University of Nevada

Reno

Timing of Folding and Uplift of the Pismo Syncline, San Luis Obispo County, California

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Geology

by

Katheryn Marie Killeen

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The thesis of Katheryn M. Killeen is approved:

Thesis Advisor

Department Chair

Dean, Graduate School

University of Nevada

Reno

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ABSTRACT

The goal of this project was to use geomorphic features such as stream and marine terraces to measure possible tectonic deformation in a tectonically active area. Marine and stream terrace elevation data were collected during the summer of 1986, along the coast of California near San Luis Obispo. A low rate of deformation between Montana De Oro State Park and Arroyo Grande in San Luis Obispo County is indicated by marine and stream terraces. A consistent gradient between strath surfaces, and a lack of significant ponding of alluvium, in most places, implies that synclinal deformation has occurred at a low rate during Quaternary time. The uplift rate for this section of coast is estimated at approximately 0.14mm/yr. Based on the exposed and easily projected inner-edge data, the marine terraces do not appear appreciably deformed.

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INTRODUCTION

LOCATION

The study area is located near San Luis Obispo, California and includes the region west from San Luis Obispo to the Pacific Ocean, and from Montana De Oro State Park in the north to Pismo Beach in the south (Fig. 1). This region is roughly the geographic boundary of the Pismo syncline, the principal structural feature in the study area.

PROJECT GOALS

The goal of the study was to determine, using geomorphic indicators, the rates and styles of tectonic activity in the Pismo syncline, a major structure southwest of San Luis Obispo. The presence of the syncline indicates that a compressive tectonic regime existed along this part of the California coast during the Late Miocene to the Pleistocene. Whether the tectonic regime has changed since the Pleistocene is one of the questions that may be answered by determining the current style of deformation in the Pismo syncline. This information could help provide a better understanding of the nature of possible seismic structures, such as the Los Osos and Hosgri faults which lie North and South, respectively, of the Pismo Syncline.

Possible types of tectonic deformation in the region of the syncline include: continued folding and/or uplift of the syncline, displacements on the Los Osos, Edna and San Miguelito faults, and uplift along the coast.

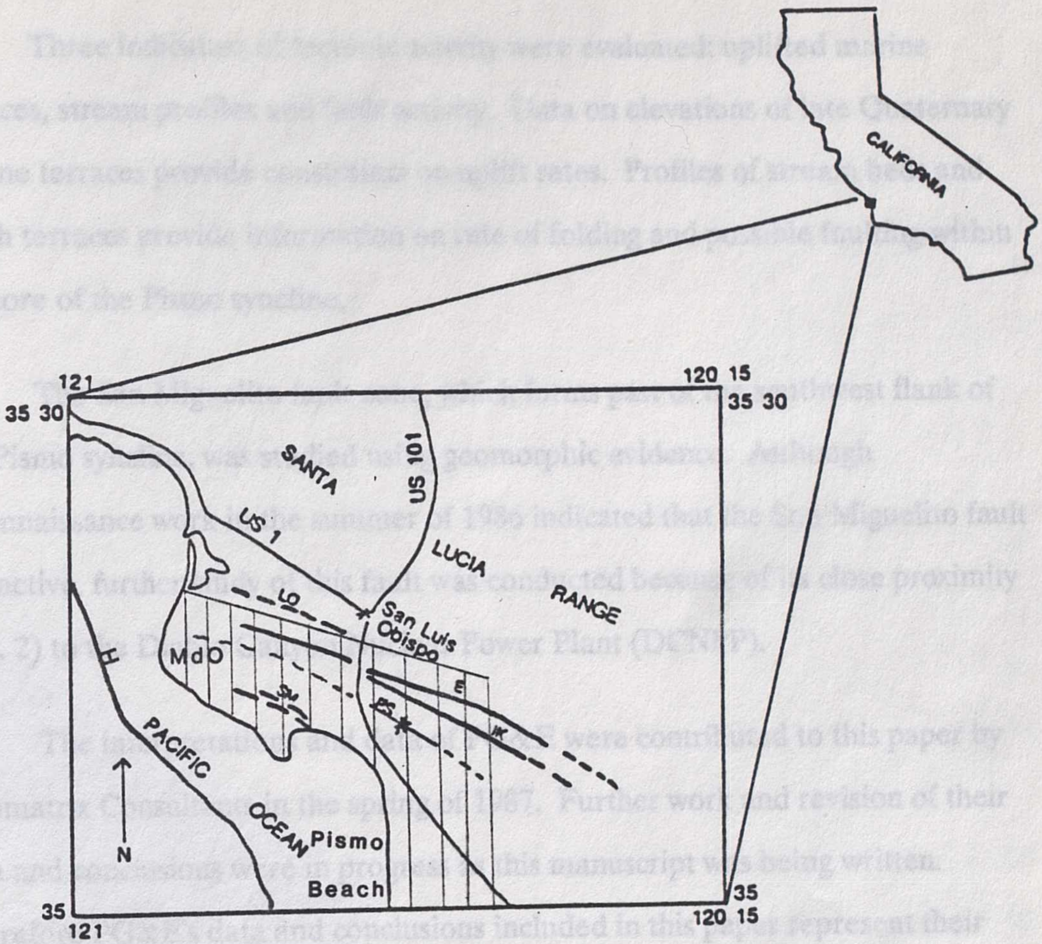


Figure 1: Location of the study area

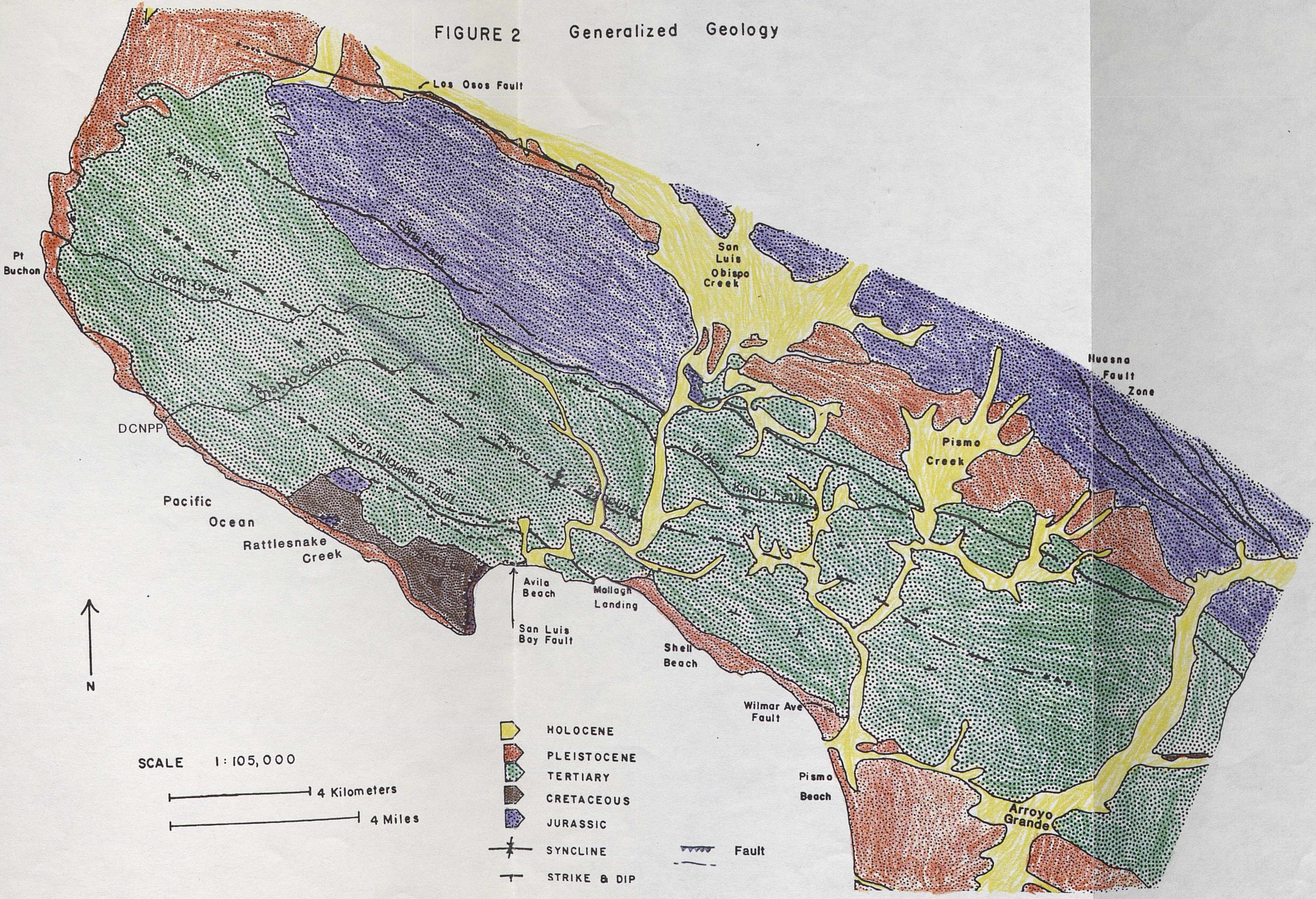
LO = Los Osos Fault; E = Edna Fault
IK = Indian Knob Fault; PS = Pismo Syncline
SM = San Miguelito Fault; H=Hosgri Fault
MdO=Montana de Oro State Park

Three indicators of tectonic activity were evaluated: uplifted marine terraces, stream profiles and fault activity. Data on elevations of late Quaternary marine terraces provide constraints on uplift rates. Profiles of stream beds and strath terraces provide information on rate of folding and possible faulting within the core of the Pismo syncline.

The San Miguelito fault zone, which forms part of the southwest flank of the Pismo syncline, was studied using geomorphic evidence. Although reconnaissance work in the summer of 1986 indicated that the San Miguelito fault is inactive, further study of this fault was conducted because of its close proximity (Fig. 2) to the Diablo Canyon Nuclear Power Plant (DCNPP).

The interpretations and data of PG&E were contributed to this paper by Geomatrix Consultants in the spring of 1987. Further work and revision of their data and conclusions were in progress as this manuscript was being written. Therefore PG&E's data and conclusions included in this paper represent their preliminary thoughts as of spring 1987.

FIGURE 2 Generalized Geology



REGIONAL SETTING

The dominant structural feature in the area west of San Luis Obispo is the Pismo syncline (Fig. 2), an approximately 5km wide by 34km long fold with a northwest trending hinge surface and hinge line. The Pismo syncline grades into a synclinorium to the northwest and southeast (Hall, 1973), and could be referred to as a synclinorium because minor folds are superimposed on the main fold, but for brevity it will be referred to as a syncline in this paper.

The strata within the syncline rest unconformably in a possible detachment relationship over the Jurassic-Cretaceous Franciscan Complex (Hall, 1973). The rocks that make up the syncline include: volcaniclastic and tuffaceous rocks of the lower Miocene Obispo Formation, siliceous and dolomitic basinal marine deposits of the middle Miocene Monterey Formation and the upper Miocene-Pliocene Pismo Formation (Table 1). The Obispo tuff, Monterey Formation and the lower part of the Pismo Formation were folded and uplifted during the Middle Pliocene and overlain unconformably by the upper part of the Pismo Formation. Folding and uplift continued into the Pleistocene as the non-marine Pleistocene (age poorly constrained) Paso Robles Formation was deposited unconformably on the older rocks (Hall, 1973).

The folding ceased, or continued at a very slow rate during the past half million years, with a change from plastic Pleistocene failure and folding to brittle failure and block uplift.

NAME	THICKNESS	AGE	DESCRIPTION
UNNAMED	0-30m	Holocene	Unconsolidated alluvium in present stream channels
PASO ROBLES FM	>32m	Pleistocene	Poorly sorted and bedded conglomerate
PISMO FM			
Squire Mbr	183m	U. Pliocene	Massive, white, soft, med.-grained sandstone, locally bituminous
Bellview Mbr	216m	U. Pliocene	Interbedded, buff, mod.-resistant, fine-grained sand and claystone
Gragg Mbr	232m	U. Pliocene	Massive, white, mod.-resistant, med. grained sandstone
Miguelito Mbr	750m	L. Pliocene	Interbedded, brown, mod.-resistant, silt and claystone
Edna Mbr	483m	U. Miocene	Massive, white, soft, med.-grained sandstone, locally bituminous
MONTEREY FM	675m	Miocene	Bedded, brown to grey, resistant chert, beds 2-10cm thick
OBISPO FM	450m	L. Miocene	Perlitic, white to grey, mod.-resistant volcanic tuff and breccia
RINCON SH	167m	Oligocene	Poorly to well bedded, dark brown, siltstone or silty claystone
UNNAMED	800m	Cretaceous	Red brown conglomerate or med.-bedded, brown, coarse sandstone
FRANCISCAN COMPLEX	>667m	Jurassic	Chaotic mixture of bedded cherts and greywackes in a mud matrix
SERPENTINE			Grey, red, blue, brown and green serpentinite and peridiotite

TABLE 1 Summary of main formations in study area. After Hall (1973)

Faults located in or near the Pismo syncline include the Edna, Indian Knob, Los Osos, San Miguelito, San Luis Bay, and Wilmar Avenue faults (Fig. 2). Each of these faults will be discussed briefly.

The Edna fault trends northwest, dips southwest, and lies within the northeast limb of the Pismo syncline. Since the Edna fault juxtaposes the Upper Pliocene Squire Member of the Pismo Formation against the Monterey Formation, the fault must be post Late Pliocene in age (Hall, 1973).

The Indian Knob fault also trends northwest, dips southwest and has approximately 46 meters of reverse displacement (Hall, 1973). It lies roughly on strike with the Edna fault in the northwest part of the syncline. The Indian Knob fault displaces only the Edna and Miguelito members of the Pismo Formation, thereby indicating a post-Early Pliocene age. However, it is not overlain by any of the younger members of the Pismo Formation or by the Paso Robles Formation and therefore its upper age limit is not constrained.

The Los Osos fault lies along the northeast flank of the San Luis Range. The northwest trending, southwest dipping Los Osos fault cuts the Paso Robles Formation, and geomorphic features suggest Holocene movement. Recent mapping by Geomatrix Consultants during the spring of 1987 indicates that this fault is active with an upper limit of approximately 1.0 mm/yr and a lower limit of 0.1 mm/yr of reverse displacement. Exploratory trenches indicate that this fault dips to the southwest and the southwest side is up (Geomatrix, 1987).

The northwest trending, northeast dipping San Miguelito fault lies within the southwest limb of the Pismo syncline. This fault may have Quaternary activity since it cuts the Upper Pliocene Squire Member of the Pismo Formation (Hall, 1973). However, there is no recognized geomorphic expression to indicate recent displacement. Field study work during the summer of 1985, discussed later, indicates that this fault is not active.

The San Luis Bay fault, west of Avila Beach, identified by Earth Sciences Associates (ESA) in the spring of 1987, is a northwest trending, northeast dipping, reverse fault with less than a millimeter per year displacement. It is located at the mouth of San Luis Obispo Creek (Fig. 2) and has not been traced to the northwest across San Luis Hill or to the southeast. It is not clear what the relationship of the this fault is to the San Miguelito fault or to other structures such as the Hosgri (Fig. 1) and Wilmar Avenue faults.

The Wilmar Avenue fault, identified by Nitchman (1987) and evaluated by ESA (1987), is a northwest trending, northeast dipping, reverse fault exposed in the marine terraces at Shell Beach (Fig. 2). The slip rate for this fault is less than a millimeter per year (ESA, 1987). The extent of the fault offshore to the northwest is unknown. To the southeast the fault projects under U.S. Highway 101 and its extent in this direction is also unknown.

The northern portion of the northeastern boundary of the Pismo syncline is defined by an active zone of reverse faults along the Los Osos fault (Geomatrix, 1987). The southern part of this border zone is defined by the apparently inactive Edna fault zone which joins with the inactive Huasna fault zone farther southeast (Fig. 2).

The southwest border of the Pismo syncline, possibly defined by the Hosgri fault, is not completely understood. The Hosgri fault, a major Quaternary fault, extends from San Francisco where it splays off the San Andreas fault and becomes a system that contains the San Gregorio, Palo Colorado and Big Sur faults parallel to the California coast to Point Conception, approximately 65 km south of the study area . Debate continues as to whether the Hosgri fault is a strike-slip or reverse fault (Crouch, 1979; Steritz, 1986; Geomatrix, 1987; and Earth Sciences Associates, 1987).

The nature of the Hosgri fault at its southern terminus has not been resolved. Crouch and others (1984), have interpreted seismic reflection data from the offshore Santa Maria Basin, in the northern Santa Barbara Channel. They interpreted the data to indicate post-Miocene compression in the offshore region of central California, which is possibly expressed today as thrust faulting on the Hosgri fault. Steritz (1986), has also interpreted seismic reflection data in the Santa Barbara Channel. According to Steritz (1986), the data indicates a tectonic regime dominated by strike-slip movement in the offshore region of central California.

In an earlier paper by Crouch (1979), the tectonic development of California is discussed. Crouch (1979) argued that lithologic belts such as the Salinian Block which make up the outer central California Continental Borderland and western Transverse Ranges were transported from their original location in northern Baja California. Translation began in the early Miocene and was linked to a change in relative plate motions from subduction to right-lateral strike-slip (Crouch, 1979).

PREVIOUS WORK

As a result of locating the Diablo Canyon Nuclear Power Plant in the San Luis Obispo area, the geology from San Simeon south to into the Santa Maria Valley has been extensively mapped by Hall (1973, 1975 and 1979) at scales of 1:48,000 and 1:24,000. Hall (1973), mapped the stratigraphy of the central California coastal area in great detail. Hall's (1973) understanding of the stratigraphy allowed him to map in the Pismo Syncline and several of the faults in the area such as the Indian Knob, Edna and San Miguelito faults. A detailed map was made by Cleveland (1978) of the Point Buchon area on a scale of 1:24,000. Cleveland's (1978), map shows landslides, marine terraces and detailed geology. Another important work is the study of the Monterey Formation within the Pismo Syncline, edited by Surdam (1984). This work contains extensive tectonic, diagenetic and stratigraphic information.

MARINE SURFACES

Timing of Quaternary Sea Level Changes

Discussions of the timing of late Quaternary sea level fluctuations and coastal uplift were given by Butzer (1973) who used deep-sea, glacial-eustatic, loess, alluvial and palynological records as evidence to suggest that there have been between six and eight cold-warm ocean water cycles since the Brunhes-Matuyama magnetic reversal, 700,000 years before present (B.P.).

Shackleton and Opdyke (1973) used oxygen isotope dating and paleomagnetic stratigraphy to study deep marine sediments to determine the timing of glacial and inter-glacial events (i.e sea level fluctuations). Bender and others (1979) used Uranium-series dating of the Pleistocene coral reef tracts of Barbados, West Indies, and found that their estimates of paleo-sea-level changes are consistent, within uncertainty limits, with Shackleton and Opdyke's (1973) oxygen isotope time scale.

Bloom and others (1974) and Chappell (1983) worked out sea level changes, by dating marine terraces carved in coral reefs and separating the tectonic uplift, on the Huon Peninsula in New Guinea. Paleo-sea-level changes have been correlated with glacial and inter-glacial stages, and dating of terraces along coastlines in many different parts of the world indicates a general synchroneity of major sea level fluctuations (Veeh, 1966; Ku and Kern, 1974; Lajoie, 1979; Bloom, 1980; and Chappell, 1983). Worldwide sea level curves have been worked out based on the assumption that most sea level fluctuations are worldwide and synchronous (Bull, 1984). If this is correct, then we have a valuable tool for working out marine terrace sequences.

Morphology of Marine Terraces

The study by Bradley and Griggs (1976) of marine terraces on Ben Lomond Mountain near Santa Cruz, California, showed that marine platforms have uniform gradients for the inner (2-4%) and outer (1-2%) part of each platform.

There are many synonymous terms used to refer to former shorelines, the point on the platform where the terrace riser meets the platform surface. Terms such as inner-edge, strand-line, back edge and shoreline angle are used most commonly. Figure 3 illustrates the morphologic features of a wavecut platform (adapted from Bradley and Griggs 1976). The term "inner-edge" as used by Bradley and Griggs (1976) will be used in this paper. The outer-edge then refers to the distal portion of the platform (Fig. 3).

Although marine wavecut platforms are thought to form over a time span of $10\text{-}10^2$ kiloannum (ka), they are considered to be time lines with which to study deformation rates, because their formation ends abruptly (Bull, 1984). Since the platforms are assumed to be cut at sea level, elevated platforms indicate crustal uplift, as long as sea level variations have been taken into account. If the paleo-sea level was higher than modern sea level while the platform was carved, then the inner-edge would now lie above sea level without any uplift. The degree of folding or tilting of a deformed platform can be determined, if the assumption by Bradley and Griggs (1976) that wavecut platforms are created essentially planar and level, is correct.

Dating of Marine Terraces in Coastal California

Many flights of marine terraces have been documented and dated along the coast of California. Veeh and Valentine (1967) dated a terrace 37-40m high near Cayucos, CA, at 124 kiloannum (ka), using Uranium series methods. This indicates an uplift rate of 0.25 millimeters per year (mm/yr) (Veeh and Valentine, 1967).

Ku and Kern (1974) used Uranium-series methods to date corals (120 ka), on 23m high marine terraces in San Diego, and found an average uplift rate of 0.11 to 0.14mm/yr. Later, Kern (1977), studied the terraces in San Diego in more detail and revised their uplift rate to an average of 0.19 to 0.24mm/yr.

Lajoie and others (1983), documented uplift rates of 3.6mm/yr and 4.6mm/yr in northern California, near Cape Mendocino. They attributed this high uplift rate to convergent plate interactions of the Mendocino triple junction.

Lajoie and others (1983) also documented uplift rates in southern California, near Ventura, of 6.0mm/yr. They suggested this uplift rate reflects north-south crustal shortening across the east-west trending Transverse Ranges.

Chipping (1980), inferred an uplift rate of 0.25mm/yr for the coast near San Luis Obispo. Chipping's (1980) conclusions were based on an amino acid racemization date of mollusc fossils taken from a 5 meter high terrace at Fossil Point (Figure 2).

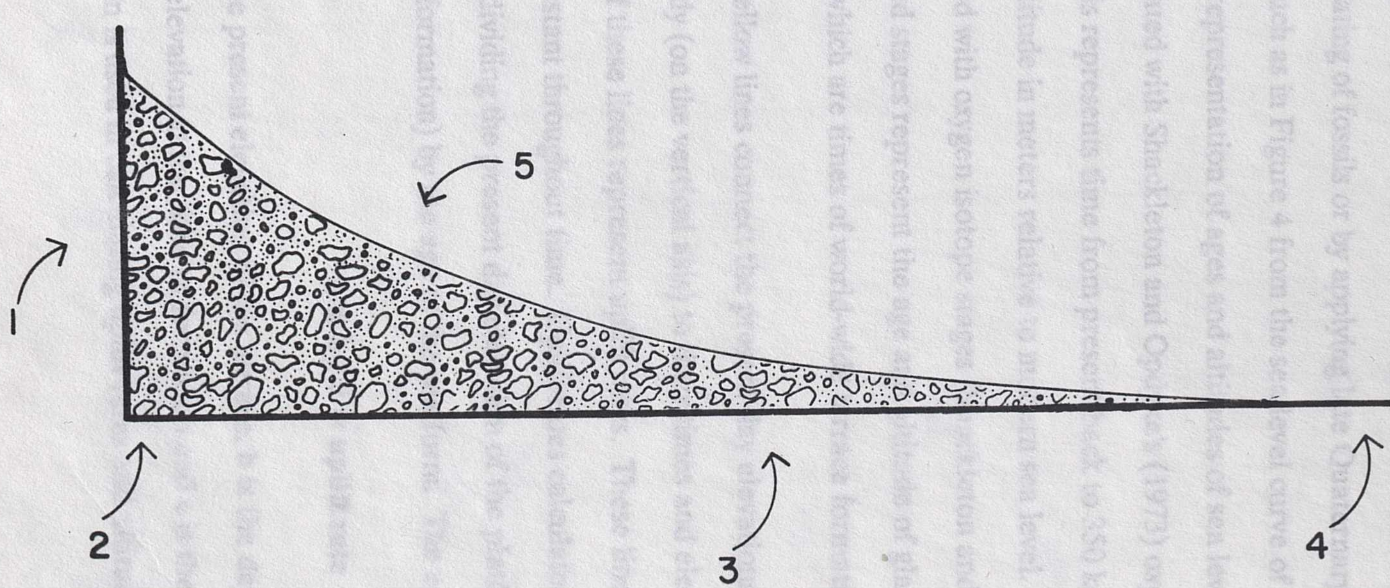


FIGURE 3: Diagrammatic cross section of a wave cut platform

1 = terrace riser 2 = inner edge 3 = abrasion platform

4 = outer edge 5 = marine lag deposits

Correlation of Marine Terraces

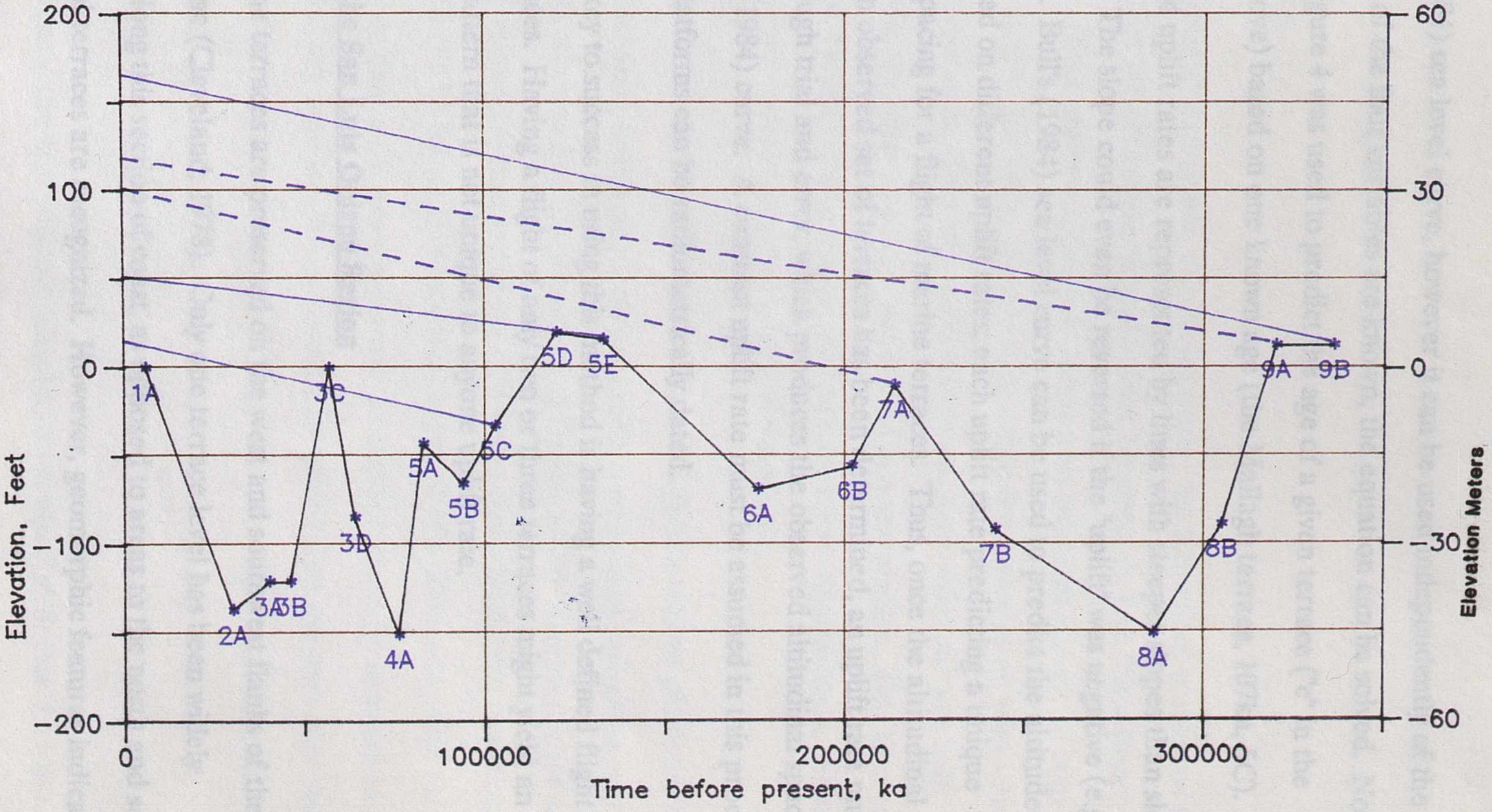
The age of formation of a marine terrace can be determined either by radiometric dating of fossils or by applying late Quaternary glacio-eustatic sea level curves such as in Figure 4 from the sea level curve of Bull (1984). This curve is a pictorial representation of ages and altitudes of sea level changes that Bull (1984) correlated with Shackleton and Opdyke's (1973) oxygen isotope stages. The horizontal axis represents time from present back to 350 ka. The vertical axis represents altitude in meters relative to modern sea level. The points 1A through 9B correspond with oxygen isotope stages (Shackleton and Opdyke, 1973), and the odd numbered stages represent the age and altitude of glacio-eustatic high stands of sea level, which are times of world-wide terrace formation.

The yellow lines connect the present day elevations of wavecut platforms from this study (on the vertical axis) to their times and elevations of formation. The slopes of these lines represent uplift rates. These lines will be parallel if uplift has been constant throughout time. Uplift rates calculated by using Figure 4, are obtained by dividing the present day elevation of the platform (plus or minus the elevation of formation) by the age of the platform. The equation is:

$$a \pm b / c = \text{uplift rate}$$

where a is the present elevation of the terrace, b is the departure from modern sea level of the elevation at the time of formation and c is the age of the platform. This equation is used in calculating uplift rates and altitudes of terraces

FIGURE 4: Glacio–Eustatic High Stands of Sea Level (Adapted from Bull, 1984)



in Bull's (1984) sea level curve, however it can be used independently of the curve. If any three of the four variables are known, the equation can be solved. Note, in this paper figure 4 was used to predict the age of a given terrace ("c" in the equation above) based on one known age (the Mallagh terrace, 107ka, 5C).

Rapid uplift rates are represented by lines with steeper slopes than slow uplift rates. The slope could even be reversed if the "uplift" was negative (e.g. subsidence). Bull's (1984) sea level curve can be used to predict the altitudes of terraces based on different uplift rates, each uplift rate predicting a unique altitudinal spacing for a flight of marine terraces. Thus, once the altitudinal spacing of an observed set of terraces has been determined, an uplift rate must be chosen, through trial and error, which produces the observed altitudinal spacing from Bull's (1984) curve. A constant uplift rate must be assumed in this procedure, unless the platforms can be radiometrically dated.

The key to success in using this method is having a well defined flight of marine terraces. Having a flight of only two or three terraces might yield an altitudinal pattern that is not unique to anyone uplift rate.

Terraces of the San Luis Obispo Region

Marine terraces are preserved on the west and southwest flanks of the Pismo syncline (Cleveland, 1978). Only one terrace level has been widely recognized along this section of coast, as opposed to areas to the north and south where several terraces are recognized. However, geomorphic features indicate the presence of one or more higher terraces. Marine terraces along the coast of the San Luis Range slope gently westward to the modern sea cliffs (12-15m high).

PROCEDURE

An altimeter survey was used to determine the altitudinal spacing of the flights of marine terraces along the coast from Montana de Oro State Beach to Shell Beach. There are several ways to conduct an altimeter survey. A leap frog method was used in this study. To minimize error, the traverses all began and ended on bench marks. Two altimeters were used. One altimeter was held stationary while the other altimeter was moved to a new station. This system is the most accurate, because changes in air pressure are noted continuously, and it is the recommended procedure when two people are available.

Because of natural irregularities in the surface of a marine platform, such as exhumed concretions, strike ridges and channels, a well-planed platform can vary in elevation as much as 2 to 3m (Bradley and Griggs, 1976). Greater relief can be found farther shoreward next to the sea cliff where shore platforms, sea stacks and surge channels can be found (Bradley and Griggs, 1976). Thus one point on a platform may deviate from other points on the same platform by as much as 3m. If a sea stack or shore platform is unknowingly measured then the data may deviate by as much as 5m (Bradley and Griggs, 1976). Also the outer-edge of a marine terrace is unreliable for measuring rates of uplift and styles of deformation because it is subject to slope failure and erosion (Bradley and Griggs, 1976).

In this study the instrumental error (± 1m) is equal to or less than the natural variation of the platforms. Therefore, consideration of the validity of each location as representative of a marine terrace platform elevation must be taken into account (Appendix).

In cases where the inner-edge was covered by alluvium, a gradient of two percent was used to project the elevation determined at a point on the platform to the inner-edge and thereby estimate the elevation of the inner-edge. A slope of two to three percent was used because, it was felt that the data stations could be located with confidence near (within 100m) the inner-edge of the terrace in question. For a two to three percent (approximately 1^{0}) slope, there is an elevation gain of 17m per 1000m of horizontal distance. Projecting elevation data is the least desirable method of determining elevations of the inner-edges of marine terraces because of its imprecision, and tilting of the inner-edge may not be detected. However this method was only used seven times in this study (Appendix).

Platforms were correlated on the basis of elevation, and continuous surfaces were traced laterally as far as possible. Marine terraces were identified by the presence of a cover of marine deposits (shown in Figure 5) as described in Bloom (1957), or the presence of holes made by rock-boring mollusks.

RESULTS OF STUDY

Five prominent marine terraces were recognized. The terraces, from lowest to highest, are referred to in this paper as the Mallagh, Pirate's Cove, Buchon (two surfaces), Pismo and Valencia. Representitive inner-edge elevations taken from these terraces are: Mallagh, 5 ±2 meters (from Pirate's Cove); Pirate's Cove, 15

Figure 5: Photograph to illustrate typical marine lag deposits on the Pirates Cove terrace. These deposits are evidence of a marine surface, however such deposits are usually eroded off older surfaces.

±2 meters (from Pirate's Cove); Buchon, 30 and 36 ±2 meters (from Point Buchon); Pismo, 122 ±2 meters (from Pismo Beach); and Valencia, 213 ±2 meters (from Montana de Oro State Park).

Description of Terraces

Mallagh Terrace, 107ka:

The Mallagh surface is well exposed in sea cliffs carved into the Obispo Formation at Mallagh's Landing, one mile south of Avila Beach (Fig. 6). The platform averages 3 meters in width and has a well exposed inner-edge. In some locations a cave (Fig. 7), or overhang (Fig. 8) formed. Occasionally, only a concave depression in the cliff face remains, such as at Pismo Beach (Fig. 9). At Montana De Oro, the Mallagh platform is well exposed at one locality (Fig. 10), but evidence is fragmentary at other localities. Mollusk boreholes provide evidence that this surface was once at sea level.

Pirate's Cove Terrace, 120-133ka:

The Pirate's Cove surface is also preserved and well exposed at Mallagh's Landing (Fig. 11). In most locations the platform is covered by marine lag deposits (Fig. 5), indicating a marine origin. The elevation of the inner-edge was projected in areas where streams do not expose the platform.

Buchon Terrace, 175-305ka:

The Buchon terrace is a couplet consisting of two distinct surfaces that are well preserved at Point Buchon in Montana De Oro park (Fig. 12). At most localities, the surfaces cannot be separated due to marine and alluvial deposits.

Figure 6: Looking southeast this photograph is taken at Mallagh Landing and shows the Mallagh terrace in the lower left.

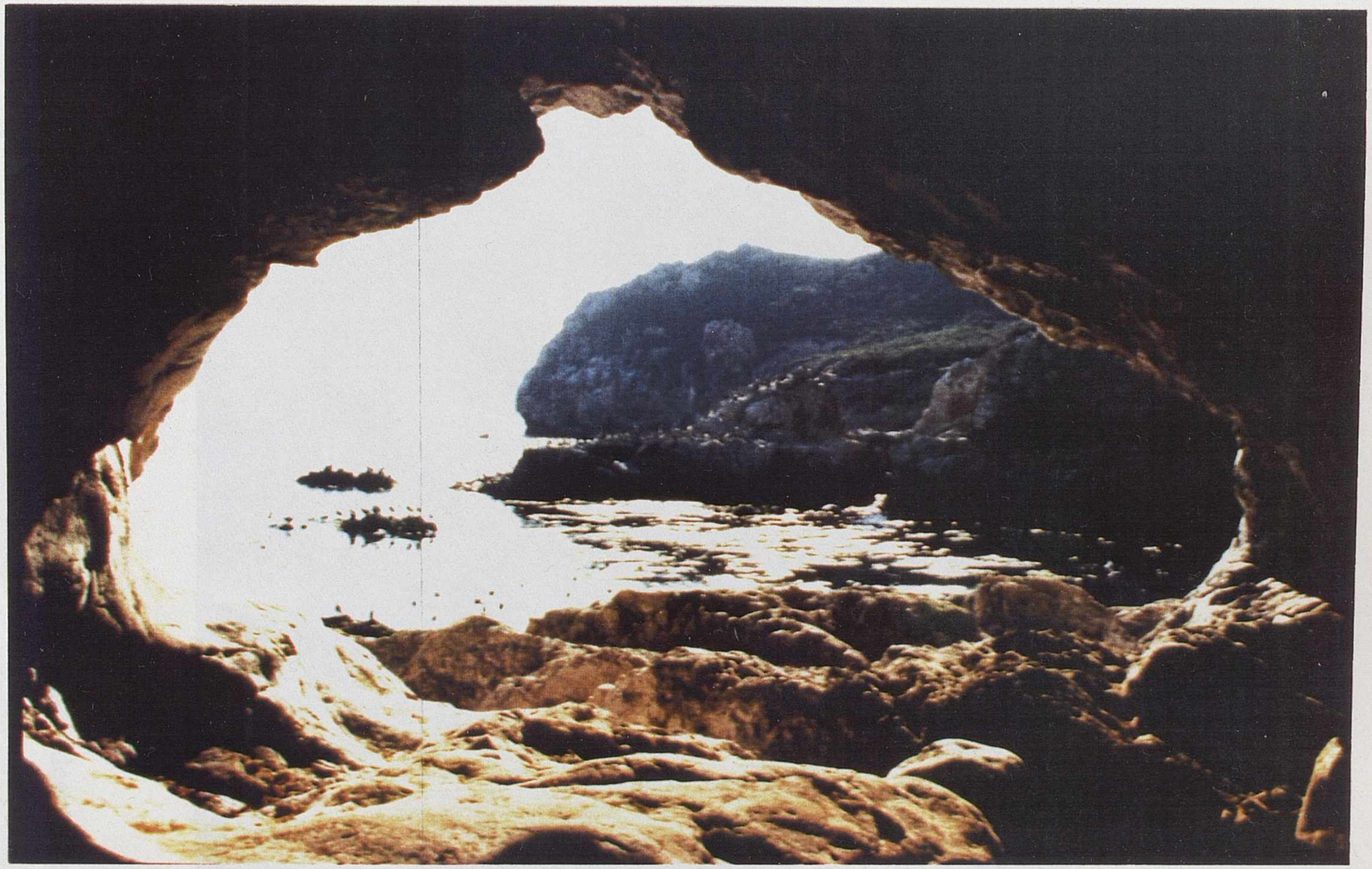


Figure 7: This photograph faces northwest and is taken at Fossil Point. The floor of this cave is part of the Mallagh terrace.

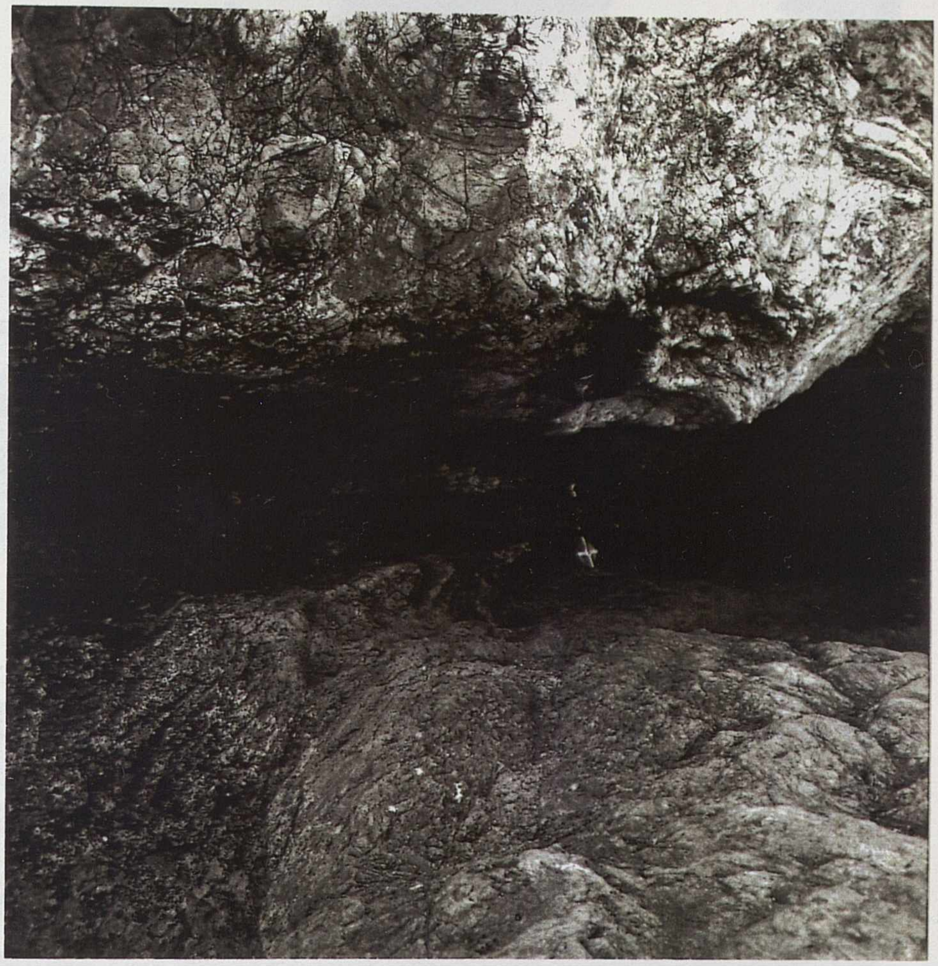


Figure 8: Photograph taken at Fossil Point illustrates how deeply marine waves can incise into soft rocks such as the Obispo Fm.

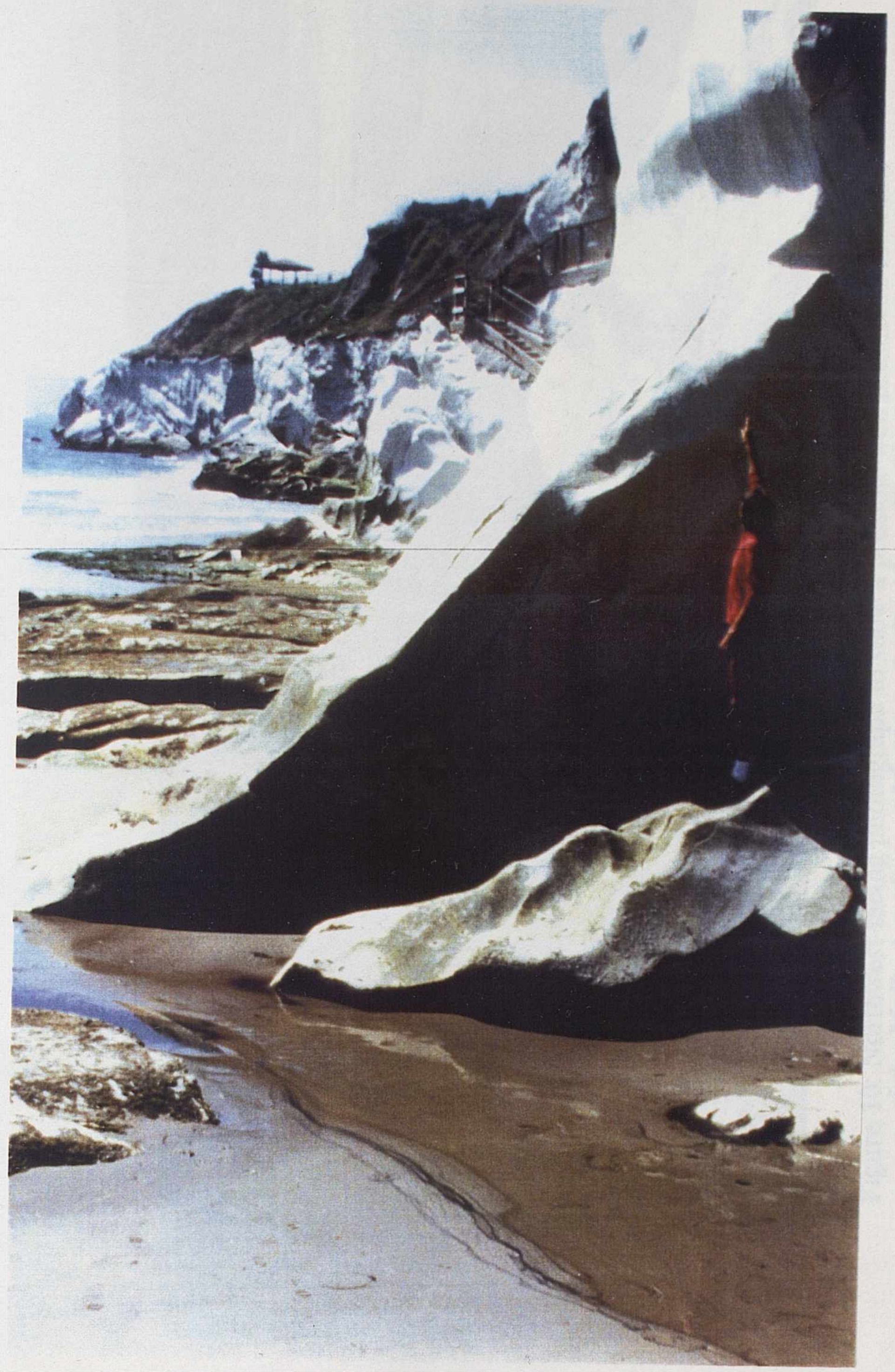


Figure 9: Photograph facing northwest shows a possible inner edge of the Mallagh terrace carved into the Obispo Fm.

Figure 10: Northwest-facing photograph to show a possible well preserved remnant of the Mallagh surface at Montana de Oro State Park.

Figure 11: Photograph faces southeast showing the Pirates Cove terrace in the foreground, and the outer edge of the Buchon couplet in the upper left corner.

Figure 12: The Pirates Cove (foreground), Buchon couplet (middle), Pismo (lowest profile), and Valencia (middle profile) are in this east facing photograph, taken at Montana de Oro State Park.

The couplet forms a prominent surface in the Obispo Formation at Shell beach (Fig. 13). The outer-edges exposed in the cliff face from Shell Beach to Pismo Beach (two kilometers in distance) undulate from a low point (approximately 1 meter high) north of Shell Beach to a high point (approximately 10 meters high) at Shell Beach and back to a low point (approximately 1.5 meters high) at Pismo Beach where the platform disappears. This apparent warping will be discussed in detail later. This surface is considered to be of marine origin because of its position between two surfaces of known marine origin and the presence in some locations of overlying marine lag deposits.

Pismo Terrace, 900ka:

The Pismo terrace is exposed above Shell Beach, with mollusk boreholes providing evidence that this surface was carved by marine erosion (Fig. 14). A surface of similar elevation with mollusk boreholes exposed at Montana De Oro Park is considered to be time correlative (Fig. 12).

Valencia Surface, 1,200ka:

The Valencia surface, located in Montana De Oro State Park below Valencia Peak (Fig. 12), is considered a marine surface because of its flat, planated surface and its position above the Pismo terrace. This surface corresponds in elevation to San Luis Hill, which is located north of Avila Beach (Fig. 2). The surface of San Luis Hill has been planated to a shape (Fig. 15) similar to that of the Valencia surface and is inferred to be a marine terrace that is correlative to the Valencia surface.

Figure 13: Aerial photograph of Shell Beach showing U.S. Highway 101 constructed on the Buchon marine terraces. These surfaces are rarely distinguishable as two surfaces.

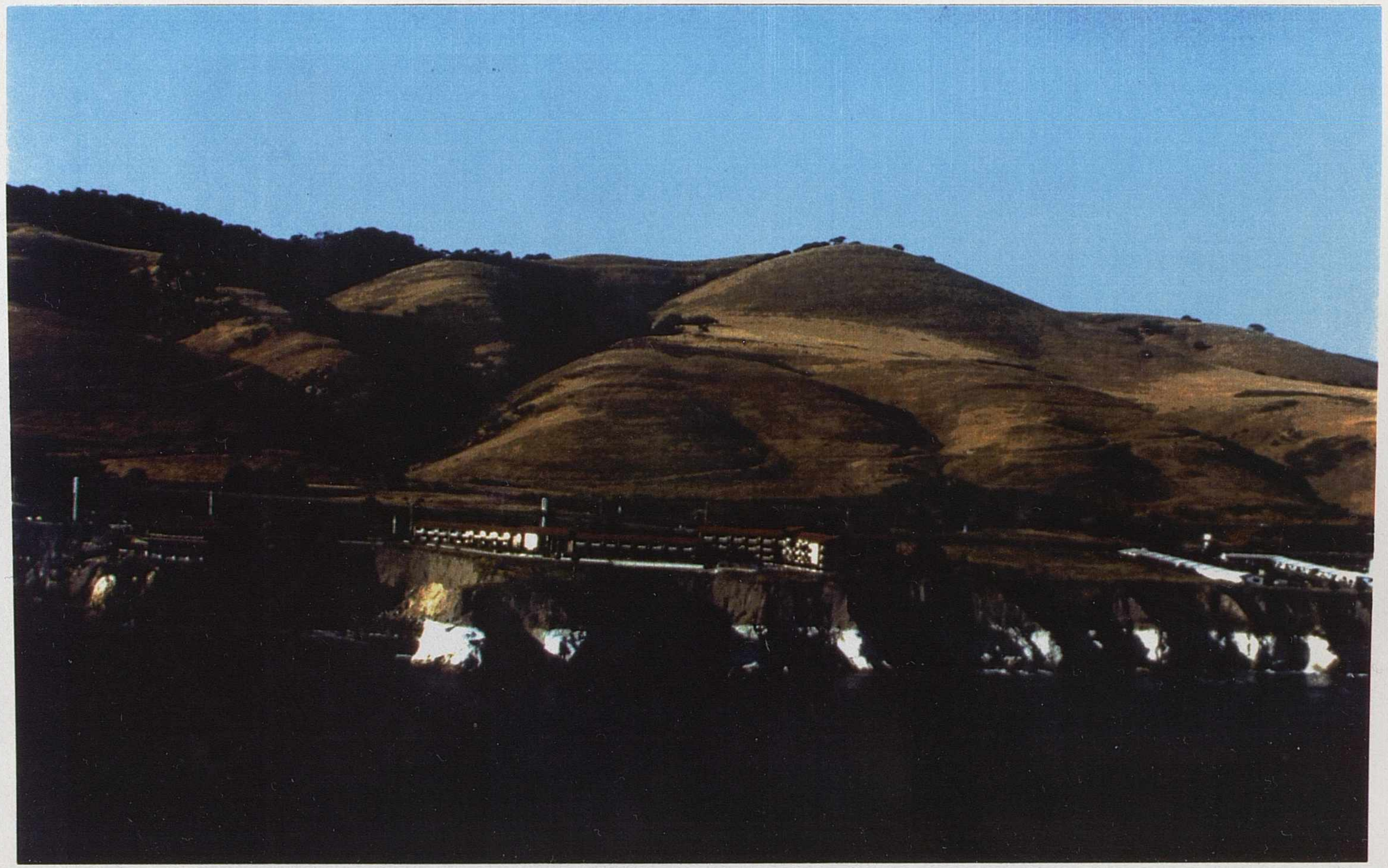


Figure 14: Aerial view showing the outer edges of the Buchon terraces exposed in the cliffs on the southern end of Shell Beach. The Pismo terrace lies directly above the Buchon terraces.

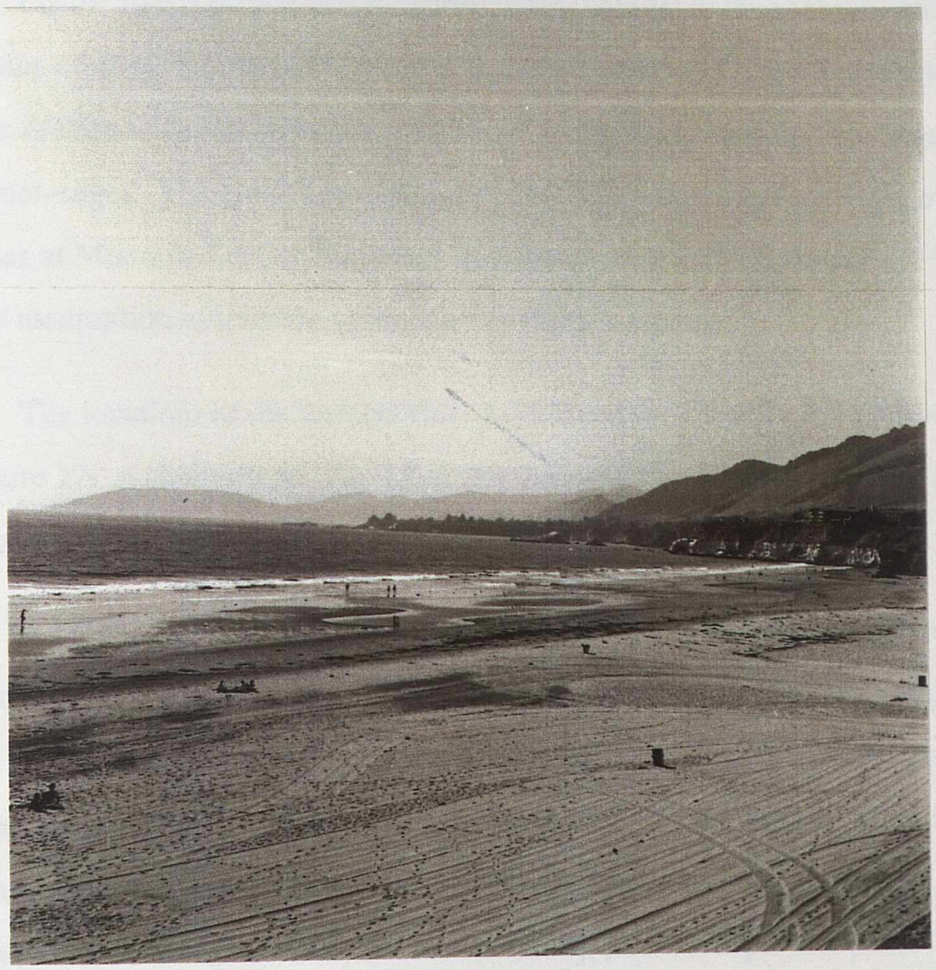


Figure 15: Looking to the northeast from Pismo Beach, the flat top of San Luis Hill can be seen in the far left of the photo.

Poorly preserved surfaces which have not been discussed are the Islay (50 ±2 meters), Arroyo (58 ±2 meters), San Luis (70 ±2 meters) and Coon (96 ±2 meters). These surfaces are discontinuous and have not been found in more than one location. Their locations are shown on Figures 16, 17 and 18.

Figure 16 is a profile that is approximately parallel to the shoreline showing the inner-edge elevations of the terraces discussed previously. This figure provides a cross section of the terraces along the coast. It shows the elevation spacings of the inner-edges. The black lines connecting the flight (altitudinal spacings) of terraces at Montana De Oro State Park and the terraces at Pismo Beach are based on the assumption of uniform uplift between these two points.

The locations of the terraces from Avila Beach to Pismo Beach are shown in Figure 17. A similar map (Fig. 18) shows the locations of marine terraces at Montana De Oro State Park.

An uplift rate has been calculated for the Mallagh platform, by applying Figure 4 and the equation described above. The age of 107 ka has been assigned to the Mallagh surface based on uranium series dating of coral (Muhs, personal communication, 1987). This age corresponds to stage 5C in Figure 4. Thus, to compute an uplift rate (the slope of the yellow lines in Figure 4), the present altitude of the Mallagh surface, five meters (16 ft), plus the departure from modern sea level at which the Mallagh surface was formed (minus ten meters, -33 ft) is divided by 107 ka (5,000mm + 10,000mm / 107,000yrs) to give an uplift rate of 0.14 millimeters per year (mm/yr).

FIGURE 16

This figure shows the data collection locations (crosses, and blue and white stars). The black points represent data collected by the author. The numbers above the black data points refer to the numbers in the appendix. The blue data points are data points collected by PG&E, this data reflects their interpretation, correlations and understanding as of July, 1987. The red data show the author's interpretation of PG&E's borehole data.

Figure 16: Inner Edge Elevations

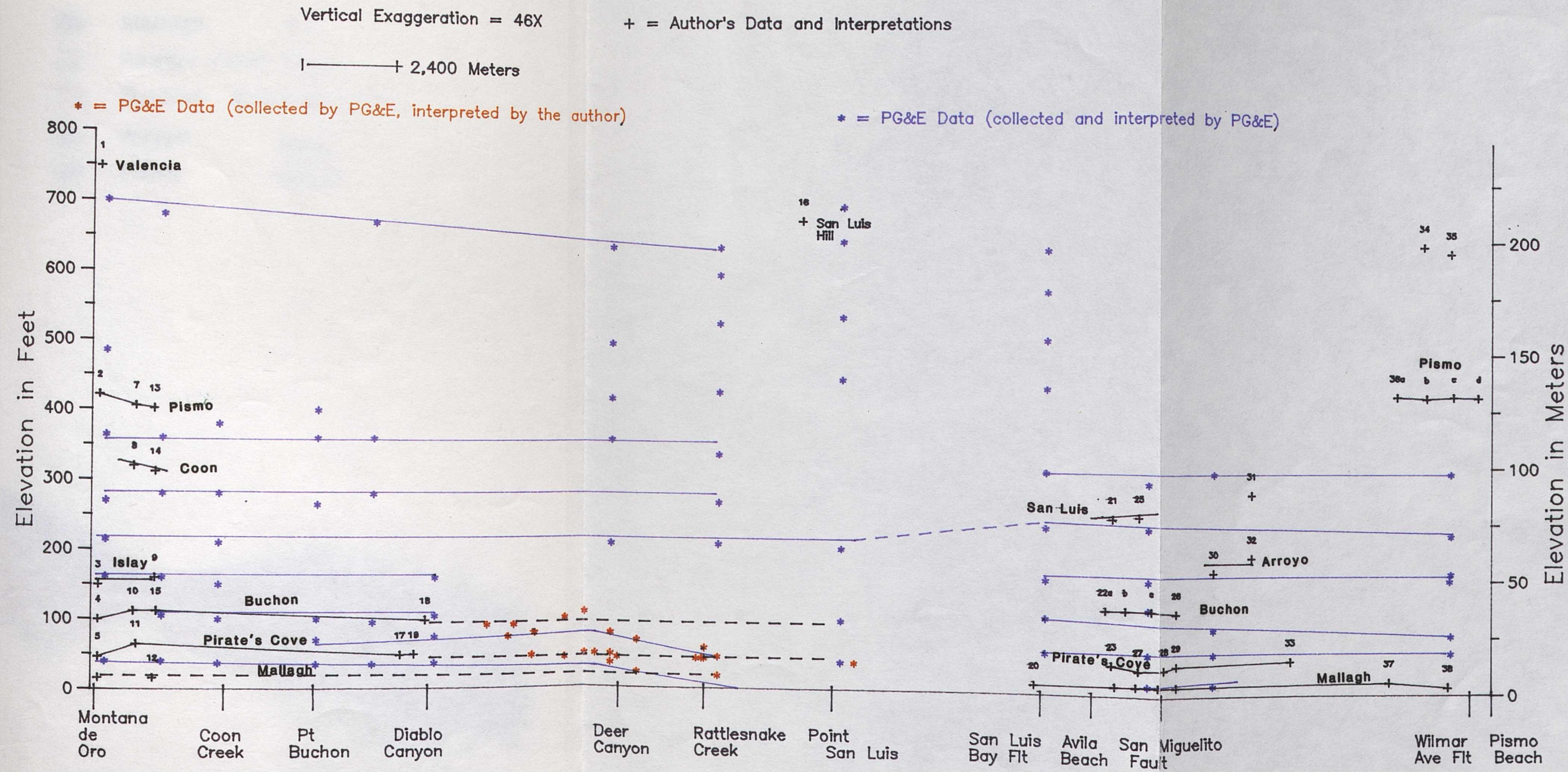


FIGURE 17 MARINE TERRACE LOCATIONS

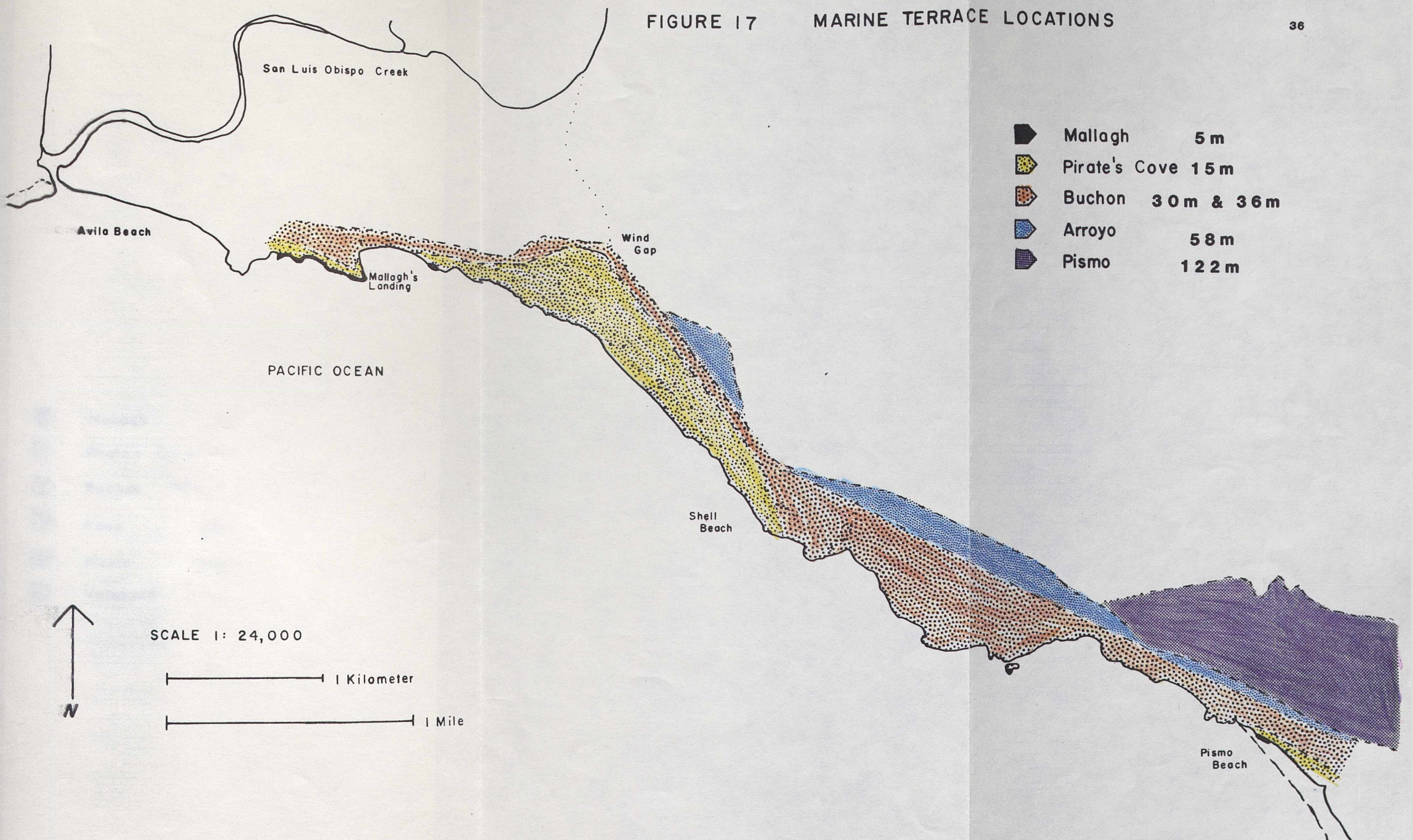
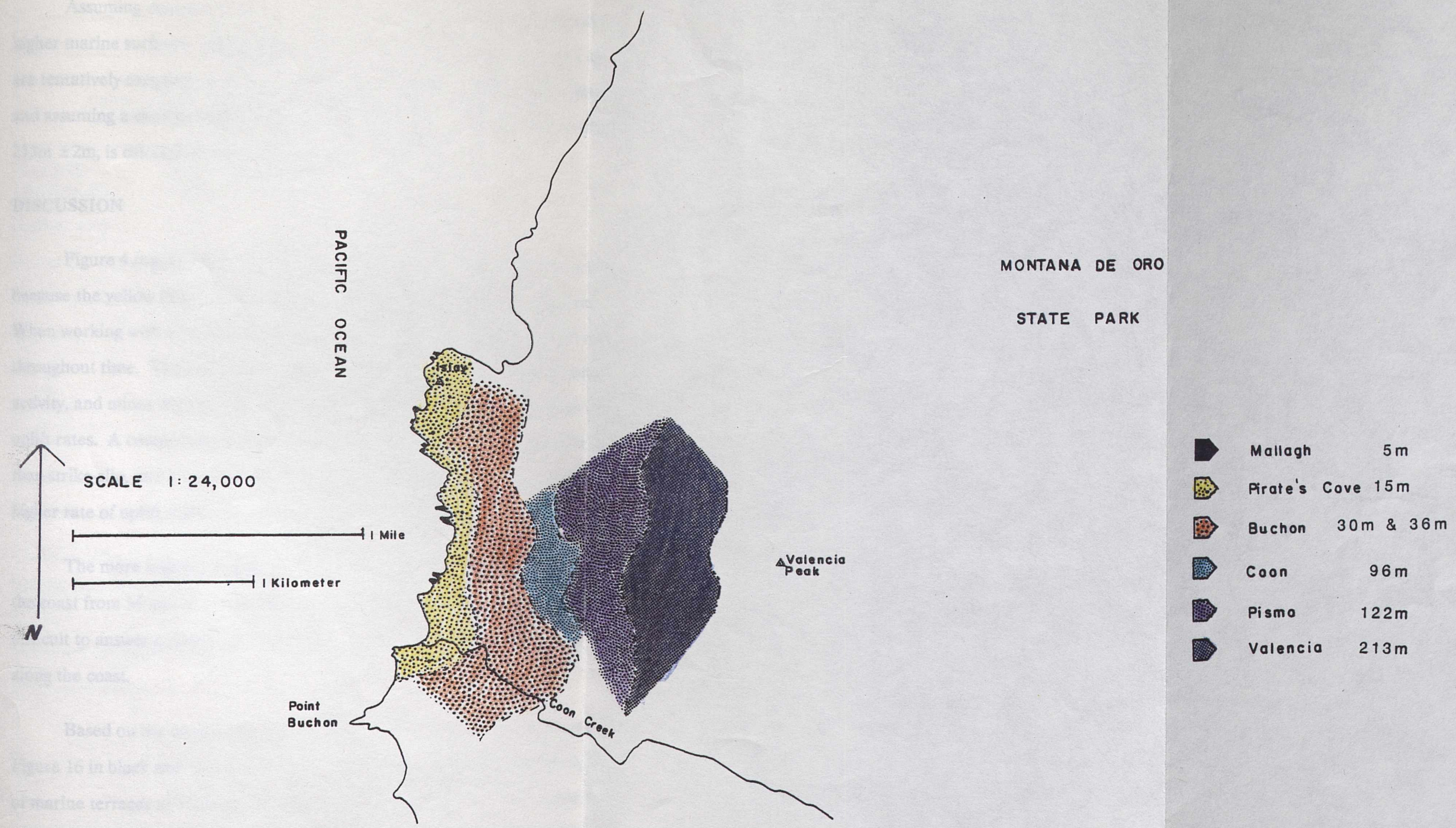


FIGURE 18 MARINE TERRACE LOCATIONS



Assuming constant uplift, this rate of 0.14 mm/yr can be extrapolated to the higher marine surfaces. Using Figure 4 and the equation described above, ages are tentatively assigned in Table 2 to the higher terraces, based on their elevations and assuming a constant uplift rate of 0.14 mm/yr. The highest terrace platform at 213m ±2m, is calculated to be 1,200,000 years old (Table 2).

DISCUSSION

Figure 4 suggests that there has not been constant uplift throughout time, because the yellow lines are not parallel, as is predicted in a theoretical case. When working with a real situation one can expect minor changes in uplift rates throughout time. The California coast is experiencing relatively high tectonic activity, and minor adjustments in the tectonic regime could cause changes in the uplift rates. A compressive regime would be associated with a higher uplift rate than strike-slip, and a tectonic regime with a high rate of activity would also have a higher rate of uplift than a regime with a low rate of activity.

The more important question is whether the uplift has been constant along the coast from Montana de Oro State Park to Pismo Beach. This question is difficult to answer conclusively without precise dates on several of the terraces along the coast.

Based on the mapping and surveying of terraces for this study (shown on Figure 16 in black and documented in the Appendix according to number), the set of marine terraces at Montana de Oro appear to correlate with the marine terraces at Pismo Beach. The Mallagh, Pirate's Cove, Buchon and Pismo are at similar elevations at Montana de Oro and Pismo Beach respectively. However, due to the

Table 2: Tentative ages of marine terraces and their representative elevations, based on an assignment of the Mallagh Terrace to 5c.

MARINE TERRACES	INNER-EDGE ELEVATIONS (m)	AGES (ka)
Mallagh (5c)	5 ±2	107*
Pirates Cove (5e)	15 ±2	120-133
Buchon surfaces	30 & 36 ±2	175-305
Islay (9b)	50 ±2	320
Arroyo	58 ±2	336
San Luis	70 ±2	450
Coon	96 ±2	700
Pismo	122 ±2	900
Valencia	213 ±2	1,200

* Muhs, personal communication, 1987.

lack of dated terraces and the large section of coast that was not mapped, one could easily make an argument for differential uplift and/or folding between these two localities. Based on the data collected for this study, the most simple scenario is favored (i.e. correlation of the terraces without deformation).

The coastline from Pt Buchon to one mile north of Pismo Beach could not be mapped in detail, because of problems of access. Therefore data has not been collected for this section of coast by the author personally. However, borehole data collected by Geomatrix Consultants (1987), from Pt Buchon to Pismo Beach, shown in red on Figure 16, has been interpreted by the author (two days were spent at Geomatrix Consultants' office collecting raw data, and discussing their interpretations). Data collected and interpreted by Geomatrix Consultants (1987), is shown in blue.

Evaluation of the marine terraces by Geomatrix Consultants (1987) was based on an extensive program in which sets of boreholes were drilled to bedrock, perpendicular to the shoreline to intercept the inner-edges, and to determine the elevations of the marine platforms. Geomatrix Consultants combined this drilling program with surface mapping and dating of fossil material. Their borehole data compares well with the data collected for this study, but there is not complete agreement on the interpretation near Rattlesnake Creek (Fig. 16).

The data sets of Geomatrix Consultants and the author's from Montana de Oro and Pismo Beach compare well. The same set of terraces is delineated by both sets of data at Montana de Oro, except that the Mallagh terrace was not recognized as a terrace by Geomatrix Consultants (1987). The small differences in elevation of the higher surfaces (i.e. Pirate's Cove, Buchon and Islay) are within the error limits. Again at Pismo Beach the same set of terraces is delineated by Geomatrix Consultants and the author's data sets (i.e. Mallagh, Pirate's Cove, Buchon, Arroyo, and San Luis). However, Geomatrix Consultants (1987) did not obtain any information on the Pismo terrace. In this case priorities and time constraints probably restricted Geomatrix Consultants' mapping activities to the younger terraces.

Even with data from the Geomatrix Consultants study, a case can still be made for uniform uplift between Montana de Oro State Park and Pismo Beach. The data points can be connected across the area near Rattlesnake Creek.

Geomatrix Consultants (1987) interpreted their data to suggest that from Montana De Oro to Rattlesnake Creek (Fig. 2 and Fig. 16) the uplift rate has been 0.14mm/yr, and that between Rattlesnake Creek and Avila Beach the uplift rate was 0.07mm/yr. They interpret the uplift rate to have increased again at Mallagh's Landing (Fig 2 and Fig. 16) to 0.11mm/yr.

Inner-edge elevations near Rattlesnake Creek (Fig. 2) have been interpreted by Geomatrix Consultants (1987) to be down-dropped based on their borehole data. The bedrock elevations at Rattlesnake Creek, based on the borehole data could be interpreted to indicate warping; however, their data at this location (Fig. 16) are difficult to interpret. The borehole data in the vicinity of Rattlesnake Creek were obtained parallel rather than perpendicular to the shoreline. Thus the data does not show a profile of the terraces in this location. A transverse profile is necessary for comparison with the other profiles along this section of coast to conclude whether the platform has been warped, faulted or is undeformed.

Boreholes drilled in traverses parallel to a shoreline can lead to problems. A modern shoreline can be highly convoluted, and if it were covered with alluvium, its map pattern would be difficult to predict. Thus the Geomatrix Consultants line of boreholes parallel to the shore could have crossed over two or more marine platforms. If a series of boreholes was unknowingly drilled across a paleo-bay or onto another platform, the bedrock elevations would change giving the false impression that the elevation of the inner-edge of the marine platform had changed.

Given the lack of data between Montana de Oro and Pismo Beach for this study, the author feels Geomatrix Consultants' hypothesis of downdropped marine terraces based on their data in the vicinity of Rattlesnake Creek is a better conclusion than the author's. However, the possibility exists that the data collected by Geomatrix Consultants (1987) does not accurately reveal the underlying terrace sequence.

The coastline southeast of Mallagh Landing is no less problematic. The outer-edges exposed in the cliff face from Shell Beach to Pismo Beach (two kilometers in distance) appear to be warped. This is not shown in figure 16, because figure 16 is showing inner-edge data. However a schematic of the outer-edges is shown in figure 19 and a map of the terraces is shown in figure 17.

Warping of the Buchon marine platform at Shell beach is one possible explanation for the undulations of the outer edges exposed in the cliffs from Shell beach to Pismo Beach. However, warping of the Buchon platform is not a likely explanation, because this would require too much deformation in too short of a time span.

The rate of deformation suggested by this variation in elevation of the outer-edge is greater than the deformation proposed by Bradley and Griggs (1976) for marine terraces at Santa Cruz. Bradley and Griggs' (1976) study indicated that inner-edge elevations on the Wilder terrace, dated approximately at 700 ka, vary about ten meters along a broad fold over a distance of three kilometers. The Santa Cruz section of coast has an estimated average uplift rate of 0.18 mm/yr (Bradley and Griggs, 1976) as compared to the uplift rate proposed in this study of 0.14mm/yr.

The Wilder terrace at Santa Cruz was deformed less over a longer time span than the terraces involved in the present study. The Wilder terrace is approximately 400 ka older than the Buchon terrace. The difference in uplift rate between Santa Cruz and San Luis Obispo is 0.04 mm/yr. It seems unlikely that the terraces at San Luis Obispo would show a greater degree of warping over a shorter time period, at a slower uplift rate.

An explanation for the apparent warping of the Buchon terraces from Shell Beach to Pismo Beach is that two different marine terraces, the Pirate's Cove and Buchon terrace may be exposed in the cliffs (see Figure 17 for a plan view and Figure 19 for a three dimensional view beneath the alluvium). Because the elevation of the inner-edge of the Pirate's Cove terrace is lower than that of the Buchon terrace, the outer-edge of the Pirate's Cove terrace will be lower than the

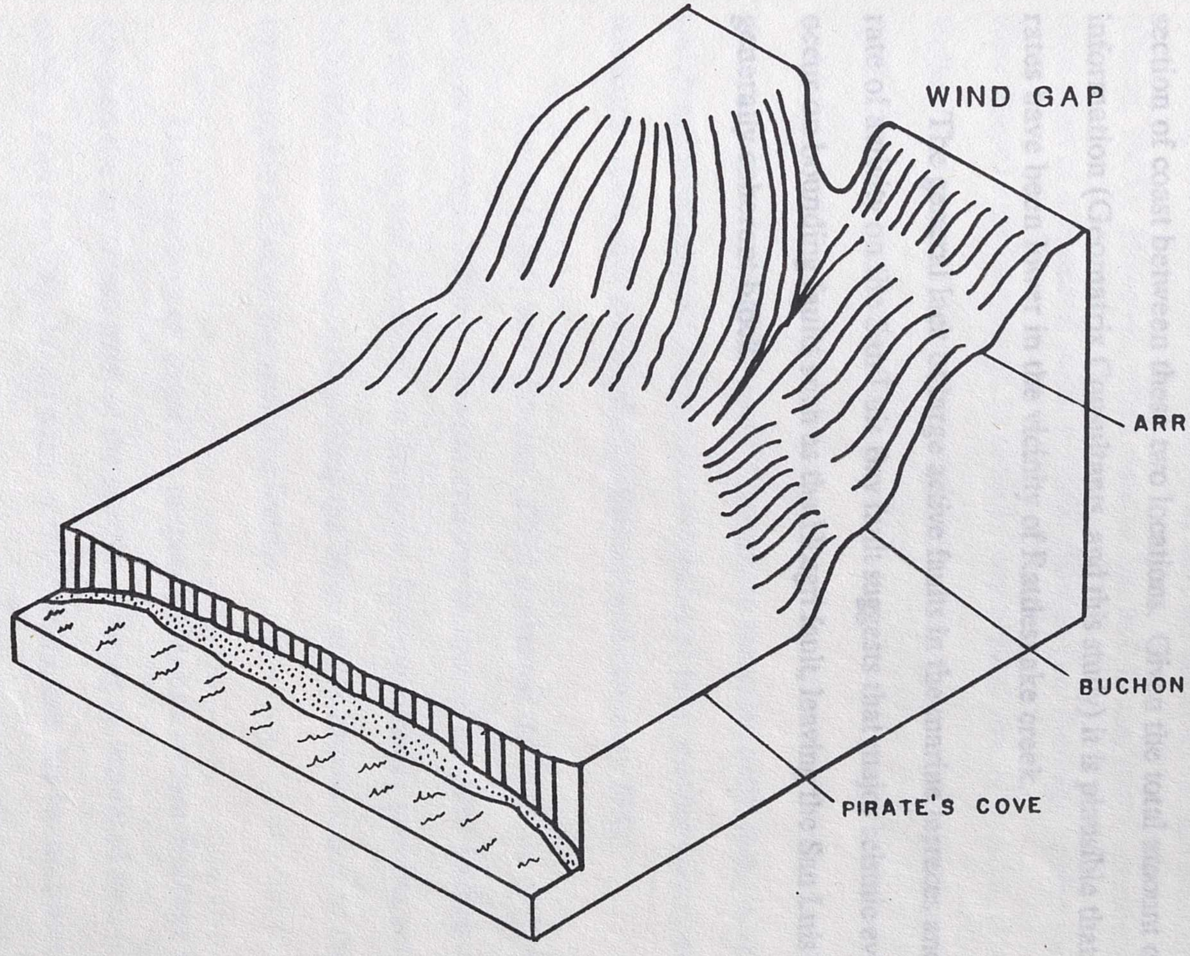


FIGURE 19 Hypothetical marine terraces beneath the alluvium at Shell Beach

outer-edge of the Buchon terrace. In brief, it appears that the uplift rate at Montana de Oro is approximately 0.14mm/yr and from Mallagh Landing to approximately the vicinity of Pismo beach the uplift rate is also 0.14mm/yr. However, it has not been completely resolved whether the uplift rate varies in the section of coast between these two locations. Given the total amount of information (Geomatrix Consultants, and this study) it is plausible that the uplift rates have been lower in the vicinity of Rattlesnake creek.

The general lack of large active faults in the marine terraces and the low rate of activity on the San Luis Bay fault suggests that major seismic events would occur on bounding faults such as the Hosgri fault, leaving the San Luis Range as a generally coherent block.

STREAMS

Background

When compared with rates of stream erosion, rates of tectonic deformation have long been considered too slow to have an effect on stream equilibrium (Ouchi, 1985). However, when rates as low as 0.10 cm/yr are considered over a time span of a hundred years, surficial changes (i.e. drainage profile shape, map view shape) may be enough to show in longitudinal stream profiles, (Ouchi, 1985). Volkov and others (1967) showed that scouring occurs where rivers pass through uplifted areas, and deposition occurs in areas of subsidence. The study by Burnett and Schumm (1983) of channel changes across active uplifts indicates that large streams adjust faster than smaller streams to the same uplift rate. Also streams which are eroding their banks and bottom faster than another steam, will adjust to the same uplift rate more quickly (Burnett and Schumm, 1983).

Ouchi (1985) and Schumm (1986) evaluated the reaction of fluvial systems to slow tectonic folding. Streams crossing an area of synclinal folding are ponded in the center and down-cut on the limbs. Streams crossing growing anticlinal folds have increased down-cutting along the hinge of the anticline, due to the increase in topographic relief as the anticline forms.

Development of a syncline perpendicular to a stream drainage should steepen the upstream limb of the syncline, causing an increased rate of down-cutting, and ponding should occur at the syncline axis due to subsidence near the hinge. The topography of the downstream limb of the syncline would also be steepened, again causing incision (Ouchi, 1985). If the syncline ceased folding but uplift continued (block uplift), the stream gradient should increase with a prograding nick point in response to the increase in altitude caused by the uplift.

Study of Creeks That Cross the Pismo Syncline

San Luis Obispo, Pismo and Arroyo Grande Creeks are perpendicular to the axis of the Pismo syncline. The most westerly creek, San Luis Obispo Creek, approximately bisects the syncline. Pismo Creek lies between San Luis Obispo and Arroyo Grande Creeks (Fig. 2) and crosses to the southeast of the most clearly defined portion of the syncline. Arroyo Grande Creek crosses the southern end of the syncline.

Profiles of bedrock, modern stream, and paleo-stream channels were constructed to determine if continued folding of the Pismo syncline has affected the drainage equilibrium (i.e. nick points) of the streams (Figs. 20, 21 and 22). Present day stream profiles were determined for all three creeks (Fig. 20). In addition, strath surfaces were mapped in the drainage of San Luis Obispo Creek (Fig 21). Profiles of strath surfaces were constructed, and a profile of the bedrock erosional surface was constructed for San Luis Obispo Creek (Fig. 22).

Each strath or terrace surface represents a time line of a different age. The modern stream profile can only be expected to show deformation if rates of folding are high enough to affect stream equilibrium over a period of about 100 years. The bedrock strath surface was carved during the last low stand of sea level, approximately 30 ka ago (Fig. 4), and thus should enable detection of lower rates of folding. The strath surfaces in San Luis Obispo Creek have been correlated to

Figure 20: Modern Day Stream Profiles

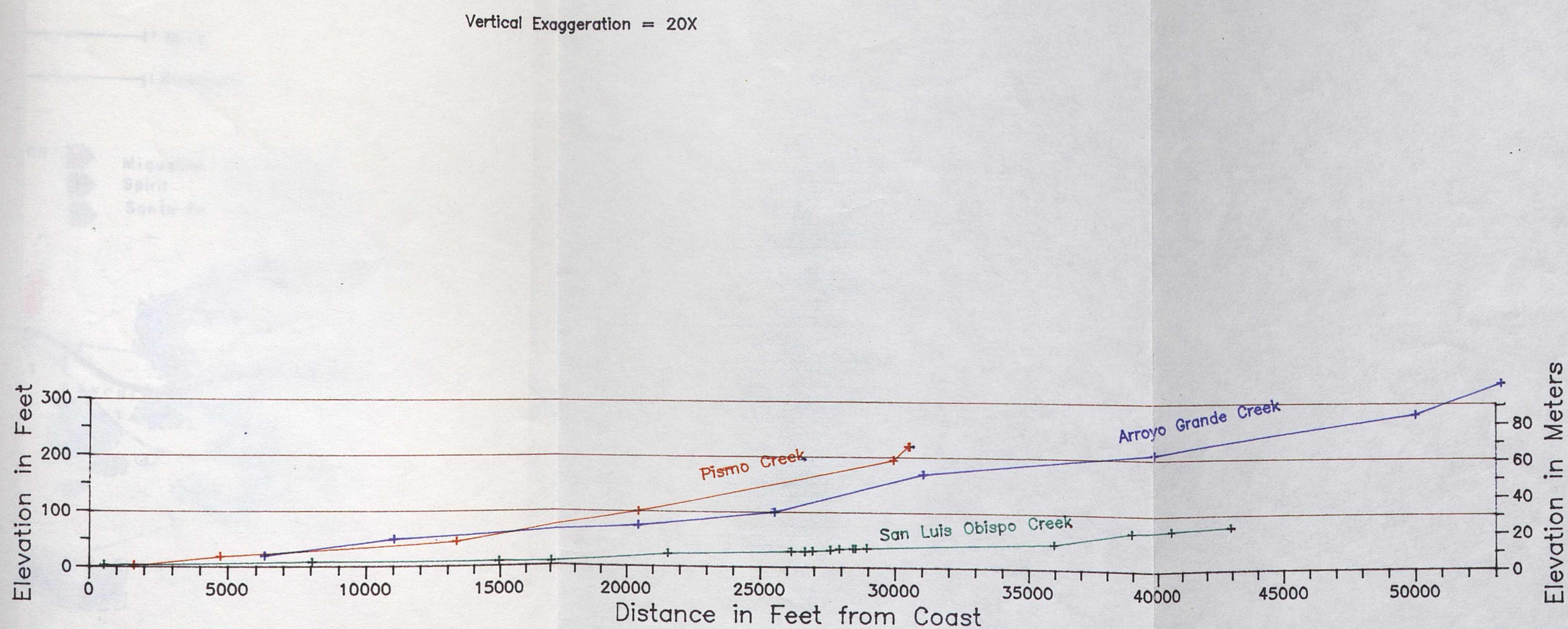


FIGURE 21 Map of paleo stream surfaces along San Luis Obispo Creek

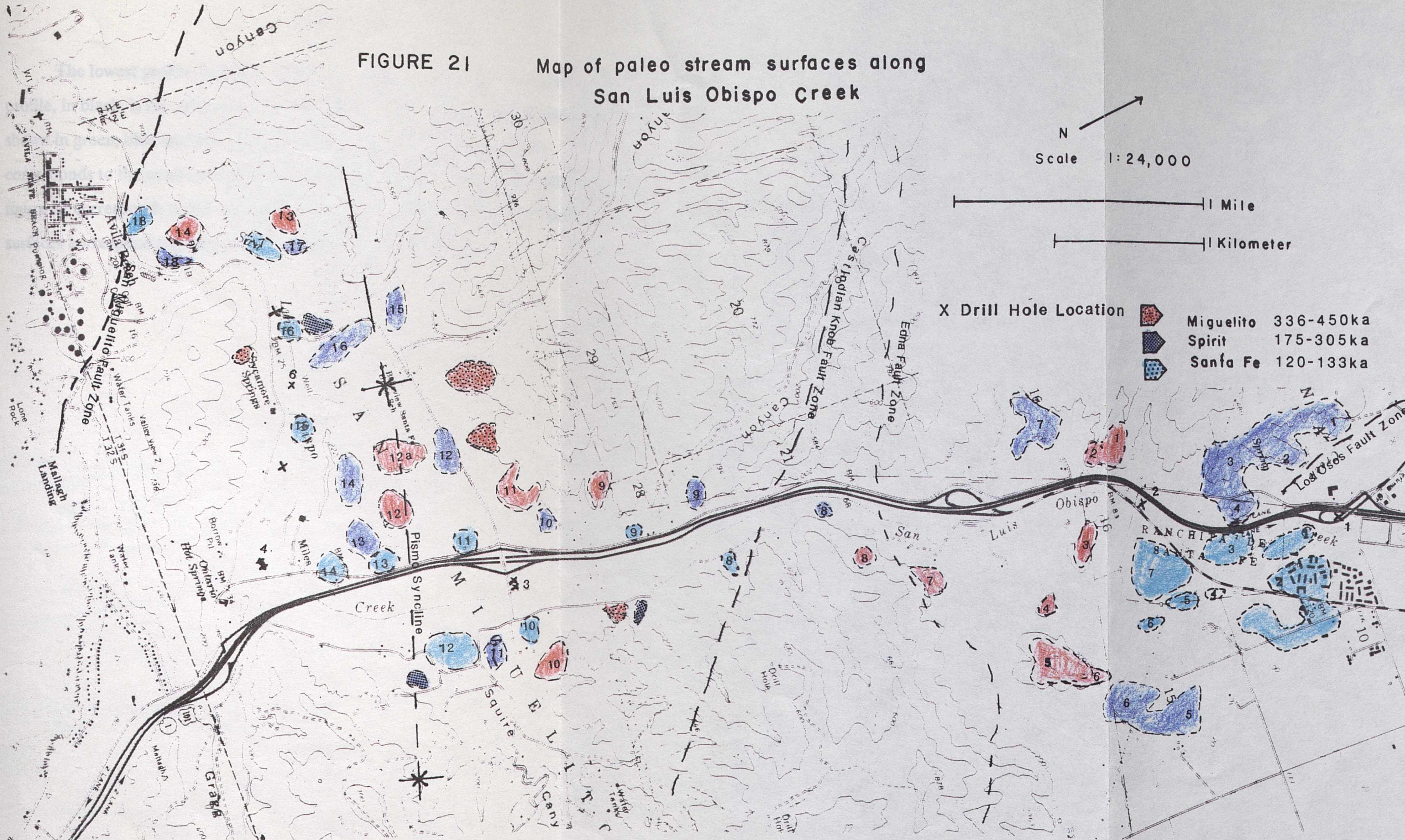
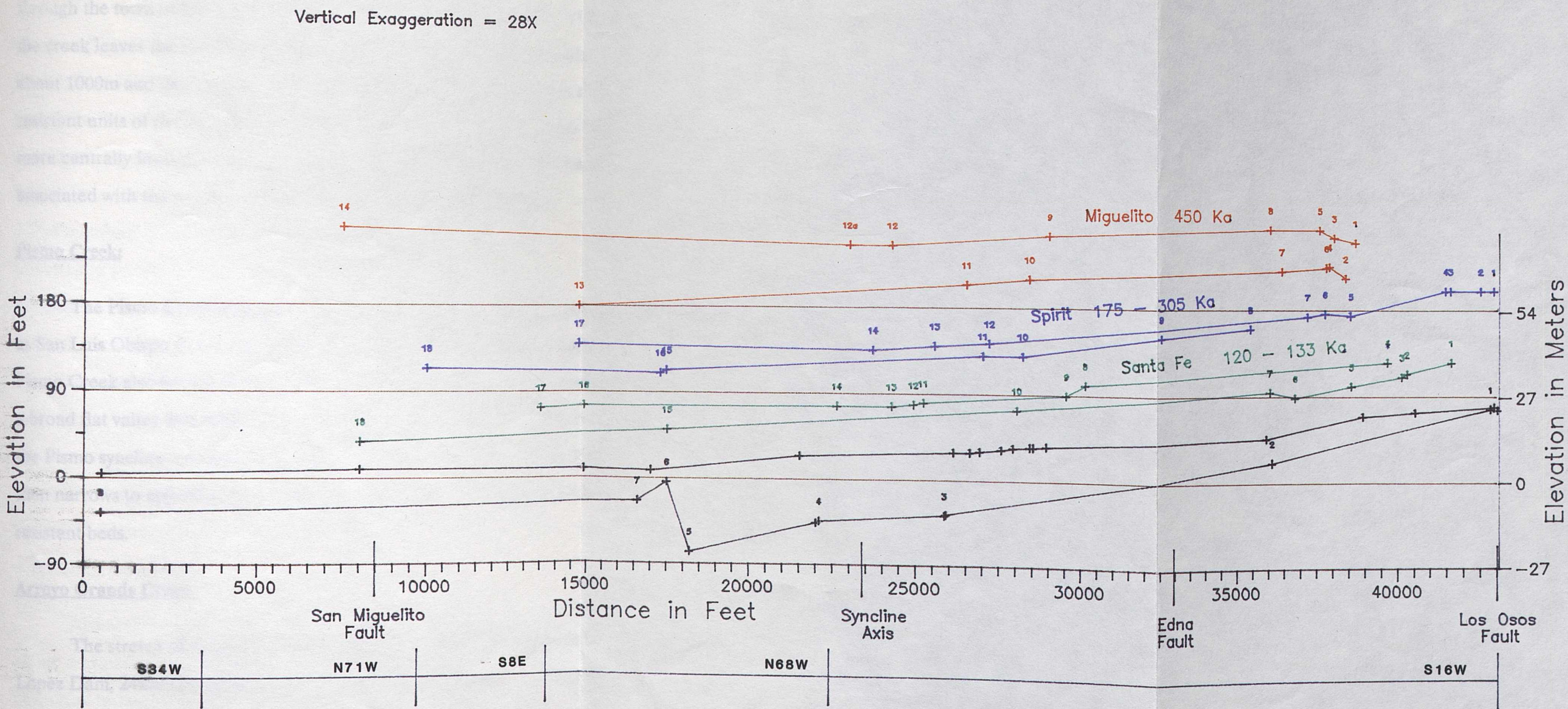


FIGURE 22

The lowest profile, in black, is the bedrock surface and the next higher profile, in black, is the present day stream channel. The paleo-stream profiles are shown in green, blue and red. The numbers above each of the data points corresponds to the numbered locations on figure 21. The red Miguelito surface on figure 22 corresponds to the red Miguelito surface on figure 21, and the blue Spirit surfaces correspond together as do the green Santa Fe surfaces.

Figure 22: Paleo Stream Profile San Luis Obispo Creek



marine terraces described earlier, and these allow an estimation of rates of uplift and folding of the Pismo Syncline.

San Luis Obispo Creek:

San Luis Obispo Creek has its source in the Santa Lucia Range and runs through the town of San Luis Obispo and into the broad flat Los Osos Valley. As the creek leaves the Los Osos Valley, it narrows to about 500m and then widens to about 1000m and then narrows again as it passes through the resistant and non resistant units of the Pismo Formation (Fig. 2). Since San Luis Obispo Creek is more centrally located within the syncline, it was expected that deformation associated with the syncline would be most obvious in this drainage.

Pismo Creek:

The Pismo Creek drainage (Fig. 2) is smaller and generally is not as broad as San Luis Obispo Creek, and the hills do not have well developed strath surfaces. Pismo Creek also has its source in the Santa Lucia Range. Its main trace begins in a broad flat valley that narrows as it crosses the Edna fault zone. Where it enters the Pismo syncline the creek valley widens from about 350m to about 900m and then narrows to approximately 400m as it passes between resistant and non-resistant beds.

Arroyo Grande Creek:

The stretch of Arroyo Grande Creek used in this study begins at the base of Lopez Dam, 24km (15 miles) up the drainage in the Santa Lucia Range (Fig. 2) and ends at the Pacific Ocean. It crosses the southeastern tip of the syncline.

Arroyo Grande Creek is the broadest of the three drainages and the valley width of 1300m is uniform. Remnants of strath surfaces are poorly defined in this drainage.

PROCEDURE

Two methods of collecting survey data were used. A theodolite and electronic distance meter (EDM) provided vertical and horizontal control on the modern creek bed and strath surfaces in San Luis Obispo Creek drainage. A theodolite is essentially a compass combined with a level. It allows the user to determine accurately the location of a point from known points through triangulation and at the same time to determine the elevation difference. The EDM measures the time it takes for a beam to pass from the instrument to a mirror, and return to the instrument, and thus calculates the horizontal distance between the instrument and the mirror pack. Triangulation stations surveyed by the U.S. Geological Survey provided the anchor stations for the surveying. Measurements of horizontal distances can be expected to be accurate to within a millimeter over a distance of one kilometer. For vertical differences in elevation, measurement accuracy is approximately one millimeter in 90 meters. Due to the possibility that part of the strath surfaces may have been eroded off thus lowering the height of the surfaces, the data is considered to be minimum elevations accurate to the nearest 5 meters.

Altimeters were used to determine elevations for the stream profiles of Pismo and Arroyo Grande Creeks. First the leap frog method used in the survey of marine terraces was used to determine the elevations of bridges crossing the creeks. A tape measure was then used to measure the distance from the creek bed to the bridge. Many of the bridges have elevation markers on them, and these elevations were used to check the altimeters.

Strath surfaces were mapped on the basis of morphology. Relatively smooth flat surfaces that slope downstream towards the creek were considered to be the result of river erosion.

The strath surfaces in the San Luis Obispo Creek drainage are exposed bedrock. Due to the lack of regional soil development, soils could not be used to correlate one surface to another. Instead, the surfaces were correlated on the basis of geomorphic expression. Surfaces with similar sizes were correlated, and surfaces at distinctly different elevations were considered to be of different ages. Their elevations were determined and profiles of paleo-streams were constructed by connecting elevations on a longitudinal profile (Fig. 22).

Since all the strath surfaces in San Luis Obispo Creek are cut in bedrock, their elevations are considered to be minimum elevations. It is difficult to estimate how much erosion has taken place, and therefore the representation of the survey data reflects only instrument and human error (vertical marks on Figs 20 and 22).

Each of the paleo-stream profiles plotted on figure 22 is interpreted to represent a former stream channel that graded out to marine terraces at the paleo shoreline; it is assumed that these surfaces were continuous with the paleo-marine shorelines. The paleo-stream surfaces were therefore projected out to the shoreline and correlated with the marine platforms of similar elevations, discussed previously. Ages were assigned to the paleo-stream surfaces based on the ages of the marine terraces. Uplift rates were then calculated for the Pismo Syncline from the uplift rate of the marine terraces.

Strath surfaces and river terraces in Pismo and Arroyo Grande Creeks were not surveyed due to poor terrace development (especially Pismo Creek), and lack of time.

Stratigraphic data from water well drilling logs were used to define the bedrock strath surface beneath the alluvium in San Luis Obispo Creek. The drill hole data were obtained from the San Luis Obispo County planning department. Data for Arroyo Grande and Pismo Creek were too sparse to be of value, and therefore the author worked only with San Luis Obispo Creek. The drillers logs are not always accurate, and therefore caution must be used when interpreting this data.

The drill holes were located on topographic maps and were used to construct the bedrock erosional profile (Figs. 20, and 22).

RESULTS OF STUDY

San Luis Obispo Creek

Figure 21 shows the locations of strath surfaces, survey points and borehole data along San Luis Obispo Creek. The numbered data points on Figure 22 correspond to the numbered data points on Figure 21.

The profile of the active channel (Fig. 20) shows the gradient to be nearly constant at 0.2% ±0.1%. The gradient of the bedrock erosional surface is 0.3%

± 0.1% (Fig. 22). The modern erosional surface and the bedrock surface converge where San Luis Obispo Creek crosses the Los Osos fault (Fig. 22). The bedrock profile could not be extended north of the Los Osos fault due to a lack of well and borehole data in the floodplain.

It must be stressed that the data from water well logs is secondhand information and supplies only an approximation of the bedrock surface. An example of the poor quality of this data is the discrepancy in Figure 22 at 18000ft (wells 5 & 6). There is no surface evidence to support the existence of a 25m high bedrock escarpment. However, if the borehole data is correct there are various explanations for this feature. It could be a buried stream channel that had been captured by San Luis Obispo Creek. This explanation is supported by the fact that a drainage intersects San Luis Obispo Creek at the location where this escarpment occurs (Fig. 21).

Three fluvial strath surfaces along San Luis Obispo Creek are referred to in this paper as the Santa Fe, Spirit, and Miguelito surfaces (Fig. 22). They appear to be couplets, have very low gradients and could not be traced northeast of the Los Osos fault (Fig. 22). None of the fluvial strath surfaces can be traced past the Los Osos fault where it crosses San Luis Obispo Creek (Fig. 22). The upper Spirit and lower Miguelito surfaces terminate at the fault, and are approximately 70m above the San Luis Obispo valley. The bedrock and modern erosional surfaces converge at this location (Fig. 20). Well data in the Los Osos valley indicates that the bedrock is buried beneath alluvium on the east side of the fault. These relationships suggest significant recent activity of the Los Osos fault. Trenches across this fault indicate current activity of 1.0 cm/yr of slip (Geomatrix Consultants, personal communication, 1987).

The significance of the couplet arrangement is not clearly understood by the author, they could be an artifact of the data gathering or data interpretation process. There is also the possibility that if these couplets are real that they are reflecting seasonal erosional levels. In the winter the streams would have more water and thus erode the banks at a higher level these bank cuts would be above the water in the summer when the water is lower.

The majority of the topographic irregularities in the paleo-stream surfaces on Figure 22 are within the error limits of ±5m. Most topographic irregularities greater than 5m cannot be vertically correlated (i.e. they do not line up with irregularities in the surfaces above or below), and thus they are considered to have no significance. At 37,000ft on Figure 22, inflections appear on all the surfaces (although some surfaces do not have data points at this locality). These irregularities occur in fault bounded serpentine surrounded by rocks of the Franciscan complex as mapped by Hall (1973). The area shows evidence of landslides, and thus the profiles probably reflect landsliding.

The paleo-stream surfaces are correlated with marine terraces in Table 3. Based on their correlation, an uplift rate of 0.14 mm/yr has been extrapolated to the Pismo syncline. It is assumed that if stream surfaces can be correlated with marine terraces, then uplift rates of the marine terraces can be correlated with the stream surfaces.

Table 3: Correlation of marine terraces to surfaces in San Luis Obispo Creek.

MARINE TERRACE	AGE (ka)	STREAM SURFACE
Mallagh	107*	outcrops in floodplain
Pirates Cove	120-133	Santa Fe
Buchon Couplet	175-305	Spirit Couplet
Arroyo	336	Lower Miguelito
San Luis	450	Upper Miguelito

*Muhs, personal communication, 1987

Pismo Creek

The active channel profile of Pismo Creek (Fig. 20) has a consistent gradient of 0.7% ±0.1%. Pismo Creek is more deeply incised than San Luis Obispo Creek, having cut approximately five to seven feet (1.8 - 2m) into Holocene back fill which was deposited as the sea level rose to its present height. At approximately 30,000 feet (Fig.20) there is a sharp change in gradient. This corresponds to a change in lithology from the resistant Monterey Formation to the softer Pismo Formation.

Arroyo Grande Creek

The profile of Arroyo Grande Creek (Fig. 20) shows a fairly uniform gradient of 0.6% ±0.1%. The amount of incision varies along the creek. In areas of Holocene sedimentary cover the creek has incised three or four feet (1 - 1.3m), but at one location corresponding to a poorly defined contact between the Edna and Squire members of the Pismo Formation, the creek meanders to the west and cuts a gorge approximately thirty feet (9m) deep. This also corresponds to an increase in gradient between 25,000 and 31,000 in figure 20. This could be the result of a change as the creek passes from the harder Edna member to the softer Squire member of the Pismo Formation or it could be a nick point forming due to block uplift.

DISCUSSION OF RESULTS

The gradients of Pismo and Arroyo Grande Creeks are equivalent within error limits (Fig. 20), but the gradient of San Luis Obispo Creek is significantly lower. Many factors influence the gradient of a drainage, such as the suspended load and the size of the upstream drainage basin. If these parameters are assumed to have been equal between the three creeks when deformation began, the much lower gradient of San Luis Obispo Creek as compared to Pismo and Arroyo Grande Creeks could indicate a difference in rate or style of deformation. Pismo and Arroyo Grande Creeks cross the Pismo syncline to the south of the most well defined portion of the Pismo syncline where the syncline might be changing deformational style. Tightening of the syncline could be occurring in its northern portion and could be expressed as a flattening of the San Luis Obispo Creek gradient near the hingeline of the syncline, while in the south, block uplift, expressed by the steeper gradients of Pismo and Arroyo Grande Creeks, could be occurring.

The assumption that the parameters affecting the three stream gradients were equal is probably not valid however. The drainage basin for San Luis Obispo Creek is larger than the Pismo and Arroyo Grande Creek drainages and appears to be in a mature stage of development. The Pismo and Arroyo Grande Creek drainage basins appear to be in a more youthful stage of drainage development based on their steeper gradient and narrower valleys. This may reflect renewed tectonic activity.

The strath surfaces of San Luis Obispo Creek are progressively flatter with increasing elevation and age (Fig. 22). This does not appear to fit the model for an actively folding syncline in which the reaches of a stream crossing the limbs of the syncline are oversteepened compared to the stretch of stream in the center. A possible explanation is that these strath surfaces reflect a situation in which the coast is rising faster than the land just inland from the shore. This would have the effect of back tilting the downstream end of a creek and decreasing the overall gradient of older strath surfaces. Since the gradient of San Luis Obispo Creek is less than Pismo and Arroyo Grande Creeks, the possibility of continued folding is favored.

There is very little data on the history of the cultural development of these three streams. These creeks pass through rural developments of cattle ranchers and farmers and it is clear that human influence must have played a role in the development of the modern alluvial basins of these three creeks. Arroyo Grande Creek has been dammed since the early 1960's. San Luis Obispo Creek has had a weir in its lower reach since the late 1970's and the stretch that flows through the town of San Luis Obispo has been cemented. Thus any conclusions made about the history of the modern profiles (Fig. 20) of these three creeks can only be speculation unless they take into account the cultural influence. The strath surfaces and bedrock surfaces of San Luis Obispo Creek are old enough that human influence has not been a factor in their development.

There does not appear to be any brittle deformation within the Pismo syncline, based on the lack of activity on the Edna, Indian Knob and San Miguelito faults. However, significant deformation is suggested by the truncation of the strath terraces by the Los Osos fault. These relations suggest that the Pismo Syncline may be a coherent block bounded by active faults.

Based on the profiles of the paleo-stream terraces it appears that the syncline may not be actively folding, or if the syncline is folding, then it is too slow to detect. There is a suggestion however, (based on the flat gradient of the Miguelito surface, Fig. 22) that the syncline has been back tilted. If back tilting is still occurring, then the indication is that more deformation is occurring offshore rather than inland on faults such as the Los Osos fault.

SAN MIGUELITO FAULT ZONE

The San Miguelito fault zone (Fig. 2) extends northwest from Mallagh's Landing to Montana De Oro State Park (Hall, 1973). Its trace has been mapped to within three miles (4.8km) northeast of the Diablo Canyon Nuclear Power Plant (Hall, 1973). This study investigated the possibility of recent fault activity.

The fault was examined for geomorphic indicators of recent activity such as offset drainages, beheaded streams, sag ponds, linear springs, shutter ridges, side hill ridges and soil disturbances. No indicators were found. Had there been any indication of recent activity, further work such as trenching would have been conducted to determine the geometry and timing of faulting.

PROCEDURE

Anomalous features across the San Miguelito fault zone were studied from aerial photographs and on the ground. Aerial photographs were used to identify large scale features such as offset stream channels, linear ridge lines, and sag ponds. They were used to find anomalous lineaments which did not have any other obvious explanation, thus providing a target area from which to begin the field work on the ground.

Field inspection of the San Miguelito fault zone was conducted to verify the airphoto interpretation and to look for minor features such as fault gouge, disrupted beds, and soils. Marine and stream terraces which would provide a useful strain gauge, were field checked for offsets where they crossed the fault.

RESULTS OF STUDY

Surface mapping indicates that the fault has not been active during the late Quaternary. Traces of the fault expressed as stratigraphic offsets do not have topographic relief. Outcrops which display faulted surfaces in bedrock contain no disrupted soils. Stream terraces are not offset across the fault. Where the fault crosses marine platforms at Mallagh's Landing there is no indication of offset. Concordant ridge lines could be matched across the fault with out any offset.

DISCUSSION

On trend five kilometers to the northwest with the San Miguelito fault zone is a faulted marine terrace at Montana de Oro State Park. The Pismo terrace, at the north side of the Coon Creek drainage (Fig. 2) displays fault gouge and reverse displacement of the bedrock platform. The soils on top of the Pismo terrace are not disturbed. Since this feature is on trend with the San Miguelito fault it could be related to movement of the fault. However, the San Miguelito fault zone is considered to be predominantly strike-slip (Geomatrix Consultants, personal communication 1987).

If movement on the San Miguelito fault was related to the offset of the Pismo terrace, the timing of movement of the fault can be estimated. The Pismo terrace has an inferred age of 900 ka, and therefore movement of the fault would be younger than the Pismo terrace (900 ka) but older than the Coon terrace (700 ka), which does not appear to be faulted.

CONCLUSIONS

Geomorphic indicators of tectonic activity, marine terraces, and stream profiles show low, zero to almost zero rates of late Quaternary activity around the Pismo syncline. Data from paleo stream terrace gradients suggest that synclinal folding of the Pismo syncline has ceased and that block uplift is the dominant style of deformation. The lack of significant folding of the Migualito stream terrace profile of estimated 450,000 year inferred age, idicates that the synclinal folding ceased at least 450,000 years although it post-dates the approximately 1.0 Ma age of the Squire member of the Pismo Formation

An uplift rate of 0.14 mm/yr determined from the study of uplifted marine terraces at the mouth of San Luis Obispo Creek. Correlation of paleo stream surfaces with marine terraces suggests the same, or similar uplift rate across the Pismo syncline.

The fluvial strath surfaces along San Luis Obispo Creek are truncated by the Los Osos fault where it crosses San Luis Obispo Creek (Fig. 22). Approximately 70m above the San Luis Obispo valley, the upper Spirit and lower Miguelito surfaces terminate at the fault. The alluvium in San Luis Obispo Creek on the west side of the fault thins to insignificant amounts towards the Los Osos fault (Fig. 20), while on the east side of the fault well data in the Los Osos valley indicates that the bedrock is buried beneath alluvium. These relationships suggest significant recent activity of the Los Osos fault. A slip rate of 1.0 mm/yr is indicated by trenches across this fault (Geomatrix Consultants, personal communication, 1987).

Surface mapping and elevation data collected for this study suggest that the marine terraces have not been folded between Montana de Oro State Beach and Shell Beach. However, borehole data collected by Geomatrix Consultants (1987) on the marine platforms at Rattlesnake Creek indicate possible deformation of the bedrock in this area.

The San Miguelito fault has no geomorphic expression. Based on possible correlation with a faulted marine terrace at Montana de Oro State Park, vertical separation on the San Miguelito fault zone appears not to have occurred since more than 700 ka ago. Further study is needed to determine whether these two features are associated.

Faults parallel to the San Miguelito Fault zone, (i.e. the Wilmar Avenue Fault, Figure 2), to the southeast are considered to be active with a slip rate 0.10 mm/yr (Geomatrix Consultants, personal communication, 1987; Nitchman, personal communication, 1987). In close proximity to the San Miguelito Fault Zone, the San Luis Bay Fault (Fig. 2), is considered to be active with a slip rate of 0.10 mm/yr (Geomatrix Consultants, personal communication, 1987).

The low rate of activity on the Wilmar Avenue, San Luis Bay and Los Osos faults demonstrates that there is some tectonic activity in the area. Whether all of the neotectonic strain is being taken up on these faults or whether some of the strain is being taken up by folding of the Pismo syncline, is a question that cannot be clarified without further study.

Further study is also needed to clarify inconclusive data and questions. A series of boreholes could be drilled to bedrock in the modern stream bed of San

Luis Obispo Creek to determine the shape of the Pleistocene erosional surface. This data would clarify the confusing data on the bedrock profile of San Luis Obispo Creek (Fig. 21).

The marine terraces near Rattlesnake Creek had many boreholes drilled into them. However, a set perpendicular to the shoreline crossing the set that is parallel to the shoreline might help to clarify uncertainties in this location concerning the possible downdropping or faulting.

To answer the question whether the faulted marine terrace at Montana de Oro State Park is associated with the San Miguelito fault, a closer study of topographic maps and aerial photographs of the land between the mapped trace of the San Miguelito fault and the marine terraces at Montana de Oro State Park is needed. This would also provide target areas for surface mapping.

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APPENDIX

DATA FOR FIGURE 16

Point 1 - Method: Altimeter; Elevation: 749 feet; Error: +20 feet; Rock type: Monterey Formation; Alluvial cover: Sparse cobbles; Comments: This is a minimum elevation due to erosion.

Point 2 - Method: Altimeter; Elevation: 422 feet; Error: ±10 feet; Rock type: Monterey Formation; Alluvial cover: Colluvial wedge; Comments: Data taken from inner edge exposed in drainage.

Point 3 - Method: Altimeter; Elevation: 150 feet; Error: ±10 feet; Rock type: Monterey Formation; Alluvial cover: Colluvial wedge; Comments: Data taken from inner edge exposed in drainage.

Point 4 - Method: Altimeter; Elevation: 100 feet; Error: ±10 feet; Rock type: Monterey Formation; Alluvial cover: Colluvial wedge; Comments: Data taken from inner edge exposed in drainage.

Point 5 - Method: Altimeter; Elevation: 47 feet; Error: ±10 feet; Rock type: Monterey Formation; Alluvial cover: Colluvial wedge; Comments: Data taken from inner edge exposed in drainage.

Point 6 - Method: Altimeter; Elevation: 17 feet; Error: +20 feet; Rock type: Monterey Formation; Alluvial cover: None; Comments: Minimum Elevation due to erosion.

Point 7 - Method: Altimeter; Elevation: 406 feet; Error: ±10 feet; Rock type: Monterey Formation; Alluvial cover: None; Comments: Data taken from inner edge exposed in drainage.

Point 8 - Method: Altimeter; Elevation: 319 feet; Error: ±10 feet; Rock type: Monterey Formation; Alluvial cover: None; Comments: Data taken from inner edge exposed in drainage.

Point 9 - Method: Altimeter; Elevation: 161 feet; Error: ±15 feet; Rock type: Monterey Formation; Alluvial cover: Colluvial wedge; Comments: Inner edge estimated using trigonometry explained in text.

Point 10 - Method: Altimeter; Elevation: 112 feet; Error: ±15 feet; Rock type: Monterey Formation; Alluvial cover: Colluvial wedge; Comments: Inner edge estimated using trigonometry explained in text.

Point 11 - Method: Altimeter; Elevation: 65 feet; Error: ±15 feet; Rock type: Monterey Formation; Alluvial cover: Colluvial wedge; Comments: Inner edge estimated using trigonometry explained in text.

Point 12 - Method: Altimeter; Elevation: 22 feet; Error: ±20 feet; Rock type: Monterey Formation; Alluvial cover: None; Comments: Minimum elevation due to erosion.

Point 13 - Method: Altimeter; Elevation: 398 feet; Error: ±10 feet; Rock type: Monterey Formation; Alluvial cover: Colluvial wedge; Comments: Data taken from inner edge exposed in drainage.

Point 14 - Method: Altimeter; Elevation: 312 feet; Error: ±10 feet; Rock type: Monterey Formation; Alluvial cover: Colluvial wedge; Comments: Inner edge estimated using trigonometry explained in text.

Point 15 - Method: Altimeter; Elevation: 112 feet; Error: ±10 feet; Rock type: Monterey Formation; Alluvial cover: Colluvial wedge; Comments: Inner edge estimated using trigonometry explained in text.

Point 16 - Method: Altimeter; Elevation: 680 feet; Error: +20 feet; Rock type: Cretaceous Sands; Alluvial cover: Sparse cobbles; Comments: Minimum elevation due to erosion.

Point 17 - Method: Altimeter; Elevation: 49 feet; Error: ±15 feet; Rock type: Obispo tuff; Alluvial cover: Colluvial wedge; Comments: Data taken from PG&E hearing transcripts 1976.

Point 18 - Method: Altimeter; Elevation: 99 feet; Error: ±15 feet; Rock type: Obispo tuff; Alluvial cover: Colluvial wedge; Comments: Data taken from PG&E hearing transcripts 1976.

Point 19 - Method: Altimeter; Elevation: 50 feet; Error: ±15 feet; Rock type: Obispo tuff; Alluvial cover: Colluvial wedge; Comments: Data taken from PG&E hearing transcripts 1976.

Point 20 - Method: Altimeter; Elevation: 15 feet; Error: ±10 feet; Rock type: Squire member; Alluvial cover: soil; Comments: Island.

Point 21 - Method: Altimeter; Elevation: 254 feet; Error: +20 feet; Rock type: Obispo Tuff; Alluvial cover: None; Comments: Minimum elevation due to erosion.

Point 22 - Method: Altimeter; Elevation: 124 feet; Error: +20 feet; Rock type: Obispo Tuff; Alluvial cover: None; Comments: Minimum elevation due to erosion.

Point 22b - Method: Altimeter; Elevation: 124 feet; Error: +20 feet; Rock type: Obispo Tuff; Alluvial cover: None; Comments: Minimum elevation due to erosion.

<u>Point 22c</u> - Method: Altimeter; Elevation: 124 feet; Error: +20 feet; Rock type: Obispo Tuff; Alluvial cover: None; Comments: Minimum elevation due to erosion.

<u>Point 23</u> - Method: Altimeter; Elevation: 42 feet; Error: +20 feet; Rock type: Obispo Tuff; Alluvial cover: None; Comments: Minimum elevation due to erosion.

<u>Point 24a</u> - Method: Altimeter; Elevation: 15 feet; Error: +20 feet; Rock type: Obispo Tuff; Alluvial cover: None; Comments: Minimum elevation due to erosion.

<u>Point 24b</u> - Method: Altimeter; Elevation: 15 feet; Error: +20 feet; Rock type: Obispo Tuff; Alluvial cover: None; Comments: Minimum elevation due to erosion.

<u>Point 24c</u> - Method: Altimeter; Elevation: 15 feet; Error: +20 feet; Rock type: Obispo Tuff; Alluvial cover: None; Comments: Minimum elevation due to erosion.

<u>Point 24d</u> - Method: Altimeter; Elevation: 15 feet; Error: +20 feet; Rock type: Obispo Tuff; Alluvial cover: None; Comments: Minimum elevation due to erosion.

<u>Point 25</u> - Method: Altimeter; Elevation: 254 feet; Error: +20 feet; Rock type: Obispo Tuff; Alluvial cover: None; Comments: Minimum elevation due to erosion.

<u>Point 26</u> - Method: Altimeter; Elevation: 120 feet; Error: ±15 feet; Rock type: Obispo Tuff; Alluvial cover: Colluvial wedge; Comments: Inner edge exposed in drainage.

<u>Point 27</u> - Method: Altimeter; Elevation: 38 feet; Error: +20 feet; Rock type: Obispo Tuff; Alluvial cover: None; Comments: Minimum elevation due to erosion.

<u>Point 28</u> - Method: Altimeter; Elevation: 40 feet; Error: +20 feet; Rock type: Obispo Tuff; Alluvial cover: None; Comments: Minimum elevation due to erosion.

<u>Point 29</u> - Method: Altimeter; Elevation: 40 feet; Error: ±15 feet; Rock type: Obispo Tuff; Alluvial cover: Colluvial wedge; Comments: Projected using trigonometry explained in text.

<u>Point 30</u> - Method: Altimeter; Elevation: 174 feet; Error: +20 feet; Rock type: Miguelito member; Alluvial cover: None; Comments: Wind gap from topographic map.

Point 31 - Method: Altimeter; Elevation: 292 feet; Error: ±10 feet; Rock type: Miguelito member; Alluvial cover: Colluvial wedge; Comments: Inner edge exposed in drainage.

Point 32 - Method: Altimeter; Elevation: 200 feet; Error: ±15 feet; Rock type: Miguelito member; Alluvial cover: Colluvial wedge; Comments: Projected using trigonometry explained in the text.

Point 33 - Method: Altimeter; Elevation: 49 feet; Error: ±15 feet; Rock type: Monterey Formation; Alluvial cover: Colluvial wedge; Comments: Caltrans borehole data.

Point 34 - Method: Altimeter; Elevation: 656 feet; Error: ±10 feet; Rock type: Monterey Formation; Alluvial cover: none; Comments: Minimum elevation due to erosion.

Point 35 - Method: Altimeter; Elevation: 636 feet; Error: ±10 feet; Rock type: Monterey Formation; Alluvial cover: none; Comments: Minimum elevation due to erosion.

Point 36a - Method: Altimeter; Elevation: 432 feet; Error: ±10 feet; Rock type: Obispo tuff; Alluvial cover: Sparse cobbles; Comments: The sparse cobbles had mollusc boreholes, evidence of an ancient sea shore.

Point 36b - Method: Altimeter; Elevation: 432 feet; Error: ±10 feet; Rock type: Obispo tuff; Alluvial cover: Sparse cobbles; Comments: The sparse cobbles had mollusc boreholes, evidence of an ancient sea shore.

Point 36c - Method: Altimeter; Elevation: 432 feet; Error: ±10 feet; Rock type: Obispo tuff; Alluvial cover: Sparse cobbles; Comments: The sparse cobbles had mollusc boreholes, evidence of an ancient sea shore.

Point 36d - Method: Altimeter; Elevation: 432 feet; Error: ±10 feet; Rock type: Obispo tuff; Alluvial cover: Sparse cobbles; Comments: The sparse cobbles had mollusc boreholes, evidence of an ancient sea shore.

Point 37 - Method: Altimeter; Elevation: 19 feet; Error: +20 feet; Rock type: Obispo tuff; Alluvial cover: none; Comments: Minimum elevation due to erosion.

Point 38 - Method: Tape measure; Elevation: 12 feet; Error: +3 feet; Rock type: Obispo tuff; Alluvial cover: none; Comments: Minimum elevation due to erosion.