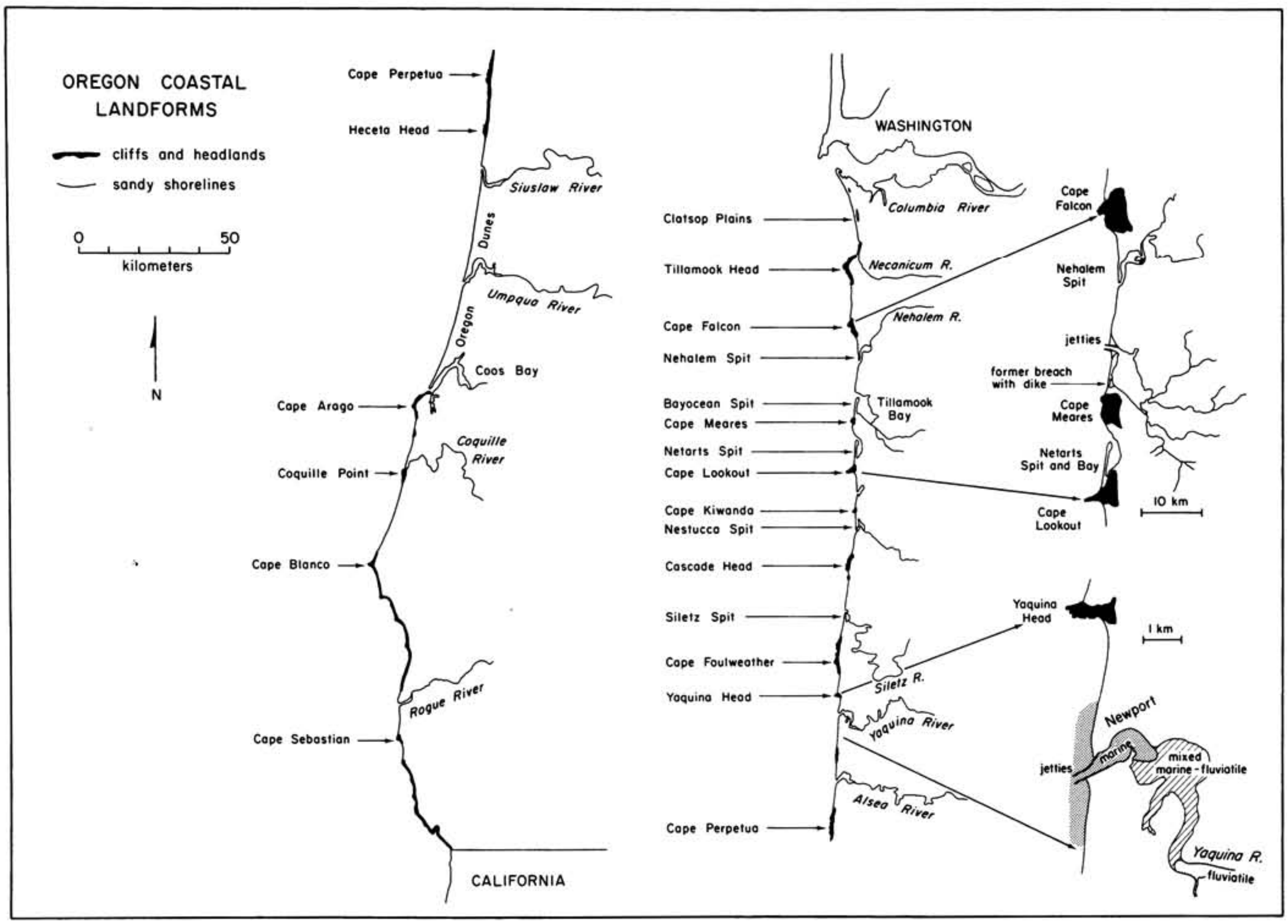

Figure 1. Coastal landforms of Oregon, consisting of stretches of rocky shorelines and headlands, separating pockets of sandy beaches. From Komar (1985).

Oregon is experiencing developmental pressures. Homes and condominiums are being constructed immediately behind the beaches, within the dunes, and atop cliffs overlooking the ocean. Everyone wants a view of the waves, passing whales, and an evening sunset, as well as easy access to a beach. These desires are not always compatible with nature, and as a result there are increasing problems with homes that are being threatened and sometimes lost to beach erosion and cliff landsliding.

Such problems can usually be avoided if one recognizes that the coastal zone is fundamentally different from inland areas because of its instability. This requires some knowledge of ocean waves and currents and how they shape beaches and attack coastal properties, and it requires an understanding and recognition of the land's potential instabilities that might cause disasters such as sudden landslides. A familiarity with the processes and types of problems experienced in the past can aid in the selection of a safe location for one's home. It can also enhance enjoyment of the coast and, it is hoped, lead to an appreciation of the qualities of the Oregon coast that must be preserved.

TECTONIC SETTING AND GEOMORPHOLOGY

The tectonic setting of the Oregon coast is extremely important to the occurrence and patterns of erosion. Especially significant is the presence of active sea-floor spreading beneath the ocean to the immediate west. New ocean crust is formed at the Juan de Fuca and Gorda Ridges, and the movement of the resulting plates is generally eastward toward the continent. These ocean plates collide with the North American plate (which includes the continental land mass). That collision zone lies along the margin of the coasts of Washington, Oregon, and northern California. There is also evidence that the oceanic plates have been undergoing subduction beneath the continental North American plate, evidence that includes the still-active volcanoes of the Cascades, the existence of marine sedimentary rocks accreted to the continent, and the occurrence of vertical land movements along the coast.

Most of the marine sediments deposited on the oceanic plates are scraped off during the subduction process and are accreted to the continental plate. The addition of ocean sediments to the continent has led to the long-term westward growth of the Pacific Northwest. The oldest rocks found in the Coast Range date back to the Paleocene and Eocene epochs, some 40-60 million years ago. These accreted marine sediments, mainly gray mudstones and siltstones, can be seen in many sea cliffs along the coast (see cover photo, lower left). As will be discussed in a later section, the presence of these mudstones is important to the erosion of sea cliffs and particularly the occurrence of landslides.

In addition to Tertiary mudstones, many sea cliffs contain an upper layer of clean sand (cover photo, lower left). These Pleistocene marine terrace deposits consist of uplifted beach and dune sands. In some areas, the Pleistocene sands form the entire sea cliff, with no outcrop of Tertiary mudstones beneath. The flat marine terrace seen in the photo is the lowermost and youngest of a series of terraces that in some places form a stairway up the flank of the Coast Range. Their presence documents that the Oregon coast has been tectonically rising for hundreds of thousands of years, while at the same time the level of the sea has oscillated due to the growth and retreat of glaciers.

The general uplift of the Northwest coast is also demonstrated by records from tide gauges where the hourly measurements are averaged for the entire year, removing the tidal fluctuations and leaving the mean sea level for that year (Hicks and others, 1983). Examples obtained by yearly averaging and covering up to 80 years are shown in Figure 2.

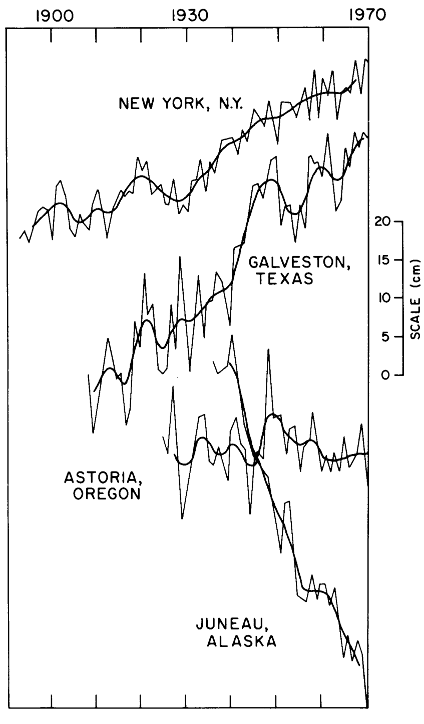

Figure 2. Yearly changes in sea levels determined from tide gauges at various coastal stations. After Hicks (1972).

Each record reveals considerable fluctuations in the level of the sea from year to year, with many small ups and downs. The sea level in any given year is affected by many oceanic and atmospheric processes that produce these irregular fluctuations. In spite of such irregularities, most tide-gauge records reveal a long-term rise in the sea that can in part be attributed to the melting of glaciers. The record from New York City is typical of such observations: in that example, the long-term average rise is 3.0 mm/year, about 12 in. per century (1 in. = 25 mm). The record from Galveston, Texas, also shows a rise, but the average rate is much higher at 6.0 mm/year (24 in. per century). The actual level of the sea cannot be going up faster at Galveston than at New York City—the discrepancy results from changing levels of the land that affect the record obtained at a specific tide-gauge site. It is known that the Galveston area is subsiding, so the 6.0-mm/year record from that tide gauge represents the combined effects of the local land subsidence plus the actual rise in sea level. An extreme case of this is Juneau, Alaska, which is tectonically rising at a rate that is faster than the rise in sea level. The Juneau tide-gauge record, therefore, indicates a net fall in the water level relative to the land. According to the record from the tide gauge at Astoria, Oregon, as included in Figure 2, the level of the sea there has remained relatively constant with respect to the land. This must indicate that during at least the last half century Astoria has been rising at just about the same rate as the sea. A detailed analysis of the measurements from the Astoria tide gauge indicates that the land is actually rising slightly faster than the water, the net increase in the land elevation relative to the sea being 0.1 to 0.2 mm/year. This change is small, amounting to 10 to 20 mm (<1 in.) of land elevation increase if continued for 100 years. Greater rates of uplift of the land must be occurring at Neah Bay on the north coast of Washington, the net rate there being 1.3 mm/year (5 in. per century) in excess of the global sea-level rise, and at Crescent City in northern California with 0.7 mm/year or 2.8 in. per century of net land emergence (Hicks and others, 1983).

Data from geodetic surveys collected by the National Geodetic Survey permit us to infer the movement of the land relative to the sea along the remainder of the Oregon coast. Vincent (1989) and Mitchell and others (1991) have analyzed the geodetic data along a north-south line extending the full length of the Oregon coast. Surveys made in 1931 and 1988 were compared to establish elevation changes; the values are graphed in Figure 3. The movement so determined is relative rather than absolute, so the elevation changes have been normalized to the bench mark in Crescent City. Accordingly, the elevation-change scale on the left of the diagram gives 0 for Crescent City. Positive values for other locations represent an increase in elevation relative to Crescent City, and negative values indicate reduced elevation relative to Crescent City (but could still involve tectonic uplift).

The overall pattern seen in Figure 3 indicates that the smallest uplift has occurred along the north-central coast between Newport and Tillamook, with progressively higher uplift further south and along the very north-

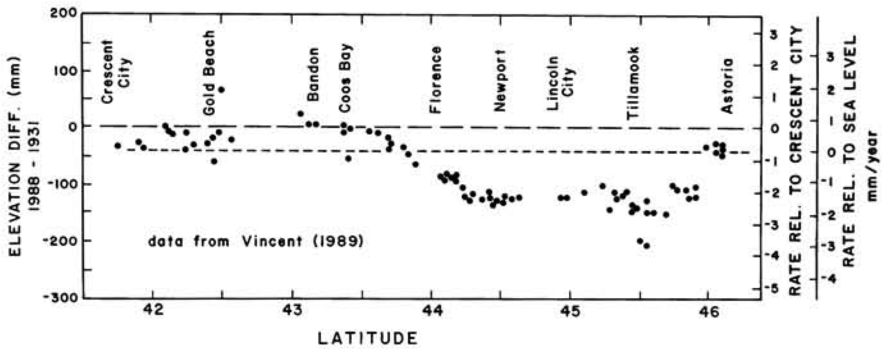

Figure 3. Elevation changes and the relationship to sea-level rise along the length of the Oregon coast from Crescent City in California north to Astoria on the Columbia River, based on repeated geodetic surveys along the coast. After Vincent (1989).

ernmost portion of the coast toward Astoria and the Columbia River. The first scale on the right of Figure 3 indicates the equivalent rates, the elevation changes divided by the lapsed time between surveys, 1988-1931 = 57 years. The differential rates are significant, for example amounting to 2-3 mm/year when comparing Astoria and the south coast with the Newport and Lincoln City areas.

It is possible to use the tide-gauge data to convert the elevation changes relative to Crescent City as they were determined by Vincent (1989) into rates compared with the global change in sea level. This is done simply by shifting the first scale on the right of Figure 3, the one that is relative to the Crescent City bench mark, by an amount of 0.7 mm/year as determined from the tide gauge at that location. This shift yields the rate scale furthest to the right in Figure 3, the rate of land-level change relative to the changing global sea level. A positive value again indicates that the elevation of the land is increasing relative to the sea, while a negative value corresponds to inundation of the land by the rising sea. This coast-wide shift of the scale by 0.7 mm/year (based on the tide gauge at Crescent City) indicates that Astoria at the far north is rising faster than the sea by an amount on the order of 0.1-0.2 mm/year, just as found by the tide gauge at that location—confirming the validity of Vincent's analysis of geodetic data to determine elevation changes and of the analyses undertaken to convert those data into a rate of change compared with the increasing level of the sea.

According to the results graphed in Figure 3, the southern half of the Oregon coast and the far north coast near Astoria are presently rising faster than the global sea level, while the central stretch between Newport and Tillamook is being submerged by the rising sea. The submergence rates are on the order of 1-2 mm/year (4-8 in. per century) and therefore are small, compared with submergence rates experienced on most coastlines: Rates of 4-6 mm/year (16-24 in. per century) are common along the east and Gulf coasts of the United States (Figure 2). The global rise in sea level has been estimated by various workers to be on the order of 1-3 mm/year (4-12 in. per century). The large range is due to the difficulty of separating that worldwide component from local tectonic and isostatic effects included in records from tide gauges. Assuming that the eustatic rise in sea level is on the order of 2 mm/year (8 in. per century), the results from Figure 3 indicate that the south coast of Oregon is tectonically rising at a rate of about 2-3 mm/year (8-12 in. per century), while the stretch between Newport and Tillamook is approximately stable, neither rising nor falling tectonically.

It is apparent that the along-coast differences in tectonic uplift versus changing levels of the sea deduced from Figure 3 will be relevant to spatial patterns of coastal erosion. However, there also appears to be a temporal change in the tectonics that would be important to erosion. Earthquake activity is generally associated with subduction zones such as the one in the Northwest—seismic events formed by the plates' scraping together as the oceanic plate slides beneath the continental plate. The Northwest coast is anomalous in that respect in that there have been no historic earthquakes that can be attributed to plate subduction.

However, recent evidence suggests that the plates are temporarily locked together and that the 200-year historical record from the Northwest is too limited to establish whether earthquakes do accompany subduction. This evidence has come from investigations of estuarine marsh sediments buried by sand layers, deposits suggesting that during prehistoric times portions of the coast have abruptly subsided, generating an extreme tsunami that swept over the area to deposit the sand (Atwater, 1987; Darienzo and Peterson, 1990; Atwater and Yamaguchi, 1991).

Based on the number of such layers found in Willapa Bay, Washington, and Netarts Bay, Oregon, it has been estimated that catastrophic earthquakes have occurred at least six times in the past 4,000 years, at intervals ranging from 300 to 1,000 years. The last recorded event took place about 300 years ago. Therefore, there is strong evidence that major subduction earthquakes do indeed occur along the Northwest coast—but with long periods of inactivity between events. An earthquake releases strain built up by subduction, and the result is that some areas of the coast drop by 1-2 m (3-6 ft) during the release, whereas other areas undergo minimal subsidence. Between earthquake events the strain is accumulating, and this produces a general uplift of the coast as recorded by the tide gauges and geodetic surveys within historic times (Figures 2 and 3).

Another potential change in the present-day pattern of sea-level rise versus coastal uplift is associated with predictions for an accelerated rise in sea level associated with future greenhouse warming. Global temperatures have been predicted to increase from 1.5° to 4.5° by the year 2050 (National Research Council, 1983). Those predictions in turn have led to a variety of estimates for accelerated sea-level rise, caused by increased glacial melting and thermal expansion of seawater. For example, a report by the National Research Council (1987) predicts that by the year 2025 the global sea level will rise by 10-21 cm (4-8 in.). Although this may seem insignificant, the effects on sandy shorelines may be magnified 100 times in the horizontal direction, resulting in shoreline erosion of 10-21 m (33-70 ft).

There are many uncertainties in the analyses of sea-level rise resulting from greenhouse warming, and therefore the resulting predictions have been controversial among scientists. Different investigators who studied sea-level curves derived from tide gauges have reached conflicting results, some concluding that they see an increase in the rate of rise in recent decades, others concluding that they do not. Despite the uncertainties, there is a growing consensus that some increased rate of sea-level rise can be expected in the next century. This recognition has led to recommendations that future sea levels be given more serious consideration in coastal management decisions.

OCEAN PROCESSES AS AGENTS OF EROSION

The Northwest coast is one of the world's most dynamic environments. Ocean waves and currents continuously reshape the shoreline. Portions of the beach are cut away, while others are built out. Severe storms strike the coast during the winter, generating strong winds that drive rain against sea cliffs and homes and form huge ocean waves that crash against the shore. Beaches give way to waves and currents, retreating back toward the land. At times, this beach loss continues until the erosion threatens homes and motels and cuts away at public parklands.

Ocean waves

The extreme seasonality of the Oregon climate results in parallel variations in ocean processes and exerts the primary control on natural cycles observed on beaches. The varying energy of ocean waves parallels the seasonally varying storm winds, because the strength of those winds is the primary factor in causing the growth of waves. In general, the greater the wind velocities blowing over the ocean's surface, the higher the resulting waves. Other factors are involved in addition to the wind speed. One is the duration of the storm—the longer the winds blow, the more energy they are able to transfer to the waves. The third factor is the fetch, the area or ocean expanse over which the storm winds are effective. Fetch operates much like storm duration in that the area of the storm governs the length of time the winds are able to act directly on the waves. As the waves are forming, they move across the ocean's surface and may eventually pass beyond the area of the storm so they no longer acquire energy from the winds. The importance of fetch is apparent when one contrasts wave generation on the ocean with that on an inland lake. The fetch on the lake can be no greater than its length, so the waves can acquire only a small amount of energy from winds before they cross the entire lake and break on the shore.

Wind-generated waves are important as energy-transfer agents. They first obtain their energy from the winds, transfer it across the expanse of the ocean, and finally deliver it to the coastal zone when they break on the shoreline. Therefore, a storm need not be in the immediate coastal zone. Waves reach the shores of Oregon from storms all over the Pacific Ocean, even from storms in the southern hemisphere near Antarctica. Our largest waves are derived, however, from winter storm systems moving down from the north Pacific and Gulf of Alaska.

Ocean waves reaching the shores of Oregon are measured daily by a unique system, a microseismometer like those that are usually employed in measuring small earth tremors. In this application, the microseismometer senses ground movements produced by ocean waves as they reach the shore and break. Many Coast Guard stations in the Northwest now use this system to obtain better estimates of wave conditions than they formerly obtained by visual determination. A microseismometer system is also in operation at the Oregon State University Hatfield Marine Science Center in Newport, one that is connected to a recorder to obtain a permanent record of the waves. This system has been in operation since November 1971 and has yielded the longest continuous record of wave conditions on the west coast of the United States. These measurements have been valuable in research examining the causes of beach erosion along the Oregon coast.

It might come as a surprise that a microseismometer in the Marine Science Center can provide records of ocean waves—after all, the Center is nearly 2 mi from the ocean. However, even more impressive is the fact that the waves can be detected on the seismometer at Oregon State University in Corvallis, 60 mi inland. When the surf is high on the coast, its effects can be seen as small jiggles in the seismometer recordings.

The microseismometer in the Marine Science Center differs from normal seismometers in that it is so tuned as to amplify small tremors, whether they are caused by earthquakes too minor to be felt or generated by ocean waves along the coast. In order to use the recordings from the microseismometer to measure ocean waves, it was necessary to first calibrate the system (Zopf and others, 1976; Creech, 1981). This calibration was accomplished by obtaining direct measurements of waves in the ocean at the same time their tremors were measured with the microseismometer. The direct measurements of waves were taken with a pressure transducer, an instrument that rests on the ocean bottom and records wave pressures that are directly proportional to the heights of the waves passing over the transducer.

The pressure transducer, the most commonly used instrument for measuring ocean waves directly, would be preferable to the microseismometer. However, winter storms experienced along the Northwest coast are so intense that they usually destroy pressure transducers or other wave-measuring instruments that must be placed in the water. On this coast, we need a microseismometer that can remain in the Marine Science Center, safe from the reach of waves.

Although the direct comparisons between the pressure-transducer records and those obtained with the microseismometer were continued for only a few months, the results showed that the motions on the microseismometer are directly proportional to the heights of the offshore waves. Now only the microseismometer is needed to monitor daily ocean-wave conditions.

An example of the daily wave measurements obtained from the microseismometer is shown in Figure 4, covering the period from mid-December 1972 through January 1973. Most apparent in this series are the storm waves that struck the Oregon coast during Christmas. The breaker heights at that time reached 7 m, about 23 ft, roughly the height of a three-story building. This reported height represents what is termed a "significant wave height", defined as the average of the highest one-third of the waves.

Thus, the significant wave height can be evaluated from measurements obtained with wave-sensing instruments. However, it turns out that the significant wave height also roughly corresponds to a visual estimate of a representative wave height. This

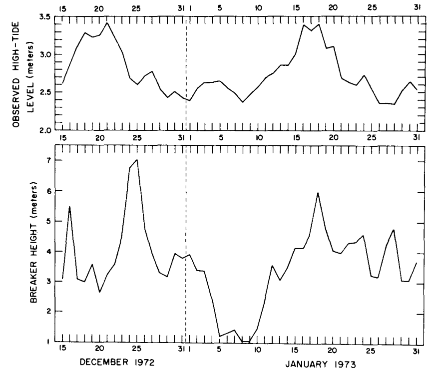

Figure 4. An example of daily variations in wave conditions measured by the microseismometer at Newport, covering the interval from December 1972 through January 1973. From McKinney (1977).

is because an observer normally tends to weight the observations toward the larger waves, ignoring the smallest. There will, of course, be many individual waves that are still higher than this reported significant wave height, which remains something of an average. Measurements have shown that the largest wave height during any 20-minute time interval will be a factor of about 1.8 times the significant wave height (Komar, 1976). Therefore, when the graph of Figure 4 indicates the occurrence of a significant wave height of 7 m during Christmas 1972, there must have been individual waves having heights of about 1.8 x 7 m = 12.6 m (>41 ft)! As might be expected, there was considerable erosion along the coast during that storm, the severest impact occurring at Siletz Spit on the mid-Oregon coast.

Figure 5 gives an example of the annual changes in wave-breaker heights as measured by the microseismometer. The measurements were obtained from July 1972 through June 1973, but they are typical of annual variations (Komar, Quinn, and others, 1976). These data again represent significant wave heights. The solid line gives the average of significant breaker heights that were measured during each one-third-month interval. It shows that the breakers are on the order of 2 m (7 ft) high during the summer months, nearly doubling to about 4 m (13 ft) in the winter. The dashed lines show the maximum and minimum breaker heights that occurred during those one-third-month intervals and provide a better impression of the effects of individual winter storms. The largest waves recorded within this 1972-73 period reached the coast during the final third of December 1972, as shown on a daily basis in Figure 4.

Although extremely high, the waves during that December 1972 storm are well below the largest that have been measured off the Northwest coast. In the early 1960s, a wave-monitoring program on offshore

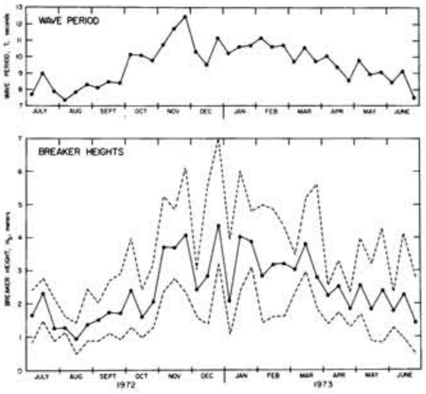

Figure 5. The monthly variations of wave breaker heights and periods at Newport, illustrating the occurrence of higher wave conditions during the winter months. Solid line is for mean heights (significant wave heights) for one-third-month intervals; dashed lines are for largest and smallest breakers for those intervals. From Komar, Quinn, and others (1976).

rigs exploring for oil measured an individual wave at a height of 29 m (95 ft) (Rogers, 1966; Watts and Faulkner, 1968). This is close to the 112-ft height of the largest wave ever reliably measured in the ocean, observed from a naval tanker traveling from Manila to San Diego in 1933 (Komar, 1976). All of the measurements on the Oregon coast confirm that it has one of the highest wave-energy climates in the world.

Beach cycles on the Oregon coast

Beaches respond directly to the seasonal changes in wave conditions. The resulting cycle is similar on most coastlines and is illustrated schematically in Figure 6. The beach is cut back during the winter months of high waves, when sand is eroded from the shallow underwater and from the beach berm (the nearly horizontal part of the beach profile that is above the high-tide line). This eroded sand moves to deeper water, where it then accumulates in offshore bars, approximately in the zone where the waves first break as they reach the coast. Sand movements reverse during the summer months of low waves, moving back onshore from the bars to accumulate in the berm. Although this cycle between two beach-profile types is approximately seasonal due to changing ocean waves, the response is really one to high storm waves versus low regular swell waves. At times, low waves can prevail during the winter, and the beach berm may actually build out, although not generally to the extent of the summer berm. Similarly, should a storm occur during the summer, the beach erodes.

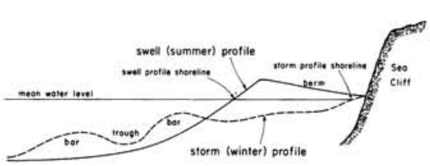

Figure 6. General pattern of seasonal changes in beach profiles associated with parallel variations in wave energies. From Komar (1976).

This cycle has been demonstrated to occur on Oregon beaches, just as it has been observed along other coasts. In one study, profiles were obtained monthly during the winter of 1976-77 from two beaches, that to the south of Devil's Punchbowl at Otter Rock and the one at Gleneden Beach south of Lincoln City (Aguilar-Tunon and Komar, 1978). These two beaches were selected because of their contrasting sand sizes that produce marked differences in overall slopes of the profiles. The sediment grain size is the primary factor that governs the slope of a beach: the slope increases as grain size increases. Gravel beaches are the steepest, their slopes sometimes reaching 25°-30°, whereas the overall slope of a fine-sand beach may be only 1°-2°. This is seen in the comparison of the beach profiles at Gleneden Beach and Otter Rock (Figure 7), the beach at Gleneden being coarser and hence steeper.

The month-by-month changes in the profiles at Gleneden Beach are shown in Figure 8. These profiles were obtained with standard surveying gear and by wading into the water. They do not show the offshore bars, which were too deep to reach. However, these profiles do illustrate the rapid retreat of the beach as the winter season develops. Erosion began as early as October and continued through the spring. The return of sand to the berm and the buildup of the beach did not take place until April through June. The cycle of profiles at the Otter Rock beach was basically the same, at least in its timing. However, the magnitude of change was much smaller than at Gleneden Beach. Sand elevations at Gleneden changed by as much as 2-3 m (8 ft) (Figure 8), while the changes at Otter Rock amounted to less than 1 m (3 ft). This again can be attributed to differences in grain sizes between these two beaches. In general, the coarser the grain size of the beach sand, the larger the changes in its profile in response to varying wave conditions. The response to storms is also much faster for the coarser grained beach—the storm waves not only cut back the coarser beach to a greater degree but also erode it at a much faster rate. Here nature goes counter to what might intuitively have been expected.

The greater response of coarser grained beaches to storm waves is of importance to coastal-erosion processes, since the waves are able to rapidly cut through the beach to reach homes and other structures. This points to the general role of the beach as a buffer between the ocean waves and coastal properties. During the summer, when the beach berm is wide, the waves cannot reach the properties. So, erosion is not a problem, thanks to the buffer protection offered by the beach. However, when the beach is cut back during the fall and early winter, it progressively loses that buffering ability, and property erosion is more likely. If a storm strikes the coast in October, there may be enough beach to serve as a buffer so that property erosion does not occur. It is only when the beach berm completely disappears and the waves can wash against the cliffs and foredunes that the potential for property losses is great. This is often the condition from about November through March, but in fact the extent of the remnant berm is extremely variable along the coast as is the parallel threat of property erosion. This longshore variability results from the patterns of nearshore currents that assist the waves in cutting back the beach.

Nearshore currents and sediment transport

Waves reaching the coast generate currents in the nearshore zone that are important to sand movements on the beach and thus

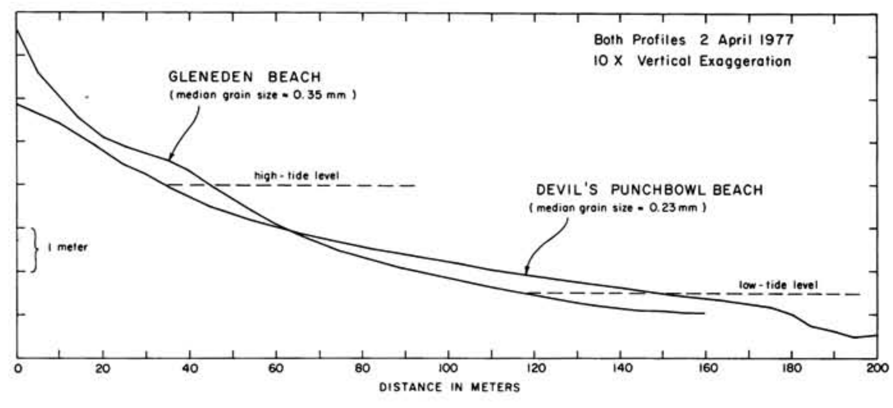

Figure 7. Beach profiles from Gleneden Beach and Devil's Puchbowl Beach (Otter Rock), Oregon, illustrating that coarser-sand beach (Gleneden) is steeper. From Aguilar and Komar (1978).

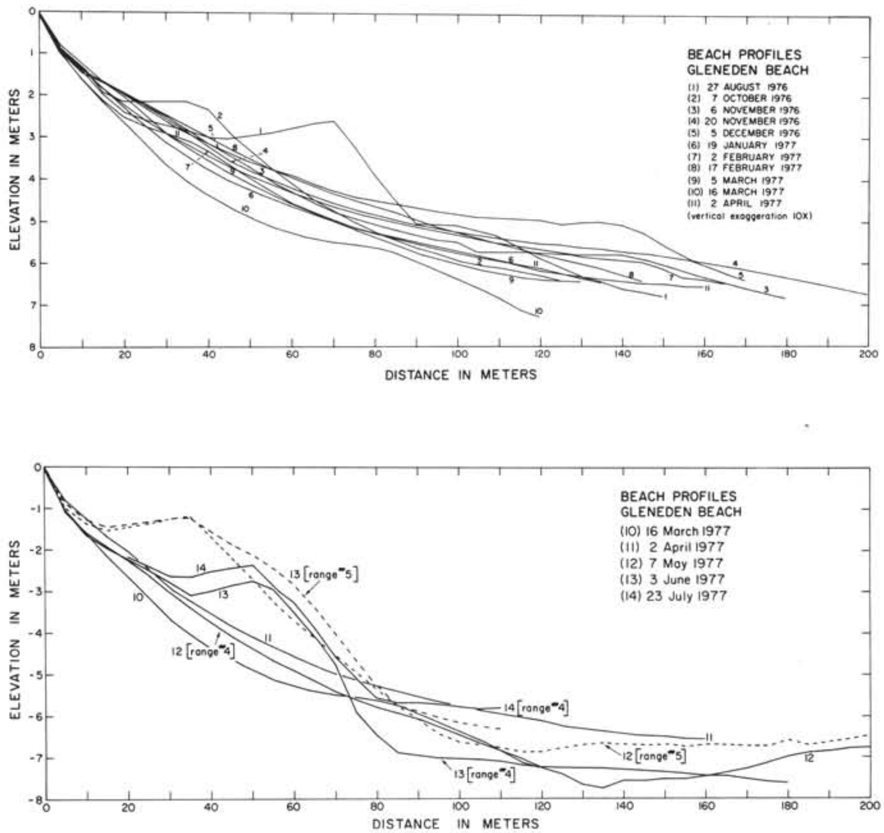

Figure 8. Series of beach profiles obtained at Gleneden Beach, Oregon, illustrating seasonal variations for Oregon coast beaches as shown schematically in Figure 7. From Aguilar-Tunon and Komar (1978).

to erosion processes. These wave-generated currents are independent of ocean currents that exist farther offshore, since those deep-ocean flows do not extend into the very shallow waters of the nearshore.

Most of the time, waves along the Oregon coast approach the beaches with their crests nearly parallel with the shoreline. Under such circumstances, the nearshore currents take the form of a cell circulation, the most prominent part of which are the seaward-flowing rip currents (Figure 9). The rip currents are fed by longshore currents flowing roughly parallel to shore, but they extend along only a short stretch of beach. The currents of this cell circulation are able to move sediments and so affect beach morphology. The longshore currents hollow out troughs into the beach that are generally increasing in width and depth as a rip current is approached. Rip currents can be very strong, cutting through the offshore bars to produce deeper water and a steeper but more uniform beach slope. The rips move sand offshore and thereby tend to erode crescent-shaped embayments into the beach berm. Aerial views of the coast typically show beaches that are extremely irregular: a series of rip embayments of various sizes together with troughs cut by the longshore currents and rip currents (Figure 10). At times these rip-current embayments extend across the entire width of the beach and begin to cut into foredunes and sea cliffs. Such rip embayments have played a major role in property losses due to erosion. Although rip embayments seldom produce much property erosion on their own, they have the effect of eliminating the buffer protection of the beach berm. When a storm occurs, the waves are able to pass through the deep water of the rip embayment, not breaking until they reach the properties. Thus, rip embayments can control the center of attack by storm waves. The resulting erosion is commonly limited in longshore extent to only 100 or 200 yd, the longshore span of a rip embayment that reaches the foredunes or sea cliff (Figure 11).

When waves break at an angle to the beach, they generate a current that primarily flows parallel to the shoreline, although even then seaward-flowing rips may be present. This longshore current, together with the waves, produces a transport of sand along the beach, a sand movement that is known as "littoral drift." This is more than a local rearrangement of the beach sand with accompanying topography changes as produced by rip currents and the cell circulation. Instead, the littoral drift may involve along-coast movements that displace sand by many miles.

On Oregon beaches, the waves tend to arrive from the southwest during the winter and from the northwest during the summer (corresponding to changes in wind directions). As a result, there is a seasonal reversal in

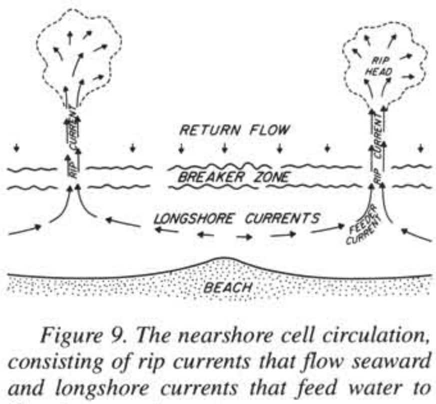

Figure 9. The nearshore cell circulation, consisting of rip currents that flow seaward and longshore currents that feed water to the rip currents.

Figure 10. Beach along Nestucca Spit, photographed during low tide, showing troughs and embayments eroded by longshore currents and rip currents.

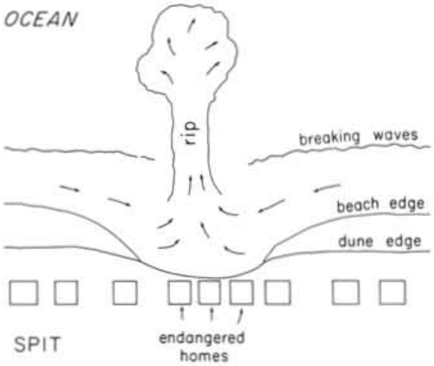

Figure 11. Schematic diagram illustrating how rip currents erode embayments that can cut through the beach and locally threaten properties.

the direction of littoral drift—north in the winter, south during the summer. The net littoral drift is the difference between these north and southward sand movements. Along most of the Oregon coast, this net drift is essentially zero, at least if averaged over a number of years. This is demonstrated by the absence of continuous accumulations of sand on one side of jetties or rocky headlands, with erosion on what would be the downdrift side (Komar, Lizarraga-Arciniega, and others, 1976).

Patterns of sand accumulation and erosion on opposite sides of jetties (Figure 12A) are found on many coasts where the net littoral drift is not zero; for example, along the shores of southern California and most of the east coast of the United States. In those areas, erosion in the downdrift directions from jetties has caused major problems and considerable losses of property (Komar, 1976, 1983b). In contrast, when jetties have been built on the Oregon coast, sand has accumulated on both their north and their south sides. This pattern is diagrammed schematically in Figure 12B and is illustrated specifically by the Yaquina Bay jetties in Figure 13. In the case of the Yaquina Bay jetties, more sand accumulated on the south than on the north, but this was due to the oblique orientation of the jetties to the overall trend of the coastline and because the pre-jetty shoreline curved significantly in toward the bay. More significant is that sand accumulated both north and south of the jetties until the embayments between the jetties and the pre-jetty shoreline filled and an equilibrium shoreline developed. Subsequent to achieving equilibrium, there has been almost no change in the shoreline configuration. The sand that accumulated adjacent to the jetties was derived from erosion of the beaches more distant from the jetties, so an overall symmetrical pattern emerged, one that is significantly different from the asymmetrical pattern found on coasts where there is a large net littoral drift (Figures 12A versus 12B). This reduces the potential for major erosion and property losses due to the construction of jetties on the Oregon coast, at least in comparison with other coasts where there is a large net littoral drift. However, one severe erosion problem did occur on the Oregon coast in direct response to jetty construction: the events that led to the destruction of the town of Bayocean (discussed below).

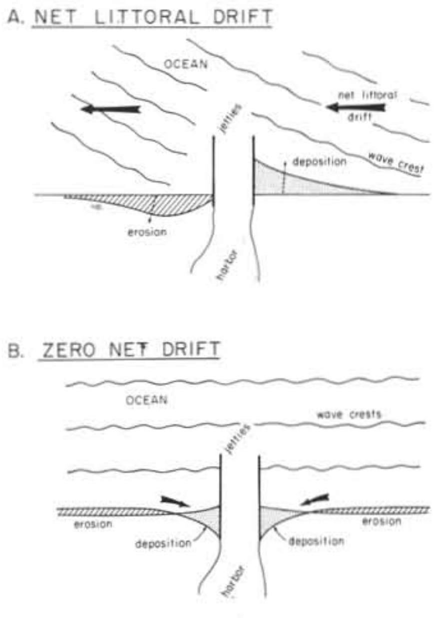

Figure 12. Patterns of sand accumulation around jetties, contrasting condition where jetties block a net littoral drift with condition where there is no net littoral drift. Jetties on the Oregon coast correspond to the latter condition.

The pocket-beach nature of the Oregon coast and sources of nearshore sands

The ultimate cause of the zero net littoral drift of sand along the Oregon coast is that beaches are contained between rocky headlands, in effect forming pocket beaches (Figure 1). The headlands are large and extend to sufficiently deep water to prevent beach sand from passing around them. Therefore, the sand within each pocket beach is isolated. Sand may move north and south within a pocket due to the seasonality of the wind and wave directions, but the long-term net movement must be zero. Each of these pocket beaches on the Oregon coast can be thought of as a littoral cell. This is a useful concept in considering sources and losses of sediments on the beach, the so-called budget of littoral sediments. As will be discussed later, there are even contrasting patterns and magnitudes of erosion from cell to cell, particularly the erosion of sea cliffs.

The one beach on the Oregon coast that does not fit this pattern of a zero-drift pocket and self-contained littoral cell is the shoreline that extends south from the Columbia River past Seaside to Tillamook Head. This is the Clatsop Plains area, formed by the accumulation of sand derived from the Columbia

Figure 13. Shoreline changes at Yaquina Bay jetties, 1830 (representing pre-jetty configuration) to 1974, and photo of September 5, 1974, status. Sand accumulated both north and south, but volume to south is greater because the embayment created between the constructed jetty and the pre-jetty shoreline was larger; also due to oblique orientation of jetties compared with trend of shoreline. From Komar, Lizarraga-Arciniega, and others (1976).

River, part of which moves southward until it is blocked by Tillamook Head. However, the bulk of sand derived from the Columbia River moves northward along the coast of Washington. The quantities of this northward sand transport can be only roughly estimated, but the primary evidence for this sand supply is that many of the beaches along the southern half of the Washington coast are growing (Phipps and Smith, 1978). The highest rates of beach growth tend to be in the south, closest to the Columbia River, decreasing to the north until, beyond Copalis Head, net erosion prevails.

On many coastlines, sand spits grow in the direction of the net littoral drift. The Long Beach Peninsula extends northward from the Columbia River and likely reflects the net sand movement along the Washington coast. It is unclear whether this northward growth has continued within historic times, since there have been many cycles of growth and erosion at the tip of the Peninsula. There are several sand spits along the northern coast of Oregon, some pointing north, while others point to the south (Figure 1). Those spits are located within the beach cells where zero net littoral drift prevails, and their directions do not provide testimony as to net longshore sand movements.

In view of the pocket-beach nature of the Oregon coast, the question arises as to the sources of beach sand contained within those littoral cells. These sources are reflected in the small quantities of heavy minerals contained within the beach sand. On the Oregon coast, the beach sand generally consists of grains of quartz and feldspar minerals. Those particles are transparent or a light tan, and this is what governs the color of most beaches. However, the sands also contain small fractions of heavy minerals that are black, pink, various shades of green, and other colors. These grains are readily apparent as specks in a handful of beach sand and are sometimes concentrated by the waves into black-sand placer deposits on the beaches. Of importance is that these heavy minerals are indicative of the rocks they came from and in many cases can be traced back to specific rocks and therefore geographical sources. That is the case for the heavy minerals in the sands of the Oregon coast. Most distinctive are the minerals derived from the Klamath Mountains: a variety of ancient metamorphosed rocks is found in those mountains of southern Oregon and northern California. As shown in the diagram of Figure 14, sands derived from the Klamath Mountains contain such minerals as glaucophane, staurolite, epidote, zircon, hornblende, hypersthene, and the distinctive pink garnet that, in particular, can often be seen concentrated on the beach. In contrast, the rivers that drain the Coast Range transport sand containing almost exclusively two heavy minerals: dark-green augite and a small amount of brown hornblende (Figure 14). Augite comes from volcanic rocks and is contributed to the rivers by erosion of the ancient sea-floor rocks uplifted into the Coast Range. With the sand of the Columbia River comes a diversity of heavy minerals because the river drains a vast area that contains many types of rocks (Figure 14).

The presence of sand derived from the Klamath Mountains in beaches along almost the entire length of the Oregon coast is at first surprising—in view of the many headlands that prevent any longshore sand transport for that distance. However, thousands of years ago, during the maximum development of glaciers, the sea level was considerably lower, the shoreline was then on what is now the continental shelf, many miles to the west of its present position, and the beaches were backed by a smooth coastal plain. At that time, sand derived from rivers draining the Klamath Mountains could move freely northward as littoral drift without being blocked by headlands. Studies of heavy minerals contained within continental-shelf sands demonstrate that this was indeed the case (Scheidegger and others, 1971): the metamorphic minerals from the Klamaths can be found in the shelf sands nearly as far north as the Columbia River. As the Klamath-derived sand moved north, additional sand was contributed to the beaches by rivers draining the Coast Range, so there is progressively more augite and a smaller proportion of metamorphic minerals from the Klamaths in these beach sands. The Columbia River was a large source of sediment, but most of that sand

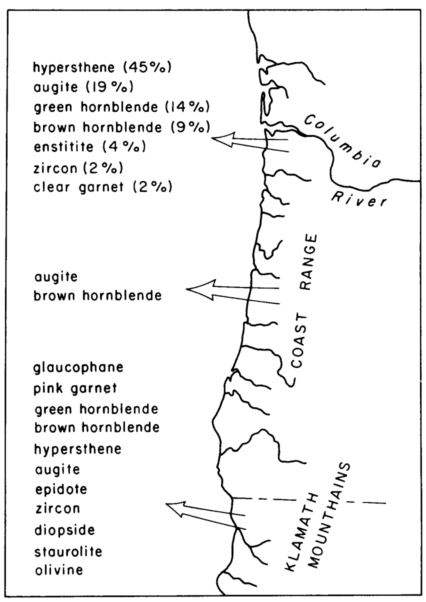

Figure 14. Principal sources of sand to Northwest beaches are the Columbia River and rivers draining the Coast Range and the Klamath Mountains. Each source supplies different suites of heavy minerals to beach and estuarine sands. From Clemens and Komar (1988b).

moved to the north and dominates the mineralogy of ancient beach sands found on the Washington continental shelf. Some Columbia River sand did move south along the Oregon beaches during lowered sea levels and mixed with the sand from the Klamath Mountains and the Coast Range.

Therefore, the absence of headlands during lowered sea levels permitted an along-coast mixing of sands derived from multiple sources, principally from the Klamath Mountain metamorphics, the Coast-Range volcanics, and the Columbia River sands. Varying with the location along this former shoreline of the Oregon coast, the beach consisted of various proportions of mineral grains from those sources. Although a portion of the beach sand was left behind during the rapid rise in sea level and now can be found on the continental shelf, some of it migrated landward with the transgressing shoreline. The beaches would have been low in relief so that storm waves were able to wash over them, transporting sand from the ocean shores to the landward sides of the beaches and thereby producing the migration. Additional sand was contributed by the various river sources and from sediments eroded from the coastal plain.

About 5,000-7,000 years ago, the rate of rise in sea level decreased as the water approached its present level. Just about at that time, the beaches of Oregon came under the influence of headlands that segmented the formerly continuous shoreline. At some stage several thousand years ago, the headlands extended into sufficiently deep water to hinder further along-coast transport of the beach sands. This is shown by a study of the mineralogy of sand found on the present-day beaches (Clemens and Komar, 1988a,b). The pattern of along-coast mixing of sand from the various sources, established during lowered sea levels, is still partly preserved within the series of pocket beaches now separated by headlands. Therefore, one can still find minerals derived from the Klamath Mountains in virtually all of the beaches along the Oregon coast, even though it is certain that the sand can no longer pass around the many headlands that separate those beaches from the Klamath Mountains. In most cases, the Klamath-derived sand could have reached the modern beach only by along-coast mixing during lowered sea levels and subsequent onshore transport with the rise of the sea. However, there has been some modification of the beach-sand mineralogy from that along-coast mixing pattern, as local sources have contributed sand to the beaches during the last few thousand years. Such beach-sand sources include eroding sea-cliffs and some sand from the rivers and streams entering the isolated pocket beaches.

There can be distinct changes in beach-sand mineralogies on opposite sides of headlands, that is, within adjacent but isolated pocket beaches or littoral cells (Clemens and Komar, 1988a,b). One such case is found at Cascade Head north of Lincoln City, continuing at Cape Foulweather farther south. To the north of Cascade Head, the beach sand is rich in augite, which either came from the local rivers and streams draining the Coast Range or from sea-cliff erosion that cuts into alluvium derived from that same volcanic source. In contrast, to the south of Cascade Head, the augite content of the beach sand is much reduced. Sea-cliff erosion is of obvious importance there, but these cliffs are cut into a marine terrace that contains sands of uplifted ancient beaches and dunes. Analyses of the mineralogy of those terrace sands indicate that they are also composed of mixtures of Klamath Mountain, Coast Range, and Columbia River sands (Clemens and Komar, 1988a). Apparently these terrace deposits also record an along-coast mixing of sediments at lowered sea levels, a mixing that was preserved much as it has been on the modern beaches. This conclusion has an unfortunate aspect in that it makes it virtually impossible to distinguish what portion of the sand on the modern beach in that area has been contributed by recent cliff erosion and what portion moved onshore during the last rise in sea level. At any rate, the change in beach-sand mineralogy on opposite sides of Cascade Head demonstrates the effectiveness of that headland in isolating the adjacent pocket beaches and shows that recent contributions to the beaches have been sufficient to alter the pattern established by along-coast mixing during lowered sea levels.

A still more dramatic change in the beach sand occurs at Tillamook Head, south of Seaside (Figure 15) (Clemens and Komar, 1988a,b). North of this headland, the beach sand is derived almost entirely from the Columbia River, and the abundant supply of sand from that large river has built the shoreline out significantly within historic times. South of the headland, the beach sand is abundant in augite, again indicating a Coast Range source from local rivers or cliff erosion. This beach sand also contains small amounts of Klamath Mountain minerals, the northernmost instance where the relict pattern of along-coast mixing during lowered sea levels can be found preserved in the modern beaches. There is some Columbia River sand in this beach to the south of Tillamook Head, but it got there by mixing southward with sands from the other sources during lowered sea level and then migrating onshore. That Columbia-derived sand has been on the beach for thousands of years, whereas to the north of the headland the beach sand came from the Columbia within the last century or two. This contrasting history of the beach sands is also indicated by the degree of rounding of the individual grains as shown in Figure 15. North of the headland, the grains are fresh in appearance and angular, attesting to their recent arrival from the Columbia: the grinding action of the surf has not had sufficient time to abrade and round the grains. To the south of the headland, the grains are much rounder: their sharp edges have been worn away during thousands of years of movement beneath the swash of waves on the beach.

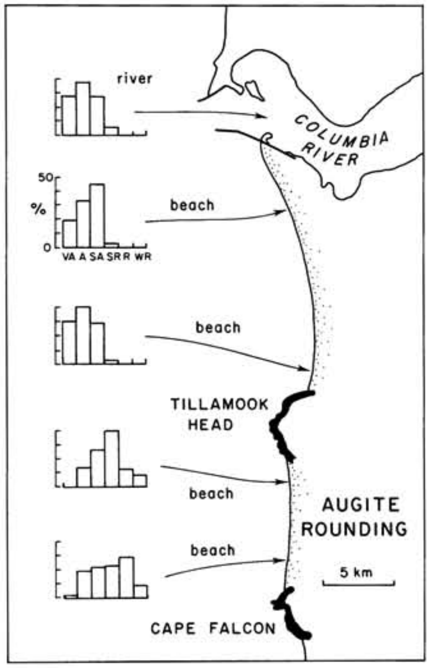

Figure 15. Diagram showing changes in degree of rounding of beach sand on opposite sides of Tillamook Head. VA = very angular, A = angular, SA = subangular, SR = subrounded, R = rounded, and WR = well rounded). After Clemens and Komar (1988a).

During low stands of sea level, the coastal rivers were able to cut down their valleys. When the water rose at the end of the ice age, these valleys were drowned and developed into estuaries. These estuaries are important, serving as harbors and the centers of many of our coastal communities. They are also environments of significant fisheries and, as will be discussed here, play a central role in sediment movements on the coast that govern contributions of sand to the beaches.

An estuary is a zone of complex mixing of fresh water from the river with the ocean's salt water. The fresh water is less dense and therefore tends to flow over the top of the sea water. At times, much of the fresh water from the river flows through the entire estuary and enters the ocean before it finally mixes with the underlying sea water. In such a case, the lens of salt water at depth within the estuary has a net flow from the ocean into the estuary. This situation is found in many Northwest estuaries and is significant, since it is one mechanism that transports sediment from the ocean into the estuary and inhibits the river sands from reaching the ocean beaches.

The restriction of sand movement through Northwest estuaries was first demonstrated in a study of the sediments within Yaquina Bay (Kulm and Byrne, 1966). Similar to the other rivers draining the Coast Range, the Yaquina River transports sand containing augite as its principal heavy mineral. This contrasts with the beach sand outside of the Bay, which contains a large variety of minerals, including the metamorphic minerals that were derived from the Klamath Mountains. In addition, some of the quartz and feldspar grains on the beach are coated with red iron oxide. These are probably grains contributed to the beach from sea-cliff erosion of the marine terraces; such coated grains are not found in the Yaquina River. These differences make it possible to trace the movement of the river and beach sands entering the estuary. The result is summarized in Figure 16, where it is seen that the river sand (fluviatile) forms 100 percent of the estuarine sediment in only the landward portion of the Bay. Marine sand has been carried into the Bay through the inlet and dominates the estuarine sediments near the mouth. Much of the Bay is a zone where the river and marine sands are mixed in varying proportions.

The results indicate that Yaquina Bay is slowly being filled with sediment—from the direction of the land by fluviatile sands and from the ocean side by marine sands. This has also been shown for Alsea Bay, where drilling through the sediments indicates that the bay began to fill immediately after the formation of the estuary with the last rise in sea level and is continuing to fill (Peterson and others, 1982, 1984b). Becoming filled with sediments is generally the fate of estuaries. Having developed by the drowning of river valleys at the end of the ice age, they represent an environment that is out of equilibrium. As a result, estuaries tend to fill until reduced to a river channel that is able to transport all of its sediments to the ocean. Such a development involves thousands of years, so we should not view our estuaries as ephemeral features.

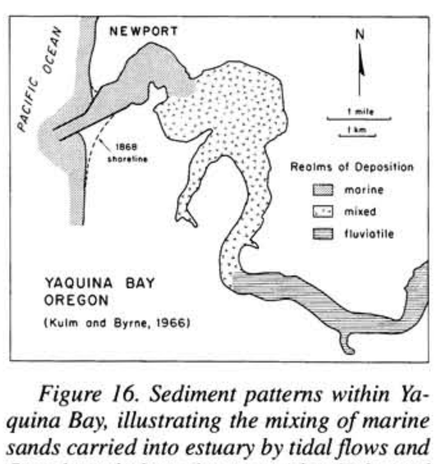

Figure 16. Sediment patterns within Yaquina Bay, illustrating the mixing of marine sands carried into estuary by tidal flows and fluvial sands from the river. After Kulm and Byrne (1966).

Another implication of the results in Figure 16 is that little if any sand from the Yaquina River is presently reaching the ocean beach. This conclusion applies only to sand-size grains. The fine clays that remain in suspension in the water are carried into the ocean, evident by the brown plumes that emanate from the inlet during river floods. Most of the major coastal rivers are separated from the ocean by large estuaries and are not likely to be significant contributors of sand to the modern beaches. This in part explains why many of the Oregon beaches have relatively small volumes of sand and why their mineralogies still reflect the along-coast mixing of sand sources during low stands of sea level rather than more recent contributions.

Such patterns of sand deposition have been shown to occur in other major estuaries of the Northwest (Scheidegger and Phipps, 1976; Peterson and others, 1984a). However, a study of the small Sixes River of Oregon, which does not really have an estuary, indicates that it supplies sand to the adjacent beach, although the amounts would be minor given the small size of that river (Boggs, 1969; Boggs and Jones, 1976). In general, the major rivers have sufficiently large estuaries to make it doubtful whether much, if any, of the river sand reaches the adjacent beaches. The one clear exception to this is the Columbia River, which transports more than 100 times as much sand as the next largest river (the Umpqua) and on the order of 1,000 times as much sand as other coastal rivers (Clemens and Komar, 1988a).

CASE STUDIES OF SAND SPIT EROSION

The most dramatic occurrences of erosion on the Oregon coast have centered on the sand spits. The causative factors have ranged from jetty construction at Bayocean Spit, to natural processes of waves and currents at Siletz and Nestucca Spits, to extreme examples of erosion processes at Alsea and Netarts Spits initiated during the 1982-83 El Niño.

Jetty construction and the erosion of Bayocean Spit

The story of Bayocean Spit is of particular interest in that it provides the earliest example on the Oregon coast of a failed attempt at a major development and also of the erosive impacts that are associated with jetty construction (Terich and Komar, 1974; Komar and Terich, 1976). The San Francisco realtor T.B. Potter was attracted to Tillamook Bay during a fishing trip in 1906 and vowed to build the "Atlantic City of the Pacific Coast" on the spit separating the bay from the ocean. His vision soon took form with the construction of an elegant hotel, a natatorium (housing a heated swimming pool with artificial surf), a number of permanent homes, and a "tent city" for summer visitors. The downtown contained a grocery, bowling alley, and agate shop. However, the development soon ran into economic problems as lots did not sell at the hoped-for rate, primarily due to the inaccessibility of the area and delays in construction of the railroad from Portland.

But the chief threat came from erosion caused by jetty construction in 1914-17 at the mouth of Tillamook Bay (Figure 17). Due to economic constraints, only a north jetty was completed at that time (the south jetty was not built until 1974), and this turned out to be critical to the magnitude of the resulting erosion. The overall pattern of sand movement and shoreline changes was similar to that depicted schematically in Figure 12B, made more complex by the fact that only one jetty was constructed. Sand quickly accumulated north of the jetty (Figure 17), with the shoreline building out. At the same time, sand also accumulated to the south but formed a shoal within the mouth of the inlet, thus greatly increasing the hazards to navigation. The sand that formed the shoal was derived from erosion along the length of Bayocean Spit. It is likely that some of the sand brought to the shoal was carried into the bay and some perhaps to the offshore, so that erosion of Bayocean Spit continued for many years rather than reaching a new equilibrium as is possible where two jetties are constructed (Figure 12B).

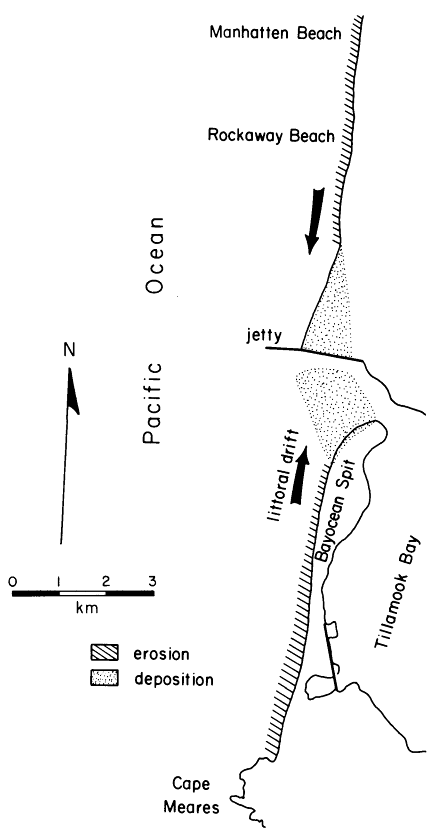

Figure 17. Schematic diagram illustrating patterns of erosion and accretion in response to construction of the north jetty at the inlet to Tillamook Bay. Sand that came from erosion along the length of Bayocean Spit accumulated to form an extensive shoal at the mouth of the inlet.

The erosion of Bayocean was most rapid during the 1930s and 1940s following reconstruction and lengthening of the north jetty. The ocean edge of the spit retreated, dropping houses, the natatorium (see cover photo, upper left), and finally the hotel into the surf. A storm during November 1952 brought the final demise of the development, breaching the spit at its narrowest point. This breach was diked by the Corps of Engineers in 1956, rejoining what had become an island to the mainland. All that remains of Potter's development is bare land with a few slabs of concrete foundations that now litter the beach.

Natural processes and the erosion of Siletz and Nestucca Spits

The erosion of Siletz and Nestucca Spits provides examples of the impact of natural processes: the combined effects of rip currents, storm waves, and elevated water levels (Komar and Rea, 1976; Komar and McKinney, 1977; Komar, 1978, 1983a). The development of Siletz Spit began in the 1960s with the construction of a number of homes, many within the foredunes immediately backing the beach. The first major episode of erosion leading to property losses occurred during the winter of 1972-73. One house under construction was lost (see cover photo, lower right). Others ended up on promontories extending into the surf zone, when riprap was first installed along their seaward fronts and then on their flanks, as adjacent empty lots continued to erode. The main factor in that erosion episode was the occurrence of major storm waves: the 23-ft significant wave heights of December 1972 in the microseismometer record of Figure 4. However, the erosion was limited to only a small portion of the spit, determined by the presence of a rip current that had hollowed out an embayment in the beach, so that waves were able to reach the foredunes and houses (Figure 18).

A series of aerial photographs of Siletz Spit revealed the repeated occurrence of such erosion events over the years. In general, during any one winter, the erosion would occur in only one or two locations determined by the largest rip-current embayments. In subsequent winters, the erosion would shift to other areas, as the rip currents changed positions. (We do not know what controls the locations of rip currents and therefore cannot predict where the erosion will occur.) In the meantime, earlier "bites" taken out of the foredunes by rip currents and storm waves would fill in with drift logs, which in turn captured wind-blown sands, so the dunes quickly formed again. This cycle of dune erosion and reconstruction occurred repeatedly on Siletz Spit, with no measurable long-

Figure 18. Rip currents cutting embayments through beach and reaching development on Siletz Spit during December 1972. Large embayment seen in upper photograph was center of property losses photographed in cover photo, lower right.

term net retreat of the seaward edge of the foredunes on the spit.

The principal mistake made in developing Siletz Spit was to build homes in this zone of foredunes that is susceptible to periodic erosion. We quickly became aware of this during the erosion of 1972-73 (cover photo, lower right): the erosion exposed drift logs within the heart of the spit, often beneath homes built in the 1960s—drift logs that had been cut by saws. What clearer indication could one have of the ephemeral nature of the sites where these homes had been built?

Siletz Spit has repeatedly eroded during subsequent winters, but each time more riprap was added, so that the properties are now reasonably secure. Lots lost to erosion have been filled with beach sand and leased again for development.

Large storm waves combined with high spring tides during February 1978 to cause extensive erosion in many areas of the Oregon coast (Komar, 1978). The greatest impact occurred along Nestucca Spit on the northern Oregon coast, where an uninhabited area of the spit was breached and foredune erosion threatened a new development where houses were still under construction (Figure 19 and cover photo, center). Storm waves again combined with rip-current embayments to control the zones of maximum erosion along the spit as well as to determine the area of breaching. However, of particular importance to the erosion was the simultaneous occurrence of high perigean spring tides plus a storm surge that raised water levels by some 8-9 in. above predicted tide levels. Spring tides occur when the Moon, Earth, and Sun line up so that the gravitational forces causing the tide superim-

Figure 19. Upper photo: Riprap placed to protect homes under construction at Kiwanda Shores on Nestucca Spit in response to erosion during February 1978. Lower photo: Subsequent accumulation of dune sands, completely covering riprap and becoming a problem for homes (1988 photo).

pose, producing the highest monthly tides. A perigean spring tide occurs when the Moon comes closest to the Earth in its eliptical orbit, so that the tide-producing force is still greater than during normal spring tides. Typical spring tides on the Oregon coast reach +9 ft MLLW (= "mean lower low water"—the average of the lowest daily tides, which is taken as the 0-reference tidal elevation), whereas perigean spring tides achieve +10 ft MLLW . At the time of the February 1978 storm that eroded Nestucca Spit, measured high tides reached +10.2 ft MLLW—unusually high tides for the Oregon coast and substantially higher than the tides during the December 1972 erosion of Siletz Spit.

It was this combination—high perigean spring tides with a significant storm surge, exceptionally energetic storm waves, and the development of a major rip-current embayment that by chance focused the erosion along the thinner section of the spit—that resulted in the unusual occurrence of breaching at Nestucca Spit. The only other spit breaching known to have occurred during historic times was at Bayocean Spit, and that breach was due to jetty construction rather than natural causes. On spits and barrier islands of the east and Gulf coasts of the United States, there are frequent occurrences of breaching and washovers, due to the rise in sea level with respect to the land. However, the Northwest coast is rising tectonically, so there is minimal transgression of the sea over the land, and this probably accounts for the rarity of spit breaching here. It took the unusual circumstances of the February 1978 storm to produce a breach.

When the storm struck in February 1978, a development of new houses was under construction on the foredunes at Kiwanda Beach at the north end of Nestucca Spit (Figure 19, upper). Like the erosion of Siletz Spit, drift logs were exposed within the eroding dunes, some of which had been sawed. However, these logs were more rotten than those found within Siletz Spit, suggesting that erosion episodes on Nestucca Spit are less frequent. The lower frequency of erosion occurrences at Nestucca Spit is probably due to the fact that the beach sand here is finer grained than at Siletz (recalling from the discussion earlier that coarser-sand beaches respond more rapidly and to a greater degree to storm-wave conditions). Nestucca Spit began to mend during the summer following its erosion. Similar to the dune reformation on Siletz Spit, drift logs accumulated within the breach and helped to trap wind-blown sand. So much sand has returned to the beach fronting the Kiwanda Beach housing development that the masses of riprap are now buried and the overabundance of sand has become a problem (Figure 19, lower).

The 1982-83 El Niño—an unusual erosion event

A decade ago, an El Niño was thought to involve only a shift in currents and a warming of ocean waters to the west of South America. Its occurrence was primarily of interest because an El Niño caused the mass killing of fish off the coast of Peru. No one imagined that an El Niño had wide-ranging consequences, including that of playing a major role in beach erosion along the west coast of the United States. This awareness came during the El Niño of 1982-83, an event of unusual magnitude, when erosion problems were experienced along the shores of California and Oregon. The natural processes usually involved in beach erosion also played a role during the 1982-83 El Niño, but generally at much greater intensities than normal. In addition, there were unusual effects that enhanced the overall erosion problems and caused them to continue well beyond 1982-83.

It once was thought that the onset of El Niño off Peru was caused by the cessation of local coastal winds that produce upwelling. This view changed when it was demonstrated that these local winds do not necessarily diminish during an El Niño, but that it is instead the breakdown of the equatorial trade winds in the central and western Pacific that triggers an El Niño. During normal periods of strong southeast trades, there is a sea-level setup in the western equatorial Pacific with an overall east-to-west upward slope of the sea surface along the equator. The same effect is obtained when you blow steadily across a cup of coffee: the surface of the coffee becomes highest on the side 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. 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 that are not adapted to warm water. In association with this warm-water movement eastward along the equator, a wavelike bulge in sea level occurs. The Coriolis force, which results from the rotation of the Earth on its axis, causes currents to turn to the right in the northern hemisphere and to the left in the southern hemisphere. Since this released water during an El Niño flows predominantly eastward along the equator, the Coriolis force acts to confine the wave to the equatorial zone, constantly turning it in toward the equator. This prevents the dissipation of the sea-level high by expansion to the north and south away from the equator. The eastward progress of the sea-level wave can be monitored at tide gauges located on islands near the equator (Wyrtki, 1984). As discussed earlier, measurements from a tide gauge can be averaged so as to remove the tidal fluctuations, yielding the mean sea level for that period of time. Sea-level variations at islands along the equator during the 1982-83 El Niño are shown in Figure 20. From these tide-gauge records one can easily envision the passage of the released sea-level wave as it traveled eastward across the Pacific. Its crest appears to have passed Fanning Island south of Hawaii in late August, Santa Cruz in the Galapagos at the end of the year,

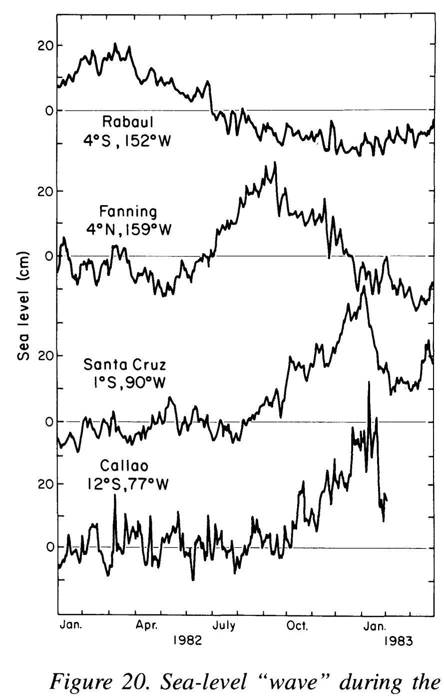

Figure 20. Sea-level "wave" during the 1982-83 El Niño measured at a sequence of islands from west to east near the equator, and finally at Callao on the coast of Peru. After Wyrtki (1984).

and reached Callao on the coast of Peru in January 1983. Water-level changes associated with these sea-level waves during an El Niño are very large, as Figure 20 shows. They typically involve variations up to 50 cm (20 in.) and take place within a relatively short period of time, 4-6 months. Translated into an annual variation, this is equivalent to a rate of approximately 1,000 mm/year, far in excess of the 1-2 mm/year global rise in sea level that is caused by the melting of glaciers.

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. Now the wave is held by the inclination of the continental shelf and slope, by the combined effects of wave refraction over the slope and the Coriolis force. This again prevents the sea-level high from flowing out to sea and dissipating. Analyses of tide-gauge records along the coast have demonstrated that the sea-level waves can travel as far north as Alaska (Enfield and Allen, 1980). The analyses have also shown that as the sea-level wave travels northward, it looses relatively little height at the coastline itself. The Coriolis force increases in strength at higher latitudes, so the wave hugs the coast more tightly and thereby maintains its height, even though it may loose some of its energy. The wave travels at a rate of about 50 mi per day and thus quickly reaches California and Oregon following its inception at the equator. The water-level changes associated with these shelf-trapped sea-level waves are an important factor in beach erosion along the west coast of North America during an El Niño.

In summary, one aspect of an El Niño is the generation of large sea-level variations that take the form of a wave; the wave first moves eastward along the equator and then splits into poleward-propagating waves when it reaches the eastern margin of the Pacific Ocean. These basin-wide responses involve several months of wave travel, and at any given coastal site the sea-level wave may significantly raise water levels for several months.

Figure 21 shows the monthly mean-sea levels measured by the tide gauge in Yaquina Bay during the 1982-83 El Niño (Huyer and others, 1983; Komar, 1986). The sea level reached a maximum during February 1983, nearly 60 cm (24 in.) higher than the mean water surface in May 1982, nine months earlier. The thin solid line in the figure follows the ten-year means for the seasonal variations, and the dashed lines give the previous maxima and minima measured in Yaquina Bay. These curves in part reflect the normal seasonal cycle of sea level produced by parallel variations in atmospheric pressures and water temperatures. However, it is apparent that the sea levels of 1982-83 were exceptional, reaching some 10-20 cm higher than previous maxima, about 35 cm (14 in.) above the average winter level. Much of this unusually

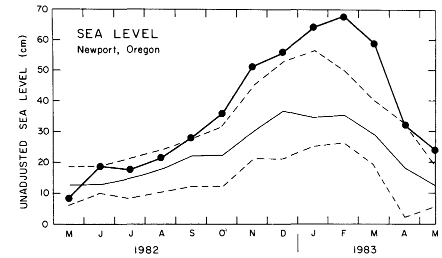

Figure 21. Monthly sea levels measured with tide gauge in Yaquina Bay. Record from 1982-83 El Niño year (dots) shows that water levels exceeded all previous records. Mean values given by solid line, previous maxima and minima by dashed lines. From Huyer and others (1983) and Komar (1986).

high sea level can be attributed to the effects of a coastally trapped sea-level wave generated by the El Niño.

Wave conditions on the Oregon coast were also exceptional during the 1982-83 El Niño (Komar, 1986). Figure 22 shows the daily measurements from the microseismometer at Newport, collected from August 1982 through April 1983. There were several storms that generated high-energy waves, three achieving breaker heights on the order of 20-25 ft.

The erosion which occurred on the Oregon coast during the 1982-83 El Niño was in response to these combined processes. The large storm waves that struck the coast arrived at the same time as sea level was approaching its maximum. High spring tides were also a factor. During the December 1982 storm, high tides reached +11.0 ft MLLW, 23 in. higher than the predicted level due to the raised sea level. The tides during the January 1983 storm were still more impressive, reaching +12.4 ft, 34 in. higher than predicted. This pattern continued during the February 1983 storm, when high tides up to +10.3 ft were measured, 17 in. above the predicted level. All of these high tides represent exceptional water elevations for the coast of Oregon.

As expected, the intense storm activity and high water levels during the winter of 1982-83 cut back the beaches of the Oregon coast. However, for a time the patterns of erosion were puzzling. There were numerous reports of erosion problems along the coast,

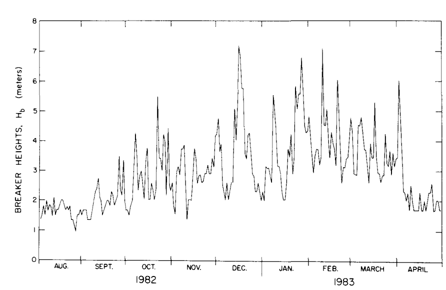

Figure 22. Wave breaker-height measurements from Newport during 1982-83 El Niño period. From Komar (1986).

yet beaches in other areas were building out. It took some time to determine what was happening.

As discussed earlier, the summer waves normally approach from the northwest, while the winter waves arrive from the southwest, so there is a seasonal reversal in sand transport directions along the beaches. Over the years there is something of an equilibrium between the north and south sand movements within any pocket, yielding a long-term zero net littoral drift. This equilibrium condition was upset during the 1982-83 El Niño due to the southward displacement of the storm systems. The waves approached the Oregon coast from a more southwesterly direction, and this together with the high wave energies of the storms caused an unusually large northward movement of sand within the beach cells (Figure 23). The resulting effect was one of sand erosion at the south end of each pocket beach and deposition at the north. This can be viewed as the reorientation of the pocket beaches 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.

This pattern is illustrated in Figure 24 for the beaches north and south of Yaquina Head. North of that headland, the beach eroded down to bed rock (Figure 24, upper), while south of it, at Agate Beach, so much sand accumulated that it formed a large field of dunes (Figure 24, lower). Those who had the misfortune to live north of the headlands, at the south ends of the pocket beaches, experienced some of the greatest beach and property losses along the coast. There, the beaches eroded back to a greater degree than during normal winters, the sand not only moving offshore to form bars but also northward along the shore. Having lost the buffering protection of the fronting beaches, properties north of headlands suffered the direct attack by storm waves, which in many areas resulted in considerable erosion losses.

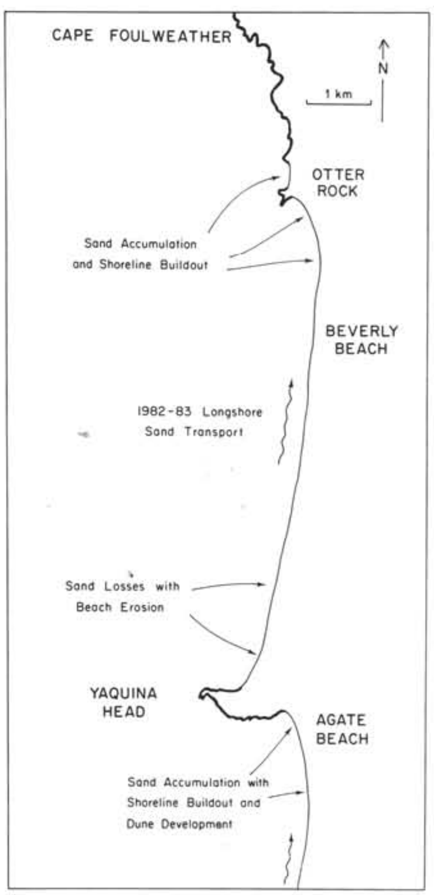

Figure 23. Patterns of beach erosion and accretion during 1982-83 El Niño, resulting from northward transport of sand within the littoral cell. From Komar (1986).

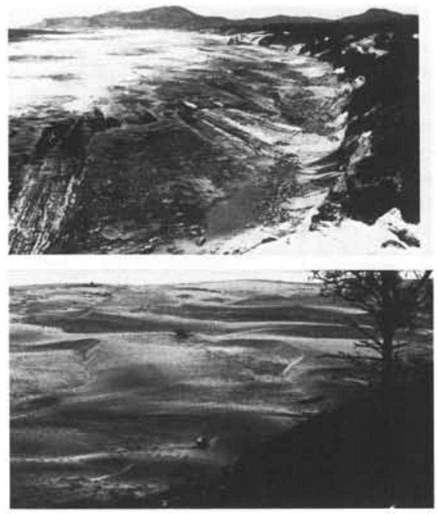

Figure 24. Beaches north and south of Yaquina Head during 1982-83 El Niño, with a total depletion of sand to the north (upper), while large quantities of sand accumulated to the south on Agate Beach (lower).

Figure 25. Deflection of channel leading into Alsea Bay by northward growth of longshore bar in response to storm waves related to 1982-83 El Niño and arriving from southwest. From Komar (1986).

The area that suffered the greatest erosion during the 1982-83 El Niño was Alsea Spit on the central Oregon coast (Komar, 1986). The erosion there was mainly in response to northward longshore movement of beach sand, a movement which deflected the inlet to Alsea Bay. Although the problem originated during the 1982-83 El Niño, the erosion continued for several years due to the disruption from normal conditions. During normal periods, the channel from Alsea Bay continues directly seaward beyond the inlet mouth, but during the 1982-83 El Niño this channel was deflected well to the north, as seen in the photograph of Figure 25. The inlet mouth itself migrated little; the deflection instead took place in the shallow offshore area. Apparent in this photograph is an underwater bar that extends from the south and is covered with breaking waves. It was the northward growth of this bar that diverted the channel from its normal course, the bar growth having occurred as a result of the northward sand transport during El Niño.

The erosion experienced on Alsea Spit, which continued for about three years, can be directly attributed to this northward deflection of the channel. The earliest property losses on the spit occurred during the winter of 1982-83 on the ocean side, well to the north of the inlet. 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 by the oversteepened beach profile leading into the deep channel and by direct wave attack: waves passing through this channel did not break over an offshore bar and therefore retained their full energy until they broke directly against the properties on the spit. The erosion continued for more than three years with more losses of property, as the deflected channel slowly migrated southward towards its former position. Figure 25 shows a photograph taken during July 1985, by which time significant migration had already taken place 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 south. In September 1985, there was an abrupt increase in the rate of erosion, as the focus was then on the unvegetated, low-lying tip of the spit seen in Figure 25. Within a couple of weeks, this tongue-extension of Alsea Spit completely eroded away. At the same time, the deep water of the offshore channel shifted landward, directly eroding the developed portion of the spit where it curves inward toward the inlet. Seven houses were threatened by this erosion, particularly one that was adjacent to an empty lot initially left unprotected (Figure 26).

The beach fronting Alsea Spit grew significantly during the summer of 1986, and the tongue of sand began to reform at the end of the spit. Erosion during the winter of 1986-87 was minimal, so that Alsea Spit and the inlet to the bay finally returned to the configurations that had prevailed for many years prior to the 1982-83 El Niño.

The effects of the 1982-83 El Niño persisted still longer in the erosion of Netarts

Figure 26. Erosion of Alsea Spit as a result of inlet deflection during 1982-83 El Niño. From Komar (1986).

Spit (Komar and others, 1988; Komar and Good, 1989). That erosion has been of particular concern in that its impact has been in Cape Lookout State Park, a popular recreation site. Netarts Spit forms most of the stretch of shore between the large Cape Lookout to the south and Cape Mears to the north (Figure 27). Erosion of Netarts Spit during historic times had been minimal. In the late 1960s, a seawall was constructed at the back of the beach in the park area. Its construction was not entirely a response to wave-erosion problems but in part to people walking on the dune face and causing renewed activity of sand movement by winds. Therefore, the sudden and dramatic erosion during the 1982-83 El Niño came as a surprise. Being one of the smallest of the littoral cells on the coast, the pocket beach within the Netarts cell underwent a marked reorientation due to the southwest approach of waves during the El Niño. This depleted the beach of sand immediately to the north of Cape Lookout, leading to erosion of the low-lying sea cliffs and sand dunes in that area. However, of more lasting significance is that much of the sand transported northward along the beach was apparently swept through the tidal inlet into Netarts Bay, and perhaps some to the offshore. This effectively removed the sand from the nearshore zone, leaving the beach depleted in sand volumes and thus less able to act as a buffer between park properties and storm-erosion processes. Because of this, erosion problems on Netarts Spit have been endemic in recent years and have continued even though the direct processes of the 1982-83 El Niño have ceased.

Figure 27. Netarts Spit and inlet to Netarts Bay with Cape Lookout in background, March 1978. Oregon State Highway Department photo.

The occurrence of rip currents and storm waves have been the chief agents of erosion on Netarts Spit. These cut back the beach in the park area so that much of it was covered by exposed cobbles rather than sand (Figure 28). The seawall was destroyed, so that erosion of park lands became substantial. The placement of riprap in order to prevent additional losses of park lands was considered. However, in subsequent winters the rip currents could be positioned in other areas along the spit, causing erosion there. The more fundamental problem is the depleted volume of sand on the beach. To solve this, State Parks officials have considered a beach nourishment project, the placement on the beach of sand brought in from some other location. Sand nourishment would restore the beach along its full length, both in its ability to act as a buffer and in its recreational uses. Possible sources of sand for such a nourishment project might come from the yearly dredging by the Corps of Engineers within Tillamook Bay or in the Columbia River. A more logical source would be from dredging sandy shoals in Netarts Bay in that 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. However, Netarts Bay contains many acres of protected wetlands and has the highest diversity of clam species of any Oregon estuary. Accordingly, dredging and sand removal would have to be balanced against the probable negative impacts of such operations in the bay.

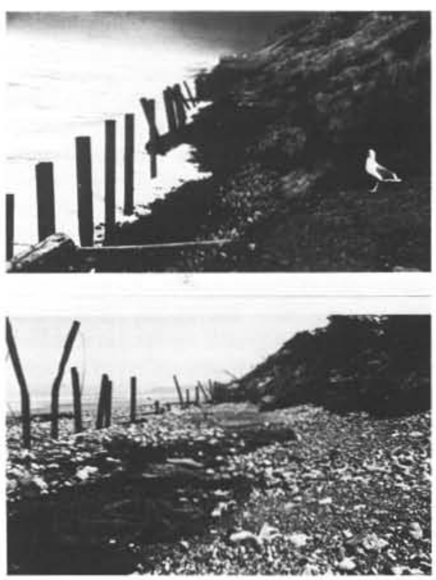

Figure 28. Progressive erosion of Cape Lookout State Park following the 1982-83 El Niño. (upper) Destruction of log bulkhead and initiation of dune erosion during October 1984. (lower) Erosion during winter of 1988, leaving a beach composed of cobbles and gravel rather than sand, and I-beams of log bulkhead at mid-beach. From Komar and others (1988).

PROCESSES AND PATTERNS OF SEA-CLIFF EROSION

The erosion of sea cliffs is a significant problem along many of the world's coastlines, including Oregon (cover photo, upper right). Most communities of the Oregon coast are built on uplifted marine terraces or on alluvial slopes emanating from the nearby Coast Range. These elevated lands are subject to erosion along their ocean margins with the formation of cliffs. State lands are also being lost as cliff erosion occurs in coastal parks and affects state highways.

Considering the extent and importance of sea-cliff erosion, it is surprising how few studies have focused on this problem, at least in comparison with beach-erosion problems and processes. Part of the reason for this is the inherent difficulty in accounting for the multitude of factors that can be involved in cliff erosion (Figure 29). One of the most problematic aspects is the cliff itself, its material composition and structure, the latter including bedding stratification (horizontal or dipping), and the presence of joints and faults. These factors are important in determining whether the cliff retreat takes the form of abrupt large-scale landsliding or the more continuous failure of small portions of the cliff face. The processes of cliff attack are also complex. The retreat may be primarily caused by groundwater seepage and direct rain wash, with the ocean waves acting only to remove the accumulating talus at the base of the cliff. In other locations, the waves play a more active role, directly attacking the cliff and cutting away its base.

Only limited study has been devoted specifically to cliff erosion along the Oregon coast. The earliest work examined the oc-

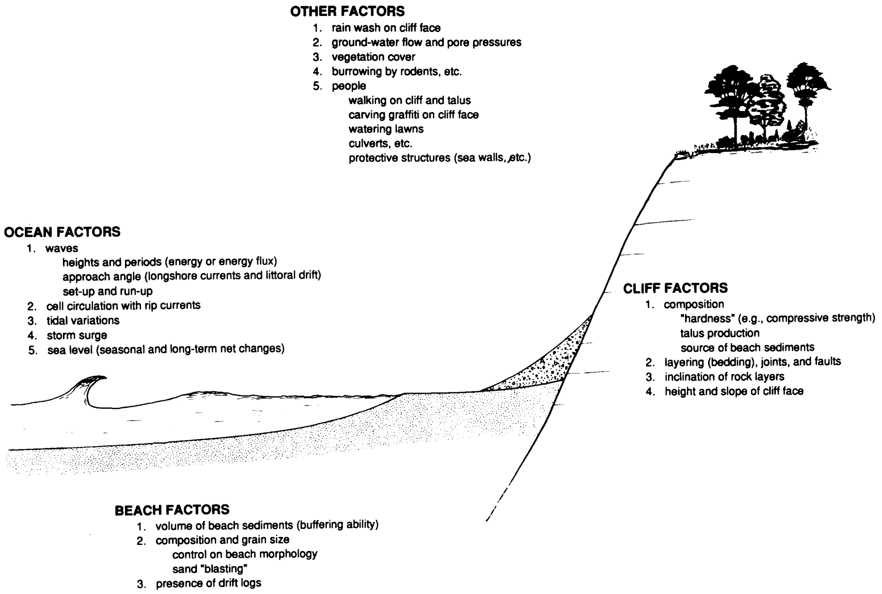

Figure 29. Schematic diagram illustrating the many factors and processes involved in sea-cliff erosion.

currence of major landslides and documented the importance of factors such as rainfall intensity and rock jointing and bedding (Byrne, 1963, 1964; North and Byrne, 1965). Little information is available on the long-term erosion rates of sea cliffs not affected by major landslides. Stembridge (1975) compared two sequences of aerial photographs (1939 and 1971) to estimate erosion rates, but his analysis was limited to only a few areas along the coast and yielded rough estimates of long-term changes. In a more detailed study but limited to Lincoln County, Smith (1978) also used aerial photographs to document average cliff-erosion rates. Both studies revealed a considerable degree of variability along even short distances of the coast. They also recognized the episodic nature of the cliff erosion processes.

Our ongoing Sea Grant research is focusing on the patterns and processes of cliff erosion along the Oregon coast. This work has examined the tectonic controls on the spatial variability of cliff erosion along the full length of the coast, beach-process factors in cliff retreat within more limited stretches of shore, erosion/management issues at specific locations, and the impacts of engineering structures (Komar and McDougal, 1988; Sayre and Komar, 1988; Komar and others, 1991; Komar and Shih, 1991).

Our research has confirmed that sea-cliff erosion is highly variable along the Oregon coast but suggests that the patterns are systematic and depend in part on the tectonic uplift versus global sea-level rise (Figure 3). The north-central portion of the coast, including the areas of Newport and Lincoln City, is experiencing some relative sea-level rise, while further north toward Cannon Beach and south of Coos Bay, the tectonic uplift has exceeded the rate of sea-level rise, at least within historic times. There is a rough first-order parallelism between the extent of cliff erosion and relative sea-level changes, with greater amounts of erosion occurring in the Lincoln City area of the central coast (Komar and Shih, 1991).

Of particular interest is the minimal erosion within historic times of sea cliffs in the Cannon Beach and Bandon areas. What little cliff retreat exists is associated with ground-water seepage, whereas direct wave attack of cliffs backing the beach accounts for little or no erosion. Yet the steepness of the cliff and its alongshore uniformity without appreciable degradation by subaerial processes suggest that the cliff has experienced wave erosion in the not-too-distant past. This condition is more evident at Bandon on the south coast, where, in addition to the steep cliff backing the beach, a number of stacks exist in the immediate offshore, many having flat tops that continue the level of the marine terrace (Komar and others, 1991). Our interpretation of both the Cannon Beach and Bandon areas is that cliff erosion was initiated following the last major subduction earthquake 300 years ago, an event that likely resulted in the abrupt subsidence of those areas. However, the subsequent aseismic uplift has progressively diminished the cliff erosion to the point where it has essentially ceased at Cannon Beach and Bandon. The central coast around Lincoln City likely also experienced subsidence followed by uplift, but its rates of uplift have been insufficient, relative to rising sea level, to halt continued cliff erosion.

Such tectonic/sea-level controls of cliff erosion along the Oregon coast can be viewed as a first-order pattern or trend. Superimposed on this coastwide variability are more local processes that can be viewed as second-order factors. Most important is the size of the beach, since it governs the ability of the beach to act as a buffer between the sea cliffs and the eroding processes of waves and nearshore currents. That size varies from one littoral cell to another, the stretches of beach isolated by rocky headlands. For example, the beach extending north from Yaquina Head to Otter Rock and Cape Foulweather, the Beverly Beach littoral cell, does not offer adequate buffer protection, and as a result the sea cliffs backing this beach have undergone significant retreat (though still at low rates when compared with other coastlines). Its limited buffering capacity is evident in our ongoing measurements of wave run-up (Shih, unpublished data). The objective is to document the frequency with which waves reach the talus and base of the sea cliff and the intensity of the swash run-up when it does so; video-analysis techniques are being employed to record the run-up. Measurements have established that the swash of waves frequently reaches the cliff base in the Beverly Beach cell but rarely in the other cells. Beach surveys show that this is due to the low elevations of the beach profile with respect to mean sea level and high-tide elevations.

Of particular interest in our study of sea-cliff erosion has been the littoral cell containing Lincoln City and Gleneden Beach, extending north from Government Point (Depoe Bay) to Cascade Head. This cell is of interest due in part to the extensive development along this stretch of coast and the associated management problems. In addition, one unusual feature enhances its scientific interest: there are marked longshore variations in the coarseness of beach sands, and this produces longshore changes in beach morphology, in the nearshore processes, and in the resulting factors important to cliff erosion. We have completed a detailed study of the changing grain-size distributions from beach-sand samples collected along the full length of this cell (Shih, unpublished data). Our analyses show that the longshore variations in grain sizes are produced by the relative proportions of discrete grain-size modes within the overall sand-size distributions. We have succeeded in tracing these individual modes back to specific areas of the eroding sea cliffs. Of interest are (1) the longshore movements and mixing of these grain-size modes, and (2) questions as to why the mixing processes of the nearshore have not succeeded in homogenizing the beach sands to eliminate longshore variations. However, the overall effect of this longshore sorting is that the beaches toward the central to south part of the cell are coarsest; this includes the beaches fronting Siletz Spit and the community of Gleneden Beach. Sand sizes decrease somewhat toward the south but particularly toward the north, where the sand is finest in the Roads End area of Lincoln City. The effects on the beach morphology are significant, with the coarse-grained beach at Gleneden being a steep "reflective" beach for most of the year while the beach at Roads End has a low slope and is highly "dissipative" of the waves as they cross the wide surf zone.

Beach profiles have been obtained from eleven stations spaced at roughly even intervals along the length of the Lincoln City littoral cell in order to document the beach morphologies and how they change with sediment sizes. Furthermore, high-density profiling has been undertaken at approximately monthly intervals for over a year at Gleneden Beach State Park (reflective beach) and at the 21st Street beach access at the northern end of Lincoln City (dissipative beach). This high-density profiling permits generation of detailed topographic maps of the beach and more accurate analyses of seasonal changes. Of particular interest in this series of profiles is the contrast in the response of the reflective and dissipative beaches to winter storms and the determination of whether they offer different degrees of buffering protection for the sea cliffs. The results document that the profile changes and the accompanying quantities of cross-shore sediment transport are much greater on the coarse-grained reflective beach (Gleneden Beach) than on the finer grained dissipative beach at the north end of the littoral cell. The rates of change as well as total quantities of sand moved under a given storm are larger on the steep reflective beach. This makes the reflective beach a weaker buffer from wave attack, and cliff erosion is therefore more active than in the area where the cliff is fronted by a fine-grained dissipative beach. In addition, we have found that the development of rip-current embayments is extremely important on the reflective beach and largely controls the locations of maximum episodic cliff erosion. The process is similar to that described earlier for the erosion of Siletz Spit, immediately north of Gleneden Beach, which is also fronted by a reflective beach (Figure 18). Ground observations and aerial photographs show that rip currents on steep reflective beaches tend to cut narrow, deep embayments, so they play a significant role in controlling the erosion impact along the sand spit and also in the the sea-cliff areas. In contrast, rip-current embayments on the dissipative beaches of north Lincoln City and elsewhere on the coast are broader in their longshore extents, but they do not cut as deeply through the beach berm.

Bluff retreat in north Lincoln City, behind the dissipative beach, depends mainly on subaerial processes of rainfall against the cliff face and ground-water seepage. People have also had a significant impact; in some places their carving graffiti on the cliff face is the dominant factor in bluff retreat (Figure 30). The loosened material accumulates as talus at the base of the cliff. That accumulation can continue for several years, until it is removed by wave action during an unusually severe storm accompanied by high-tide levels. There is little direct wave attack on the cliff and no evidence of undercutting. However, once the talus has been removed by waves, sloughing of the cliff surface accelerates so that a new mass of talus quickly forms.

Figure 30. Retreat of bluff in Lincoln City caused by children carving graffiti and digging caves.

Landsliding has been a problem at some locations along the Oregon coast. This is particularly the case where Tertiary marine formations are included in the sea cliff (cover photo, lower left), since their muddy consistency makes them particularly susceptible to sliding. Furthermore, it has been estimated that these units dip seaward along more than half of the northern Oregon coast (Byrne, 1964; North and Byrne, 1965), a geometry which also contributes to their instability. In some cases this instability results in the slow mass movement of the cliff material toward the sea, amounting to only a few tens of centimeters per year. Although the movement is slow, it thoroughly disrupts the land mass and any attempts to place developments on the site. Other landsliding involves the whole-scale movement of large masses at more rapid rates. Best known is the infamous Jump-Off Joe area of Newport. In 1942, a large landslide developed in the bluff, carrying more than a dozen homes to their destruction (Sayre and Komar, 1988). In spite of the area's continued slumping, in 1982 a condominium was built on a small remnant of bluff adjacent to the major slide. Within three years, slope retreat had caused the foundation to fail (Figure 31), and the unfinished structure had to be destroyed by the city.

Figure 31. Construction (above) and destruction (below) of condominium built in 1982 and small remnant of marine terrace at Jump-Off Joe. From Sayre and Komar (1988).

SUMMARY

The Oregon coast is renowned for the intensity of its wave conditions. The winter storms commonly generate individual waves having heights of 40-50 ft, with a 95-ft record height. Such storm waves deliver a tremendous amount of energy to our coast, cutting back beaches and attacking coastal properties. They are assisted by rip currents that locally erode embayments into the beach, as well as tides and other processes that elevate water levels in the nearshore. In addition to these natural processes, people have contributed to the erosion, ranging from a child carving his name on the face of a sea cliff to the Corps of Engineers constructing a jetty at the inlet to Tillamook Bay.

The Oregon coast has had its share of erosion problems. Most dramatic has been the impact on sand spits; several case studies have been summarized in this paper. Though less dramatic, the cumulative erosion of sea cliffs has affected a number of coastal communities as well as parklands and highways. However, the Oregon coast has actually suffered relatively few erosion impacts leading to major property losses, at least in comparison with most other coastal states. This is in part due to its physical setting. The coast consists of a series of pocket beaches or littoral cells separated by rocky headlands or more extensive stretches of rocky shore. In each cell there is a seasonal reversal in the direction of longshore sand transport, but with a long-term net drift that is essentially zero. As a result, the construction of jetties on the Oregon coast has caused only a local rearrangement of beach sands and adjustments of the shorelines with no lasting major impacts. (The one exception was Bayocean Spit, due to the construction of one jetty rather than two.) This contrasts with most U.S. shorelines, where jetty and breakwater construction has blocked a net littoral drift and severely eroded the downdrift beaches and communities.

The tectonic setting of the Oregon coast is also important in limiting its erosion. Most important is the tectonic uplift that presently exceeds the global rise in sea level over much of the coast, while it minimizes the transgression of the sea in other areas. Unlike the east and Gulf coasts of the U.S., where the transgression has resulted in substantial landward migrations of the shoreline and property losses, erosion of Oregon's sandy shores is cyclical with minimal net loss. This was first noted on Siletz Spit, where an episode of erosion cutting into the foredunes was followed by a decade of accretion so that the dunes built back out to their former extent. An extreme example was noted on Nestucca Spit, where an extensive mound of riprap placed during erosion in 1978 is now covered by dune sands that are blowing inland, inundating houses. Similarly, the tectonic uplift has resulted in low rates of cliff recession, much smaller than documented in other coastal areas.

This may change in the future. There is the potential for accelerated rates of sea-level rise due to greenhouse warming that could exceed the tectonic rise and bring about more extensive erosion. Although the impact would be smaller and come later than along the low-relief and subsiding coastal states, it is important that potential increases in sea level enter into management considerations for the Oregon coast. More ominous is the possibility that an extreme earthquake will occur on the Northwest coast. In addition to the immediate impacts of the ground shaking and the generation of a tsunami, the abrupt subsidence of portions of the coast will initiate extensive erosion in areas that have not suffered from wave attack within historic times. The implications of this scenario for coastal planning are staggering, yet the decisions are not simple ones. As discussed above, it has been estimated that catastrophic earthquakes and land-level changes have occurred at least six times in the past 4,000 years, at intervals ranging from 300 to 1,000 years. The last recorded event took place about 300 years ago, so we are clearly in the window of potential for another event. At some stage, and preferably sooner than later, coastal management decisions need to be made that reflect this potentially extreme hazard. In the mean time, we have to reflect on the wisdom of developing low-lying areas and the edges of ocean cliffs along the coast.

In developing the Oregon coast, we have made numerous mistakes that have placed homes and condominiums in the path of erosion. Development has been permitted in foredunes of sand spits immediately backing the beach, along the edges of precipitous sea cliffs, and even in the area of the active Jump-Off Joe landslide. Such unwise developments and the accompanying proliferation of seawalls and riprap revetments have progressively degraded the qualities of the Oregon coast that we cherish.

ACKNOWLEDGMENTS

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