CLIFF EROSION AND BLUFF RETREAT ALONG THE CALIFORNIA COAST

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ABSTRACT

While the cliffs and bluffs making up the California coastline may appear at first glance to provide a resistant barrier against the Pacific Ocean, nothing could be further from the truth. Eighteen thousand years ago the coastline of the state was as much as 45 km offshore to the west. With the melting of the icecaps and glaciers at the end of the last Ice Age, and the warming and thermal expansion of the world oceans, ~43,000,000 km^3 of seawater was released which raised sea level about 120 meters globally. As a result, the coastline of California migrated east and continues to do so but at a reduced rate as sea level rise has slowed over the past ~3000 years. The coastline has been advancing and retreating for as long as a landmass recognizable as California has existed and sea level has fluctuated. The shoreline of today is, therefore, only a single point on a constantly changing curve.

Seventy-two percent of California's 1760 km coastline consists either of high steep cliffs or lower bluffs eroded into nearly horizontal marine terraces. Four processes and factors interact to produce sea cliff retreat. Two of these are very large in scale and provide the overall regional framework for coastal evolution: sea level change and tectonic activity. The other two, the inherent properties of the cliffs or bluffs (rock strength, structural weaknesses, presence of groundwater, for example) and the external forces (wave energy, tidal range, degree of protection offered by a beach, climate, and frequency and magnitude of severe storm events) are the most influential local factors. While the entire coastline of the state is eroding, the weaker sedimentary rocks typically erode at average rates of 10 to 30 cm/year, whereas the harder igneous and metamorphic rocks, which often make up the resistant headlands and steep mountainous areas, erode at slower rates. The wide, flat, uplifted marine terraces, which are characteristic of much of California's coast and have usually been eroded into sedimentary rock, are easily developed and have been the sites where many of California's coastal communities have evolved. The low cliffs and bluffs fronting these terraces, however, are often easily eroded and coastal land loss in these areas has become a statewide concern. Cliff erosion hot spots are well recognized and public and private property damage during the last twenty-five years dominated by El Nino conditions has been high. Historical approaches to dealing with the ongoing erosion of the state's cliffs and bluffs have focused historically on seawalls and revetments, but concerns with the long-term effectiveness and impacts of these structures have begun to restrict additional armor emplacement.

INTRODUCTION

California is on the leading edge of a large tectonic plate (the North American Plate) that has been colliding with the Pacific Plate to the west for millions of years. This collision and the subsequent plate interaction have produced California's unique and dynamic coastline. Surface processes such as waves, rainfall and runoff, and landslides, rockfalls and other mass movements have also shaped the large-scale coastal landforms such as the mountains, uplifted marine terraces, and sea cliffs. In addition, sea level along the coast has changed continuously throughout geologic time in response to constantly changing global climate. As a result, the present position of the coastline is only a temporary one. While the changes are not rapid, the evidence is clear that sea level has been rising for the past 18,000 years and will continue to rise into the foreseeable future.

The period of global warming and ice melting that began at the end of the last ice age, and the accompanying sea level rise, flooded the continental shelves that surround the continents. Along the coastline of California sea level rise advanced the shoreline 10 to 20 km landward along most of the state, but over 50 km off of San Francisco, where the continental shelf is considerably wider. Waves eroded back the continental edge forming coastal cliffs and bluffs as the sea advanced inland into areas

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of higher relief. Throughout the period of major sea level rise (~18,000 to 5,000 years ago), most of the California coastline was retreating landward at average rates of about 50 to 150 cm annually. As sea level rise slowed over the past several thousand years, the erosion rate declined and began to approach the rates of sea cliff retreat we witness today, closer to 10 to 30 cm/year in most places in the state.

GEOGRAPHIC DISTRIBUTION OF SEA CLIFFS IN CALIFORNIA

On a statewide scale, the coastline of California is extremely diverse, from the steep coastal mountains along the Big Sur and Mendocino coasts to the broad coastal plains and wide beaches of Los Angeles County. California's coast can be divided into: 1] steep coastal mountains and sea cliffs with hundreds of meters of relief (Figure 1), 2] uplifted marine terraces and sea cliffs a few meters to perhaps 100 meters in height (Figure 2), and 3] coastal lowlands with beaches, and often sand dunes and wetlands (Figure 3). The great majority (1267 km or 72%) of the California coast consists of actively eroding sea cliffs that would include 1 and 2 above. Of this 1267 km, 1038 km consists of lower relief cliffs or bluffs typically eroded into uplifted marine terraces, and 229 km consists of steep cliffs or coastal mountains.

Fig. 1 Steep coastal cliffs in Marin County.

Fig. 2 Marine terrace and eroding cliffs in San Mateo County.

Fig. 3 Coastal lowlands (Newport Bay). Orange County

The high relief, steep cliffs or coastal mountains are located predominantly in northern California from Del Norte County to Mendocino county, at the Marin Headlands just north of the Golden Gate, in the Pacifica to Montara area of San Mateo County, and along the Big Sur coast of Monterey and San Luis Obispo counties. Steep cliffs and headlands also occur in the Santa Monica Mountains and at Pt. Loma in San Diego Count. These cliffed areas of coast typically consist of older and more resistant rock types such as the Franciscan Formation, as well as granitic and volcanic rocks. Along the northern California coast, Pt. St. George, Trinidad Head, and Pt. Delgada are all Franciscan Formation outcrops. Bodega Head, Pt. Reyes, Montara Point, Pt. Pinos and Pt. Cypress are all granite. Proceeding southward, Pt. Sur, Pt. San Martin, Piedras Blancas and Pt. San Luis are all Franciscan Formation. These are resistant rock types that erode very slowly, but in the case of some units of the Franciscan, may also be subject to large-scale landsliding or slumping as along the Big Sur coast (Figure 4).

Elevated marine terraces are characteristic features of collision coasts where uplift is taking place, and the coastline of California has many excellent examples of these features. These terraces, which typically resemble a flight of stairs, are commonly less than a kilometer or two in width and may ascend to elevations of several hundred meters above present sea level. Each terrace consists of a nearly horizontal or gently seaward-dipping erosional bedrock platform backed by a steep or degraded, relict sea cliff along its landward margin (Figure 2). A sequence of uplifted Pleistocene marine terraces is the geologic and geomorphic record of repeated global sea-level highstands superimposed on a tectonically rising coastline. Thus a rising coastline is a continuous strip chart on which relatively brief sea-level highstands were successively recorded as erosional or depositional landforms (Lajoie, 1986).

Fig. 4 Large landslide repair along Big Sur coast.

Low bluffs characterize much of the coastline of San Diego, Orange, Santa Barbara, San Luis Obispo, Santa Cruz, and San Mateo counties or cliffs cut into uplifted marine terraces, typically consisting of Tertiary sedimentary rocks (Figure 2). Along the northern California coast, portions of the Sonoma, Mendocino, Humboldt and Del Norte county coasts are also eroded into marine terraces. The number of terraces exposed along the coast of California ranges from one in Santa Barbara to as many as thirteen on the Palos Verdes peninsula of Los Angeles County. The existence and distribution of these flat, nearly horizontal marine terraces, adjacent to the shoreline, have allowed California's extensive and intensive coastal development to take place (Figure 5).

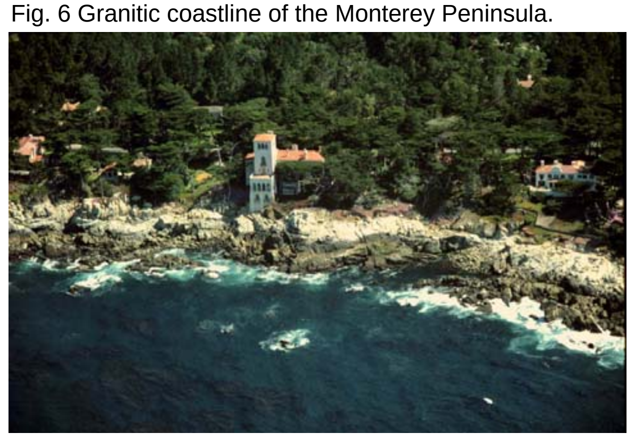
Fig. 5 Intensively developed coastal terrace in San Diego County.

Ease of access and construction has made development easy in oceanfront communities situated on these widespread terraces. Unfortunately, however, the relatively weak, often well-bedded sedimentary rocks that lent themselves to wave erosion and the formation of wave cut terraces in the geologic past, are also the same materials exposed in the coastal cliffs today. These sedimentary rocks and their overlying marine terrace deposits are typically very susceptible to erosion by waves as well as by sub-aerial processes. The continued breakdown and retreat of the cliffs as sea level rises has produced a land loss dilemma of increasing magnitude for California coastal communities.

SEA CLIFF EROSION AND FAILURE

While the overall long-term, statewide rates of cliff erosion or retreat are primarily a function of the rate of sea level rise and the coastal topography, there are significant local or regional differences in the rates of sea cliff erosion. Sections of coast consisting of unweathered crystalline rock usually erode at very slow rates. At some locations on the Monterey Peninsula, for example, which consist of granite, virtually no change has been detected between photos taken over a 50-year time span (Griggs and Savoy, 1985). Within these generally resistant areas, however, erosion rates can very considerably. Waves attack the weaker zones over time, the fractures and joints for example, to form inlets and coves (Figure 6). The more resistant rock is left behind as points, headlands and sea stacks.

Fig. 6 Granitic coastline of the Monterey Peninsula.



In striking contrast, erosion can be far more rapid (up to 30 cm or more per year, on average) where cliffs consist of weaker sedimentary rocks such as shale, siltstone or sandstone, or even higher where bluffs consisting of unconsolidated materials such as alluvium, dune sand, or marine terrace deposits occur. In these areas, which are characteristic of much of San Diego, Santa Barbara, Santa Cruz and San Mateo counties, for example, the cliffs often retreat in a more linear fashion, producing relatively straight coastlines.

Cliff erosion rates and resulting cliff geomorphology vary as a function of both the resistance of the materials making up the cliffs to erosion (*intrinsic factors*; Benumof and Griggs, 1999) and the physical forces acting to wear away the cliffs (*extrinsic factors*; Benumof et. al., 2000) as well as the dominance of either marine or subaerial processes (Emery and Kuhn, 1982). The hardness or degree of consolidation of the cliff rock, the presence, spacing, continuity and orientation of internal weaknesses such as joints, and the presence of groundwater, all directly affect the resistance of the materials to both slope failure and wave action. The wave energy reaching any particular stretch of cliffs, the presence or absence of a protective beach, the tidal range or sea level fluctuation, frequency of El Niño events or damaging storms, as well as the climate, including rainfall and runoff, as well as groundwater flow, also influence the rate and scale of sea cliff retreat. In a detailed study of the coastal cliffs of San Diego County, Benumof and Griggs (1999) noted that the cliffs display significant variations in rate of erosion, lithology, structure, exposure and susceptibility to marine and non-marine erosive agents. The sea cliffs are retreating at mean rates ranging from 3 cm/yr (where the cliffs consist of well-lithified Cretaceous sandstone) to 43 cm/yr (in unlithified Pleistocene sands) (Figure 7), and the variations in the rates of cliff retreat are directly related to the properties of the cliff forming materials (intrinsic factors) rather than to wave energy (Figure 8).

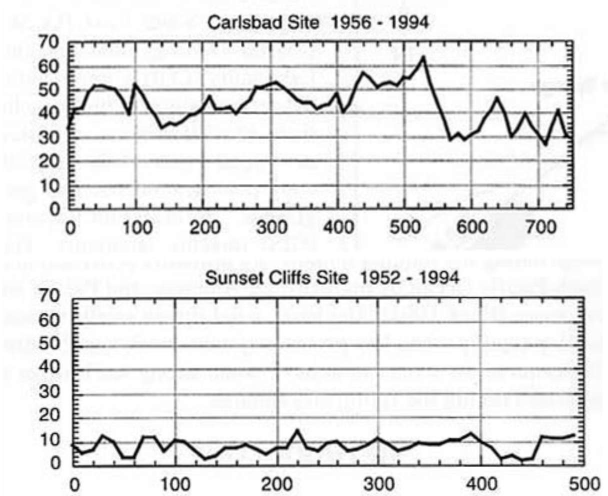


Fig.7 Long term coastal cliff erosion rates along portions of the San Diego County coast.

Vertical axis: Erosion rate (CM/YR)
Horizontal axis: Alongshore sum length (M), from North to South

Cliff erosion, as mentioned earlier, is due not only to waves undercutting the base of the cliff followed by collapse of the overlying unsupported material, but also to rockfalls, landsliding and slumping higher on the cliff face. The orientation and spacing of joints in the sandstones, siltstones, and mudstones that make up the cliffs surrounding northern Monterey Bay are the dominant factors affecting cliff retreat in this area (Figure 9; Griggs and Johnson, 1979). Moore, Benumof and Griggs (1999) determined average long-term erosion rates in the sedimentary rocks making up the cliffs of Santa Cruz County in the 10-15 cm/year range, with maximum rates being as high as 63 cm/yr.

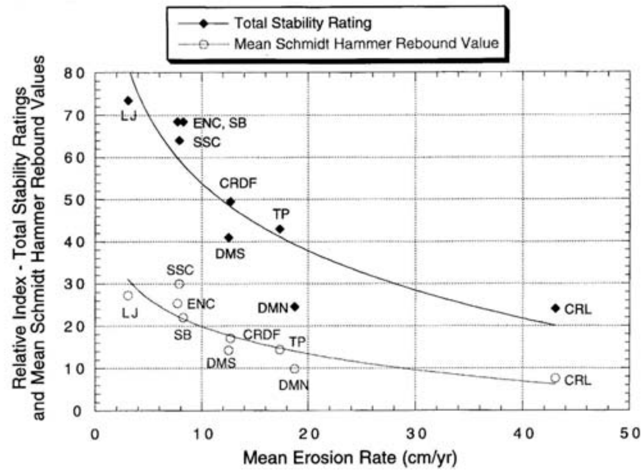


Fig. 8 Relationship between rock stability ratings and seacliff erosion rates in San Diego County.

Fig 9. Large-scale cliff failure along joint sets in Northern Monterey Bay.

Cliff failure in California during strong seismic shaking represents a significant but little appreciated coastal hazard, primarily due to the infrequent nature of large earthquakes (Figure 10). The potential for earthquakes that can affect coastal cliffs is high along the entire length of the state's coastline (Griggs and Scholar, 1997; Plant and Griggs, 1990 a,b). No part of the coastline of California is more than 25 km from an active fault (Jennings, 1975), and many areas are considerably closer. Future earthquakes, particularly in southern California, can be expected to produce widespread failure of the heavily populated cliffs and bluffs of areas like San Diego County where removal or demolition of at least one large building is now being contemplated (Figure 11).

Fig. 10 Seismically induced bluff failure at Daly City, 1989 Loma Prieta Earthquake.

DOCUMENTING SEA CLIFF EROSION RATES

It has been long recognized by coastal researchers working with sea cliff evolution and erosion that cliff or bluff retreat is usually an episodic process (Figure 9). Most of the major episodes of cliff erosion occur during the simultaneous occurrence of high tides and large storm waves, typically combined with heavy rainfall. At these times, waves can reach high enough up on the shoreline to attack those areas that are less frequently inundated and the material that has been weakened progressively through weathering can be dislodged and removed. The sequence of processes may include beach scour followed by direct cliff or bluff attack, undercutting of the base of the cliff followed by collapse of the overlying unsupported material, or simply hydraulic quarrying of blocks which were stable during summer conditions of lower wave energy and low pore pressures in voids and joints in the cliff forming materials. Terrestrial processes such as landsliding, slumping, or rock falls triggered independently of wave attack, may also be important, and even dominant in areas where the base of the bluff is protected by a seawall, revetment or a wide sandy beach (e.g., Norris, 1990).

Fig. 11 National Marine Fisheries Service Building perched precariously on steep cliff in La Jolla.

Although we often use or report average annual cliff retreat or erosion rates, in reality we are simply comparing the position of the cliff edge at different points in time (whether from historic maps or aerial photographs, or actual field measurements), and dividing by the total number of years between these data points, to derive an *average* erosion rate. Cliffs or bluffs may remain superficially unchanged for years, and then due to the right combination of bluff saturation, tidal level, wave attack, and/or seismic shaking, several meters may fail instantaneously. Averaging this loss over the time interval between major storms produces an average rate that may vary from cm per year along resistant granitic coasts to a meter or more per year in weak sedimentary rock or unconsolidated materials.

Because of the time involved as well as the equipment and aerial photographic or map data base needed to accurately measure long term sea cliff erosion rates, there have been surprisingly few comprehensive studies and relatively few data are readily available. *Living with the California Coast* (Griggs and Savoy, 1985) included regional input from a group of coastal geologists in California and maps in that volume summarize the site specific cliff erosion rates known at that time. More recently, Moore, Benumof and Griggs (1998) determined continuous coastline erosion rates for San Diego and the developed portions of Santa Cruz County as part of a nationwide FEMA-funded study.

In a statewide coastal hazards study (Griggs, Pepper and Jordan, 1992) it was determined from interviews with local government planning staff that the most frequently cited data need was that of coastal erosion rates. Nearly half of the respondents indicated a need for such information. Yet, there are still very few additional published or easily accessible cliff erosion rates beyond those previously published for Santa Cruz and San Diego counties. There have been a number of local, site specific studies for individual parcels where documentation of cliff erosion rates were required as a condition for construction or protection permits, but there has been no attempt to date to consolidate or compile these for broader application. While qualitative information on coastal bluff retreat is readily available (e.g. old photographs, abandoned roads, exposed storm drains and similar structures), accurate rates of coastal erosion are more difficult to come by. Yet it is these long-term rates that are critical in establishing safe setback lines for any proposed oceanfront construction.

HUMAN OCCUPANCY OF THE CALIFORNIA COASTLINE AND CLIFF EROSION HOT SPOTS

California has ~1760 km of shoreline; this length has not changed significantly during the period of human occupancy, but the population that utilizes and has developed and occupied the coast continues to increase. At the time of the damaging El Niño of 1982-83, the state's population stood at 24.8 million people. When the 1997 El Niño arrived, the state's population had increased 29% to 32 million, and by 2003 it had reached 35 million. Eighty percent of these people live within 50 km of the shoreline and over 4 million live within five kilometers of the water's edge. The coastline itself has continued to fill in with houses, condominiums, hotels and other structures.

Eroding bluffs and cliffs represent California's most extensive coastal hazard. Because of California's location in an active geologic setting, uplift of the coastline has produced many square kilometers of easily developed, nearly level marine terraces. From Humboldt County in the north to San Diego County in the south, these flat benches have been developed with homes, condominiums, apartments, restaurants and hotels. In most locations, this development has encroached right to the cliff or bluff edge, where views of the ocean are unobstructed and property values are the highest, but where the risks to structures of continuing bluff retreat are the greatest.

Coastal communities from one end of the state to the other have lost entire oceanfront streets, utility lines, lots of record and homes through the ongoing process of cliff erosion over the last century (Figure 12).

Fig. 12 Coastal cliff failure at Capitola during the Loma Prieta earthquake led to demolition of these apartments.

New developments are still being proposed on eroding or unstable bluff tops and small weekend beachfront cottages are still being torn down and replaced by larger new homes. When the California Coastal Act was passed in 1972, coastal hazard issues were not as obvious as they have become since 1978. During the last 25 years, winter storm wave attack has been more severe along the coast than it had been in the previous three decades. Although statewide guidelines were established in the Coastal Act for determining the stability of coastal bluffs and potential development sites, there is no statewide policy establishing safe setback distances from cliff or bluff edges. As a result, some jurisdictions use a predetermined, fixed setback, although these vary from as little as 3 to as much as 100 meters. Others employ a cliff retreat rate applicable over a specific time period or structural lifespan, most commonly a 50-year period.

An investigation of local government policies on coastal hazards in California (Griggs, Pepper and

Jordan, 1991 and 1992) revealed the following limitations in the approaches to regulating cliff or blufftop development: (a) regulations apply only to new development and fail to include provisions governing major remodeling and enlargements of existing structures, an increasingly common practice; (b) the increasing use of variances in infill, thus propagating or increasing the level of hazard and risk; (c) prescribed structure-lifetimes (often based on 30-year mortgage periods) do not accurately reflect the reality of structure longevity in California, generally much greater than those prescribed; (d) geologic information is frequently incomplete and jurisdictions are often not adequately staffed to make necessary technical and scientific evaluations; (e) the perceived threat of litigation appears to lead local elected officials to approve development applications that are recommended for denial at the planning staff level. Any one of these limitations can override a primary intent to site development well away from hazards of bluff erosion.

Each area of the state's coastline has its problem areas or erosional hot spots that have been repeatedly damaged and which regularly are featured in news stories (Moore and Griggs, 2002). Gleason Beach, along the Sonoma County coast, is an area where a group of cliff-top homes was built in an otherwise very rural and undeveloped area. The underlying geology consists of the heterogeneous Franciscan Formation which forms both resistant headlands and very erodible, slide prone slopes. Homes have been undermined, have collapsed and been destroyed with many of the others in precarious positions 25 meters above the waves.

In Pacifica, a row of oceanfront homes was built on an uplifted marine terrace consisting of poorly consolidated Tertiary marine sediments, terrace and eolian deposits. During the 1982-83 El Niño, these homes were threatened but undamaged (Figure 13).

Fig. 13 Bluff failure in Pacifica during the 1982-83 El Nino winter.

A protective rock revetment was subsequently built at the base of the bluff. When the 1997-98 El Niño high tides and storm waves struck, the revetment was undermined and collapsed. The waves attacked the unprotected bluff and groundwater weakened the cliff sediments—erosion proceeded until most of the oceanfront houses were undercut or collapsed to the point where they had to be destroyed (Figure 14).

Fig. 14 1997-98 El Nino failure at Pacifica that led to loss of homes.

In the Isla Vista area of Santa Barbara County, a number of apartment buildings were built on a coastal bluff cut into weak sedimentary rocks in the 1960's and 1970's to accommodate the rapidly growing student population of a University campus. The beaches appear to have narrowed in recent years from sand supply reduction, and a number of dwellings are now being undermined with structural collapse a very real threat to their survival (Figure 15).

Fig. 15 Eroding cliffs in Isla Vista area of Santa Barbara County.

In the Torrey Pines area of San Diego County, cliffs exceeding 90 meters in height have been eroded into Eocene sandstone and shale. Subaerial mass wasting is the dominant failure mechanism in this area and many landslides have occurred (Figure 11). In 1982, a 175 m long section of the cliffs failed and approximately 1.4 million cubic meters of material were deposited on the beach (Vanderhurst, et. al., 1982). The Torrey Pines area is devoid of any coastal armoring and the top edge of the cliff has been retreating at average rates of a few to over 50 cm/yr.

HUMAN RESPONSES TO COASTAL CLIFF EROSION

As the development of the southern and central California coast has intensified, and the state has experienced a recent (beginning in 1978) era of increased coastal storm damage and property loss, the extent of shoreline protected by armor has incrementally increased. In a 1971 Corps of Engineers shoreline inventory, 42.4 km of shoreline (2.4%) was listed as protected by some sort of armor (exclusive of breakwaters and groins). Only seven years later, in 1978, the California Department of Navigation and Ocean Development (Habel and Armstrong, 1978) determined that 100 km or 5.7% of the state's coastline had been protected by engineering structures.

In *Living with the California Coast* (Griggs and Savoy, 1985), a group of coastal geologists analyzed coastal hazards kilometer by kilometer along the state's coastline. Their maps indicate that approximately 136 km or 7.7% of the coast was armored by seawalls or revetments and another 32 km was protected by breakwaters, for a total of 168 km of armor by 1985 (9.5% of the entire 1760 km of coastline). This is a four-fold increase in the length of shoreline protected by seawalls in just 14 years.

The most recent compilation was completed in 2001 (Runyan and Griggs, 2003; Runyan and Griggs, 2002), and was based on earlier data augmented by oblique video photography of the more developed and armored southern and central coast flown in 1998. This work determined that about 180 km or 10.2 % of the state's entire coastline has now been armored, and that 172 km of this represents seawalls and revetments while the remaining 8 km are breakwaters and similar offshore structures. Expectedly, the extent of armoring is far greater along the central and southern California coastline, where 33% of the combined coastlines of Ventura, Los Angeles, Orange and San Diego counties are now armored.

A concern has arisen in recent years in California with the impacts of seawalls and revetments (Griggs, 1999). These include visual or aesthetic impacts, potential loss of beach access, loss of beach through placement of revetments, the loss of beach sand that would have been provided by the continued erosion of the bluffs, as well as passive erosion, or the ultimate loss of beach as sea level rise and coastal retreat impacts a hard or armored shoreline (Figure 16).

Fig. 16 Passive erosion in Central Monterey Bay due to placement of riprap.

CONCLUSIONS

Seventy-two percent of California's 1760 km of coastline consists either of high steep cliffs or lower bluffs eroded into nearly horizontal marine terraces. Sea level rise over the past 18,000 years has led to continuous coastal retreat of the coastline with cliffs and bluffs being cut into the coastal landscape. Cliff erosion takes place through a combination of marine and terrestrial processes and is dependent upon the properties of the cliff forming materials (rock type, structural weaknesses, presence of groundwater, for example) as well as physical forces such as wave energy, tidal range, degree of protection offered by a beach, climate, and frequency and magnitude of severe storm events. In general, the softer sedimentary rocks making up the coastal bluffs erode at average rates of 10 to 30 cm/year whereas the harder igneous and metamorphic rocks, which often make up the resistant headlands, erode at slower rates. Cliff erosion rates can be measured using sequential aerial photographs or historic surveys or maps, and are necessary for making wise coastal land use decisions and establishing setbacks for coastal construction. The wide, flat uplifted marine terraces, which are characteristic of much of California's coast, are easily developed and have been the sites where most of California's coastal communities have evolved. The low bluffs fronting these terraces, however, typically are easily eroded and coastal land loss has become a key issue along the state's shoreline. Cliff erosion hot spots are widespread and well recognized along the state's coastline and public and private property damage during the last two major El Niño events (1982-83 and 1997-98) was high. Historical approaches to dealing with the ongoing erosion of the state's cliffs and bluffs have focused on seawalls and revetments but concerns with the effectiveness and impacts of these structures have begun to restrict additional armor emplacement.

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