FIELD TRIP GUIDE

COASTAL GEOLOGIC HAZARDS AND COASTAL TECTONICS

NORTHERN MONTEREY BAY AND SANTA CRUZ/SAN MATEO COUNTY COASTLINES

GARY B. GRIGGS
GERALD E. WEBER

ASSOCIATION OF ENGINEERING GEOLOGISTS
MARCH 3, 1990

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Dear Colleagues:

Welcome to the AEG—San Francisco Section Coastal Geologic Hazards and Coastal Tectonics field trip. On behalf of the field trip leaders — Gary Griggs and Gerry Weber, — I hope you will have a pleasant day.

This field trip is divided into two parts: The morning will highlight coastal processes, protection, and planning at selected locations along the northern portion of Monterey Bay. This portion of the trip will be lead by Gary Griggs. The afternoon will concentrate largely on the interrelationship of marine terraces and tectonics associated with the San Gregorio fault zone in northern Santa Cruz County and southern San Mateo County. Gerry Weber will be our leader throughout the afternoon.

The contents of the field trip guidebook corresponds to the day's itinerary. This field trip guide book is written specifically to provide information on field localities and other areas of possible interest; thus it includes more field trip stops than can be taken in one day. We hope your interest will be sufficiently aroused that you will want to visit the stops we may not get to today.

Both Gary and Gerry have given unselfishly of their time and efforts to prepare this guidebook. When you have a moment today, a word of thanks would be greatly appreciated. In addition, we would like to express thanks to Gary Strachen, Head Ranger, and the staff at Ano Nuevo State Park; Tony and Dave Landino of Landino Drilling and Construction for the area to turn the bus around at lunch; the other property owners along Back Ranch Road, and Dave Cleveland for access to our exquisite lunch site.

So, enough said, sit back and enjoy the surf, sites, and suds.

John Coyle

John Coyle
AEG—San Francisco Section
Field Trip Coordinator

MORNING SECTION

COASTAL GEOLOGIC HAZARDS
NORTHERN MONTEREY BAY

ASSOCIATION OF ENGINEERING GEOLOGIST FIELD TRIP

COASTAL EROSION AND PROTECTION-NORTHERN MONTEREY BAY

Gary B. Griggs
University of California, Santa Cruz

STOP 1. RIO DEL MAR BEACH

GEOLOGICAL SETTING AND HAZARDS

The coast from New Brighton Beach to the Pajaro River constitutes southern Santa Cruz County and lies within the usually protected inner portion of Monterey Bay. The coastline follows a very gentle, smooth curve throughout this entire reach which is in equilibrium with the wave refraction pattern followed by the dominant northwesterly waves. Wide sandy beaches border this stretch of coast and protect the flanking seacliffs almost permanently. From New Brighton Beach State Park to La Selva Beach an uplifted marine terrace is the dominant coastal landform. A very steep cliff, approximately 100 feet high, forms the seaward edge of the terrace. To the south, the terrace disappears, and a field of recent and active sand dunes mantles the low-lying area and dominates the topography all the way to Monterey.

The terrace and seacliff between New Brighton and Aptos Creek are composed of the moderately resistant sandstones, siltstones, and mudstones of the Pliocene Purisima Formation. Although these rocks are identical to those making up the cliffs in the Santa Cruz to Capitola area, the cliffs backing the northern portion of the inner bay are more stable and vegetated because they are protected from wave action and erosion by wide, sandy beaches (as well as beach houses and seawalls).

South of Aptos Creek the material exposed in the bluff consists the Aromas Formation, a sequence of weakly consolidated sands that represent ancient dune and fluvial deposits. This material is less stable than the Purisima to the north, and can erode very quickly where it is exposed to rainfall, streamflow, or wave action. It is also prone to slumping and debris flows and, therefore, should be considered potentially unstable in any hillside or bluff area. Unfortunately, the loose and unstable nature of these sands was not given consideration either in the development at the top of the bluff, or in the beach-front construction at the base of the bluffs along Beach Drive.

During the 100 year 24 hour storm of early January 1982, numerous failures occurred in the Aromas Formation and in the terrace deposits above Beach Drive (Figure 1). Two houses were destroyed at beach level including one which was pushed off its foundation onto the roadway. Houses at the top of the bluff lost significant portions of their rear yards. Recently proposals for development of the remaining parcels on the bluff side of Beach Drive at its southern end have been received by the Santa Cruz County Planning Department. The geological and soil investigations accompanying these

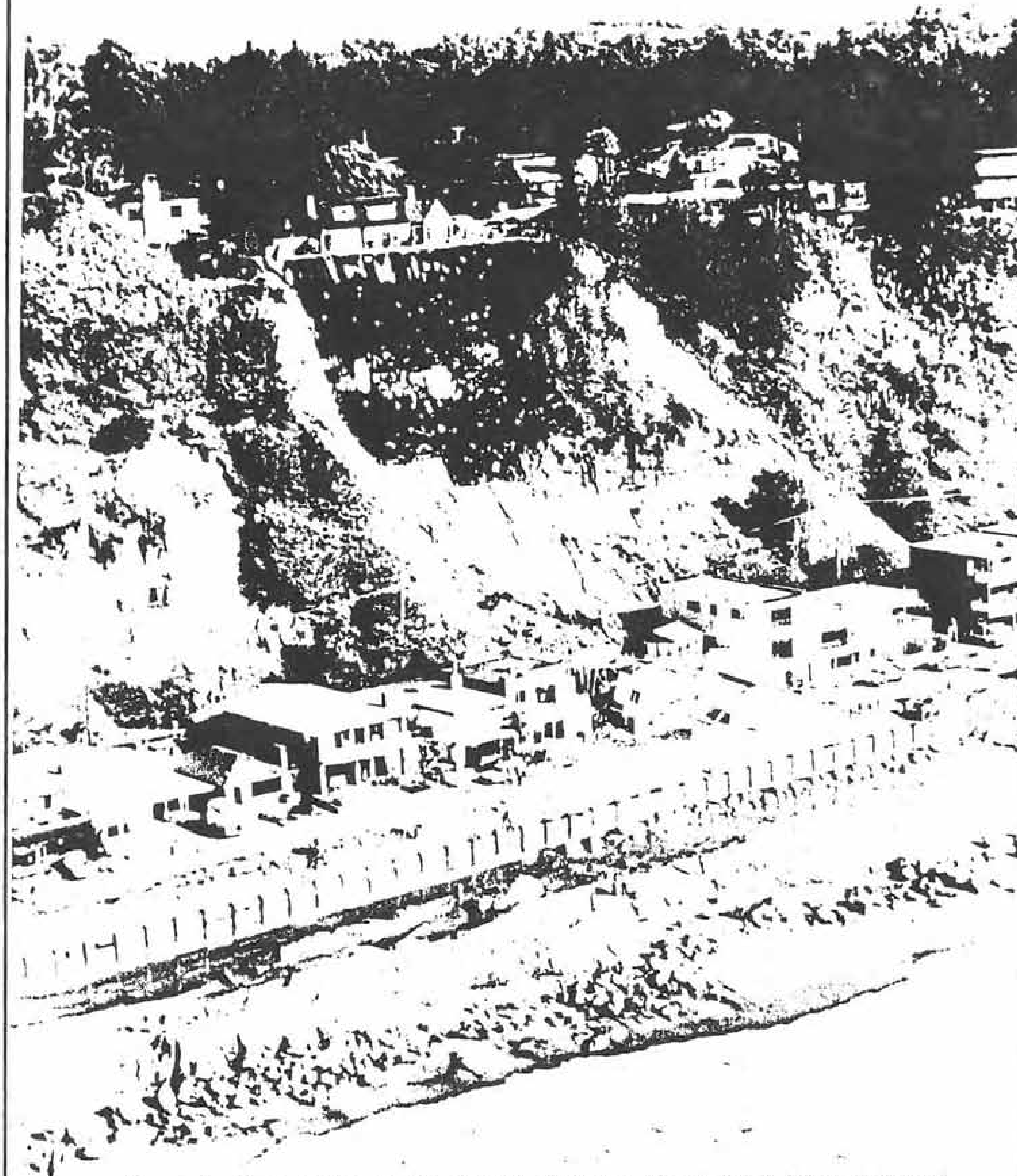


Figure 1. Slope failure in the Aromas Formation above Beach Drive following the 100 year 24 hour storm of early January 1982.

building permit requests have raised the issue of long term slope stability and whether or not slope failures can be effectively mitigated.

Some difficulties in the analysis of slope stability on these parcels have arisen which have not yet been completely resolved. These include:

1] The generalized nature of the slope stability analyses and the accuracy and reliability of the results
2] The inability to obtain samples from depth on these steep slopes and therefore the uncertainty of the soil strenth parameters utilized
3] Uncertainties involved in analyzing slope stability under seismic loading, including values used for acceleration and pore pressures
4] Uncertainty of the nature of the failure which may take place and, therefore, value of mitigation measures proposed

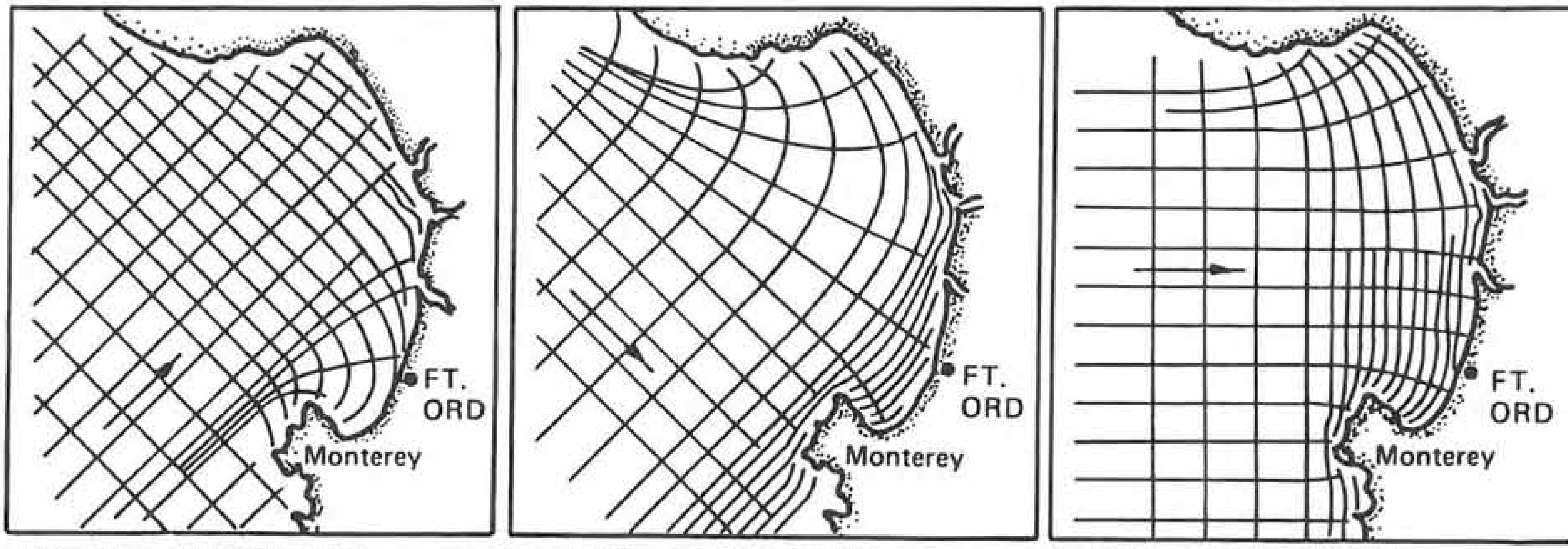
These sites present challenges for both the geologists and geotechnical engineers. One dilemna lies in the differences in their approaches to the analysis of hillslope stability, and perhaps, understandably, the differences in their conclusions. At this particular site the major uncertainty lies in the area of potential seismically induced slope failure. The geologist has 60 years of stereo aerial photographs, the present geomorphology, and the knowledge and observations of recent failure. The soil engineer has whatever information can be collected from short hand auger samples, a general slope stability model, and a slope profile and seismic coefficient supplied by the geologist.

To date none of these property owners have obtained permits and in at least one case, legal action is being contemplated.

Upcoast approximately a mile, between Seacliff State Beach and New Brighton State Beach, construction of beachfront homes is also being proposed at the base of the bluff, here composed of the Purisima Formation. Similar issues arise in this instance, although the type of bedrock failure is very different. The Purisima is extensively jointed (this will be seen at Stop No. 2 in Capitola and discussed in the next section) and the most common mode of seacliff failure in the Purisima is rock fall of joint bounded blocks. Under what conditions might bluff failure occur? How much material may break loose and what size of block may form when failure does occur? and, How far away from the base of the bluff will this material be a hazard to a structure, are the questions which need resolution.

COASTAL EROSION AND PROTECTION

The interior of Monterey Bay (Rio del Mar in this instance) presents a clear example of the problems associated with building permanent structures on the beach. A wide, sandy beach, which is in equilibrium or balance with the predominant northwesterly waves, normally flanks this entire stretch of coast. These waves undergo considerable refraction or bending as they enter the bay (Figure 2), and in doing so lose much of their energy. The historic record, however, shows the repeated impact of storm waves from the southwest that remove much of the sand, carry large logs across the beach, and often reach the sea cliff itself. The very presence of the beach sand and driftwood logs stranded at the base of the sea cliff are clear testimony to past storm activity. This backbeach area, now intensively developed, is equivalent to a



T = 12 SEC., DIRECTION: SW

T = 12 SEC., DIRECTION: NW

T = 12 SEC., DIRECTION: W

Figure 2. Refraction patterns for waves entering Monterey Bay.

river's floodplain. The question to ask as a consultant is not IF it will be inundated, but how often, and to what depth?

Most coastal communities now have official FEMA coastal runup and inundation maps for determining these elevations for the "100 year storm". My own experience is that these maps have been prepared by consultants lacking local experience or knowledge, using only a few widely spaced topographic profiles and a standard wave runup model. Nowhere along the coast of California do we have 100 years of wave height or runup records such that extrapolation to a 100 year event may involve considerable uncertainty. Nonetheless, these are the accepted values used for minimum elevations along the oceanfront for new construction or development by the planning departments. The historic record of storm runup from recent years (1983 in particular) provide excellent records of these runup or inundation extremes and should be researched to compare with the "official" maps.

For a distance of nearly three miles from Pot Belly Beach (just south of New Brighton State Beach) to Aptos Seascape, extensive public and private development has taken place on the backbeach. Dozens of private homes, in addition to a recreational vehicle campground (Seacliff State Beach), several roads, restrooms, and a major sewer line have been built on or buried beneath the beach. Storm damage in 1978 and 1983 was extensive in this area. A look at the historical record, however, shows that these storms are not new to this portion of northern Monterey Bay.

The northern portion of Monterey Bay (Santa Cruz to Moss Landing) is most susceptible to damage when storm waves approach from the west or southwest. Waves from the northwest, which predominate along the central California coast, undergo major refraction, which results in significant energy reduction as they bend around Pt. Santa Cruz to strike the beaches of the inner bay. In contrast, storm waves approaching from the west, west-southwest, and southwest, pass primarily over deep water on their way to the shoreline within the bay and, therefore, lose little energy. These waves undergo little refraction before striking the coastline directly and have consistently produced the most damage at Capitola, Seacliff, Rio del Mar, and adjacent areas. Of the 20 large storms which have produced the greatest damage to the coastline of northern Monterey Bay, only one is described as coming from the northwest, 13 arrived from the southwest, and no direction was listed in the newspaper accounts for the remaining six.

For the 73 years of good historical record, damaging storm waves have struck the beaches of inner Monterey Bay every 3.6 years on average. The storms have not, however, been evenly distributed over time. No major storms were recorded for some intervals as long as seven years (1916-1923) but, in another case, five significant storms struck the coast in a single year (1931). The winter of 1983 was similar to 1931 with repeated storm attack. The past storm damage to the coastline was most often caused by the simultaneous occurrence of high tide and large waves. This was a critical factor during both the winters of 1978 and 1983.

The shoreline from Seacliff to Aptos Seascape thus has a long history of storm impact and damage. Homes and public facilities and utilities have been built on the beach, elevated just above the beach, and on the flanking sea cliff. A variety of protective structures have been built and rebuilt over the years in order to protect this development. The approaches have varied widely, as have their success and costs. The major examples are discussed and pictured in the following pages.

Seacliff State Beach

In the Seacliff Beach area, major storms from the west or southwest in 1926, 1927, and 1931 destroyed or partially destroyed a concrete seawall, a bathing pavilion and a concession building. In 1934, this beach front area was purchased by the state for camping and picnicking. The continued impact of storms on the protective structures built along this beach has been well documented (Table 1; Griggs and Johnson, 1983; Griggs and Fulton-Bennett, 1987). Seven times in 60 years, or about once every seven years, seawalls and bulkheads at Seacliff Beach have been damaged or destroyed (Figure 3). After extensive damage in 1939 and 1940, the bulkhead was rebuilt. Storms in the winter of 1941 destroyed it again (Figure 4). Following extensive damage to a piling and timber bulkhead and a recreational vehicle campground on the beach in 1978 and again in 1980, a new 817 m long piling and timber bulkhead was reconstructed along with the RV parking area at a cost of $1,700,000. The new structure was intended to last 20 years; in late January 1983, within two months of its completion and dedication, the waves and high tides overtopped the bulkhead (Figure 5). Large logs battered the timber lagging and pilings and over 214 m of the structure was destroyed (Figure 6). The parking lot, utilities, and the RV camping sites were damaged as logs, sand and debris were carried over and through the seawall to the base of the seacliff. Damage costs were estimated at $740,000, or half of the cost of the wall and improvements just completed several months earlier.

The Department of Parks and Recreation subsequently requested funds to rebuild the timber wall for the seventh time with only minor modifications. The case for rebuilding was based on the high usage of beach-level recreational vehicle camping sites and parking areas. Although the report justifying reconstruction estimated that damage to the seawall was less than 15%, the funding request ($707,000 total, $497,000 for the seawall) was 30 to 50% of the cost of the $1.7 million spent in 1982. The State Public Works Board approved the request, and reconstruction was carried out (Figure 7).

To date, the ineffectiveness of a wood piling and timber seawall in a high energy location has not been recognized by the Department of Parks and Recreation (Figure 8). With the exception of the original 1926 concrete wall, and some minor modifications in the most recent wall, every structure has been rebuilt in the same manner. Although a 20 year lifetime has been used regularly for economic calculations, none of the walls has survived intact this long. The lifespan of any individual wall is primarily a function of how soon after construction the next period of high tides and large waves occurs.

The timber bulkheads constructed at Seacliff State Beach have had some major deficiencies which have never been remedied:

1) The timber lagging has been poorly attached to the pilings.
2) The lagging and pilings have been repeatedly broken by wave and log impact, leading to loss of fill behind the wall.
3) The wall has not been built high enough to prevent overtopping by water and debris, and the drainage system has been inadequate to remove the water

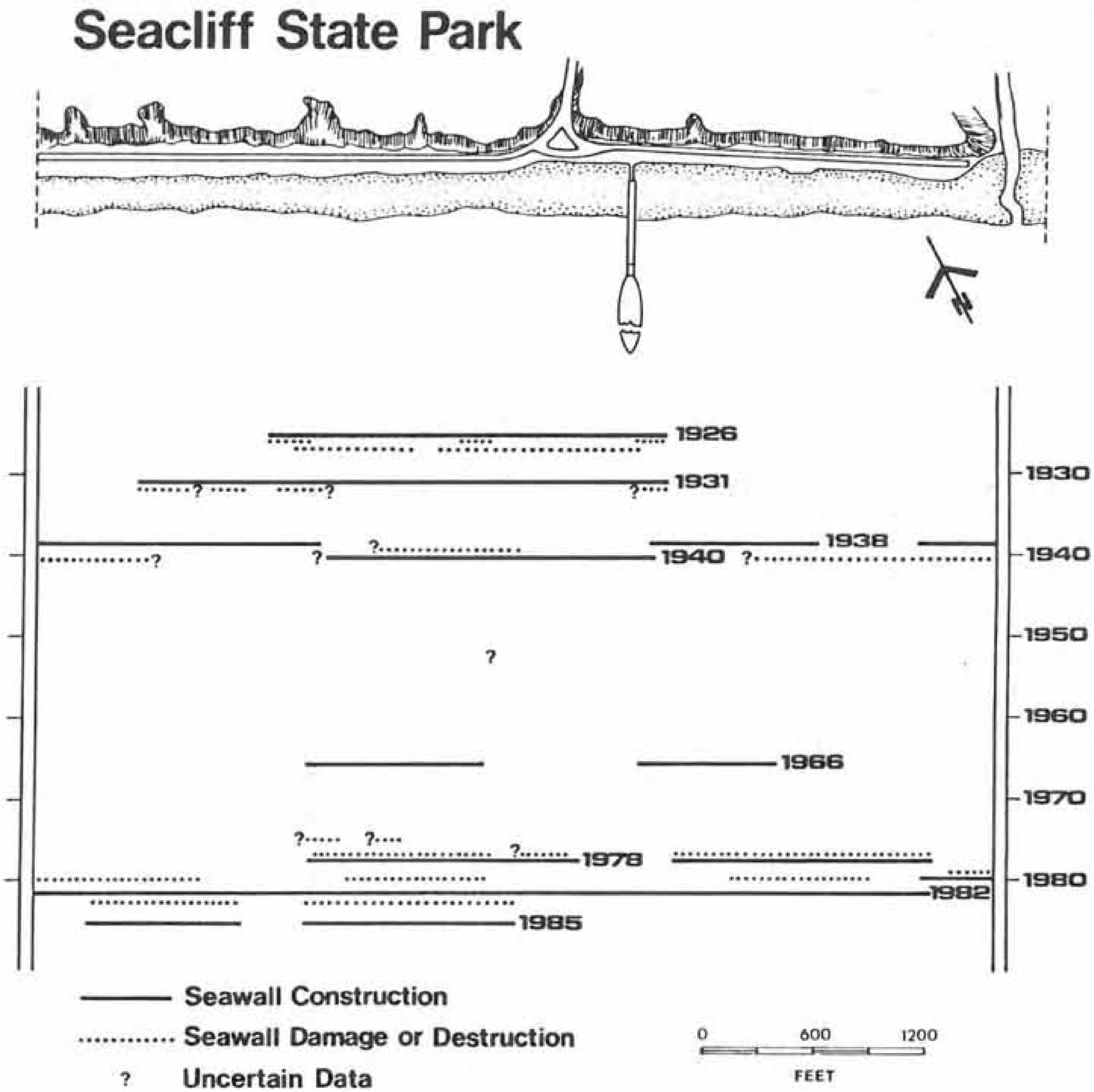


Figure 3. History of coastal protection efforts at Seacliff State Beach.

Table 1 HISTORICAL DAMAGE TO THE SEACLIFF BEACH AREA
(From files of *Santa Cruz Sentinel*)

DATE OF STORM	DAMAGE DESCRIPTION	DIRECTION/TYPE OF STORM
Feb 14-16, 1927	Concrete seawall at Seacliff Beach destroyed.	"heavy southwester"
Dec 9-10, 1931	Timber bulkhead at Seacliff destroyed.	"southwest wind waves"
Dec 23-29, 1931	Concession building and bathing pavilion at Seacliff wrecked.	"winds first from southwest then northwest"
Dec 26-27, 1940	Crux of local weather problem at Seacliff. Logs up to 10 feet tossed onto road, houses damaged, 80 feet of state park lost, two sections of bulkhead ripped out.	
Jan 8-13, 1941	At Seacliff Beach, about one half of a timber bulkhead destroyed. Beach eroded to bedrock.	"waves and swell from southwest"
Feb 11-13, 1941	Residents in Seacliff cut off by slides.	
Feb 9-10, 1960	Camping sites destroyed, restroom nearly destroyed.	"southerly and westerly storms"
Feb 11-15, 1976	High waves washed completely over new seawall, carrying debris back to cliff. Portions of seawall undercut and caved in.	"southerly gale"
Jan 8-9, 1978	Seawall overtopped and logs and debris scattered across parking and camping areas. Extensive damage to seawall.	"storm from southwest"
Feb 1980	$1.1 million in damage at Seacliff. Storm destroyed entire lower beach portion of park, taking roads, parking lots for 324 cars and a 2672 foot seawall.	"southwest"
Jan 28-30, 1983	$740,000 in damage. 2800 feet of new seawall damaged, 700 feet totally destroyed; eleven RV sites destroyed restroom heavily damaged, logs and debris washed back to cliff.	"waves from southwest"

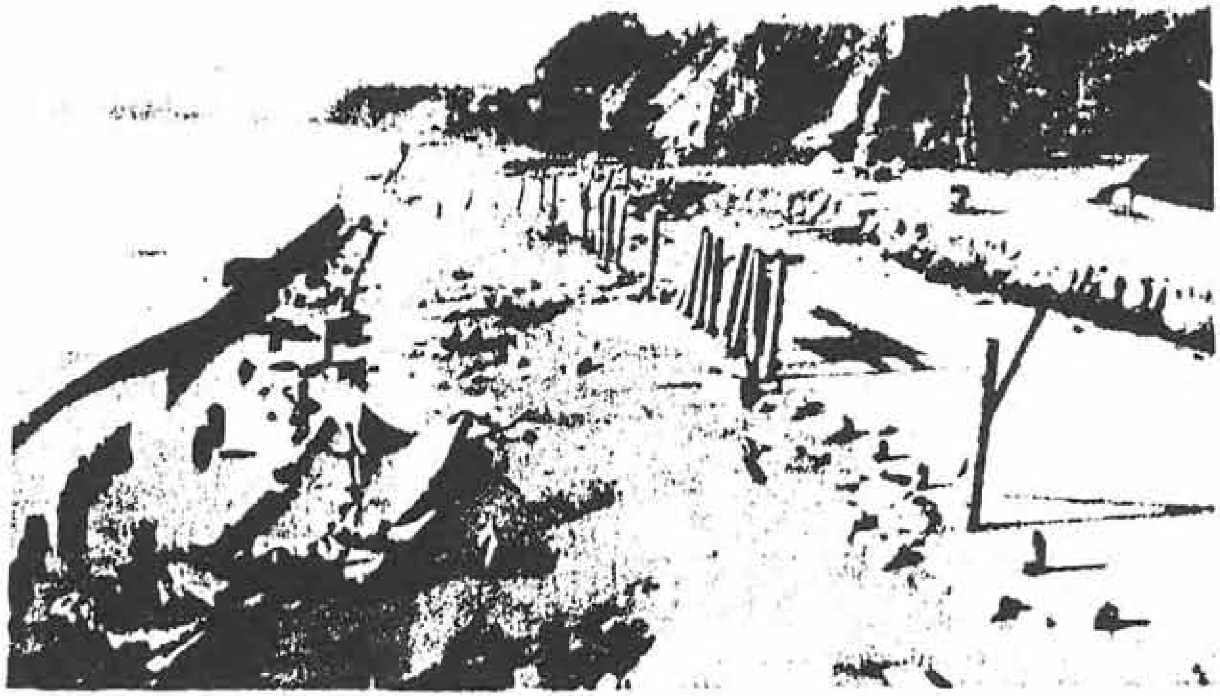


Figure 4. Seacliff State Beach after winter of 1940-1941. Structure on left is remains of seawall constructed in 1926 and destroyed the following winter. Pilings further shoreward are part of bulkhead destroyed during winter of 1940-1941.

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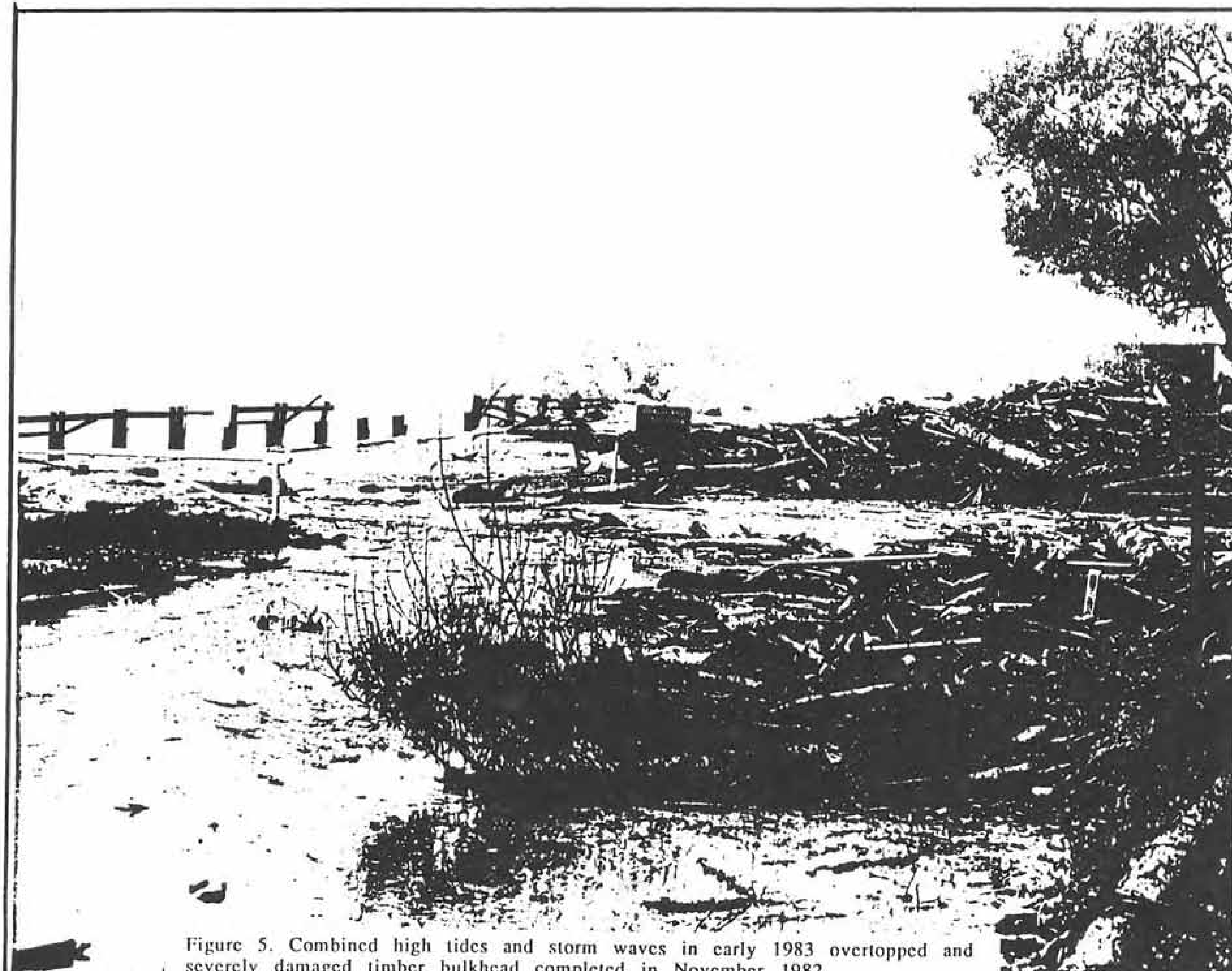

Figure 5. Combined high tides and storm waves in early 1983 overtopped and severely damaged timber bulkhead completed in November 1982.

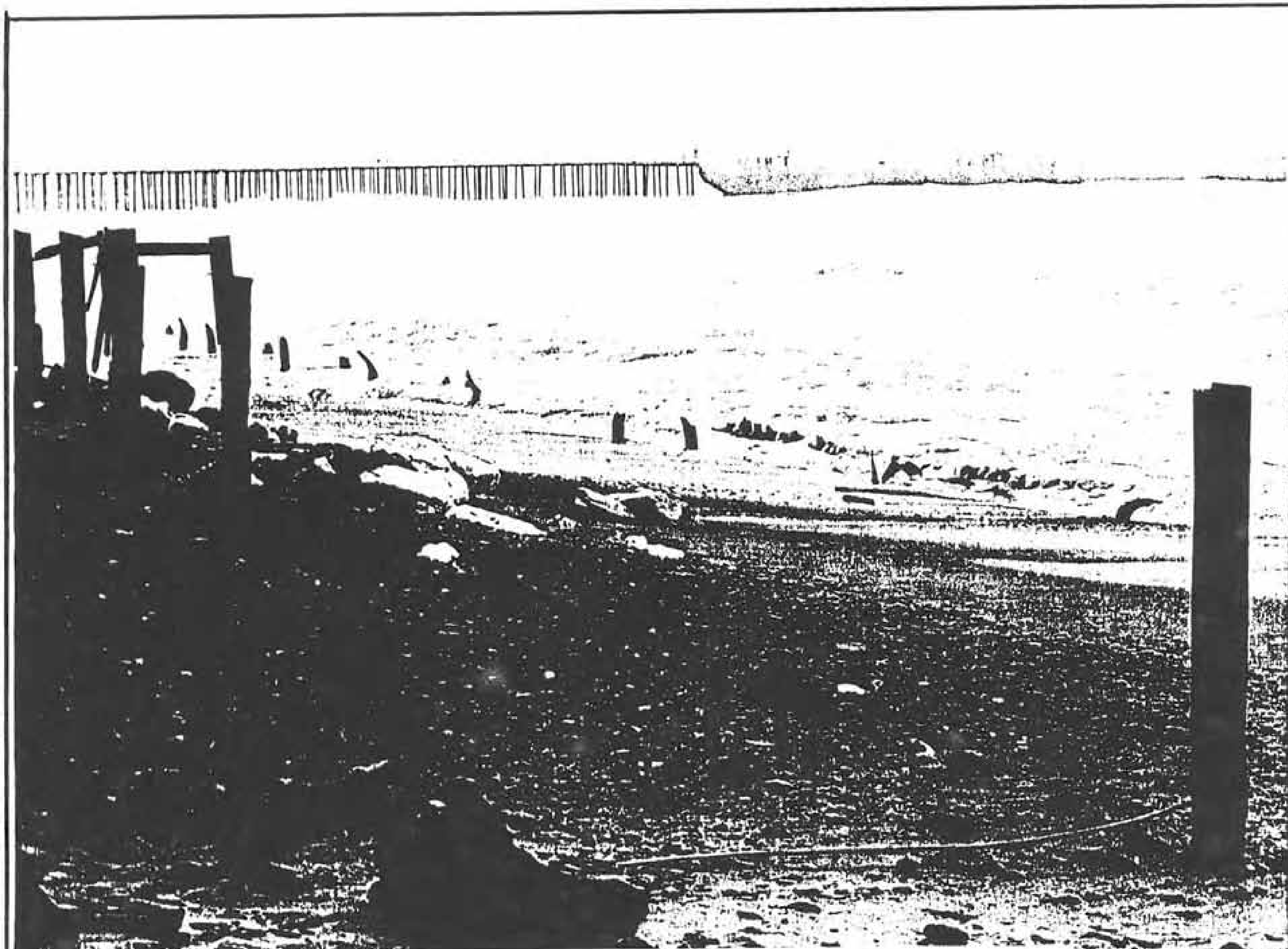

Figure 6. Loss of timber lagging and pilings during winter storms of 1983. Note remnants of earlier walls in the surf zone.

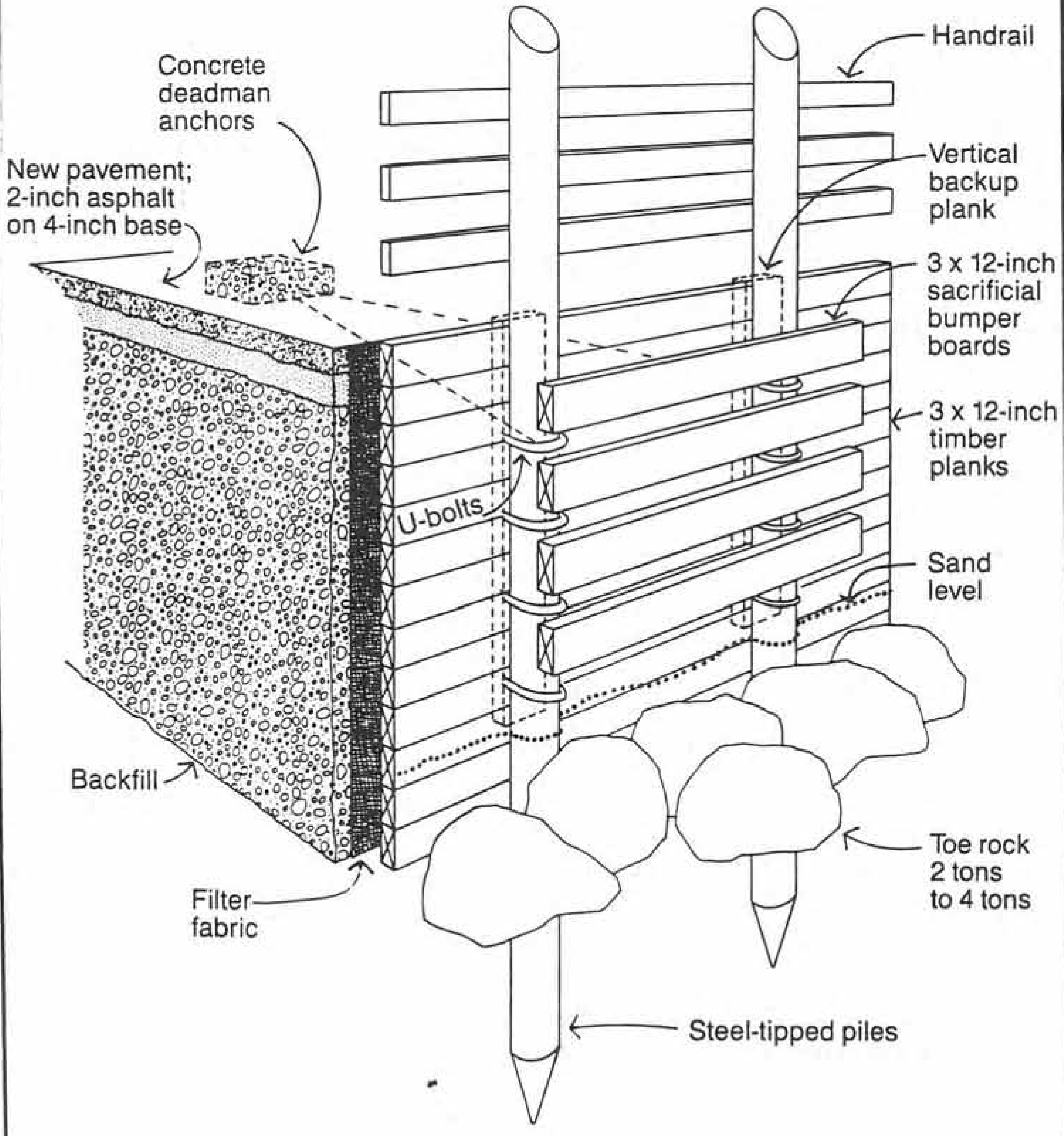

Figure 7. Plans for last (1985) reconstruction of wall at Seacliff State Beach.

which has overtopped the wall. As a result the fill has been removed leading to loss of support for the wall (Figure 8).

Aptos Seascape

Aptos Seascape is a beach front development south of Rio del Mar's Beach Drive. The first of these homes were built in 1969 despite initial disapproval and warnings by the County Planning Department. Twenty-one homes were eventually built on fill added to raise the elevation of the back beach. The project initially approved called for a protective sheet pile seawall with the homes set back at least 20 feet from the seawall. Instead a rip-rap revetment was used and a ten foot setback was utilized; later even this ten foot setback was removed. During the first heavy storms of 1983, 10 to 12 foot waves combined with 6.6 foot tides overtopped the revetment. Nine of the 21 homes were heavily damaged. In most cases the waves broke through the windows, doors and house fronts facing the ocean and washed all the way through the homes (Figure 9). One house partially collapsed as the wall facing the ocean was demolished (Figure 10). Damage estimates at Seascape ranged from $2 to $2.5 million.

In addition, about half of the rip-rap was removed as sand was scoured beneath it and the rock tumbled onto the beach and rolled seaward. In June 1983, less than 6 months later, county approval was given to a new seawall (Figure 11) that would extend 1000 feet and cost $2.9 million; this amounts to $2900 per front foot for protection, or over $100,000 per property owner (although insurance is apparently paying for the seawall). This wall is in liltigation. The curved face concrete seawall is supported on deep steel pilings and extends to a height of +21 ft MLLW (+18 ft MSL). The remaining original rip-rap was added at the toe of the structure to protect from scour. This wall lies about 250 feet seaward of the base of the bluff at this location and thus extends well into the surf zone under winter storm conditions.

South Beach Drive (Private) Seawall

At the time the 1983 storms and high tides struck northern Monterey Bay, twenty-six homes built on the seaward side of Beach Drive on the back beach were protected by a variety of structures including timber seawalls, large concrete blocks, and a concrete seawall made of old bridge panels. The top of most of these walls was only at +13 to +14 ft MSL. When the storms of January 1983 struck, the walls were battered by waves and logs, overtopped, and undermined. The consequences of a lack of a uniform approach were all too obvious. As soon as the weakest unit was damaged such that waves could pass through it and reach under the homes, beach scour was rapid, the fill behind the walls which provided the resistance to wave impact was lost. Each wall in turn was overturned or destroyed (Figure 12).

By the end of January with the protection gone, waves had exposed piers and pilings; two houses with shallow piers sank to beach level and were destroyed (Figure 13). Initial damage estimates on South Beach Drive were $2,000,000. Emergency rip-rap was brought in to provide temporary protection. Ultimately, the rip-rap became a permanent structure at the downcoast end of Beach Drive (without filter cloth or core stone). A concrete sheet pile seawall was constructed at the upcoast end of South Beach Drive in 1986. Neither structure, however, was allowed to be higher than the original wall which was

Figure 8. Progressive lateral failure of a wooden seawall/bulkhead.

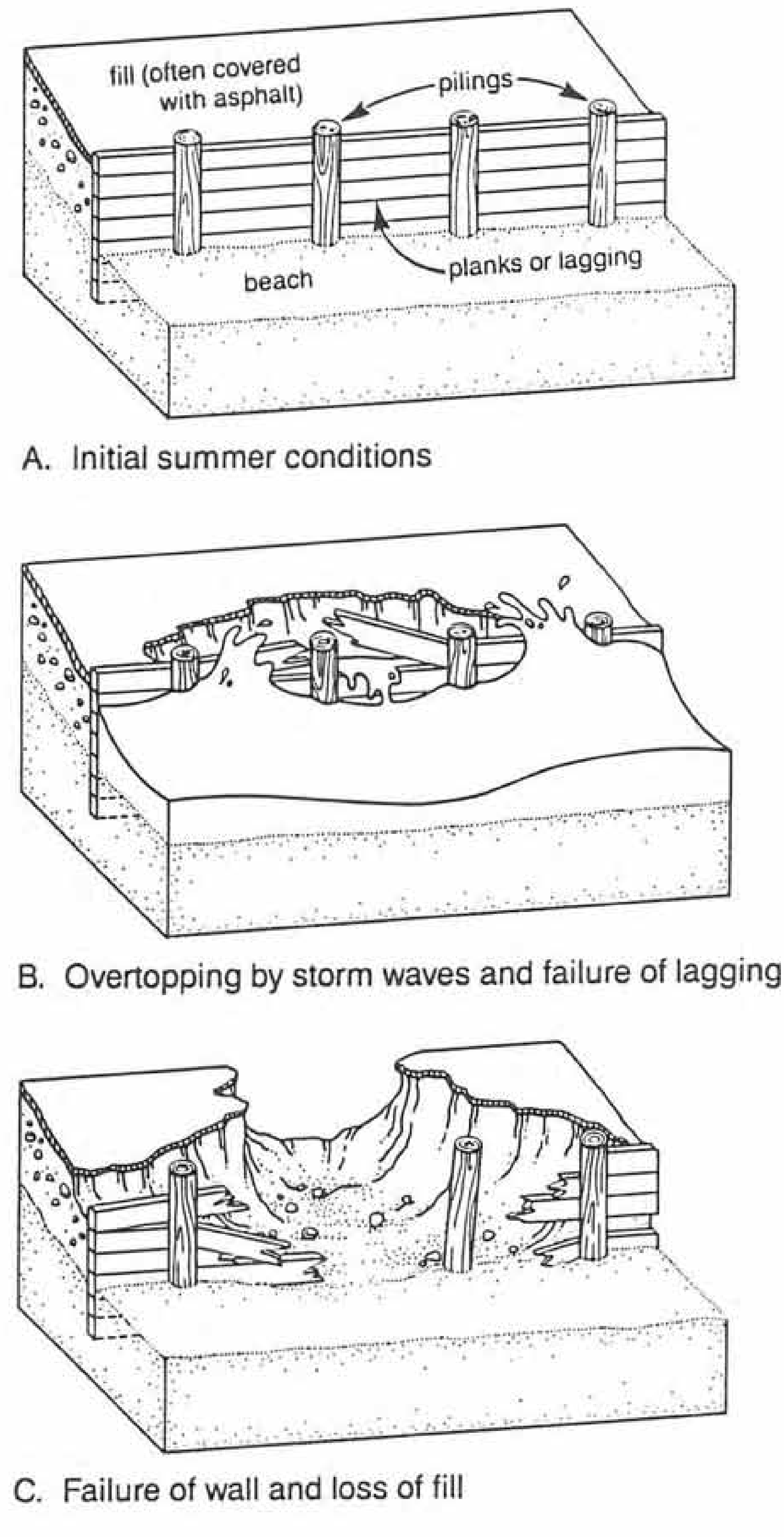

Figure 9. Damage to homes at Aptos Seascape in January 1983 due to storm waves overtopping rip-rap revetment.

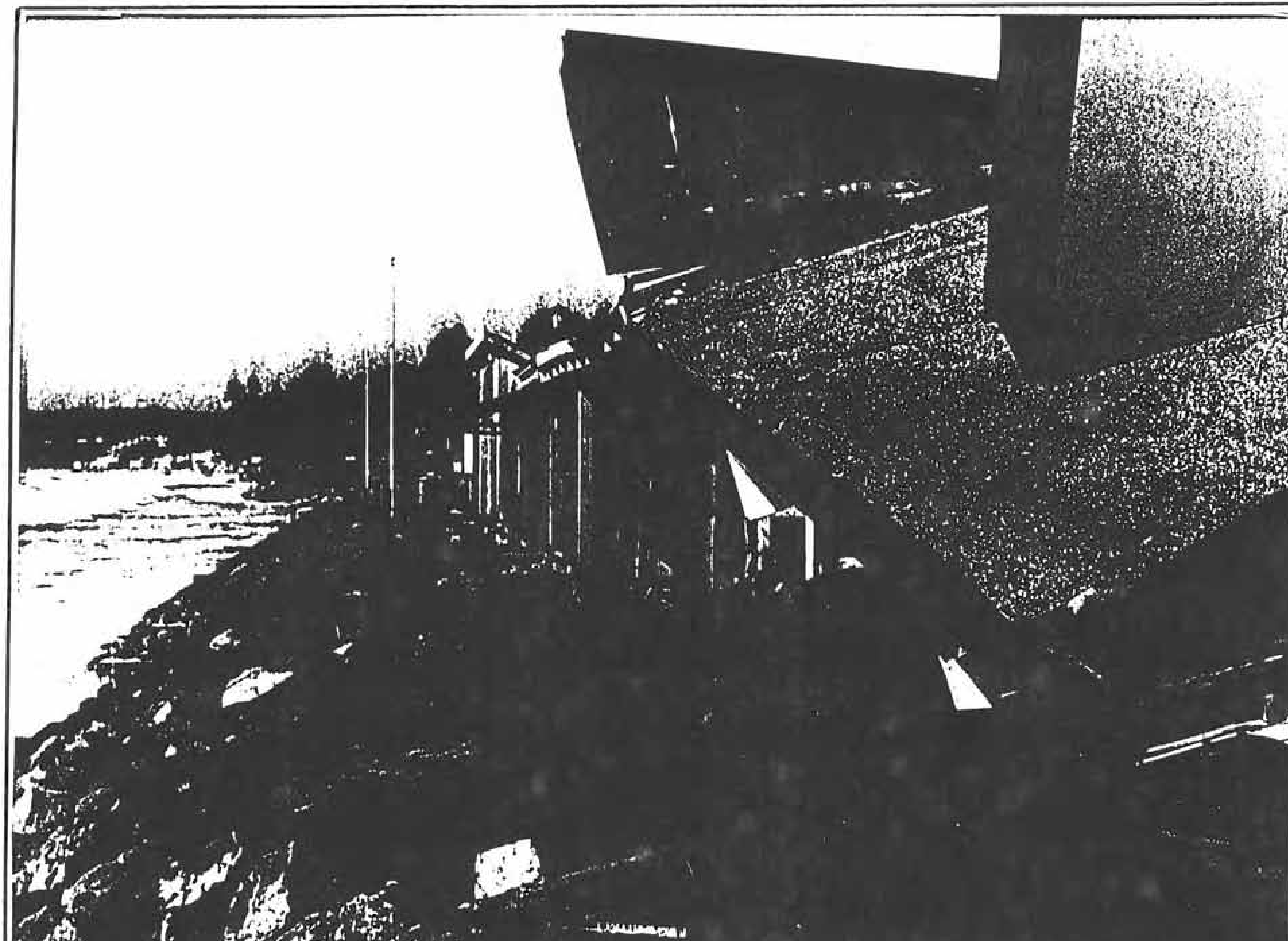

Figure 10. House collapse at Aptos Seascape in January 1983 due to loss of front wall from wave impact.

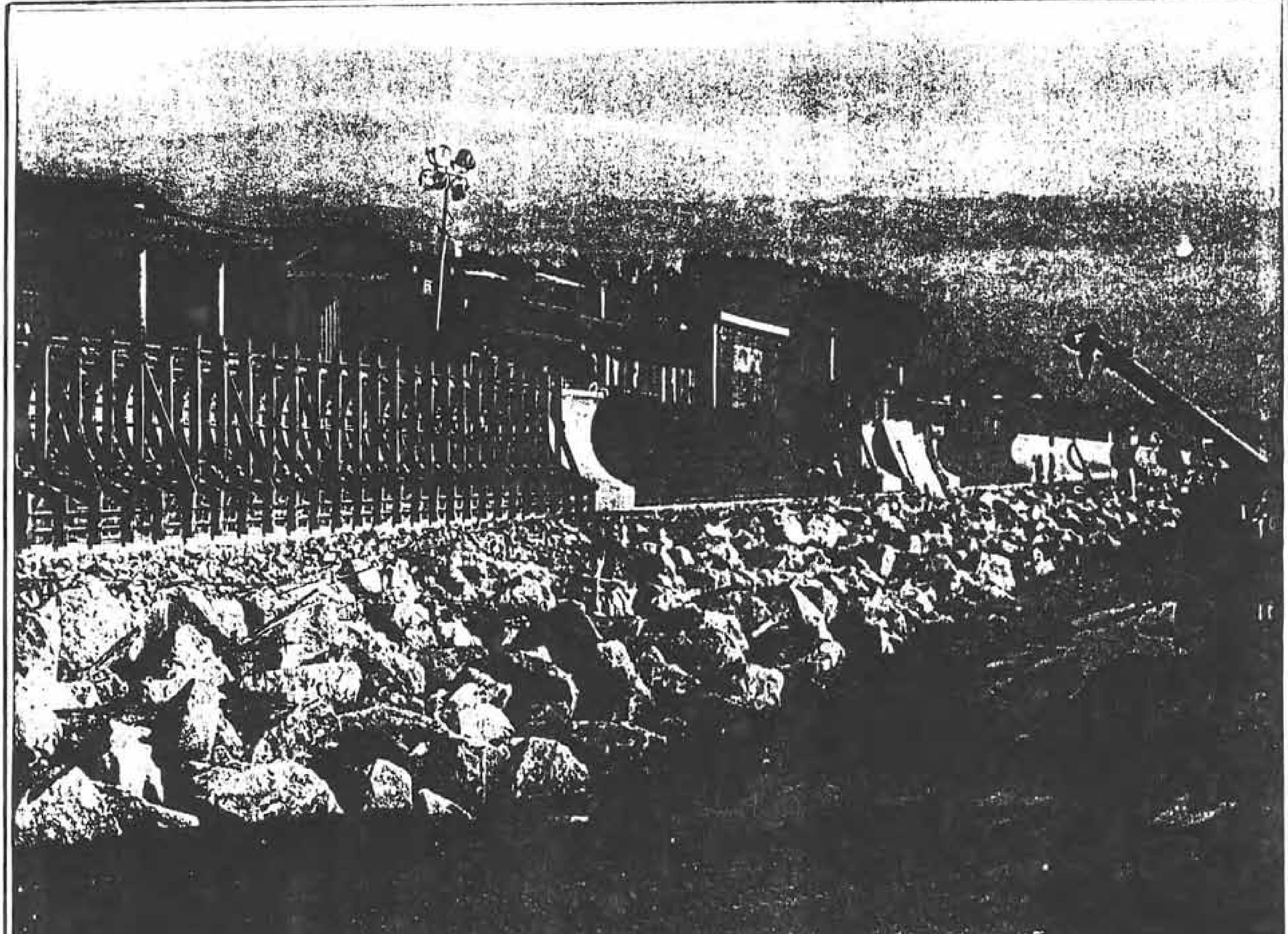

Figure 11. Construction of new curved face concrete seawall at Aptos Seascape.

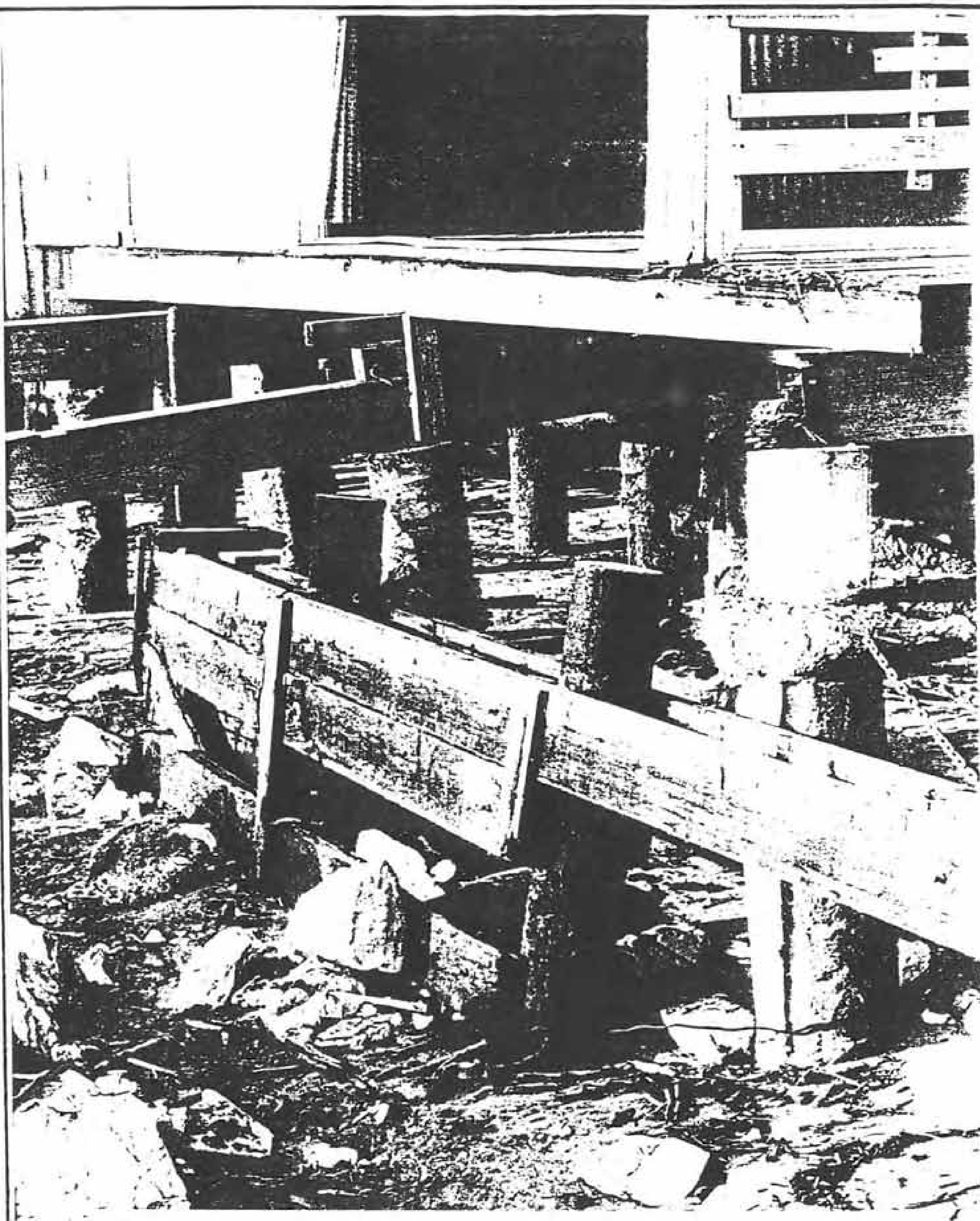

Figure 12. Remains of a portion of the seawall protecting South Beach Drive after the winter storms of 1983.

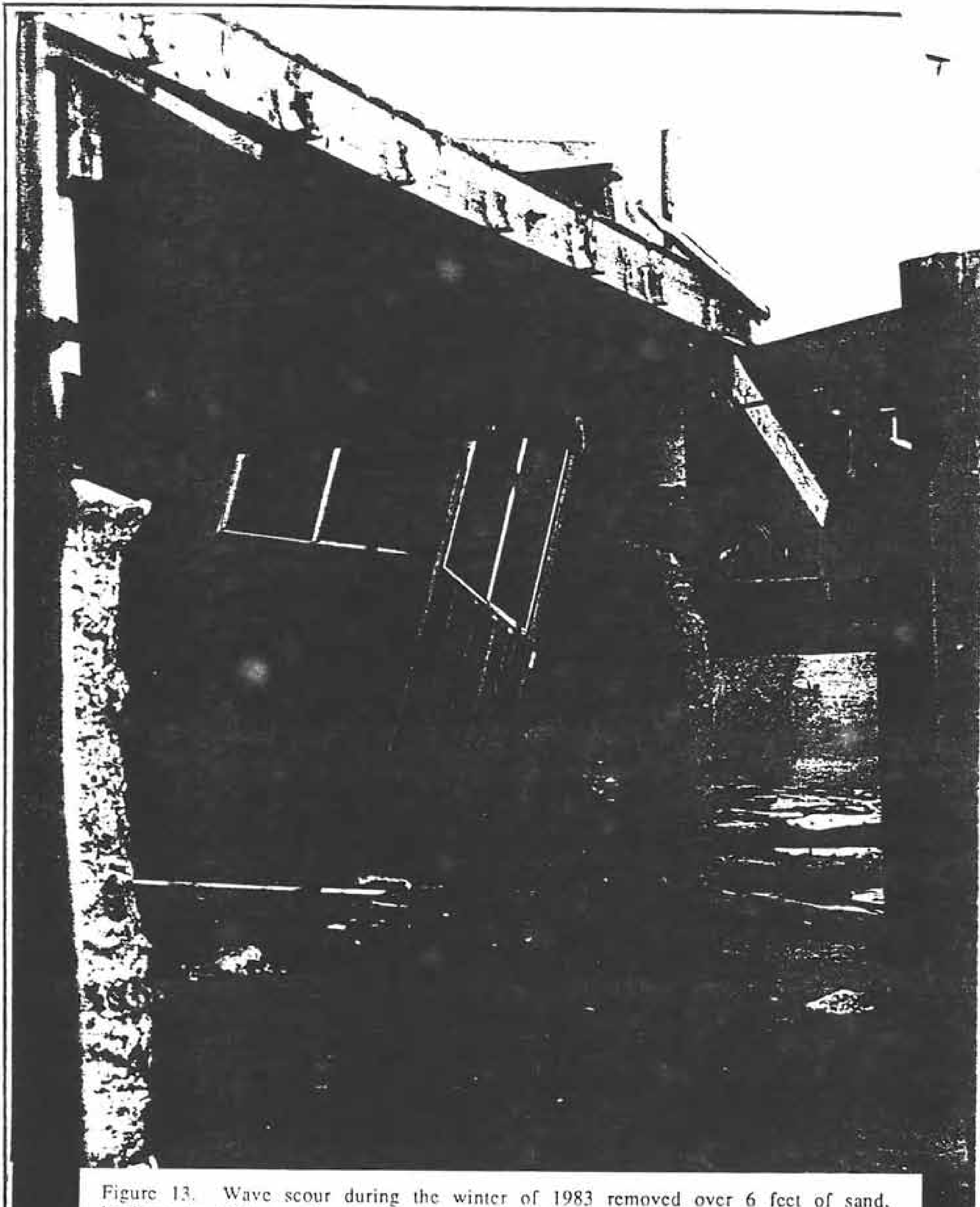

Figure 13. Wave scour during the winter of 1983 removed over 6 feet of sand, leading to failure of shallow piers beneath two houses along Beach Drive followed by collapse.

destroyed. The concrete wall was poured in 8 inch thick panels on the beach; individual panels were jetted into place. Tie-backs were used and attached through a thicker grade beam within the panels. The major deficiency in the wall was its drainage system. Storm waves scoured the sand from in front of the wall in early 1986 such that 12 vertical feet of the wall was exposed (Figure 14). Subsequent wave overtopping and vibration of the wall due to wave impact initiated piping through the 4 inch diameter weep holes, leaving large collapse pits behind the wall. Without the support behind the upper wall, continuing wave impact completely cracked a number of the 8 inch thick 26 foot wide panels (Figure 15). Perforated plugs were finally placed over the weep holes in order to halt piping by retaining the gravel pack behind the wall. This particular wall cost $750,000 for 1000 lineal feet, or $750 per front foot. For a few more dollars caps could have been placed over the weep holes or filter cloth placed behind the entire wall. This wall is presently in litigation.

Beach Drive (Public)

Following destruction of a low concrete seawall along the public section of Beach Drive in 1978, a joint private, state, and county funded project was initiated to construct a new protective structure. In this location, the sewer line runs beneath the public road, so that both private and public property is being protected. This seawall was built in 1982 at a cost of about $750/foot (essentially the same as the private wall just down coast and the wall at Seacliff State Beach) and consists of steel H piles, 6 inch thick timber lagging and a slightly curved concrete cap (Figure 16). Although the wall was overtopped during the winters of 1983 and 1986, it survived with only minor damage for several reasons. The major problems with adjacent walls (Beach Drive private and Seacliff State Park), battering by logs, undermining and outflanking, and lack of drainage control, were for the most part mitigated by the design. The H piles constrained the lagging, the 6 inch thick lagging was able to withstand the log impact far better than the 2 to 3 inch lagging used elsewhere, and drainage, while suffering some problems, worked better than adjacent projects.

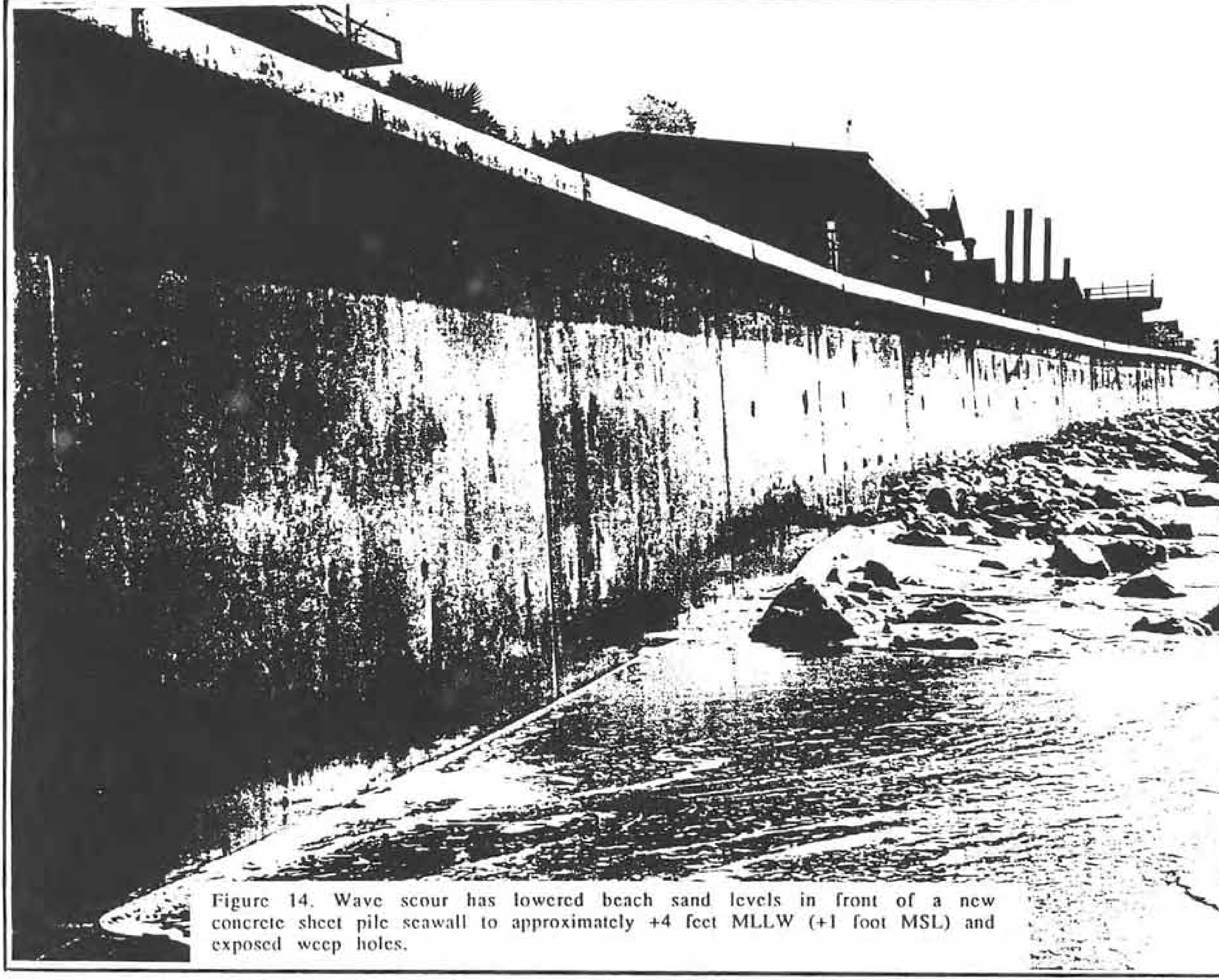

Figure 14. Wave scour has lowered beach sand levels in front of a new concrete sheet pile seawall to approximately +4 feet MLLW (+1 foot MSL) and exposed weep holes.

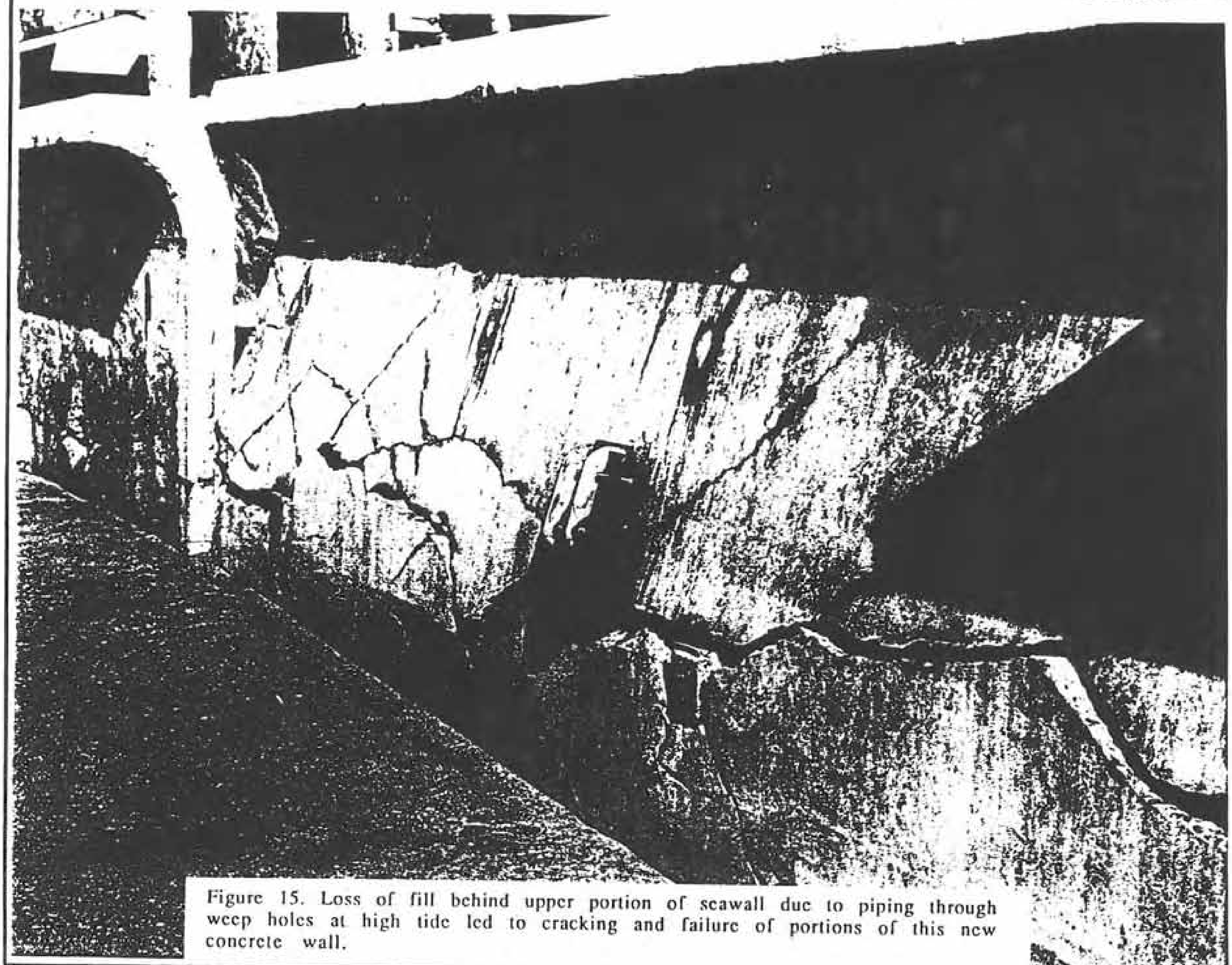

Figure 15. Loss of fill behind upper portion of seawall due to piping through weep holes at high tide led to cracking and failure of portions of this new concrete wall.

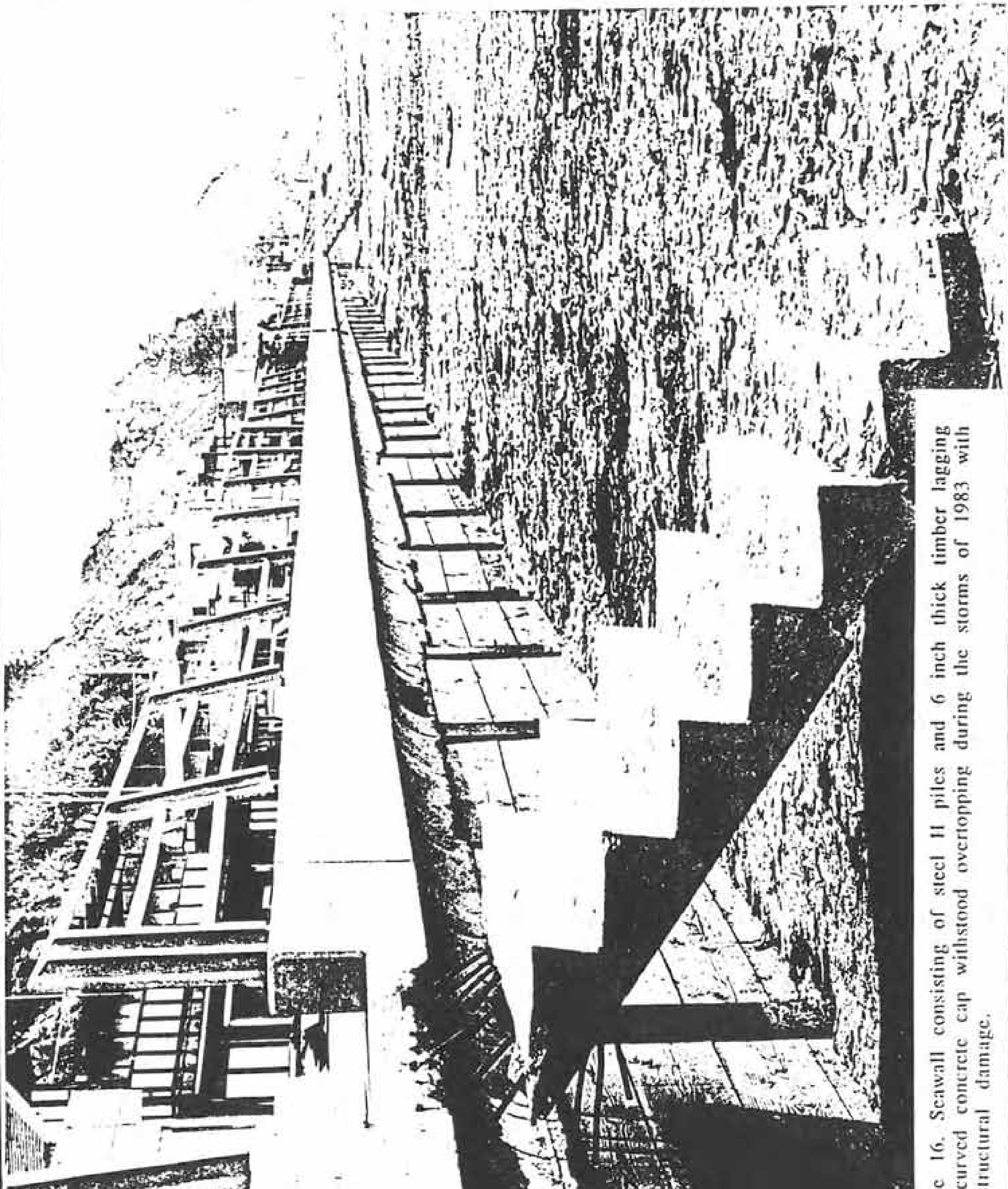

Figure 16. Seawall consisting of steel H piles and 6 inch thick timber lagging and curved concrete cap withstood overtopping during the storms of 1983 with no structural damage.

STOP 2. CAPITOLA

CAPITOLA BEACH

The beach at Capitola was considerably reduced in size following the construction of the Santa Cruz Harbor in 1963-65 (Figures 1 & 2). The changes are well documented in the aerial photographic history (Griggs and Johnson, 1975. The average beach width was reduced almost 90% from 56 m to about 6 m in the years immediately following harbor completion. As a result, the waves began to attack the parking lot and street adjacent to the pre-existing beach. Capitola is built in part on the flood plain of Soquel Creek and in part on old beach materials. To alleviate the wave inundation and loss of protection, as well as to provide a beach for the summer tourists on which the community depends, Capitola eventually contracted a firm (1970) to build a 75 m groin at the downcoast end of the beach and bring in about 2,000 truckloads of local quarry sand (Santa Margarita Formation). The cost of rebuilding the beach was $160,000, somewhat less than an earlier $420,000 plan proposed by the Corps of Engineers which involved two longer groins. Since that project, a moderately wide beach has continued to exist during the summer and fall months.

The obstruction of littoral drift by the west jetty of the Santa Cruz Harbor has been well documented as the primary cause of the loss of beach at Capitola (Griggs and Johnson, 1976). Immediately following harbor construction dredging was initiated (see next section on Harbor) such that some littoral sand again began to flow downcoast. The total volume of sand dredged, however, did not reach natural pre-harbor levels for years due to the charging of the west jetty which needed to take place. Nonetheless, with the groin and beach fill project, Capitola was able to return their beach to a satisfactory width.

This beach is in equilbrium with waves from the northwest which refract around Lighthouse Point into northern Monterey Bay and have lost considerable energy by the time they reach Capitola. The beach is completely exposed to waves from the west or southwest, however, and it is these storm waves which have on occasion eroded the beach and inundated the shoreline businesses and facilities. This happened in 1978 and again in 1983 with considerable downtown damage (Figure 3). Although a very low seawall has been in existence for years, once the beach has been removed, the wave runup is capable of overtopping the wall and inundating the adjacent streets and businesses.

Additional hazard concerns have arisen at Capitola Beach due to its high usage and the human modifications to the system. These include both the construction of the groin and yearly impoundment of Soquel Creek to form a protected swimming area. With the past ten years there have been at least two serious diving accidents (resulting in paralysis) which have led to major lawsuits against the city. The issue of public or local government liability for beach diving accidents has been partially reduced as of January 1988 as a result of new state legislation. There are still many active lawsuits filed before that time, or incidents which took place after that time in which unnatural

Figure 1. Capitola Beach in December 1961 prior to harbor construction at Santa Cruz.

Figure 2. Capitola Beach in November 1965 following construction of the harbor at Santa Cruz.

Figure 3. Logs and debris were washed over the low seawall into downtown Capitola during the storms and high tides of January 1983.

conditions are being cited as the reasons for the accident. This opens the door to public liability.

BLUFF EROSION AT DEPOT HILL

The 75 foot high bluffs immediately downcoast from Capitola Beach are among the most rapidly eroding cliffs in Santa Cruz County. The erosion of these bluffs has been an ongoing process since sea level reached nearly its present elevation hundreds of years ago. As development of the bluff top occurred over the past century the issue of bluff retreat has become a more important one to the residents of the area as well as to the city. A large number of homes as well as the Crest Apartments line the bluff top; in addition the city has streets, water mains and sewer lines near the edge of the sea cliff. All of these structures and utilities are threatened as the cliff continues to erode. Over the past 12 years, two homes on ocean front lots on Depot Hill have been moved to sites further inland as their foundations were threatened.

The Crest Apartments were built in 1964 on the westernmost edge of Depot Hill immediately above a sewer pumping station. This structure, which has a concrete and masonry seawall (built in about 1930) as its outer edge, has protected much of the apartment complex from marine erosion. The southernmost 85 feet, however, fronts directly on the unprotected seacliff east of the pumping station. In 1965, shortly after construction, the front edge of the easternmost apartments was only a few feet from the cliff edge. During the subsequent 24 years, the cliffs have continued to fail such that portions of the foundations of these three apartments are now partially suspended over the edge of the bluffs. (Figure 4). The original foundation engineer apparently realized that loss of support would be an issue at some future date and as a result designed a cantilevered foundation. Some remedial support work has been done in recent years with the construction of concrete caissons beneath the grade beams supporting these units. Due to the perceived hazard, however, four units have been declared unsafe to occupy by the city of Capitola.

Twelve years ago the owners of the apartment complex initiated a proposal to install a rock revetment and concrete plug along the base of the bluff in an attempt to halt or slow the erosion on the site. Actual construction never took place. Bluff failure has continued to take place to the present.

The bluff edge at Depot Hill constitutes the outer edge of the lowest marine terrace (about 85,000 years old). This outer edge has been extensively developed from Natural Bridges State Park west of Santa Cruz, well into the middle of Monterey Bay. Due to differential uplift, the terrace surface has been tilted alongshore such that it is 75 feet high at Capitola, and nearly at sea level only a few miles upcoast (Moran Lake-Stop No. 3).

The bedrock beneath Depot Hill consists of Pliocene Purisima Formation, thickly bedded sandstones, siltstones, and mudstones that are poorly to moderately indurated. Occasional interbeds or lenses of marine molluscs form characteristic layers in the cliffs which are easily recognized. The Purisima is nearly flat lying but the rocks are warped slightly and have also been offset in places by faulting. None of the faults exposed in the seacliffs, however, break the terrace surface.

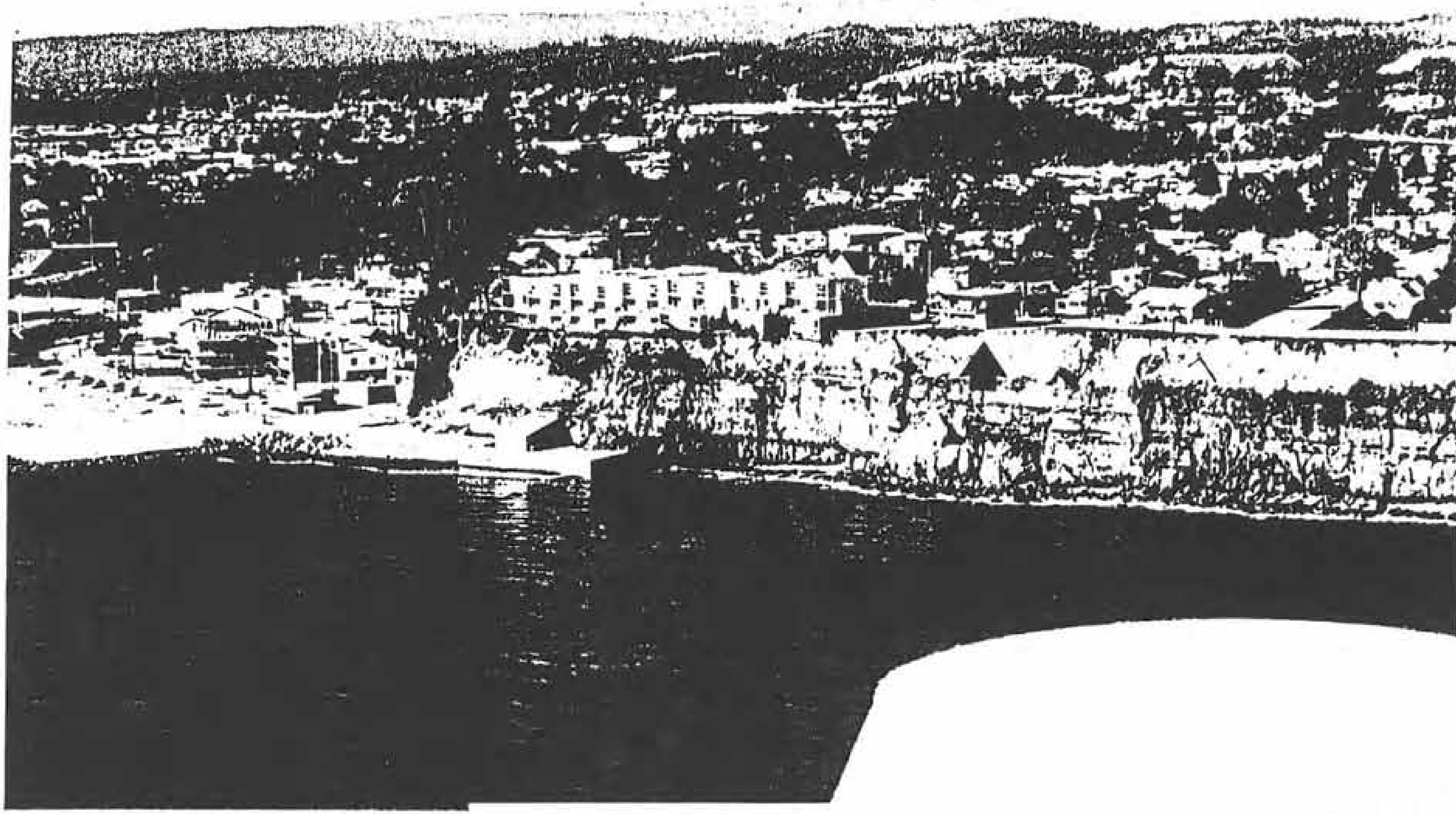

Figure 4. The foundation for the Crest Apartments on Depot Hill in Capitola has been undermined by failure in the underlying Purisima Formation and terrace deposits.

Long term (60 years of stereo aerial photo coverage exists for this site) measurements of cliff retreat along Depot Hill ranges from about 0.7 to 2.5 feet/year, with higher rates occurring downcoast.

There are four particular aspects of this stetch of bluffs which are important in producing these rapid rates of erosion:

1] The shoreline orientation is NE-SW, nearly at right angles to the dominant waves such that littoral drift is rapid and no permanent beach forms. Thus the bluffs are typically exposed to wave action almost year around.
2] The stratigraphy of the Purisima is such that weak erodible interbeds are exposed in the surf zone at the base of the bluffs along Depot Hill. The result is typically an undercut notch at beach level.
3] The Purisima is extensively jointed. There are three general master joints sets which control the stability of the Purisima at this location. The most critical is shore parallel and dips about 75 to 80 degrees seaward. Joint spacing varies from several inches to several feet, and failure along these joints forms much of the exposed cliff face. The other dominant joint sets are typically at right angles to the cliff face and often dip about 60 degrees to either direction.
4] Ground water moving seaward along the marine terrace surface (at the base of the terrace deposits) appears to be important in weakening the contacts between joint bounded blocks and increasing pore pressures producing block or wedge failure.

The typical failure mode is through marine erosion of the weak units exposed at the base of the cliff. When the sand levels drop and expose this notch, support is partially lost for the overlying joint bounded blocks which then topple to the beach (Figure 5). As recently as the summer of 1987, large blocks 6 to 9 feet in width and up to 20 feet in alongshore length, toppled to the beach below. This same type of failure extends all the way to New Brighton Beach where the shoreline orientation changes and a wide stable beach appears.

Although numerous shoreline protection schemes have been proposed for this particular stretch of coast (including artificial seaweed), as of yet no project has been approved or initiated. Grand Avenue at the top of the bluff has been closed, two houses have been moved, and 4 apartments have been declared unsafe to occupy. The owners of the apartment complex have been working with geologists, geotechnical firms, engineers and contractors for over two years to develop some system to protect their investment. There are numerous difficulties to resolve, including:

1] The lack of a protective beach
2] The magnitude and nature of the typical cliff failure which makes working conditions very hazardous and difficult
3] Erosion and cliff failure is taking place through both marine and terrestrial processes; even if marine erosion is temporarily halted at the base of the cliff, the failure of the overlying terrace deposits is still a major concern
4] Completely protecting a 75 foot high bluff requires some expensive engineering and construction, probably working from the top down in order to reduce the hazard to workers.

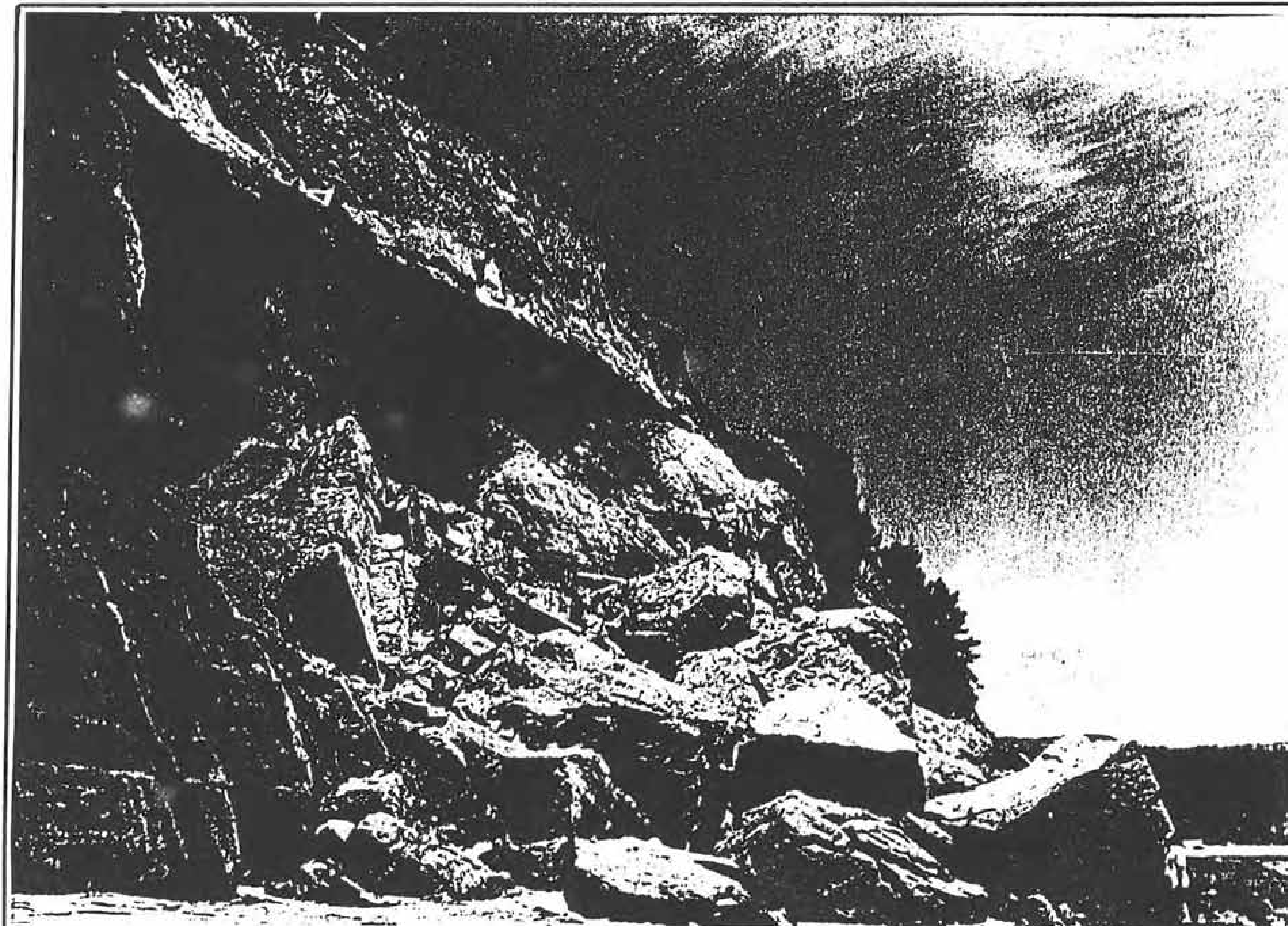

Figure 5. Large blocks of sandstone, siltstone, and mudstone commonly break loose from the bluffs at Capitola along intersecting joint sets and fall to the beach below.

5] The City of Capitola and Coastal Commission are against top to bottom cliff protection.

STOP 3. MORAN LAKE-EAST CLIFF AREA

MARINE TERRACE UPLIFT AND IMPACT OF CLIFF HEIGHT AND COMPOSITION ON SHORELINE EROSION AND PROTECTION

The shoreline in the vicinity of Corcoran Lagoon and Moran Lake consists of a 20 to 25 foot high near-vertical cliff eroded into the seaward edge of the first marine terrace. As stated earlier, uplift has been uneven such that the terrace has been warped alongshore (Figure 1). The bluffs for perhaps a kilometer alongshore at this location consist of a bedrock surface which is at or slightly above sea level. The bedrock is Purisima Formation which is capped by up to 25 feet of poorly consolidated terrace deposits. Because the terrace deposits offer little resistance to erosion, the bluffs in this area prior to the emplacement of coastal protection structures were eroding at a rapid rate (Figures 2 & 3; Griggs and Johnson, 1979).

Natural annual erosion along this stretch of coast averaged about 1 to 2 feet per year prior to rip-rap emplacement. Construction of the harbor about a mile upcoast in 1963-65 led to temporary beach loss followed by the initial rip-rap emplacement. Rip-rap is the most widely used protection method along East Cliff Drive.
Rip-rap or rip-rap revetments (which typically consist of a layered sequence of filter cloth, smaller core stone, and large armor or cap stone; Figure 4) have been credited with a number of advantages (Fulton-Bennett and Griggs, 1985):

1] They usually cost less to install than to concrete structures
2] Their flexibility allows themn to settle without massive or rapid structural failure
3] They do not require special drainage systems
4] They are easily maintained and modified
5] They are resistant to damage by debris
6] They tend to absorb and dissipate wave energy instead of reflecting it
7]They allow less runup and overtopping than do vertical wood or concrete walls.

The Army Corps of Engineers (1956, 1982) have repeatedly shown properly installed rip-rap to be one of the more cost-effective types of protection for individual homeowners. Their 1975 investigation of protection along the Great Lakes revealed the following typical causes of failure of rip-rap:

1] scour at the toe
2] outflanking
3] undersized rock
4] inadequate height
5] improper placement

Settlement typically presents the biggest problem for rip-rap walls founded on sand. Most recent projects have attempted to determine a maximum scour depth based on storm erosion data and/or subsurface information and placed the base of the wall accordingly. In addition, very large rocks (4-8 tons) are now often placed at the toe of the wall in a keyway trench and used as a buttress. In many locations rock has been stacked too steeply (at 35 degrees, 1.5:1 or steeper, horizontal to vertical), leading to toppling or plucking of the rocks by

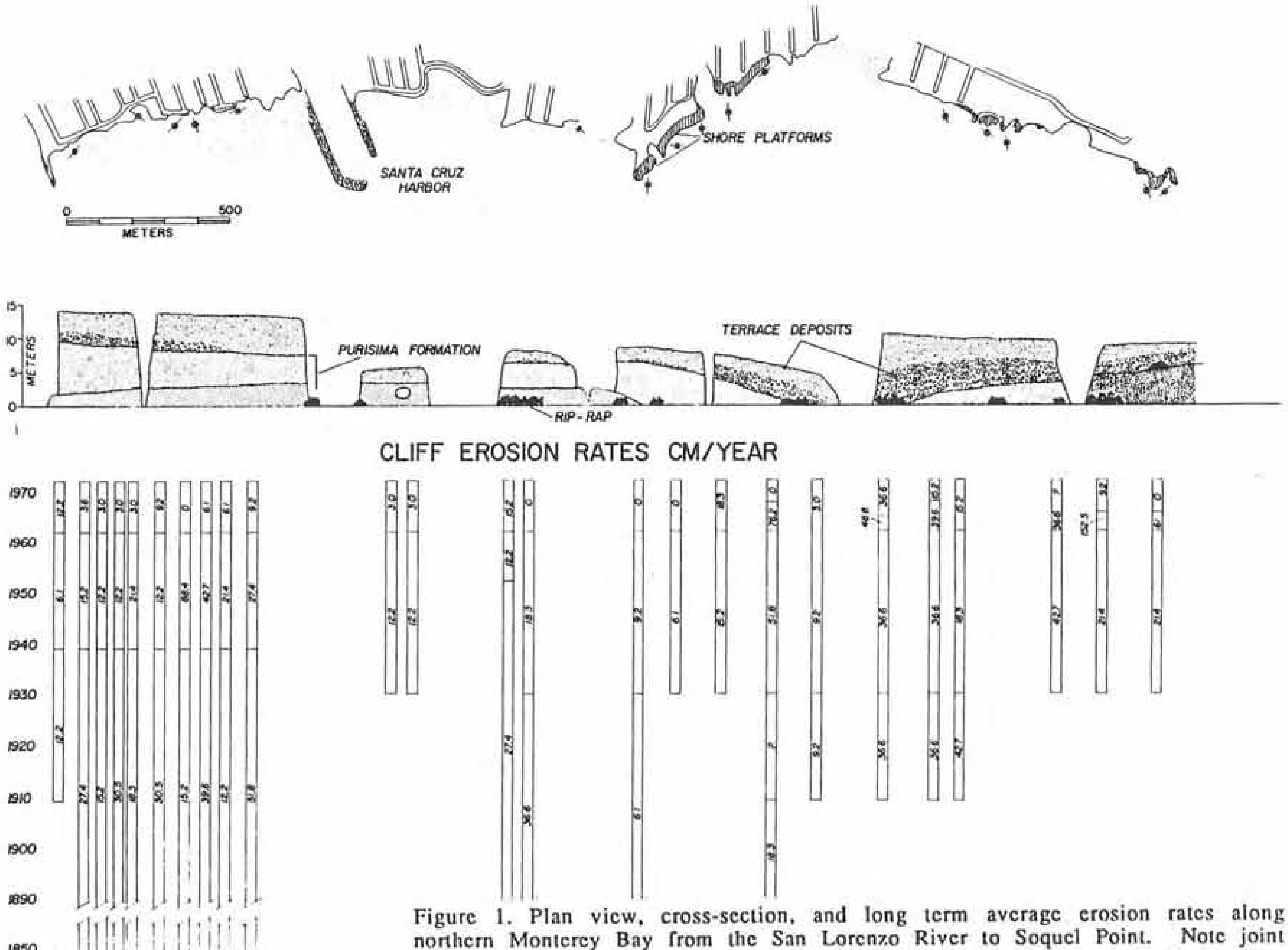

Figure 1. Plan view, cross-section, and long term average erosion rates along northern Monterey Bay from the San Lorenzo River to Soquel Point. Note joint orientation, variations in elevation of marine terrace bedrock surface alongshore, and variations in cliff erosion rates.

Figure 2. Rapid seacliff retreat at the end of 26th Avenue in the East Cliff area of Santa Cruz. The lack of bedrock exposed in the seacliff result in little resistance to wave erosion.

Figure 3. The remains of a house at Moran Lake on East Cliff Drive which was destroyed in January 1983. The concrete slab was undermined by beach scour, the slab tilted seaward and the house slid off into the waves at high tide.

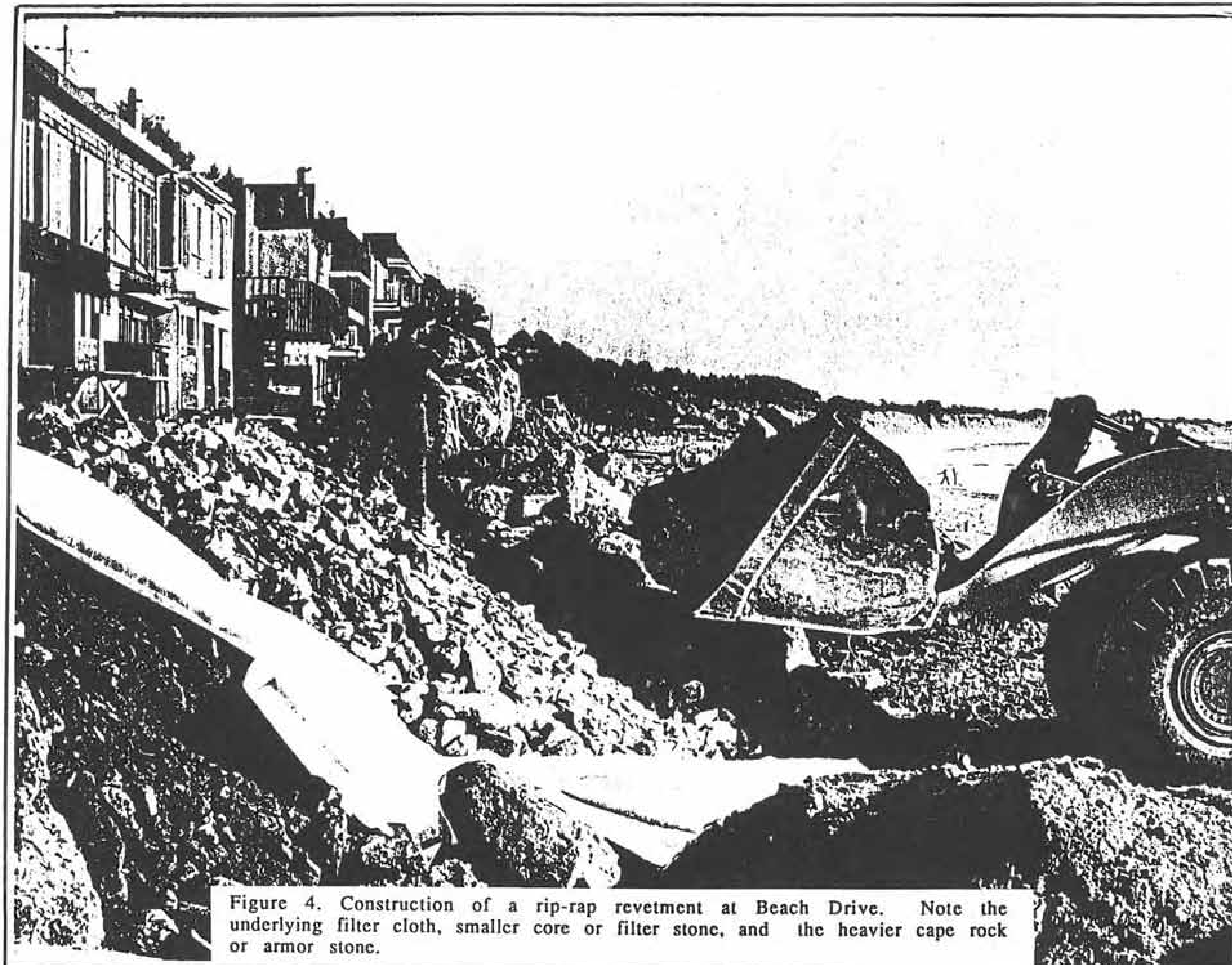

Figure 4. Construction of a rip-rap revetment at Beach Drive. Note the underlying filter cloth, smaller core or filter stone, and the heavier cape rock or armor stone.

wave action. Typically, over time, rip-rap revetments must be rebuilt with additional rock as the original rock settles and moves seaward. One site at Corcoran Lagoon, just upcoast from Moran Lake, has required 13 installations of rock and rubble over a 30 year period, at a cost of $185,000 (Figure 5). There is a deep sand beach at this site and the rock continues to move downward and seaward. Other engineered revetments, in contrast have fared far better. A revetment at Waddell Bluffs protecting State Highway 1 at the Santa Cruz-San Mateo County line was placed on an intertidal bedrock platform and remains in good conditions after 35 years. The key at this location was the bedrock foundation of Santa Cruz Mudstone which supports the revetment.

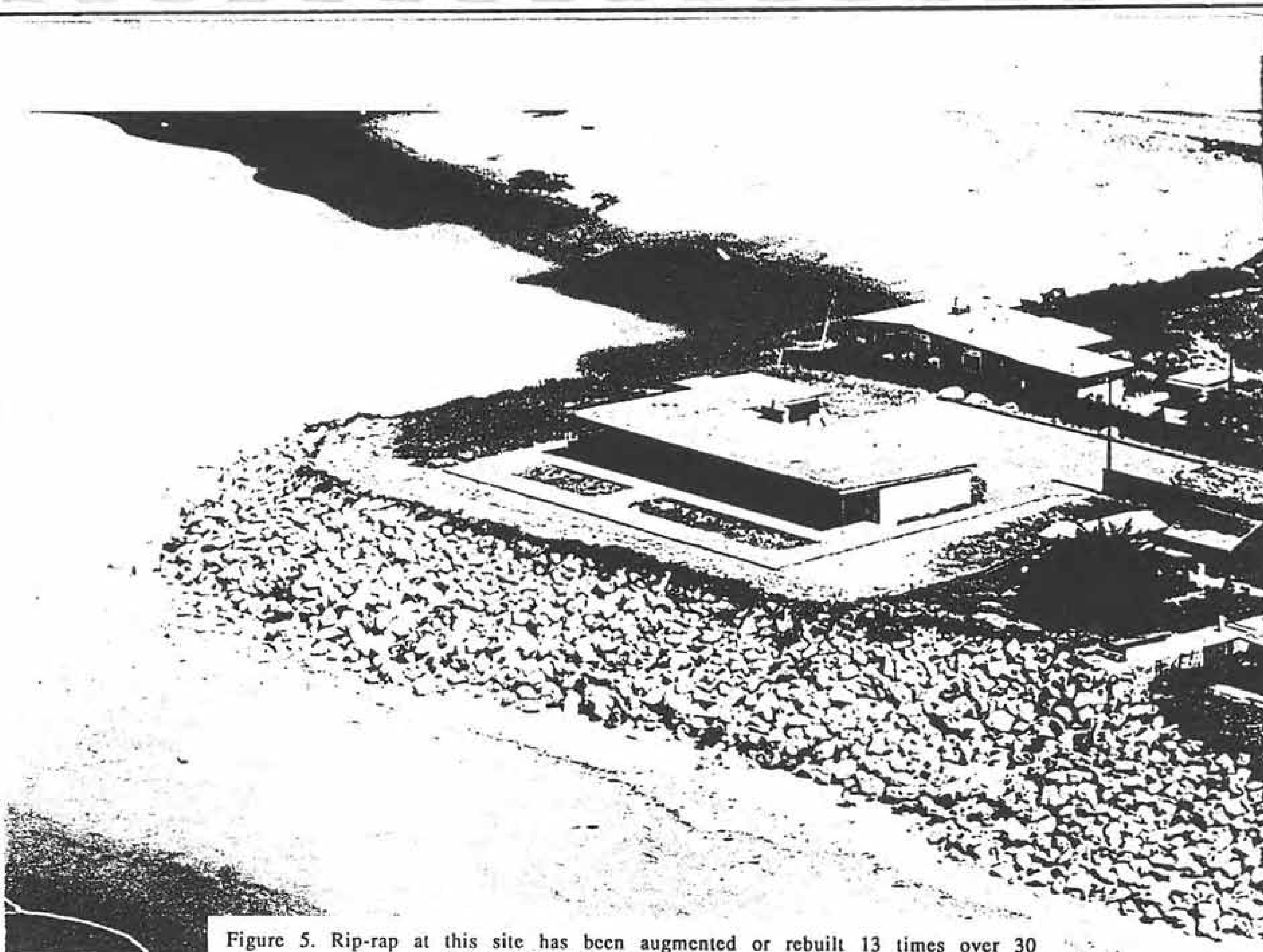

Figure 5. Rip-rap at this site has been augmented or rebuilt 13 times over 30 years at a total cost of $185,000. The deep sand beach beneath the site has led to settling and seaward movement of the rock at depth.

STOP 4. SANTA CRUZ HARBOR

LITTORAL CELLS AND HARBOR DREDGING ALONG THE CALIFORNIA COAST

The movement of sand along the coastline under the influence of waves has been observed for many years. In addition, the impacts and costs of tampering with or obstructing the littoral drift process have been painfully obvious for over half a century. Construction of the Santa Barbara small craft harbor (initiated in 1927) and the consequent interruption of littoral drift was perhaps one of the first well-studied examples along the California coast and still stands as a monument of sorts. Many of the immediate effects of breakwater construction at Santa Barbara, including upcoast accretion, costly annual dredging, and increased downcoast erosion have been well documented at other California artificial harbor locations as well (for example, Norris, 1964; Griggs and Johnson, 1976; Adams, 1976; LaJoie and others, 1979). Annual dredging costs at some southern California harbors now exceed $1 million. On the other hand, there are other breakwaters and harbors which have very little impact on the coastline and where no littoral drift obstruction and, therefore, dredging problems, have arisen (Griggs, 1987).

The concept of littoral cells or beach compartments is now recognized as a key element in the littoral drift system, but was not well understood at the time many California harbors were built. Littoral drift has normally been seen as a factor which had to be dealt with after harbors were constructed rather than as an environmental variable which would preclude building harbors at particular sites. At some locations, littoral drift rates were seriously underestimated or inadequately understood prior to harbor construction. At the Ventura Marina, for example, which became operational in 1963, the port district anticipated that littoral drift would accumulate against the north jetty and could be bypassed every two or three years (Adams, 1976). Annual dredging at an average rate of 187,000 cubic yards had to be initiated, however, soon after construction. Since 1978, average annual dredging has amounted to 575,000 cubic yards/year, with 1983 costs alone reaching $1,425,000.

LITTORAL CELLS/BEACH COMPARTMENTS

Inman and Frautschy (1966) were the first to recognize the existence of littoral cells or beach compartments. These cells can be considered as distinct segments of the coastline and include three elements: (1) a source or sources of littoral sediment, (2) littoral transport or longshore drift, and (3) a sink or depositional site for the sediment (Figure 1).

Along the California coast, input from coastal streams and rivers is the dominant source of sediment, although cliff or bluff erosion, dredging or harbors, marinas, and embayments, and offshore sands of the inner shelf can be locally important as well. Littoral drift is predominantly from north to south or west to east along most of California's coast because of the dominant wave approach from the northwest.

The sand can be lost from the system through downslope transport into submarine canyons, through transport by wind onshore into dunes, and direct

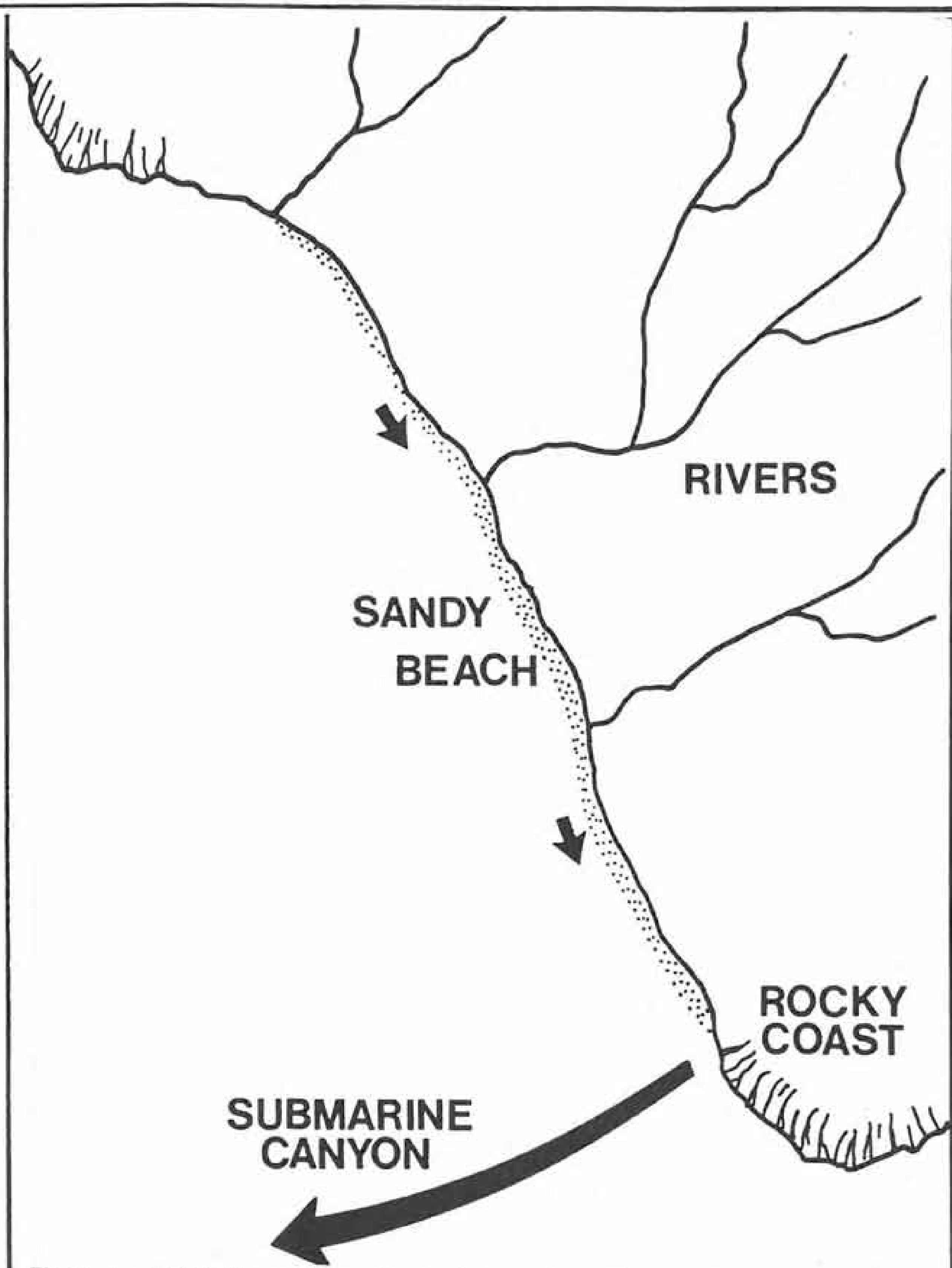

Figure 1. Typical littoral cell with sand input from rivers moved downcoast by littoral drift. Beach sand may ultimately be lost offshore into a submarine canyon or onshore into a dune field, leaving a rocky headland.

removal of sand through mining. Measurements in Scripps Submarine Canyon near La Jolla, for example, indicate that as much as 150,000 cubic meters of sand each year, enough to form a beach 50 m wide, 2 m deep, and 1500 m long, moves down the canyon. Similarly sand mining in southern Monterey Bay has removed an estimated 300,000 to 450,000 cubic yards of sand annually for decades from the littoral system.

The sediment traps which California's harbors have created and the annual volumes of sand dreged can give us important data regarding littoral drift and littoral cell boundary locations. Additionally, planning and engineering efforts for any new small craft harbor locations must start by considering the littoral drift system within which they must operate. We are well past the point of either approximating littoral drift rates or dealing with the issue after harbor construction is completed.

THE SANTA CRUZ SMALL CRAFT HARBOR

For a number of years local interests in Santa Cruz desired a protected small-boat harbor to serve the needs of the existing fishing fleet and prospective recreational craft on a year-round basis. The Army Corps of Engineers in 1958 suggested that Woods Lagoon, a drowned river mouth about a kilometer east of the mouth of the San Lorenzo River, be improved northward to form the harbor, and that parallel rubble mound jetties be provided to protect the entrance channel.

The was initial concern with an existing downcoast bluff erosion problem due to potential for the proposed jetties to trap littoral drift and produce downcoast beach loss, thereby accelerating erosion. Based on a short term groin study and observations elsewhere in Monterey Bay, the Corps estimated that average littoral drift in the vicinity of the proposed harbor ranged from 25,000 to 300,000 cubic yards annually. If the drift approached the larger values, the Corps concluded that the jetties would trap the sand, thereby benefitting the upcoast beaches, but that this would cause downcoast beach loss and acceleration of ongoing bluff erosion. The potential problems could be offset by providing a means of annually bypassing 300,000 cubic yards of sand. Due to the uncertainties in littoral drift rates, the decision was made to wait and see what happened prior to developing a sand bypass or dredging system.

With an understanding of littoral cells along the central coast clearly in mind, it is obvious in retrospect that the jetties built at the harbor entrance were going to have a significant impact on coastal processes (Griggs and Johnson, 1976). The harbor was to be built at the downcoast end of a long littoral cell (probably extending to the entrance to San Francisco Bay) with a very large littoral drift rate (Figure 2). As we might predict with hindsight today, the jetties had a major impact on coastal processes and the beaches both upcoast and downcoast (Figures 3 & 4). These impacts included the following:

(1) During the first two winters following harbor completion, 600,000 cubic yards of sand accumulated against the west jetty. In addition to continued accumulation in subsequent years, the sand began to move out around the west jetty and into the harbor entrance channel. It took perhaps 10 or 15 years until the upcoast beach was fully charged and all of the upcoast littoral drift began to move around the jetty. A formerly narrow upcoast beach backing an

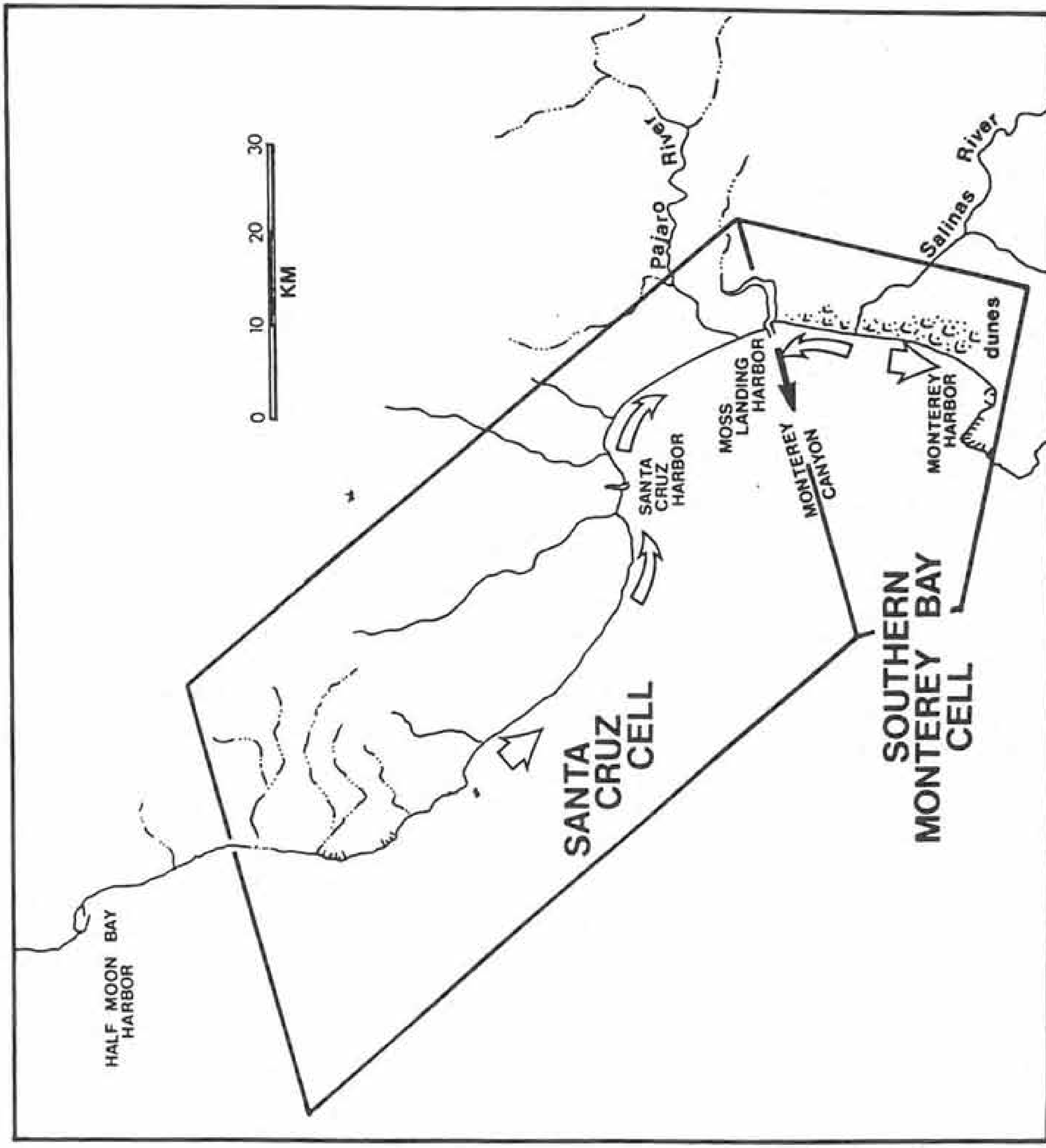

Figure 2. Monterey Bay showing the Santa Cruz and Southern Monterey Bay Littoral Cell boundaries and harbor locations. Recent work has extended the upcoast boundary of the Santa Cruz Cell to the entrance of San Francisco Bay.

Figure 3. The coastline between San Lorenzo Point and Black Point in December 1961 prior to harbor construction.

eroding seacliff was modified to a permanent beach over 300 feet wide which offered year around protection to the bluffs (Figures 4 & 5).

(2) Dredging of the entrance channel began the year the harbor was completed (1965) and has been carried out yearly ever since. Initially the volumes of sediment dredged from the entrance channel were only a small portion of the annual littoral drift rate; as the upcoast jetty was fully charged, however, these volumes increased to their present 200,000 cubic yards (Figure 6). Average annual costs now amount to about $500,000 to move sand from one side of the harbor to the other.

(3) The downcoast beaches began to thin as the west jetty began to trap sand. This trend continued all the way to Capitola (Figure 5). Ultimately dredging began to return this sand to the system, although on an irregular basis. Most of the blufftop property owners between the harbor and Capitola have now put in rip-rap for protection as a result of the continuing erosion.

Although over a dozen approches have been suggested for dealing with this sand bypassing/dredging problem, there is really no permanent solution. The price of interrupting littoral drift is to move it artificially at considerable cost and inconvenience.

Figure 4. Coastline between San Lorenzo Point and Black Point in May 1965 following harbor completion.

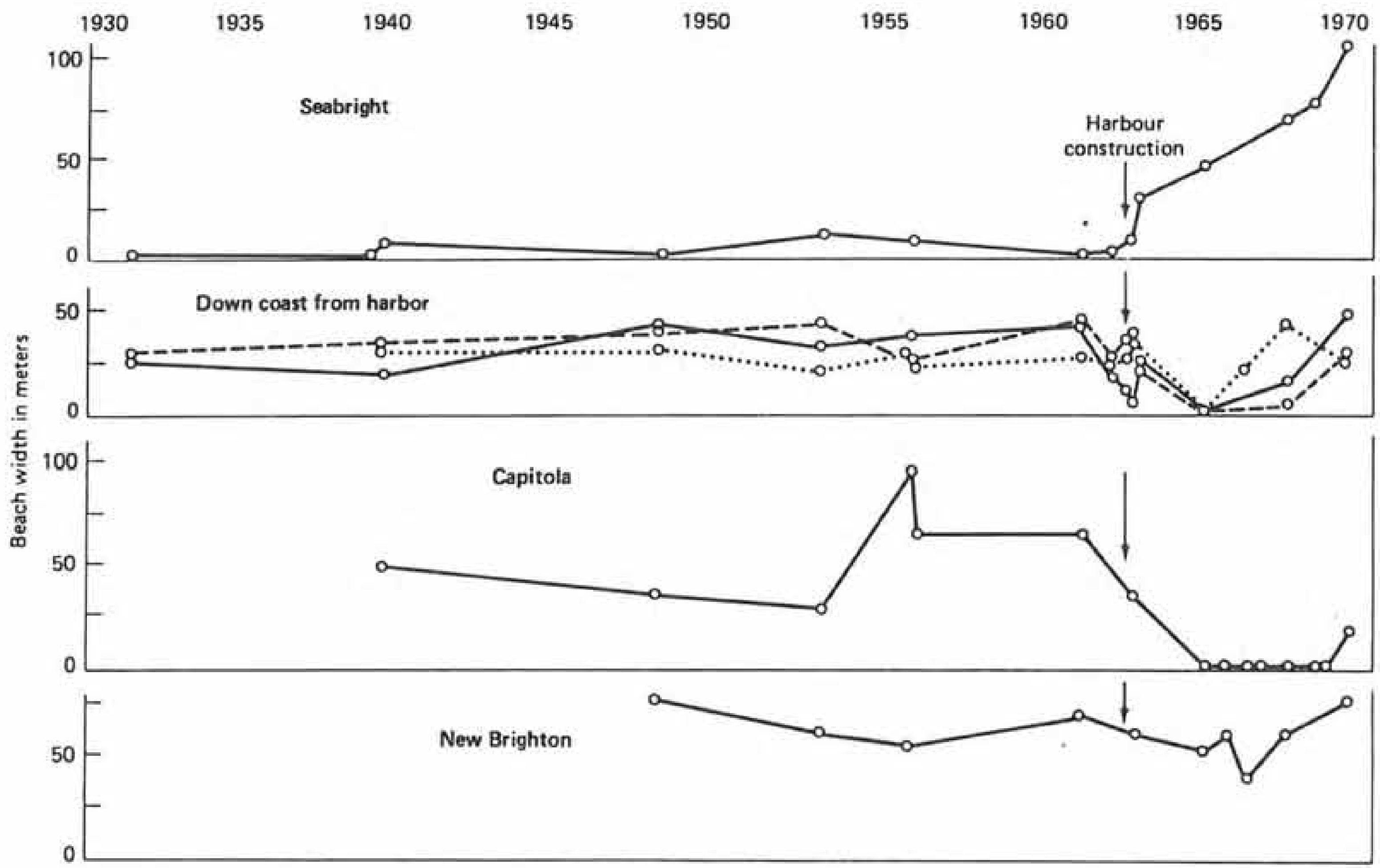

Figure 5. Changes in beach width upcoast and downcoast from the Santa Cruz Harbor following harbor construction.

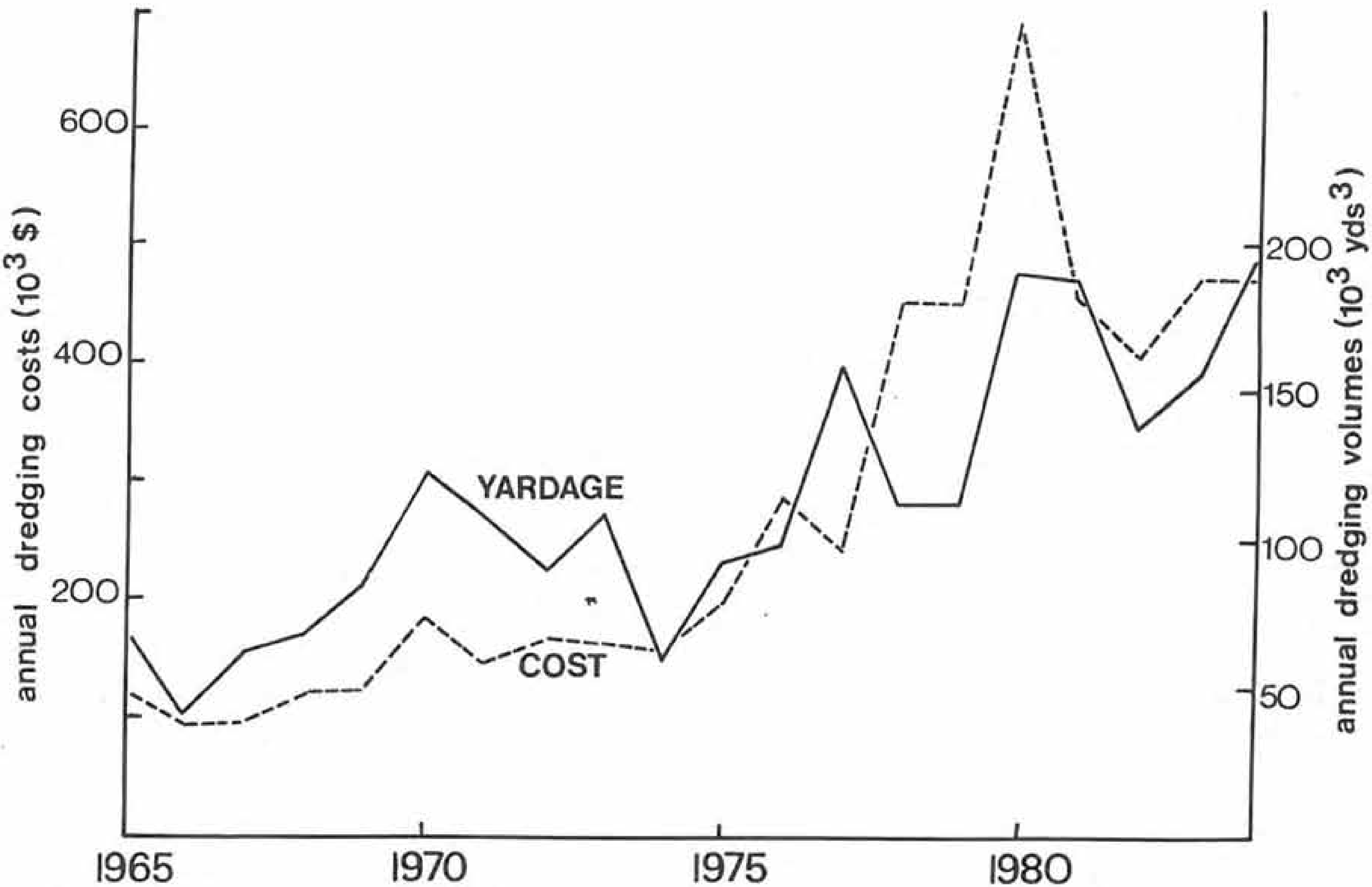

Figure 6. Dredging history for the Santa Cruz Harbor.

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AFTERNOON SECTION

COASTAL TECTONICS

SANTA CRUZ/SAN MATEO COUNTY COASTLINES

PLEISTOCENE MARINE TERRACES AND NEOTECTONICS OF THE SAN GREGORIO FAULT ZONE IN SANTA CRUZ & SAN MATEO COUNTIES, CALIFORNIA

FIELD TRIP GUIDE

by

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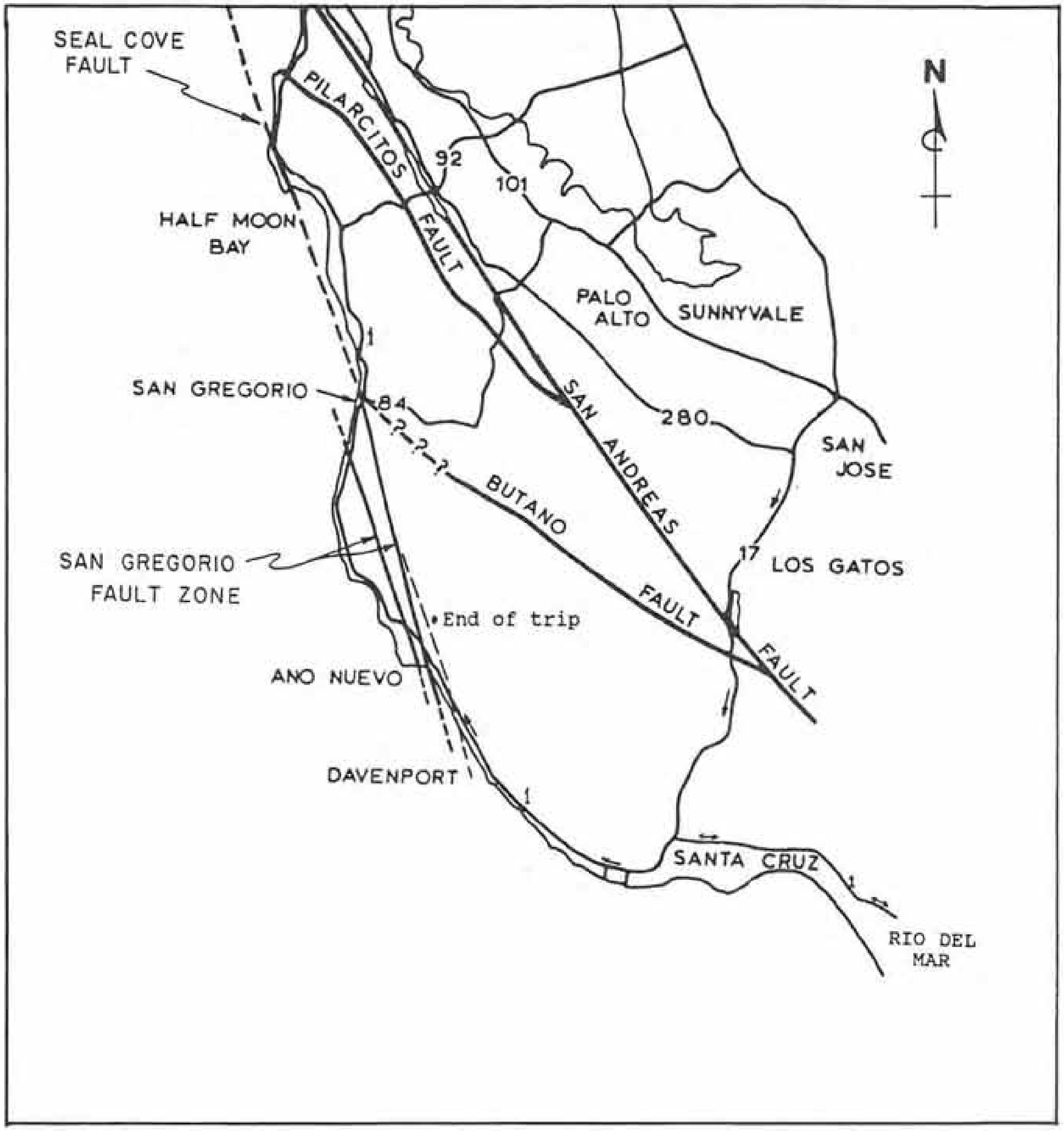
Association of Engineering Geologists
San Francisco Section

March 3, 1990

INDEX MAP OF FIELD TRIP AREA



PLEISTOCENE MARINE TERRACES AND NEOTECTONICS OF THE SAN GREGORIO FAULT ZONE

Gerald E. Weber
Weber and Associates
&
Earth Sciences Board
U.C.S.C.

The second half of this field trip emphasizes Quaternary marine terraces, the tectonics of the San Gregorio fault zone, and coastal erosion north of Monterey Bay. The marine terrace sequence on Ben Lomond has long been recognized as an exceptionally well preserved and exposed sequence. Beginning with Rode (1930), many geologists have studied this sequence of terraces, largely because of the lack of deformation and excellent preservation. Studies of marine terraces have increased in both number and detail during the past 40 years, as techniques for more acurate age dating, and more detailed records of sea level fluctuations have become available. In this area Bradley (1957, 1958) Bradley and Griggs (1976), Hanks and others (1984), Lajoie (1986) and Weber (unpublished b.s. in his field notebook) have all attempted to interpret the Quaternary history of the area from these terraces.

This field trip guidebook has borrowed heavilly from the Weber, Lajoie and Griggs (1979) G.S.A. Field Trip Guidebook. Most of the material has been updated and reinterpreted, as the age dating of marine terraces has improved greatly in the intervening 10 years, as have numerous other aspects of Quaternary studies. Much of my interest as well as guidance in the the study of marine terraces over the past 20 years has come about from my association with Ken Lajoie. I have also benefited from numerous discussions with a number of persons including Gary Griggs, Bill Bradley, Bud Burke, Bill Lettis, Bert Swan, Tim Hall, Bill Cotton, Sandy Hay, Braueri Beck, and others. Any errors, misinterpretations, or pseudo scientific delusions present in this guidebook, however, are entirely my responsibility.

MARINE TERRACE STRATIGRAPHY BEN LOMOND MOUNTAIN

Highway 1, north and west of Santa Cruz, is on the first of 5 prominent marine terraces (Bradley and Griggs, 1976) cut into the southwestern flank of Ben Lomond Mountain. The modern seacliff, the first emergent terrace and also most of the upper terraces from Santa Cruz north to Point Ano Nuevo are cut into a single rock type, the Santa Cruz Mudstone, a hard, blocky fracturing, siliceous mudstone of Delmontian age (late Miocene). Marine terraces are essentially undeformed from Santa Cruz north to Point Ano Nuevo except for minor warping, tilting, and fault offset near Greyhound Rock. Some of the marine terraces are not present along the entire coast from Santa Cruz to Point Ano Nuevo. The Wilder terrace and the Cement terrace of Bradley and Griggs, (1976), for example, are present along only a portion of the coastline (refer to Figure 1 , and Plate 1). These terraces were obviously destroyed by wave erosion during a subsequent highstand of sea level.

First Emergent Marine Terrace (Santa Cruz Terrace)

West Santa Cruz is built on the first emergent marine terrace, the Santa Cruz terrace of Bradley and Griggs (1976). The terrace consists of a single broad topographic bench, that slopes gently toward the ocean. As indicated in Figure 2, the single topographic bench (terrace landform) is underlain by two wave-cut platforms (wcp), the youngest and lowest Davenport platform and the older and higher Highway 1 platform. Each of these wave-cut platforms was probably formed during a post Sangamon and pre-Wisconsinian high-stand of sea level.

Tentative correlation of platforms to highstands of sea-level:

Sea-level Highstand	Wave-cut platform
105,000 yrs B.P.	Highway 1
84,000 yrs B.P.	Davenport

Correlations are based on faunal assemlages, amino acid racemization studies, U-series age dates, and the assumption of constant rate of uplift for the late Pleistocene and Holocene (modified from Lajoie, 1986; Weber and Lajoie, 1979, Bradley and Griggs, 1976). If uplift rates are constant, and the Davenport and Highway 1 platforms are 84 ka and 105 ka respectively, then the 125 ka platform is represented by the Cement terrace of Bradley and Griggs (1976). This narrow bench is preserved in one small area north of Davenport (Plate 1, Figure 1). **(ka = 1000 years)**

Age Determination - Santa Cruz Terrace

As indicated elsewhere (Weber, this guidebook), ages of most terraces can only be approximated. Absolute ages can often be determined for one or perhaps two terraces in a sequence, but only in exceptional circumstances can an entire flight of terraces be radiometrically dated. However, terrace ages can be estimated if a radiometric age is available for one terrace,

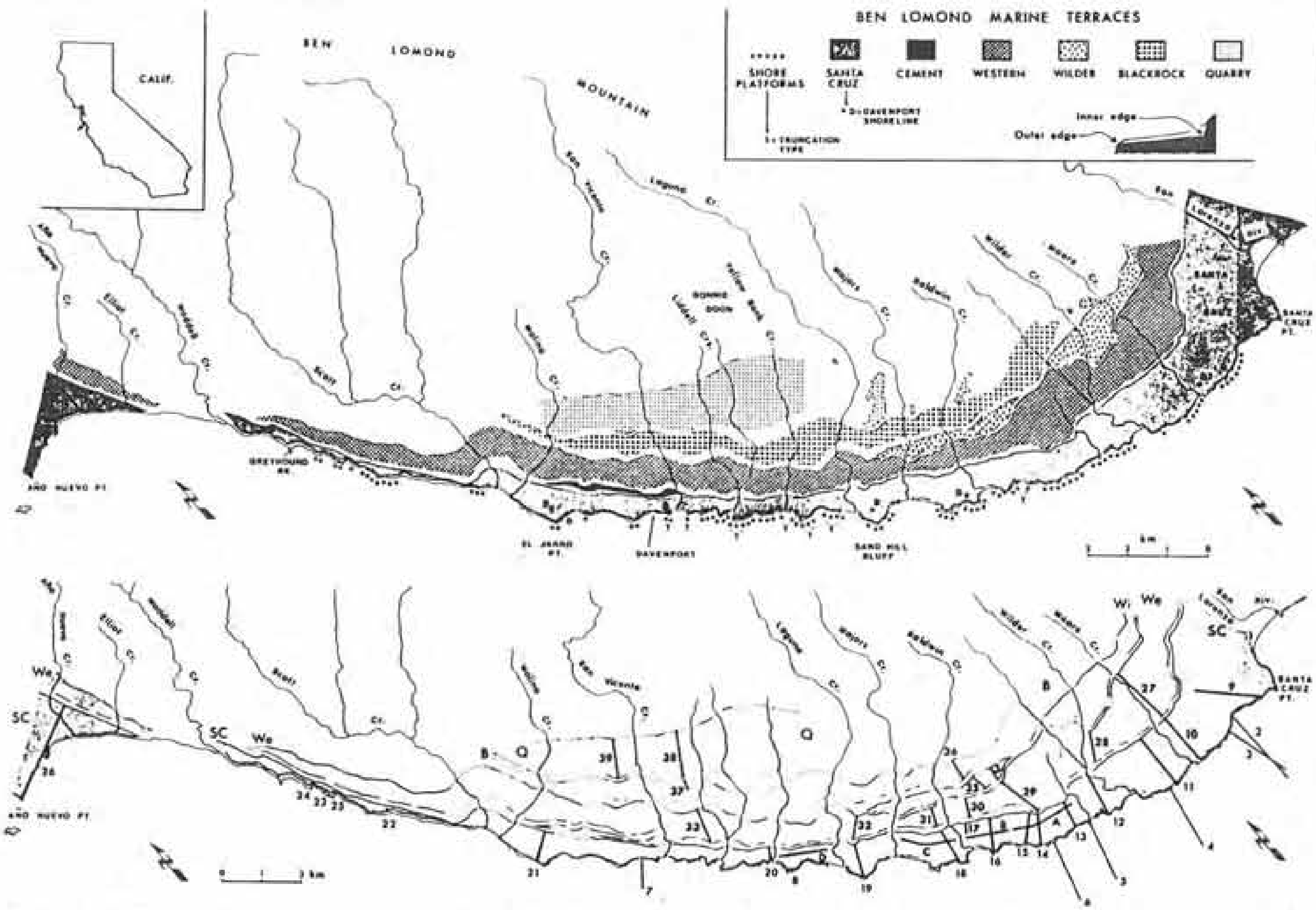


Figure 1. Top: Wave-cut platforms (within marine terraces) on Ben Lomond Mountain, central California; inner and outer edges are dotted where dissected. Names are correlated with previous terminologies in Table 1. Outliers of Quarry and Blackrock terrace deposits are taken from Clark (1966, 1970). Three Santa Cruz platforms are lumped together, although Davenport shoreline (D) is shown where it has been identified. Bottom: Locations of platform profiles (except profile 1, which is located off mouth of Santa Cruz Harbor, 2.5 km northeast of Santa Cruz Point). Profile data are summarized in Table 2.

FIGURE 1. Figure from Bradley and Griggs, 1976.

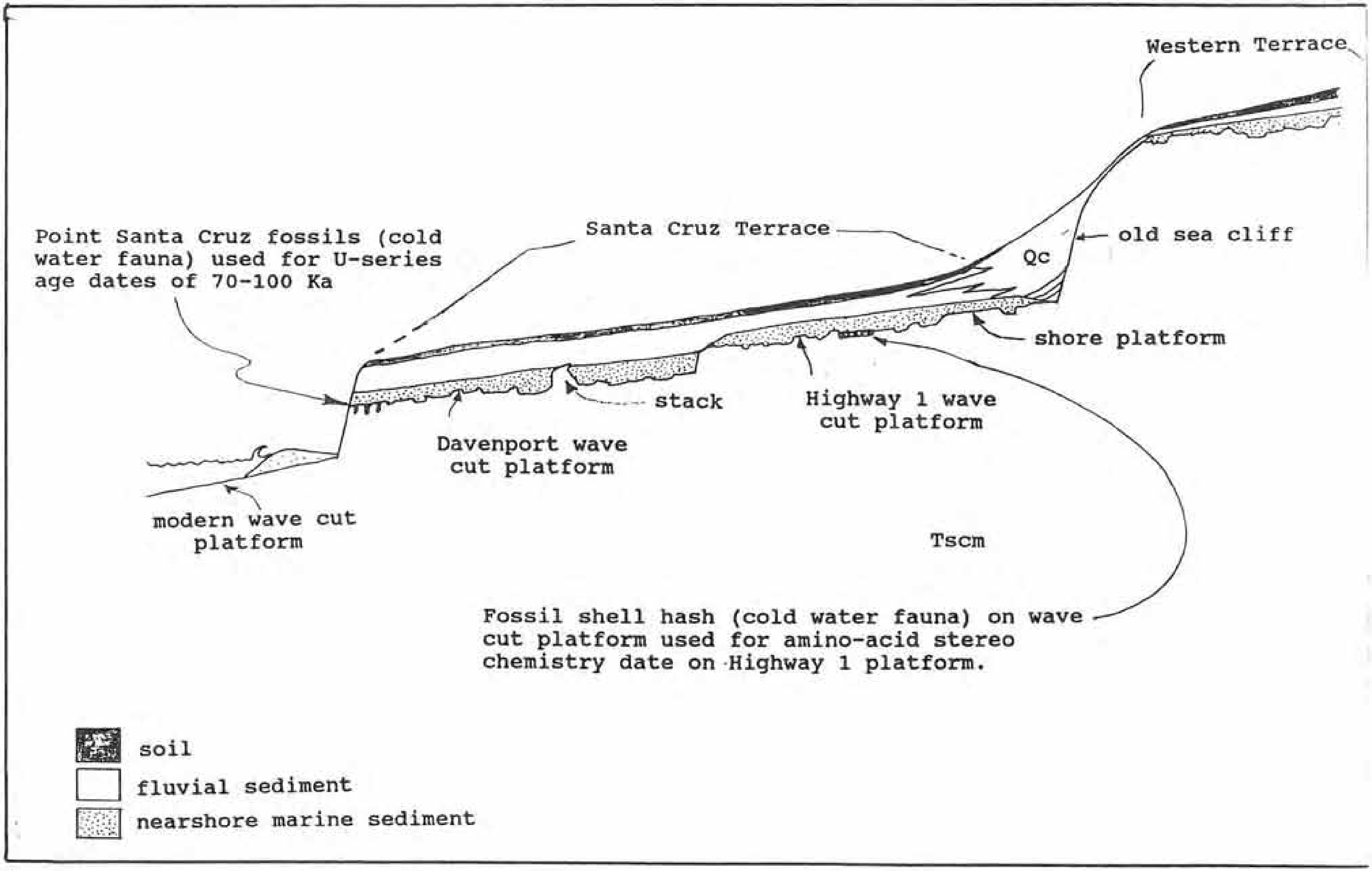


FIGURE 2. Diagrammatic cross section of the Santa Cruz marine terrace om west Santa Cruz. Shows relative positions of the Davenport and Highway 1 wave cut platforms.

constant uplift is assumed, and terrace platforms were cut during rising sea-level culminating with a sea-level highstand. Within the Santa Cruz - Ben Lomond Mountain terrace sequence the ages of the Davenport platform and the Highway 1 platform are known with reasonable certainty.

Bradley and Addicott (1968) reported U series ages of 76,000 + 800 years and 95,500 + 700 years for fossil mollusks taken from the Davenport platform near Point Santa Cruz. Kennedy and others (1982) estimated the age of the Davenport platform using amino acid racemization data for the fossil mollusks and the cold water aspect of the fauna as 84 ka or 105 ka.

Fossil mollusks collected in 1983 by G. E. Weber from a hand auger boring on the Santa Cruz terrace in west Santa Cruz came from a higher platform within the terrace - the Highway 1 platform. The fauna from the Highway 1 platform also displayed a cold water aspect. This in combination with the platform's higher topographic position and different amino acid racemization ratios than the Point Santa Cruz (Davenport platform) fauna indicated a tentative age of 105 ka B.P. (Kenneth R. Lajoie, personal communication) for the Highway 1 platform. To summarize:

1) Both of the molluscan faunas; **a)** the Point Santa Cruz fauna from the Davenport platform; and **b)** the hand auger boring fauna from the Highway 1 platform, are **"cold-water faunas"**.

2) The amino acid racemization ratios are different between the faunas, with the Davenport platform younger.

3) The uranium series dates on mollusks from the Davenport platform indicate an age of 76,000 to about 95,000 years B.P.

Based on these data it is reasonable to assign an age of 84 ka to the Davenport platform. The radiometric age is "about right" and 84 ka is the correct time for a high stand of sea level. If that is true, we can determine an uplift rate. If that uplift rate is applied to the shoreline angle elevation of the Highway 1 platform, then the age of that platform should be about 105 ka. This is also about the time of a sea level highstand, and that highstand would have had a cold-water fauna. Therefore data are internally consistent, which suggests that this is the correct interpretation for the platform ages. Note that the age of the terrace is based more on its relative position, correlation with a sea-level highstand and the faunas than on the radiometric date.

Higher Terraces

Northeast and above Highway 1 are at least 4 higher and older marine terraces in varying stages of preservation. Typically terraces become more dissected and erosionaly modified with time, and older marine platforms can be completely destroyed by younger episodes of erosion. Along the Santa Cruz County coast two terraces are discontinuous, being present only in restricted areas. The Cement terrace is only present between Davenport and Scott Creek, while the Wilder terrace is present only east of Laguna Creek (Figure 1, after Bradley and Griggs, 1976, and Plate 1). This indicates that in any terrace sequence, not all potential terrace forming highstands of sea-level will be represented by a terrace.

Fossils are rarely preserved in marine terrace deposits older than Sangamon, and none have been found in the Santa Cruz area. Consequently, it is not possible to directly determine the ages of these older terraces using either radiometric dating or amino acid racemization. Ages of upper (older) terraces are derived by correlating the shoreline angle elevations of terraces with known high-stands of sea-level. The tentative age assigned to an older (higher) terrace is the age of the sea-level high-stand with which its elevation most closely correlates, if uplift rates are constant. The uplift rate can usually be determined from knowing the age and elevation of at least one terrace. However, if no dateable material is found in terrace deposits one can approximate terrace ages by determining which assumed rate of uplift best matches the known shoreline angle elevations with known sea level high stands.

Age Determination, Correlation, and Deformation of the Ben Lomond Mountain Marine Terrace Sequence - Santa Cruz to Ano Nuevo

Bradley and Griggs (1976) made the initial attempt to estimate terrace ages for the Ben Lomond Mountain terrace sequence. They had little faunal control upon which to base their age interpretation and correlation, only the U-series age dates on molluscs collected from the Davenport platform, dates that were, and still are, considered questionable. They reasoned that world-wide, generally the widest and best developed of the low emergent terraces, and the most extensive of the Barbados reefs had been demonstrated to be associated with the 125 ka highstand of sea-level (Sangamon interglacial). Consequently, they assumed that the broad Highway 1 platform most probably formed during the 125 ka highstand of sea-level. All other terrace age estimates were based on this original assumption or interpretation.

This interpretation differs from mine. Based largely on data not available to Bradley and Griggs, (faunal assemblages, amino acid racemization studies) and the uranium series age dates I interpret the Davenport platform as having formed about 84 ka B.P., and the Highway 1 platform about 105 ka B.P. Using these ages as a starting point, and the assumption of constant uplift we can determine the uplift rate as 3.5 m/ka for the area just east of Majors Creek. I would follow the lead of Hanks and others (1984) and Lajoie (1986), and approximate the ages for the higher (older) marine terraces as indicated in Table 1. Tables 1 & 2 present shoreline angle (inner edge) elevations and uplift rates for the different segments of coastline from Santa Cruz north to Point Ano Nuevo.

TABLE 1. SHORELINE ANGLE ELEVATIONS AND TERRACE AGES SANTA CRUZ TO SCOTT CREEK

South of Majors Creek (uplift rate = 0.35 m/ka , 1.1 ft/ka)

Terrace	SL Elev. m/ft	Age	
		Hanks et al	Bradley & Griggs
Quarry	222 m / 730'	630 ka	1,200 ka
Blackrock	171 m / 560'	490 ka	900 ka
Wilder	130 m / 425'	370 ka	700 ka
Western	82 m / 270'	230 ka	450 ka
Santa Cruz			
Highway 1 wcp	27 m / 88'	105 ka	125 ka
Davenport wcp	14 m / 46'	84 ka	(?) 140 ka
deposit		84 ka	100 ka

Majors to Scott Creek (uplift rate = 0.39 m/ka, 1.25 ft/ka)

Terrace	SL Elev. m/ft	Hanks et al	Bradley & Griggs
Quarry	240 m / 790'	630 ka	1,200 ka
Blackrock	190 m / 625'	490 ka	900 ka
Western	92 m / 300'	230 ka	450 ka
Cement	58 m / 190'	124 ka	260 ka
Santa Cruz			
Highway 1 wcp	30 m / 98'	105 ka	125 ka
Davenport wcp	19 m / 62'	84 ka	140 ka

Both the Hanks and others (1984), and the Bradley and Griggs (1976) attempts at estimating the ages of individual terraces within the sequence have strong and weak points. However, the Hanks and others model is internally consistent and is the least complex. These factors, combined with constraints imposed on the terrace ages by the application of the diffusion equation model of landform development to the paleo-seacliffs (Hanks and others 1984), indicate that the ages advanced by Hanks and others are probably the most reasonable approximations.

North of Scott Creek the number and distribution of terraces changes drastically. Only two terraces (Western and Santa Cruz) are preserved along this segment of the coast, and these are present only to the west of Scott Creek. The probable reason that higher terraces have not been preserved east of Scott Creek is that they have been destroyed by the extensive glide block landsliding that has occurred in the southwest dipping mudstones on the east limb of the Davenport Syncline. The Santa Cruz terrace contains two well developed wave-cut platforms.

If the Western terrace is correctly identified north of Scott Creek, and if it is 230 ka old, then the average uplift rate is 0.48 m/ka at Greyhound Rock. If this uplift rate is applied to the two wave-cut platforms in the Santa Cruz terrace; the Greyhound platform's age is estimated as 104 ka B.P., and the Highway 1 platform's age as 82 ka B.P. These ages differ greatly from those published by Bradley and Griggs (1976). Specifically, Bradley and Griggs interpretation of platform ages north of Scott Creek are: the Greyhound platform is greater than 125 ka B.P., while the Highway 1 platform is 125 ka B.P. I believe the Greyhound platform is 105 ka, and that the Highway 1 platform is 82 ka B.P., and that they are consequently, misnamed.

This discrepancy in age estimates suggests that the platforms in the Santa Cruz terrace may be mis-identified northwest of Scott Creek. This could have resulted from mis-correlation across the mouth of Scott Creek. Bradley and Griggs correlated the Highway 1 platform on the basis of elevation across the mouth of Scott Creek (Figure 3). However the same points can be interpreted in at least two different ways (Figure 3). I believe that the Greyhound platform of Bradley and Griggs north of Scott Creek, is really the Highway 1 platform, and that the Highway 1 platform north of Scott Creek is probably really the Davenport platform (Figure 3). This is more consistent with the estimated ages of the wave-cut platforms.

TABLE 2. SHORELINE ANGLE ELEVATIONS AND TERRACE AGES NORTH OF SCOTT CREEK

Scott Creek to Point Ano Nuevo - Uplift rate at Greyhound rock 0.48 m/ka (1.6 ft/ka)

Terrace	SL Elev. m/ft	Age Weber	Age Bradley & Griggs
Western terrace	112 m / 365'	230 ka	450 ka
Santa Cruz terrace			
Greyhound wcp	50 m / 164'	104 ka	160 ka
Highway 1 wcp	39 m / 128'	82 ka	125 ka

I believe that elevation differences across the mouth of Scott Creek may result from movement on a late Pleistocene fault that lies along the valley of Scott Creek. The fault is not exposed as it lies along the axis of the stream valley (Figures 3 & 4). The movement would be west side up, east side down, with possibly 11-13 meters of vertical offset within the past 84 ka.

If my interpretation is incorrect, and the Highway 1 platform is correlative across the mouth of Scott Creek as shown by Bradley and Griggs (1976) then the interpretations of terrace ages by Hanks and others (1984), Lajoie (1986) and I (this field guide) contain a major inconsistency. If Bradley and Griggs are correct and the "Highway 1 platform" (the lower platform north of Scott Creek) is 104 ka in age, then the Greyhound platform (upper platform) is not correlative with a highstand of sea-level capable of having cut the platform. There are several possible interpretations for the origin of the Greyhound platform even if it doesn't correlate with any known highstand of sea-level, but none seem very probable. The most probable is that the Greyhound platform reresents a shore platform formed during a still stand of sea-level that occurred during the decline in sea-level between 125 and about 110 ka.

I correlate the marine terraces north of Scott Creek as follows:

Western terrace - 230 ka

Highway 1 wcp - 105 ka (former Greyhound)

Davenport wcp - 84 ka (former Highway 1)

This terrace sequence is continuous north of Scott Creek to the mouth of Waddell Creek, where the lowest terrace has been destroyed by erosion at Waddell Bluffs. Higher terraces are

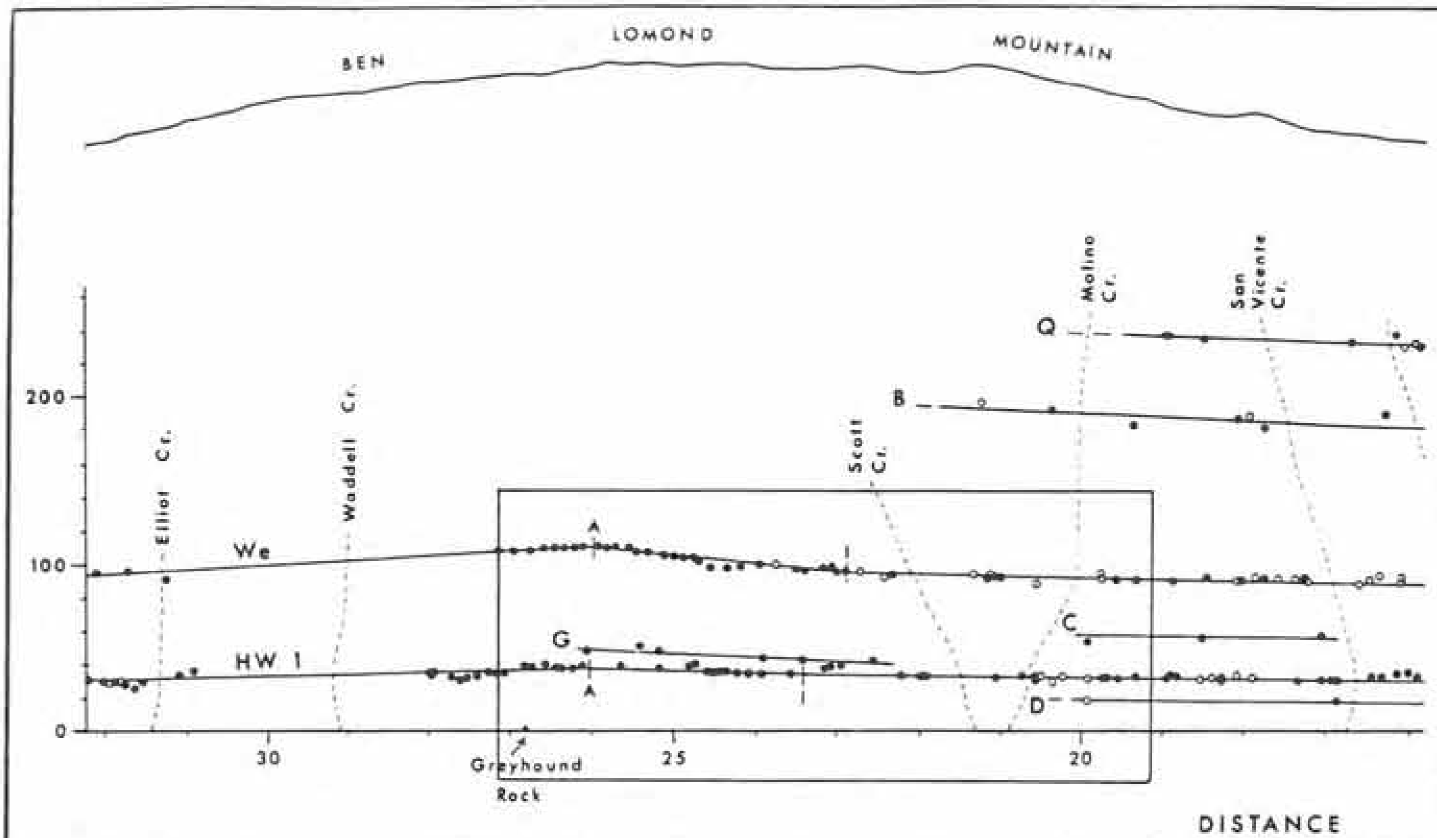


Figure 13. Inner-edge elevations of Ben Lomond platforms: Q = Quarry, B = Blackrock, Wi = Wilder, We = Western, C = Cement, G = Greyhound, HW 1 = Highway 1, D = Davenport. Points were determined by procedure described in text and are based on outcrop data (solid circles) and seismic data (open circles); lines were drawn visually. Vertical exaggeration is ×20. Deformational elements, discussed in text, are A, crest of arch; I, inflection point; S, trough of sag. Elevations of these elements and longshore component of tilting are summarized in Table 3. Generalized crestline of Ben Lomond Mountain is shown, but scale is different from rest of diagram; summit elevation exceeds 800 m.

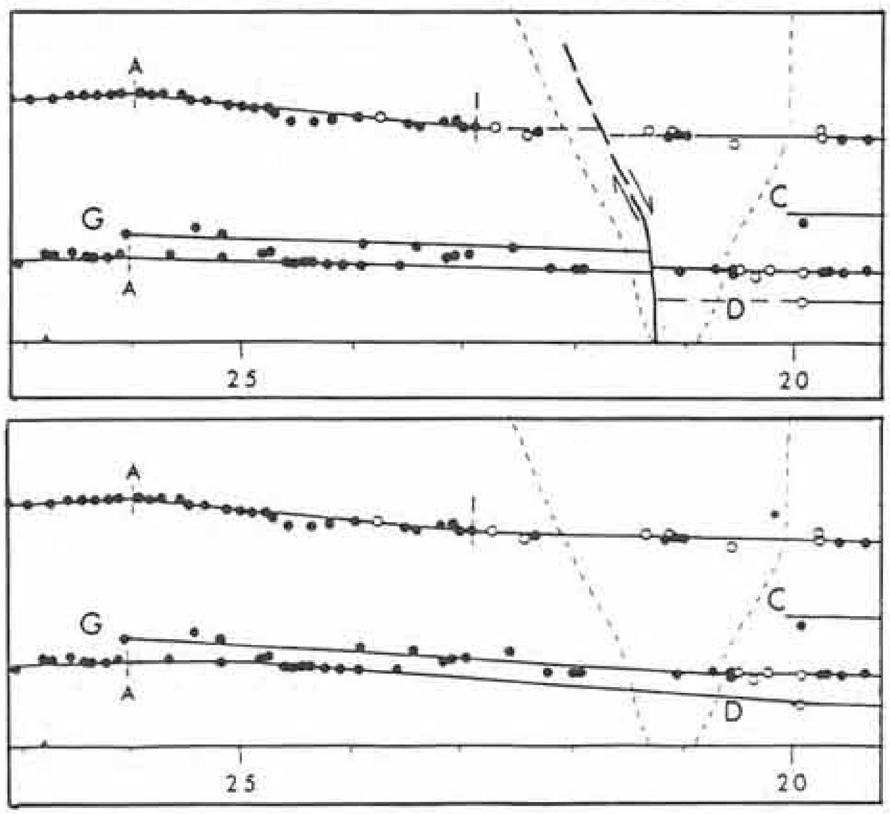


FIGURE 3. Alternate interpretations of correlation of terraces across mouth of Scott Creek. Figure 13 from Bradley and Griggs (1976) modified by Weber.

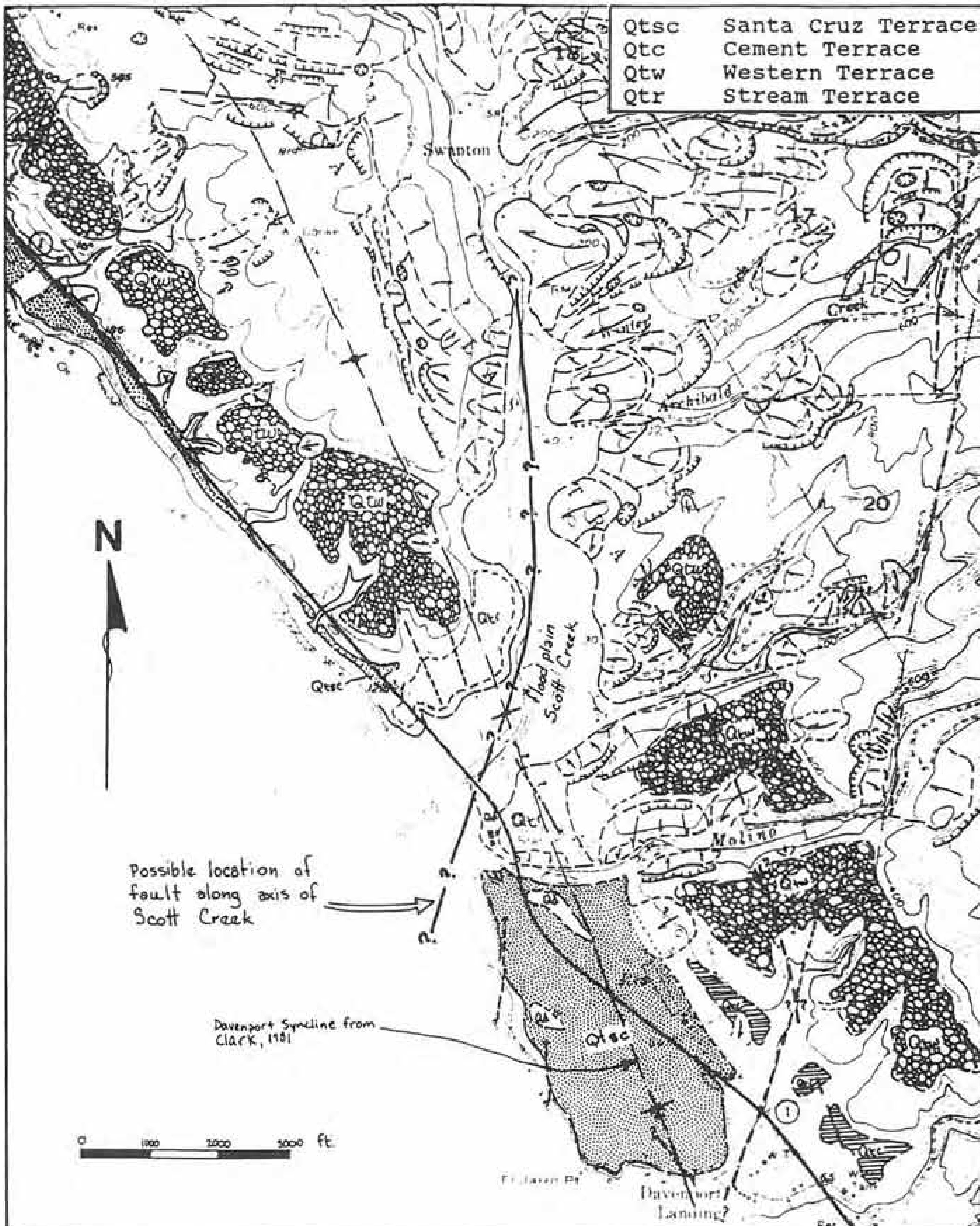


FIGURE 4. Map of Quaternary deposits in the Scott Creek area. Modified from Weber and Lajoie (1980), and Weber and others (1979).

not obviously correlative across the Waddell Bluffs, but a thin remnant of the terrace, probably the Cement terrace, is present at the top of the high bluffs.

Terrace stratigraphy changes dramatically within and to the west of the San Gregorio fault zone, because of the severe tilting and faulting of the terraces within and west of the fault zone. It is difficult to correlate terraces, either across or within the San Gregorio fault zone, except for the lowest and youngest terraces. Terraces within the Santa Cruz Mountains Structural Block are essentially undeformed, particularly when compared to the terraces west of the San Gregorio fault zone (Plate 1).

> Researchers have already cast much darkness upon the subject, and if they continue their investigations, we shall soon know nothing at all about it.
>
> Mark Twain

> The greater the circle of light, the greater the circumference of darkness around it.
>
> Albert Einstein

This half of the trip starts at the intersection of Mission Street (Highway 1) and Almar Street in west Santa Cruz - Safeway is on the southwest corner. Re-calibrate your odometer to zero at this point.

miles

int. cumm.

0.0 0.0

ALMAR STREET AND HIGHWAY 1: From this point northward Highway 1 is located near the back edge of the first emergent marine terrace (Santa Cruz terrace), with the steep slope on the right (northeast) the erosionally modified 105 ka B.P. seacliff. Two wave-cut platforms have been identified within this terrace (Figure 2). Fossil mollusks exposed in the sea cliff both at Point Santa Cruz and about 500 meters northwest of the Point yielded an average U-series age of 86,500 years B.P. (Bradley and Addicott, 1968) and an amino-acid age estimate of 85 ka for the Davenport platform. Shell fragments from a basal lag recovered in a hand auger boring near King and Walnut Streets in 1983 displayed a "cold water fauna" and an amino-acid age estimate of 105 ka B.P. This suggests the upper platform in West Santa Cruz is the Highway 1 platform (105 ka B.P.). The 125 ka platform is apparently not represented in this area. The two wave-cut platforms in the Santa Cruz terrace are apparently separated by a 1-2 meter sea cliff. This cliff is buried by a continuous alluvial apron that forms the topographic surface of the terrace. This ancient sea cliff is visible in the modern seacliff at two places near Davenport.

The second marine terrace (Western terrace of Bradley and Griggs, 1976) is visible to the right (northeast) as a series of erosionally dissected topographic flats above the 105 ka sea cliff. The age is estimated to be aproximately 230 ka years based on its shoreline angle elevation and an assumption of constant uplift during the late Pleistocene.

Between Santa Cruz and Point Ano Nuevo, east of the San Gregorio fault zone, the marine terraces lie within a single structural block, the Santa Cruz Mountains structural block (Bradley and Griggs, 1976; Weber and Lajoie, 1979). Marine terraces within this structural block are essentially undeformed, except for a broad shallow anticlinal flexture in the terrace near Greyhound Rock (Plate 1). As indicated in this guidebook, a small, late Pleistocene fault may offset the Santa Cruz terrace near Scott Creek.

1.0 1.0

MOORE CREEK: This creek and other large streams along this segment of the Santa Cruz County coast have eroded their bedrock canyons to the Wisconsinian lowstand of sea-level (probably 300 to 350 feet below present sea-level). The late Wisconsinian - Holocene rise in sea-level flooded the lower reaches of these streams resulting in their alluviation. Small lagoons present at the mouths of most streams result from damming of the streams by a combination of storm berms and small aeolian dunes.

COASTAL EROSION RATES

Measured rates of cliff retreat along this section of coast are generally less than 1 foot per year (Griggs, 1979). Along the Santa Cruz County coast from Almar Street north to the San Gregorio fault zone at Point Ano Nuevo, the modern seacliff has formed in the Mio-Pliocene Santa Cruz Mudstone. Consequently the rock resisting wave attack in the surf zone is essentially uniform along this entire stretch of coastline, except for a few scattered sedimentary (sandstone) dikes.

1.7 2.7

SANDY FLAT GULCH: Miocene Santa Margarita Sandstone is being quarried for construction sand on the northeast side (right) of the road. The road cut exposes Quaternary colluvium overlying Santa Cruz Mudstone, as Highway 1 is built above the Santa Cruz terrace at this point and on the colluvial wedge at the base of the 105ka seacliff.

3.1 5.8

MAJORS CREEK: Creek ends in a lagoon, indicating it was originally graded to a late Wisconsin low stand of sea level.

The black colored cliffs to the right (up Majors Creek) are bitumen saturated sandstones that were injected into the overlying Santa Cruz Mudstone, presumably in a liquid state. Numerous large clastic intrusions (sandstone dikes), most of which contain some bituminous material, are exposed in the modern seacliff between Wilder Creek and Greyhound Rock. The Santa Margarita Sandstone contains varying amounts of bitumin saturation throughout its outcrop area from Santa Cruz to the vicinity of Big Basin State Park. The hydrocarbons are believed to have migrated into the Santa Margarita Sandstone from the underlying Monterey Formation.

The bituminous sandstones in this area have been mined since the late 1880's for paving material for roads. Asphaltic content of the sand ranges from about 4% to as much as 18% by weight, with the bituminous sands varying greatly in density, hardness and thickness. Oil impregnated beds very from 1-40 feet in thickness, and range in quality from dry and brittle to soft and gummy. In some outcrops tar will drip or flow out of the bituminous sands when sufficiently warmed by the sun. San Francisco streets were reportedly paved in the 1890's with bituminous sandstone mined near Majors Creek and transported to San Francisco on sailing vessels. Bituminous sandstone was mined from two main areas, one northwest of Majors Creek and north of Highway 1, the other along Majors Creek about 2 miles northeast of Highway 1 (Figure 5). An estimated 614,000 tons of asphaltic sand, worth approximately $2,360,000, was produced from this area between 1888 and 1914 (Page and Holmes, 1945). Production has been intermitent since the 1920's with the last of the operating quaries (Calrock Quarry) ceasing operations in the late 1940's.

Page and Holmes (1945) estimated that reserves of approximately 9.8 million cubic yards of asphaltic sand were present in the area west of Santa Cruz. This sand contains approximately 10 million barrels of asphalt. In oilfield terms, this is about 24 gallons of bitumen per ton, or equivalent to a tar sand with 38% porosity, 53% oil saturation, and a recovery factor of 1,562 barrels of oil per acre-foot.

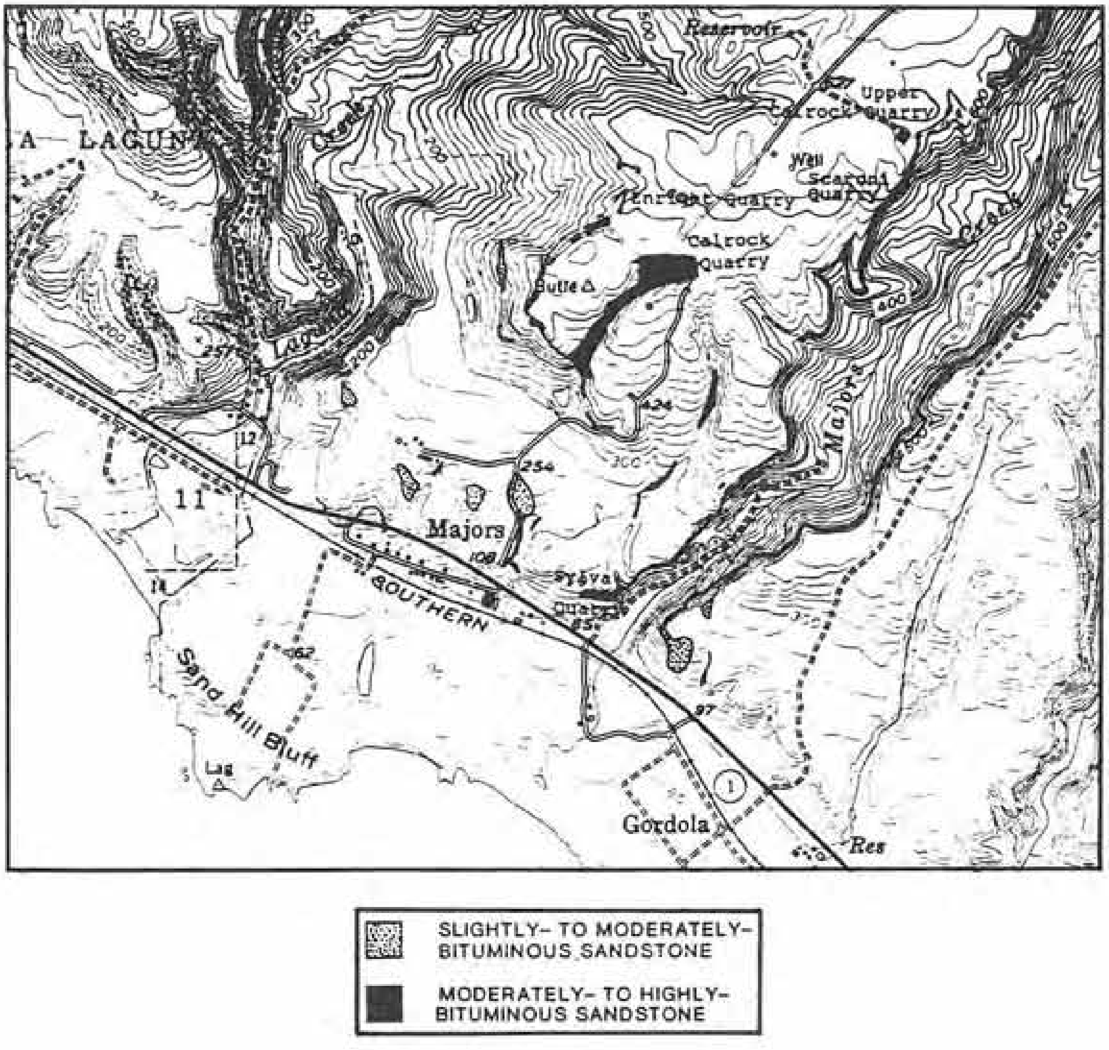


FIGURE 5. Map of bituminous sandstone mining areas near Majors Creek.

OIL AND GAS PRODUCTION AT MAJORS CREEK

In 1955 Husky Oil Company in partnership with The Swedish Shale Oil Company began an experimental project to adapt the Swedish Company's Ljungstrom method to the recovery of hydrocarbons. It was essentially a thermal recovery experiment, utilizing down-hole, gas fired burners to perform in situ retorting. In the fall of 1957, Union Oil Company of California joined in the project. During the next 2-3 years a total of 228 burner-producer wells, 78 temperature observation wells, 31 gas wells, and 32 miscellaneous wells were drilled, largely through the Blackrock and Quarry terrace deposits into the oil saturated sandstone that underlay the terrace. The top of the bituminous sandstone bed lay 8-10 feet below the surface, was about 40 feet thick in its saturated section and averaged about 8% by weight of 4-degree gravity tar throughout.

Wells were typically drilled in a triangular patern on a ten foot spacing to an average depth of 53 feet. They were completed with 14 feet of 4-inch surface pipe and 50 feet of 2 7/8 inch casing. Underground heaters, fueled by propane were used in the heating phase of the test, with downhole temperatures reaching 600 degrees F. The test area was heated from a depth of 15 feet to 45 feet, with much of the crude oil vaporizing. Products produced in a vapor form were condensed using a water cooled condenser. The heating phase was completed in January of 1959, with a total production of 2665 barrels of oil, 4520 Mcf of gas and 9232 barrels of water. Average gravity of the recovered oil was 27 degrees. The operator reported that in zones 30 feet thick, a recovery of about 18,000 barrels per acre could be achieved - a recovery of 38% of the oil in place. Although this is a respectable recovery factor (similar to some steam stimulation projects) it is doubtful that such an operation could be economical due to high heat losses and high fuel costs. Strip mining does not appear to be an attractive alternative because of limited volume of oil in place and the large amount of overburden; ignoring entirely for the moment the probable difficulty of obtaining a permit for strip mining along the coast from the either the California Coastal Commission or the Santa Cruz County Planning Department.

0.3 6.1

STOP #1 BLACKROCK QUARRY - For the October 21, 1989 field trip we will turn right and proceed to our lunch stop on Back Ranch Road - a private road. If you are taking this field trip on any date other than the 10-21-89 field trip - **PLEASE DO NOT USE THIS ROAD WITHOUT HAVING RECIEVED WRITTEN PRIOR PERMISSION FROM THE RESIDENTS.** At this stop we will view the terrace sequence and hike up to the Blackrock Quarry to examine the terrace deposits and the bituminous rocks exposed in the old Calrock Quarry.

Please continue with the trip as indicated.

0.3 6.1

Left turn, then an immediate right turn onto Old Coast Highway at Majors. The isolated hill near the edge of the seacliff is a stabilized Holocene sand dune (Sand Hill Bluff). It is capped by a 1 meter thick midden deposit containing remains of an extinct flightless scoter (Chendytese, a type of sea duck). It is possible that the bird may have become extinct due to the hunting pressures of the coastal Indians.

The dune is dated at less than or equal to 5,000 years B.P. on geologic evidence (stabilization of sea-level, after the Wisconsinian and Holocene rise), and at 3,500 - 5,000 years B.P. by C-14 analysis of marine shells from the midden deposit.

More recently, Pacific Mariculture, Inc. has recieved a permit to build an Abalone Farm out near Sand Hill Bluff. The project will ultimately consist of 400 abalone grow-out tanks under 2.5 acres of shade cloth structure. Raising abalone to commercial size (4 inches) will take about 3-4 years in the grow out tanks. Production is estimated at 500,000 red abalone per year, that will yield about 170,000 pounds of meat. Abalone will be fed a mixture of kelp and commercial feed, with the kelp harvested by hand from kelp beds off the coast.

Proceed to the intersection of Old Coast Highway and Highway 1. Note the vertical contact in the roadcut on the north side of Highway 1, and also in the cut along Old Highway 1. This is the old (105,000 year B.P.) seacliff associated with the Highway 1 platform of the Santa Cruz marine terrace. Hard siliceous mudstones of the Santa Cruz Mudstone are juxtaposed with moderately dipping colluvial deposits along a nearly vertical contact. The basal portion of the old seacliff is preserved by the accumulation of talus and colluvium that fell at the base of the cliff, and is characterized by a concave upward profile typical of depositional surfaces.. The upper half of the ancient seacliff has been eroded back forming the convex upward portion of the slope profile. It is along this section of coast where Hanks, and others (1984) used the profiles of the ancient seacliffs between terraces to develop their paper on scarp degradation.

North of this point the third major terrace (Wilder Terrace) is no longer present, having been destroyed by subsequent erosion during the formation of the Western terrace (Plate 1). Turn left (north) onto Highway 1.

1.6 7.7

YELLOW BANK CREEK: Some of the largest and most enigmatic of the sedimentary intrusions injected into the Santa Cruz Mudstone are exposed in the seacliff near the mouth of the creek. Two higher terraces are visible out the window to the right (northeast).

0.8 8.5

Intersection of Highway 1 with Bonny Doon Road. Continue north on Highway 1. The county's best known nude beach is on the left. During the recent 10-17-89 earthquake a visitor to the beach was killed by a small rock fall landslide off of the face of the seacliff.

1.1 9.6

TOWN OF DAVENPORT: One of several historic, land-based whaling stations along the central California coast active during the late 1800's. Grey whales migrate from the Bering Sea to Baja California each winter and pass close to shore at this location (from the first of January until the middle of May). During the whaling days, a lookout stationed at the top of the cliff watched for passing whales. When whales were spotted, an alarm was sounded and the whalers launched their skiffs from the shore. Slain whales were hauled to the beach where they were cut up and the blubber rendered locally in try pots. This method of hunting allowed the whalers to live on shore rather than spending the better part of each year at sea.

Just south of the town of Davenport, the Davenport and Highway 1 wave-cut platforms of the Santa Cruz terrace, and the Davenport platform shoreline angle are exposed in the seacliff (Figure 8, Bradley and Griggs, 1976).

0.4 10.0

DAVENPORT CEMENT PLANT: Now operated by RMC Lonestar, this plant,built between 1905-07 has been a major producer of cement in the San Francisco Bay area. Limestone and shale are both quarried locally. The relatively pure limestone is quarried about 2 miles northeast of the plant and transported to the plant on a 2 mile long enclosed conveyor belt. Energy for producing cement is derived from low-sulfur bituminous coal mined in eastern Utah and shipped to the plant via rail. The plant was extensively remodeled in the 1970's resulting in a great reduction in stack emissions, and is now one of the most advanced cement manufacturing operations in the world.

The railroad tracks on the right are part of a rail system originally intended to connect Santa Cruz and San Francisco (Ocean Shore Railroad) . In the early 1900's the stretch between Davenport and Tunitas Creek, about 30 miles to the north was graded, but the tracks were laid no further north than Swanton siding, a few miles north of this point.

CEMENT TERRACE - probable age 125 ka B.P. is visible to the right (northeast) between Davenport and El Jarro Point. This narrow marine terrace remnant occurs only in this area, lying between the Santa Cruz and Western terraces (Plate 1). Although only locally developed within the Santa Cruz Mountains Structural Block, the Cement terrace appears to be extensively developed west of the San Gregorio fault zone on the Pigeon Point Structural Block.

0.9 10.9

DAVENPORT LANDING ROAD: Water wells in the Davenport Landing area produce sizeable amounts of methane gas with the water. Analysis of gas samples collected from a well at Davenport Landing indicated the gas that contained 74 - 91% methane, <1% ethane, 7 - 23%

nitrogen and 2% carbon dioxide (Mullins and Nagel, 1982). The well was drilled to a depth of 655 feet, with a standing water table near 330 feet. The gas is produced along with hot water (90 F, 32 C). Some wells may produce as much as 200 Mcf per day. The gas is presently being discharged directly to the atmosphere and is not being used. The gas apparently originates within the Santa Cruz Mudstone, a siliceous, organic mudstone. It is thought to be of thermogenic origin, and has apparently migrated upward from depth.

Davenport Landing is also the site of Silverking Oceanic Farms. For the past 10 years this facillity has been releasing hundreds of thousands of hatchery grown sub-adult King Salmon and Steelhead. An increasing number of returning adults are captured each year. The salmon are hatched in Scotts Valley and raised to fingerling size in the King City area prior to being transferred to the Davenport Landing facillity where the young salmon are kept for two weeks before being released into the ocean.

0.4 11.3

Swanton Road to the right, Davenport Landing Road to the left.

0.4 11.7

EL JARRO POINT: The terrace on both sides of the road was the proposed site of a P.G. & E. nuclear power plant in the late 1960's. The site was abandoned largely because of the close proximity of the San Gregorio fault zone. More recently (mid 1970's) this was one of the proposed sites of the west coast LNG terminal.

0.7 12.4

SCOTT CREEK: A large drowned valley with a lagoon that is confined by sand dunes and a well developed berm. The dune area near the mouth of the creek was originally the site of a mushroom farm, that was abandoned, in the 60's, while the buildings were torn down in the mid 1970's. At that time the dunes were stabilized by thick and extensive beach-dune vegetation. However, off-the-road vehicles (4-wheelers, dirt bikes, quads, etc.) started using this beach at about that time, destroying the vegetative cover in about 2 years. This allowed the dunes to re-mobilize, and sand soon started to drift once again over Highway 1 (much to the delight of

Caltrans). The continuing dune activity that moves sand onto Highway 1 (requiring continued clearing by Caltrans) is the direct result of ORV use of this beach. The beach is still used on occasion by "pick-up truck bubba's", even though vehicles are illegal on county beaches. If one is lucky, during the winter, one can occasionally see a 4-wheel drive vehicle stuck in the beach sand being pounded by the waves.

As we drive north out of the valley of Scott Creek, the road which rises back up onto the Santa Cruz terrace, lies almost exactly on the inward edge of the "Greyhound platform" of the Santa Cruz terrace (as interpreted by Bradley and Griggs). The terrace platforms in this area are very narrow and are covered with a thick wedge of colluvial and alluvial cover. From here north to Waddell Creek there is only one higher terrace present - the Western terrace. Note that the moderately sloping terrace surface lies to the left (southwest) and that the road cuts expose Santa Cruz Mudstone to the right (northeast).

North of Scott Creek, the Santa Cruz Terrace is composed of two wave-cut platforms. The upper platform is named the Greyhound platform and the lower the Highway 1 platform (Bradley and Griggs, 1976). As discussed earlier, I believe that the correlation of the Highway 1 platform across the mouth of Scott Creek may be incorrect. Figure 3, shows the original correlation of Bradley and Griggs (1976) and my reinterpretation of their original correlation. I believe, the Greyhound Rock platform north of Scott Creek is really the Highway 1 platform, and the so-called Highway 1 platform is really the Davenport platform. If this interpretation is true, then a small fault with approximately 11-13 meters of vertical movement (west side up, east side down) may lie in the valley of Scott Creek, buried by Holocene alluvium (Figures 3 & 4).

The seacliff is about 160 feet high along this portion of the coast and nearly vertical. The views are spectacular, but the cliff is dangerous. The local Davenport Fire Department and Rescue Team (a volunteer organization) rescues numerous numbskulls each year who have managed to get "stuck" on the cliff face or are injured trying to climb the cliffs.

OFFSHORE OIL AND GAS POTENTIAL - The presence of thick sequences of organic mudstones (Santa Cruz Mudstone and Monterey Formation), gas production in water wells, and the presence of bituminous sandstones along the coast suggest that hydrocarbons are present, both onshore and offshore. High resolution reflection seismic profiles surveyed across the continental shelf along the Santa Cruz County coastline, both west and east of the San Gregorio fault, by Mullins and Nagel (1982) revealed the presence of over 100 water column anomalies. The water column anomalies are associated with anticlinal structures and faults and are interpreted as hydrocarbon seeps (primarily gas) on the ocean floor. Associated with these apparent seeps are other seismic evidence of shallow oil accumulations - "seismic smear/wipe outs", and "bright spots". Mullins and Nagel also recovered oil saturated sandstone from dredge hauls in the head of the Ascension Canyon. Although these data indicate that hydrocarbons are present in the offshore, they are insufficient to allow a complete evaluation of the petroleum producing potential of the Outer Continental Shelf and/or the Outer Santa Cruz Basin.

1.4 13.5

STOP #2 (Honk Stop) COLLUVIUM FILLED GULLIES: In this road cut (also in others) is a large "V" shaped gully filled with coluvium. About 6 of these colluvium filled gullies are present in the road cuts between Scott Creek and Greyhound Rock These curious features appear to be small drainages and gullies that were cut into the mudstone bedrock, that were later filled with locally derived colluvial sediments. These colluvial deposits are characterized by crude stratification sub-parallel to the sides of the "V" shaped drainage. There are fluvial deposits within this gully, or other similar gullies. The age of the gullies and their fills is not known with certainty, but they must postdate the formation of the Highway 1 platform (correlation of Weber, this guidebook). These small deposits are of interest as there is no surface evidence (geomorphic, topographic, vegetative, etc.) of their presence. The ground surface passes unbroken over these gully fills with no evidence of differential erosion between the fills and the bedrock.

0.4 14.3

TEXAS OIL CO., POLETI #1: Immediately west of this point near the edge of the seacliff was the site of the deepest exploratory oil well drilled in Santa Cruz County. Drilled between June and December of 1956, to a depth of 9201 feet, the well penetrated 9135 feet of mudstones and siltstones before entering granitic basement. The well was dry, and the objective of the drilling, the Santa Margarita Sandstone, was not present in the well. The well apparently was looking for the updip edge of a stratigraphic pinchout of the Santa Margarita Sandstone on the west limb of the Scott Creek syncline, or a bowing of beds against a branch of the San Gregorio fault zone. Although weak to fair gas shows and slight oil shows were sporadically encountered throughout the section, no strong gas shows were reported from the well. This is surprizing in light of the gas production near Davenport Landing and the presence of numerous gas seeps on the ocean floor east of the San Gregorio fault zone (Mullins and Nagel, 1982).

0.9 15.7

STOP #3 CHINA LADDER: Park on the left side of the road. The site is identified by the presence of a small tree on the northeast (right) side of the road, the only one for several miles. Attempt to find the trail out to the edge of the seacliff. There are numerous narrow trails through the brush and poison oak, and selecting the right trail may take a few trys. But go out there and crash around in the poison oak till you find the one that leads out to the edge of the cliff. You are on the correct trail if it leads out onto the face of the seacliff and then down to the base of the seacliff. Climb down the trail till you are about 15 - 20 feet below the top of the seacliff and look north - right. The shoreline angle of the **Davenport platform** (Highway 1) and the wave-cut platforms of the **Davenport platform** (Highway 1) and **Highway 1 platform** (Greyhound) are beautifully exposed in the seacliff (Bradley and Griggs terminology in parenthesis, Weber interpretation in **bold**). The elevations of the shoreline angle of the higher **Highway 1 platform** (Greyhound) and the lower **Davenport platform** (Highway 1) are 50 and 40 meters respectivly. A plot of the shoreline angle elevations (Bradley and Griggs, 1976, p. 442-443, and this guidebook, Plate 1, Figure 3) indicate that this area is near the crest of a broad late Pleistocene arch.

0.7 15.9

STOP #4 GREYHOUND ROCK: Greyhound Rock is a tombolo, an offshore rock connected to the beach by a small sand spit. Park in the parking lot and walk down to the beach along the fisherman's access road. Then walk south out onto the beach about 300 yards. Refer to Figure 6.

EASTERN FAULT ZONE - GREYHOUND ROCK FAULT: The Highway 1 platform of the Santa Cruz terrace is offset about 30 feet by 3 steeply diping faults with apparent normal motion. These three closely spaced faults are informally refered to as the "eastern fault zone" of the Greyhound Rock fault, a branch of the San Gregorio fault zone. All three faults offset the Santa Cruz Mudstone, the platform and the overlying marine and non-marine elements of the terrace deposits. These three faults are exposed along the access road below the parking lot where they clearly cut through the terrace deposits. Refer to article in this guidebook for a more complete discussion of the controversy surrounding the interpretation of the origin of these faults. Are the "faults" of tectonic or landslide origin?

The "eastern fault zone" can be traced with difficulty 1500 feet to the northwest where it cuts colluvial deposits overlying the terrace deposits. A well developed, erosionally modified fault scarp 6-7 feet high was present along the eastern fault prior to the construction of the parking lot and a 4 foot high scarp was present along the western fault (W.C. Bradley personal communication, 1970). A single modified scarp can still be seen if one walks out to the edge of the seacliff on the headland north of the access road and looks back to the east.

WESTERN FAULT- GREYHOUND ROCK FAULT: From your location in the middle of the beach, look back to the northwest toward the access road. A second fault is exposed both above and below the access road about 200 feet west of the 3 closely spaced faults (eastern fault zone). The wave-cut platform and the overlying marine sediments are offset 4-5 feet vertically along this fault, but the fault is erosionally truncated by a wedge of fluvial

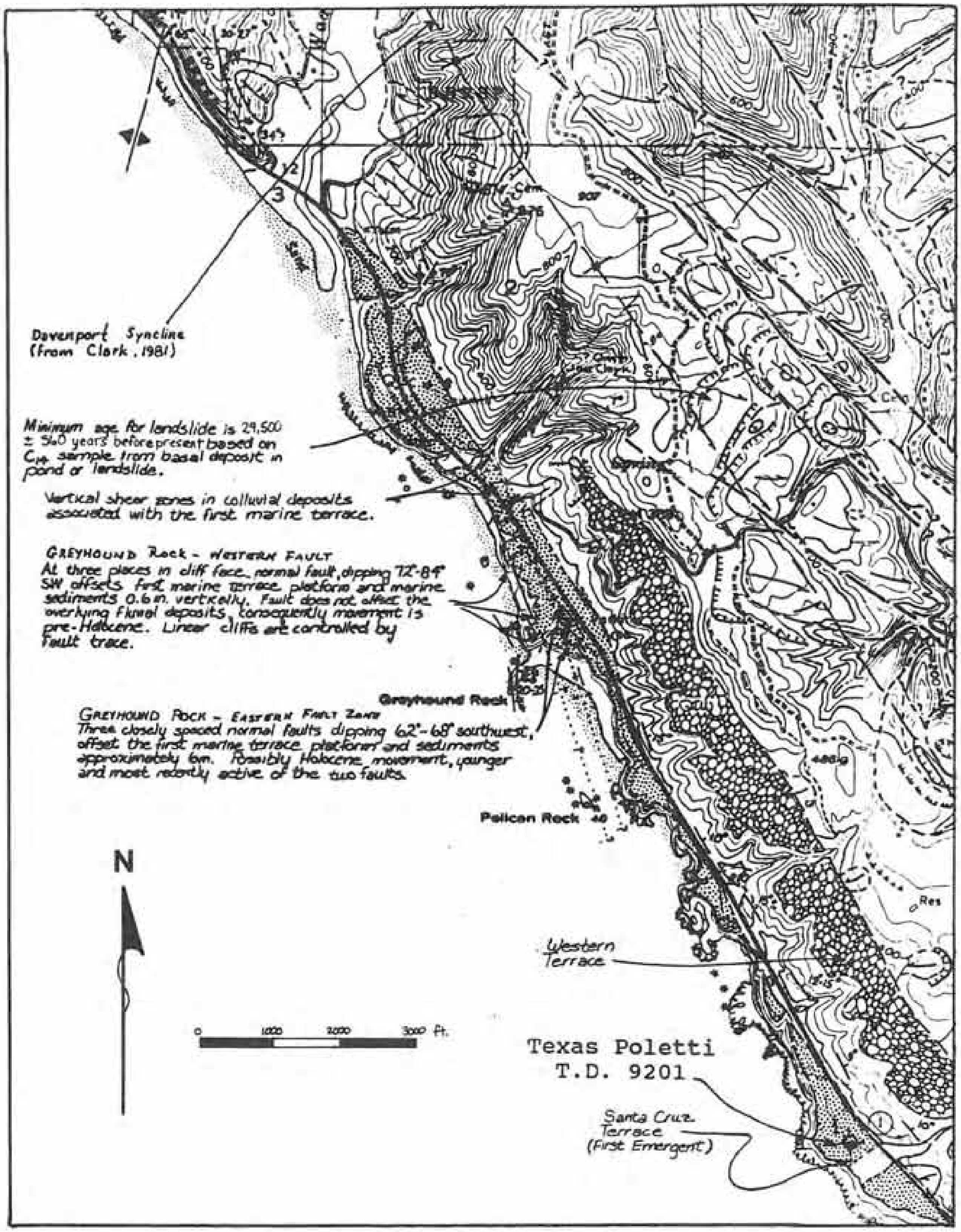


FIGURE 6. Map of Quaternary faults and marine terrace deposits near Greyhound Rock.

sediments built out onto the surface of the marine terrace. This fault can also be traced over 1000 feet to the northwest. Neither of these faults can be clearly demonstrated to branch off of the main fault trace of the San Gregorio fault zone, because of poor exposure away from the seacliff (Figures 4 & 5).

Greyhound Rock beach has been slowly eroding away, steadily decreasing in width over the past 12-15 years. The reduction in beach width is thought to result from a decrease in the volume of sand available to the littoral drift along this section of the coast.

0.3 16.2

SWANTON ROAD: Near the top of this ridge, east of the road a small pond (Laguna de las Trancas) on a rotational block landslide was cored and studied by Dave Adam Roger Byrne and Ed Luther (1979). A piece of pine wood from a depth of 3.12 meters at the base of the core yielded a C-14 age of 29,500 +560 years B.P. The core represents the period between roughly 30,000 years B.P. and 5,000 B.P. Pollen studies indicate that the flora and climate were significantly different during the Wisconsinian glaciation that ended about 15 - 17 ka years B.P. The presence of grand fir pollen suggests a southward displacement of floral zones by about 150 km. This was probably equivalent to a mean monthly temperature depression of 2 - 3 degrees C. Adam, Byrne and Luther estimated that precipitation was about 20% higher than at present, and indicated that these changes are only for the coastal climate and should not be extrapolated inland.

More recent pollen studies of two cores from Clear Lake, north of San Francisco Bay, indicate that climatic changes were far greater at inland locations. At Clear Lake temperatures were 7-8 degrees C cooler during the Pleistocene, and precipitation was 300% to 350% of present (Adam and West, 1983). Wisconsinian precipitation levels in the Santa Cruz Mountains probably lie somewhere between the values of Clear Lake and Laguna de las Trancas.

0.4 16.6

BIG CREEK LUMBER CO.: The lumber mill on the right processes timber that has been selectively cut in the Santa Cruz Mountains. The lumber mill is built on the crest of a large recently-stabilized, post Flandrian (Holocene sea-level rise), dune. This dune is part of a large stabilized dune ramp that extends from the beach at the mouth of Waddell Creek up onto the Santa Cruz terrace. Photographs taken around 1900 indicate the dune was active and a sufficient sand supply was available on the beach at that time to nourish the dune ramp and dune.

0.6 17.2

WADDELL CREEK: Another drowned valley. Just north of the creek, the high cliffs of Santa Cruz Mudstone (Waddell Bluffs) were originally undercut by waves. The highway is built entirely on artificial fill. These bluffs formed a natural barrier to coastal travel in the 1800's and early 1900's, when stagecoaches could only pass the bluffs during low tide on the wet beach. The southern tip of present day San Mateo county, including Point Ano Nuevo, originally was part of Santa Cruz County. However, because access to the county seat in Santa Cruz was often impeded by this natural barrier, the portion of Santa Cruz County that originally lay north of the Waddell Bluffs was annexed by San Mateo County in 1868.

The debris that ravels down the cliff and collects in the trench behind the berm on the east side of the road is periodically removed by Caltrans, stockpiled on the west side of Highway 1 and eventually dumped into the ocean to become part of the longshore drift of sediment to the south. Large rock falls are uncommon, probably because of the manner in which the Santa Cruz Mudstone weathers - small blocks and chips typically less than several inches in diameter. Occassionally blocks the size of a Volkswagen bug fall and bounce out onto Highway 1. About 10 years ago a passenger in a truck traveling north was killed by a rock that bounced through the front window. Litigation against Caltrans for improperly maintaining the debris trap ensued (Griggs, 1984).

A resistant bed of siliceous mudstone is exposed in the surf zone and forms a natural groin at this location. The result is a protective beach upcoast and active erosion downcoast. Rip rap was placed here in 1946 to protect Highway 1, which was under construction. Because of its placement on a bedrock platform, this rip rap has successfully protected the road for over 40 years.

At the top of the bluffs is a poorly exposed, narrow remnant of a marine terrace that lies between the Santa Cruz and Western terraces, probably the Cement terrace. Exposed in the bluff is a broad anticlinal fold in the Santa Cruz Mudstone. The fold extends for several miles to the northwest, parallel to the trend of the San Gregorio fault zone. An unsucessful exploratory oil well was drilled on this structure several miles north of here in 1956 (Seaboard Atkins #1, T.D. 3535).

1.2 18.4

SANTA CRUZ COUNTY LINE - ENTERING SAN MATEO COUNTY: The pines in this area are Monterey Pine (Pinus radiata). This is the northernmost natural stand of this extremely restricted pine. Monterey pine hybridizes naturally with closely related Knobcone Pine (Pinus attenuata) found on the higher and drier slopes in this area.

0.5 18.9

COASTWAYS FAULT OF THE SAN GREGORIO FAULT ZONE: The fault crosses the highway at the small dip in the road (Figure 2). This fault has long been considered as the primary trace of the San Gregorio fault zone because of the obvious bedrock offset across a small re-entrant in the coastline. The fault is obscured by thick wedges of colluvium and dense vegetation, but flat lying Santa Cruz Mudstone on the east is juxtaposed against flat lying Purisima Formation west of the fault. Terrace deposits and the 104 ka B.P. wave-cut platform are not exposed near the fault. However, leveling across the re-entrant indicates the marine terrace is offset about 16 feet, with the northeast side up (W.C. Bradley, personal communication, 1970).

0.4 19.3

ANO NUEVO CREEK ROAD: This portion of old Highway 1 (the former entrance to the State Reserve) was recently abandoned when the bridge over Ano Nuevo Creek was deemed unsafe for bus traffic due to severe cracking in the abutments. Just north of this intersection Highway 1 enters a shallow road cut that exposes the deposits of the Ano Nuevo Creek fan.

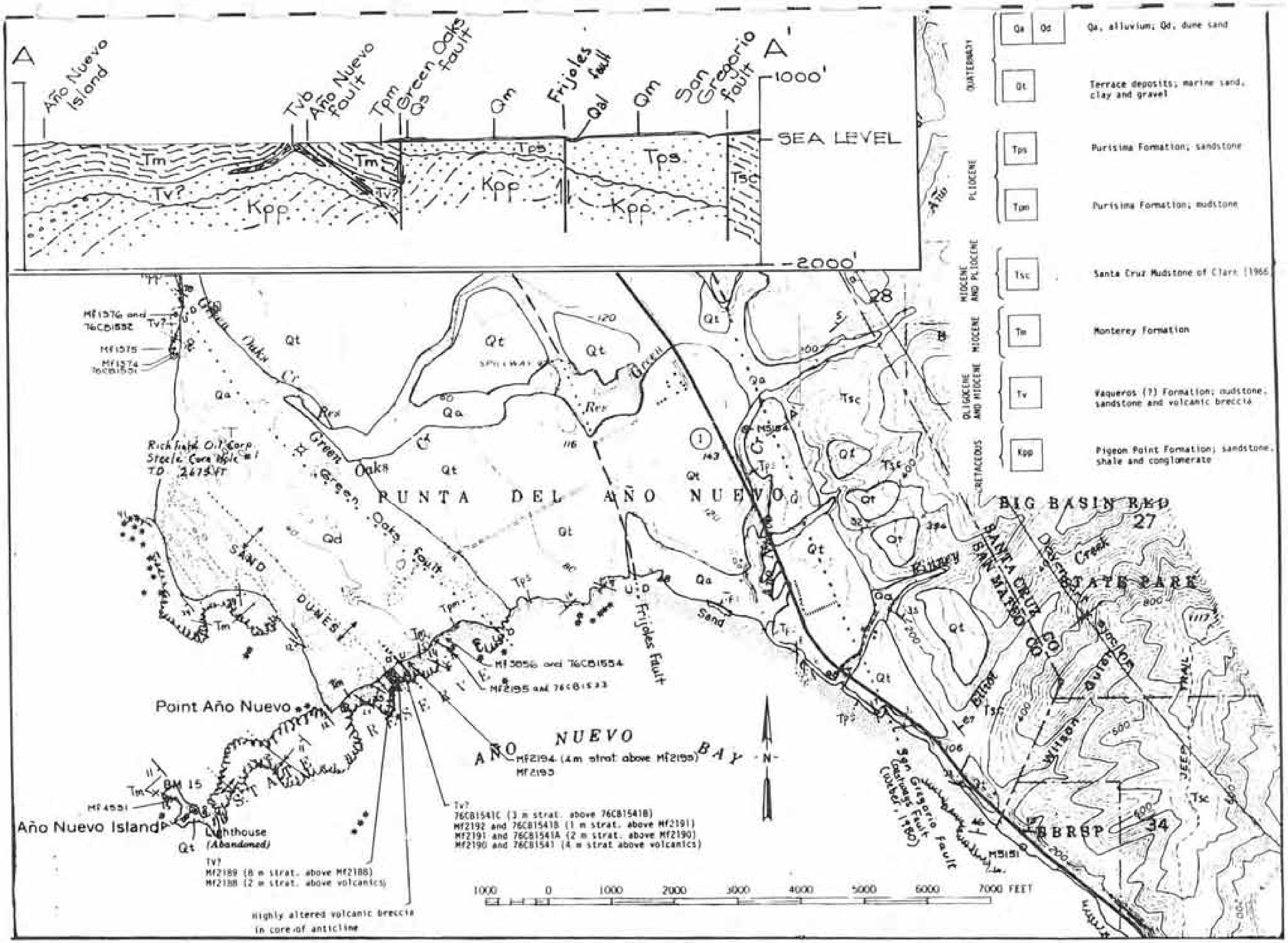


FIGURE 7. Pre-Quaternary Geology of Point Ano Nuevo. Bedrock geology by Clark and Brabb.

0.3 19.6

ANO NUEVO CREEK: Late Pleistocene - Holocene strath terraces of Ano Nuevo Creek are visible in the agricultural fields to the east. North of Ano Nuevo Creek, Highway 1 again cuts through the late Pleistocene alluvial fan formed by Ano Nuevo Creek (Figure 8). Ano Nuevo Creek has incised deeply into its late Pleistocene fan. Similarly, the creek is incised into the Holocene fill of the valley originally incised into the fan during the maximum depression of sea level. The basal portion of the Highway 1 cut exposes clean quartzose beach sands while the upper two thirds of the cut exposes fluvial pebble conglomerates composed primarily of Santa Cruz Mudstone. If you plan to examine these deposits you should be prepared to dig into the face of the cut, and explain your actions to the C.H.P.

0.3 19.9

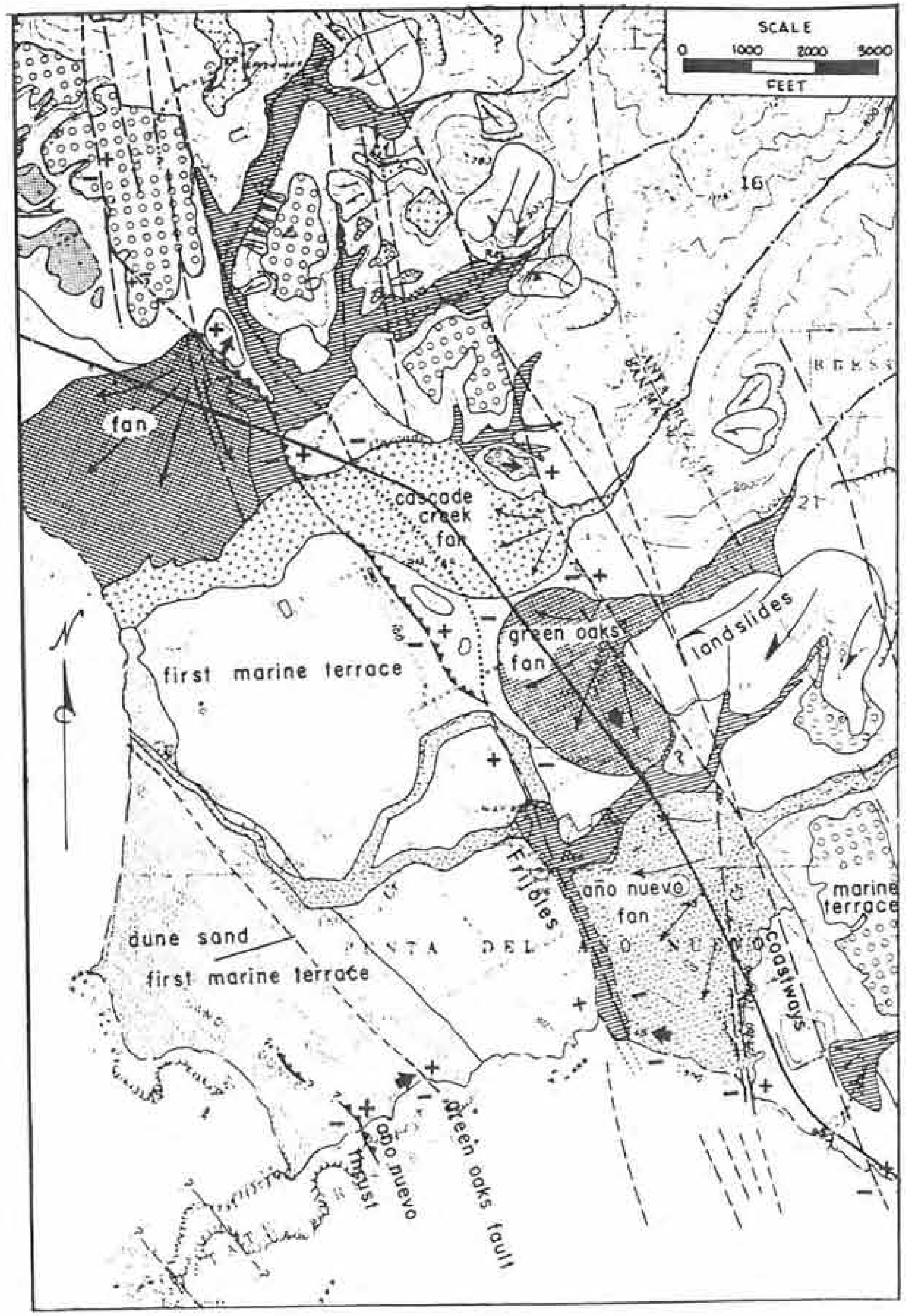
ENTRANCE TO THE ANO NUEVO STATE RESERVE: Turn left, enter the reserve - pay the ranger - and proceed to the main parking lot. Restrooms are available. Exhibits, and a natural history bookstore are usually open in the Dickerman Barn, one of the remaining buildings of the Steele Ranch. Refer to articles in this guidebook for a discussion of the geology of Point Ano Nuevo, and Figures 7, 8, 9, & 10 for the location of the hike at **Stop # 5**.

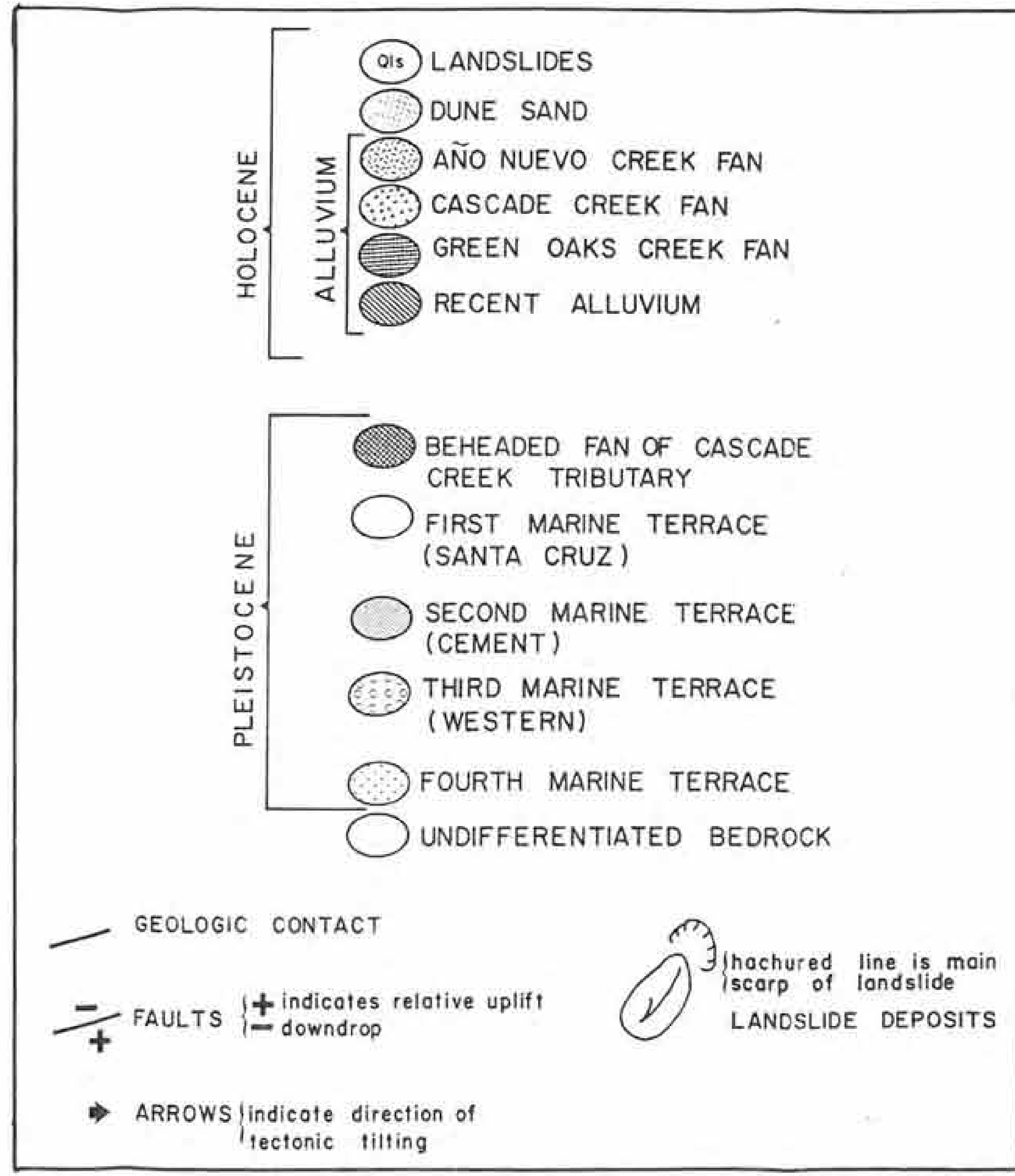
TIPS FOR VISITING AND ENJOYING THE ANO NUEVO STATE RESERVE: I personally suggest that you visit the reserve when there aren't any elephant seals present. THEY NEVER DO ANYTHING ANYWAY. All they do is lie on the beach and get in the way. Boring! Come on a week day with a good low tide. This will allow you observe the geology of the sea cliff without getting washed out to sea, and you can avoid all of the geek tourists and the dredful babbling hordes of elementary school children on science class outings.

NOTE: If you enter the State Reserve parking lot add 0.4 miles to your trip mileage. This mileage is not included in the road log.

STOP #5 SAN GREGORIO FAULT ZONE - FRIJOLES FAULT

As indicated on Figure 9, proceed south from the Dickerman Barn on the remnant of old Highway 1 to Ano Nuevo Creek. Walk down the partially overgrown





QUATERNARY DEPOSITS & LATE PLEISTOCENE FAULTS at POINT AÑO NUEVO, SAN MATEO CO, CALIFORNIA. by: Gerald E. Weber access road to the beach at the mouth of the Creek. Hike southeast on the beach, cross Ano Nuevo Creek, to the base of the seacliff (Figures 8, 9, & 10).

STOP "A": Exposed in the seacliff is the contact (buttress unconformity) between fluvial deposits of Ano Nuevo Creek and the "upper sandstone member" of the Purisima Formation. Detrital charcoal fragments collected near the base of the deposits of Ano Nuevo Creek yielded a C-14 age of 10,200 + 300 years B.P. This date combined with C-14 dates on charcoal collected from the upper portion of the Ano Nuevo Creek deposits near the Frijoles fault exposure, indicate the fluvial deposits of Ano Nuevo Creek, exposed in the seacliff, were deposited between about 10,500 and about 8,000 years B.P. The presence of the charcoal in these fluvial deposits is probably related to the seasonal burning of grasslands and undergrowth by the Indians to facillitate grass-growing and to aid in the capture of small game. Naturally occurring forest fires due to lightning are excedingly rare in the Santa Cruz Mountains because of the lack of convection in the atmosphere during the dry summer season. Air masses are stable during the summer and fall because of temperature inversion in the atmosphere related to the seasonal formation of advection fogs.

Southeast of the mouth of Ano Nuevo Creek the 100 foot high near-vertical seacliffs in the Purisima Formation are capped by about 20 feet of Quaternary marine terrace deposits. This terrace correlates with the main terrace at Ano Nuevo Point that has been identified as the 105,000 year B.P. terrace, on the basis of amino acid racemization studies and the coldwater aspect of the fauna. The base of the terrace deposits (the wave-cut platform) is about 70-80 feet in elevation southeast of the mouth of Ano Nuevo Creek.

HIKE NORTHWEST; along the beach, crossing the mouth of Ano Nuevo Creek and examine the stream deposits exposed in the seacliff. The cliff exposes pebble conglomerates interbedded with poorly sorted sandstones and siltstones. Beds are discontinuous, channeling and cross bedding are common as are thin interbeds of silts and silty sands. Weakly developed soils are present in some of the fine grained overbank deposits. The deposits are clearly channel deposits and overbank deposits of a small

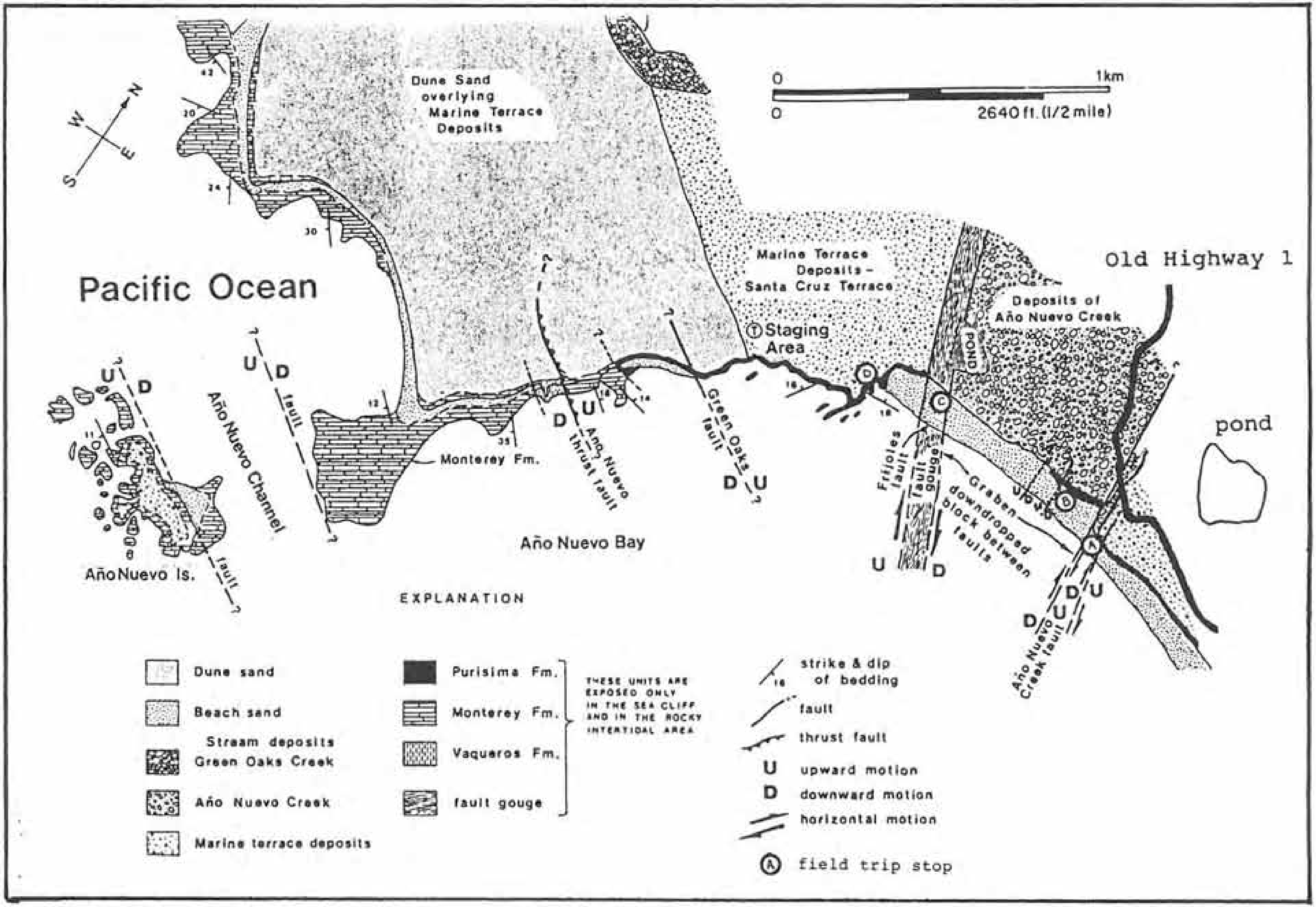
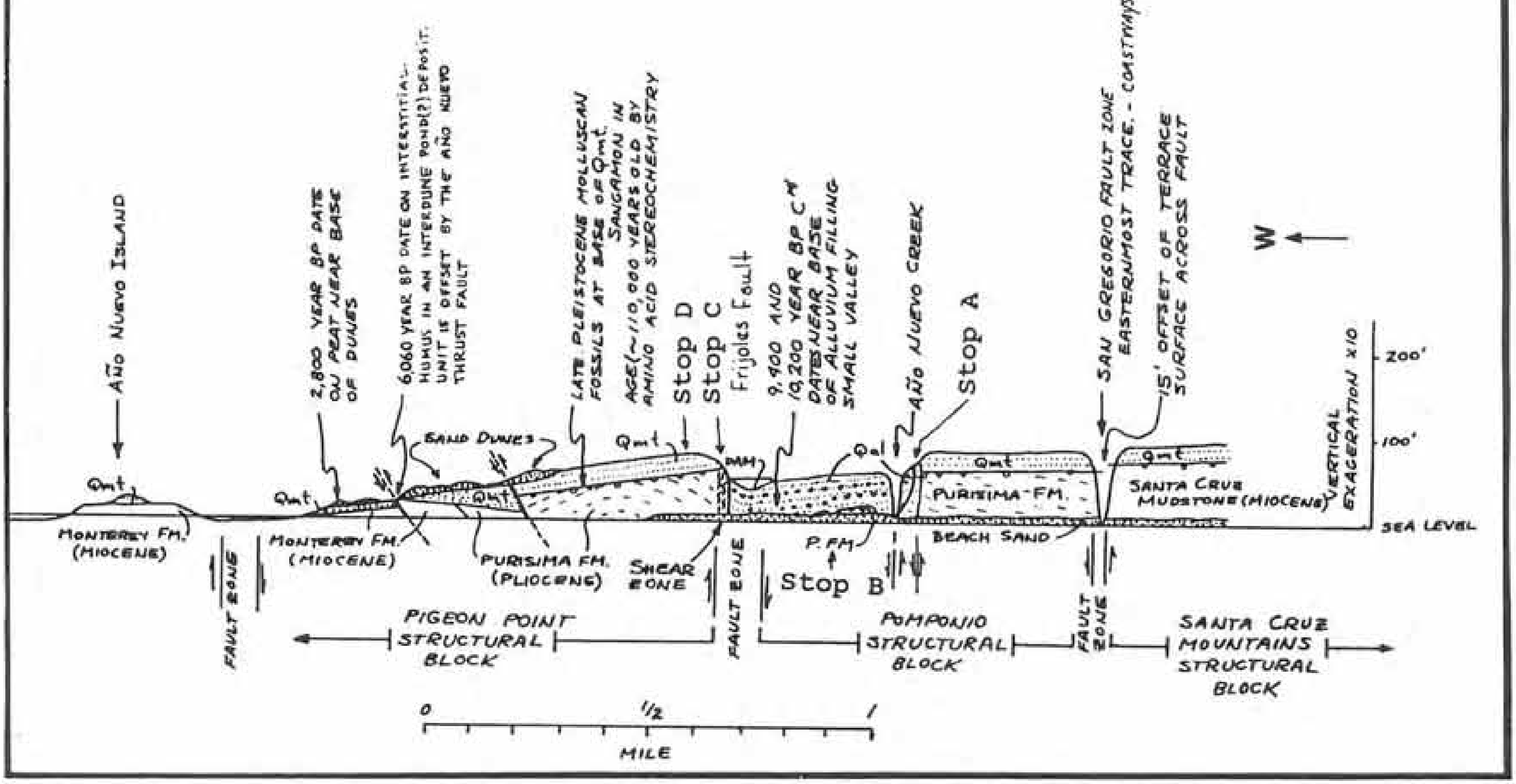


FIGURE 9. Generalized geologic map of Point Ano Nuevo showing field trip stops.

FIGURE 10 GENERALIZED SEACLIFF GEOLOGY

SOUTH SIDE OF PUNTA DEL AÑO NUEVO

SAN MATEO COUNTY



stream. Channel deposits are typically imbricated pebble conglomerates, clast supported, composed of pebbles and cobbles of Santa Cruz Mudstone. The matrix is clay and silty clay. The Santa Cruz Mudstone clasts indicate a fluvial origin, as mudstone bedrock is present only in the heads of the drainage basins of streams that originate northeast of the Coastways fault strand of the San Gregorio fault zone. Santa Cruz Mudstone bedrock is not present southwest of the San Gregorio fault zone in San Mateo County or in the near offshore.

Ano Nuevo Creek deposits are continuously exposed along 1700 feet of seacliff from the mouth of Ano Nuevo Creek northwest to where they are truncated by the Frijoles fault. The beds dip gently 3-5 degrees to the northwest along this section of coastline (Figures 9 & 10), and grade from predominantly pebbble conglomerates near the mouth of the creek to predominantly silts, clays and sandy clays at the northwest end of the beach. The depositional topographic surface forming the top of the deposit also slopes 3-5 degrees to the northwest, as apparently does the bedrock surface that underlies the deposits of Ano Nuevo Creek. The northwest dip is interpreted to be the result of tilting of the deposits to the northwest in the late Holocene.

STOP "B": Small cove along seacliff. Deposits of Ano Nuevo Creek overlie Pliocene Purisima Formation. Carefully examine the contact between the stream deposits and the Purisima Formation, and note the presence of numerous pholas borings in the Purisima Formation along the contact. The pholas borings conclusively indicate that the surface between the Ano Nuevo Creek deposits and the Purisima Formation is a former wave-cut platform, a marine terrace. Careful examination of the outcrops in this cove reveal a small wedge of well sorted sand, not composed of Santa Cruz Mudstone detritus. This thin wedge of sediment is a remnant of the nearshore marine deposits that once covered this wave-cut platform.

Apparently the nearshore marine deposits that originally lay on the wave-cut platform of the terrace were eroded off of the platform by ancestral Ano Nuevo Creek, exhuming the old wave-cut platform. The creek then proceeded to deposit its fluvial sediments on the exhumed erosional surface originally cut by wave erosion.

Examination of the Purisima Formation outcrops west of the mouth of Ano Nuevo Creek reveals that in most areas the contact between the stream deposits and the Purisima is along the old wave-cut platform, exhumed by Ano Nuevo Creek. However Ano Nuevo Creek has also channeled deeply into the bedrock in several areas destroying the wave-cut platform. Extensive areas of intensly bored wave-cut platform, that have had the stream deposits stripped from the surface, are exposed about 50 feet northwest of this cove.

Along the northwest side of the cove a small fault, consisting of two planes of breakage, offsets the Purisima Formation, and the old wave-cut platform that forms the contact between the creek deposits and the Purisima Formation. The basal layers of the deposits of Ano Nuevo Creek are also offset, but the fault is truncated by younger beds within the creek deposits, and does not extend to the surface. The fault is active as it offsets the basal sequence of the deposits of Ano Nuevo Creek that are about 10,000 years old, yet there is no surface evidence of this fault. Although the obvious offset is vertical - northwest side up and southeast side down, it is probable that this fault also experienced right lateral strike-slip movement.

Consider the problem of trying to identify this obviously active fault using standard engineering geologic techniques. Without the luxury of a seacliff exposure it would be impossible to even find this fault, much less determine its level of activity.

The elevation of the wave-cut platform between the Purisima Formation and the Ano Nuevo Creek deposits, northwest of Ano Nuevo Creek is about 10 to 20 feet, about 60 feet lower than the 105,000 yr B.P. wave-cut platform southeast of Ano Nuevo Creek. This suggests the presence of a fault along the valley of Ano Nuevo Creek, that offsets the 105,000 year old wave-cut platform - down to the west and up to the east.

This small section of the exhumed wave-cut platform northwest of Ano Nuevo Creek cannot be dated because no fossil material exists. However, it is obviously correlative with the 105,000 year old wave-cut platform that lies both southeast and northwest of this section of coastline.

The broad, low terrace, visible to the west, that forms Point Ano Nuevo is interpreted to be 105,000 years old, based on amino acid recemization data and the presence of a cold-water fauna (Ken Lajoie, personal communication). The main terrace at Point Ano Nuevo, therefore, is correlative with the Highway 1 platform of the Santa Cruz terrace of Bradley and Griggs (1976). Younger platforms and the 125,000 yr B.P. platform are not present at Point Ano Nuevo.

INTERPRETATION: The Holocene deposits of Ano Nuevo Creek lie in a small late Pleistocene - Holcene graben formed by the Frijoles fault and the Ano Nuevo Creek fault (Figures 8, 9 , & 10). The Ano Nuevo Creek fault is not exposed as it lies along the valley of Ano Nuevo Creek. However, the 60 foot difference in elevation between the Santa Cruz terrace southeast of the creek and the exhumed wave-cut platform exposed northwest of the creek clearly indicates a late Pleistocene - Holocene fault must lie along the valley of Ano Nuevo Creek.

Prior to approximately 12,000 years ago, Ano Nuevo Creek flowed northwestward along what is now the course of Green Oaks Creek and flowed into the ocean on the north side of the point. About 12,000 years B.P. Ano Nuevo Creek was captured, probably by headward erosion, by a high gradient stream flowing along the trace of the Ano Nuevo Creek fault. This short, high gradient stream flowed into the Pacific south of Point Ano Nuevo, and prior to its capture of Ano Nuevo Creek was a low discharge creek with a small drainage basin. After its capture of Ano Nuevo Creek capturing drainage must have experienced a dramatic increase in both discharge and sediment load. Sea-level was still greater than a 100 feet lower than at present and Ano Nuevo Creek, flowing in a valley with a steeper gradient, proceeded to erode the existing marine terrace sediments out of the down-dropped fault block in which it was flowing, exhuming the 105 ka wave-cut platform.

As the creek proceeded to "cleanse" the graben of marine terrace sediments, sea-level was slowly rising, the graben was slowly being lowered along its bounding faults, and the climate was slowly becoming warmer and drier. These three processes interacted to push the stream from an erosional regime toward a depositional regime. Between approximately 11,000 and 8,000 years ago, as sea-level slowly rose Ano Nuevo Creek deposited a sequence of fluvial sediments in the graben it had erosionally stripped of sediments a few thousand years earlier.

The slow, continuing sea-level rise during the mid Holocene was accompanied by rapid surf zone erosion and seacliff retreat, with seacliff retreat being rapid enough to essentially lower base level for Ano Nuevo Creek. Post approximately 8,000 years B.P., Ano Nuevo Creek reverted to its erosional regime and began to entrench into the sediments it deposited betweeen 11,000 and 8,000 years B.P. The return to an erosional regime was accompanied by a slow decrease in precipitation and subsequently runoff, thereby reducing the erosional ability of Ano Nuevo Creek. Following the stabilization of sea-level about 5,500 years B.P., Ano Nuevo Creek has continued to incise its channel into the deposits of Ano Nuevo Creek, largey in response to the slow lowering of base level brought about by coastal retreat due to wave erosion.

ONWARD THROUGH THE FOG: Continue to hike northwest along the beach. In at least two other areas small faults in the seacliff offset the exhumed wave-cut platform and the basal 3-6 feet of fluvial deposits. Again these faults are truncated by younger depositional units, and do not extend to the surface.

Ano Nuevo Creek fluvial deposits become finer grained to the northwest. Several, weakly to moderately developed paleo soils can be found in the fine grained overbank deposits in the seacliff outcrop northwest of Stop "B". It is probable that the change in sediment size is related to overbank deposition along the distal edges of the floodplain. A large obvious wet area in the seacliff marks an area of seepage from a poorly sealed reservoir (pond) that lies several hundred feet north of the seacliff. This seepage is the approximate location of Waddell's Wharf, built in 1864 by William Waddell. The wharf, about 700 feet long, was used for loading lumber, cut in Waddell Creek and transported to the wharf on flatbed cars hauled by horses along a 3 mile long wooden railway. The wharf operated till about 1877, serving several small mills, but declined after Waddell was killed by a grizzly bear in 1875. The wharf burned in the early 1880's. The excavation of the roadway to the wharf, now filled with dark grey, "A" soil horizon, can be identified if one closely examines the soil profile near the top of the seacliff.

In 1974 I found a single piling of this wharf "in place" in the beach at the base of the modern seacliff. The piling was about 3 feet from the face of the cliff, indicating that little if any erosion had occurred in the 110 years since the wharf was built. However, a period of extensive cliff erosion was initiated in the winter of 1977-78 when 10 feet of cliff retreat occurred in a single storm season. In the following 5-6 years over 50 feet of cliff retreat occurred along the coast between Ano Nuevo Creek and the steep cliffs that form the south shore of the point. The piling unfortunately was ripped out of the beach and destroyed during a large storm on December 21, 1979. The rate of seacliff retreat has slowed recently, but active surf erosion occurs along this seacliff each winter. The apparent absence of cliff erosion along this 2000 feet of coast north of Ano Nuevo Creek for 113 years, followed by yearly wave erosion and cliff retreat over the past 14 years suggests a major change in the erosional equilibrium along this section of coast. Consider for a moment that the coast from west of the Frijoles fault to Ano Nuevo Creek has retreated between 60-80 feet during the past 14 years.

STOP "C" - Frijoles fault. Exposed in the seacliff is one of the two large primary faults of the San Gregorio fault zone, the Frijoles fault. It juxtaposes steeply dipping fluvial deposits of Ano Nuevo Creek on the southeast with crushed Purisima Formation on the northwest (Figures 10 & 11).

The Holocene deposits exposed along the seacliff from Stop "C" to the mouth of Ano Nuevo Creek dip uniformly northwest 3-5 degrees for a distance of about 1600 feet. Approximately 50 feet from the

FIGURE 12 (NEXT PAGE) Deformed Holocene sediments along Frijoles fault, South Shore of Point Ano Nuevo. The dark bands are peats that probably formed in a sag pond along the fault.

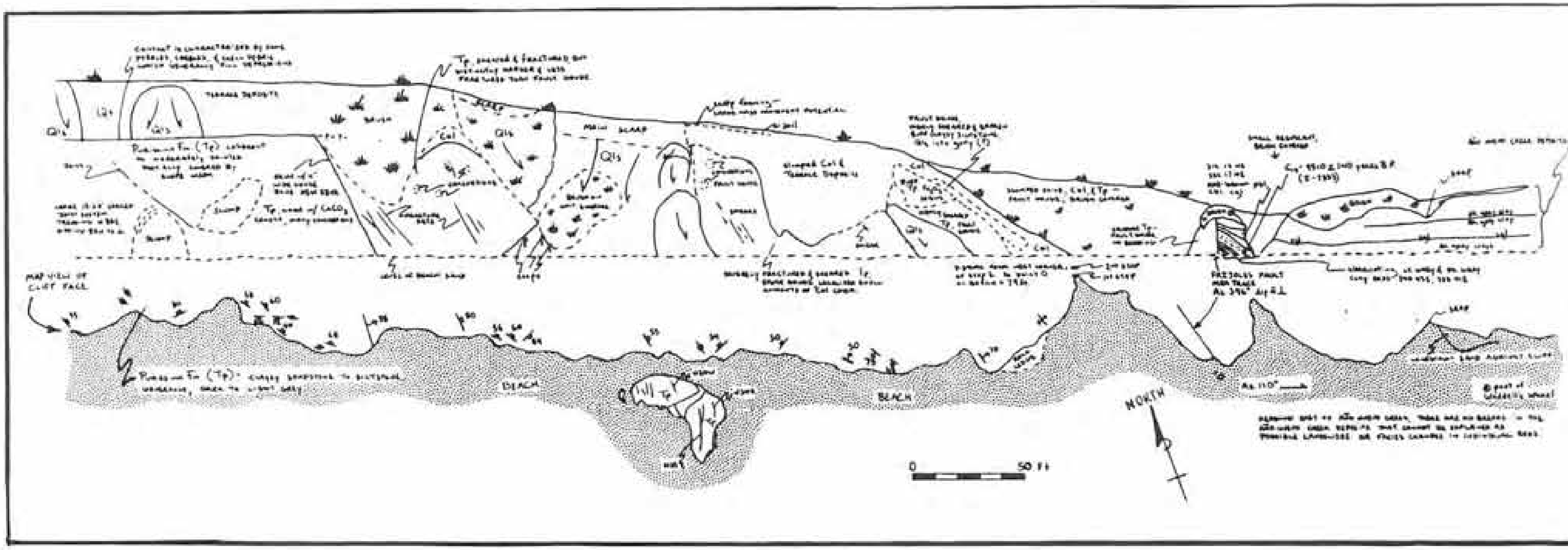


FIGURE 11 Generalized seacliff geology across the Frijoles fault on the South Shore of Point Ano Nuevo. Lower half of diagram is a map view of the seacliff. Zone of intensely sheared rock in seacliff approximately 300 feet in width characterized by landslides and slumps.

Frijoles fault the Holocene beds are abruptly folded upward forming a small syncline in the deposits of Ano Nuevo Creek. This small "drag fold", or fault-bend fold, has formed in response to movement on the Frijoles fault. The fold plunges to the north, suggesting right-lateral strike-slip movement with a vertical component - east side down, west side up. The movement indicated by the drag fold is consistent with the offset. By projecting the wave-cut platform of the terrace in the seacliff northwest of the fault into the fault, and by projecting the wave-cut platform that underlies the Ano Nuevo Creek deposits southeast of the fault into the fault I would approximate the vertical offset of the 105 ka B.P. platform as 100 - 110 feet. The amount of strike-slip offset cannot be approximated at this outcrop.

Northwest of the fault exposure is a broad zone of crushed Purisima Formation in the seacliff. The northwest boundary of this crushed zone (gouge zone) is difficult to define(Figures 8, 9 , 10, 11 & 12). The crushed zone is about 250 feet wide, with varying degrees of deformation within the zone. However, there appear to be three main areas of deformation that correspond to the zones of active movement within the fault zone. The crushed rock is weak and susceptible to both wave erosion and landsliding, with the landslides moving and expanding their main scarps each rainy season. Landslides of this type are not present in seacliffs formed in the upper sandstone member of the Purisima Formation except in shear zones, both at Point Ano Nuevo and 15 miles to the north at San Gregorio Creek where landslides are present in the seacliff along the zones of crushed rocks associated with the San Gregorio fault zone. Cliff height and the slope angle of the cliff face also reflect the effect of intense shearing in the fault zone on slope angle, slope stability and erodibility.

Walk northwest to the end of the beach. Note the difference in hardness, bedding and structures between unfaulted Purisima Formation and the gouge zone along the Frijoles fault.

ONWARD: Hike up the stairs to the top of the cliff and out onto the levee that dams the small pond. The levee is porous and permeable and leaks badly. Compaction is inadequate, and the dam is not stable.

During the heavy rains in 1982-83, a 150 foot long slab of this dam failed and slid off of the face of the dam. Although the main scarp formed down the center of the top of the levee, the dam was not breached, and water did not escape from the reservoir. The levee was repaired the following summer but its stability is still questionable.

Note that the dam for the reservoir lies across the axis of a northwest-southeast trending depression that is the locus of the Frijoles fault. The steep slope to the west is a northeast facing scarp of the Frijoles fault heavily modified by erosion. To the east and southeast is the depositional surface at the top of the Ano Nuevo Creek fluvial sequence exposed in the seacliff east of the Frijoles fault. A broad linear valley has formed along the trace of the Frijoles fault. This linear valley and a well developed set of northeast facing scarps mark the trace of the Frijoles fault to the northwest where the fault crosses the Santa Cruz terrace on Point Ano Nuevo.

Hike west, following the trail along up onto the top of the first marine terrace. Hike off of the trail out across the field to the top of the sea cliff near the first small headland west of the main beach (Figure 9, STOP "D").

STOP "D": This is an excellent vantage point from which to view the geology described in this guidebook, and put it in perspective. To the west and northwest, the Santa Cruz terrace is visible as a broad, nearly planar surface sloping gently to the west. The vegetated remnants of the Ano Nuevo dune field (Holocene) are visible lying on top of the deposits of the Santa Cruz terrace. To the north, the surface trace of the Frijoles fault is marked by the linear topographic trough eroded along its trace. To the east the depositional surface of the Holocene deposits of Ano Nuevo Creek are clearly visible. The Dickerman barn lies on fluvial deposits that form the Ano Nuevo Creek alluvial fan. Further east, the base of the west facing slope of the Santa Cruz Mountains marks the trace of the Coastways fault. Higher forested marine terraces are visible southeast of Ano Nuevo Creek. To the southeast, the Holocene graben formed between the Frijoles and Ano Nuevo Creek faults is visible as the surface gently sloping toward the northwest.

The surface of the Santa Cruz terrace is visible southeast of Ano Nuevo Creek, gradually thinning and finally disappearing just north of the Waddell Bluffs. To the south the Santa Cruz and Western terraces are visible as far south as Scott Creek. Highway 1 lies at the back edge of the Santa Cruz terrace and below the Western terrace. The headland jutting out from the coastline just south of Scott Creek is El Jarro Point, the proposed site of the Davenport Nuclear Power Plant in the 1960's, and the west coast LNG Terminal in the 1970's.

RESUME HIKING; NEXT STOP - A COLD BEER: Hike back to the northeast toward the parking lot that lies just north of the Dickerman barn. Along the path you will walk down the scarp of the Frijoles fault, cross the fault and walk up the tilted Holocene depositional surface of the graben filling deposits of Ano Nuevo Creek.

0.0 19.9

Return to Highway 1 - turn left and proceed north. As you proceed north, note that Highway 1 is now built on an extensive fill prism that bridges the interfan area between the alluvial fans of Ano Nuevo Creek and Green Oaks Creek (Figure 8). To the northeast, the the abrupt base of the mountain front is controlled by the Coastways fault. To the southwest, the Frijoles fault forms an uphill scarp (antislope scarp) across the distal ends of the Holocene fans and the Santa Cruz terrace. The lake to the left (southwest) is the upper reservoir on Rancho Ano Nuevo. The dam for the reservoir is built in the narrow notch where the abandoned drainage of Ano Nuevo Creek has cut through the bedrock ridge formed by the southwest-side-up vertical component of movement along the Frijoles fault.

0.6 20.5

STOP #6 (Honk Stop) - GREEN OAKS CREEK FAN: Note that Highway 1 once again rises as we approach this stop. We are driving up toward the crest of the Late Pleistocene - Holocene fan of Green Oaks Creek. Note that the fan surface slopes uniformly to the southwest and west to the vicinity of a small reservoir. There it is interupted by the northeast facing scarp of the Frijoles fault. The three fans in this area - Ano Nuevo, Green Oaks, and Cascade Creeks - are filling a small graben between the

Frijoles fault, on the southwest, and the Coastways and Ano Nuevo Creek faults, to the northeast. A trench excavated across the Frijoles fault scarp by the USGS in 1975 exposed the fault offsetting marine terrace deposits and the surface soils.

To the northeast, the topographic surface of the Green Oaks Creek fan is offset about 8 feet by the Coastways fault that lies along the base of a well developed fault scarp. The Coastways fault, on a large scale, controls the base of the mountain front.

The excellent geomorphic shape and size of the Green Oaks Creek fan is anomalous, since Green Oaks Creek is a minor creek in a very small drainage basin. The creek seems to be too small to have formed the Green Oaks Creek fan. An alternative interpretation is that the Green Oaks Creek fan may have been formed by Ano Nuevo Creek and transported to its position by right lateral movement along the Caostways fault.

The open grass covered area of lower, undulating slopes in the mountains to the northeast is an ancient landslide deposit. The slide mass unconformably overlies near shore marine deposits of the Western marine terrace, but the landslide toe appears to have been eroded by the 105 ka highstand in sea-level that formed the Highway 1 platform.

Above the main scarp of the slide Seaboard Oil company drilled Atkins #1, a 3535 foot dry hole in 1956. This well drilled on a northwest - southeast trending anticline penetrated mostly fine-grained sandstones, siltstones and mudstones of the Santa Cruz Mudstone. According to local legend, this well was abandoned above its objective; the Santa Margarita Sandstone, when the Texas Poleti well (6 miles south) failed to find any trace of the Santa Margarita Sandstone on the west flank of the Scott Creek syncline.

0.4 20.9

Interfan area - between Green Oaks and Cascade Creek fans. The low linear ridge to the southwest is a bedrock hill capped by terrace deposits. I interpret it to be a narrow block between faults; uplifted along a reverse fault that lies along the southwest side of the hill, and a high angle oblique slip fault that lies northeast of the hill (Figure 8). These faults are part of the Frijoles fault, which consists of a complex of anastamosing oblique-slip and reverse-slip faults from north of Green Oaks Creek to the vicinity of Arroyo de los Frijoles. The abrupt change from a strike-slip fault near the south shore of Point Ano Nuevo to a group of reverse faults and right-lateral oblique slip faults may be related to local convergence along the fault zone.

The Coastways fault lies along the base of the mountains to the right, but does not form any scarps where it crosses the floodplain of Cascade Creek. Proced north across the Cascade Creek fan. Again, note the well developed fan landform.

HORIZONTAL SLIP ON THE SAN GREGORIO FAULT ZONE: Attempts have been made (Weber, 1980, Weber and Cotton, 1980, Weber and Lajoie 1979, 1976) to determine late Pleistocene slip rates for the San Gregorio fault. Although the analysis has been fraught with inconsistencies and unwarranted assumptions, it is obvious that some lateral offset of the marine terrace shoreline angles has occurred (Figure 12). Refer to article in this guidebook. As indicated by Weber (1980) slip rates of 6 - 8 mm/yr are consistent for offsets of both the Western and Santa Cruz terraces. Slip rates as high as 16 mm/yr and as low as 2 mm/ yr can also be justified, depending upon how the shoreline angle offsets are determined. The higher slip rates are consistent with the long term slip rates (Miocene to present) for the San Gregorio fault zone determined by Clark and others (1984), who suggest that the average slip rate over the past 13 million years is approximatly 16 mm/yr.

0.4 21.3

CASCADE CREEK. To the east, three remnants of what is probably the Western terrace dip steeply to the northeast into the Coastways fault. Due to deformation related to faulting and differences in uplift rates on opposite sides of the San Gregorio fault, correlation of terraces across the fault zone is exceedingly difficult. Refer to Plate 1.

0.2 21.5

Road cut to the left (southwest) exposes medium to coarse grained sands and gravels of marine origin. These are deposits of the Santa Cruz marine terrace that have been uplifted along a small reverse fault at the base of the hill. The majority of the Highway 1 platform of the Santa Cruz terrace lies to the west of this small uplifted terrace remnant.

0.3 21.8

CASCADE RANCH QUARRY - LAKE ELIZABETH - About 500 feet east of Highway 1 is a small quarry used for material to construct the dam for the reservoir. A small reverse fault that is part of the Frijoles fault complex is exposed in the wall of a small quarry and also in the spillway of the dam for the reservoir. The exposure is very poor, and would require extensive clearing to make it decipherable, but Tertiary Purisima Formation is clearly thrust out over the deposits of the Santa Cruz terrace. Detailed studies of these exposures and exploratory trenches (Weber and Cotton, 1980, Weber and others, 1981 and Weber, 1980) revealed a complex stratigraphy that records episodes of faulting as colluvial wedges on the foot-wall block. Numerous episodes of faulting are clearly visible in a complex series of colluvial wedges, faults and liquifaction deposits that are present in the wall of the quarry and the exploratory trenches. I estimate that the 105 ka wave-cut platform has been offset approximately 60 to 80 feet along this small fault, and that at least 20 to 30 episodes of fault movement are needed to create this offset. This suggests a long and complex history of movement along this fault during the late Pleistocene and Holocene. **IF YOU WISH TO VISIT THIS OUTCROP PLEASE OBTAIN PERMISSION BEFORE ENTERING FROM CALIFORNIA STATE PARKS AND BEACHES OFFICE IN HALF MOON BAY.**

If you stop here, return to Highway 1. Turn right and proceed north.

0.3 22.1

You are now west of the Frijoles fault complex. To the right, a Pleistocene marine terrace caps a hill of Cretaceous Pigeon Point Formation. The Purisima - Pigeon Point contact is exposed in the seacliffs just south of the mouth of Cascade Creek. Here the contact is an angular unconformity. However, the basal Purisima Formation contact is not exposed north of the mouth of Cascade Creek. The linearity of the Purisima - Pigeon Point contact in this area suggests that it is fault controlled. Exposure in the upland area north of Point Ano Nuevo is exceedingly poor, and most fault mapping consisted of mapping air photo lineaments on aerial photographs.

0.5 22.6

WHITEHOUSE CREEK ROAD. Turn right and proceed 1.2 miles along road to the top of the hill. Stop #7. Overview of Point Ano Nuevo and the San Gregorio fault zone. Note the extent and development of the Santa Cruz terrace and the linear contact between the marine terrace terrain and the steep face of the Santa Cruz Mountains to the south - the trace of the Coastways fault. The Frijoles fault bounds the narrow bedrock hill out on the Santa Cruz terrace and traces of the fault lie along linear valleys in the low hills south and west of this stop. Higher terraces are poorly developed and/or preserved but are present west of the Coastways fault in this area.

END OF TRIP. Return to vehicles. Retrace path to Highway 1, turn left (south) and proceed back to Santa Cruz. If you are so inclined stop at the Whaler in Davenport - a nice bar.

There is something fascinating about science.
One gets such wholesome returns of conjecture
out of such a trifling investment of fact.

Mark Twain

MARINE TERRACES
A BRIEF INTRODUCTION

Gerald E. Weber

INTRODUCTION

Marine terraces are wave-cut benches characteristic of exposed, tectonically active coastlines. They are old ocean floors formed by wave erosion in the surf zone that have been subsequently stranded by a combination of tectonic uplift and sea level drop. They typically occur as narrow, bench-like steps, in the coastal topography within a few hundred meters of present sea level. Each terrace (Figure 1) consists of a gently sloping erosional platform backed by a near vertical sea cliff at its inland edge. The intersection of the sea cliff and the erosional (abrasional, wave-cut) platform is the shoreline angle (strandline, back edge), which closely approximates the sea level that formed it and is virtually horizontal.

The wave-cut platform is commonly covered by a regressive sequence of shallow marine deposits, overlain by sub-aerial fluvial and colluvial deposits, and wind blown sand (Figures 1 & 2). The veneer of near shore marine sediments (sand, gravel, cobble) are often characterized by a thin cobble and boulder lag directly overlying the wave-cut platform, that may contain fossil shells. Terrace deposits are thickest along the back or inner edge of the terrace and thin progressively toward the seaward or distal edge (Figures 1 & 2). Marine deposits are not always present on the wave-cut platform. Along the distal edges of broad terraces, nearshore marine deposits have often been completely removed from the platform by sub-aerial erosion, and fluvial deposits directly overlie the platform.

The formation of the abrasional platform and the deposition of terrace sediments cam be clearly observed today along cliffed coastlines; where the modern wave-cut platform covered with a thin layer of beach sediment, backed by a near vertical seacliff provides a modern day analog (Figures 1 & 2).

AGE DETERMINATION

Unfortunately, there is no easily applied, fool-proof method of determining the absolute age of either a marine terrace platform and shoreline angle or the deposits that cover the wave cut platform. However, several aspects of terrace formation, allow reasonable interpretations to be made of terrace ages for many flights of terraces. Refer to Lajoie (1986) for a more complete discussion of terrace dating techniques.

1. Since marine terraces are cut into rising coastlines, it is obvious that each episode of terrace cutting must occur

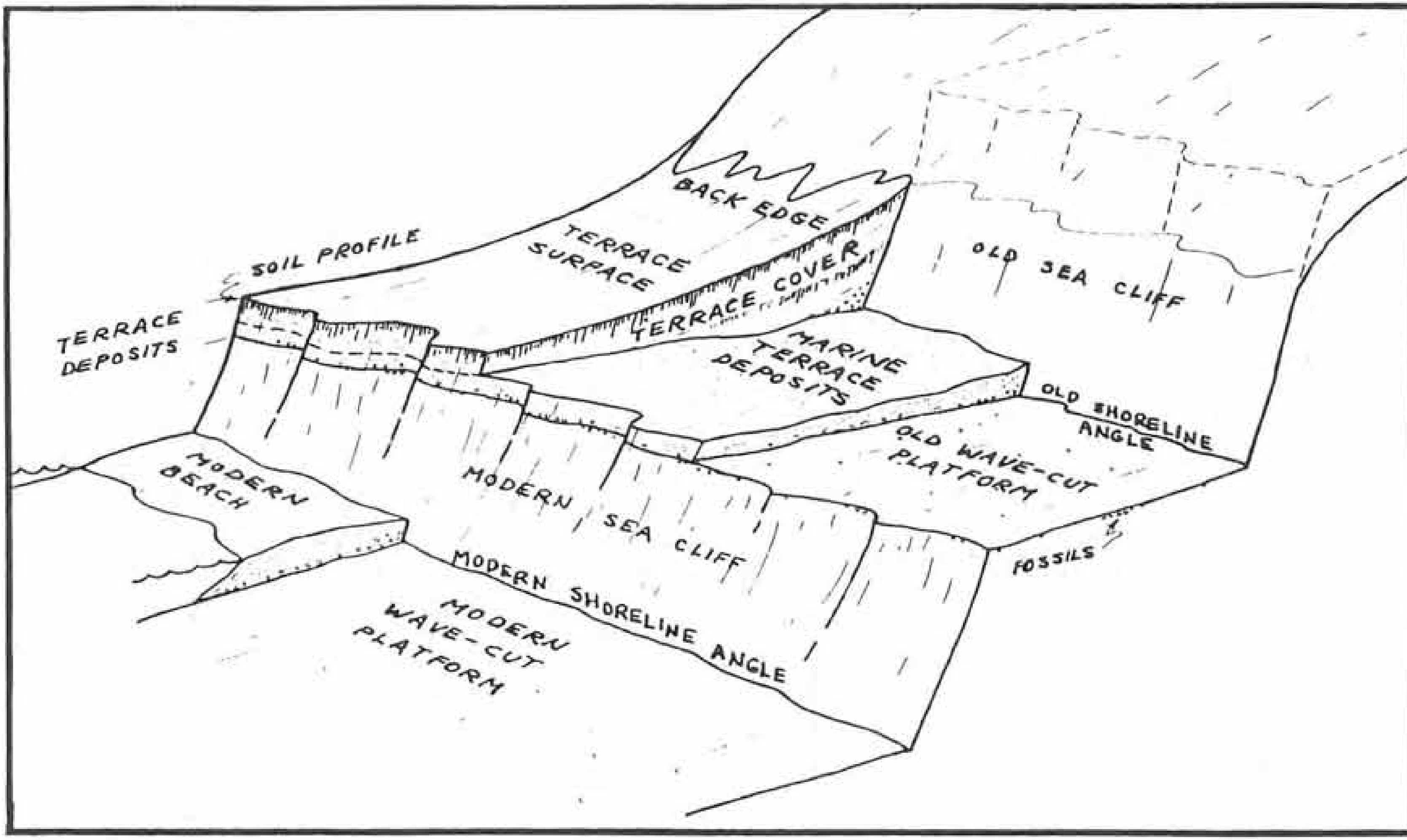


FIGURE **1** Diagram of the major elements of a marine terrace. Indicates relationship of wave-cut platform to the overlying terrace deposits and the shoreline angle.

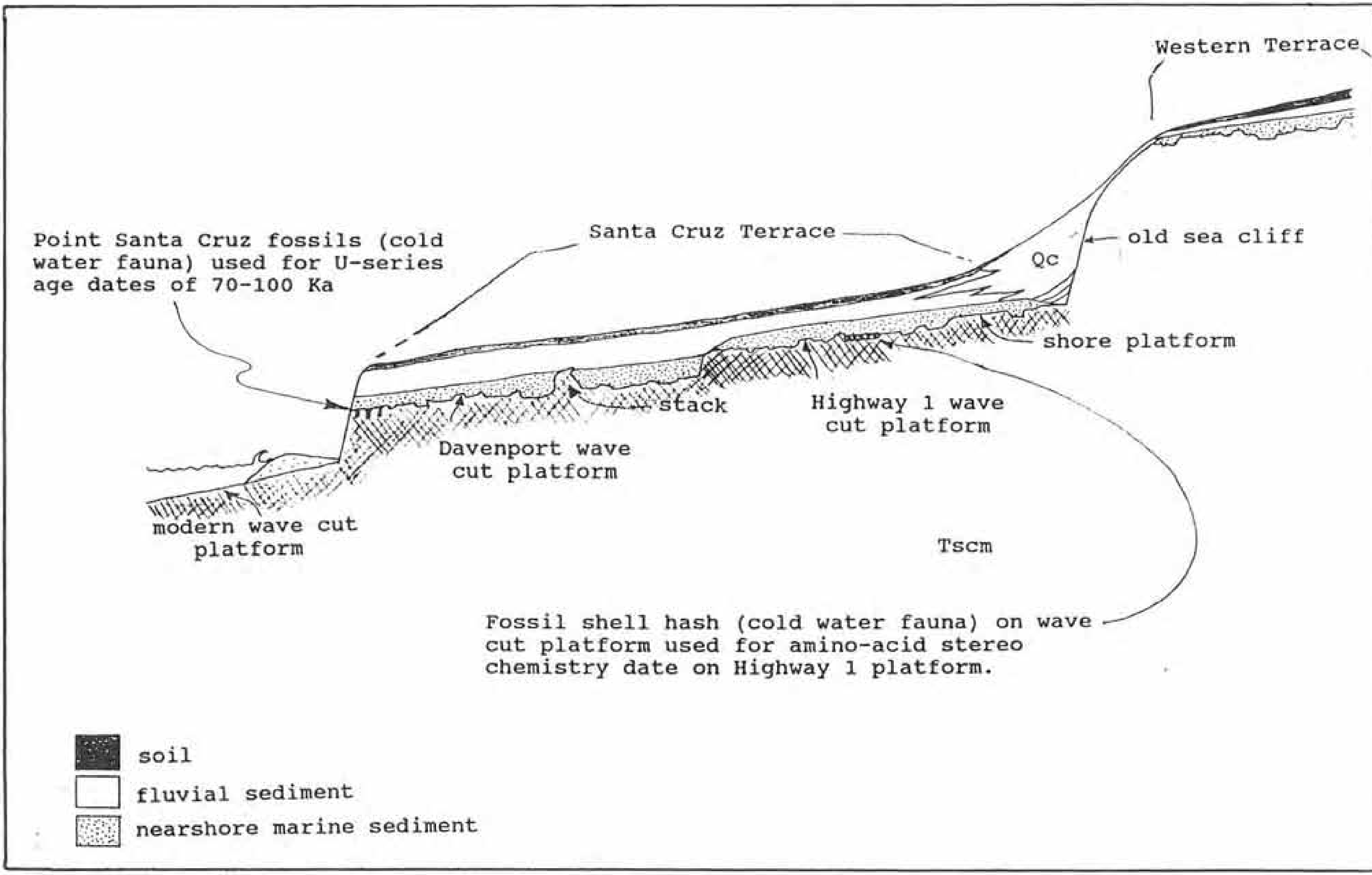


FIGURE 2. Diagrammatic cross section of the Santa Cruz marine terrace om west Santa Cruz. Shows relative positions of the Davenport and Highway 1 wave cut platforms.

during a rising sea level, culminating with a highstand of sea level. Therefore, a sequence of marine terraces is generally regarded to be the record of glacio-eustatic sea-level highstands recorded as a series of erosional notches on a rising coastline.

2. Each terrace shoreline angle must therefore be associated with a sea-level highstand; and as pointed out by Lajoie (1986) **"...the task of dating a particular strandline is reduced to correlating it with a specific peak on the New Guinea paleosea-level curve using one or more absolute or relative dating techniques."**

3. Evidence of lowstands of sea-level (strandlines) are typically not preserved in the geologic record as they are destroyed by wave erosion during subsequent sea-level fluctuations.

4. As indicated by Lajoie (1986) the most detailed datum from which to determine terrace ages is the paleosea-level curve obtained by subtracting tectonic uplift from the record of emergent coral-reef strandlines (terraces) on the Huon Peninsula of Papua New Guinea. This terrace sequence, accurately dated using U-series techniques on corals provides a paleosea-level curve back to about 340 ka B.P. (Figure 3, from Lajoie, 1986, Bloom et al., 1974, Chappell, 1983).

Graphic Technique of Age Determination

It is possible using the New Guinea sea-level curve to approximate, or determine the ages of individual terraces using a simple graphic technique (Figure 4). The shoreline angle elevations of the terraces are plotted on the vertical axis, and lines are drawn between the shoreline angle elevation and sea-level highstands. If uplift rates are constant, then all of the lines connnecting shoreline angle elevations to sea-level highstands will be parallel (Figure 4).

This technique can be used effectively a number of ways, but it is most reliable if at least one and preferably two of the terraces can be dated independently using either absolute or relative techniques. This allows the determination of uplift rate for the coastline. Unfortunately, most absolute and relative age dating techniques are dependent upon the preservation of marine fossils either on the paleo wave-cut platform or in the marine terrace deposits.

Absolute and Relative Dating Techniques

Fossils are generally scarce in marine terrace deposits. If present, fossils are typically found in a basal lag on the wave-cut platform, or in the burrows the organisims formed in the wave-

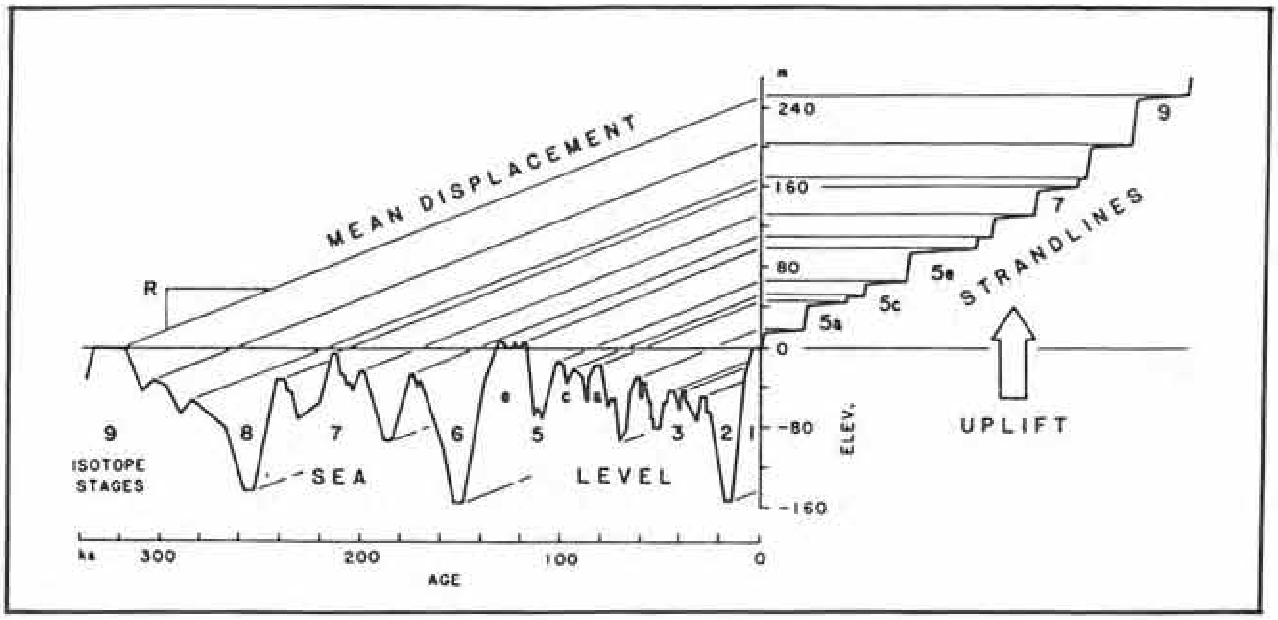


Figure 3. Sea-level curve derived from U-series dated corals in terrace sequence on the Huon Peninsula, Papua New Guinea. Curve is modified from Chappell (1983), Oxygen isotope stages are from deep-sea cores (Shackleton and Opdyke, 1973). Diagram modified from Lajoie, 1986.

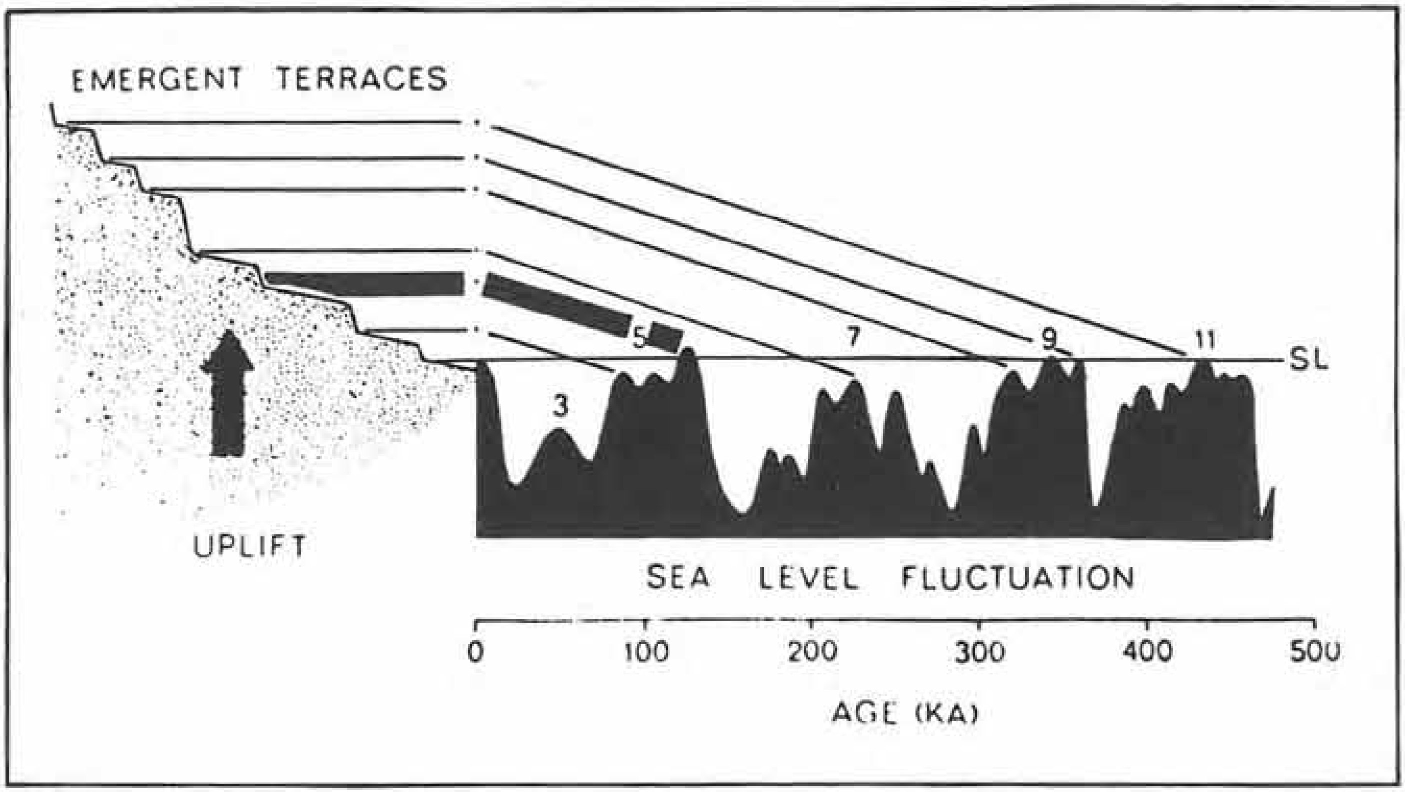


Figure 4. Graphic technique of determining ages of marine terraces and uplift rates. Each terrace must correlate with a sea-level highstand. The slope of the line connecting each highstand to the elevation of the terrace (uplift line) is the uplift rate. If uplift rate is constant then all the uplift lines will be parallel. If the age of one terrace is known, each terrace in the sequence can be reliably dated if uplift rate was constant. Even if terrace ages are not known use of a "trial and error" technique will allow a unique matching of terraces to highstands of sea-level, if uplift was constant.

cut platform. These holes in the platform (pholas borings) are attributed to rock boring clams, and are present on almost every wave-cut platform, regardless of age. They are one of the methods of clearly and unambiguously identifying old wave-cut platforms in the field. Only rarely, however, are fossils actually found in the burrows the boring clams formed on the platform.

Absolute age dates can be obtained from marine fossils through either Uranium series dating or, if young enough, C-14 techniques. However, U-series techniques are of questionable reliability when used on molluscs, and are best suited for use on corals. This obviously restricts the usage of this technique to tropical latitudes.

Relative dating techniques include, 1) amino acid stereochemistry studies of fossil shell material, 2) faunal associations indicating relative water temperature, and 3) geomorphic studies of the modification of paleo sea cliffs (Hanks and others, 1984). All of these techniques allow the determination of relative ages, and are particularly useful in correlation of terraces along the coastline.

These techniques are often difficult to use to determine absolute age. However, even the relatively simple determination of whether a fauna has a warm water or cold water aspect can be extremely useful. As indicated elsewhere in this guidebook, the Santa Cruz terrace is obviously either Sangamon or post Sangamon in age. It contains two wave-cut platforms, which both display cold water faunas. It is therefore reasonable to interpret the two wave-cut platforms as corresponding to the 82 ka and 105 ka highstands of sea-level present on the Chappell sea-level curve. Since the 125 ka sea-level highstand contains a fauna with a warm water aspect, both platforms within the Santa Cruz terrace are excluded from being the 125 ka platform because of the cold water aspect of the faunas.

Even without any absolute or relative terrace ages, the graphic technique can be used to analyse terrace ages, if one assumes either constant or changing uplift. The graphic technique allows for a trial and error determination of the best correlation between terraces and sea-level highstands (Lajoie, 1986, Weber, 1982).

Constant Uplift

The effects of constant uplift are shown in Figure 5. Rapid constant uplift will result in a greater number of terraces, with generally greater vertical separation between terraces. Slow, constant uplift results in fewer terraces with less vertical separation. In both instances the lines connecting the elevation of the shoreline angle to the sea-level highstand will remain parallel, and the best graphical correlation of terraces with paleosea-level highstands will simultaneously yield both the most reasonable uplift rate and terrace ages.

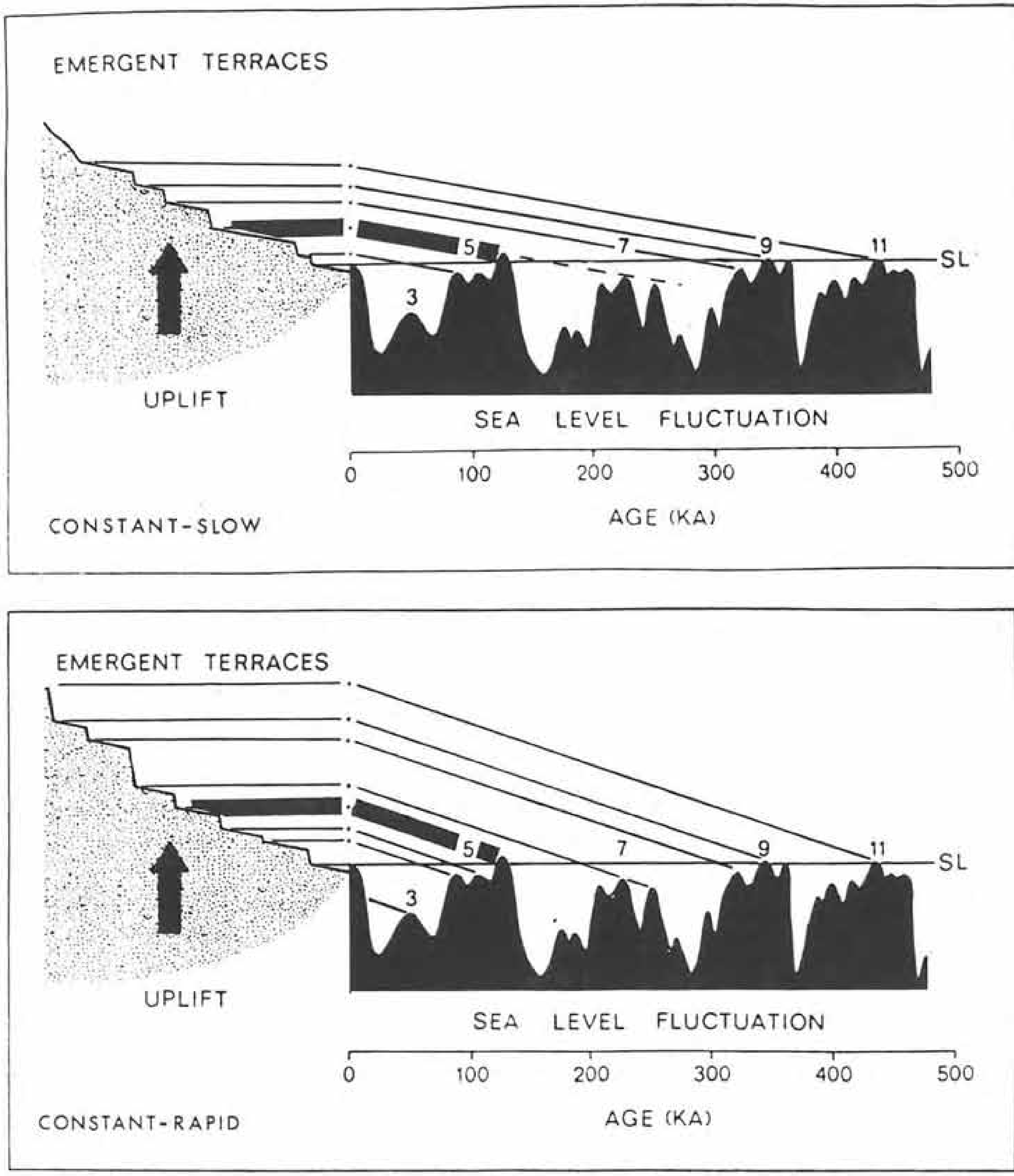


FIGURE 5. Diagrammatic relationship between emergent marine terraces and sea level fluctuations. The slopes of the diagonal lines are uplift rates. The sea level curve and oxygen isotope stages (3,5,7,9 and 11) are from Shackleton and Opdyke (1973).

Non-uniform Uplift

Figures 6 & 7 reflect the effects of decreasing, increasing, and variable uplift on the graphic technique. Occassionally, terraces will not be the result of uniform uplift (Weber, 1982). In these instances one should systematically assume either a decreasing or increasing uplift rate; and attempt to determine if the terrace sequence is best explained by systematic changes in the uplift rate. If neither of these assumptions allows a reasonable correlation of paleosea-levels with terraces, it is probable that the uplift rate is highly variable and is neither constant nor changes systematicaly.

In summation, it shold be noted that although absolute dating of marine terraces is often impossible, the combination of relative dating techniques with the graphic analysis, generally reduces the variables sufficiently to allow a reasonable determination of the terrace ages.

FIELD MAPPING

Accurate mapping of marine terraces, including the determination of both the vertical and horizontal position of the shoreline angle can be quite difficult. Poor exposure of the wave-cut platform and the terrace deposits (except for the modern sea cliff) is typical. Thick wedges of talus and fluvial deposits (Figure 1), and also paleo-dune deposits bury the shoreline angle, and the wave-cut platform. The paleo sea cliff has usually been degraded by sub-aerial erosion, and is further obscured by vegetation and soils.

Because of poor exposure, terraces are typically mapped on the basis of their topographic or physiographic expression, and correlated on the basis of elevation. This technique, while acceptable for regional or reconnaissance studies, is insufficient for detailed studies of coastal tectonics, since it does not provide adequate information on the position of the shoreline angle. If field work is to provide data that are adequate to determine uplift rates, slip rates on faults, etc., the position of the wave-cut platform and the distribution of marine terrace deposits must be accurately mapped. Bill Bradley's studies of platform shape (Bradley, 1958, Bradley and Griggs, 1976) my study of the San Simeon terraces (Weber, 1982), and the P.G. & E. Final Report on the Diablo Canyon Long Term Seismic Program (1988) are examples of the detail necessary to accurately determine uplift rates and fault slip rates.

Determination of the elevation of the wave-cut platform, even along the front edge of a terrace remnant, will allow a more accurate determination of the elevation of the shoreline angle as graphically indicated in Figure 8. The wave-cut platform is projected inland as shown, and its location is based on the following assumptions:

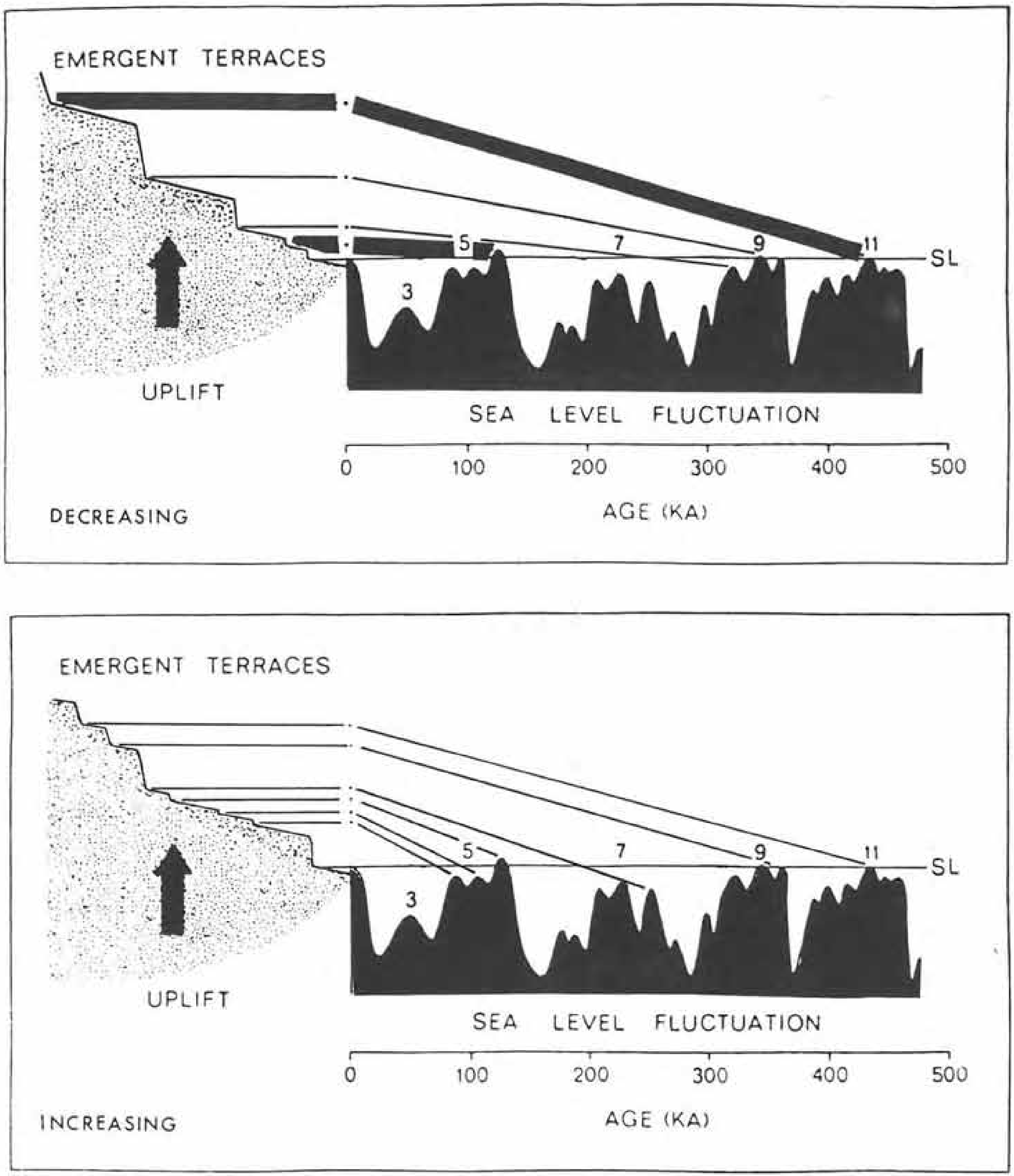


FIGURE 6. Diagrammatic relationship between emergent marine terraces and sea level fluctuations. The slopes of the diagonal lines are uplift rates. The sea level curve and oxygen isotope stages (3,5,7,9 and 11) are from Shackleton and Opdyke (1973).

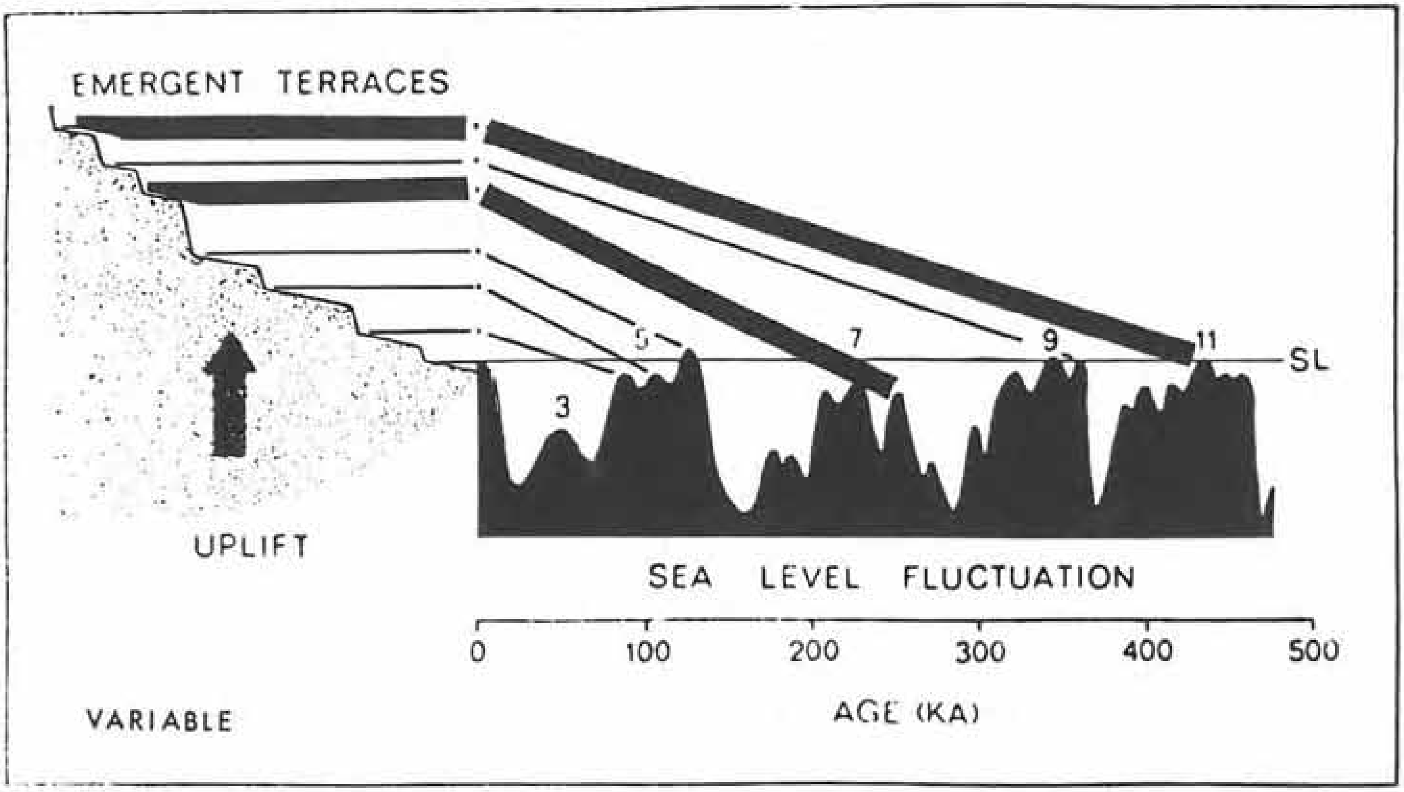


FIGURE 7. Diagrammatic relationship between emergent marine terraces and sea level fluctuations. The slopes of the diagonal lines are uplift rates. The sea level curve and oxygen isotope stages (3,5,7,9 and 11) are from Shackleton and Opdyke (1973).

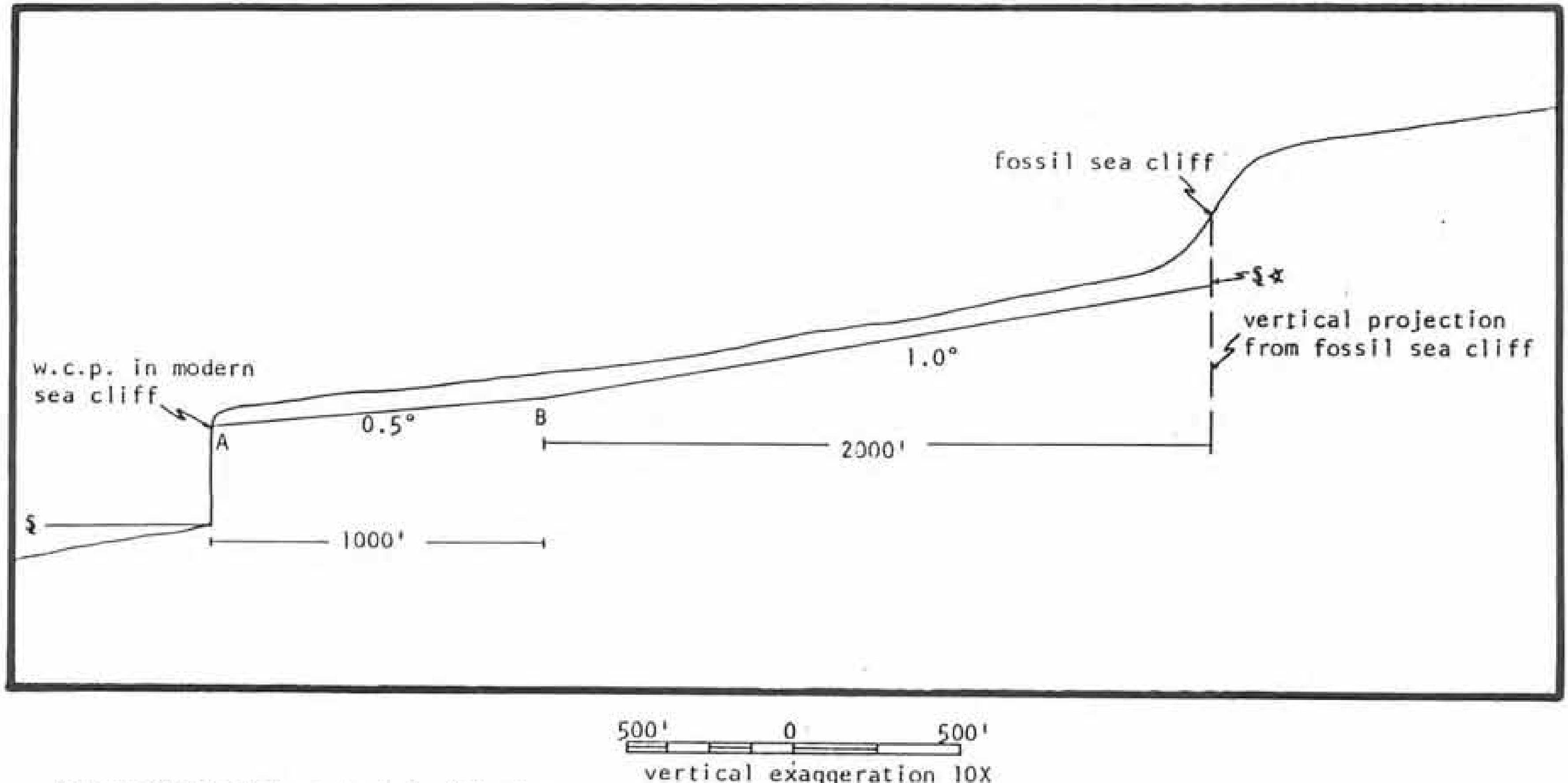


Figure 8: Technique Used to Calculate
Shoreline Angle Elevations

If elevation of wave cut platform (w.c.p.) in modern sea cliff and horizontal distance to fossil sea cliff is known; elevation of shoreline angle (§☆) can be calculated.

Example: Elevation at point A = 30'
1000' @ tan 0.5°= 9' elevation at point B = 39'
2000' @ tan 1.0°= 35' elevation at = 74'

1. The inner portion of the wave-cut platform (from the shoreline angle seaward to about 2000 feet offshore) slopes 1 degree seaward.

2. The outer portion of the wave-cut platform (greater than 2000 feet from shore) slopes about 1/2 degree seaward.

3. The paleo sea cliff lies near the inflection point on the face of the erosionally modified paleo sea cliff.

These assumptions on the natural slope of wave-cut platforms is based on studies of platform shape on Ben Lomond Mountain (Bradley and Griggs, 1976).

Obviously, this simplistic technique for approximating the vertical position of the shoreline angle is fraught with problems, particularly in areas where terraces have been tilted or otherwise deformed. However, it generally provides a means of limiting the position of the shoreline angle, and allows the quick recognition of multiple abrasional platforms and the presence of tilting or warping of terrace platforms. When used with shallow refraction seismic techniques and hand-leveling for elevation control it is possible to accurately map the shape of the buried platform and determine the position and elevation of the shoreline angle.

MARINE TERRACE DEFORMATION

Since marine terrace shoreline angles are originally horizontal, they provide excellent strain gagues for the measurement of crustal deformation. However, they will preferentially record vertical deformation more clearly than horizontal deformation. Along tectonically active coastlines, accurate mapping of the marine terrace shoreline angles and determination of the terrace ages, has become the accepted technique for investigating coastal tectonics. Consequently, terrace studies have become increasingly important in analysing the recent tectonic history of coastlines (particularly nuclear power plant sites) and in analysing fault activity. For a complete discussion of the relevance of marine terrace studies in coastal tectonics refer to Lajoie (1986).

Vertical Deformation

The highest rates of vertical ground displacement (Lajoie, 1986) are related to volcanic tumescence and glacio-isostatic rebound. Both processes can result in sustained uplift rates greater than 100 mm/yr, and Lajoie indicates that terrace studies at Iwo Jima indicate average uplift rates of 200 mm/yr over the past 800 years.

Tectonic deformation, conversely, is generally slower with the highest vertical uplift rates varying between 4-10 mm/yr. As pointed out by Lajoie (1986) these high uplift rates are usually related to minor secondary faults and do not reflect the long term tectonic uplift of the continental land masses, where most rates are less than 2 mm/yr. In some areas, the rapid uplift rates are produced by intermittent co-seismic displacement events along faults. Terrace studies have long been associated with emergent shorelines, and although areas of crustal depression are probably as common as those uplifting, they do not lend themselves well to onshore studies. Tectonic deformation can also manifest itself as tilting, folding and faulting of terrace sequences. For a detailed discussion of the coastal tectonics refer to Lajoie (1986).

Terrace deformation is best analysed from plots of the shoreline angle on a cross section drawn parallel to the shoreline. This technique was first used by Alexander (1953) in his study of the terraces between Santa Cruz and Aptos, and has been used in essentially all terrace studies since. Examples of this technique include Plate 1, this guidebook, Figure 13 of Bradley and Griggs (1976), and numerous plots in Lajoie (1986). This method is particularly useful for both correlating and analysing the deformation of terrace sequence across large faults, and through area of folding and tilting. As one would expect, this technique is particularly useful for studies of vertical deformation, but is less useful for analysing horizontal deformation.

Horizontal Deformation

As indicated by Lajoie (1986) and Weber (this field guide, 1980, 1982) and by P.G. & E.(1988) lateral fault movement is difficult to interpret from the marine terrace shoreline angle record. Despite the numerous problems involved with such studies I believe that reasonable slip rates for fault offset can be estimated (Weber, this guide, and P.G. & E., 1988). Other evidence of sense of lateral fault movement, but not the amount, can be determined from marine terraces include the orientation of drag folds in the terrace platforms (Lajoie, 1986 and Lajoie and others 1979).

In summation, marine terraces are excellent datums from which to determine coastal tectonics. They are particularly useful in determining uplift rate, the extent of tilting and folding and vertical fault displacement, because they are horizontal datums. Terraces are more difficult to use in analysing lateral fault movement, but careful studies can result in reasonable approximations of lateral slip rate.

LATE PLEISTOCENE SLIP RATES ON THE SAN GREGORIO FAULT ZONE AT POINT ANO NUEVO, SAN MATEO COUNTY, CALIFORNIA

Gerald E. Weber

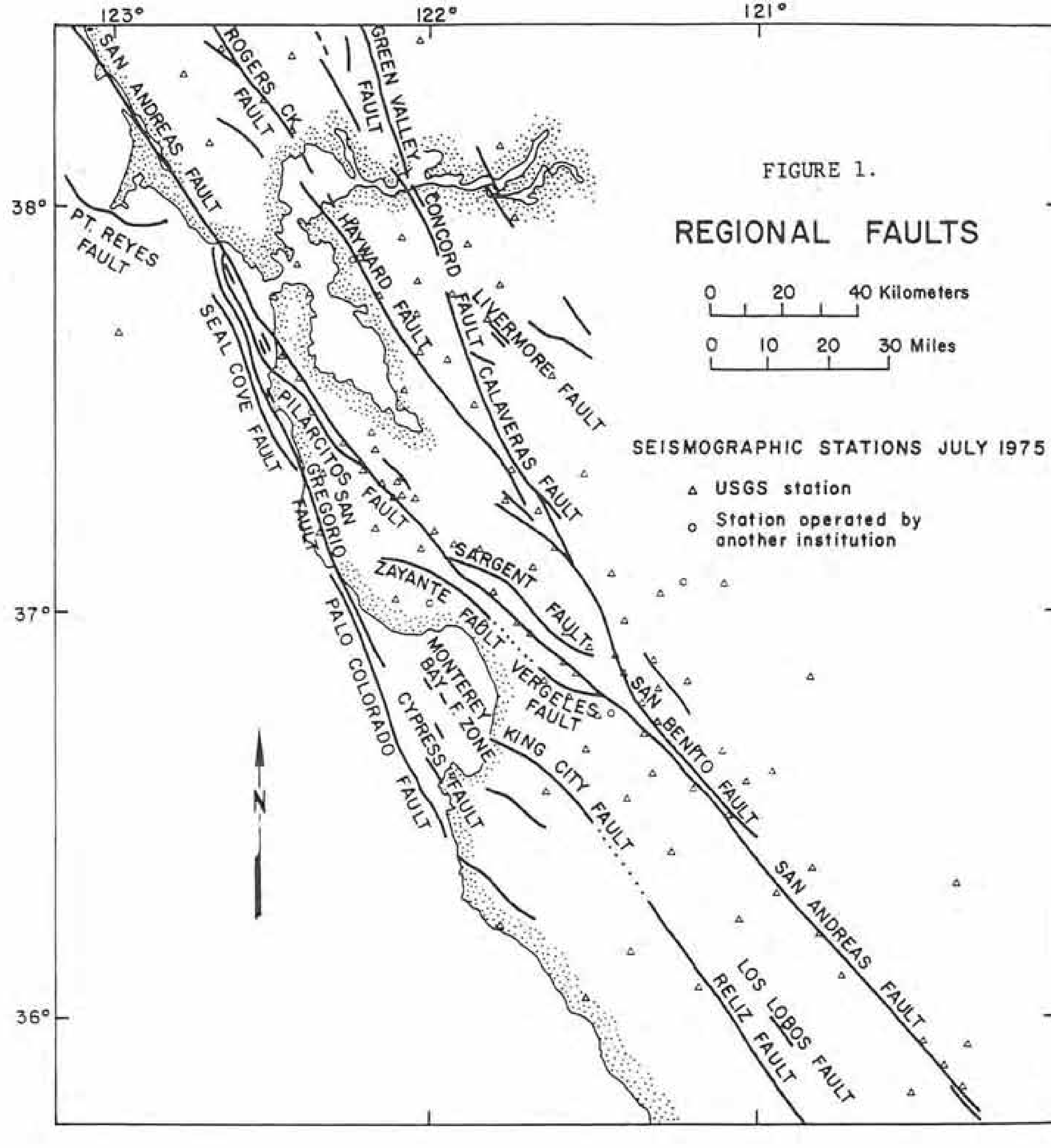
INTRODUCTION

Although the San Gregorio fault zone has been long recognized as a major, active fault of the San Andreas system in central California (Figure 1), there is little agreement on either the late Tertiary or Pleistocene slip-rates along the fault. Graham and Dickinson's (1978) summary of evidence for offset of sedimentary basins across the San Gregorio fault indicates the following: Movement initiated in the middle Miocene, appproximately 12-15 million years (my) ago, with approximately 115 km of right lateral slip having occurred since the initiation of movement. The average rate of movement is approximately 7.5 - 9.5 mm/yr, but is interpreted to be slowly decreasing during the late Pleistocene. Clark and others (1984) determined late Tertiary slip rates on the order of 13 - 16 mm/yr for the fault by determining the displacement of bedrock units across the fault. Other studies (Silver and Normark, Eds. 1978), Nagle and Mullins (1984) all indicate offsets of 70 - 150 km over the past 10 - 12 million years, suggesting average slip rates of 6 to 16 mm/yr throughout the late Tertiary and Quaternary.

Quaternary slip rates are known with less certainty, largely because of the small area in which the fault zone is exposed on shore (Figure 1). Throughout most of is length the San Gregorio fault zone and its related faults lie underwater on the continental shelf. However, at Point Ano Nuevo in southern San Mateo County the fault zone cuts across a well developed sequence of marine terraces and Pleistocene fluvial deposits, which allow rough approximations to be made of Pleistocene rates of movement.

The analysis presented here is based on field mapping by the author during the 1970's and early 1980's, and previous analysis of shoreline angle offsets (Weber and Lajoie, 1979; Weber and Cotton 1980, Weber 1980). Although the data are rough, I believe they clearly indicate continuing late Pleistocene and Holocene offset along the two major primary fault strands and numerous secondary faults within the San Gregorio fault zone (Figure 2).

The two types of Quaternary deposits offset along the fault zone at Point Ano Nuevo are marine terraces, and the alluvial fans and fluvial deposits of Ano Nuevo, Cascade, and Green Oaks Creeks.



Weber and Associates

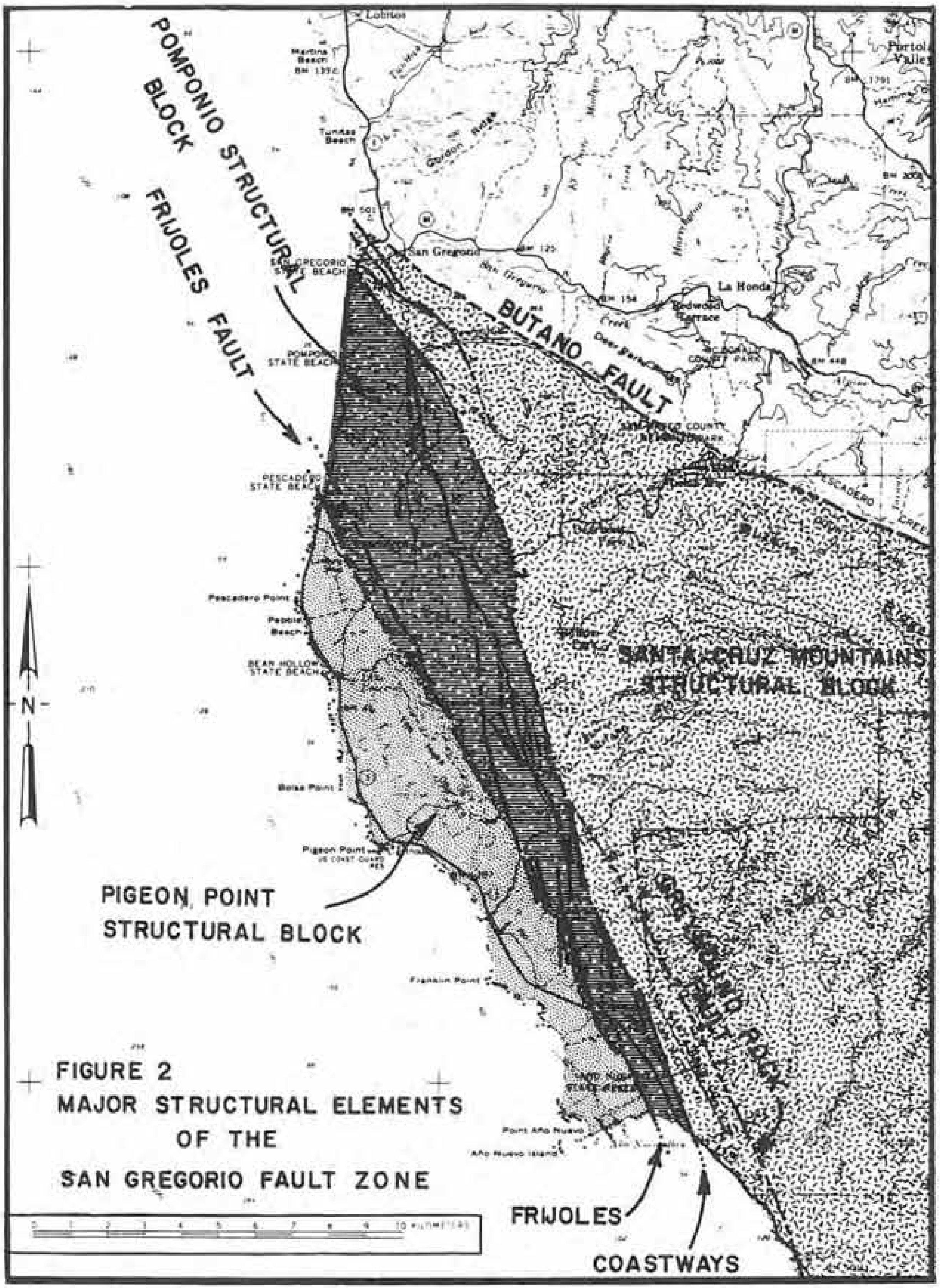


FIGURE 2
MAJOR STRUCTURAL ELEMENTS
OF THE
SAN GREGORIO FAULT ZONE

Base: San Francisco Bay Region Topographic Map,
Sheet 3 of 3, U. S. Geological Survey, 1970, 1:125,000

MARINE TERRACES

The marine terrace shoreline angle (Figure 3) is the line formed by the intersection of the sea cliff and the wave cut platform. Theoretically, shoreline angles are excellent referrence markers because they have a known relationship to the sea-level that formed the seacliff and wave cut platform, and the shoreline angle is essentially horizontal. Consequently, shoreline angles form perfectly horizontal "time lines", from which subsequent deformation can be easilly measured.

Vertical deformation of shoreline angles (tilting, folding, fault offset, uplift, etc.) has been recognized and described by numerous workers (Alexander, 1953, Bradley and Griggs 1976, Weber and Lajoie, 1979, Weber, 1980), and are neatly summarized by Lajoie (1986). However, horizontal deformation, although known to have occurred, has been more difficult to accurately measure (Weber and Lajoie, 1979; Weber and Cotton, 1980, Weber, 1980, 1982, Weber and others 1982, Weber and others 1987).

Using marine terrace shoreline angles to determine offset along a fault is difficult, largely because of the difficulty of accurately mapping the shoreline angle of the marine terrace across faults. The following problems are inherent to detailed mapping of marine terrace shoreline angles.

1. Marine terraces, particularly the higher and older terraces, are present as scattered erosional remnants. Most of the original terrace has been destroyed by erosion, and perhaps only 10 - 20% of the original shoreline angle has been preserved.

2. The shoreline angle is always buried by thick deposits of colluvium and alluvium. It is often difficult to determine the horizontal position of the shoreline angle to within 50 - 75 feet. Vertical position of the shoreline angle must also often be approximated because of thick alluvial/colluvial cover (Figure 4).

3. The normal irregularities of the wave-cut platform, including shore platforms, stacks, etc., add great complexity to the shape of the nearshore area. These features can obscure the horizontal position of the shoreline angle by many hundreds of feet. Platform irregularities are directly related to the lithology of the coastline. For example; a comparison of wave-cut platforms at Santa Cruz with San Simeon indicates: Variations in erosional resistance are far greater in the Franciscan melange at San Simeon than in the relatively massive sandstones of the Purisima Formation, and the wave-cut platform in Franciscan melange is far more complex and irregular.

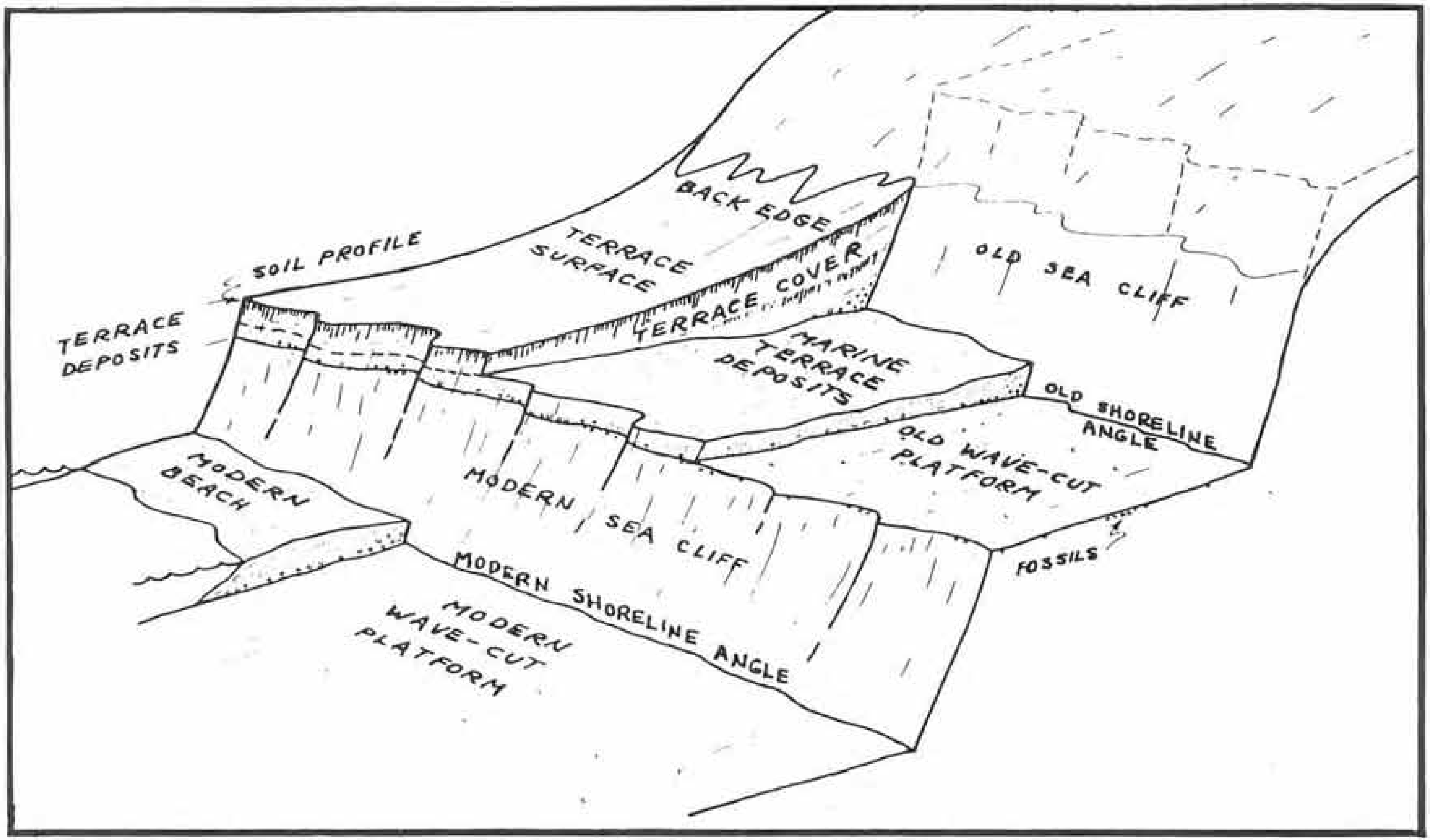


FIGURE 3 Diagram of the major elements of a marine terrace. Indicates relationship of wave-cut platform to the overlying terrace deposits and the shoreline angle.

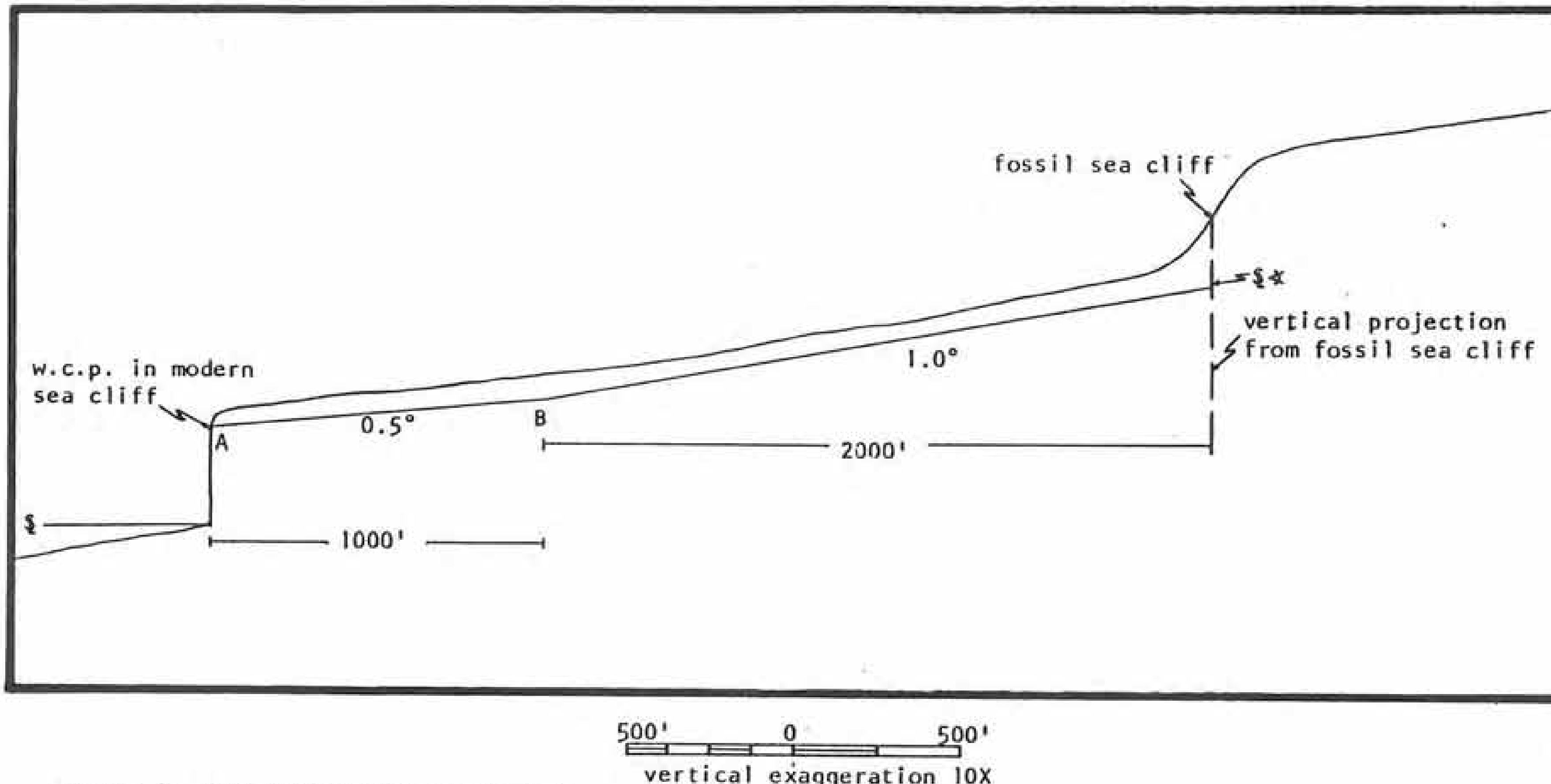


Figure 4: Technique Used to Calculate
Shoreline Angle Elevations

If elevation of wave cut platform (w.c.p.) in modern sea cliff and horizontal distance to fossil sea cliff is known; elevation of shoreline angle (§*) can be calculated.

Example: Elevation at point A = 30'
1000' @ tan 0.5°= 9' elevation at point B = 39'
2000' @ tan 1.0°= 35' elevation at = 74'

4. The natural complexity in the shape of the coastline prevents accurate prediction of the former position of the shoreline angle. Headlands, and headland-bay beaches add to the difficulty of determining the position of the shoreline angle. Cliffed, rocky shorelines are generally not linear, but contain numerous headlands, coves, stacks, etc. that add to the complexity of the shape of the coastline, and the shoreline angle.

5. If faults juxtapose rocks of widely varying resistance to erosion, wave erosion will differentially erode out the softer rock, and the shoreline angle will form along the fault. Similarly, if the fault is parallel to the trend of the coastline, wave erosion will tend to form the shoreline angle along the fault. These geologic settings may make it impossible to determine offset using marine terrace shoreline angles.

Consequently, except for lower terraces, the reconstruction of the position of the shoreline angle requires the smoothing of the shoreline angle between a few control points at the back edge of the terrace remnants. One must also assume that in each instance the paleo shoreline crossed the fault cleanly (that the paleo shoreline had not eroded along the fault). Idealy, the paleo-shoreline would cross the fault at nearly right angles, without major indentations, similar to the present shoreline where it crosses the San Gregorio fault zone along the south shore of Point Ano Nuevo (Figures 2 & 6).

If the paleo shoreline angle has actually been formed along the fault plane as along the Greyhound Rock fault, north of Greyhound Rock (Figure 5), it is impossible to determine accurate slip rates from shoreline angle offset.

SAN GREGORIO FAULT ZONE - POINT ANO NUEVO

At Point Ano Nuevo the San Gregorio fault zone is about 2 miles wide and contains numerous active primary and secondary fault traces. Accurate mapping of the faulting is difficult because of the poor exposure resulting from a combination of thick soils and colluvium, dense vegetation, and 200 years of cultivation of the terraces. Two interpretations of the fault pattern are indicated in Figure 6. The best interpretation of the fault pattern and probable offset of the shoreline angles of the Western and Santa Cruz terraces is shown on Figure 7. Refer to Weber, (1980) for a more complete discussion of alternate interpretations for fault patterns near Point Ano Nuevo.

The complexity of the fault pattern, and the presence of convergent slip (exhibited as small reverse faults) makes reconstruction of the shoreline angles exceedingly difficult. Although the majority of the displacement is occurring on only two faults (Coastways and

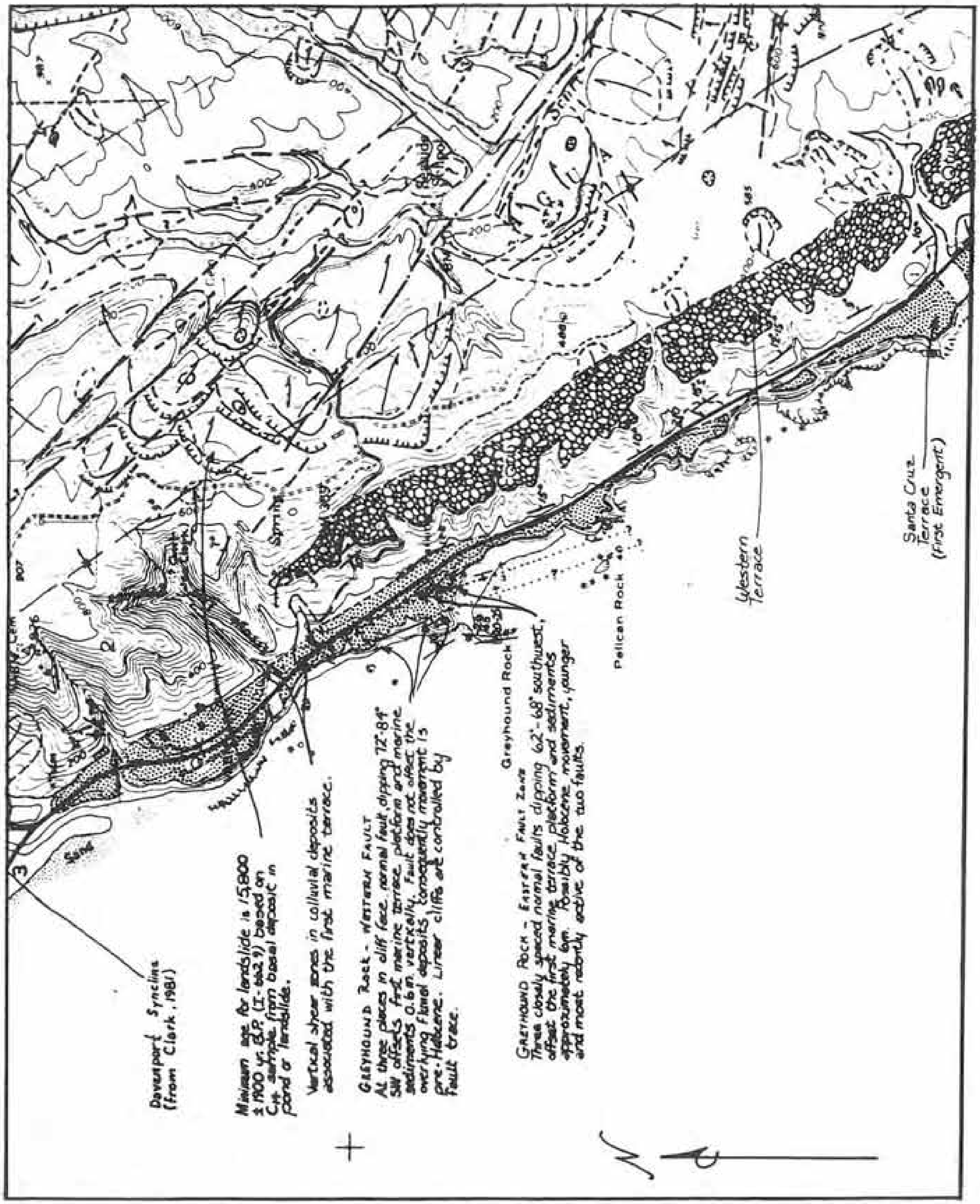


FIGURE 5. Map of Quaternary faults and marine terrace deposits near Greyhound Rock.

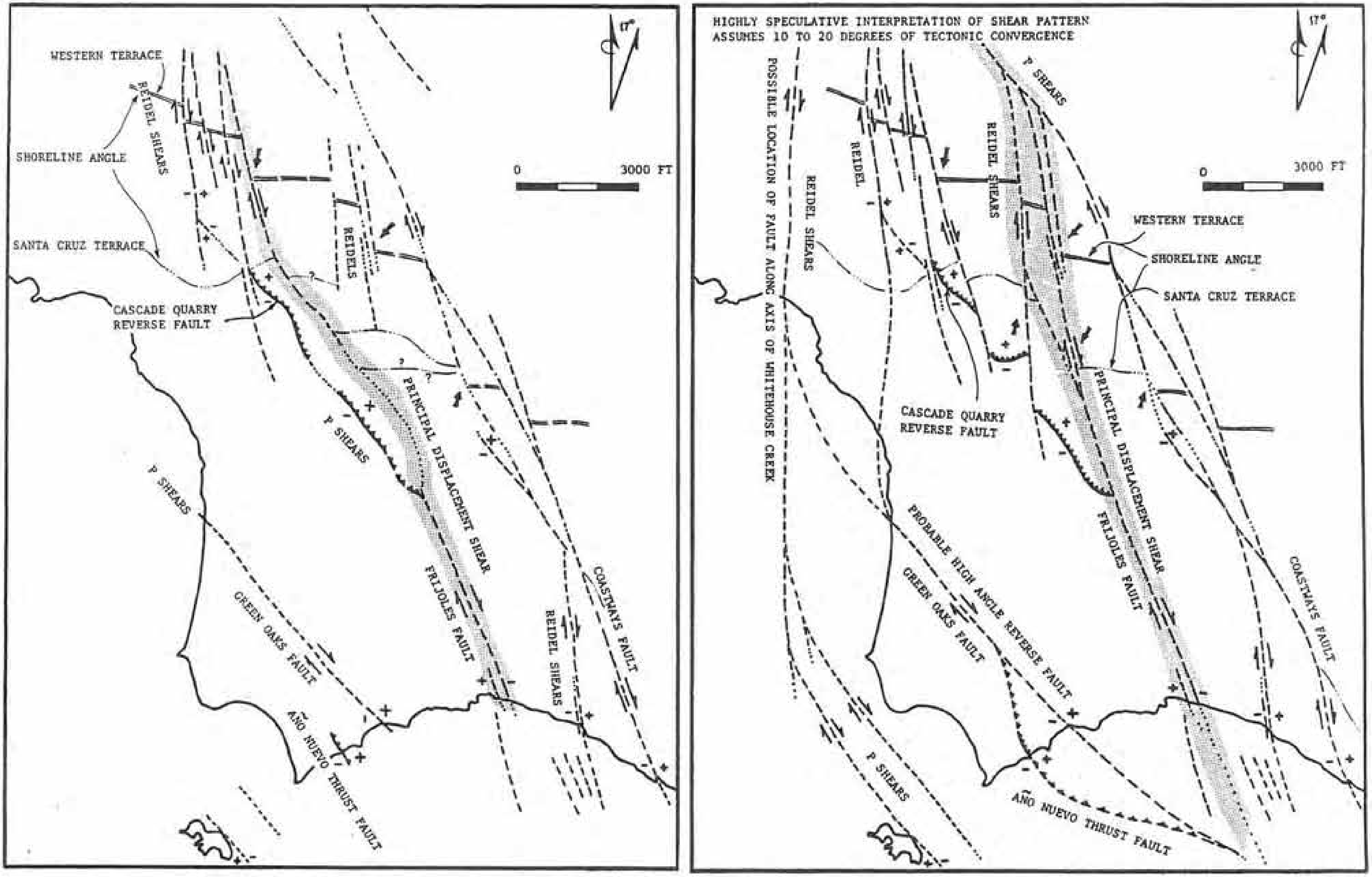


Figure 6. Two interpretations of Quaternary faulting at Point Ano Nuevo, San Mateo County, California. Field data will support either interpretation.

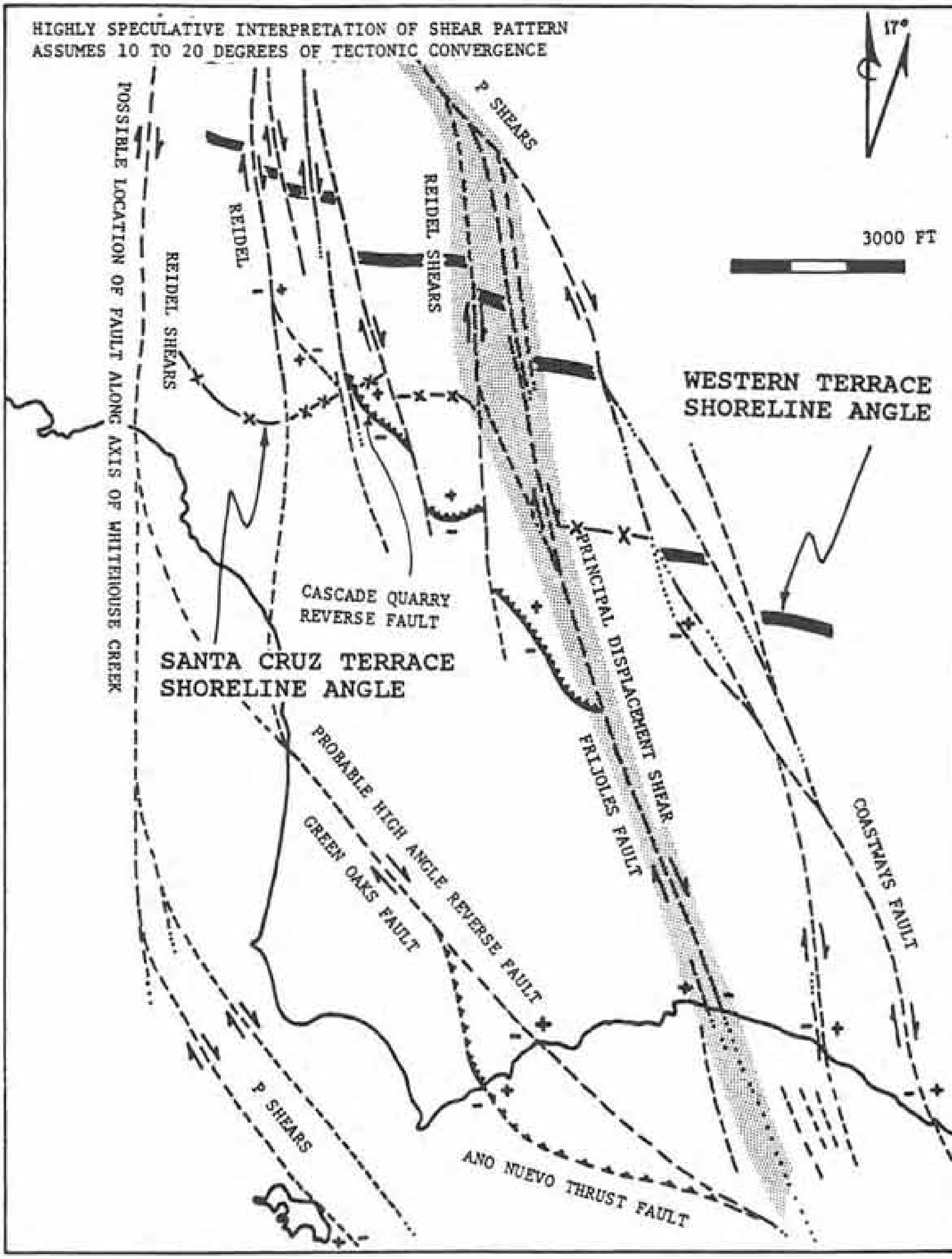


Figure 7. Preferred interpretation of offset of marine terrace shoreline angles along the San Gregorio fault zone at Point Ano Nuevo.

Frijoles), there are at least 7 seven secondary faults along which it is possible to clearly demonstrate either late Pleistocene (past 105 ka) or Holocene movement. Reconstruction of the shoreline angles across the Coastways fault is complicated by the presence of the alluvium filled graben that lies between the Coastways and Frijoles faults, and the burial of the Western terrace by a giant paleo-landslide north of Ano Nuevo Creek. Stream erosion and thick deposits of colluvium near Lake Elizabeth prevent accurate reconstruction of the shoreline angles across the Frijoles fault.

As indicated in Figure 7, the estimates of terrace offset along individual fault traces suggest that movement rates have been continuous during the late Pleistocene. Best estimates for late Pleistocene - Holocene slip rates from offset shoreline angles are:

Western Terrace	2300 m in 230 ka	=	10 mm/yr
Santa Cruz Terrace	945 m in 105 ka	=	9 mm/yr

The analysis is based on the Santa Cruz terrace shoreline angle having formed about 105 ka B.P., and the Western terrace shoreline angle having formed about 230 ka B.P. Estimates of average slip rates across the San Gregorio fault during the late Pleistocene appear to be on range from 6 - 10 mm/yr, with the best estimate being 9 - 10 mm/yr. Most of this slip is occuring on the two principal displacement shears (primary traces) the Frijoles and Coastways faults. This rate compares favorably with the long term late Tertiary slip rates determined by other investigators.

OFFSET STREAMS AND FANS

As indicated on Figure 8, (Geologic map of Quaternary deposits at Point Ano Nuevo), the normal drainage patterns of Ano Nuevo Creek and Cascade Creek appear to be offset along faults of the San Gregorio faults zone. Cascade Creek flows southwest out of the mountain front, swings to the north and flows out to sea over a 1000 feet northwest of the projected path of the creek as it leaves the mountain front (Figure 8).

Ano Nuevo Creek flows southwest from the mountain front (Figure 8) turning abruptly south as it crosses the Coastways fault. The creek is deeply incised into its deposits. Northwest of Ano Nuevo Creek are a series of abandoned drainage channels (Figure 8) one of which is presently ocupied by Green Oaks Creek. As these channels are deeply incised into the Purisima Formation bedrock, it seems unlikely that they were incised by a creek as small as Green Oaks Creek. Clearly, Green Oaks Creek is "underfit" for the channel it flows in, and it is highly improbable that the channel it flows in was cut by this small creek. It seems probable that the channel lying between the Green Oaks and Ano Nuevo Creek fans was once occupied by Ano Nuevo Creek. Ano Nuevo Creek abandoned those drainages when it was captured by a small, high gradient stream that was eroding headward along the Ano Nuevo Creek fault.

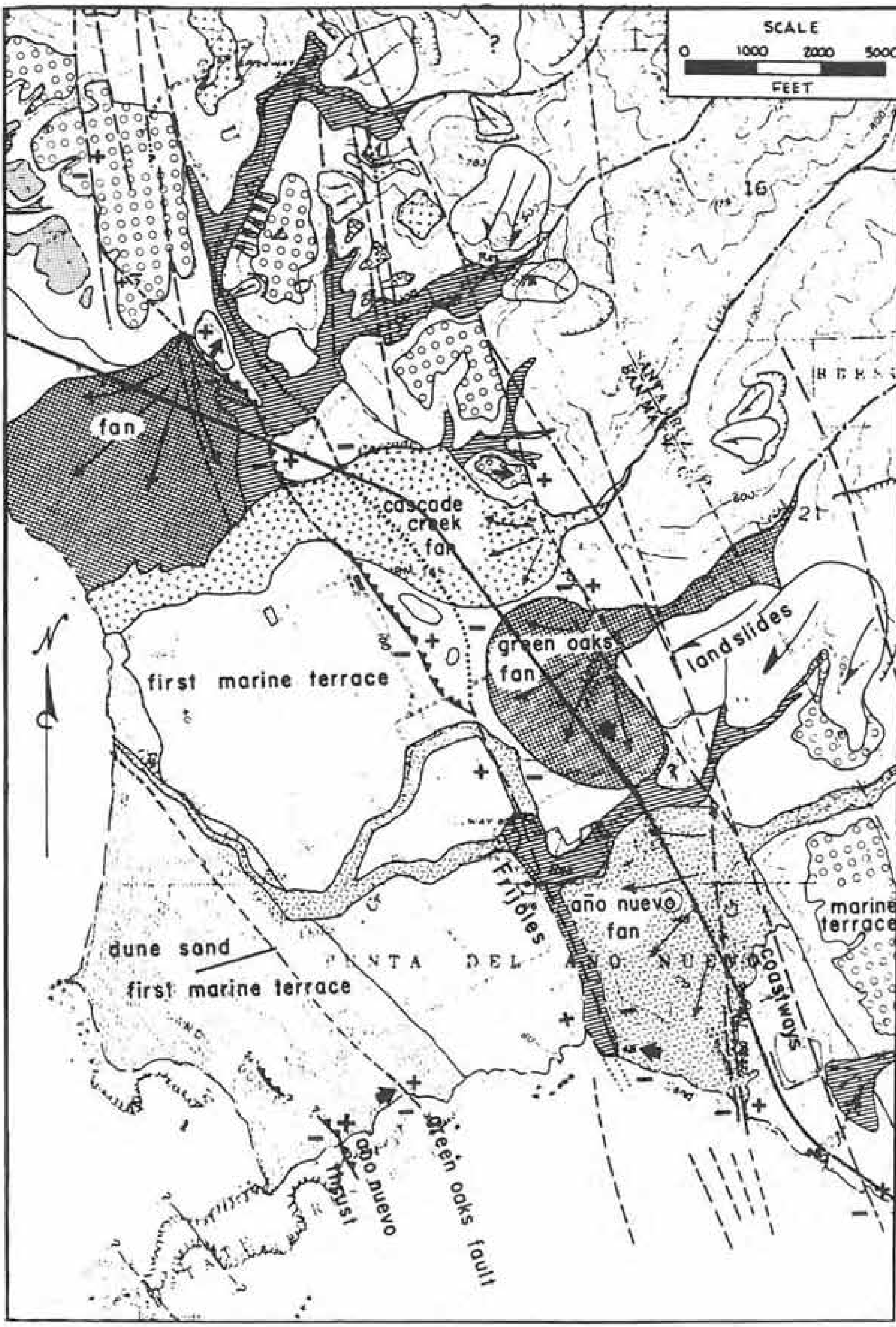
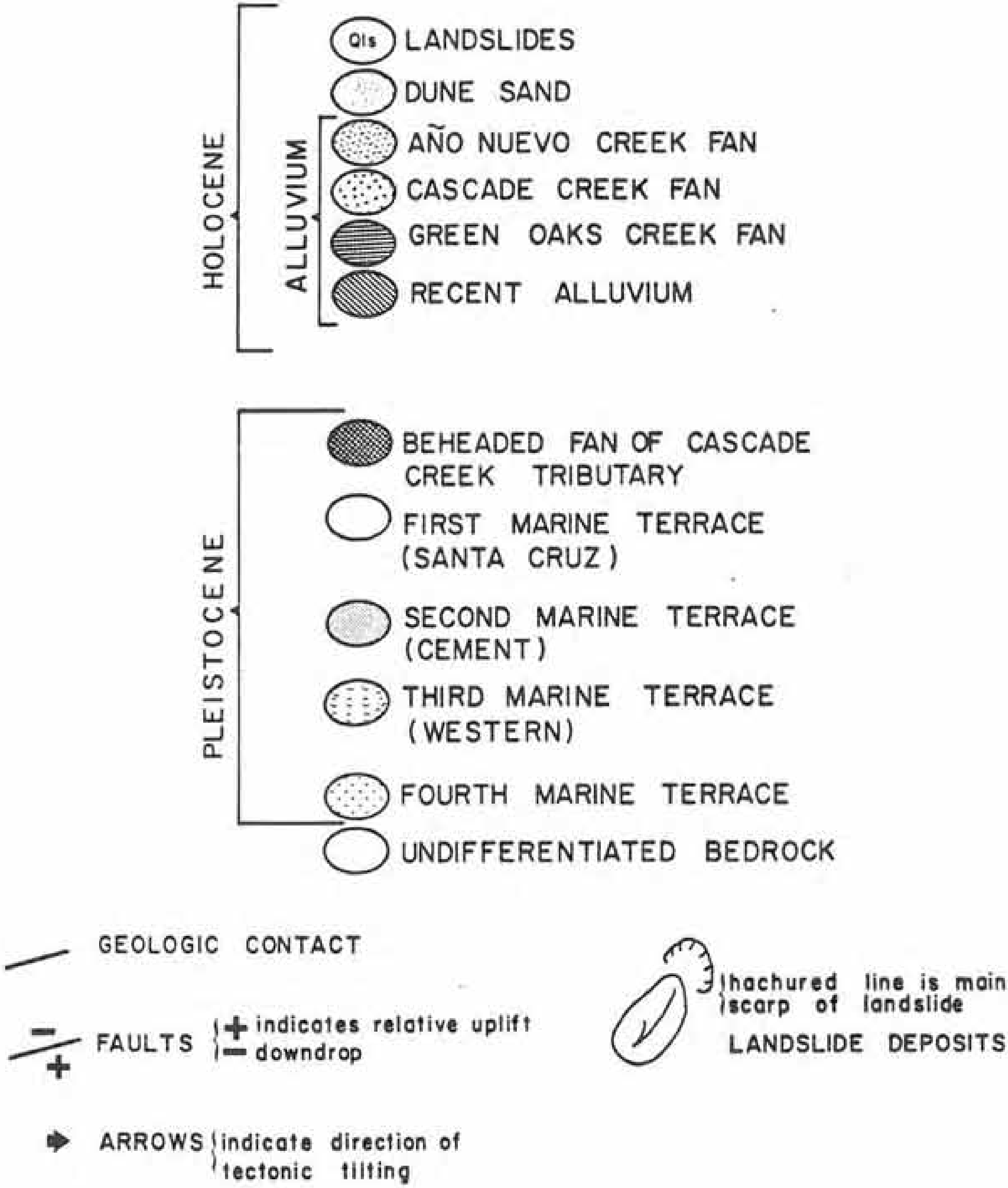


Figure 8. Explanation on next page.



QUATERNARY DEPOSITS & LATE PLEISTOCENE FAULTS at POINT AÑO NUEVO, SAN MATEO CO, CALIFORNIA. by: Gerald E. Weber

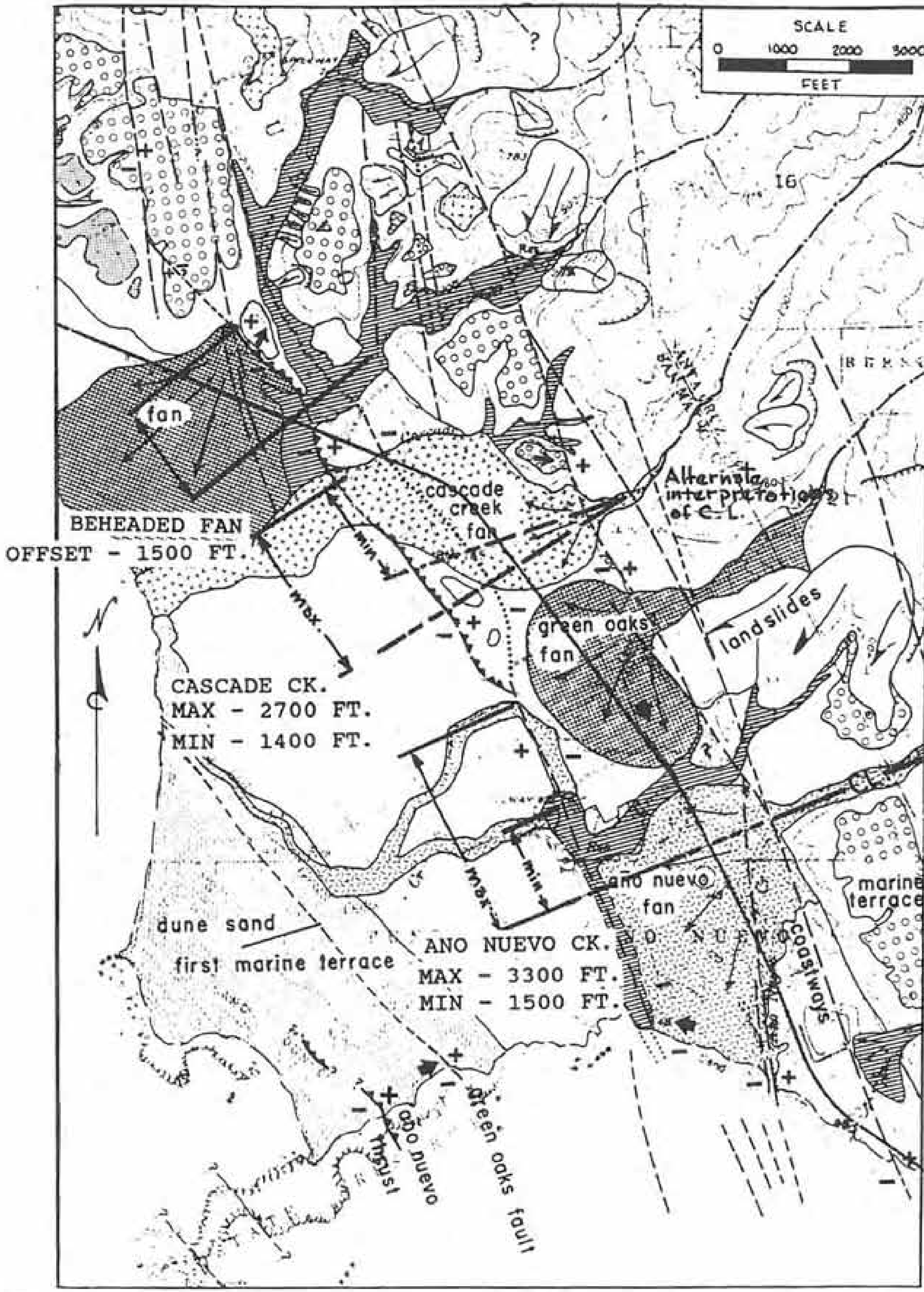


Figure 9. Interpretive map, showing the probable offset of late Pleistocene drainages near Point Ano Nuevo. Refer to text for discussion of the assumptions inherent in this type of reconstruction.

Radio-carbon dates from charcoal collected from Ano Nuevo Creek deposits suggest that stream capture took place about 11 ka B.P.

Another geomorphic feature suggestive of right lateral movement along the Frijoles and Coastways faults during the late Pleistocene is the beheaded and abandoned fan that lies north of Cascade Creek. This fan is thought to have formed near the present dam across Lake Elizabeth and been transported to the northwest along the Frijoles fault.

Interpretation

Although the overall distribution of Quaternary deposits at Point Ano Nuevo clearly indicates disruption of drainages by right-lateral movement along the Coastways and Frijoles faults, determination of the amount and rate of slip are beset with numerous problems. Consequently, I have constructed the following interpretation of the events associated with the offset of the drainages.

1. We know that the age of the shoreline angle of the Santa Cruz terrace is approximately 105 ka B.P. Therefore the courses of the streams was established across the 105 ka wave-cut platform as sea level dropped, probably between 105 and 100 ka B.P.

2. We assume that the as sea level dropped the streams established themselves in roughly linear channels across the former ocean floor. The stream channels did not bend or swing to either the north or south as the streams exited the mountain front. Initially the streams probably incised channels into the deposits on the wave-cut platform and prehaps the platform itself. This is probable since sea level was depressed and the streams were trying to erode their channels to the lowered base-level.

3. It is these original drainages that we see today southwest of the Frijoles fault.

4. The factors controlling the deposition of alluvial fans are not known. Climate, the fluctuating base level of the late Pleistocene-Holocene, and the tilting, uplift and/or downdropping associated with movement on the San Gregorio fault all must have affected whether the streams were eroding or depositing west of the Coastways fault.

5. The dominant control on the regime of the stream must have been the downdroping of the graben block between the Coastways and Frijoles faults. The continual depression of this structural block resulted in the deposition of a thick mass of alluvial fill in the graben. Climate was probably the most important secondary factor in the deposition of the fans. It

is probable that the streams carried greater amounts of sediment during the wetter and colder climates associated with the glacial maxima.

6. Ano Nuevo Creek changed its course several times, and was twice captured by high gradient streams. Fault offset, and possibly tilting of the block between faults could have accompanied or even led to these captures.

7. Cascade Creek has been displaced slowly to the northwest along the faults. There is no evidence of stream capture.

8. The beheaded fan north of Cascade Creek (Figures 8 & 9) was probably once the lower portion of the northern tributary of Cascade Creek. It was cut off from its source by movement along the Frijoles fault and the small Cascade Quarry reverse fault. It could possibly be the lower portion of the Cascade Creek paleo-drainage.

Using these simplifying assumptions we can measure the offsets as indicated on Figure 9. Ano Nuevo Creek may have been offset 457-1005 meters in about 100,000 years - an average offset rate of 4.5 to 10.0 mm/yr. Cascade Creek may have been offset 426-823 m in about 100,000 years - an average offset rate of 4.0 to 8.0 mm/yr. The beheaded fan north of Cascade Creek appears to have been offset about 450 m in possibly 100,000 years - an average rate of 4.5 mm/yr. If the beheaded fan was once the lower portion of Cascade Creek, it has possibly been displaced 1524 m (5000 feet) in the past 100,000 years an average offset rate of 15 mm/yr. These rates include movement across both of the primary faults, and are rounded off to the nearest half millimeter.

Ano Nuevo Creek	4.5 - 10.0 mm/yr
Cascade Creek	4.0 - 8.0 mm/yr
Beheaded fan	4.5 - 15.0 mm/yr

Obviously, this analysis of the paleo-drainage changes is speculative. Models requiring far greater and far less offset can be constructed from the existing data. I believe that the simplifying assumptions made above are generally reasonable and theat the slip rates are reasonable.

CONCLUSIONS

Marine terrace shoreline angles make excellent reference lines from which to measure Pleistocene deformation. They are horizontal datums formed at a point in time. However, mapping of terraces and reconstruction of the shape of the paleo-shoreline are fraught with a variety of practical difficulties. Despite these problems detailed mapping of marine terraces at Point Ano Nuevo clearly indicates that the shoreline angles of the Santa Cruz and Western marine terraces are offset by the Frijoles and Coastways faults.

My analysis and the determination of the amount of late Pleistocene slip along faults at Point Ano Nuevo depends in part upon which of the interpretations of the fault pattern is used in the analysis. Slip rates determined from the offset of the Santa Cruz terrace shoreline angle range from 6 - 10.4 mm/yr. Slip rates determined from the offset of the Western terrace shoreline angle vary from about 9.5 - 10.5 mm/yr.

Analysis of the obviously deranged stream drainages at Point Ano Nuevo indicate clearly that late Pleistocene - Holocene slip along the San Gregorio fault zone has been offsetting the stream channels of 3 small drainages. The determination of the amount of offset and the slip rates along the faults is again dependent upon making a number of simplifying assumptions. The late Pleistocene and Holocene tectonic history of Point Ano Nuevo is complex (probably far more complex than we can imagine), and the assumptions made are generally reasonable. Over the past 100 - 105,000 years slip rates across the two primary faults in the San Gregorio fault zone are between 5 - 9 mm/yr.

Obviously, the slip rates determined from the shoreline angle offset (6 - 10.5 mm/yr) and the offset of the post Sangamon drainages (4 - 10 mm/yr) compare favorably with the long term slip rates (7.5 - 9.5 mm/yr) determined from the offset of late Tertiary rocks. They are less than the rate determined by Clark and others (1984), which range from 13 - 16 mm/yr. My interpretations of late Pleistocene slip rates at Point Ano Nuevo suggest the San Gregorio fault zone is active and that the zone has been a locus of continuing activity throughout the late Pleistocene and Holocene. Late Pleistocene slip rates are similar to the long term Tertiary slip rates and if there has been a decrease in slip rate along the fault in the Pleistocene it has been relatively minor.

VERTICAL DISPLACEMENTS OF THE SANTA CRUZ TERRACE NEAR GREYHOUND ROCK, SANTA CRUZ COUNTY CALIFORNIA FAULT OR LANDSLIDE INDUCED?

Gerald E. Weber

INTRODUCTION

This paper is a revision of a paper in the 1979 G.S.A. Field Trip Guidbook (Weber, Lajoie and Griggs, 1979) on the nature of faulting near Greyhound Rock. Both articles address the question of the origin of faults that offset the terrace deposits of the Highway 1 platform of the Santa Cruz terrace, and emphasize the subjective nature of the available data. Data are insufficient to answer most of the questions regarding the nature and amount of fault movement and the dimensions of the fault, except that the Greyhound Rock fault strand of the San Gregorio fault zone is not as large, and has not experienced as much movement as the main fault strands within the San Gregorio fault zone - the Frijoles and Coastways faults.

This article is a brief summary of the information available on the faults and is based upon my field studies, information from N. Timothy Hall (personal communication) and upon field studies by Earth Sciences Associates of Palo Alto. Figures 2, 3, 4, and 5 are modified from ESA illustrations in ESA's report to P.G.&E. on the geology of the proposed Davenport Nuclear Power Plant Site. Vertical offsets across faults are modified from ESA's report and also from surveys made by W.C. Bradley in the 1950's and 60's (personal communication).

If you plan to do justice to the field observations available in the Greyhound Rock area, plan on about 2-3 hours, so that you can hike the beach to Pelican Rock, climb the talus pile to view the faults up close, hike to the headland 1200 feet to the north and hike up the ravine north of the Headland. After doing all of that, draw your own conclusions regarding the origin of these features.

SITE GEOLOGY

Greyhound Rock beach is one of several small pocket beaches that lie along the Santa Cruz County coastline south of Point Ano Nuevo. The beach is protected from the predominant northwest swell by Greyhound Rock, a tombolo, an offshore rock connected to the beach by a narrow sand spit (Figure 1). Siliceous organic mudstones of the Santa Cruz Mudstone dip gently eastward (10 - 15 degrees) on the west flank of the Davenport Syncline. The sea cliffs, 100 - 120 high, are cut in Santa Cruz Mudstone which is overlain by about 30 - 40 feet of marine terrace deposits.

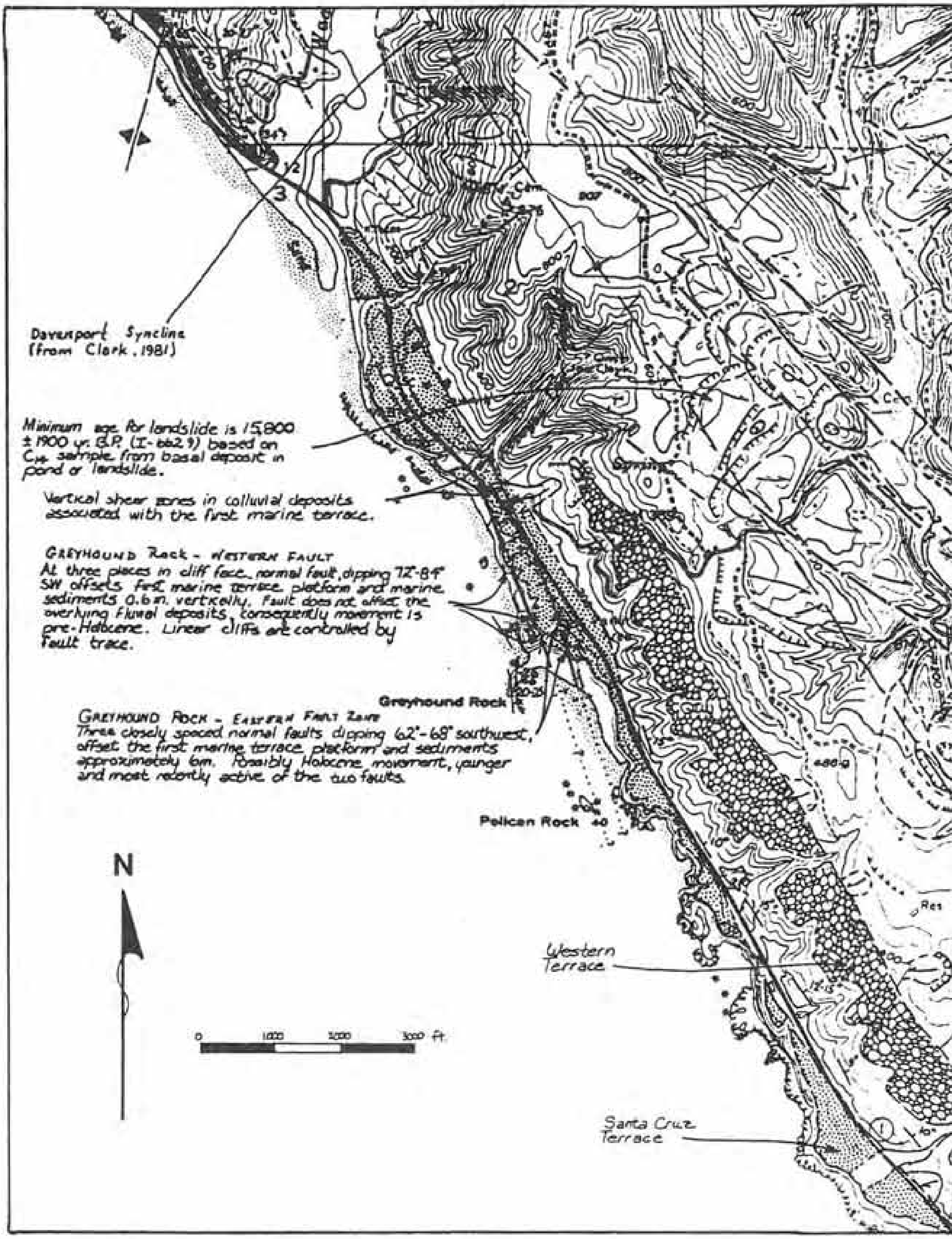


FIGURE 1. Map of Quaternary faults and marine terrace deposits near Greyhound Rock.

From Greyhound Rock south to Pelican Rock (Figure 1) the base of the cliff is protected from wave erosion by a broad, permanent beach. As the cliffs have not been subjected to wave erosion for a considerable time, a thick talus cone or apron has formed at the base of the seacliff (Figures 2, 3, &4). Both north and south of the Greyhound Rock beach, talus cones and beaches are rare, and typically seasonal - being removed during large winter storms.

The Greyhound Rock fault strand of the San Gregorio fault zone (Weber and Lajoie, 1977, 1980) consists of 4 separate fault strands (Figures 1 & 2) that clearly offset the Santa Cruz marine terrace. Three closely spaced faults, hereafter refered to as the "eastern fault zone", lie 200 - 250 feet northeast of a single fault - the "western fault" (Figures 1 & 2).

Eastern Fault Zone

The three closely spaced faults offset the wave-cut platform and the overlying deposits a total of 34 feet (Figure 3-A). The offsets were determined by hand leveling by W.C. Bradley (personal communication). Individual fault offsets from northeast to southwest are 15.9 ft., 14.3 ft., and 3.8 feet. These values appear to be inconsistent with the seacliff sketch by ESA (Figure 3), and I have not field checked these numbers. Bradley also shows the northeast and southwestern faults within this threesome as forming fault scarps, with scarp heights of 6.5 and 4.0 feet respectively. Since Bradley studied these faults prior to the construction of the parking lot at the top of the cliff, his observations regarding scarp height are the best values available. However, Bradley's values for fault offset of the wave-cut platform may be incorrect. The three faults strike approximately N 15 W, and dip 60-70 degrees southwest, with the southwest side down and the northeast side up - normal movement.

As indicated the faults are clearly exposed in both the seacliff and in a shallow cut along the access road adjacent to the parking lot (Figures 1, 2 and 3-A). The faults offset the wave-cut platform of the Davenport platform, the nearshore marine sands and gravels, the fluvial and colluvial gravels that overlie the marine sediments, and the ground surface along two of the faults. Where the faults cut the marine sediments in the sea cliff they are commonly, but not always, exposed as iron oxide cemented layers of sand along the fault surface(s).

The underlying Santa Cruz Mudstone bedrock has also been sheared and broken along these faults, with breccia zones commonly six inches to 1 foot thick. The blocks between faults have also experienced more intense shearing and fracturing than the rocks outside the fault zone. The surface of the cliff

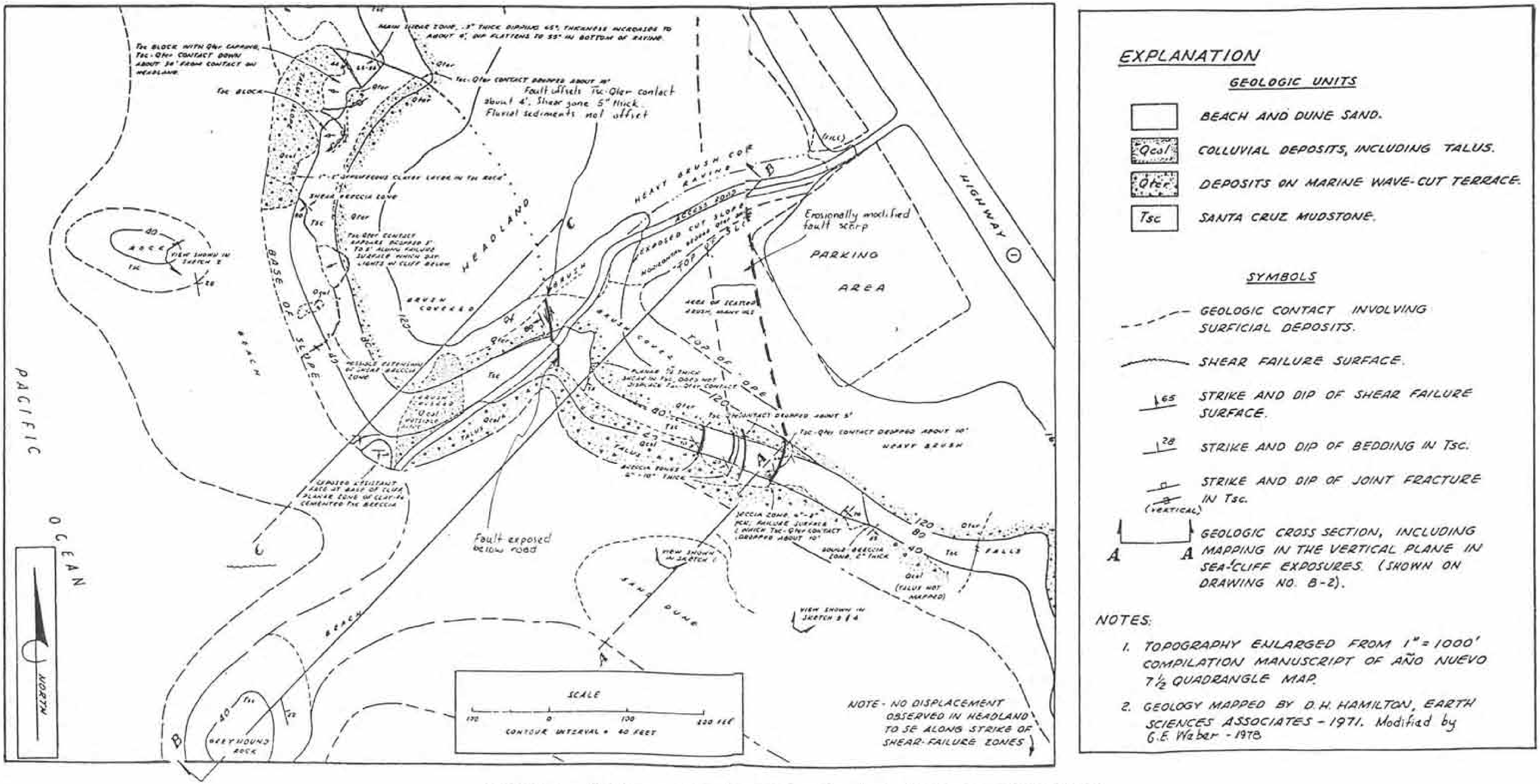
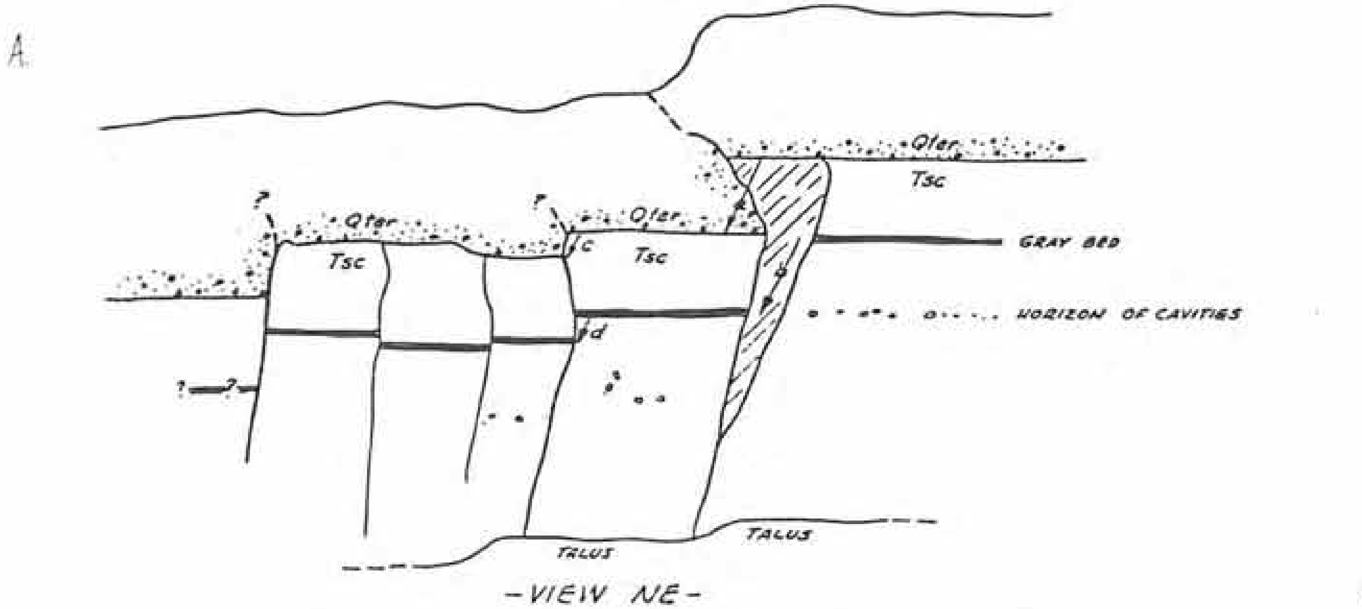
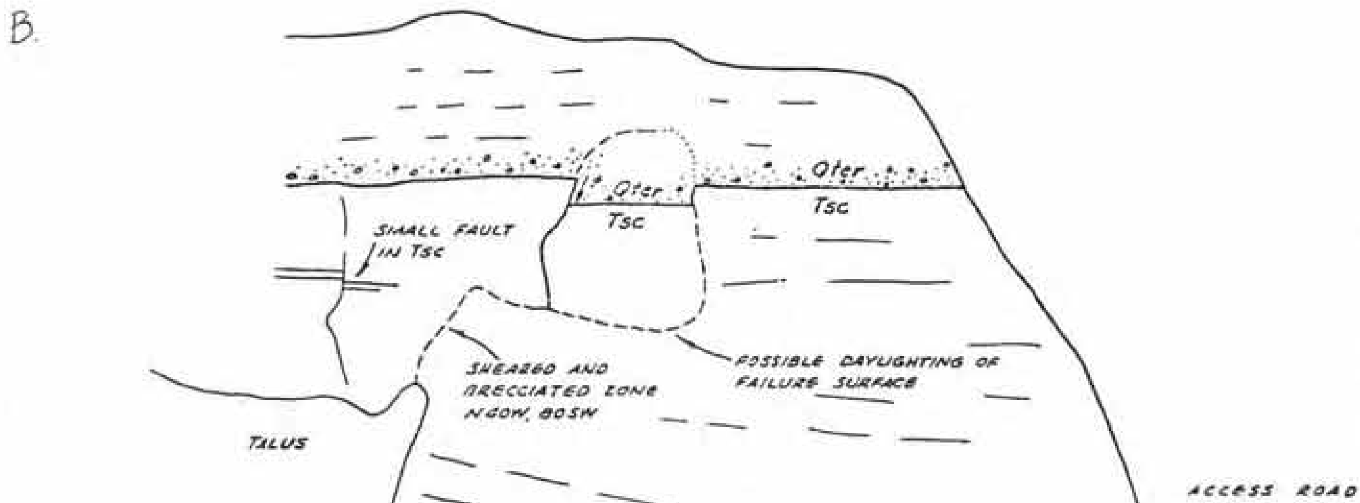


FIGURE 2. Terrace offsets and breaks in bedrock near Greyhound Rock, geologic map (drawing #B-1 from Earth Sciences Associates, Davenport Power Plant Site Geology Investigation, PG & E, 1972; modified by G. E. Weber, 1978)



SKETCH OF SEA CLIFF 250 TO 350 FEET SE OF GREYHOUND ROCK ACCESS ROAD. NOTE THAT THE APPARENT Tsc DIP SLIP SEPARATION ALONG FAILURE SURFACES (b, d) APPROXIMATES AMOUNT OF DOWN-DROPPING OFFSET OF THE Tsc-Qter CONTACT (a, c). FAILURE SURFACES, THEREFORE, DO NOT APPEAR TO HAVE DEVELOPED ALONG PREEXISTING FAULTS IN THE Tsc ROCK.



SKETCH OF HEADLAND AT GREYHOUND ROCK, SHOWING PROBABLE (AS VIEWED FROM BELOW) LOCAL DISPLACEMENT OF Tsc-Qt CONTACT AT CLIFF FACE.

FIGURE 3. Terrace offsets and breaks in bedrock near Greyhound Rock.

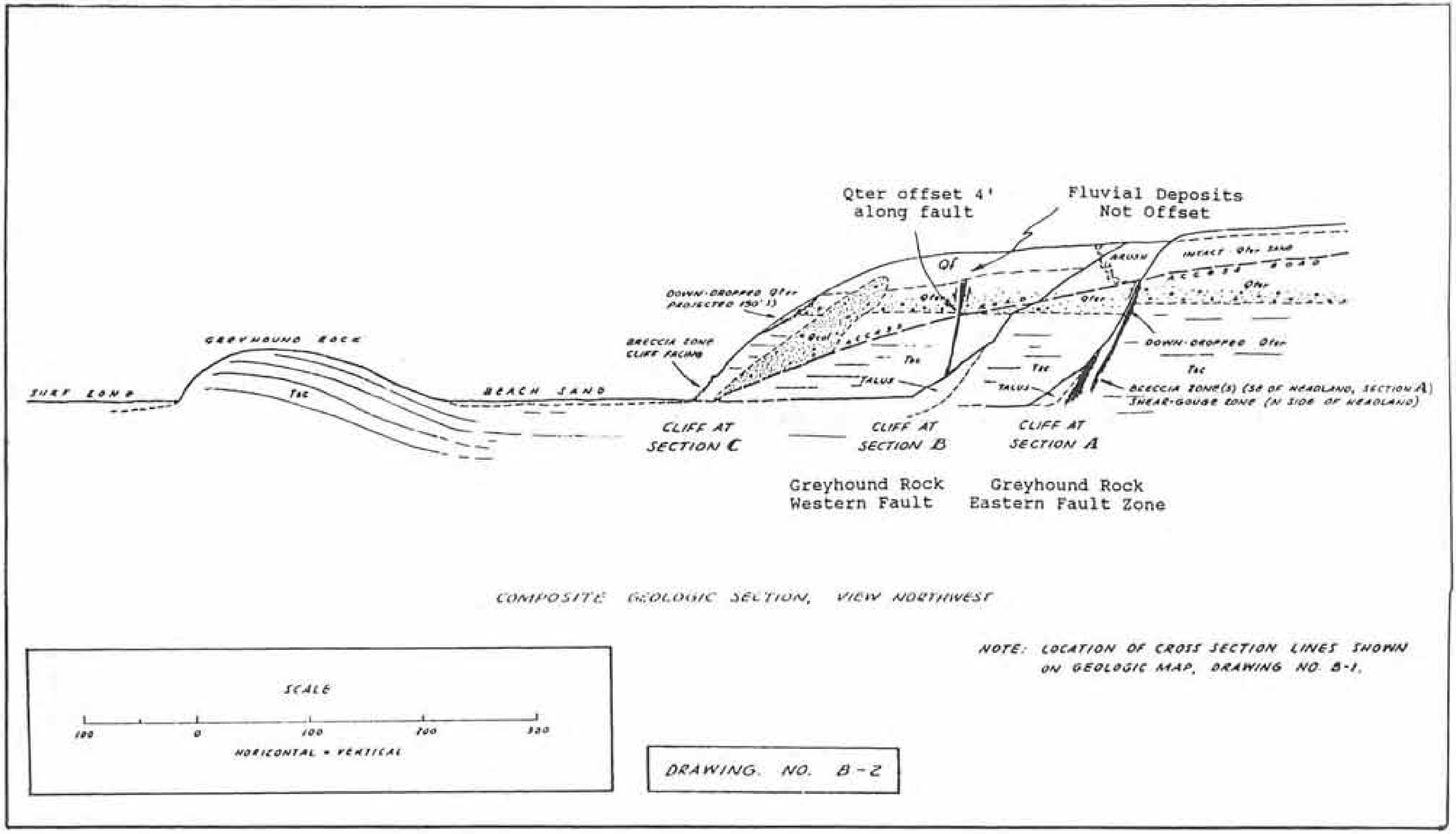
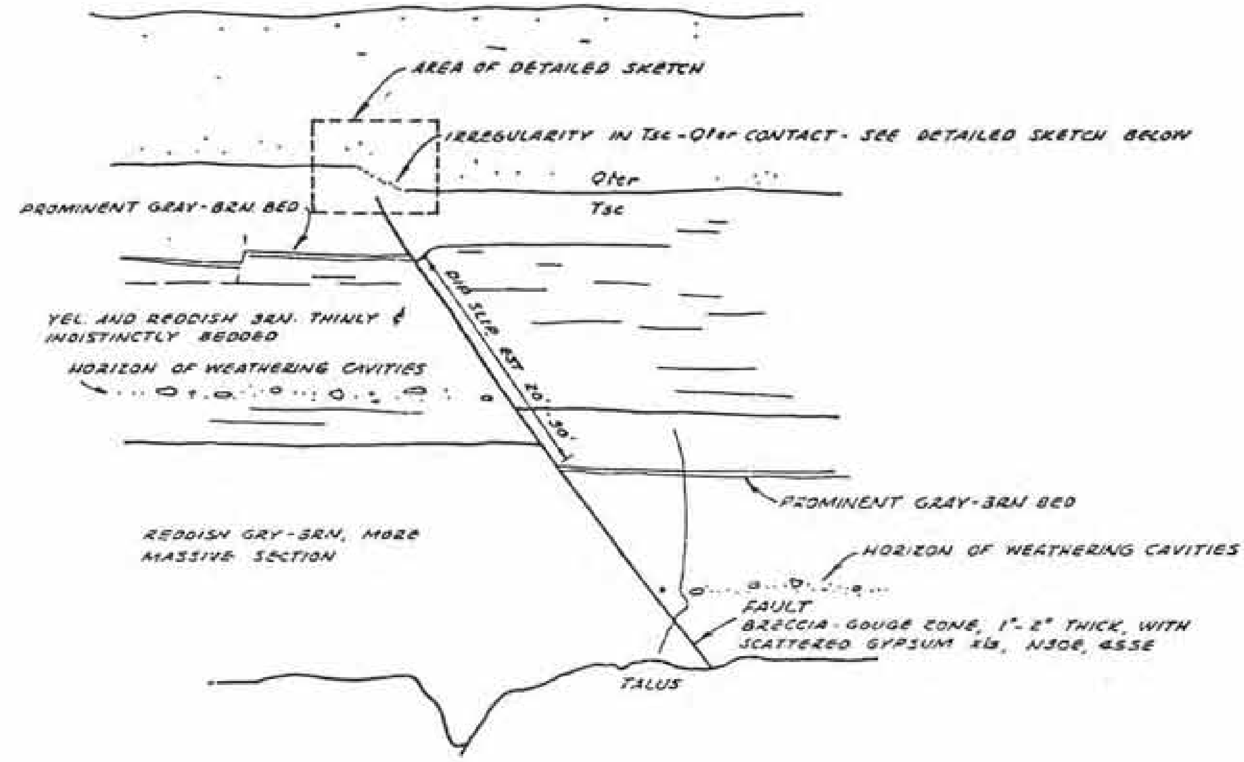
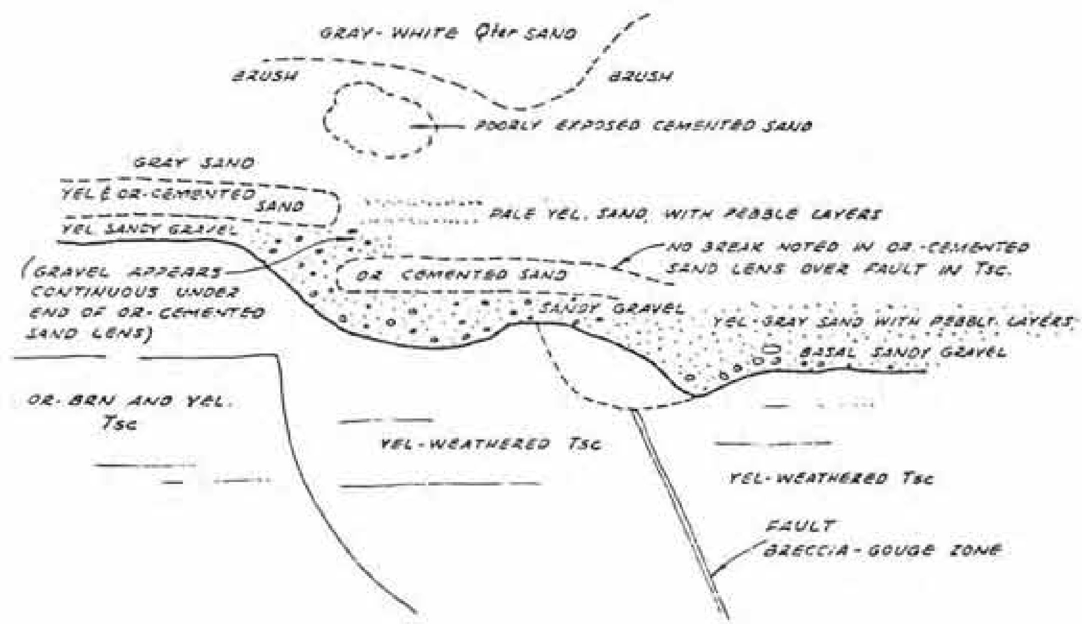


FIGURE 4. Geologic cross section from drawing B-2 from Earth Sciences Associates, PG & E report, 1972.



C. SKETCH OF SEA CLIFF, 500 FEET SE OF GREYHOUND ROCK ACCESS ROAD



D. DETAILED SKETCH (MADE FROM BEACH, USING 8X BINOCULARS)

FIGURE 5. Location of sketches shown on geologic map, drawing no. B-1.

within the fault zone is covered with a yellow to yellow brown stain, probably jarosite (iron sulphate) leached out of the fractured rock.

Although the scarps associated with these faults were better exposed prior to construction of the parking lot, it is still possible to see the erosionally modified scarp from the headland that lies north of the access road.

This small fault zone is dificult to trace to the northwest because of the road cuts and fills along Highway 1, and thick colluvium and vegetation. North of the intersection of Highway 1 with Swanton Road (Figure 1), a shallow road cut along Highway 1, and also a cut along a rough dirt road expose vertical fractures, with orientations similar to the "eastern fault zone". These fractures cut through alluvial/colluvial deposits, but it is difficult to determine if they offset bedding, as bedding within these deposits is very crude. It is impossible to determine if any vertical offset is associated with these fractures. Careful examination and excavation of pebbles within one of these fractures by Ken Lajoie, Ray Wilson and I, resulted in the discovery of two pebbles with horizontal grooves - interpreted to possibly be striations resulting from fault movement.

Western Fault

The "western fault" is exposed along the north side of the beach access road where it offsets the wave-cut platform and the near shore marine sands about 4 feet vertically. The fault strikes N15-20 W, dips 70-80 degrees southwest and is characterized by the development of iron oxide cemented sandstone layers along the shear planes. The fault can be traced upward in the road cut through the marine sediments, but the fault is erosionally truncated and covered by fluvial sediments. Therefore, the most recent movement along this fault is younger than the deposition of the marine sands on the terrace platform, but older than the deposition of the fluvial deposits over the beach sands. No dateable material has yet been recovered from these deposits.

The location and extent of the western fault is quite easily defined as the fault is exposed in the ravine north of the Headland (Figures 1 & 2). The fault is also present on both sides of a smaller headland 1200 t0 1500 feet northwest of the Greyhound Rock Headland. Between the two headlands the sea cliff is linear, as it is northwest of the second headland (Figure 1). In both areas the modern seacliff appears to be fault controlled, with the shoreline angle of the modern platform forming along the fault. The western fault, as presently mapped, consists of three fault exposures and 1200 feet of nearly continuous linear seacliff north of the Headland at Greyhound Rock.

There is no data from which to judge the amount and type of movement along the western fault. Along the access road the terrace sediments on the northeast block (upthrown relative to the southwest block) have been "dragged" upward forming a small, crude, shallow syncline that may plunge gently to the northwest. The drag appears to be incompatible with purely normal fault movement, and suggests that the true displacement on the fault may not be normal movement but some type of oblique movement.

INTERPRETATION

The extent of both the western fault and the "eastern fault zone"; the amount of movement, and the nature of the movement - normal or strike-slip - are not known, and are open to conjecture. The two possible interpretations are: 1) the faults are tectonic in origin and form a branch of the San Gregorio fault zone, and 2) the faults are part of the main scarp of a large landslide.

Landslide Origin:

The landslide interpretation was originally suggested by Doug Hamilton of Earth Sciences Associates in the original report to P.G. & E. on the Davenport Nuclear Power Plant site. As indicated in Figure 3, the "eastern fault zone" offsets the wave-cut platform about 30 feet. Hamilton notes, however, that the offset of a "cavernous weathering zone" and "the grey bed" in the Santa Cruz Mudstone bedrock are about the same as the offset of the wave-cut platform (Figure 1). Hamilton suggested that the faults in the "eastern fault zone" cannot be major breaks if the Miocene Santa Cruz Mudstone (10 million years B.P.) and late Pleistocene terrace (84 ka B.P.) are both offset the same amount. Identical offset of both these units would indicate that movement on this fault is relatively recent (past 84 ka) and would suggest that this is a relatively minor break not a major strand of the San Gregorio fault zone. The faulting could be interpreted as the result of the formation of a large rotational landslide block that slid out of the modern seacliff. Greyhound rock is an erosional remnant of that landslide block which has been largely removed by wave erosion.

This landslide origin for the "eastern fault zone" is consistent with the ESA interpretation of the field geology - refer to Figure 2. A fault mapped north of the Headland is referred to as the Main Shear Zone, and is described as having 15 feet of offset of the wave-cut platform. It appears that ESA correlates this fault with the faults in the "eastern fault zone", which would support the landslide interpretation since the faults would then have the "arcuate main scarp" map pattern of a classic landslide. I disagree with this interpretation because it can be clearly shown that the western fault must connect with the fault exposed on the south side of the headland. ESA also pointed out that bedding in Greyhound Rock dips 22 degrees to the east, a dip somewhat steeper than the regional dip of the Santa Cruz Mudstone. This increased dip is also consistent with a rotational landslide interpretation for the faults in the "eastern fault zone". It ignores, however, the fact that the bedding is parallel on opposite sides of the eastern fault zone. Other data supportive of the landslide interpretation are the difficultly of tracing the faults to the northwest and the absence of good evidence of strike-slip movement.

The fault shown on the south side of the Headland with four feet of offset (Figure 2 & 4) was not mapped by ESA. Tim Hall initially found this fault while field checking the Santa Cruz County fault map in 1973, and subsequently informed me of its presence.

Fault Interpretation:

I believe that the sea cliff geology is inconclusive. There are actually several "grey beds" exposed in the cliff, and the cavernous weathering zone is not unique as cavernous weathering is present elsewhere in the crushed rock between faults. I have not been able to construct a stratigraphic sequence in the Santa Cruz Mudstone east of the faults that is comparable to the mudstone west of the faults (Figure 3). Consequently, it is by no means certain that the "grey bed" exposed in the sea cliff west of the fault is correlative with the "grey bed" east of the faults, and it cannot be conclusively demonstrated that vertical movement on this fault zone is identical for both Miocene and late Pleistocene rocks.

Even if the amount of vertical offset of the Miocene rocks is identical to the offset of the late Pleistocene deposits, it does not conclusively demonstrate that the "eastern fault zone" is of landslide origin. Similarly it cannot be used as proof that the "eastern fault zone" is not a large branch fault of the San Gregorio fault zone. It is possible that the "eastern fault zone" is a relatively young fault that formed after the deposition of the Santa Cruz terrace. It is also possible that the outcrop relationships at Greyhound Rock are a coincidental juxtaposition of similar offsets and do not reflect either the horizontal or vertical offset of the mudstone bedrock along this fault.

Based on field mapping I believe that the "eastern fault zone" can be traced to the northwest and that it does not connect with the fault on the north side of the Headland. The mapping of the "western fault" by Tim Hall demonstrated that the Main Shear Zone of ESA, shown on Figure 2, probably connected with what we refer to as the "western fault". This "western fault" can be traced about 1200 feet northwest of Greyhound Rock, suggesting that a landslide origin is improbable.

Horizontal Offset Along The Greyhound Rock Faults

In an attempt to determine if evidence of horizontal movement was present along the Greyhound Rock faults, I mapped marine terraces and shoreline angles in respect to the faults. The results are shown in Figure 1, a map of terrace deposits, and Figure 6, a map showing the possible deformation of the shoreline angle of the Santa Cruz terrace - Highway 1 platform. Figure 5 suggests that the shoreline angle of the Highway 1 platform may have been offset 1600 - 1700 feet (490 meters) in the past 105,000 years - an average slip rate of about 0.18 inches per year (4.5 mm per year). Since the shoreline angle and terrace are almost everywhere covered with fluvial, colluvial or aeolian deposits the 1600 - 1700 feet of right-lateral offset, is an interpretation at best.

Adding to the complexity at this site is the parallelism of the shoreline angle and the faults, a situation in which the shoreline angle can often form along the fault by differential erosion. A modern example of this is the location of the present day shoreline angle along the "western fault" north of Greyhound Rock (Figure 1). If the shoreline angle of a marine terrace has formed along the fault, it is impossible to acurately determine either the absolute value for offset of the shoreline angle or the rate of offset along the fault. Consequently, the evidence of right-lateral offset is not conclusive, but strongly suggestive. The rate of offset along the fault has to be less than 4.5 mm per year, and is probably on the order of 1 - 2 mm/yr.

CONCLUSIONS

There is little conclusive evidence regarding the dimensions, amount of offset and origin of the faults exposed near Greyhound rock. The Greyhound Rock fault consists of and "eastern fault zone" and a "western fault". The "eastern fault zone" consists of 3 closely spaced faults that vertically offset the wave-cut platform of the Davenport platform 34 feet (Bradley, personal communication), offset the overlying terrace deposits, and also offset the ground surface forming surface scarps. The "western fault" vertically offsets the wave cut platform 4 feet and 15 feet on opposite sides of the Headland (Figure 2). The fault offsets the shallow water marine deposits on the platform, but does not offset the overlying fluvial and coluvial wedge built out across the top of the

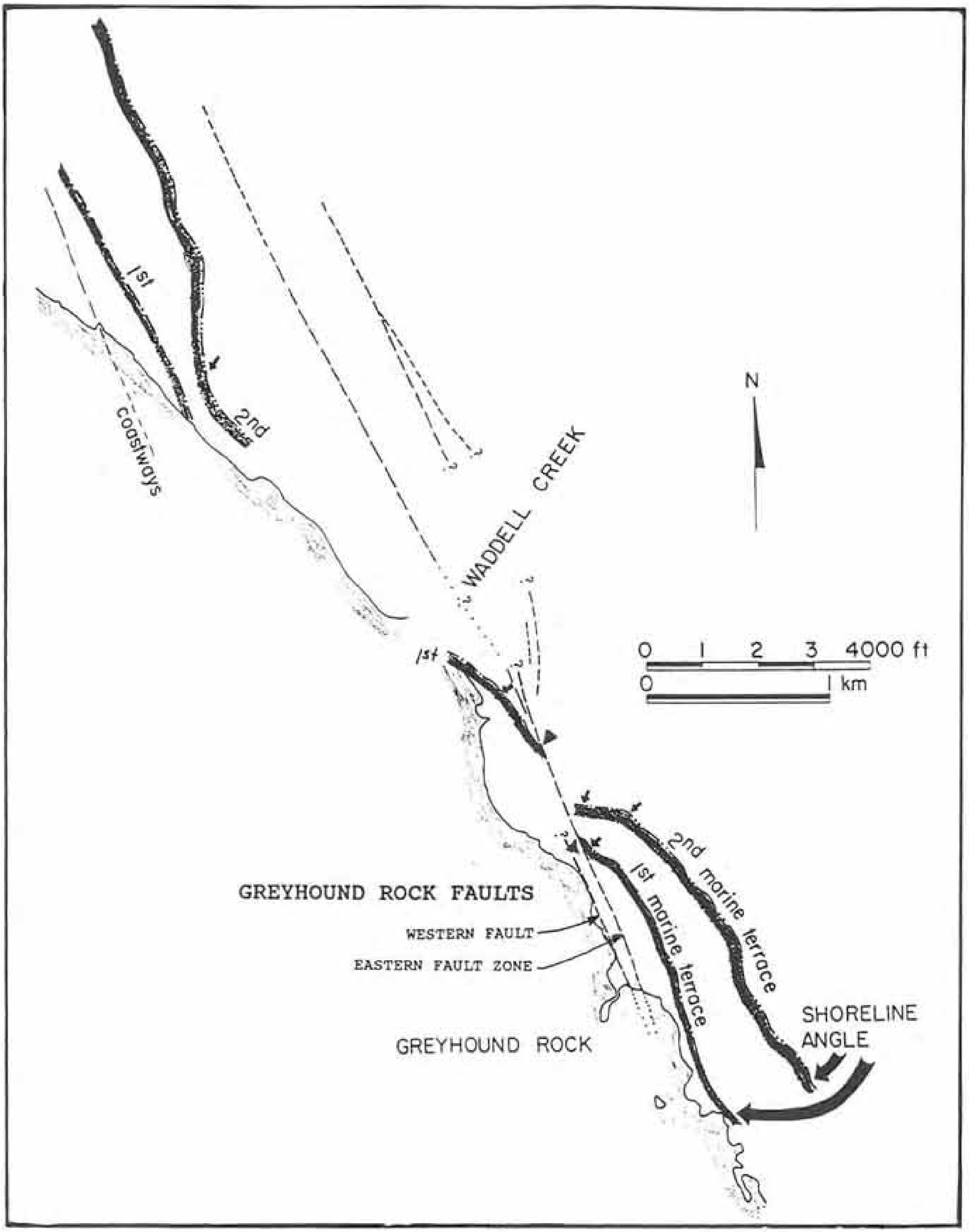


FIGURE 6. Deformation of the shoreline angle of the Santa Cruz terrace along the Greyhound Rock faults at Greyhound Rock. Arrows indicate the topographic limits on the position of the shoreline angle.

marine deposits. All of the faults strike N15-20W and dip 60 to 80 degrees to the southwest.

The "eastern fault zone" can be traced with great uncertainty to the northwest and may be exposed as near vertical fractures in colluvium northeast of Highway 1. The 'western fault" is exposed on the north side of the Headland (Figure 2), and can be traced along the linear seacliff to another headland about 1200 feet northwest of Greyhound Rock (Figure 1).

All of these faults offset the wave-cut platform of the Davenport platform, and the shallow water marine deposits on this platform. If I am correct in correlating the lower wave-cut platform north of Scott Creek with the Davenport platform, then movement has occurred within the past 84 ka B.P. The total amount of offset of the Santa Cruz Mudstone across these faults is not known. It is possible that the offset of the Miocene units is identical to the offset of the Pleistocene units, based on offset of the "grey bed", as shown on Figure 3. It is also possible that offset has been significantly greater than suggested by the "grey bed" interpretation. Consequently, the two possible interpretations of these faults are that they ; 1) represent a secondary trace of the San Gregorio fault zone and are tectonic in origin, and 2) they are the main scarp of a Holocene landslide that formed in the modern seacliff.

Arguements favoring a landslide origin are :

1. The "grey bed" suggests the vertical offset of rocks 10 ma old and rocks 105 ka old is the same.

2. Bedding plane orientation and apparent slip - normal suggesting landslide movement.

3. No good evidence of horizontal slip.

4. The shear zones are relatively narrow.

Arguements favoring a tectonic interpretation are:

1. The "western fault" can be traced as a linear feature for a distance of 1500 - 1800 feet northwest of Greyhound Rock.

2. The "western fault" offsets the wave-cut platform and marine deposits, but not the overlying fluvial / colluvial wedge. This is highly unlikely in a landslide since the "eastern faults" offset the entire sedimentary sequence.

3. Mapping of terrace shoreline angles suggests that a significant amount of horizontal movement may have occurred.

4. The fault orientation (N 15-20 W) is consistent with normal and strike-slip movement within a large right-lateral strike slip fault zone.

5. Absence of an arcuate main scarp, and insufficient rotation of the landslide block.

6. Coastal evolution and sea cliff erosion rates argue strongly against a landslide origin.

In summation, I would interpret the Greyhound Rock faults as a large secondary trace or branch of the San Gregorio fault zone. Movement has been predominantly right-lateral strike-slip, with a minor normal component. The fault may be relatively young, having formed only within the past 84 thousand years. It is not a major primary fault trace of the San Gregorio fault zone like the Frijoles fault and Coastways fault. Although I believe that fault interpretation is correct, the field data are inconclusive and an final interpretations must await the development of aditional field data.

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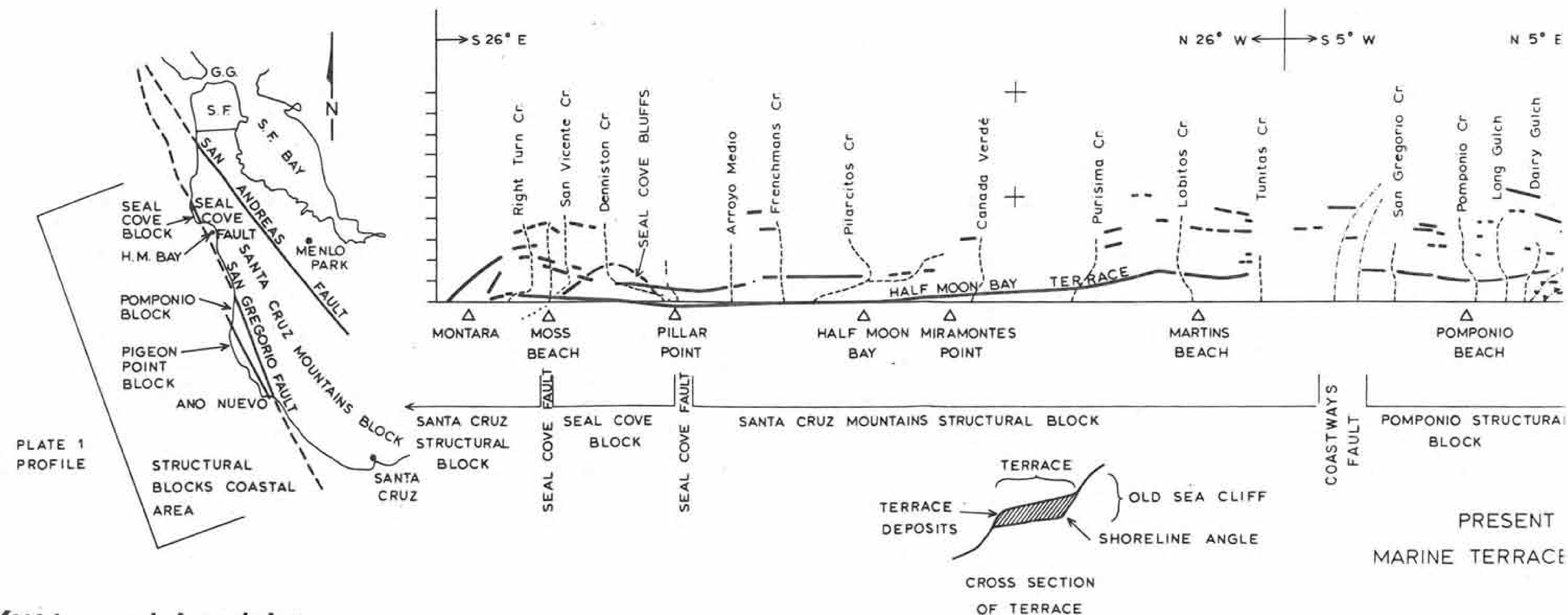

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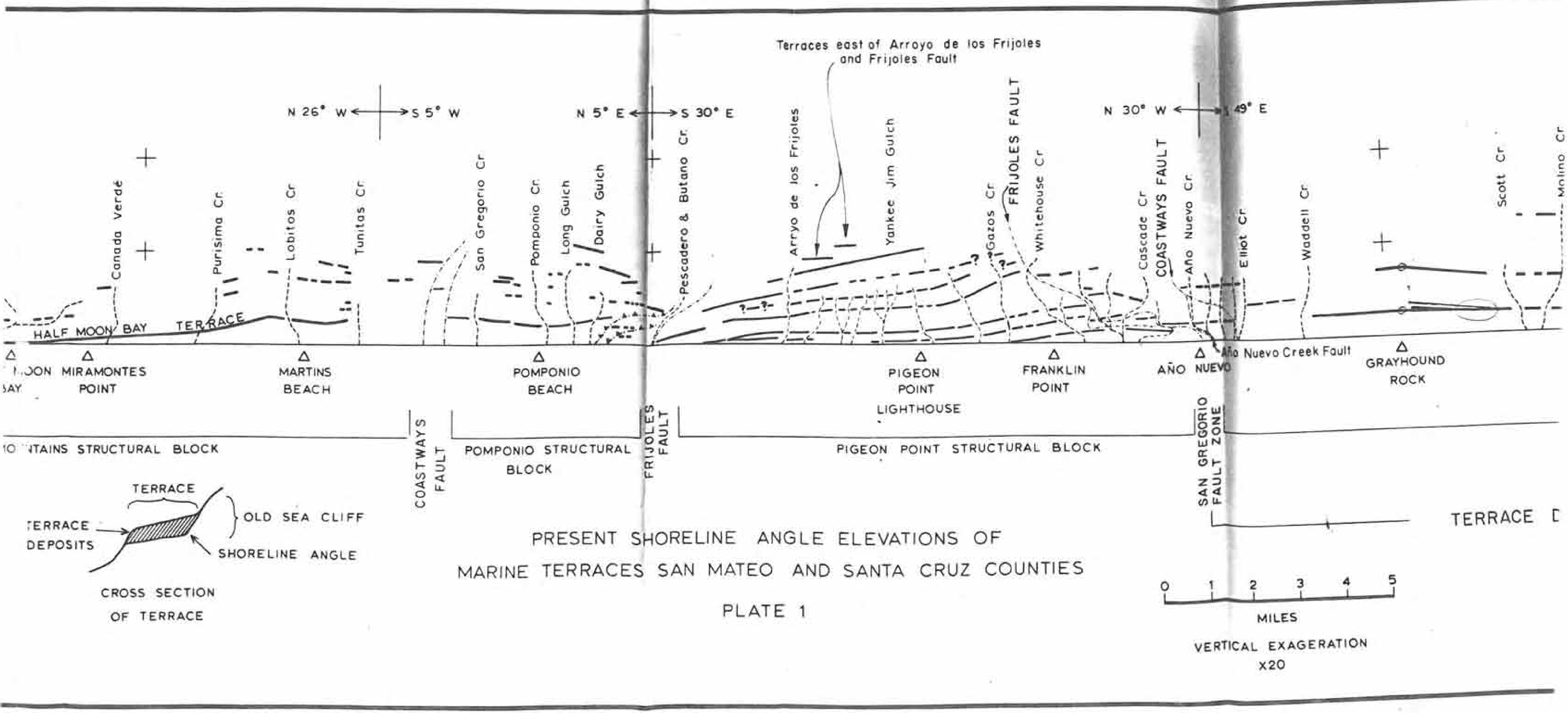
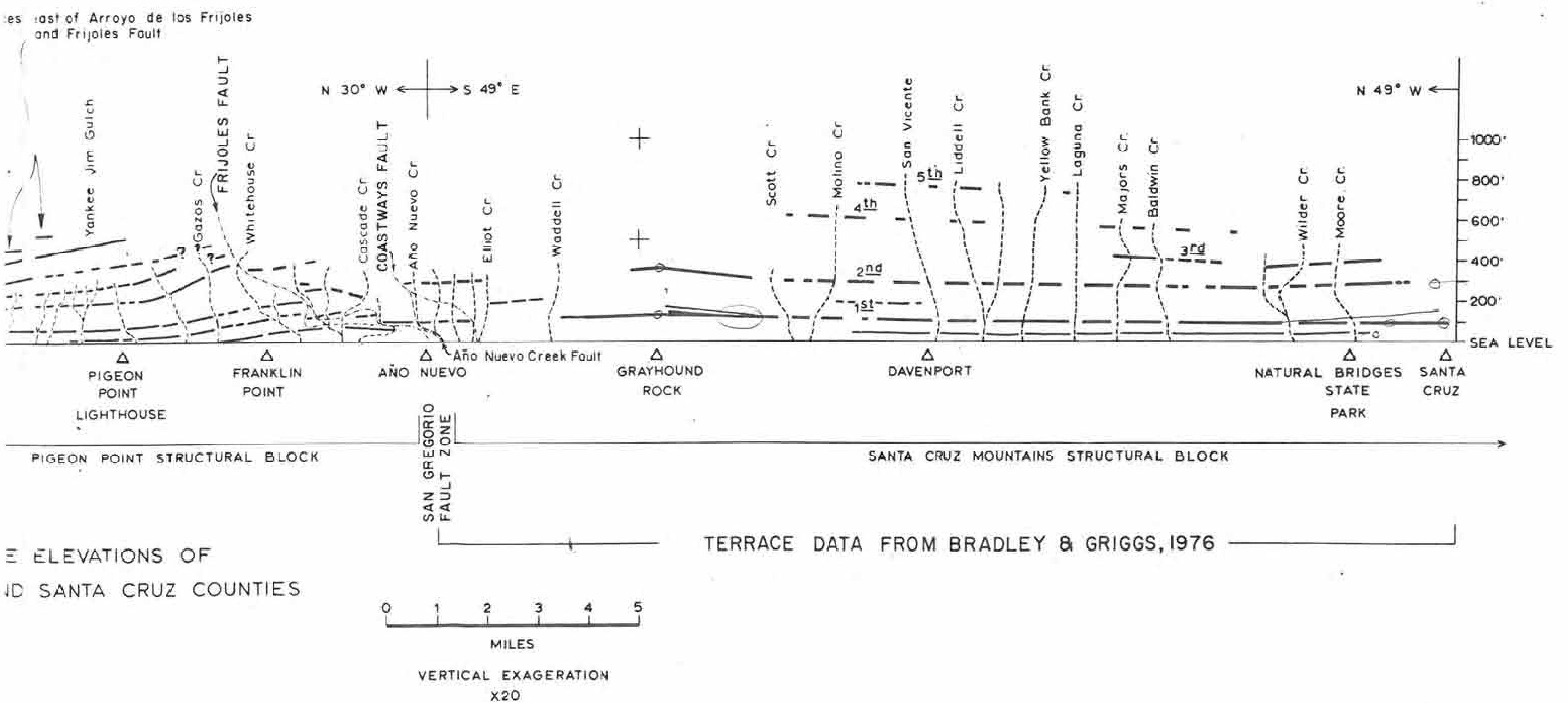


PRESENT SHORELINE ANGLE ELEVATIONS OF
MARINE TERRACES SAN MATEO AND SANTA CRUZ COUNTIES

PLATE 1



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