# The Roles of Tectonic Subduction and the Earth's Changing Climate in the Morphologic Evolution of the Oregon Coast

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**Abstract - The Oregon coast is characterized by extreme events and processes, ranging from occurrences of subduction earthquakes that every few hundred years rock the coast and produce land-elevation changes on the order of 1 to 2 m, to major winter storms that generate deep-water significant wave heights reaching 14 m. The Earth's changing climate has produced a progressive increase in wave heights spanning at least the past 25 years, while occurrences of El Niños further enhance the annual wave heights as well as elevating winter tides by more than 0.5 m. The decadal to millennial evolution of the Oregon coast is the product of the interplay of these tectonic and climate-controlled processes.**

## I. INTRODUCTION

The Oregon coast is highly variable in its geomorphology, with its south dominated by long stretches of rocky shore, the central coast consisting of a 250-km long beach backed by the most extensive coastal dune sheet in North America, and its northern half characterized by a series of rocky headlands that isolate littoral-cell beach compartments that individually are 10s of kilometers in length [1]. This diverse geomorphology is the product of Oregon's tectonic setting, lying within a zone of plate convergence and subduction that every few hundred years produces a major earthquake that alters land elevations. Such tectonic events have a lasting impact on the patterns of erosion that control the large-scale evolution of the coast. In the shorter time frame, years to decades, the changing climate of the Earth is affecting the erosion and evolving coastal geomorphology, through the eustatic rise in sea level, a progressive increase in wave heights measured by offshore buoys, and by occurrences of major El Niños that temporarily increase wave heights and sea levels, but most importantly produce significant redistributions of beach sand within the littoral cells, resulting in localized "hot spot" erosion sites. These tectonic and climate controls on the erosion and geomorphic evolution of the Oregon coast are the topics of this paper.

## II. SUBDUCTION EARTHQUAKES AND LAND-ELEVATION CHANGES

Important to the geology and geomorphology of the Oregon coast is its tectonic setting, located within the zone of collision of three of the Earth's tectonic plates, the oceanic Juan de Fuca and Gorda plates, and the continental North American plate. The newly formed ocean crust at the ocean ridges is carried eastward toward the continent, resulting in their collision and the subduction of the denser ocean plates, which slide beneath the less-dense continental plate. There has not been a subduction earthquake off the Oregon coast since settlement by Euro-Americans, but evidence demonstrates that such earthquakes have occurred in the pre-historic past. The principal evidence has come from investigations of estuarine marsh sediments buried by layers of sand that had been transported by huge tsunami waves created by the earthquakes [2]. Based on the numbers of such layers found in estuaries, it is concluded that catastrophic earthquakes have occurred repeatedly at intervals ranging from 300 to 600 years. Carbon-14 dating of the buried marshes indicated that the most recent earthquake occurred approximately three hundred years ago. Its exact timing was established as having been on January 26,1700, based on the historic occurrence of a large tsunami that crossed the Pacific Ocean from Oregon and destroyed a number of villages along the coast of Japan [3]. From the size of the tsunami waves that reached Japan, it was concluded that the earthquake must have been of approximately magnitude 9.

Associated with this tectonic setting are significant land elevation changes that are interpreted in terms of the accumulation of subduction strain between earthquake events, causing the slow rise of the land while the plates are

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locked together and accumulating strain. With the release of that strain during a subduction earthquake, the land is immediately lowered. Evidence for this comes from studies of buried marsh deposits in estuaries, which demonstrate that much of the coast is abruptly lowered by 1 to 2 m. On the other hand, tide-gauge records and analyses of bench marks used by surveyors show that much of the Oregon coast has been rising during the past century as tectonic strain again accumulates. Along the southern half of the coast, south of Florence, the land is rising at a rate that exceeds the global rise in sea level, the net rate of emergence being about +1 mm/yr, while along the north coast the relative sea-level rise is on average -1.5 mm/yr, the negative value signifying that the rate of sea-level rise exceeds the change in land elevation [4].

The consequence of this along-coast variation in relative sea-level change is that during historic times shoreline erosion has been much less on the southern Oregon coast since the land is emerging from the sea, whereas significant erosion continues along the northern coast where there is a slow transgression of the water over the land. Therefore this tectonic control is an important "first order" factor in determining the on-going degrees of beach and property erosion, as well as being important to the long-term evolution of the coast. The coast's geomorphology also provides evidence that a prolonged period of erosion followed the most recent earthquake in 1700, produced by land subsidence that allowed waves to directly attack sea cliffs. For example, at Bandon on the south coast the ensuing period of erosion has produced a high sea cliff with an extensive group of resistant stacks extending far offshore [5]. The subsequent aseismic uplift of the land has slowly elevated the toe of the sea cliff, so that now waves rarely reach it and cliff retreat is negligible.

The millennium-scale change in the coast is evident in stair-case series of marine terraces up the flanks of the Coast Range mountains, best developed along the south coast. Along-coast variations in the elevations of individual terraces demonstrate that in addition to the general tectonic rise of the land relative to the changing levels of the sea during the Ice Ages, there has been a degree of warping, folding and faulting of the coastal rocks, that also contributes to the coast's evolving morphology.

## III. CLIMATE CHANGE AND EROSION PROCESSES

From year to year, and through the decades, the erosion and changing morphology of the Oregon coast is determined mainly by the severity of storms and the heights of waves they generate, by the global rise in sea level, and by processes that cause measured tides to be elevated above predicted elevations. Such processes are connected with the Earth's changing climate, the focus of our recent research being devoted to clarifying that connection.

The Oregon coast is noted for the severity of its winter storms and the heights of waves they generate. The strongest storms typically form waves having deep-water significant wave heights of 7 to 10 m. The most extreme storm in recent years occurred on 2-3 March 1999, generating deep-water significant wave heights of 14 m [6]. Daily measurements of wave heights and periods have been collected by NDBC buoys in deep water since the mid 1970s, and of interest and concern, the accumulated measurements demonstrate that the wave heights on average have been progressively increasing during at least the past two decades [7, 8]. An up-dated version of this analysis is presented in Fig. 1A for the annual averages of the winter (October through March) deep-water significant wave heights, yielding a rate of increase of 0.032 m/yr, a 0.8-m increase over a 25-year time span [9]. In terms of wave heights measured during the stronger winter storms, the increase in the past 25 years has been from about 9 m in 1975 to nearly 12 m in the year 2000. Data for storm intensities in terms of wind speeds and atmospheric pressures extend further into the past than do wave data, and their analysis for the North Pacific demonstrates that they have been increasing for at least the past 50 years [10]. Although the exact cause is uncertain, it may be associated with global warming.

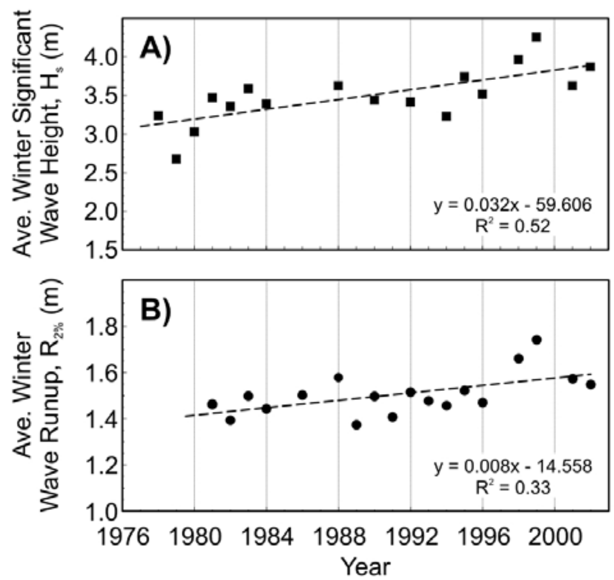


Fig. 1. A. The decadal increase in average deep-water winter wave heights measured offshore from the Pacific Northwest coast. B. The parallel increase in wave swash runup levels on beaches, calculated from the deep-water wave heights and periods.

This progressive increase in deep-water wave heights is clearly an important factor in occurrences of erosion experienced along the coast. It has produced parallel increases in processes operating on Oregon's beaches, particularly the sizes of breaking waves and the elevations of the swash runup when the waves reach the shore. The runup elevations are particularly important in that they combine with high tides to produce erosion of dunes and sea cliffs backing beaches. Fig. 1B graphs the decadal increase in runup levels, its vertical component, calculated from the measured deep-water wave heights and periods.

On a beach slope of 0.04 (1-in-25), typical of the Oregon coast, this progressive increase in runup in effect represents a 5-m "transgression" of the water in 25 years, greater than the effect of the relative rise in sea level.

The variations from year to year in measured deep-water wave heights and calculated runup levels, seen in Fig. 1, have been found to depend in large part on the ENSO range of climate events from El Niños to La Niñas [7, 9]. This is shown by correlations with the Multivariate ENSO Index (MEI) proposed by [11], which demonstrates that the largest wave heights occur on average during El Niños, the smallest during La Niñas (such correlations are found for wave data along the entire US West Coast [9]). Therefore, in addition to there being progressive increases in wave heights and swash runup levels, possibly connected with global warming, the annual variations are also climate controlled, being enhanced during major El Niños like those in 1982-83 and 1997-98.

It is also recognized that El Niños elevate mean water levels along the US West Coast, raising tides by 10s of centimeters [12, 13, 14], produced by warmer offshore water temperatures, the enhanced geostrophic effects of currents, and sea-level "waves" arriving from the Tropics. The effect on Oregon's annual mean sea levels is dramatic, evident in Fig. 2 from an analysis of tide gauge data from Yaquina Bay [9]. Most apparent is the marked increase during the 1982-83 El Niño, with a peak also for the 1997-98 El Niño. While the parallel trend with the annual MEI is apparent in Fig. 2, the correlation in Fig. 3 between the detrended annual mean sea level and the MEI is seen to be dramatic, showing the occurrence of elevated water levels during El Niños, and depressed levels during La Niñas. Nearly identical correlations are found for other tide-gauge sites along the entire US West Coast [9].

The extensive erosion created by El Niños can be attributed in part to both increased wave heights and mean water levels, so that the swash runup plus tides combine to reach their highest elevations on coastal beaches, impacting shore-front properties. There is an additional effect of El Niños that is particularly important to the resulting erosion -- the storm waves shift sand to the north within Oregon's littoral cells (and in northern California), resulting in "hot spot" erosion sites, primarily at the south ends of the cells and north of inlets. This pattern of El Niño erosion was first noticed during the 1982-83 event when beaches north of headlands entirely disappeared while at the same time their widths increased to the south of headlands, and in some locations where marked northward migrations of tidal inlets occurred [13]. These responses were clearly due to the southward shift of storm tracks during El Niños, crossing the coast of central California, with their generated waves reaching the Oregon coast more from the southwest quadrant, producing an unusual degree of northward winter sand movement within the littoral cells. During the 1982-83 El Niño the resulting "hot-spot" shoreline erosion patterns were found to account for most of the property losses experienced along the Oregon coast [13], but the actual sand redistributions were not documented by surveys. This became possible during the 1997-98 El Niño, thanks to the availability of LIDAR surveys along the coast obtained in October 1997 and April 1998. On the Oregon coast the LIDAR surveys were used to decipher the sand movements that occurred within the Netarts Littoral Cell [15], showing a clear "standing-wave" oscillation of sand between the headlands confining the cell, with its node half way along the cell length, the volume of sand lost from the beaches to the south equaling the gain to the north. Subsequent analyses of LIDAR surveys in other Oregon littoral cells show a similar response, but with the blockage of the northward sand movement by jetties [16]. The same response has been found on the central to northern coast of California [17], so this El Niño response of shorelines appears to be pervasive along much of the US West Coast.

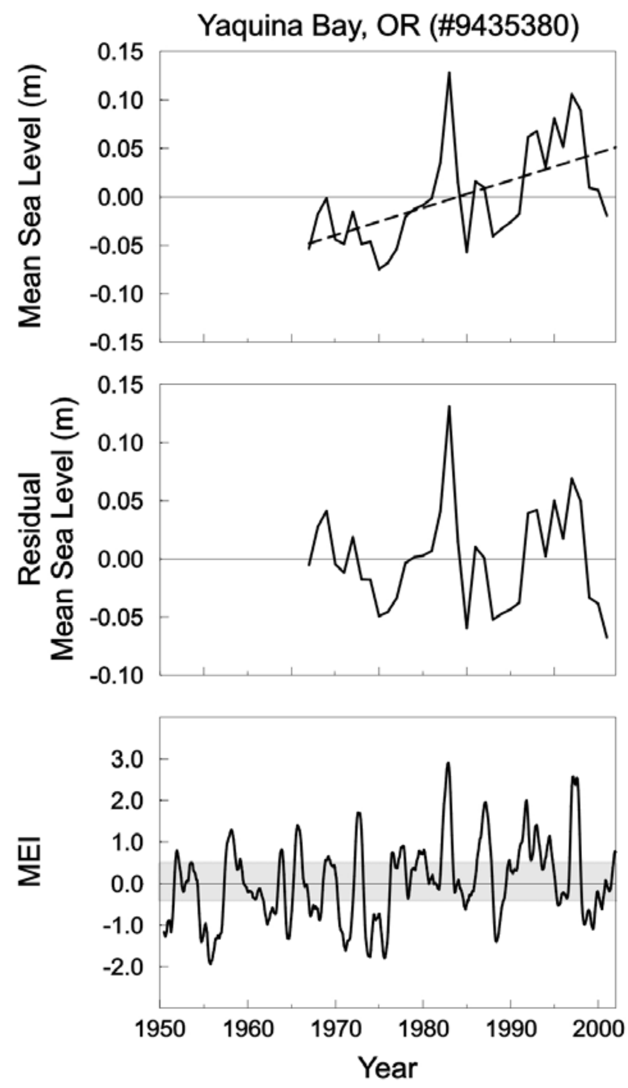


Fig. 2. The sea-level curve derived from tide-gauge data in Yaquina Bay (Newport), Oregon, the de-trended annual variations, and the annual MEI values. Shaded band indicates "normal" climate conditions.

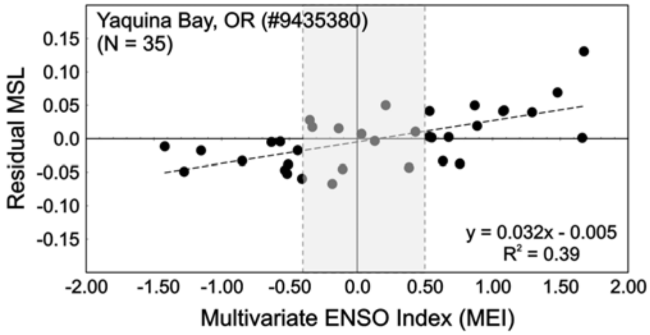


Fig. 3. The correlation between the de-trended sea levels from fig. 2 and the MEI values. Shaded band indicates "normal" climate conditions.

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