FINAL TECHNICAL REPORT

SOUTHERN SAN GREGORIO FAULT DISPLACEMENT: STEPOVER SEGMENTATION VS. THROUGH-GOING TECTONICS

USGS Award No. 1434-HQ-98-GR-00007
National Earthquake Hazards Reduction Program
Program Element I: Evaluating National and Regional Hazard and Risk

Submitted to:

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MARCH 1999

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 1434-HQ-98-GR-00007 to Joseph C. Clark and Lewis I. Rosenberg. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

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ABSTRACT

An important outstanding problem is the southern extent of the San Gregorio fault zone (SGFZ) and its postulated continuity with the Hosgri fault zone to the south. Whereas Graham and Dickinson (1978) postulated that the SGFZ is continuous with the Hosgri fault zone, Greene and others (1973) suggested that the main SGFZ turns inland south of Monterey Bay to join the Palo Colorado fault in the northern Santa Lucia Range.

We identified a zone of late Quaternary faulting north of Point Sur that is as much 2 km wide and trends N. 40–50° W. The two most important faults within this zone are the Garrapata fault, which offsets Holocene colluvium; and the Rocky Creek fault, which offsets and deforms marine terrace deposits.

The Garrapata fault strikes N. 55°W., intersecting the coast in a 55-m-wide shear zone, and vertically offsets the lowest marine terrace by 1.7 m. Offshore, a 150-m-wide gap in the kelp aligns with this zone; and onshore features suggesting active faulting include aligned drainage offsets, ridge saddles, and springs. A weak air photo lineament trends N. 52° W. across this terrace, and the shoreline angle appears right-laterally offset as much as 122 m. Along this trend, the Garrapata fault juxtaposes granitic rock and colluvium along a near-vertical shear zone and juxtaposes two different Holocene colluvial deposits with radiocarbon ages of 1,200±60 and 9,750±60 ybp.

The Rocky Creek fault offsets and deforms a marine terrace deposit at an elevation of 110 m above sea level. This fault offsets Bixby Creek approximately 1.4 km in a right-lateral sense and continues to the south along the linear canyon of Sierra Creek.

Preliminary calculations of slip rates suggest that most displacement is horizontal with an estimated rate of 3 mm/yr on the Garrapata/Palo Colorado fault and an estimated rate of 1.3 mm/yr on the Rocky Creek fault. The average vertical component of slip ranges from 0.03 mm/yr (Garrapata/Palo Colorado fault) to 0.22 mm/yr (Rocky Creek fault). Vertical uplift is ongoing and affects stream sinuosity and gradient on coastal streams between these two fault zones.

Although the continuity of these faults with offshore segments of the San Gregorio fault is still to be confirmed, our results to date strongly suggest that at least some of the dextral shear of the offshore SGF is distributed to en echelon intra-Salinian fault segments of the northern Santa Lucia Range.

INTRODUCTION

General Statement

The San Gregorio fault (SGF) is the principal fault west of the San Andreas fault (SAF) in central California and is part of the larger SAF system that forms the active tectonic boundary between the Pacific and North American plates. From its type area in the western Santa Cruz Mountains, where at Año Nuevo the SGF zone is 2–3 km wide and includes seven fault segments, the SGF has been traced northward to its juncture with the SAF near Bolinas in Marin County and southward across Monterey Bay, a distance of as much as 200 km (figure 1). Based on its dimensions and associated youthful geomorphic expression, this fault appears to be a potential source of significant earthquakes, although the Monterey Bay doublet ($M_L = 6.2$) of 1926 is the only known large event probably associated with this zone during historic time.

An important outstanding problem for seismic hazard analysis is the southern extent of the San Gregorio fault zone (SGFZ) in coastal central California and its postulated continuity with the Hosgri fault zone (HFZ) to the south. Most workers have followed Silver (1978) and Graham and Dickinson (1978), who postulated that the SGFZ is continuous, via a portion of the Sur fault zone, with the San Simeon/Hosgri fault zone to the south. Greene and others (1973), on the other hand, suggested that the main SGFZ turns inland south of Monterey Bay to join the Palo Colorado fault in the northern Santa Lucia Range. A related problem is the apparent discrepancy between recent estimates of total offset on the SGFZ compared to that on the HFZ. Based on cross-fault correlations, Clark (1998) postulates 150–160 km of cumulative right slip on the SGFZ. Dickinson's (1996) reconstruction infers 156±8 km of slip on the SGFZ and 110±5 km slip on the HFZ.

The purpose of this study was to determine to what extent SGF displacement has been transferred to eastward-splaying fault segments of the northern Santa Lucia range rather than continuing southward via the Sur thrust zone to the San Simeon/Hosgri fault zone. Several faults in the northern Santa Lucia Range deform and locally offset Quaternary deposits suggesting that these faults are active. We believe that some of the slip may be partitioned along en echelon intra-Salinian faults of the northern Santa Lucia Range rather than along a continuous Sur/Hosgri fault zone to the south. To investigate this hypothesis, we performed the following tasks:

Methods of Investigation

Assessing the extent and activity of Quaternary faulting requires a critical evaluation of Quaternary offsets suggested by published and unpublished mapping. To accomplish this goal, our investigation included the following major work tasks:

1. Reviewing pertinent literature related to the geologic conditions in the study area and surrounding region. Sources of data included government agencies (U.S. Geological Survey, California Division of Mines and Geology, Monterey Peninsula Water Management District, and the Monterey County Planning Department); unpublished theses and dissertations; and geotechnical consultant reports.

2. Logging critical exposures along the Garrapata and Rocky Creek faults and sampling offset colluvium at the former site to determine recency of movement.

3. Geomorphic analysis using black-and-white stereoscopic aerial photography flown in 1985.

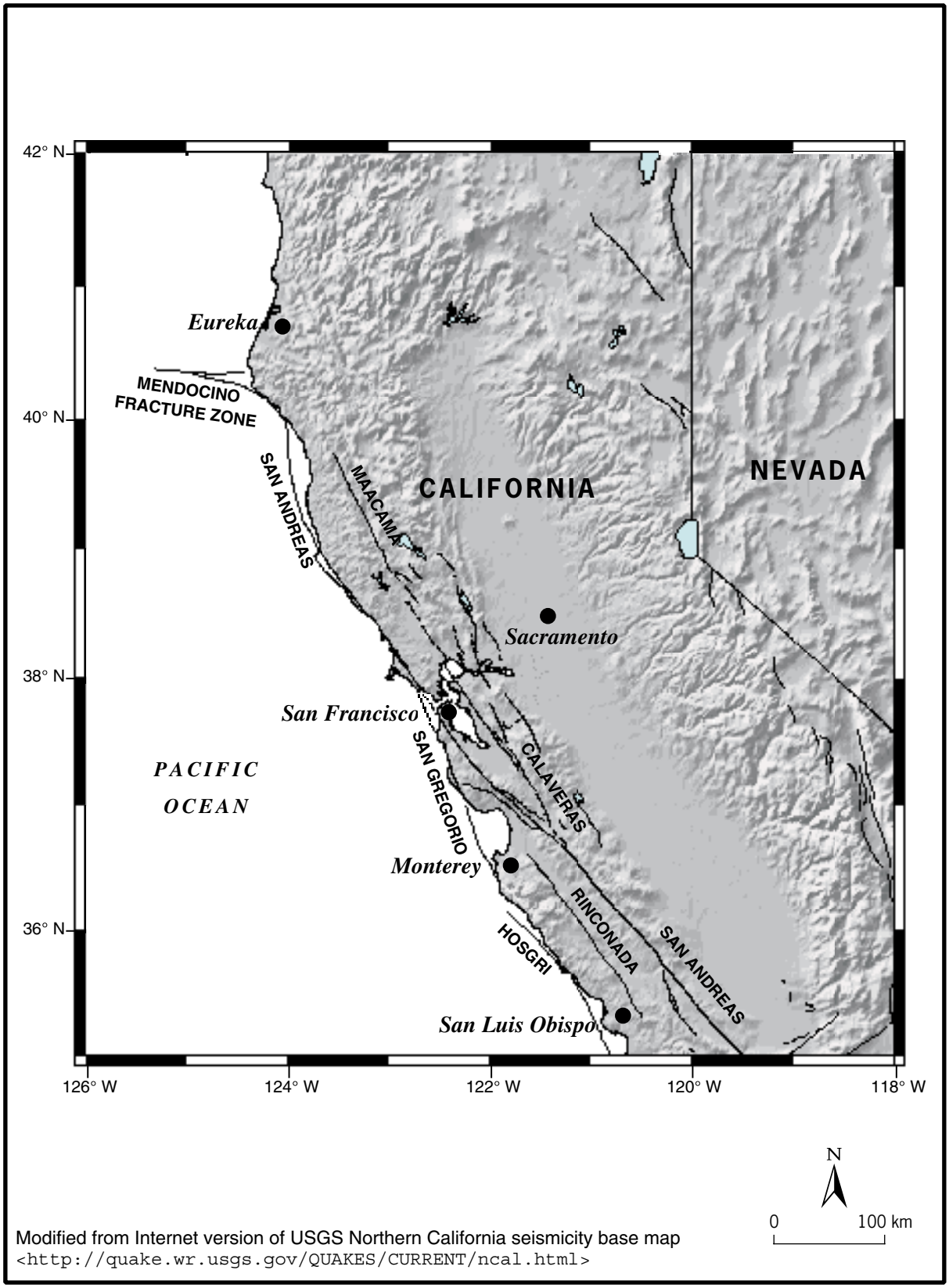


Figure 1. Regional faults of the San Andreas fault system, northern California

4. Comparing our onshore Quaternary-active fault trends to offshore San Gregorio fault extensions as recently determined by Eittreim and others (USGS, written commun., 1999) to ascertain the northwestward extent and possible continuity of these onshore segments with offshore segments of the southern SGF.

5. Evaluating changes in stream gradients and sinuosity of Garrapata and Bixby Creeks as possible indicators of active faulting (Schumm, 1986). This involved using paper copies of 1876 U.S. Coast Survey 1:10,000 scale topographic maps (Rodgers and Dickins, 1876; Rodgers, 1877) and digital elevation models derived from 1983 USGS 1:24,000 scale topographic maps.

6. Sampling the granitic rocks south of the Garrapata fault for strontium-isotope analysis by Ronald Kistler (USGS) for comparison to the Soberanes mass to the north in order to test limits on cumulative right-slip.

7. Sampling the basaltic andesite on both sides of the Tularcitos fault for K-Ar dating and chemical analyses to test postulated right-lateral displacement on this active fault.

8. Creating a geographic information system (GIS) database using ArcView 3.1.1 software (ESRI, 1999). This database contains fault locations and activity status, Quaternary deformation localities, geomorphic features indicative of recent faulting, radiocarbon dates of faulted colluvium, and earthquake fault-plane solutions.

Accompanying this report are three oversize map sheets. Plate 1 shows faults, geomorphic features, locations of Quaternary deformation, and epicenters on a digital raster graphic 7.5-minute topographic base map. Plate 2 shows the location and relative activity of the faults on a cadastral base map enhanced with shaded relief derived from a 7.5-minute digital elevation model. Plate 3 is a roadcut log of the Rocky Creek fault.

Acknowledgments

We are grateful to William Lettis and Gerald Weber for joining us in the field and sharing their insight into Quaternary deformation. We thank John Williams for directing us to several critical localities and for facilitating our access to private land in the area. We also thank David Oppenheimer of the U.S. Geological Survey for providing unpublished earthquake fault-plane solutions, H.G. Greene of the Moss Landing Marine Laboratories for sharing unpublished mapping, Gail Foss of the County of Monterey for supplying cadastral base maps, and Frank Carey of the California State Lands Commission for furnishing historical topographic maps of the study area.

FAULTS OF THE NORTHERN SANTA LUCIA RANGE

General Statement

To investigate the possible onshore continuity of the southern San Gregorio fault and possible distribution of shear onto other intra-Salinian faults, we focused our studies on a coastal section from Soberanes Point southward to Division Knoll (figure 2). There, a series of en echelon faults that generally strike N. 40°–50° W. intersect the coast and define a zone of shearing as much as 2 km wide. Within this zone, we believe that the three most important faults are the Garrapata, the Palo Colorado, and the Rocky Creek faults. Although the Tularcitos fault is not part of the SGFZ, it is a major tectonic structure that accommodates part of the deformation of the Salinian block and is discussed separately.

Garrapata Fault

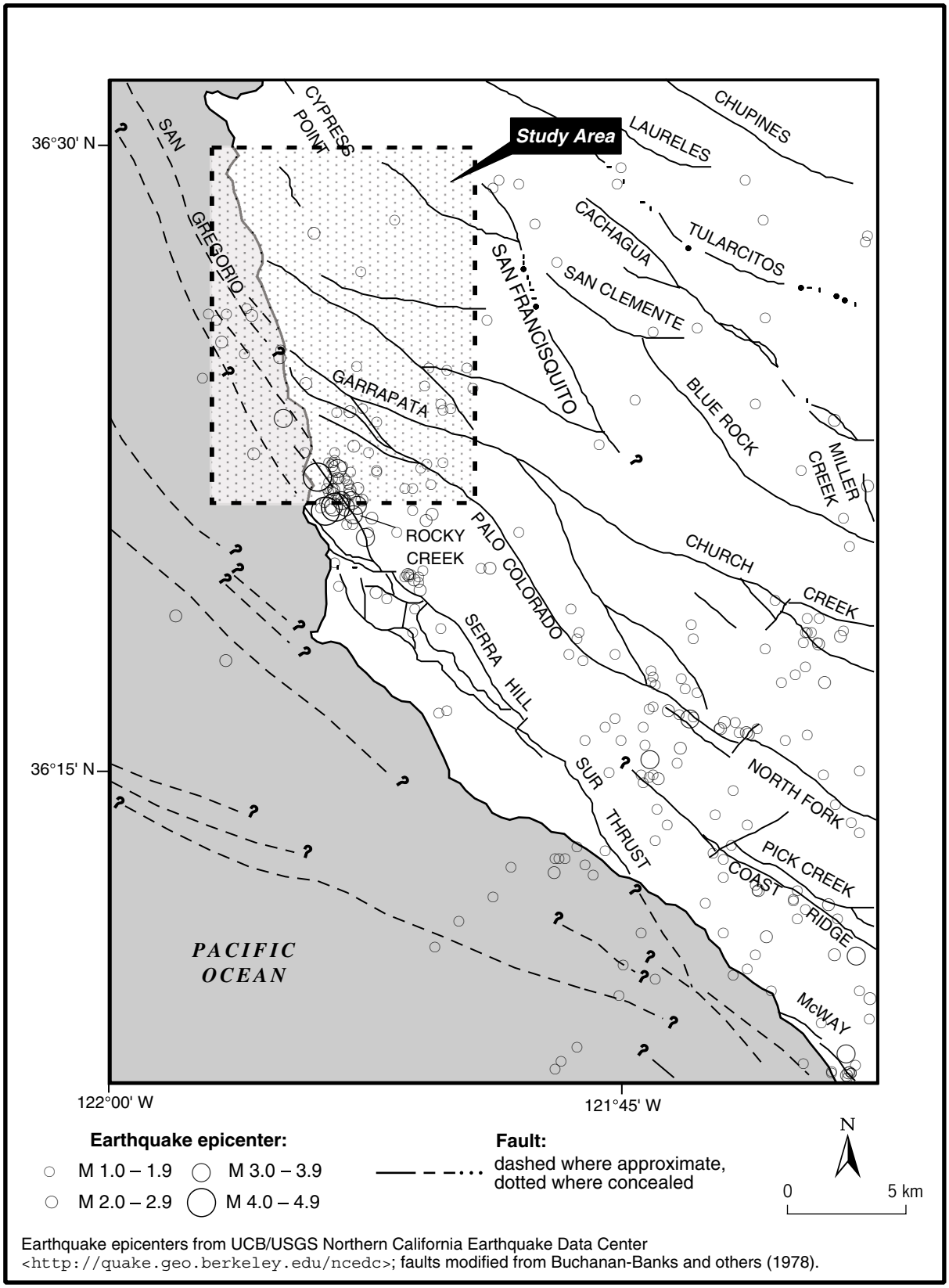
The Garrapata fault strikes N. 45° W. and intersects the coast at Garrapata Beach in a 55-m-wide shear zone in granitic rocks that displays horizontal slickensides. Although the granitic rocks on both sides of this fault zone are petrologically similar and mapped by Ross (1976) as the hornblende-biotite quartz diorite of Soberanes Point, the granitic exposures north on this zone commonly contain the salmon-pink pegmatites characteristic of the Soberanes mass, whereas to the south similar pegmatites are rare and dark schlieren are conspicuous. The strontium-isotope ratio of the granitic rock from south of the Garrapata fault is presently being analyzed by Ronald Kistler (USGS, oral commun., 1999) for comparison to the Soberanes mass to the north.

Dibblee (1973) mapped the Garrapata fault as veering inland to the east with questionable right-slip and as trending into the Church Creek fault, a northeast-dipping reverse fault with perhaps as much as 1.5 km of dip-slip displacement (Dickinson, 1965). On the other hand, based on aerial photograph interpretation and strongly aligned topographic features, we believe that this fault continues its relatively straight course S. 67° E. to join the inland Palo Colorado fault of earlier mappers (Trask, 1926; Dibblee, 1973), which in turn continues southward along the same trend through a series of saddles and prominent linear valleys (plate 1).

Richardson (1923) reported that the youngest terrace near Garrapata Creek "is cut by a large and recent fault." As exposed in the seacliff at Garrapata Creek, the lowest emergent marine terrace appears to be vertically offset 1.7 m with the south side up. Additionally, a weak air photo lineament trends N. 52° W. across this terrace and appears to offset the shoreline angle as much as 122 m in a right-lateral sense.

On trend offshore, a 150-m-wide gap in the kelp beds aligns with this fault zone, whereas onshore numerous geomorphic features indicative of active faulting include aligned drainage offsets, ridge saddles, linear topography, and springs (plate 1). At one key locality along this trend approximately 0.9 km inland, the Garrapata fault juxtaposes granitic rock and colluvium along a near-vertical shear zone; and near the top of this exposure, this fault juxtaposes two different colluvial deposits (figure 3). Radiocarbon dating gives conventional ^{14}C ages of 1,200±60 and 9,750±60 yr B.P for these deposits (Beta Analytic samples Beta-123220 and Beta-123221), indicating Holocene activity. Thus, we regard the Garrapata fault as an active, right-lateral strike-slip fault.

Offset drainages along Garrapata Creek suggest right-slip of as much as 3.3 km, which is comparable to the apparent right offset along the inland Palo Colorado fault of southwestward flowing Rocky Creek to westward trending Palo Colorado Canyon (plate 1).



Earthquake epicenters from UCB/USGS Northern California Earthquake Data Center <http://quake.geo.berkeley.edu/ncedc>; faults modified from Buchanan-Banks and others (1978).

Figure 2. Regional faults and seismicity (1977–1997), northern Santa Lucia Range, Monterey County, California

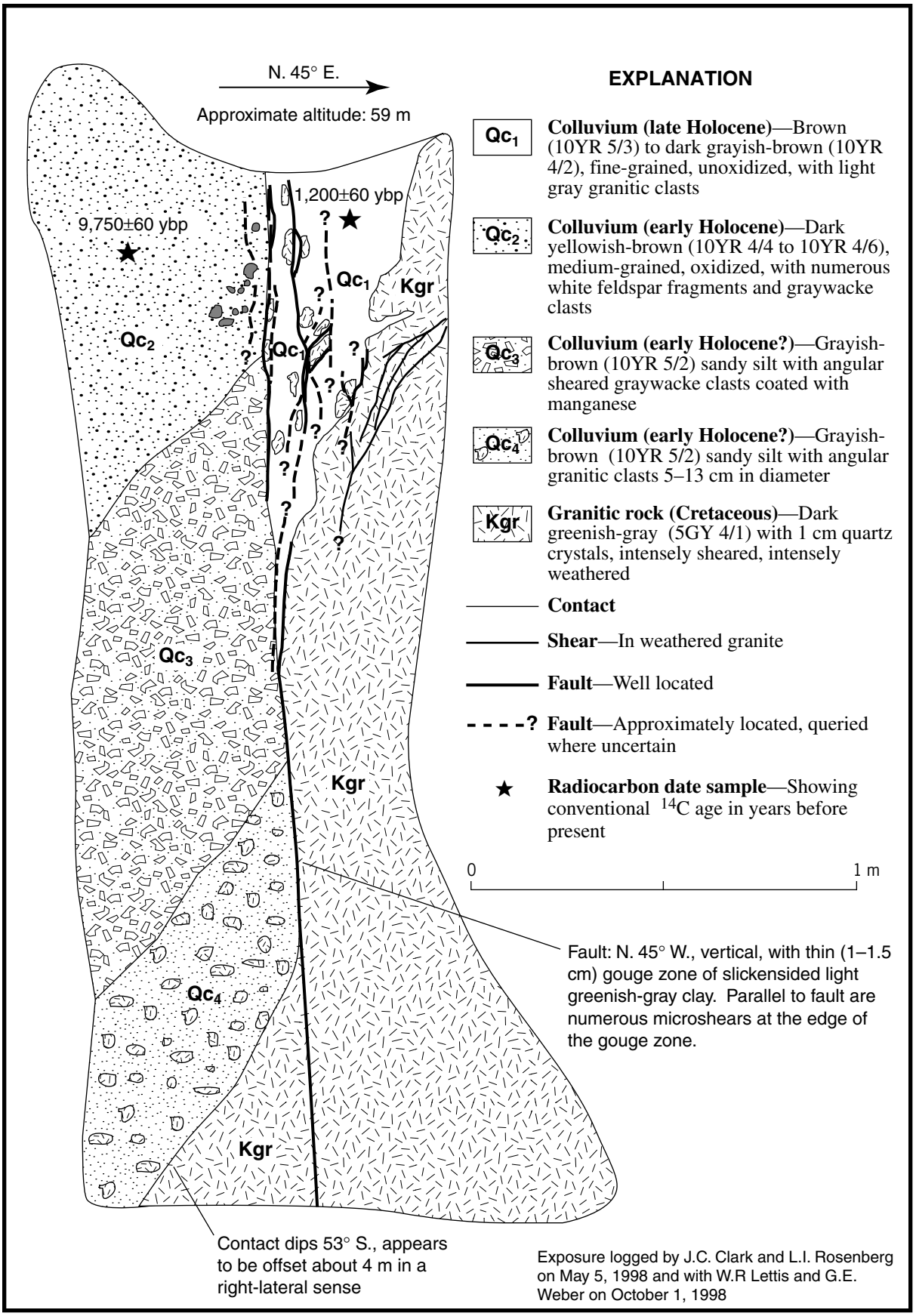


Figure 3. Log of gully exposure of Garrapata fault near Trout Farm, Big Sur, California

Palo Colorado Fault

The Palo Colorado fault has been mapped by Trask (1926) and Dibblee (1973) as a high-angle, northwest-southeast trending fault that in our study area juxtaposes sandstone of probable late Cretaceous age against granitic rocks to the northeast. This fault was mapped as trending more northerly near the coast, them curving inland to become a more prominent geomorphic feature with linear drainage, deflected drainages, and aligned benches and saddles that is on strike with the Garrapata fault to the north as previously discussed.

In the seacliff exposure near the south end of Garrapata Beach, the Palo Colorado fault juxtaposes probable upper Cretaceous sandstone beds against quartz diorite in a meter-thick zone that trends N. 30° W. Near-horizontal slickensides along the northeast side of this gouge zone indicate strike-slip displacement. There, the lowest marine terrace does not appear to be offset, and the coastal curved segment of this fault lacks geomorphic expression.

We interpret these data as suggesting that the Palo Colorado fault had earlier been the locus of strike-slip that juxtaposed the upper Cretaceous sandstone beds with the quartz diorite. More recent movement shifted northward to the active Garrapata fault and continues southward along the inland linear segment of the Palo Colorado fault. This subsequent right-lateral displacement may have produced the present curvature of the inactive coastal segment of the Palo Colorado fault.

Most workers (Reiche, 1937; Dickinson, 1965; Dibblee, 1982) have mapped the Palo Colorado fault as terminating against the east-west trending Willow Creek fault within the granitic Salinian terrane about 40 km south of its coastal exposure. Ross (1976), on the other hand, continues the Palo Colorado fault more southerly to connect with the Coast Ridge fault zone, based on his interpretation of ERTS imagery, "which suggests that these faults are parts of one throughgoing lineament." He believes that this Palo Colorado/Coast Ridge fault zone is probably a major strike-slip dislocation that to the south separates the Coast Ridge metamorphic belt to the west from a markedly different metamorphic terrane to the east.

Although the southern continuation and cumulative displacement of the Palo Colorado fault are beyond the scope of the present study, the lithologic contrasts along this fault suggest to us extensive lateral displacement. Based on offset Holocene colluvium and associated youthful geomorphic features characteristic of strike-slip faulting, we believe that the Garrapata/Palo Colorado fault is presently active. Although a direct connection to the offshore San Gregorio fault has not been demonstrated, we believe that some of the strain from the southern San Gregorio fault has been transferred to the Palo Colorado fault and continues to be partitioned to the active Garrapata/San Gregorio fault.

Rocky Creek Fault

In seacliff exposures near the mouth of Rocky Creek, metamorphic rocks of the Coast Ridge metamorphic belt and granitic rocks are pervasively sheared in a zone as much as 200 m wide. There, the Rocky Creek fault zone strikes approximately N. 30° W. with a near-vertical shear fabric and near-horizontal striations (Bryant, 1985).

Approximately on strike to the south of Division Knoll, the metamorphic rocks are pervasively sheared and include quartz diorite possibly related to the charnockitic tonalite that crops out along the coast 20 km to the south (Ross, 1979). To the east along the Old Coast Road, these metamorphic rocks are faulted against Salinian granitic rocks that are capped by a veneer of marine terrace sand (plate 3). There, at an altitude of 110 m the marine terrace deposits are clearly faulted and tilted in a zone approximately 80 m wide. This fault zone continues S. 38° E. along the linear canyons of Bixby Creek and Sierra Creek and is mapped by Dibblee (1973) as continuing to the southeast where it

trends into the Sur fault zone, about 6 km inland from where it intersects the coast at Rocky Creek. Bixby Creek appears to be right-laterally offset about 1.4 km along this fault.

The offset of Pleistocene terrace deposits confirms Quaternary activity and clustered seismicity strongly suggest that this fault is active. Projection of the "main break" of the offshore San Gregorio fault as mapped by Eittreim and others (USGS, written commun., 1999) roughly aligns with the onland Rocky Creek fault zone and suggests that this fault is an onshore segment of the southern San Gregorio fault as suggested by Graham and Dickinson (1978).

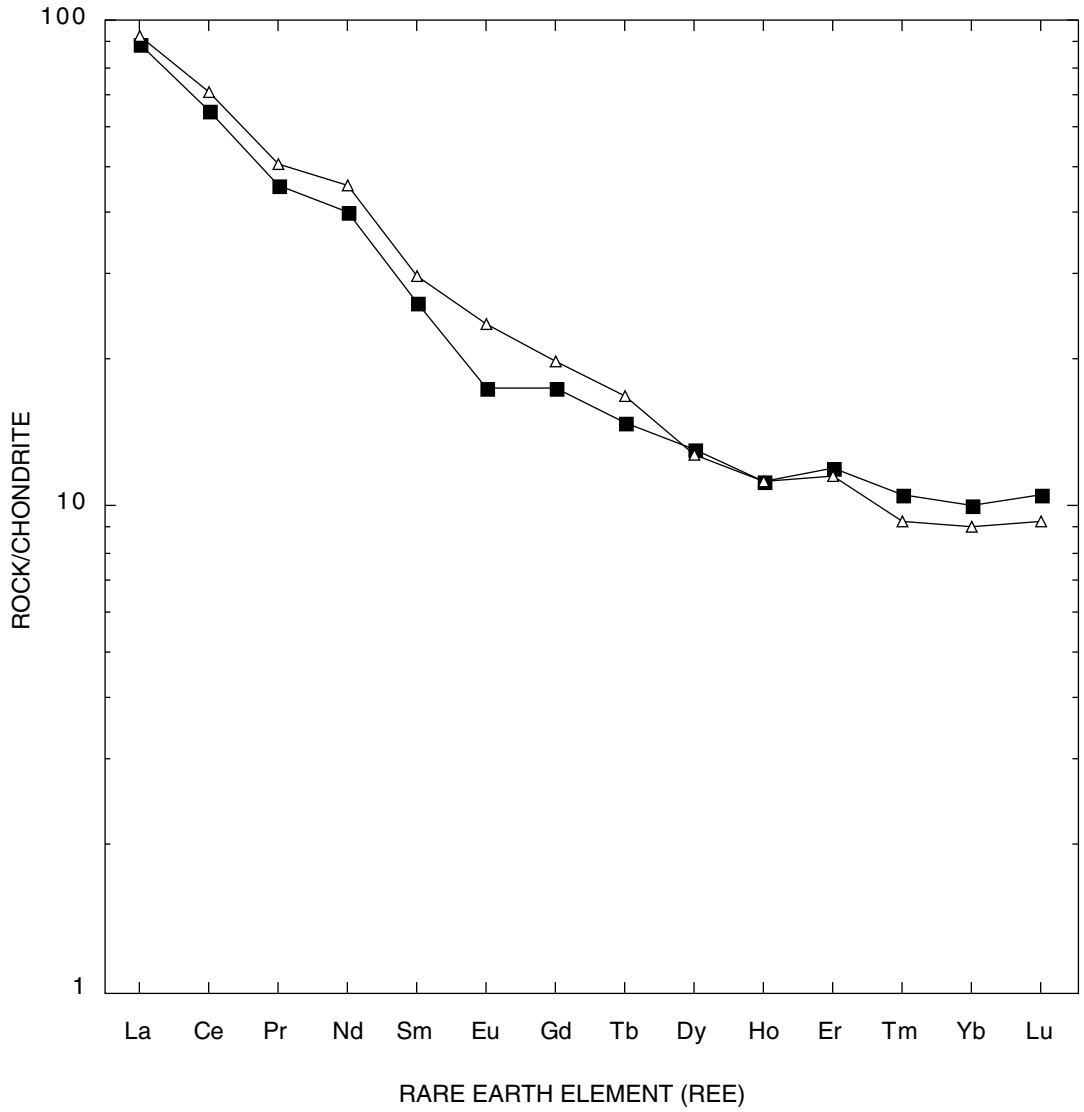
Tularcitos Fault

Jachens and others (1998) have recently postulated 175 km of offset on the northern San Andreas/San Gregorio/Hosgri fault system. They assign 150 km of this slip to the SGFZ and partition 25 km eastward to the Reliz/Rinconada fault zone of the central Coast Ranges.

Some strain from the SGFZ may be partitioned eastward via the Tularcitos fault (figure 2), which is a major intra-Salinian fault of the northern Santa Lucia Range that separates two different tectonic blocks with different rock assemblages. As mapped by Clark and others (1997), the Tularcitos fault strikes northwestward to cross the foothills near Monterey as the Navy fault and continues offshore as part of the Monterey Bay fault zone, which in turn is truncated by or more probably merges with the SGF. Radiocarbon dating of offset colluvium in upper Carmel Valley (Rosenberg and Clark, 1994) together with the offset of the seafloor in Monterey Bay (Greene and others, 1973) confirms Holocene activity along this trend.

Graham (1976) postulated that at least 3.2 km and possibly as much as 16 km of right-lateral displacement may have taken place on the Tularcitos fault, based on the apparent offset of distinctive facies of the Monterey Formation. Additionally, distinct basaltic andesites that crop out at Hastings Reserve north of the Tularcitos fault may have been offset by at least 16 km and possibly as much as 40 km of right slip from similar volcanic rocks of lower Carmel Valley and Carmel Bay that were dated at 27.0±0.8 Ma (Clark and others, 1984). Both outcrops consist of petrologically similar basaltic andesites in which the original olivine has been completely altered to iddingsite. Although the Hastings andesite is not dateable because of alteration of the cryptocrystalline matrix (Robert J. Fleck, USGS, written commun., 1999), comparison of rare earth elements (figure 4) shows that these volcanic rocks are chemically very similar, with the difference in europium values probably the result of plagioclase fractionation, and thus supports their correlation and the possibility of more than 16 km of dextral slip.

To further test and constrain this postulated offset on the Tularcitos fault, andesitic volcanic rocks that crop out at Rancho San Carlos and "basaltic" clasts in conglomerates of Cachagua Grade, both south of the Tularcitos fault, need to be analyzed for comparison to the basaltic andesites north of the fault at Hastings Reserve.



Samples analyzed by ACTLABS, May 1997
Chondrite values from Boynton (1984)

EXPLANATION

CV-1 (Hastings Reserve)

LMP-10 (Arrowhead Point, Carmel Bay)

Figure 4. Rare earth element concentrations for northern Santa Lucia Range volcanic rocks

QUATERNARY DEFORMATION

General Statement

Throughout the study area, well-developed geomorphic features such as topographically aligned saddles, benches, and ridges are common along mapped fault traces. These features are characteristic of active strike-slip faulting (Keller, 1986). In addition to the faulted Pleistocene marine terraces and Holocene colluvium discussed in previous sections, changes in stream gradient and sinuosity and historical seismicity also provide evidence for active faulting along the southern San Gregorio fault zone. These offset terraces, stream channels, and colluvial deposits allow preliminary estimates of slip rates.

Stream Geomorphology

The courses of many of the larger streams in the northern Santa Lucia Range probably are structurally controlled. Trask (1926, p. 164) commented about the Palo Colorado fault, "All of the streams have straight courses where they follow the fault, and the divides between the drainage lines through which the fault passes are remarkably notched." Hamilton (1984) reported the apparent right deflection of drainages crossing the Palo Colorado and Garrapata fault segments and noted increasing deflection with increasing elevation. The increasing amount of deflection upstream suggests that these offsets are probably tectonic in origin, rather than a result of stream capture.

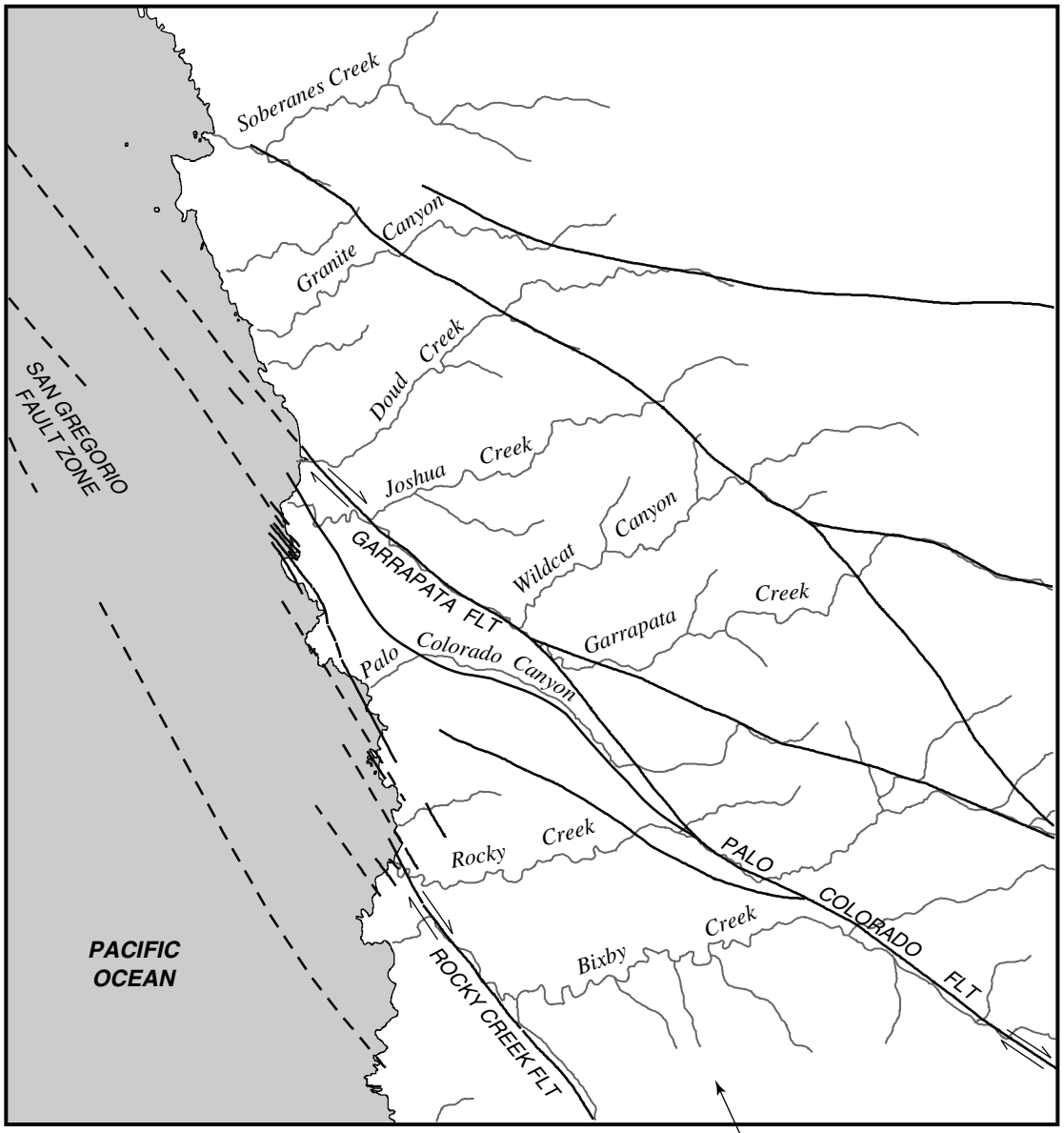
Changes in stream sinuosity and gradient can indicate active faulting. Within the tectonic block bounded by the Garrapata/Palo Colorado and the Rocky Creek faults, stream segments have relatively increased sinuosity compared to segments outside this zone (figure 5). Also, stream gradients abruptly change at the Garrapata/Palo Colorado fault, steepening on the east side of the fault zone (figure 6). The stream-gradient index developed by Hack (1973) is a valuable tool in evaluating active tectonics with a strong vertical component of deformation (Keller, 1986) and is defined as:

$$SL = (\Delta H/ \Delta L)L,$$

where SL is the stream-gradient index, $\Delta H/ \Delta L$ is the local gradient of the stream reach where the index is computed (ΔH is the drop in elevation of the reach and ΔL is the length of the reach), and L is the total channel length from the drainage divide to the center of the reach, measured along the channel. The stream-gradient index changes markedly from 461 to 757 where Rocky Creek crosses the Garrapata/Palo Colorado fault and from 340 to 1726 where Bixby Creek crosses the Palo Colorado fault, suggesting that the tectonic block east of the Garrapata/Palo Colorado is experiencing vertical uplift in addition to right-lateral slip.

An increase in slope will produce an increase in meander length and amplitude. Hence, a river that is being tilted will increase its sinuosity to maintain a constant gradient (Leopold and Wolman, 1960; Schumm, 1986). Bixby Creek and Rocky Creek flow over quartz diorite, schist, and hard Cretaceous sandstone, so differences in erosion due to lithology are unlikely. Changes in stream load such as sediment generated from forest fires can also affect the sinuosity and gradient. If changes in sinuosity and gradient were caused by changes in stream load, then the sinuosity and gradient should not differ outside the Garrapata/Palo Colorado and the Rocky Creek fault zones.

In addition to the right-lateral slip indicated by bedrock lithology and by stream displacement, there is a significant component of vertical slip. Elevated marine terraces along the coast also indicate vertical uplift along the southern San Gregorio fault zone (McKittrick, 1988). Therefore, we believe that on-going vertical uplift is responsible for the changes in stream sinuosity and gradient.



Streams digitized from USGS 1:24,000 topographic quadrangles:
Big Sur, Mt. Carmel, Point Sur, Soberanes Point, 1983

Note the increased stream sinuosity between the Garrapata/Palo Colorado fault and the Rocky Creek fault

N

0 1 MILE

0 1 KILOMETER

Figure 5. Stream sinuosity, southern San Gregorio fault zone, Monterey County, California

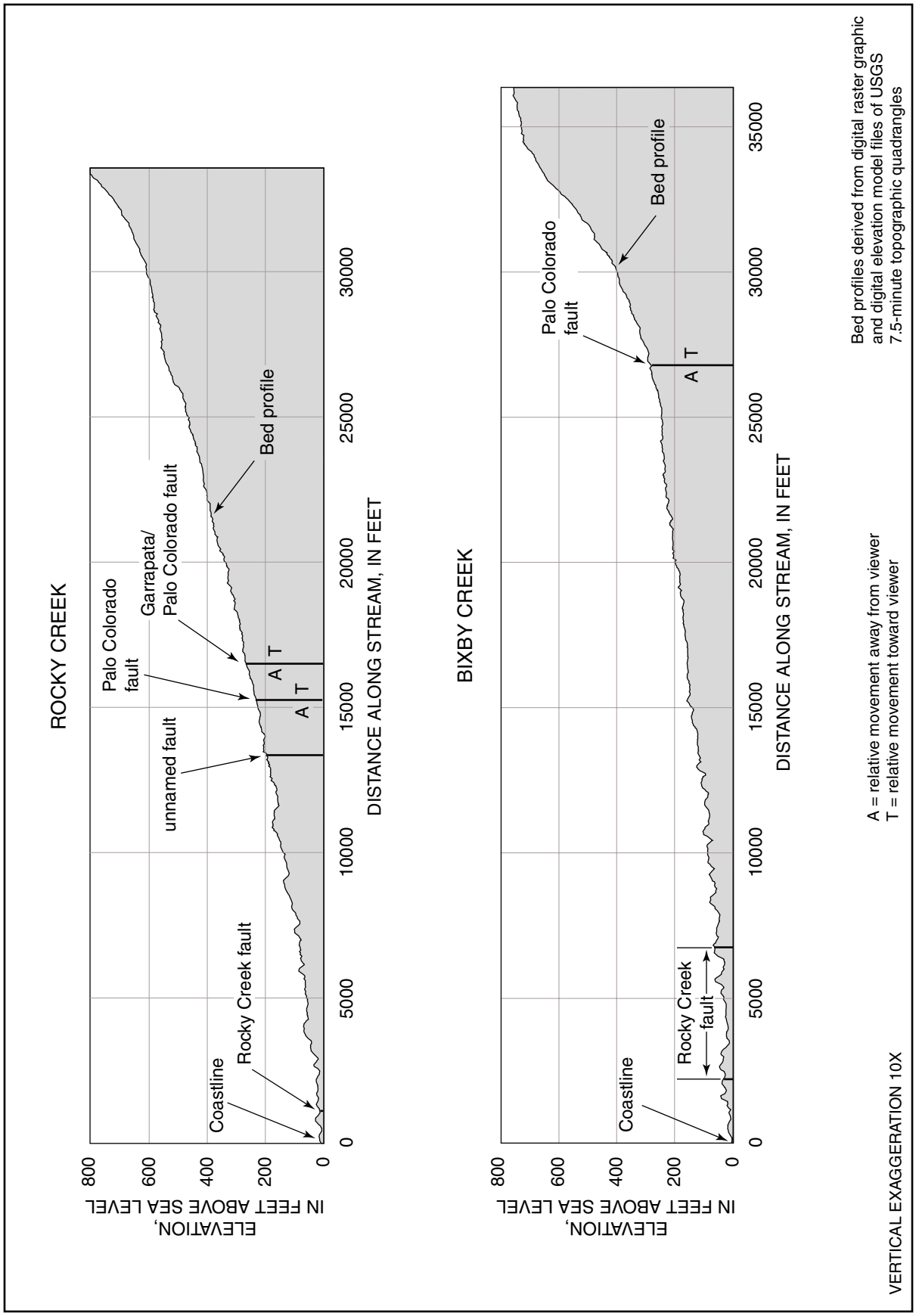


Figure 6. Stream profiles, southern San Gregorio fault zone, Monterey County, California

As Page and others (1998) suggest, this uplift may be a result of transverse shortening accommodated by folding and thrusting within the central Coast Range.

Seismicity

The largest historical earthquake in the region was the 1926 M_L 6.2 doublet in Monterey Bay. Because the locations of these events are mainly based on reports of felt shaking, their location is poorly constrained. Although Mitchell (1928) plots the epicenters along the trend of the San Gregorio fault, they could also have been on the Monterey Bay fault zone. McNally and Stakes (1998) recently developed a new crustal velocity model for the offshore Monterey Bay region that may help resolve the source of earthquakes in Monterey Bay. They reported that first-motion mechanisms indicate east-dipping thrust movement at 8–12 km depth and oblique right-slip striking N. 20°–40° W. at shallower depth on the San Gregorio fault. They also noted that relocated events show right-lateral slip trending N. 50° W. on the Monterey Bay fault zone

Within the study area, nearly all the epicenters are concentrated within a 1-km-wide zone along the Rocky Creek fault and the offshore San Gregorio fault. Only events with at least 25 first-motion readings are included on plate 1 and in appendix 2. Most of these events are associated with the January 1984 M_L 4.9 Big Sur earthquake. First-motion plots show that the main shock had reverse right-slip movement on a fault striking N. 40±3°W. and dipping 71±13° NE., at a depth of 18±1.1 km (David H. Oppenheimer, USGS, written commun., 1999). Aftershocks also have a similar sense of movement. The focal mechanisms are consistent with the right-lateral offset drainages and increased stream gradients northeast of the Garrapata/Palo Colorado and the Rocky Creek fault zones. Reported local effects of this earthquake included rock falls along State Route 1 and items falling off shelves (Telfer, 1984).

Tuttle (1985) studied the pattern of seismicity along the San Gregorio fault, and concluded that the segments from Santa Cruz to San Francisco and from Monterey to Ragged Point had fewer earthquakes than other segments and represent seismic gaps because of the lack of large ($M \geq 6$) earthquakes. If this hypothesis is correct, then the southern San Gregorio fault zone may be in a "locked" part of its seismic cycle and may represent a high risk for large earthquakes. Alternatively, some of the stress may be bled off along intra-Salinian faults of the northern Santa Lucia Range, and therefore present less of a seismic risk. At present, there is insufficient information regarding the regional tectonic stresses to evaluate which scenario is more likely. Additional paleoseismic studies may help elucidate the long-term earthquake history and seismic risk of the southern San Gregorio fault.

Slip Rates

One of the significant questions about the San Gregorio fault system is the apparent discrepancy in slip rates between the slip rate of 5.0±2.0 mm/yr at Año Nuevo and the slip rate of 2.5±1.0 mm/yr on the San Simeon/Hosgri fault at San Simeon. From these postulated slip rates (Petersen and others, 1996), it would appear that approximately 2.5 mm/yr of right-lateral slip is "missing" between Año Nuevo and San Simeon. Our preliminary work suggests that the "missing" slip may be partitioned to en echelon intra-Salinian faults such as the Garrapata/Palo Colorado and the Rocky Creek faults.

Offset of geologic features such as marine terrace surfaces and stream channels provides an estimate of vertical and horizontal Quaternary movement where faults displace these features. Vertical displacements are more readily estimated than horizontal displacements. This is because the unique horizontal piercing point where a fault crosses the shoreline angle of a marine terrace requires accurately locating the back edge of the terrace, which is difficult. A related problem with slip rate estimates is the lack of absolute ages for the offset geologic features. A framework for determining

the relative ages of the Quaternary deposits is outlined by Dupré (1990). Dupré estimated ages of the Monterey terraces by correlating these terraces with known sea level highstands and radiometrically dated terraces in Santa Cruz. Farther south, McKittrick (1988) calculated ages of terraces along the Big Sur coast (table 1).

Table 1. Marine terrace terminology, Monterey Peninsula and Big Sur region

Age Of Deposits	Source Of Data			
	Phifer (1972)	McKittrick (1988)	Dupré (1990)	this study
late Pleistocene (10 ka to 125 ka)	"TERRACE A" (12 m)	"terrace 1" (9 ± 2 m) 100 ka*	"Ocean View" (10 m) 102 ka§	Qmt_1
late Pleistocene	"TERRACE B" (32 m)	"terrace 2" (27 ± 3 m) 120 ka*	"Lighthouse" (25 m) 118 ka§	Qmt_2
middle Pleistocene (125 ka to 700 ka)	----------	----------	"College" (55 m) 319 ka§	----------
middle Pleistocene	"TERRACE C" (60 m)	"terrace 3" (66 ± 5 m) 330 ka†	"Silvan" (75 m) 415 ka#	Qmt_3
middle to early Pleistocene	----------	"terrace 4" (136 ± 10 m) 700 ka†	"Monte Vista" (130 m) 750 ka#	----------
early Pleistocene (700 ka to 1800 ka)	----------	----------	"Huckleberry" (210 m) 1200 ka#	----------

* indicates age based on soil-profile development.
† indicates age based on extrapolating 0.16 mm/yr rate of uplift inferred from lower terraces.
§ indicates age determination by altitude correlation to known highstands (as described by Lajoie and others, 1991).
\# indicates age based on extrapolating 0.18 mm/yr rate of uplift inferred from lower terraces.

The earliest geologic reports along the Big Sur coast noted the prominent uplifted marine terraces (Richardson, 1923; Trask, 1926). Later work by Tuttle (1985) and McKittrick (1988) measured the altitude of coastal terraces and showed that the two lowest terraces were cut by faults. These are summarized below in table 2.

Table 2. Vertical Quaternary slip rates, Big Sur region

Fault	Unit offset	Estimated age of unit (years)	Amount of offset (m)	Displacement rate (mm/yr)	Source of offset data
Garrapata fault	Qmt_1	100,000	1.7	0.02	this study
Garrapata fault	Qmt_1	100,000	2.8	0.03	Tuttle (1985)
Palo Colorado fault	Qmt_2	120,000	4.25	0.04	Tuttle (1985)
Rocky Creek fault	Qmt_2	120,000	24	0.20	Tuttle (1985)
Rocky Creek fault	Qmt_1	100,000	22	0.22	McKittrick (1988)
Rocky Creek fault	Qmt_2	120,000	29	0.24	McKittrick (1988)

Because most of the movement along faults in the study area is strike-slip, horizontal slip rates are more useful for evaluating the activity of these faults. Shoreline angles and stream channels are the two main features that can be used to estimate the amount of offset and resultant slip rates. As we were not able to locate the back edge of the marine terrace at more than one point along the Garrapata fault, the offset may be an apparent amount rather than an absolute amount.

Stream channels along the Garrapata/Palo Colorado and the Rocky Creek fault zones are clearly displaced along the trace of the faults. Using offset stream channels to calculate slip rates requires several assumptions such as the amount of time needed for the stream to incise and that the streams began to form when the faults it crosses were active.

One approach is to assume that the river incision rate is equal to the regional uplift rate. However, uplift rates are not well constrained for the northern Santa Lucia Range. In their seismotectonic studies for the nearby Carmel River Dam project, William Cotton and Associates (1995) used incision rates for a similar geomorphic and geologic setting to estimate the ages of fluvial terraces in upper Carmel Valley. Their reasoning was that "very well constrained incision rates of 0.5 to 0.2 mm/yr have been estimated in the Feather River drainage of the northern Sierra Nevada, where bedrock materials and the fluvial stage are similar to the project area (Wakabayashi and others, 1994)."

Following this line of reasoning, we measured the distance from ridgetop to thalweg for eight coastal stream canyons from Malpaso Creek southward to Bixby Creek to obtain the amount of incision, which was approximately 1,020 feet. Using the incision rates of 0.5 and 0.2 mm/yr gives an average time of 1,092,000 years to downcut to the present stream level. Considering the youthful, rugged topography and the changes in stream gradient and sinuosity, the downcutting time estimate of 1,100,000 years seems more reasonable that the 3,000,000 year posited by Hamilton (1984) and Tuttle (1985). Likewise, the uplift rate of 1.4 mm/yr for the Coast Ranges postulated by Page and others (1998), yields a downcutting time of approximate 227,000 years, which seems too young for this part of the Coast Ranges.

We also were able to use offset of a buttress unconformity to estimate a slip rate for the Garrapata fault (figure 3). Interestingly, if the youngest colluvium is part of this offset, this yields a slip rate of approximately 3.5 mm/yr; similar to the 3.0 mm/yr indicated by offset stream channels. These data are summarized in table 3.

Table 3. Horizontal Quaternary slip rates, Big Sur region

Fault	Feature offset	Estimated age of unit (years)	Amount of offset	Displacement rate (mm/yr)	Source of offset data
Garrapata fault	stream channel	1,100,000	3.3 km	3.00	this study
Garrapata fault	stream channel	3,200,000	3.28 km	1.03	Tuttle (1985)
Garrapata fault	stream channel	3,000,000	2.7 km	0.90	Hamilton (1984)
Garrapata fault	stream channel	3,000,000	2.7 km	0.90	Hamilton (1984)
Garrapata fault	colluvium	1,200±60–9,750±60	4 m	3.51–0.41	Weber (written commun., 1998)
Garrapata fault	shoreline angle	105,000–125,000	122 m	1.16–0.98	Weber (written commun., 1998)
Garrapata fault	shoreline angle	120,000	121 m	1.01	Tuttle (1985)
Palo Colorado fault	shoreline angle	120,000	162 m	1.35	Tuttle (1985)
Rocky Creek fault	shoreline angle	120,000	50 m	0.42	Tuttle (1985)
Rocky Creek fault	Bixby Creek	1,100,000	1.4 km	1.27	Tuttle (1985), this study

CONCLUSIONS

The southern San Gregorio fault is a Holocene active fault zone that extends from Monterey Bay southward to the Big Sur area. Part of the fault zone forms an onshore shear zone of en echelon faults (the Garrapata/Palo Colorado and the Rocky Creek) that displace stream channels and marine terraces and are associated with the 1984 M_L 4.9 Big Sur earthquake. The other part of the southern San Gregorio fault continues southward toward San Simeon via the Serra Hill fault and the Sur fault zone.

Preliminary calculations of slip rates suggest that most displacement is horizontal with an estimated rate of 3 mm/yr on the Garrapata/Palo Colorado fault and an estimated rate of 1.3 mm/yr on the Rocky Creek fault. The average vertical component of slip ranges from 0.03 mm/yr (Garrapata/Palo Colorado fault) to 0.22 mm/yr (Rocky Creek fault). Vertical uplift is ongoing and affects stream sinuosity and gradient on coastal streams between these two fault zones.

Because the Garrapata fault offsets Holocene dated colluvium and the Rocky Creek fault appears to be the locus of the 1984 M_L 4.9 Big Sur earthquake, these faults could produce large earthquakes. Additional work to resolve the slip rates and dates of most recent earthquakes on these faults would help in recognizing the seismic risk to the Monterey Bay region.

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APPENDICES