CHAPTER 42

RECESSION OF MARINE TERRACES - WITH SPECIAL REFERENCE TO THE COASTAL AREA NORTH OF SANTA CRUZ, CALIFORNIA

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ABSTRACT

The concept "wave base" (or "surf base"), i.e. the maximum depth below mean sea level at which shoaling waves will effectively erode the ocean bottom leading to the recession of a shoreline, is discussed. Also, past and present opinions as to the magnitude of wave base in general and specifically in the area near Santa Cruz, California, and the variables controlling this phenomenon are presented.

Then, an account of the author's successful and unsuccessful attempts to determine average rates of cliff retreat in the study area is presented along with the specific cliff recession rates obtained. These compare favorably with the recession rates measured by the U. S. Army Corps of Engineers for nearby areas of similar geology and topography and with rates determined for similar coastal areas in various parts of the world. A brief discussion of the spectrum of cliff recession rates found in areas of varying geology and wave climate is also presented.

The accepted history of sea level since the last glacial maximum, particularly during the last 7,000 years, is reviewed as well as pertinent information on the geology, topography and wave climate of the study area.

It is then shown that average recession rates estimated by relating extrapolated bedrock profiles of the lowest marine terraces with the accepted history of the latest sea level rise compare favorably with the recently measured recession rates. However, a conflict exists between the present wave-cut terrace profiles, the accepted history of sea level and the accepted value of wave base.

INTRODUCTION

The objective of this study was to measure, wherever possible, the average rate of marine terrace cliff recession at points along the Pacific Coast around and north of Santa Cruz, California. The seaward slopes of the coastal range in the study area are occupied at many locations by one or several elevated marine terraces and the sea floor at many of these locations is a modern wave-cut platform being extended shoreward by wave erosion.

Recession rates were to be determined by comparing cliff locations shown on old dated maps, photographs, etc., with the present location of the cliffs in the same areas. If any recession rates could be determined, they were to be compared to average historic recession rates roughly estimated by a comparison of the seaward extrapolation of the lowest marine terrace and the generally known late Quaternary (20,000 years Before Present, to date) history of sea level.

Average historic recession rates generally agree with rates of cliff recession now taking place. However, a comparison of the modern wave-cut platform profiles with the profiles to be expected considering the accepted sea level history of the last 7,000 years, the recent rates of cliff retreat and the concept of wave or surf base indicates that the existing and expected profiles are in disagreement.

THE STUDY AREA

The specific areas of interest in this study are located along the California coast at 36°55'N to 37°40'N and 122°00'W to 122°30'W; that is, from south of San Francisco to Santa Cruz (see Figure 1). Of special concern are the areas around Rockaway Beach, Montara, Halfmoon Bay, Davenport and just to the west of Santa Cruz.

Topography

The sea coast along the entire study area borders on the steep seaward slopes of a section of the tectonically active California coastal range that is historically uplifting and tilting seaward. At many locations the seaward slopes are interrupted by steep cliffs over 100 feet high, while in other areas there is a single marine terrace or many step-like marine terraces mantled by deposits that are marine and nonmarine in origin.

The lowest marine terraces at Montara and Santa Cruz vary in elevation between 100 feet or less at the base of the old sea cliff and 40 to 50 feet at the top of the modern sea cliff. These elevations include a mantle of marine sands deposited on the old wave-cut platform as the ancient beach that covered these terraces prograded seaward during a period of relative emergence as sea level lowered (Bradley, 1957). The terrace mantle deposits are generally 5 to 15 feet thick but at some places they exceed 20 feet in thickness. Figure 2 is a photograph of the interface between the old wave-cut platform (lowest marine terrace) and the prograded beach sediments at Montara. Boulders deposited on the old wave-cut platform can be seen at the interface. Figure 3 is a photograph of the lowest marine terrace with its beach deposits, taken near Santa Cruz. Carbon 14 dating of mollusk shells found in bore holes in the old wave-cut platform near the area shown in Figure 3 (Bradley, 1956) show dates of around 39,000 years. This indicates that the terrace was carved prior to 39,000 B.P. (Before Present), beach sands were then deposited, and sea level has been lower than the elevation of this terrace since that time. At Santa Cruz there are five distinct raised terraces between sea level and an elevation of 850 feet (see Alexander, 1953 for example).

The continental shelf varies in width from approximately 25 miles at San Francisco to 7 miles at Santa Cruz. The nearshore sea floor over most of this area is a modern wave-cut platform of varying width.

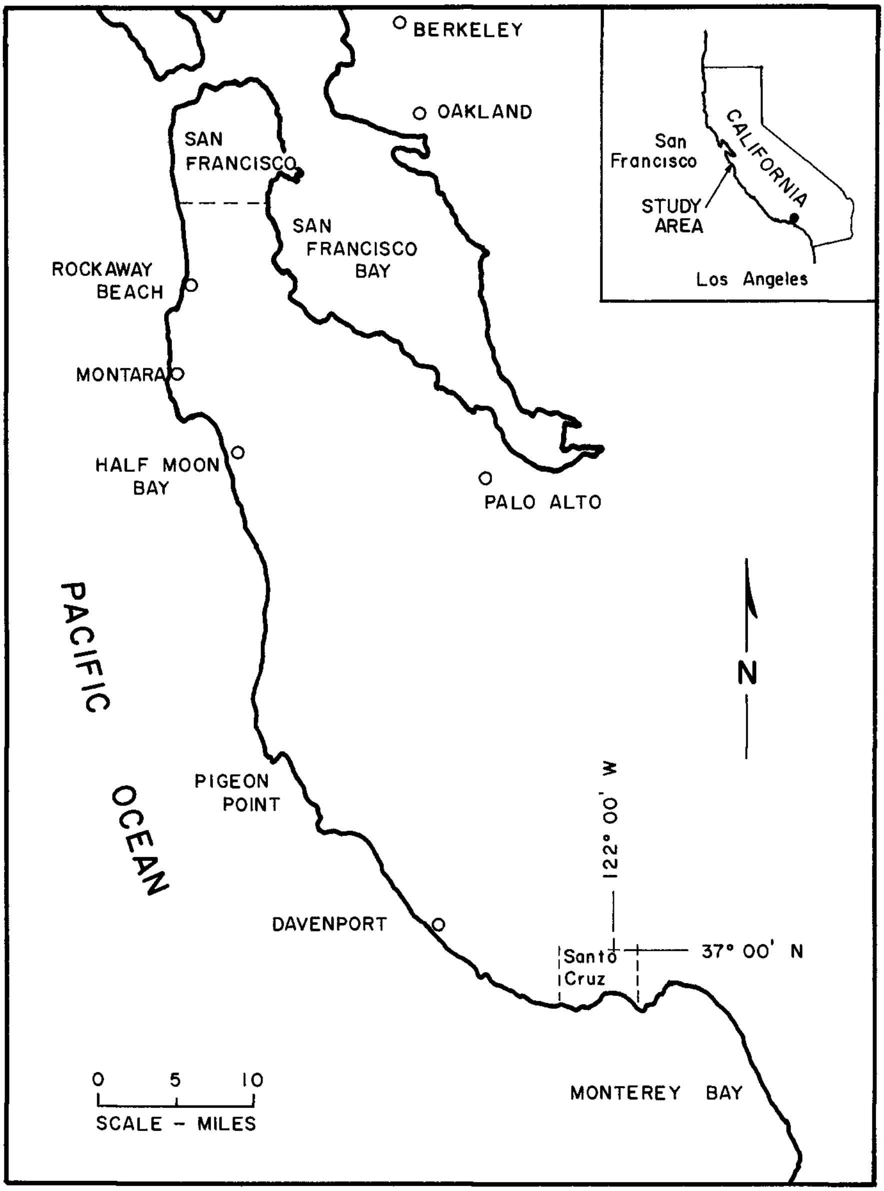

FIGURE 1 - LOCATION MAP

FIGURE 2 - INTERFACE BETWEEN OLD WAVE-CUT PLATFORM AND PROGRADED BEACH SEDIMENT, AT MONTARA

FIGURE 3 - LOWEST MARINE TERRACE AT SANTA CRUZ

Figure 4 shows a schematic profile of the wave-cut platform and lowest marine terrace at the City of Santa Cruz. Small undulations in the profile have been "smoothed out". Profiles in the areas near Davenport and Montara are somewhat similar in nature but the wave-cut platform reaches to a slightly greater depth at the same distances offshore. The wave-cut platform is continuous for at least the inner half mile (Hyde and Howe, 1925-26) and is thought to be so for at least the first 1.5 miles or to a depth of 75 feet (Bradley, 1957). Over this distance the platform is covered by a layer of sand generally 2 to 4 feet thick but reaching 10 feet in thickness at some locations as the natural relief of the platform varies by as much as 7 feet. Sand grain sizes on the platform are typically smaller than those found on the beach and decrease seaward.

The platform slope is in the order of 1° near the shore becoming uniform seaward at about 0.5° as the inshore upward concavity evens out in the seaward direction. Except for a slight tectonic warping the lower marine terrace is similar in slope and profile to the modern wave-cut platform.

Along the coast, north of Santa Cruz to Davenport, the shoreline remains irregular with the 30 foot depth contour being located about 0.25 miles seaward and the 75 foot depth contour lying about 0.8 miles seaward of the cliffs. At Montara, these contours are approximately 0.2 miles and one mile from the cliffs, respectively.

Geology

Near Santa Cruz and Davenport the marine terraces and the modern wave-cut platform are carved into the southwest tilting seaward slopes of Ben Lomond Mountain. Willis (1925) believed the mountain to be a block that has been faulted along the northeast resulting in tilting toward the southwest while Rode (1930) stated that faulting is of minor significance and that the mountain is an asymmetric elongated dome. In either case, active lifting and tilting have occurred in the geologic past.

The core of Ben Lomond Mountain consists of Mesozoic granitic rocks exposed at higher elevations (California Division of Mines, 1961). The core is flanked by outward dipping Miocene marine sedimentary rocks that dip at angles of 3° to 15°. In the area of interest near the northwest city limit of Santa Cruz the Miocene sedimentary rock is from the Monterey formation (see Bramlelte, 1946 for a thorough description) and consists principally of mudstone with some closely jointed, thin bedded, shales which are dark gray or brown if fresh and white if weathered. When the mudstone is eroded it breaks into particles that are too fine to make a significant contribution to local beaches.

In the Montara area Mesozoic granitic rocks that are a continuation of Ben Lomond Mountain, known as Montara Mountain, predominate. However, at the exact study site at Montara the wave-cut platform and terraces are carved into sedimentary rock that is essentially a marine conglomerate with a fine-grained base.

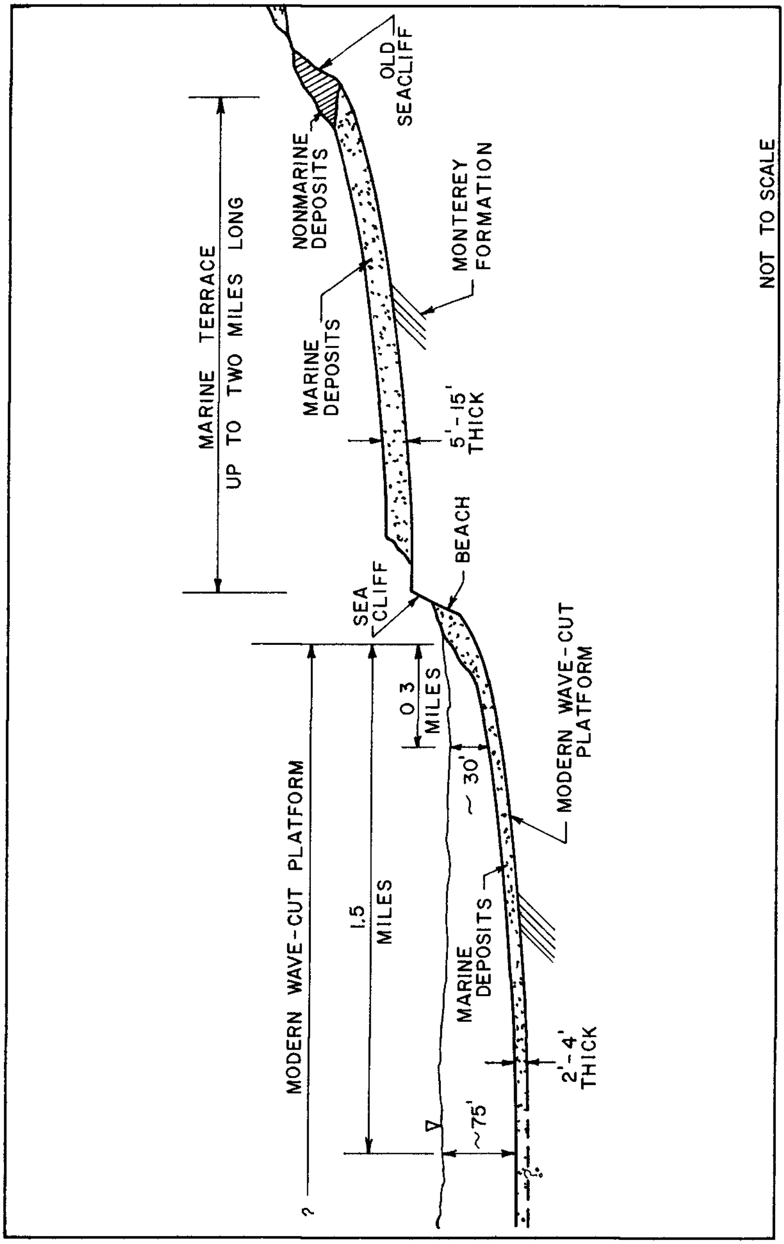

FIGURE 4 – TYPICAL SCHEMATIC PROFILE NORMAL TO THE COASTLINE NEAR SANTA CRUZ, CALIFORNIA

Marine terrace deposits near Santa Cruz and Montara are generally a fine sand with a small gravel fraction. They offer little resistance to erosion as they can generally be scraped away by hand. Thus, the terrace deposits will retreat with the sedimentary bedrock as it yields to the erosive action of waves.

Wave Climate

An indication of the deep water wave climate offshore of the study area is available from wave recordings taken at Point Sur, California (45 miles to the south of Santa Cruz) from April, 1947 to April, 1950 (U. S. Corps of Engineers, 1956) and from sea and swell hind casts for a ten year period at a point off the California coast at 37.6° N and 123.5° W (National Marine Consultants, 1960a, 1960b).

Waves will approach the study area over a sector between due south and north-northwest with periods ranging from 5 to 20 seconds. A large majority of the waves come from the west to northwest and have significant heights of 5 to 7 feet or less. However, local and distant storm waves with significant wave heights of 15 to 20 feet and higher do occur a small percentage of the time mostly from the west and southwest. Estimates (U. S. Corps of Engineers, 1956) indicate that waves with deep water heights of 15 feet may be expected on the average of 5 times a year while 20 foot waves may be expected every 8 to 10 years.

Refraction diagrams indicate that northwesterly swell are strongly refracted and suffer a large decrease in height before breaking on the shore in the study area. However, waves from the southwest are generally unaffected by refraction.

As waves from the west to northwest greatly predominate, net littoral drift is to the south and southeast. However, recent studies (Sayles, 1965; Moore, 1965; and Johnson, 1965) have indicated that little beach-size sediment is contributed to the coast between San Francisco and Santa Cruz so that quantities of littoral drift in this area are small and beaches are not well developed.

WAVE BASE CONCEPT

Definition

The term "wave base" has occurred in the literature since the early part of this century. Certain writers (Dietz and Menard, 1951; Rich, 1951; Dietz, 1963) define wave base as the depth above which sediment particles will not come to rest because of being stirred by wave action. Others (Fairbridge, 1952; Bradley, 1958) including the author define wave base as the maximum depth below sea level at which significant erosion (platform cutting) due to wave action will occur. Dietz (1963) uses the term "surf base" or "surge base" for this depth of erosion as significant erosion is believed to be limited to the surf zone.

Johnson (1919), Davis (1909) and others believed that, given a static sea level, significant erosion extends to depths in the order of 600 feet as fine sediment could be moved by waves at this depth and would act as an abrasive causing marine planation. At present, however, most authors (Dietz and Menard, 1951; Fairbridge, 1952; Longwell and Flint, 1955; Bradley, 1958) feel that, except in rare situations, vigorous wave agitation and erosion are limited to the surf zone or a maximum water depth ranging from 25 to 35 feet.

Local Wave Base

Bradley (1957, 1958) studied platform and terrace deposits between Davenport and Santa Cruz and concluded that wave base near Santa Cruz is limited to a distinct depth of about 30 feet. Twenhofel (1945) reported that sand must be of a certain size (0.5 mm for quartz grains) before it can act as an abrasive. At Santa Cruz, Bradley (1958) found that sand grains larger than 0.5 mm are found only at depths of 30 feet or less while beyond this depth deposits tend to be finer grained than 0.2 mm. Also, he found that a large percentage of pyroxene grains were finely etched at depths greater than 30 feet but at water depths of 30 feet or less nearly all the pyroxene grains sampled were blunted, and indication of vigorous abrasion.

The well known study of breaking waves conducted by Iverson (1952) demonstrated that on a beach slope of 1:50 (or 1.15°) the ratio of water depth to wave height at breaking varies between 1.1 and 1.3 for a deep water wave steepness between .005 and 0.04 (this includes all storm waves to be expected at Santa Cruz). Shoaling waves will increase in height as they move shoreward. As an example (see Wiegel, 1964, p. 17) we can expect unrefracted shoaling storm waves to increase in height by 15 to 30 percent depending upon their period. So, storm waves 20 feet high which occur at Santa Cruz and undergo little refraction when arriving from the southwest would break in water 26 to 34 feet deep. Thus, as nearly all shoreline recession occurs during storms (see discussion in next section) and within the surf zone we would expect a wave base of about 30 feet at Santa Cruz.

Platform Cutting and Cliff Retreat

The general mechanism of cliff retreat involves a relatively long period between major storms in which preparation of the cliff takes place, followed by spectacular retreat during a storm in which the beach in front of the cliff is often removed and waves strike directly upon the cliff. The amount of retreat during a particular storm depends upon the cliff geometry; bedrock material; tide and surge levels during the storm; height, period and duration of storm waves; and, to some extent, the time interval since the last major storm during which weathering, biological action, jointing, etc., prepared the cliffs for further erosion. Williams (1960) reports a case history of the easily eroded cliffs (30 feet high) at Clovehithe, England, in which little erosion occurred over a 17 month period and then, in one evening during a two-hour period, 35 feet of cliff retreat occurred due to wave attack superimposed upon a storm surge. Photographs taken in 1860 and 1960, and reported by Johnson (1961), showed that along the north coast of California where highly resistant rock outcrops total retreat was small but often retreat again involved slow preparation followed by total removal of a large block of material.

Bradley (1958) studied profiles of the wave-cut platform and five marine terraces (corrected for subsequent deformation) at Santa Cruz and found that the 30 foot depth contour consistently occured at a distance of 0.30 to 0.33 miles seaward of the cliff line. He concluded that for the rocks and wave conditions at Santa Cruz, a platform up to one-third of a mile wide can be carved by the sea at a static sea level and wider platforms, therefore, necessitate submergence, i.e. a rise in sea level and/or tectonic lowering of the land.

CLIFF RECESSION RATES

Study Area Recession Rates

As mentioned in the introduction to this paper, an objective of this study was to measure average cliff recession rates around, and north of Santa Cruz. Due to the sporadic nature of cliff retreat average recession rates can be estimated only by comparing the location of the cliff at various times over an interval of many years or decades.

The usual procedure involves the study of old maps, photographs, book descriptions, etc., that are dated and give a reasonably accurate location of the cliff. This cliff location must cover a good distance along the cliff (several hundred feet, if possible) as recession is variable with location as well as with time.

A search was conducted in the Bancroft Library of the University of California which is devoted to the history of California. Some old photographs taken in the study area were found but they were not very clear and no satisfactory reference points or scale could be determined.

During the period between 1851 and 1860 the U. S. Coast and Geodetic Survey mapped the coastline from a point 30 miles northwest of Santa Cruz to a point 10 miles to the east. They resurveyed this area in 1932 and 1933 and the U. S. Army Corps of Engineers conducted surveys in this area in 1948. In a beach erosion control report for the Santa Cruz area the Corps of Engineers (1956) reported the following erosion rates, based upon the surveys mentioned, local maps and comments from local authorities.

1. Over a 2400 foot stretch of cliffs that face to the southwest and lie along the eastern portion of the City of Santa Cruz (see Figure 1) a total average recession of 103 feet occurred in 80 years for an average rate of 1.3 feet per year. These cliffs have a general profile as shown in Figure 4 and are carved in the Monterey formation.

2. Critical areas along the western edge of the city of Santa Cruz have been receding at an average rate of one foot per year while the overall average recession rate for a section about two miles long is one-half foot per year.

The report concluded that rip-rap protection was needed to halt this rapid destruction of valuable coastal property. This protective seawall has since been constructed (Figure 5).

Shortly after the turn of the century the Ocean Shore Railroad Company (now defunct) began construction of a railroad along the coast from San Francisco to Santa Cruz. From the original plans of the railroad (dated 1912) it was possible to determine the amount of shoreline recession that has occurred in a few locations.

Figure 6 shows the cliff line for a section of the coast just north of Montara as measured in 1912 and 1965. The cliffs, including the bedrock and terrace deposits are nearly vertical along this entire section. Point recession varies from 10 to 80 feet over the fifty-three year period, with the average recession rate for this period being in the order of 0.85 to 0.95 feet per year.

Six miles north of Montara, at Rockaway Beach, a road was constructed in the early 1930's out around a point on the abandoned road bed of the Ocean Shore Railroad. The bedrock is Franciscan volcanic and metavolcanic rocks that are somewhat more resistant than the conglomerate at Santa Cruz. Comparison of the road construction date, road width and present cliff profile indicates a recession rate of one-half foot per year.

The shoreline in Half Moon Bay is presently at the same location as indicated by the 1921 survey. This is due to the wide beaches developed along the coast and to the refraction and resulting wave height decrease that storm and regular waves undergo in reaching the shore.

World Wide Shoreline Recession Rates

It is of interest, at this point, to mention some of the cliff recession rates reported throughout the world as an indication of recession rates possible for shorelines with various topographic and geologic characteristics.

The cliff height, bedrock material and size of protective beach are usually more important than wave exposure in establishing a rate of recession.

Johnson (1919) reported observing glacial striations down the face of granitic shoreline cliffs indicating no retreat of the cliffs since at least the last glacial period i.e. for over 10,000 years.

In incoherent materials such as unconsolidated sand, loess, recent alluvium, volcanic ash, etc. cliff recession rates can be extremely large. For the previously mentioned 30 feet high sand cliffs at Clovehithe, England,

FIGURE 5 - CLIFFS AND PROTECTIVE RIP-RAP SEAWALL
AT SANTA CRUZ.

Williams (1960) reported a total recession of 86 feet in 2 years and 7 months or about 30 feet per year. In his recent book, Guilcher (1958) reports that at Krakatoa, Indonesia, volcanic ash cliffs produced by an eruption in 1883 retreated 1,500 meters between 1883 and 1928 for an average recession rate of 99 feet per year. No cliff elevations were reported. Guilcher (1958) presents an interesting discussion of cliff retreat in his chapter on "Coastal Features Related to Sea Action".

Contribution to Littoral Drift

The bedrock being eroded at Montara and Santa Cruz breaks into grains that are too fine to remain on local beaches. Some of the sand from the terrace deposits probably does remain on the beach. It is interesting to consider what contribution eroding sandstone cliffs, say 50 feet high and eroding at a rate of one or two feet per year, might make to local littoral drift. A one mile section of such cliffs would provide about 15,000 cubic yards of material per year so, a long section of rapidly eroding unconsolidated sand cliffs would make a major contribution to littoral drift provided most of the sand grains were large enough to remain on the beach and not be carried offshore into deeper water.

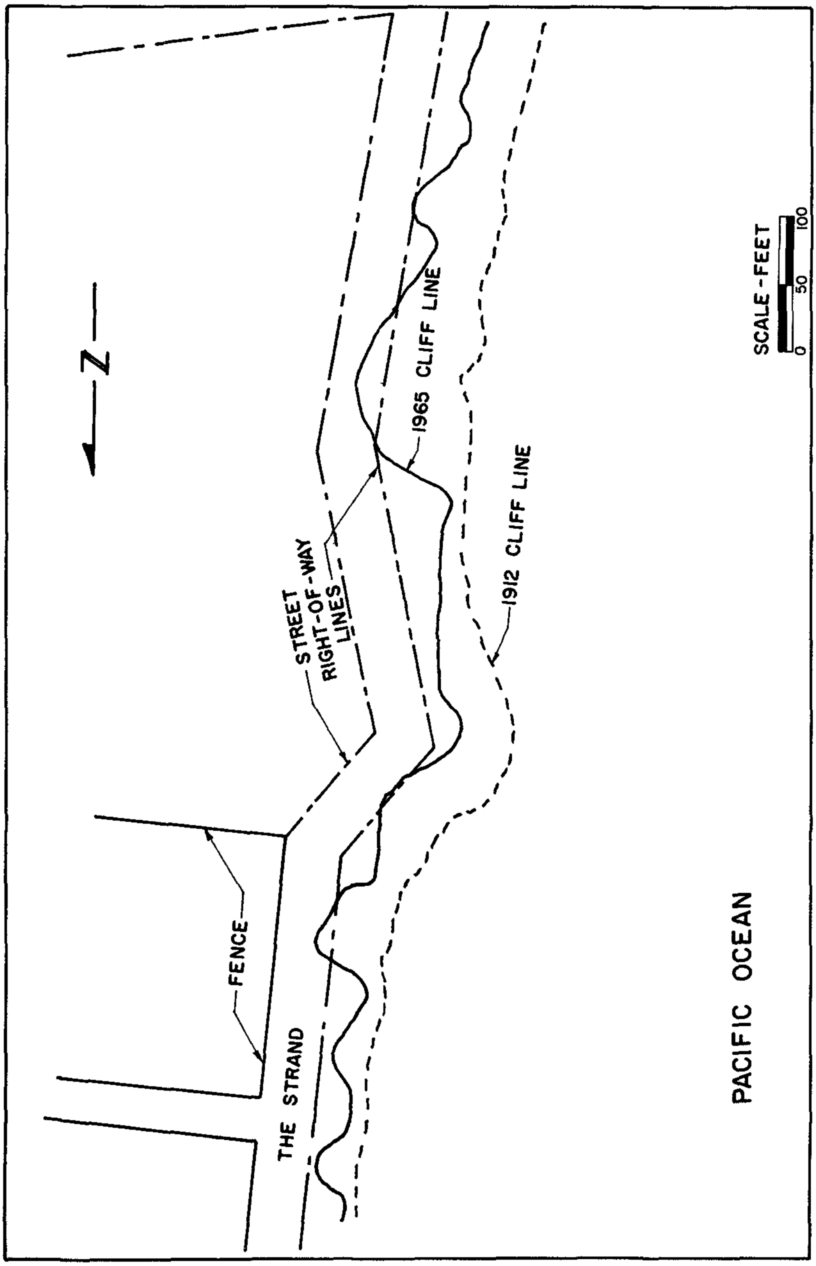

FIGURE 6 - SHORE SECTION NEAR MONTARA SHOWING CLIFF LINE IN 1912 AND 1965

RECENT SEA LEVEL HISTORY

The Quaternary history of sea level, particularly since the last or Lake Wisconsin glacial period must be considered so that the present offshore sea bottom profile can be compared with this sea level history to obtain approximate average historic marine terrace recession rates. It is not possible to perfectly define historic sea levels due to certain difficulties such as recent tectonic activity and isostatic adjustment along the coast; sparsity of data; inaccuracies in carbon-14 dating, etc. However, it is possible to present a first approximation of sea level history for the last 15,000 to 20,000 years that is adequate for our purposes. Fortunately we are most interested in the past 5,000 to 7,000 years and dating accuracy generally increases as the time span decreases.

Fairbridge (1961) has presented a thorough discussion of past attempts at defining historic sea levels, techniques used and problems encountered; and a consensus summary of Quaternary sea level fluctuations. Further data of interest are presented by Curray (1965), Shepard (1964) and others. It is generally believed that the maximum low stand of sea level during the last glacial maximum occurred 17,000 to 20,000 B.P. at 300 to 360 feet below the present sea level. This was followed by the Holocene Transgression during which sea level rose in a rapid irregular fashion to within 30 feet of its present level 6,000 to 7,000 years B.P.

There is some disagreement on the finer details of sea level fluctuations during the last 7,000 years with three basic opinions being offered: (1) Sea level has risen slowly during this time from around-30 feet to its present position asymptotically (see Shepard, 1964). (2) Sea level has been stable at its present position for the past 5,000 years (see Gould and McFarlan, 1959). (3) Sea level reached its present position at 6,000 B.P. and has fluctuated above and below this level (± 10 to 15 feet) since that time (see Fairbridge, 1961). For our purposes we can place sea level no lower than about 15 or 20 feet below its present level for at least the last 5,000 years.

DISCUSSION

As glaciers advanced and sea level lowered during the last glacial period the old wave-cut platform and sea cliffs were abandoned and a layer of beach sands was deposited over the exposed sea bottom. It is probable that no major cliffs were carved but small notches may have been carved if there were major still stands of sea level during the overall period of sea level retreat. It is of interest to try to reconstruct events as sea level returned; especially, with regard to tieing together the accepted history of sea level, offshore bottom profiles, and current average cliff recession rates.

Offshore at Montara, the bottom profile is relatively steep for the first mile but it then flattens considerably as the continental shelf is quite wide. Bottom depths in excess of 300 feet are first reached at a distance of 20 miles from shore. Seaward extrapolation of the lowest marine terrace bedrock surface (assuming a slope similar to that at Santa Cruz) indicates that the surface would intersect the present sea bottom at a distance of four to five miles from the present cliffs. Beyond this point of intersection it is unlikely that platform cutting occurred during the last or Halocene Transgression. Thus, when this rise in sea level occurred it is probable that no sea cliff developed beyond four or five miles from the present shoreline as the sea just drowned a flat beach. The point of intersection between the present sea bottom and the extrapolated terrace bedrock surface lies at a depth of 130 to 150 feet below the present sea level. This was the sea level elevation approximately 10,000 to 12,000 years ago. Cliff recession of four to five miles in 10,000 to 12,000 years gives an average recession rate of 2.0 to 2.3 feet per year. This rate is in reasonable agreement with the present rate of 0.85 to 0.95 feet per year considering our technique of estimating average historic recession rates and since recession rates would initially be higher than average as a cliff line was just developing (so cliffs were low) and sea level was actively rising. Also, we would expect the recession rate to be considerably below average when sea level remains constant, larger cliffs have developed, and waves have a longer shallow water distance to travel and dissipate energy before reaching the shore as has been the case for the last several thousand years.

Just north of Santa Cruz the offshore bottom profile reaches a depth in excess of 300 feet about six miles from shore. Extrapolation of the old marine terrace bedrock surface indicates that the bed was at approximately 260 feet below the present sea level at a distance of six miles from the present shoreline; so, a sea cliff has probably always existed in the Santa Cruz area during the Halocene Transgression. Six miles of recession in 17,000 to 20,000 years gives an average rate of 1.6 to 1.85 feet per year. As at Montara, the recession rate was probably greater than average initially and then less than average and decreasing as sea level stabilized and the wave-cut platform increased in size. Again, average historic recession rates are in reasonable agreement with current recession rates.

Bradley (1958) stated that at Santa Cruz, for a wave base of 30 feet, a wave-cut platform up to one-third mile wide can be carved with sea level remaining constant. A wider platform requires continuous submergence during cutting. This would suggest that, as the 30 foot depth contour is approximately one-third mile from shore where recession rates were measured, no cliff recession should now be occurring nor should the cliffs have undergone recession for the last 5,000 years or so as sea level has remained essentailly constant. Thus, Bradley's conclusion is in disagreement with conditions at Santa Cruz and the history of sea level.

Figure 7 shows typical near shore ocean bottom profiles at points near Santa Cruz and Montara where recession rates were measured. These profiles are inconsistent with the local wave base of 30 feet, the history of sea level that states that sea level has been constant or within $\pm$ 10

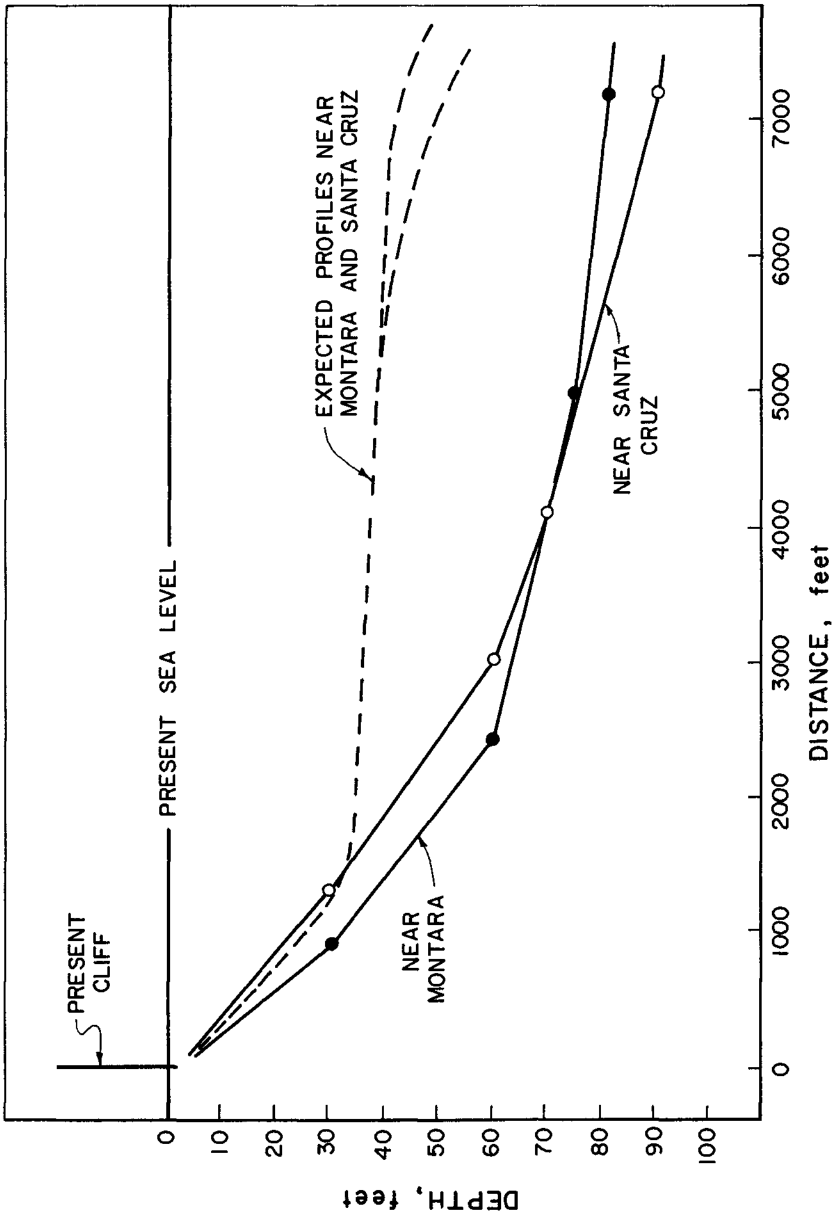

FIGURE 7 EXISTING AND EXPECTED OFFSHORE PROFILES NEAR SANTA CRUZ AND MONTARA

to 15 feet of its present location for 5,000 to 7,000 years, and the observed recession rates at Santa Cruz and Montara. With average recession rates of 0.5 and 0.85 to 0.95 feet per year (or higher) respectively over a period of 5,000 to 7,000 years and a maximum possible erosion depth of 45 feet (30 $\pm$ 15 feet), we would expect profiles similar to those shown by the broken line in Figure 7. From this, it appears that the concept and numerical value of wave base as defined herein requires further consideration.

ACKNOWLEDGEMENT

Dr. Clyde Wahrhaftig, Department of Geology, University of California at Berkeley, suggested that the author conduct this study as part of a graduate seminar course in geomorphology. Professor Wahrhaftig also provided guidance and encouragement during the study.

The author appreciates the assistance provided by employees of the California Public Utilities Commission in helping to locate the Ocean Shore Railroad route survey plans and their patience while the plans were being used.

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