Late Quaternary Deformation in the Western Transverse Ranges, California

By R. F. Yerkes and W. H. K. Lee

EARTHQUAKE ACTIVITY AND QUATERNARY DEFORMATION OF THE WESTERN TRANSVERSE RANGES, CALIFORNIA

GEOLOGICAL SURVEY CIRCULAR 799-B

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INTRODUCTION

The Transverse Ranges are a dominant geomorphic-structural province of southern California. Relative to adjoining terrain, they are distinctive not only in their east-west trend, but in the type, age, and history of their exposed basement rocks; in the spectacular rates of deformation as indicated by the imposing fault-controlled mountain fronts and extremely deep basins filled with young, intensely deformed deposits; and, perhaps most of all, in their long resistance to successful palinspastic restoration in the tectonic history of southern California. A new and significant phase in interpreting southern California geology was introduced by analyses of the 1971 San Fernando earthquake (Wesson and others, 1971; Whitcomb, 1971; Whitcomb and others, 1973), which verified not only the structural dominance but also the activity of the several north-dipping reverse faults that characterize the Transverse Ranges west of the San Andreas fault and bound them on the south.

We report on the seismicity, focal mechanisms, and related aspects of geology as based on seismic data recorded during 1970-75 in a large part of the western Transverse Ranges. The area covered by the present study is shown in figure 1; it includes most of the Transverse Ranges west of the San Gabriel fault and spans the Santa Ynez and Anacapa-Santa Monica faults, which form the northern and southern boundaries of the province. Also shown in figure 1 are the epicenters of located historic earthquakes of magnitude 6 or greater, all of which were associated with recognized faults. Of these larger earthquakes, the five in the western Transverse Ranges, especially the 1971 San Fernando and 1973 Point Mugu, are associated with east-trending north-dipping reverse faults. Fault-plane solutions for the San Fernando and Point Mugu earthquakes verify these associations and indicate north- to northeast-trending subhorizontal P axes (Wesson and others, 1971; Whitcomb, 1971; Ellsworth and others, 1973).

SEISMICITY

MAP DISTRIBUTION

The epicenters of 630 earthquakes that took place in the six-year period 1970 through 1975 are plotted on plate 1[1], as are the surface traces of mapped faults. Location quality of epicenters, derivation of local magnitude, and associated data for the earthquakes are given in Chapter A of this report.

Ninety-seven percent of the epicenters are located south of the Santa Ynez fault; none are obviously associated with the fault. The few events north of the fault were not recorded well enough for fault-plane solutions, and none are obviously associated with mapped faults. The same is true for events northeast of the San Gabriel fault. No attempt was made to relocate earthquakes of the San Fernando sequence, as it was extensively studied by Whitcomb, Allen, Garmany, and Hileman (1973).

Many of the events south of the Santa Ynez fault can be associated geometrically with specific faults on the basis of focal mechanisms and hypocentral depths (table 1). The best associations are made for the Red Mountain, Pitas Point-Ventura, Mid-Channel, and Anacapa faults. Stratigraphic and geomorphic evidence indicates that all the faults listed have ruptured the ground surface during late Quaternary time (pl. 1, Ziony and others, 1974). The Red Mountain and Pitas Point-Ventura faults have probably ruptured in Holocene time.

The quality of the associations between earthquakes and specific faults is illustrated by two examples. A vertical section (figs. 4 and 5 of Chap. A) shows that projected hypocenters of the 1973 Point Mugu earthquake sequence and the projected trace of the Anacapa fault coincide. Also, the subsurface trace of the Red Mountain fault, located independently on the basis of well data (R.S. Yeats, written commun., 1978), matches the distribution of hypocenters. These and other examples support our procedure (table 1) of deriving fault dips on the basis of geometrical associations between surface traces, hypocentral depths, and focal mechanisms.

DEPTH

Within the western Transverse Ranges, the deepest hypocenters are 19 km for an event in the north-central part of Santa Barbara Channel and 17 km for an event in the Oxnard Plain; in

[1] Plates published separately as U.S. Geological Survey Miscellaneous Field Studies Map MF-1032.

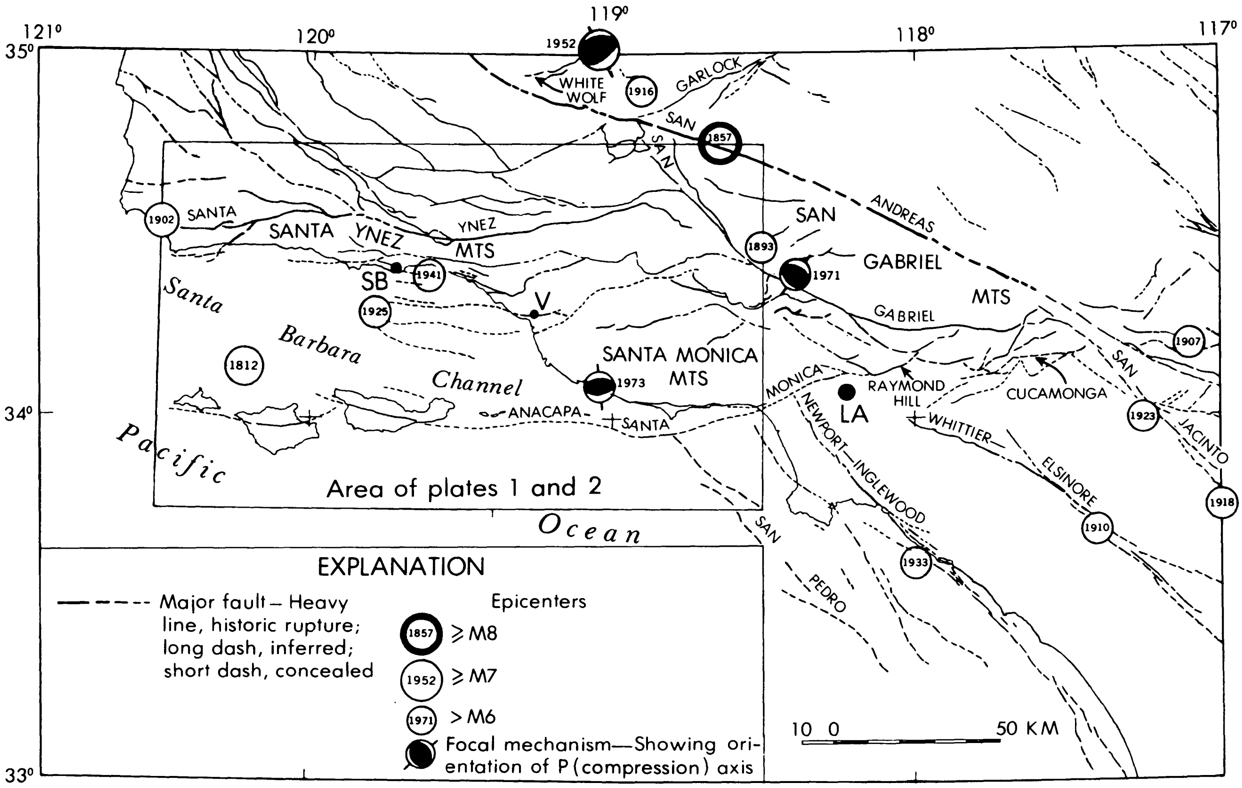

Figure 1.—Part of southern California showing area investigated, and relations of western Transverse Ranges (bounded by Santa Ynez, San Gabriel, and Anacapa-Santa Monica faults) to major faults and epicenters of large earthquakes. SB, Santa Barbara; V, Ventura; LA, Los Angeles. Modified from Jennings and others (1973).

addition, aftershocks of the 1973 Point Mugu sequence were as deep as 19 km. However, the depths of earthquakes in the band of seismicity that extends from the central and northern Santa Barbara Channel to the east center of the map area generally range from 13 to 16 km. The hypocenters do not delineate any east-west or north-south plunge.

The type and distribution of basement rocks that underlie the Upper Cretaceous and Cenozoic sedimentary rock sequence of the western Transverse Ranges between the Santa Monica and Santa Ynez Mountains are completely unknown. Regional-scale maps showing inferred structure contours on the "basement" rock surface for this area have been published (Curran and others, 1971, fig. 5; Nagle and Parker, 1971, fig. 13). Comparison of the contours shown on these maps with the focal depths of recorded earthquakes suggests that the seismicity is generated within the basement rock sequence or near its surface, but no strong correlations in trend or plunge are apparent.

FAULT-PLANE SOLUTIONS

Quality.—A set of 50 fault-plane solutions for earthquakes of local magnitude 2 or larger was selected from a total of about 200 on the basis of quality of location and solution. For most of the events tabulated, location and solution quality are "C" or better; the location is known to 5 km or less and the orientation of the nodal planes is known to ± 11° or less. First-motion data for events cited in table 1 are plotted in figure 7 and listed in table 4 of Chapter A of this report. Many of the events can be associated geometrically with mapped faults; the distribution of the fault-plane solutions relative to mapped faults is shown in plate 2. All of the solutions along and north of the Anacapa-Santa Monica fault indicate reverse displacement and can be associated geometrically with reverse faults that show geologic evidence of late Quaternary displacement at the ground surface, especially the Red Mountain fault, the Pitas Point-Ventura fault (which traverses the city of Ventura), the Mid-Channel fault zone, and the Anacapa fault.

Some northwest-trending faults south of the Anacapa-Santa Monica fault are associated with fault-plane solutions: two solutions along or near the San Pedro Escarpment indicate right-lateral movement, whereas the 1973 Anacapa earthquake near Anacapa Island (event 357, pl. 2) is best associated geometrically with northeast-dipping reverse movement, perhaps on one of the faults mapped along the southwest flank of Santa Cruz-Catalina Ridge.

P axes.— The orientations of P axes are inferred to be equivalent to the direction of

Table 1.—*Fault-plane solutions geometrically associated with specific faults*

Fault	Category[1]	Event number[2]	Depth (km)	Apparent dip
Red Mountain[3]	H	158, 396, 397, 505	5½-11	63° N.
Pitas Point	H, L	8?, 100, 162?, 365, 388, 391, 618, SB78?	12-14	60° N.
Ventura	H	40	4-8	60° N.
San Cayetano	Q, L	576?	8-16?	60-70° N.
Mid-Channel	Q	41, 51, 90, 449, 482, 558	8-14	65° N.
Oak Ridge	L	129	11	61° S.
Santa Susana	L	428	5?-11	65° N.
San Pedro	P	555, 625	5-11	~90°
Anacapa	P	197 + 30 aftershocks	8-16	44° N.
East Santa Cruz basin	Q, P	357?	13-15	38° N.

[1] Letter indicates geologic time span of latest known surface movement; H, Holocene; L, late Pleistocene; Q, early Pleistocene; P, late Pliocene.

[2] Events are listed in table 4 (chap. A) and plotted on plate 2. SB78 is the Santa Barbara earthquake of August 13, 1978.

[3] Subsurface location verified by well data.

maximum compressive stress for the analyzed events (fig. 2). Most (82 percent) are within 15° of horizontal and 60 percent are within 10°. The two maxima, at due north and N. 50° E., bracket the approximate normal to the San Andreas fault (at N. 24° E.) as well as the P axis for the 1971 San Fernando earthquake.

Slip vectors.—The distribution, orientation, and classification of slip vectors are plotted in figure 3. A dominant maximum shows a plunge of about 55° NE., indicating reverse-left-oblique displacement. Subsidiary maxima at 45° N. and 45° E. indicate north-over-south reverse displacement and left-lateral strike slip, respectively. The shaded field defined by these maxima contains 70 percent of the points. This field is dominated by reverse-left-oblique slip, which characterized the 1971 San Fernando earthquake, and north-over-south reverse slip, which characterized the 1973 Point Mugu earthquake. As indicated on figure 3 by slip vectors for the 1971 San Fernando (SF) and 1973 Point Mugu (PM) earthquakes, the displacements for the smaller earthquakes in the western Transverse Ranges are fully representative of the larger events with known displacements.

Summary.—Fault-plane solutions for events in the western Transverse Ranges can be associated with segments of several east-trending north-dipping reverse faults, especially the Red Mountain, Pitas Point-Ventura, Mid-Channel, and Anacapa faults. Geologic evidence indicates that these segments have ruptured the ground surface during late Quaternary time. The solu-

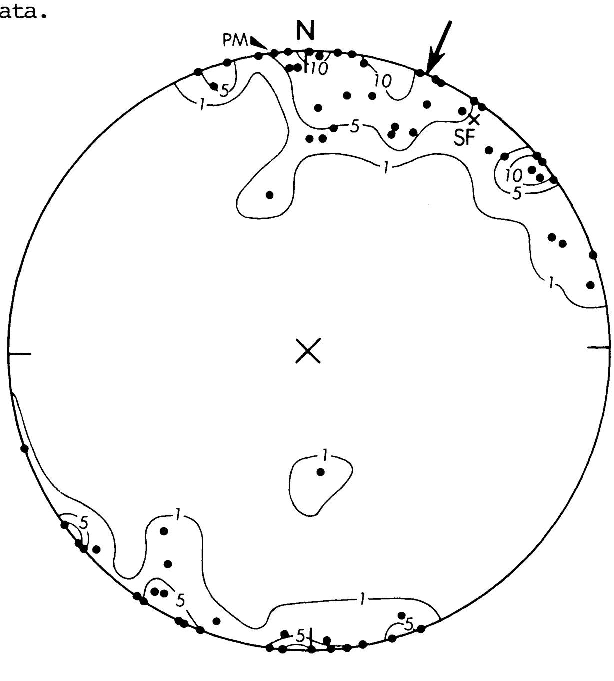

Figure 2.—Stereoplot showing distribution and orientation of P axes for 51 events, 1970-75, excluding aftershocks of 1973 Point Mugu sequence. PM, Point Mugu main shock; SF, 1971 San Fernando main shock (not contoured). Contours, 1 percent, 5 percent, and 10 percent per 1 percent area; lower hemisphere projection. Arrow at N. 24° E. normal to San Andreas fault. See table 4, chapter A for data.

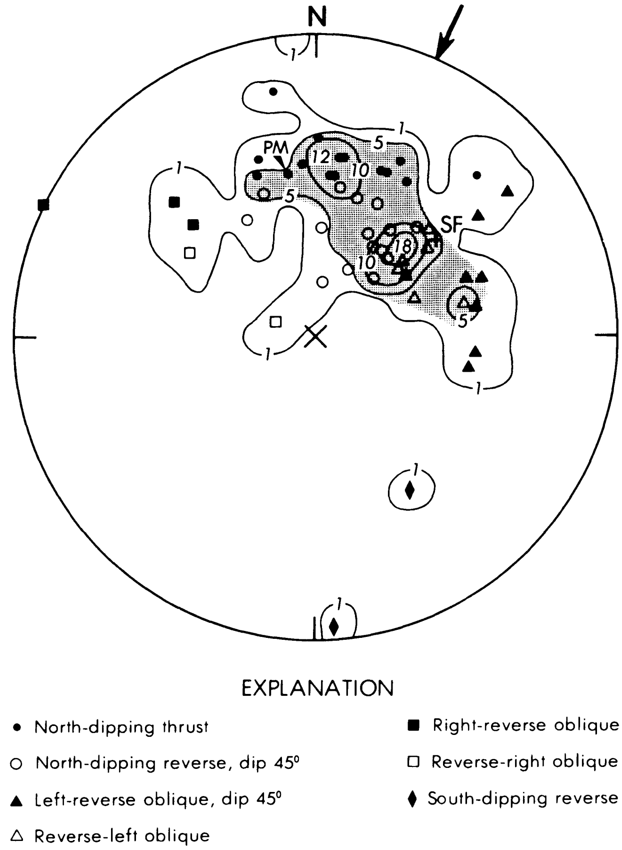

Figure 3.—Stereoplot showing distribution, orientation, and classification of slip vectors for 51 events, 1970 through 1975, excluding aftershocks of 1973 Point Mugu sequence. PM, Point Mugu main shock; SF, 1971 San Fernando main shock (not contoured). Contours 1 percent, 5 percent, 10 percent, and 15 percent per 1 percent area; lower hemisphere projection. Shaded area contains 70 percent of the points. Arrow at N. 24° E. marks approximate normal to San Andreas fault.

tions indicate near-horizontal P axes oriented generally within 30° of normal to the great bend of the San Andreas fault. The dominant type of displacement indicated by slip vectors varies between north-over-south reverse and reverse-left-oblique. These characteristics pertain to the entire range of magnitudes recorded within the network area, as well as to larger earthquakes such as the 1971 San Fernando and 1973 Point Mugu events.

EFFECTS OF DEFORMATION

In addition to the prominent topographic and geologic effects of the numerous east-trending folds and faults, well illustrated on the geologic map of southern Ventura County (Weber and others, 1974), unusually high rates of deformation across east-trending reverse faults of the western Transverse Ranges are evidenced by geodetic leveling, uplift of dated marine terrace deposits, and stratigraphic separation of dated strata.

GEODETIC EVIDENCE

Comparison of repeated level lines along the coast from the Ventura River to the Santa Barbara-Ventura County line and northward along the river has confirmed a minimum average tilt up to the north of nearly 13 microradians over the period 1920-68 across the Red Mountain-Pitas Point-Ventura set of faults (Buchanan-Banks and others, 1975); the relative uplift rate is about 5 m per thousand years.

Similarly, comparison of 1960 and 1968 level surveys shows that the upper (northern) plate of the west-trending Anacapa ("Santa Monica") reverse fault rose by 30-40 mm at least as far west as Point Mugu, consistent with continued thrusting along this frontal system of the Transverse Ranges (Castle and others, 1978). Additional warping between 1968 and 1971 perhaps indicates left-lateral reverse creep at depth, and 1971-73 (post-1973 earthquake) data indicate additional upper-plate uplift of more than 30 mm.

Regional maps of elevation changes in the western Transverse Ranges east of long 119°15' (Ventura) based on comparisons of 1960/61-1968/69 and 1968/69-1971 (post San Fernando earthquake) levelings show strong gradient changes associated with the Oak Ridge, Santa Rosa, Santa Susana-San Fernando-Sierra Madre, and Malibu Coast (Anacapa?) faults (Castle and others, 1975, figs. 2 and 5). Of these, only the Santa Rosa fault was not associated with recorded seismicity during the 1970-75 interval. The data coverage does not include the San Cayetano fault, but it does show that no prominent gradient changes were associated with the Santa Monica and Raymond Hill faults east of the shoreline.

DEFORMED MARINE TERRACES

At least three deformed marine terraces are exposed along the Santa Barbara-Ventura coast at elevations ranging from 2 to at least 226 m (table 2). The ages of mollusks from deposits on the terraces have been estimated by amino-acid stereochemistry at 2,500, 45,000, and 80,000 years (J. F. Wehmiller, written commun., 1978). The 45,000-yr terrace is exposed at elevations of 26 m or less along the seacliff for about 70 km west of long 119° near Carpinteria, where the Red Mountain and associated faults intersect the shoreline (pl. 1). East of that point all the terraces, including the 2,500-yr terrace, are tilted up to the north and east (fig. 4). Apparent average rates of uplift in this area for the last 45,000 years exceed 3 m per thousand years as referred to present sea level, including the rate for the 2,500-yr terrace. Rates of 5 to 6 m per thousand years are indicated, again for the youngest terrace, if present-day elevations are referred to pre-existing sea levels. Even greater rates, up to 9 m per thousand years,

Table 2.—*Elevations and estimated ages of collections from uplifted marine terraces*

Number in fig. 4	Collection number[1]	Name	Elevation (m) Locality	Shoreline angle[2]	Shoreline At T_o[3]	Estimated age[4] (10^3 yrs)	Uplift rate ($m/10^3$ yr) Max.	Min.
1	M5790	Goleta	5	∿15	-55	45	1.6	0.3
2	Y440B	Carpinteria	26	∿40	-55	(45)	2.1	.9
3	Y440A	Rincon Point	50	N.a.	-55	(45)	2.3	1.1
4	M7245	Punta	146	N.a.	-55	45	4.5	3.2
5	M7229	Punta Gorda	125	N.a.	-55	45	4.0	2.8
6	M7230	Rincon oil field	215	N.a.	-55	45	6.0	4.8
7	M7249	Rincon oil field	216	N.a.	-55	(45)	6.0	5.0
7a	M7283	Rincon oil field	262	N.a.	-55	45	7.0	5.8
8	M7273[5]	Rincon oil field	354	N.a.	-55	(45)	9.1	7.8
9	Y438B	Punta Gorda	2	11	0	(2.5)	5.2	5.2
10	M7228	Culvert 390.06	6	15	0	2.5[6]	6.0	6.0
11	M7242	Ventura	117	120	-13	80±10	1.7	1.5
12	Y413B	Ventura	15	N.a.	-13	80±10	.4	.2

[1] Localities shown on plate 1.

[2] N.a., not available.

[3] T_o, time of formation; from Bloom and others (1974).

[4] Age estimates by sterochemical analysis of mollusks by J. F. Wehmiller, University of Delaware, Newark, Delaware; estimates in parentheses based on map continuity with dated sample.

[5] Float of shells and rounded pebbles.

[6] Radiocarbon analysis.

are suggested by the presence of scattered shells and rounded pebbles at ridge tops up to 354 m high.

DISTRIBUTION OF DEFORMATION

The north-dipping, east-trending Red Mountain fault and associated San Cayetano, Santa Susana, Pitas Point-Ventura, and Mid-Channel faults coincide in general with an east-trending band of seismicity that extends across the north half of the area of plate 1. Detailed surface and subsurface investigations show that very large separations and late Quaternary movements have occurred on the Red Mountain fault, the Pitas Point-Ventura fault, and segments of the San Cayetano and Santa Susana faults.

Red Mountain fault.—Well data from the San Miguelito oilfield area west of the Ventura River show that upper Eocene and lower Miocene strata are thrust over Pliocene and Pleistocene strata by the Red Mountain fault (R. S. Yeats, written commun.). The age of the youngest strata involved in the faulting is not well determined on the basis of the well data. However, the fault truncates a syncline that, east of the Ventura River, involves the San Pedro Formation as used by Weber and others (1973), which has been dated at 0.4 to <0.2 million years B.P. on the basis of radiometric and stereochemical age estimates (fig. 5). On the assumption that the thrust faulting followed the folding, much or all of the 7,500 m of separation on the Red Mountain fault could have occurred during about the last one-half to one million years.

Pitas Point-Ventura fault.—Where crossed by a seismic profile about 2 km offshore in the northeastern part of the Santa Barbara Channel,

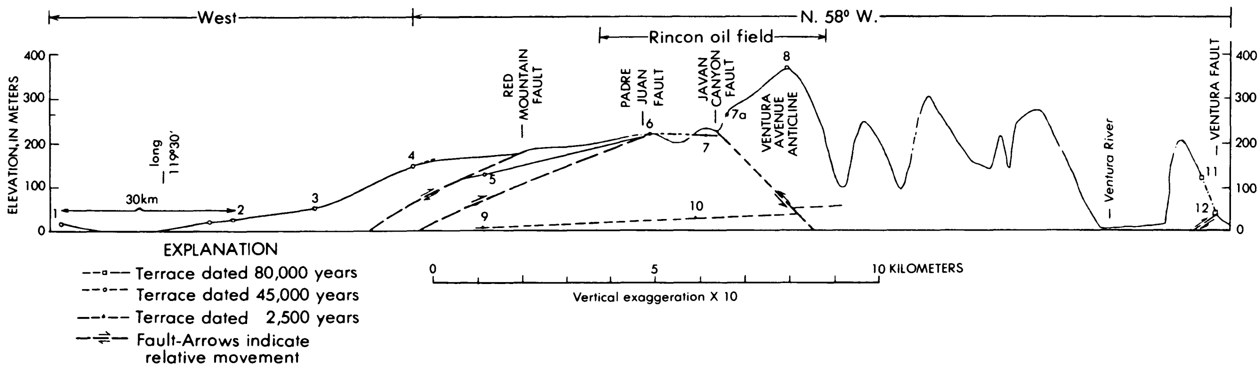

Figure 4.—Section along Santa Barbara-Ventura coast showing deformation of dated marine terraces. Numbered localities keyed to table 2.

the Pitas Point fault appears as a north-dipping reverse fault that displaces a late Pleistocene erosion surface about 25 m up on the north; it appears to cut Holocene strata but not the seafloor (Greene, 1976, p. 508-509; figs. 4, 6).

Extensive data are available for the Ventura fault (Sarna-Wojcicki and others, 1976). The surface trace is marked by a prominent, linear, south-facing scarp as much as 12 m high and about 10 km long; it is bounded on the north by an uplifted bench. Except where locally buried by young surficial deposits, the escarpment forms the boundary between old alluvial fan deposits, deformed marine terrace deposits, or deformed bedrock, all overlain by old soils on the north and young, undeformed surficial deposits overlain by young soils on the south. The gradients of all but the largest streams that cross the escarpment are deflected upward on the north by about 25 m. Test trenches cut in surficial deposits across the escarpment show numerous small soil-filled cracks that commonly are traceable downward into east-trending high-angle faults with separations as large as 40 cm. The southerly dips of strata in the trenches and adjacent boreholes increase downward south of the escarpment. The youngest strata cut by the fault are apparently Holocene.

No direct evidence is available as to the amount of displacement across the Ventura fault. A north-south structure section about 4 km east of the Ventura River shows apparent vertical separation of about 245 m, up on the north, at the base of lower Pleistocene strata (Ogle and Hacker, 1969), although that interpretation is based on permissive evidence. A similar structure section another 5 km to the east, based on more closely spaced and abundant data, shows an apparent vertical separation of as much as 275 m at the base of upper Pleistocene strata. An unknown component of left-lateral slip is indicated locally by small folds having near-vertical axes in bedrock just north of the fault, and by the fault-plane solution of an associated earthquake (no. 40, table 4 of Chap. A).

San Cayetano fault.—Apparent stratigraphic separation across segments of the San Cayetano fault diminishes eastward from a maximum of 7,300-9,000 m (vertical, up on the north) at Sespe Creek (6 km east of long 119°) (Fine, 1954; Cemen, 1977), where low scarps in late Quaternary stream terrace deposits coincide with the fault trace. Ten kilometers east of Fillmore, late Quaternary alluvium north of the Santa Clara River is warped along the buried inferred trace of the fault (Cemen, 1977). Youthful geomorphic features and upthrust Quaternary gravel beds at several localities along its trace suggest at least late Quaternary activity at the surface.

Santa Susana fault.—The apparent stratigraphic separation across faults of the Santa Susana set is at least 4,000 m, which includes about 2,000 m vertical offset (up on the north) and 3,200 m left-lateral strike slip (Yeats and others, 1977). The hanging wall locally is expressed topographically; the fault locally cuts late Pleistocene fan deposits, and northeast-trending elements along the west margin of San Fernando Valley ruptured during the 1971 San Fernando earthquake.

Mid-Channel fault zone.—Published data on faults of the Mid-Channel zone are sparse. A report by Campbell and others (1975) includes an interpretive section (B-B') through the area of most intense seismic activity near long 119°45' W., lat 34°15' N. The section shows a fault-bounded gentle anticline ("12-mile reef") that coincides with the Mid-Channel zone. A medial fault cuts upward to the seafloor, but the south-bounding fault is truncated by the Holocene part of the undivided Quaternary deposits (unit Q) and the north-bounding fault cuts upward about halfway through the lower Pleistocene part of the lower Pleistocene and upper Pliocene strata (unit Qpl). A vertical separation of about 50 m, up on the north, at the base of the upper Pliocene marine strata (unit Tpu) is shown for the north-bounding fault; a separation of similar amount, down on the north, is shown for the south-bounding fault. No vertical separation is shown on the medial fault.

A possible correlative of the north boundary fault of the zone (the isolated segment at long 119°30' W., lat 34°11' N.) is illustrated in a seismic profile and interpretive section by

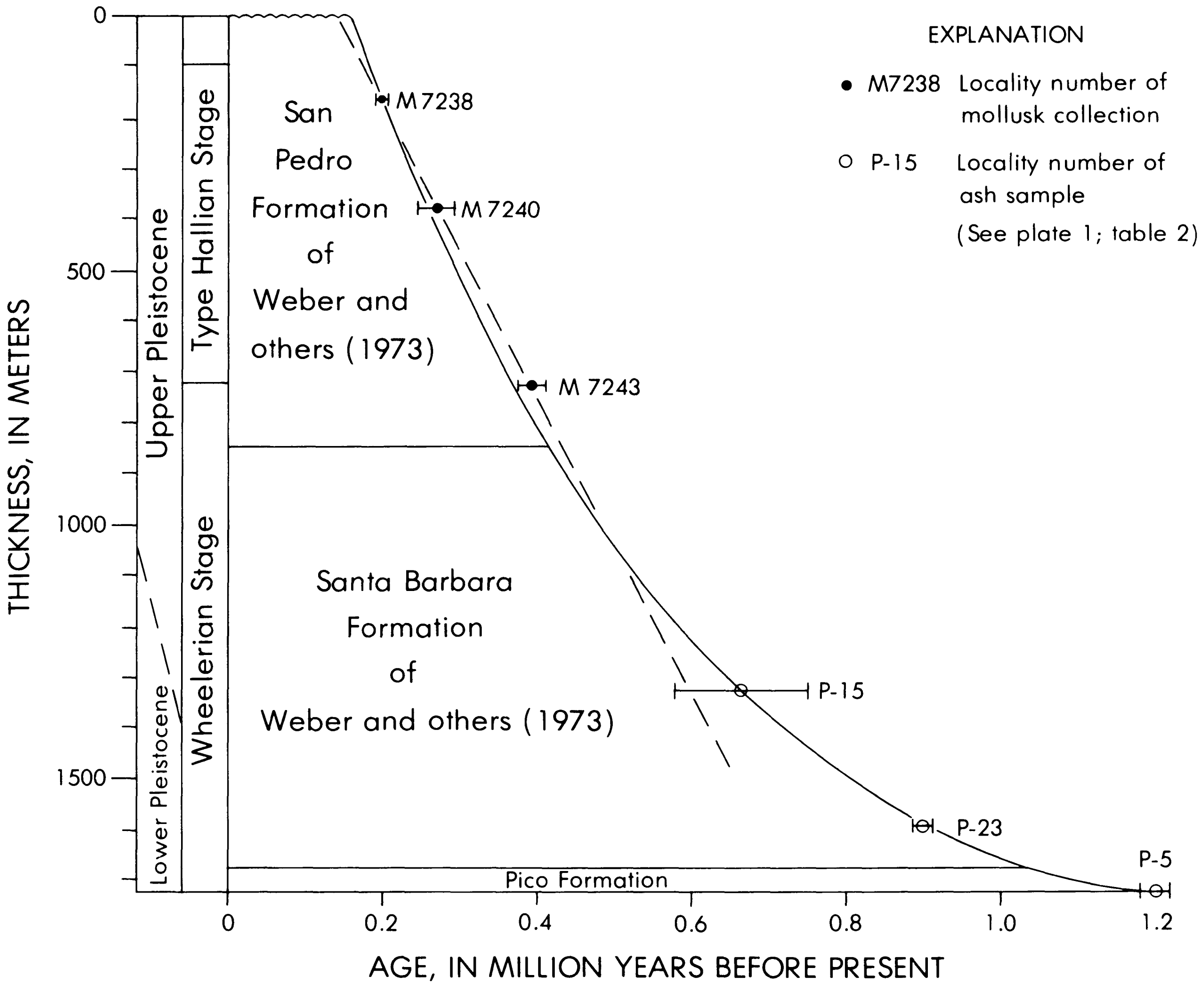

Figure 5.—Age estimates of mollusk collections and ash samples from Pleistocene strata in Hall Canyon area, near Ventura, and their stratigraphic and microfaunal stage correlations. Stratigraphic boundaries of Hallian Stage from Natland (1952, pl. 7). Age estimates on mollusks by J. F. Wehmiller; age estimates on ashes based on analyses and correlations by A. M. Sarna-Wojcicki.

Greene (1976), fig. 8, "Santa Barbara slope" fault). The section indicates about 120 m of vertical separation, up on the north, and the profile suggests that the fault cuts through lower Pleistocene deposits (unit Qs) to the seafloor. These interpretations, coupled with the geometric associations of the focal mechanisms, indicate that the Mid-Channel zone is seismically active, but whether one fault or more is active cannot be determined. The fault-plane solutions associated with the Mid-Channel zone occur in the general area where the Oak Ridge fault, which onshore is known to dip south and to parallel the south flank of the Ventura basin syncline, intersects the Mid-Channel zone. The dip of the mid-channel faults is thus not easily evaluated, and their association with the fault-plane solutions is weak.

Oak Ridge fault.—The Oak Ridge is a gently to steeply south-dipping reverse fault, the surface trace of which generally follows the south bank of the Santa Clara River. At South Mountain, just west of long 119°, the fault thrusts lower Miocene and upper Eocene strata over late Pleistocene strata, for an apparent stratigraphic separation of at least 2,000 m (Baddley, 1954). Near Saticoy, displacement in late Quaternary sediments has caused a ground-water barrier. Offshore data from seismic profiles between long 119°15' and 119°30' indicate that Pleistocene strata are upthrown on the south more than 135 m; no surface displacement at the seafloor is known (Greene, 1976). Available data indicate that displacement is dominantly reverse (see fig. 7, Chap. A, and pl. 2, event 129).

Anacapa-Santa Monica fault.—The Anacapa and Santa Monica faults are major elements of an east-trending zone of deformation that marks the southern front of the Transverse Ranges along the south flank of the Santa Monica and San Gabriel

Mountains. Other elements of the zone include the Raymond Hill and Cucamonga faults; the zone extends east onshore for about 100 km, and all faults are north-dipping reverse faults. East of its intersection with the shoreline at Santa Monica, two or more subparallel elements of the zone are recognized. One, generally called Santa Monica, is alined with a north-dipping reverse fault at the mouth of Potrero Canyon that cuts upper Pleistocene terrace deposits; to the east it is associated with topographic scarps in upper Pleistocene terrace deposits. Other elements locally are associated with a ground-water barrier in Pleistocene deposits; in the Santa Monica area, a topographic scarp in upper Pleistocene deposits is alined with the barrier (Hill and others, 1977).

The apparent stratigraphic separation across these faults is variable from west to east, according to well data. Northward dips of 40° to 70° and apparent reverse separations of 1,770 to 2,133 m at the top of middle Miocene strata are reported for the Sawtelle oil field-Beverly Hills oil field area (Knapp and others, 1962; Eschner and Scribner, 1972; Lang and Dressen, 1975) 8-15 km east of the shoreline at Santa Monica. Separations at the surface of the buried basement complex are poorly known, but a published structural contour map based on a density-residual gravity model shows vertical separations in the range of 2,400-3,660 m (McCulloh, 1960, fig. 150.1). However, vertical separations at basement may be a relatively small component of displacement across the zone, which is inferred to include a large component of left-lateral strike slip (Campbell and Yerkes, 1976), in part to account for juxtaposition of dissimilar basement rocks and pre-upper Miocene sequences west of the Newport-Inglewood zone. West of the shoreline, the fault zone includes a northern branch, the Malibu Coast fault, and a southern, offshore branch, the Anacapa fault (pl. 1). The Anacapa fault is the southern boundary of Transverse Ranges physiography, as defined by the east-trending structures of Point Dume (Junger and Wagner, 1977, fig. 4), whereas the Malibu Coast fault is a recognized boundary between wholly dissimilar rock sequences (Campbell and others, 1966).

The total vertical separation across the Anacapa fault is unknown. Up-to-the-north separations of 1,000 to 2,000 m are indicated by structure contours on the Miocene-Pliocene unconformity, and 200 to 600 m on lower Pliocene strata, in the area south and southwest of Point Dume (Junger and Wagner, 1977, fig. 7, profiles C-C', D-D'). The seismic profiles indicate that Quaternary sediments in that area are not cut by the fault.

The Malibu Coast fault dips north at 30°-70° and all evidence indicates reverse dip slip; it marks the zone of deformation along which the Santa Monica Mountains block overrides the low-lying terrain to the south. Stratigraphic separation across the zone is indeterminate, since it juxtaposes unlike rock sequences along its entire length. Topographic relief across the

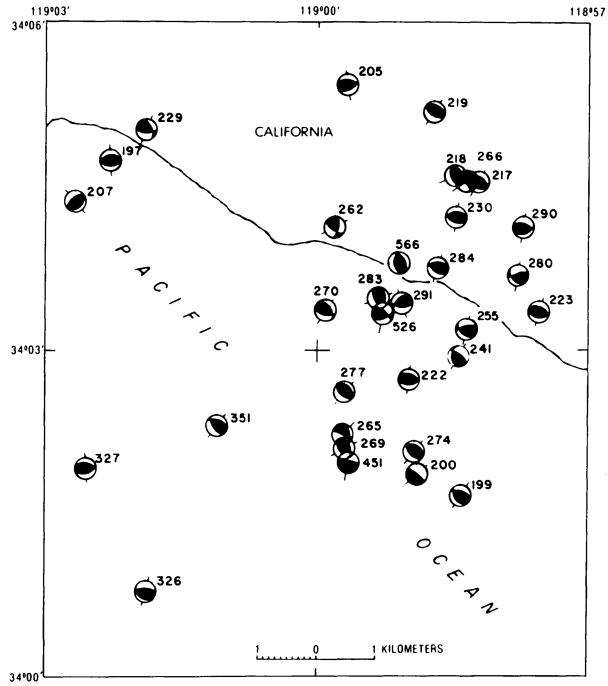

Figure 6.—Focal mechanisms for 1973 Point Mugu earthquake (No. 197) and aftershocks. Numbers indicate sequence of events (see table 2, Chap. A). Compressional quadrants dark, dilatational quadrants light; lower focal hemisphere. Bar shows orientation of P axis. Diagrams located at epicenter of event. Location and area of map shown on plate 2.

zone is at least 850 m, but very large left-lateral strike slip (60-90 km) in late middle Miocene time has been inferred on regional grounds (Campbell and Yerkes, 1976). Elements of the fault have thrust late Pleistocene (about 105,000 years old) marine terrace deposits more than 15 m over upper Miocene strata at one locality near Malibu Canyon, and deposits of similar age are cut by faults in the zone at several other localities along its length.

The fault-plane solution for the 1973 Point Mugu earthquake is well constrained and indicates reverse displacement; one of the nodal planes dips about 44° north and is geometrically and geologically compatible with the Anacapa fault (Ellsworth and others, 1973; Stierman and Ellsworth, 1976; figs. 4 and 5 in Chap. A of this report).

Although the somewhat diverse focal mechanisms and spatial distribution of the aftershocks do not correlate well with the nodal plane of the main shock (fig. 6; Stierman and Ellsworth, 1976), they do indicate dominantly reverse faulting on chiefly north-dipping faults in response to northeast-southwest compressive stress, as do other earthquakes along the zone.

A composite fault-plane solution based on five events along but just south of the trend of the Santa Monica fault, near the east end of the

Santa Monica Mountains about 25 km east of the map area, indicates a steeply north-dipping fault with predominant reverse displacement, a moderate component of left-lateral strike slip, a slip vector plunging about 55° N. 66° E., and a P axis plunging about 28° N. 18° E. (Hill and others, 1977, pl. 4, fig. 8). This solution is consistent with those reported from this study.

The segment of the Anacapa-Santa Monica fault between long 118°45' W. and 118°20' W. (15 km east of the present map area) was relatively free of recorded seismicity during the 1970-75 period, whereas many events were recorded throughout the area to the south. The latter area is bounded by the northwest-trending San Pedro escarpment and Newport-Inglewood zones, each of which is characterized by dominantly right-lateral strike slip on the basis of geologic or seismologic evidence or both (see for example Hill and others, 1977, pl. 4, fig. 6; Buika and Teng, 1978). Buika and Teng (1978) note the same concentration of seismicity (during 1973-76) along the northwest-trending faults south of the Santa Monica fault system and relatively sparse seismicity in the Santa Monica Mountains to the north. They view this as evidence that the northwest-trending faults are terminated by the Santa Monica fault system and that the Santa Monica Mountains are acting as a passive and coherent structural block. They also conclude that the Santa Monica fault system was the locus of chiefly north-over-south reverse-left-oblique slip as a result of compressive stress oriented northeast-southwest.

Anacapa earthquake.—The 1973 "Anacapa" earthquake and an aftershock (events 357 and 359, pl. 2) have epicenters very close to the Anacapa fault but are best associated geometrically with northwest-trending faults located on the Santa Cruz-Catalina Ridge 7 to 12 km southwest of the epicenters. Some northwest-trending folds and short fault segments have been mapped in that general area, including a northeast-dipping thrust fault, but no satisfactory correlation is known.

1978 Santa Barbara earthquake.—The Santa Barbara earthquake of August 13, 1978 (event SB78, pl. 2), occurred in the same general area as the larger 1925 and 1941 earthquakes; its epicenter perhaps was between those of the earlier events.

The distribution of main-shock and aftershock hypocenters describes a surface striking N. 65°-70° W. and dipping north (Lee and others, 1978, figs. 3 and 5). This surface trends toward the shoreline at Goleta, where the largest accelerations were measured and most extensive damage occurred. The fault-plane solution, distribution of aftershocks, and local geology indicate reverse slip on a fault dipping 30°-60° N. The rupture surface and fault-plane solution are not clearly associated with a recognized fault but may be associated with the Pitas Point or nearby fault (see Chap. A, fig. 2).

SUMMARY AND CONCLUSIONS

Focal mechanisms based on some 200 magnitude 2 to 6 events for the six-year period 1970 through 1975 in the western Transverse Ranges reflect the same stress regime as larger earthquakes in the province for which records are available: near-horizontal pressure axes directed generally normal to the great bend of the San Andreas fault. The inferred compressive stress is expressed chiefly by seismicity and reverse displacement along several major zones of east-trending reverse faults (Red Mountain-San Cayetano, Pitas Point-Ventura, Mid-Channel, and Anacapa-Santa Monica); some left-lateral strike slip also is indicated. This type of deformation is entirely typical of that measured after the 1971 San Fernando earthquake over an area of more than 250 square kilometers:

1. 1.4-m vertical (up on the north) separation across the rupture zone.
2. 1.9-m left-lateral separation.
3. 0.55-m north-south shortening normal to the fault trace.
4. Differential arching and depression of more than 2 m, which accentuated pre-existing landforms.
5. Horizontal deformation on a regional scale that lengthened northwest-trending control lines.

Most significantly, the evidence on rate and sense of deformation is mutually consistent for individual faults: geologic data on age and sense of latest displacement and amount and sense of stratigraphic separation, geodetic data on tilting of coastal areas underlain by faults, uplift of dated marine terrace deposits in coastal areas underlain by faults, and associated focal mechanisms. The indicated average rates of vertical deformation (5-10 m per thousand years) have been constant at least over the last 45,000 years.

The east-trending reverse faults that dominate the structure of the western Transverse Ranges are slip surfaces along which many kilometers of north-south shortening and a lesser amount of east-west extension have occurred in late Quaternary time. At the present rates, all the measured compressive deformation within the western Transverse Ranges could have occurred during the last 0.5 to 1 million years.

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