COASTAL FAULTING AND EROSION HAZARDS IN HUMBOLDT COUNTY, NORTHERN CALIFORNIA

Derek J. Rust
Department of Geology
Humboldt State University
Arcata, California 95521

FROM:

Collection of Papers presented
at the
OCEAN STUDIES SYMPOSIUM

November 7-10, 1982
Asilomar, California

Compiled by the California Coastal Commission
and the
California Department of Fish and Game

March 1984

The Ocean Studies Project was funded by the William H. Donner Foundation, the U.S. Fish and Wildlife Service, and Chevron U.S.A., Inc.

(Carver; R/CZ-53)
(Rust; R/NP-1-10F)

This work is a result of research sponsored in part by NOAA, National Sea Grant College Program, Department of Commerce, under grant numbers 04-8-M01-189 and NA80AA-D-00120, through the California Sea Grant College Program, and in part by the California State Resources Agency, project numbers R/CZ-53 and R/NP-1-10F.

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Abstract

The tectonic setting, seismic history and Quaternary fault activity of northern California, interacting with severe storm and wave conditions and a marked variability in the resistance of rocks exposed at the coast have produced extreme hazards, even in the short period of historic record. Detailed geologic analysis of the coastal zone in part of Humboldt County has extended this record to identify hazards occurring in the recent geologic past which should also be considered in planning future coastal development. Hazards include fault rupture and ground shaking from newly recognized active faults, seismically triggered coastal slope failures, tsunamies, and catastrophic rates of cliff retreat produced by recurring combinations of the hazard producing factors. Together the historic and geologic records give a long-term perspective from which the future trends of these geologically based hazards can be assessed and their potential impacts minimized.

The assessment shows that two zones of compressional faulting which parallel an 8 kms (5 miles) stretch of the coastline in the Trinidad area (Plate 1) have broken and folded a series of late Pleistocene marine terraces and that future fault rupture should be anticipated. Severe ground shaking associated with these faults and with several neighbouring faults (which contribute to an overall uplift rate of about 1-1.2 mm/yr) should be expected to occur at least once in the lifetime of a structure.

Large slump blocks periodically break away from the shoreline edge of the marine terraces; at the heads of the almost continously mobile slump-earthflows which are so common in the shaley matrix of the Franciscan mélange bedrock. These blocks which have in the recent geologic past broken inland up to 100 m (328 feet) or more, must fail during the frequently recurring intense rainfall years characteristic of this area, probably with ground shaking acting as a trigger. A numerical model of tsunami generation in the Pacific predicts a wave height of 5.7 m (18.7 feet) at Trinidad with a 500 year recurrence, and 3.1 m (10.3 feet) with a 100 year recurrence. Tsunamies could also be generated by the active dip-slip faults offshore of the region. Tectonic downwarping along part of the coast, in combination with high waves, high tides, and loss of beach sand, has produced episodes of retreat in the weak terrace sands exposed to wave attack. Over the past 100 years these episodes have caused cliff retreat at average rates up to 1.8 m/yr (6 feet/yr).

Post-glacial sea-level rise was rapid until about 5,000 years ago but since then it has been approximately matched by the overall tectonic uplift rate in the area. As anticipated from this, the geologic record indicates that cliff retreat rates were much higher in the early Holocene than now, and it seems that some parts of the coast are approaching a relatively stable equilibrium. Cliff retreat in weak bedrock areas slows down as increasingly indented bays are formed between headlands and offshore stacks of resistant bedrock; while compressional faulting activity has been able to generally define and stabilize the long-term position of another part of the coast. Where weak bedrock, especially on the downthrown side of these compressional faults, is exposed in an unprotected position on the coast average retreat rates are as high as 0.85 m/yr (2.8 feet/yr). The rapidly retreating areas can be described as furthest from the suggested equilibrium model and therefore most likely to retreat in the future. Of course, local changes in bedrock, changes in uplift rate, and especially changes in sea-level (such as the recent 10 mm/yr rise), will influence the progress towards equilibrium and perhaps its overall trend.

Impact of the hazards can be minimized if action is taken now while coastal development is still limited. The following action is recommended:

1) Detailed and relatively large scale geologic mapping studies should be carried out in developing coastal zones.

2) Within the context of this mapping routine engineering geology site investigations should continue, with particular emphasis on the hazards identified in the mapping studies.

3) Active fault zones should receive further investigation on their continuity and earthquake generating potential.

4) Zones should be designated astride the active faults, within which site studies are required to investigate the possibility of ground deformation and breakage below a proposed structure.

5) Structures should be designed to withstand anticipated levels of ground shaking.

Introduction

Three principal factors interact to produce coastal faulting and erosion hazards in California. These factors are: 1) Tectonic setting and fault activity. 2) Variations in resistance of rocks exposed at the coast. 3) Storm and wave conditions. In northern California the nature and interaction of these factors can and has produced extreme hazards. However, their impact in the past has been relatively minor due to the lack of development along the coast. This is now changing, with the potential impact of these hazards rising in step with increasing pressure for residential and commercial development in the coastal zone, and it is therefore important to identify and assess these coastal hazards so that wise planning decisions can be made.

A fundamental problem in this identification and assessment process, especially in northern California, is the extremely short historical record. Many of the most menacing hazards may be underestimated or overlooked, simply because they have not occurred or been recorded in the past hundred years or so. This raises the question of the "recurrence interval" or frequency of certain hazards and the chances of a particular hazard, a large earthquake for example, occurring within a given time. These questions can only be tackled through a detailed analysis of the recent geological record (see discussion in Allen, 1975, for example) as a means of extending the limits of recorded history.

This paper will illustrate how a detailed geological study, in conjunction with the historical record, was used to identify faulting and erosion hazards along part of the Humboldt County coastline in the Trinidad area north of Eureka. (Fig. 1) The paper has three parts: Part A discusses the factors involved in these hazards; Part B discusses the past, and possible future, hazards produced by these factors; and Part C offers recommendations for management of the hazards.

PART A

Tectonic setting

Figure 1 illustrates the regional plate tectonic setting of the study area. Motion of the Pacific, North American and Gorda plates results in a maximum compressive stress directed north eastwards from the Mendocino triple junction. The coast of Humboldt County north of the triple junction is responding to this force by deforming into a series of active folds and faults orientated northwest-southeast.

Seismic history

Engagement between these three plates produces very high rates of seismic activity. Twenty one earthquakes of magnitude 6 or greater have originated in the north coastal California region since 1871 (Table 1), with the most recent being a magnitude 7.0 event on November 8, 1980.

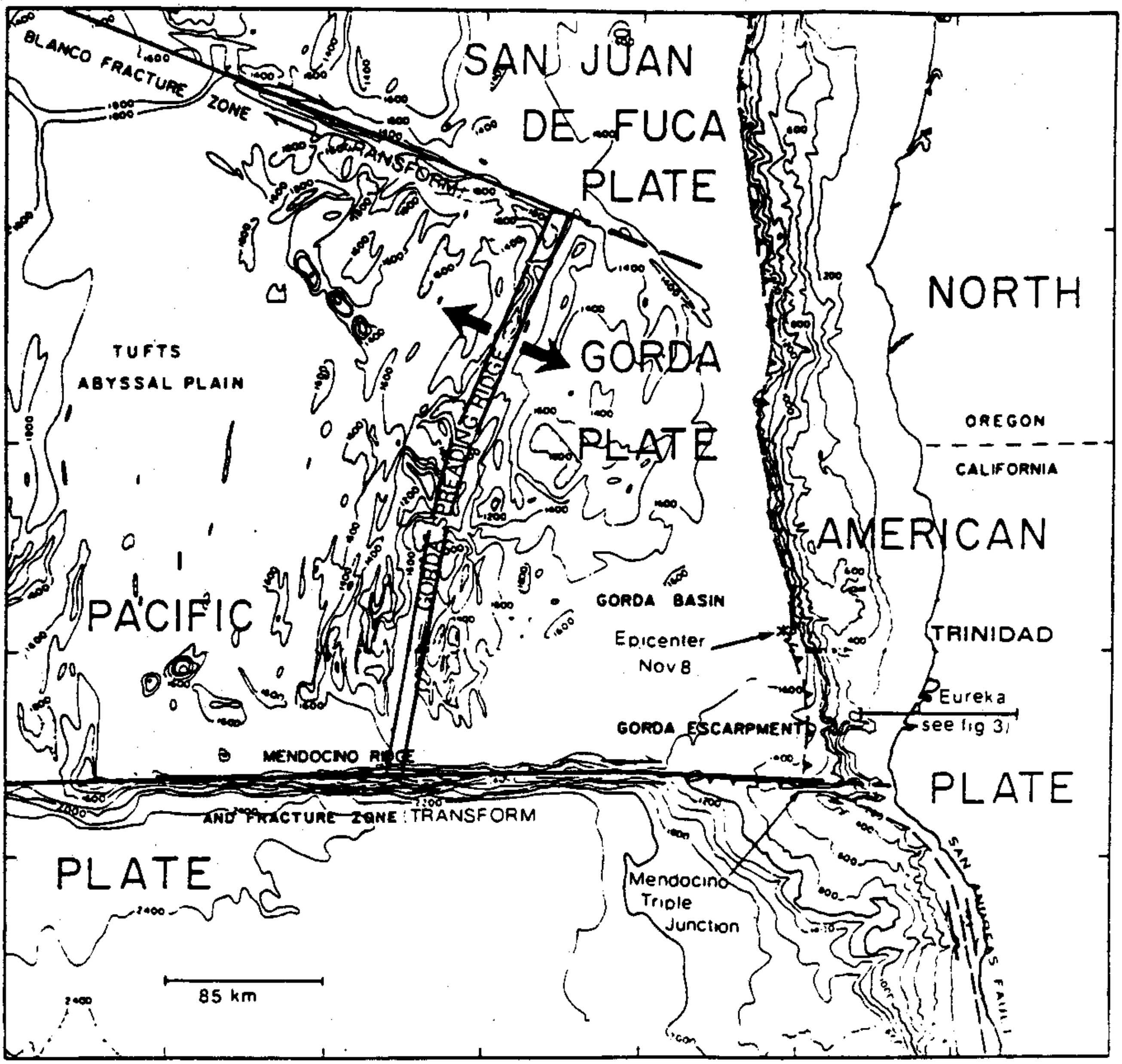


Figure 1. Generalized plate tectonic setting of the northern California coastal region and the Trinidad study area. (From Kilbourne and others, 1981, after various sources)

Table 1 Recorded earthquakes of M ≥6.0 in north coastal California (Real and others, 1978)

DATE	LOCALITY	Lat-N	Long-W	Magn. (Pre-1900 estimated)	Max. Intensity (MM)
3/2/1871	Eureka	40.4	124.2	6.2	VIII
11/23/1873	Crescent City	42.0	124.2	7.0	VIII
4/14/1898	Mendocino Co.	39.2	123.8	6.7	VIII
4/16/1899	Eureka	40.5	125.5	6.4	VI
10/29/1909	Humboldt Co.	40.5	124.2	6.0	VIII
12/31/1915	Gorda Basin	41.0	126.0	6.5	--
7/15/1918	W of Eureka	41.0	125.0	6.5	VI
1/26/1922	Gorda Basin	41.0	126.0	6.0	--
1/31/1922	Gorda Basin	41.0	125.5	7.3	--
1/22/1923	Cape Mendocino	40.5	124.5	7.2	VIII
6/4/1925	NW of Eureka	41.5	125.0	6.0	--
12/10/1926	Gorda Basin	40.8	126.0	6.0	--
6/6/1932	Arcata	40.8	124.5	6.4	VIII
2/9/1941	Gorda Basin	40.7	125.4	6.4	--
10/3/1941	SW of Eureka	40.4	124.8	6.4	VII
11/25/1954	W of Cape Mendocino	40.3	125.6	6.1	--
12/21/1954	E of Eureka	40.8	123.9	6.5	VII
10/11/1956	Gorda Basin	40.7	125.8	6.0	--
11/8/1956	Gorda Basin	41.1	125.4	7.0	VII
11/26/1976*	150 Km NW of Eureka	41.3	125.7	6.2	V
11/8/1980**	50 Km W of Trinidad	41.1	124.7	7.0 (M_s 7.2)	VII

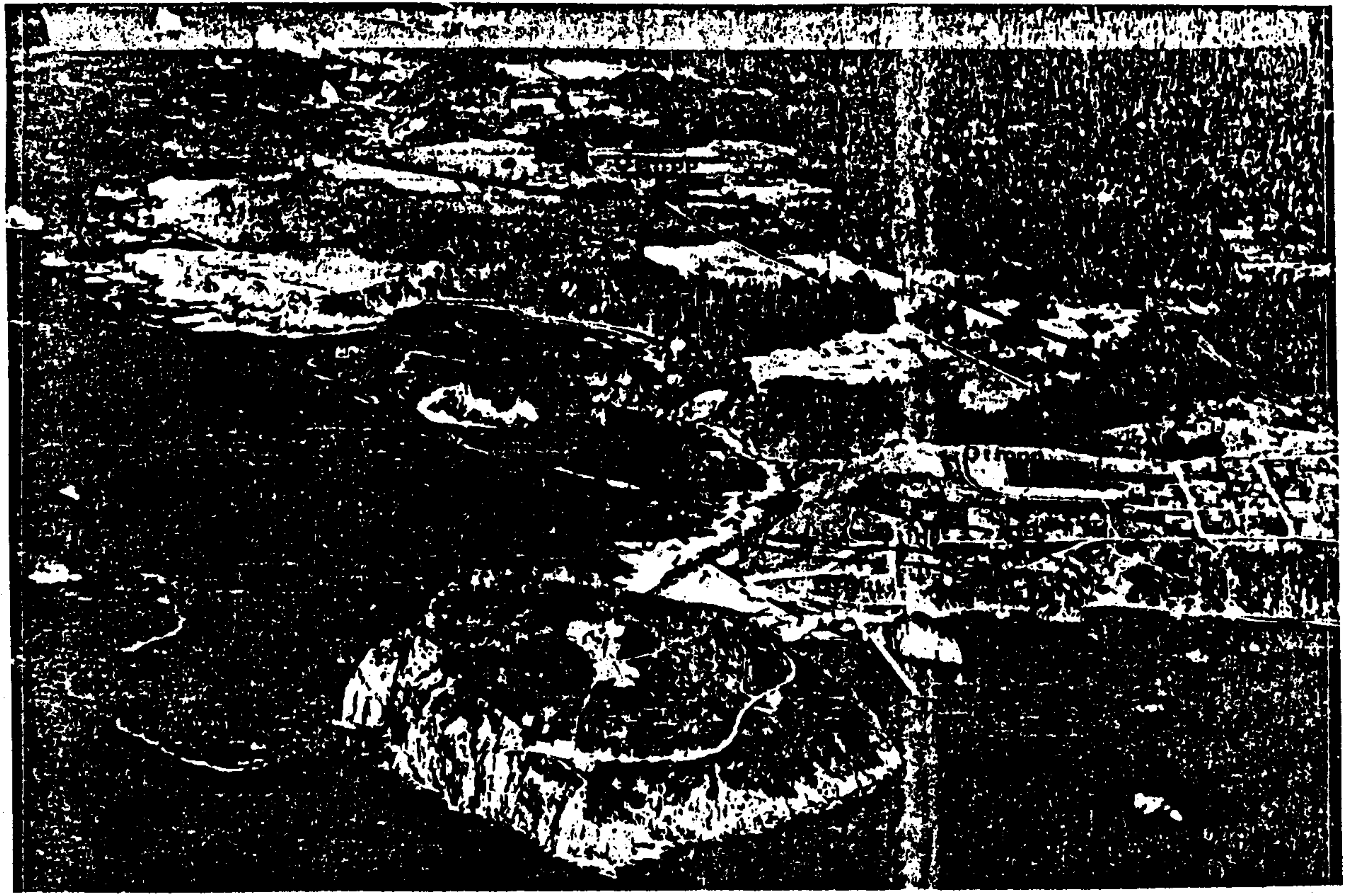
(*Woodward-Clyde Consultants, 1980. **McPherson, pers. comm., 1982.)

Variations in resistance of rocks exposed at the coast

The fold and fault trends in Humboldt County north of the Mendocino triple junction (Fig. 1) are truncated by the coastline and result in a generally alternating sequence along the coast of upfolded or upfaulted rocks with intervening stretches of downfolding or downfaulting. Uplift brings relatively resistant bedrock above sea level and produces headlands and coastal ridges, while the downdropped stretches are embayed.

This variability is compounded by extreme variations in the resistance of the bedrock itself. In the study area (Plate 1) the bedrock is appropriately referred to as the Franciscan melange complex, consisting chiefly of relatively resistant tectonically sheared and juxtaposed blocks of bedded chert, sandstone, conglomerate, metavolcanic and plutonic rocks (Aalto, 1976). These blocks range from boulder size to the size of Trinidad Head, and are dispersed in an easily eroded shaley matrix. Coastal erosion processes quickly remove the matrix, resulting in a very irregular coast with headlands and offshore stacks and islands formed by the resistant melange blocks (Fig. 2).

Figure 2. Aerial photograph looking north over Trinidad Head in 1950. Shows the Andersen Ranch fault, Trinidad Head fault zone, the Patricks Point (Qtmpp), Luffenholtz (Qtml) and Trinidad low (Qtmtl) marine terraces, the Luffenholtz shoreline, and the stream valley beheaded by coastal erosion (See also Plate 1).



Storm and wave conditions

This factor also has great significance in understanding coastal hazards in northern California. Rainfall, waves, and storm surges have all reached startling values during the short period that records have been kept.

Rainfall reduces the shear strength of coastal slopes and accelerates undercutting by streams, thereby increasing landslide activity. The mean annual rainfall in this region is the highest recorded along the California coastline, and just north of the study area the figure is 1773 mm (69.81 inches), increasing rapidly with altitude, and with almost 80% falling between November and March (Janda and others, 1975). Most notable are severe storms such as that of December 1964 when over 800 mm (31.5 inches) of rain fell during six days at stations within the Eel River basin south of Eureka (U.S. Army Corps of Engineers, 1965). Recent analysis (Coghlan, 1982) concludes that such events are characteristic of this region and may be reasonably expected to recur two or three times each century. Storms producing 178 to 203 mm (7 to 8 inches) of rain during a 24 hour period are likely to occur in the region once every 10 years an average (Miller and others, 1973).

Winter is also the time of largest waves, enhancing the effect of rainfall on coastal slope stability by rapidly removing landslide toes and protective beach sand. The alignment of the coastline in this region exposes it directly to waves generated by storms in the north Pacific, and it experiences the most powerful wave conditions in California (Johnson, 1973). Waves up to 13.5 m (44 feet) have been recorded near Crescent City (Smith, 1978) and Waverider buoys recently installed outside Humboldt Bay have recorded wave heights of over 7 m (23 feet) in two years of operation (Seymour and others, 1981). Most spectacular of all, waves breaking against Trinidad Head (Plate 1 and Fig. 2) in December 1914 produced run-up which rose to the lamp housing on the lighthouse at an elevation of 60 m (196 feet) (Harrington, 1914). When these wave conditions coincide with high tides and storm surges their potential effect can be catastrophic.

Tsunami potential is also considerable in this area (Houston and Garcia, 1978); and in 1964 Crescent City was inundated by tsunami waves up to 6.3 m (21 feet) high generated by the Alaska earthquake, causing eleven deaths and about nine million dollars worth of damage (Iida and others, 1967).

Evidence for late Quaternary fault activity

Almost all earthquakes in historical time have been located offshore (Table 1) and there are no records of fault breakage on land north of Cape Mendocino. This apparent lack of faulting is inconsistent with the tectonic setting and it is therefore necessary to examine the recent geologic record to identify fault activity. Fault rupture accompanying the November 1980 earthquake is estimated to have taken place over a distance of some 120 kms (75 miles) with an average slip of 2.1 m (6.9 feet) (McPherson, pers. comm. 1982), and an event of this magnitude on land would obviously be a major hazard.

Regional compression has resulted in uplift of the study area and thereby preserved a staircase of marine terraces climbing inland away from the coastline. This terrace sequence climbs to 410 m (1345 feet) (Woodward-Clyde Consultants, 1980), indicating a history of tectonic uplift extending well back into the Quaternary. Most importantly the terraces, in addition to offering attractive sites for development, provide invaluable datum surfaces for determining fault offset and deformation, and allow tentative fault activity estimates to be made.

1) Andersen Ranch fault and fault zone

Identification of the faulting began with recognition of the prominant scarp and associated folding of the terrace surface on the Andersen Ranch property near the north end of the mapped area (Plate 1 and Fig. 2). The identification was made using 1:12,000 scale aerial photographs, and later confirmed by field examination and mapping of the sea cliff exposure at the ranch (Fig. 3). This faulting and folding is consistant with the regional tectonic compression and immediately raises the question of its activity. Evidence bearing on this question will now be considered.

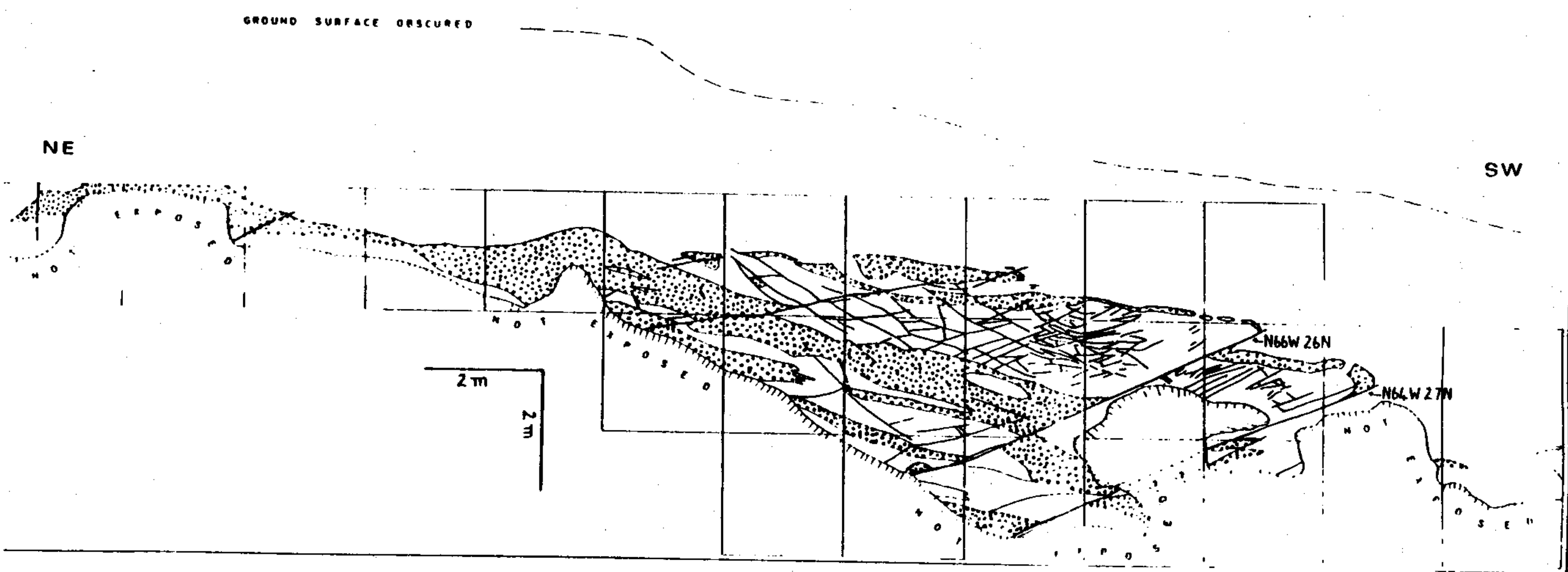
a) Age of faulted marine terraces

The deposits cut by the fault at the cliff exposure, as well as the deposits associated with the rest of the terrace sequence, have not yielded dateable material. Age estimates must be based on tentative correlations with other dated marine terraces in California, and by fitting the terrace sequence to world-wide glacier-controlled sea-level fluctuations (Bloom and others, 1974; Cronin, 1982). Using this approach Woodward-Clyde Consultants (1980), in a study of the main terrace sequence, estimate that the lowest prominant terrace (the Patricks Point terrace, Qtmpp on Plate 1) was formed during the final highstand of sea-level in the Sangamon interglacial period about 82,000 years ago.

The interbedded sands and gravels at the cliff exposure are associated with a younger marine terrace inset below the Patricks Point terrace along the coast in the study area. This terrace is designated the Luffenholtz terrace (Rust, 1982a) and appears on the map (Plate 1) as Qtml. In thickness this terrace ranges from 7-8 m (23-26 feet) at Elk Head, where the greatest width of terrace is preserved, to 1-2 m (3-6.5 feet) near the shoreline angle exposed below the abandoned sea cliff which crosses the Pewetole Island headland (Plate 1 and Fig. 2). It appears to have cut out the deposits of the Patricks Point terrace and is usually found eroded across a section of oxidized and partially cemented mid-Pleistocene marine sands, which occur throughout the study area resting on a prominent abrasion platform over the Franciscan bedrock. The terrace base is marked by a gravel and pebble lag which is interrupted in several places by coarser deposits in channels which

FAULT EXPOSURE IN LATE QUATERNARY MARINE SANDS AND GRAVELS AT ANDERSEN RANCH SEA CLIFF, TRINIDAD, NORTHERN CALIFORNIA (1979)

Figure 3



have eroded into the wave-cut contact. These channels occur most commonly near existing coastal streams and are believed to have been produced as the streams advanced across the newly exposed marine terrace as base-level fell. This interpretation is consistant with detailed observations made by Kirkby and Kirkby (1969) on raised beaches after the 1964 Alaska earthquake, and with a model for drainage evolution on marine terraces presented by Cleveland (1975). The high-stand of sea-level about 82,000 years ago ended with a glacial advance, and sea-level remained low until it rose during an interstadial warming period approximately 60,000 years ago (Bloom and others, 1974). This age is therefore tentatively assigned to the Luffenholtz terrace deposits.

b) Fault slip rate

The Andersen Ranch fault was active before the Luffenholtz marine incursion and largely controlled part of the shoreline at that time (Plate 1) by uplifting resistant Franciscan sandstone against a zone of argillite mélange matrix. Marine erosion during this incursion contributed a large part of the 21 m (69 feet) maximum scarp height at Andersen Ranch. The sequence of sands and gravels at the cliff exposure thicken from 2-3 m (6.5-10 feet) on the hanging wall to at least 8 m (26 feet) on the foot-wall and are believed to represent shoreline deposits having a relatively steep primary dip, decreasing up-section as the deposits accumulated (Fig. 3).

Therefore, since large-scale folding of the deposits is probably rather limited, a relatively accurate estimate of dip-slip fault offset, including small drag folds, can be measured directly along the fault planes. This measurement amounts to about 5 m (16.5 feet), representing a minimum value for total fault displacement because abrupt changes in thickness of the gravel units across the faults indicate an additional component of strike-slip motion. However, it does suggest a minimum average slip rate of .08-.09 mm/year for the past 60,000 years.

Further inland south of College Cove Creek (Plate 1) the surface of the Patricks Point terrace is offset by a fault scarp about 10 m (33 feet) high, and two exploratory trenches have been dug here by Woodward-Clyde Consultants. The fault plane was found to increase in dip to 45° at the bottom of the trenches and slickensides indicated that motion during at least the last faulting event was dominantly dip-slip. If this motion is assumed to be characteristic it suggests a cumulative dip-slip amounting to about 14 m (46 feet) on a fault plane dipping at 45°, which gives an average slip rate of .17 mm/year over the past 82,000 years (Woodward-Clyde Consultants, 1980). Variation in dip at the cliff and trench exposures may be related to the difference in strike of the fault at the two places.

c) Recurrence interval

These slip rates can be used to estimate a recurrence interval for large earthquakes on the fault if an idea can be gained of the amount of slip produced during such earthquakes. At the cliff exposure Woodward-

Clyde Consultants identified scarp derived colluvium offset 2-3 m (6.5-9.8 feet) and they suggest this may represent displacemnt in one faulting event. This suggestion seems in accord with the 2.1 m (6.9 feet) of displacement estimated for the M 7 earthquake in 1980, although the displacement was strike-slip rather than the thrusting at Andersen Ranch.

Using the slip rate of .08-.09 mm/year suggests a maximum recurrence interval for 2-3 m (6.5-9.8 feet) faulting events of about 25,000 to 35,000 years. If the same size of faulting event is applied to the trench site the .17 mm/year slip rate gives a recurrence interval of between 12,000 and 18,000 years.

d) <u>Geomorphic evidence of fault activity</u>

Several indicators suggest that the rate of geomorphic processes is more than matched by fault activity. For example; the long profiles of small coastal streams such as Elk Head Creek and College Cove Creek (Plate 1 and Fig. 4) preserve on oversteeped reach where they cross the fault, and a small depression produced by warping of the terrace surface on the hanging wall of the fault at Andersen Ranch (Plate 1) has not yet been filled by sediments.

Another indication of activity along the Andersen Ranch fault zone is provided by the coastline south of Trinidad. The present position of this coastline appears to be controlled by the fault and the location of the abandoned coast line of the 60,000 (?) year old Luffenholtz terrace is only a very short distance inland (Plate 1) suggesting that it was similarly influenced. Indian Creek (Fig. 4) and other coastal streams here all show very steep long profiles which are convex upwards right to beach level, while Luffenholtz Creek (Plate 1) has a pronounced convex upwards steepening at the fault crossing, but from there to the beach it possesses a "normal" concave up profile.

2) <u>Trinidad Head fault zone</u>

This zone of compressional faulting crosses the tip of the Trinidad peninsula and is responsible for depressing the melange matrix in the lee of Trinidad Head (Plate 1 and Fig. 2), forming the only part of the coastline in the map area where bedrock is below sea level. The fault zone appears to define the coast at Elk Head and field evidence indicates that it too is an active structure.

The Luffenholtz terrace surface at Elk Head is conspicuously warped on the upthrown side of the fault zone and Elk Head Creek is alluviating its valley inland of this upfold (Plate 1); thus contrasting strongly with the active incision of all other streams in the study area (see Fig. 4 for example).

Faulting along this zone, probably in conjunction with overall uplift in the study area (see next section on "Regional faults"), was sufficient to bring the resistant bedrock underlying Elk Head above sea-level thus converting the embayment here during Luffenholtz time to the present headland (Plate 1 and Fig. 2).

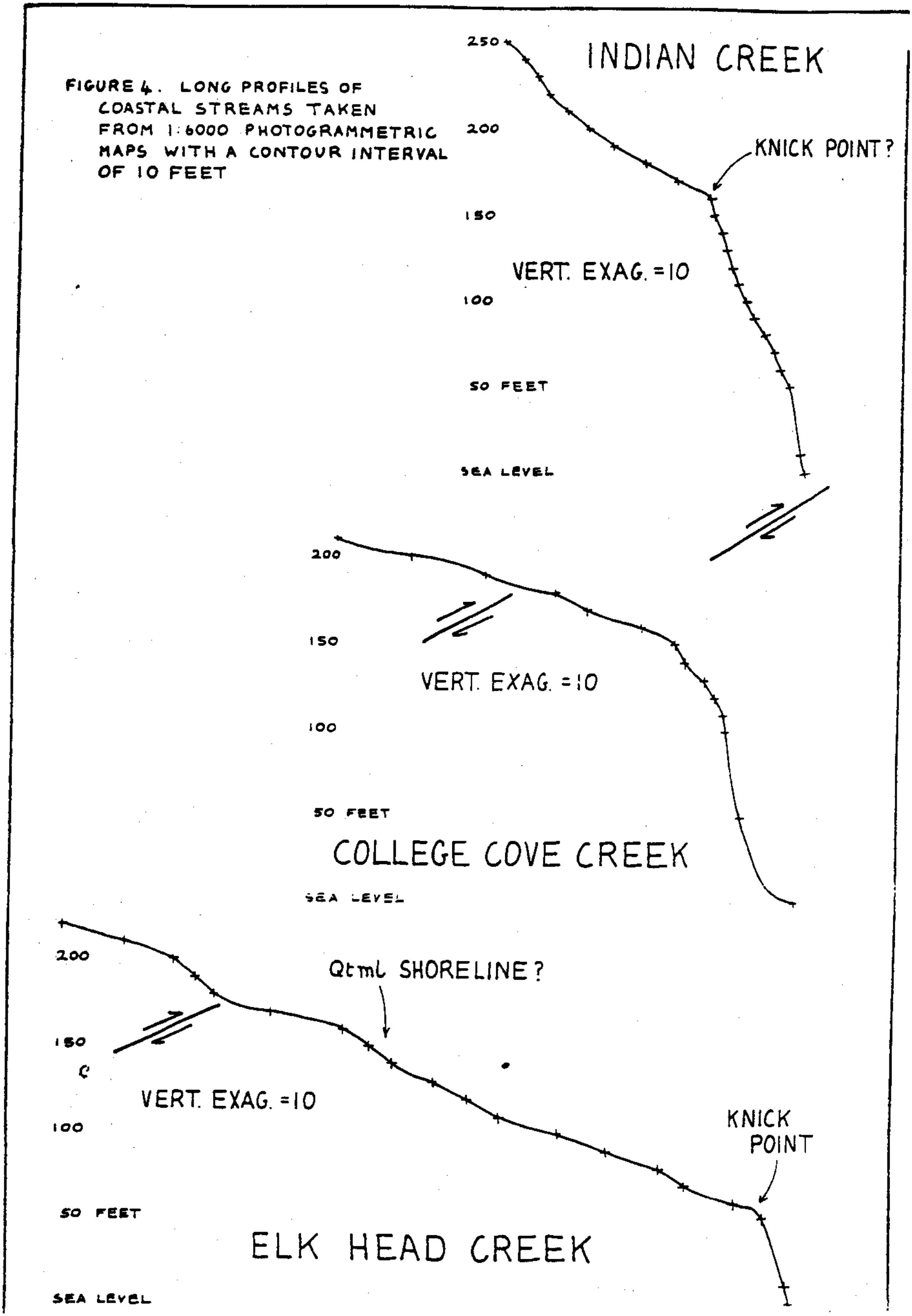


FIGURE 4. LONG PROFILES OF COASTAL STREAMS TAKEN FROM 1:6000 PHOTOGRAMMETRIC MAPS WITH A CONTOUR INTERVAL OF 10 FEET

Similar faulting and uplift is responsible for the preservation of the Luffenholtz terrace on Pewetole headland, and on Trinidad peninsula there is evidence that an additional younger marine terrace has also been preserved near the hanging wall of the fault (Plate 1 and Fig. 2). This younger terrace is designated the Trinidad low terrace (Rust, 1982a).

The terrace is clearly inset below the Luffenholtz terrace but once again its age is very uncertain. It must have been eroded during a later interstadial high sea-level stand, possible by the one dated very approximately at 40,000 years ago (Bloom and others, 1974).

There is evidence suggesting possible Holocene activity along this fault zone. At Andersen Cove (Plate 1), on the upthrown side of the fault, an emergent wave-cut bench a few meters above sea-level may be Holocene; while on the downthrown side of the fault just north of Trinidad Head, Redwood stumps in apparent growth position are occasionally exposed by wave action and have yielded ^{14}C dates of about 6,000 years BP (Tom Stephens, pers. comm. 1981). However, although this evidence of emergence and submergence is consistant with fault offset, it should be regarded with consideration of non-tectonic influences on Holocene sea-level (Clark and others, 1978; Cronin, 1982).

The fault zone probably extends southeastwards offshore from Trinidad Head to the Moonstone Beach area and possibly continues inland beyond the mouth of the Little River (Plate 1).

3) Regional faults

Other zones of active compressional faulting occur a short distance to the south (Carver and others, 1982), and these probably continue their northwest trend offshore of the study area, contributing to the overall uplift as well as to the faulting hazards. North of the mapped area the Lagoons fault zone (Carver and others, 1982) depresses the Franciscan bedrock below sea level at Agate Beach and exposes the overlying terrace sands to wave erosion.

4) Uplift rate

Calculations based on the age and elevation of the marine terraces suggest an uplift rate in the study area of between 1 and 1.2 mm/year.

The best paleo sea-level indicator is the shoreline angle (Kirkby and Kirkby, 1969), such as that for the Luffenholtz terrace exposed at approximately 35 m (115 feet) above sea-level on Pewetole headland. Assuming the approximate terrace age of 60,000 years is valid, and assuming that sea-level was then about 25 m (82 feet) lower than today (Bloom and others, 1974), produces an average uplift rate of about 1.0 mm/yr. The back edge of the Patricks Point terrace surface is about 80 m (262 feet) above sea-level at Trinidad (Woodward-Clyde Consultants, 1980), which indicates an uplift rate of about 1.15 mm/yr. assuming an 82,000 year age and a sea-level 15 m (49 feet) lower than present. Similar calculations using the Trinidad low terrace shoreline angle (Rust, 1982b) indicate a rate of about 1.2 mm/yr. However, although consistant with rates calculated from the two older terraces, this figure may be misleading because of the very equivocal terrace age assignment, the reworking by alluvial fan deposits which has occurred at the shoreline angle (Goodwin and others, 1982), and because of possible folding close to the hanging wall of the Trinidad Head fault zone. All the figures should be viewed in light of the cautions over age and paleo sea-level control expressed by Cronin (1982).

Some of this uplift is probably caused by regional up-warping rather than fault offset, and this is indicated by older terraces further inland which are warped along a northwest trending axis (Woodward-Clyde Consultants, 1980; Stephens, 1982a).

Based on the terrace surface offset at the Woodward-Clyde trench site the Andersen Ranch fault may contribute up to about 10% of the 1.15 mm/yr. uplift rate for the Patricks Point terrace. The contribution (and thus the potential hazard) of the Trinidad Head fault zone, as suggested by the relatively important role assigned to it in prograding the coastline seawards, may be higher than this.

PART B

Coastal faulting and erosion hazards

With the foregoing information on the hazard producing factors in hand, together with observations on past response to these factors, it is possible to assess potential hazards in the future.

1) Fault rupture at the ground surface

This will very probably occur again along the Andersen Ranch and Trinidad Head fault zones as in the past. When this will happen, of course, is unknown. There is evidence that the November 1980 earthquake (Fig. 1) restored northeast-southwest compressive tectonic stress to the North American plate after a long period (Table 1) of stress release concentrated in the Gorda plate (McPherson, pers. comm., 1982).

Although the recurrence interval of surface faulting events is probably measured in thousands of even tens of thousands of years, both faults should be considered active for planning purposes and capable of breaking at any time. In addition, the relatively wide zone of deformation and fracturing associated with these low-angle faults (see Fig. 3 for example) should be borne in mind before building permission is granted.

2) Seismic shaking

Both the historical record and the relatively high uplift rate indicate that ground shaking occurs frequently, and severe ground shaking should be expected during faulting events centered closer to the study area. Several hazards result:

a) Structural damage

A compilation of newspaper accounts of earthquakes in Humboldt

County between 1900 and 1972 (Tuttle, 1975) indicates considerable structural damage, especially from liquefaction, and the 1980 earthquake brought down a freeway overpass south of Eureka. However, due to the lack of development and the offshore location of most earthquakes (Table 1), structural damage has been relatively limited.

b) Coastal slope failures

Numerous large landslides have been triggered by past earthquakes in the region (Tuttle, 1975; Youd and Hoose, 1978; Kilbourne, 1981), particularly during the later part of winter and early spring when shear-strength is minimized by high moisture content. Earthquake triggered failures also occur offshore (Field and others, 1982; Field and others, 1980). In the study area slope failure processes were classified according to Varnes (1978), and are listed in the Explanation attached to Plate 1.

The clay rich matrix of the mélange bedrock is very responsive to increases in moisture, and wherever slopes are undercut by wave or stream action downslope flow occurs. The overlying terrace deposits fail by rotational slumping as the terrace margin is undermined (Aalto, 1977), with slump blocks (SB) becoming progressively broken as they ride downslope in the slump-earthflow (SEF). In some cases these blocks, capped by the displaced terrace surface, arrive relatively intact at the beach and provide inviting building plots (Plate 1).

Although all the coastal slope failure types can be triggered or accelerated by seismic shaking, slump-earthflows are easily the most common in the study area, and, through the calving off of new slump blocks, potentially the most hazardous to structures located along the terrace margin. Geologic mapping shows that very large slump blocks, breaking inland over 100 m (328 feet) from the former terrace margin, have been produced in the relatively recent past. The best examples of these slump blocks are found now in areas where earthflow activity is relatively limited due to protection from wave attack, as at College Cove (Plate 1 and Fig. 2) for example. This leads to the speculation that perhaps such extremely large blocks were produced by shaking from a nearby earthquake, occurring during a period of hign moisture levels, and are preserved only where coastal slope failure rates are waning following the post-glacial rise in sea-level.

In addition, the inactive debris flows (IDF) mapped at Andersen Cove, Trinidad State Beach, and Trinidad Head (Plate 1), may have been seismically triggered during wet conditions, possibly through liquefaction in the terrace sands.

3) Tsunami potential

A recently proposed numerical model of tsunami generation in the Pacific basin predicts tsunami height at Trinidad Bay (Plate 1) of 5.7 m (18.7 feet) with a 500 year recurrence, and 3.1 m (10.3 feet) with a 100 year recurrence (Houston and Garcia, 1978). This model agrees quite well with historical records of tsunami activity at Crescent City and

San Francisco, and should be considered before building future structures on low-lying parts of the coast.

The probability of a locally generated tsunami in California is considered rather slight by these authors because strike-slip fault offset causes very little displacement of the overlying water column. Yet the evidence of dominantly dip slip late Quaternary faulting on land, and numerous west-side down fault scarps offshore in this area (Field and others, 1980), indicates that locally generated tsunami hazards should not be ignored.

Although a large tsunami has not been recorded in the study area the recent geologic record may contain evidence of one which occurred in the past. On the downthrown side of the Andersen Ranch fault between the cliff exposure and Elk Head (Plate 1) an older soil horizon has been sharply truncated and buried (Stephens, 1982b), offering the intrigueing possibility that a tsunami was responsible.

4) Cliff retreat

The general seawards-stepping progression of successively younger marine terraces, along the coast from Little River (Plate 1) about 15 kms (9 miles) north to Agate Beach, is the result of continued Quaternary uplift with intervals of cliff retreat during high stands of sea-level. During the present interglacial period sea level rose rapidly until about 5,000 years ago, and since then has been rising at about 1 mm/yr (Cronin, 1982; Emery and Kuhn, 1982), or perhaps remained constant within 1 $\pm$ m (3.3 feet) (Clark and others, 1978). Rates of cliff retreat have undoubtedly slowed in accord with the pace of sea-level rise and there is geological and historical evidence that the present shoreline in the study area is approaching a relatively stable equilibrium position as uplift rates and sea-level rise approximately balance each other. But historic retreat clearly indicates that such an equilibrium is not yet fully established, and changes in bedrock resistance and degree of protection from wave attack will always produce more localized changes in the coastline. In addition, variation in uplift rate or sea-level may occur in the future; for example tide-gauge records indicate a 10 mm/yr rise in sea-level over the past decade or more (Emery, 1980).

These considerations, as well as the factors outlined in Part A of this paper, can be applied in assessing the potential cliff retreat hazard for different parts of the coastline. Three examples will be used to illustrate this.

a) Big Lagoon area coastline

This area lies north of the tectonically elevated terrain between Little River and Agate Beach and has experienced rapid retreat along cliffs bounding land now subdivided into building plots. The most important factor influencing cliff retreat here is the tectonic downwarping north of Agate Beach, in the footwall of the major reverse fault defining the linear north-east margin of Big Lagoon. This has two effects. First, the relatively resistant Franciscan bedrock is depressed well below sea-level allowing waves to erode the overlying poorly consolidated terrace sands. Second, the downwarping effectively increases the rate of sea-level rise for this part of the coast. As a result of this the generally linear cliff-line steps abruptly inland almost 2 kms (1.25 miles) at Agate Beach.

Historical evidence suggests that most cliff retreat is accomplished in periodic large increments when other, more transient, factors combine unfavorably. Combinations of large waves, high tides, and depletion of beach sand expose the base of the cliffs to direct wave attack. These conditions, possibly reinforced by storm surges, produced recorded retreat in February 1940 and October 1941 which required cabins to be moved back from the cliffs (Tuttle, 1981). Although the amount of retreat caused by individual storms such as these in unknown, Tuttle enlarged old aerial photographs to measure retreat up to 17.7 m (58 feet) or 1.8 m/yr between August 1931 and November 1941, with further retreat between November 1941 and February 1942 up to 9.1 m (30 feet). Between 1941 and 1974 retreat up to 46.3 m (152 feet) or 1.4 m/yr was measured, and an 1875 US Government field survey indicates about 91.4 m (300 feet) or 1.6 m/yr of cliff retreat between then and 1931. These catastrophic retreat rates have reduced several of the cliff-top building plots to half their original size since 1941 (Tuttle, 1981), and further building permits should clearly not be granted.

b) <u>Elk Head - Trinidad State Beach area coastline</u>

Running from the Andersen Ranch fault to Trinidad Head (Plate 1 and Fig. 2) this coast is made up of resistant bedrock headlands such as Elk Head, with intervening bays such as College Cove eroded in the weak melange matrix material. The bay just south and west of the Andersen Ranch fault (Plate 1) is virtually unprotected from the dominant northwest swell direction, and the terrace margins above active slump earthflows here retreated up to 61 m (200 feet), or 0.85 m/yr, between 1870 and 1942 as measured from US Coast Survey maps and aerial photographs (Tuttle, 1981). Between 1942 and 1974 aerial photographs up to 13.5 m (44 feet) or .4 m/yr of retreat occurred.

This part of the coast has obviously not reached any sort of relatively stable equilibrium position, but the rest of the coastline to Trinidad Head is much closer to such a condition. College Cove and Trinidad State Beach both retreated quite swiftly as Holocene sea-level rose, isolating the Elk Head and Pewetole Island promentories. Pewetole Island headland is crossed by a stream valley (Plate 1 and Fig. 2) which shows essentially no modification since it was isolated from its upstream continuation, probably College Cove Creek, by rapid embaying of College Cove. However, as the cove became increasingly indented it also became more protected from wave attack and retreat rates declined.

Evidence for tis decline is offered by: The relatively low coastal slope angle at College Cove compared with the steep angles at the actively retreating Andersen Ranch cliff already discussed; the long profiles of College Cove Creek (Fig. 4) and Mill Creek (Plate 1), which both have a concave-up lower reach inconsistant with a rapidly retreating outlet; the historical retreat on the more exposed southern part of Trinidad State Beach, which between 1870 and 1974 ranges up to a relatively low 21.3 m (70 feet) or .2 m/yr; and the preservation of the large slump block at College Cove and the inactive debris flow above Trinidad State Beach (Plate 1), when such features, possibly produced by past seismic shaking, are only preserved elsewhere on stable parts of the coast.

In summary, most of this part of the coastline has evolved into a relatively stable position since the Holocene rise in sea-level and future coastal retreat hazards are limited. Continuing retreat can be expected at the Andersen Ranch cliff until a deeply indented cove, possibly similar to the one suggested for the Luffenholtz terrace shoreline (Plate 1), is produced. However, under very wet conditions, and especially during severe seismic shaking, more large slump blocks may become detached above College Cove and Trinidad State Beach.

c) Coastline from Trinidad southeast to Luffenholtz Beach

The position of this linear coastline (Plate 1) appears to be generally stabilized by uplift, particularly uplift on the Andersen Ranch fault. Several large slump-earthflows here are actively disrupting the coastal road (Rust, 1982b) and ultimately cause retreat of the terrace margin. Yet the toe areas of these earthflows in some cases form headlands (Plate 1) suggesting progradation seawards. This geomorphic indication is supported by measurements from 1942 and 1974 aerial photographs made by Tuttle (1981) which show progradation up to 6.1 m (20 feet) in the seaward margin of these flows. It appears that the protective influence of Trinidad Head and the concentrations of sea stacks offshore does not fully explain this progradation because similar slump-earthflows to the south of Trinidad, on the downthrown side of the Andersen Ranch fault, do not exhibit progradation in spite of their greater degree of protection.

Since the old cliff-lines for the Luffenholtz and Patricks Point terraces are within .5 km (.3 mile) of the present coastline uplift and offset on the Andersen Ranch fault has influenced the coastline position for the most of Late Quaternary time. For this part of the coast the historic evidence on the position of the shoreline could give a misleading impression of safety since with continued uplift the slopes are actively failing and steadily encroaching on the terrace margin.

PART C

Recommendations for hazard management

Unlike the southern California coastline the coast in northern California is relatively undeveloped. This gives an opportunity, through wise management based on improved scientific knowledge, to avoid the costly problems now occurring in southern California (Kuhn and Shepard, 1980). Several recommendations can be made in order to minimize coastal faulting and erosion hazards:

1) Detailed geologic mapping, similar to the present study, should be carried out in developing coastal zones at scales between 1:6,000 and 1:12,000. Such studies can identify regional problems overlooked in studies of specific building plots. Since the work is labour intensive, costs might be reduced by assisting suitable graduate students to take on stretches of the coastal zone as thesis projects.

2) Within the context of this mapping the routine site investigations by engineering geologists should continue, with particular attention paid to identified seismic, cliff failure/retreat, and tsunami hazards.

3) Active fault zones revealed by the mapping should be earmarked for further study, particularly of their possible continuity further inland and offshore. This work should determine fault length and earthquake generating potential both in the coastal zone and close offshore.

4) Zones should be designated astride the active faults, similar to the Alquist-Priolo Special Studies Zones, where site studies would be required to investigate the possibility of ground deformation and breakage below a proposed structure. These zones should be wider for thrust faults, such as those identified in the study area, than for strike slip faults.

5) Structures should be designed to withstand anticipated levels of ground shaking.

Acknowledgements

Discussions in the field with Ken Aalto, Gary Carver, Bill Page and Tom Stephens have been very helpful in refining many of my interpretations and I am most grateful to them. Work supported under California Sea Grant numbers R/CZ-53 and R/NP-1-10F.

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