

# Timing and extent of Neogene tectonic rotation in the western Transverse Ranges, California

J. SCOTT HORNAFIUS\*  
BRUCE P. LUYENDYK  
R. R. TERRES\*  
M. J. KAMERLING\*

*Department of Geological Sciences, University of California, Santa Barbara, California 93106*

## ABSTRACT

Paleomagnetic data collected from lower Miocene rocks throughout the western Transverse Ranges Province have consistently clockwise-deflected magnetic declinations, which suggests that the entire province has experienced clockwise tectonic rotation during Neogene time. Paleomagnetic declinations in lower Miocene rocks increase westward from  $33.5^\circ \pm 11^\circ$  in the San Gabriel block to  $91.7^\circ \pm 7^\circ$  in the western Santa Ynez Range, suggesting a westward increase in the net amount of clockwise tectonic rotation. Paleomagnetic data that constrain the timing of rotation suggest that the entire western Transverse Ranges rotated uniformly  $50^\circ$ – $60^\circ$  clockwise during the middle Miocene. This implies a minimum of 200 km of distributed dextral shear along the California coast and offshore during middle Miocene time. Little tectonic rotation appears to have occurred in the western Transverse Ranges during late Miocene time. Since Miocene time, continued clockwise rotation in the western Santa Ynez Range ( $31.3^\circ$ ), combined with counterclockwise rotation in the San Gabriel block ( $-16^\circ$ ), has oroclinally bent the Transverse Ranges to the west of the San Andreas fault. The Pliocene-Pleistocene clockwise rotation implies an additional 30–60 km of distributed dextral shear across the southern California Coast Ranges during post-Miocene time.

\*Present addresses: (Hornafius) Mobil Oil Corporation, P.O. Box 5444, Denver, Colorado 80217; (Terres) Chevron Overseas Petroleum, P.O. Box 5046, San Ramon, California 94583; (Kamerling) ARCO Oil and Gas Company, P.O. Box 147, Bakersfield, California 93302.

Additional material for this article (a table) may be obtained free of charge by requesting Supplementary Data 86-27 from the GSA Documents Secretary.

Geological Society of America Bulletin, v. 97, p. 1476–1487, 11 figs., 3 tables, December 1986.

## INTRODUCTION

The western Transverse Ranges constitute an east-west-trending structural province that crosscuts the northwest-southeast structural grain of southern California. The province is bounded on the north and south by east-west-trending left-lateral strike-slip faults (Fig. 1). The northwest-trending faults in the southern California Coast Ranges and Peninsular Ranges terminate against these east-west-trending left-slip faults. Geologic relationships suggest that the northwest-trending faults have experienced large-magnitude right-lateral strike-slip displacements during Neogene time. The through-going San Gabriel and San Andreas faults bound the western Transverse Ranges on the east.

Paleomagnetic data collected from the western Transverse Ranges suggest that this cross-cutting structural province has rotated as much as  $100^\circ$  clockwise since early Miocene time (Kamerling and Luyendyk, 1979, 1985; Hornafius, 1985). Luyendyk and others (1980) proposed a geometrical model which describes the kinematics of Neogene tectonic rotation within the western Transverse Ranges. According to their model, Miocene dextral shear between the Pacific and North American plates was accom-

modated by parallel northwest-trending right-slip faults to the north and south of the Transverse Ranges and by clockwise rotation of crustal blocks within the western Transverse Ranges. The extent of the rotated terrain was assumed to be bounded on the north and south by the presently east-west-trending left-slip faults along the northern and southern margins of the province.

In this paper, the published paleomagnetic data from the western Transverse Ranges are summarized. New paleomagnetic data from dolomite beds in the Monterey Formation, which further constrain the timing and extent of tectonic rotation, are also reported. Palinspastic reconstructions of southern California for early, middle, and late Miocene time are then proposed, based on the paleomagnetic data, the simple-shear model of Luyendyk and others (1980), and geologic constraints. The paleomagnetic procedures used to collect the new data from the Monterey Formation, as well as detailed descriptions of the sampling sites, are reported in Hornafius (1984).

## PALEOMAGNETIC DATA

A large paleomagnetic data base is now available from the western Transverse Ranges and


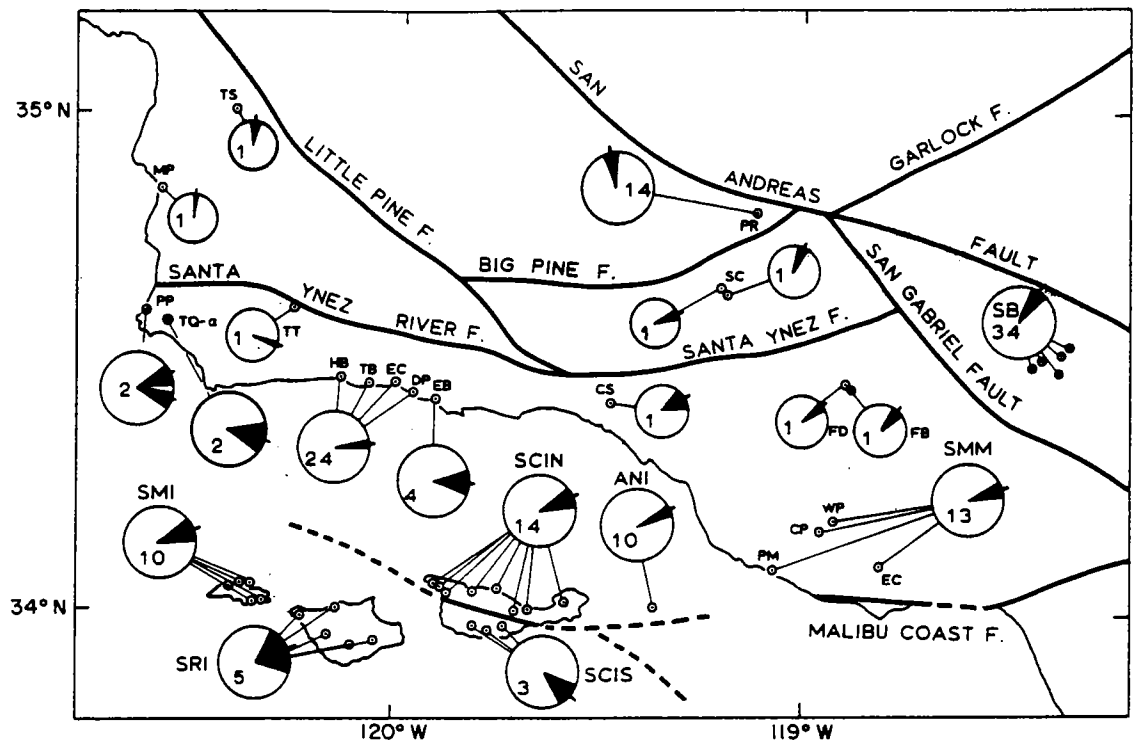


Figure 1. Fault map of southern California. Circular arrows indicate the sense and amount of post-early Miocene tectonic rotation suggested by paleomagnetic data. Straight arrows indicate the amount of displacement between piercing points along major strike-slip faults. References: (A) Ehlig and others, 1975; (B) Matthews, 1976; (C) Sharp, 1967; (D) Lamar, 1961; Sage, 1973; (E) Truex, 1976; (F) Dibblee, 1976; (G) Graham and Dickinson, 1978; (H) Hall, 1975; (I) Davis and Burchfiel, 1973; (J) Stewart and others, 1968; Stewart, 1983. SBI = Santa Barbara Island. SCI = Santa Cruz Island. CAI = Santa Catalina Island. SLI = San Clemente Island. SMI = San Miguel Island. SMM = Santa Monica Mountains. SNI = San Nicolas Island. SRI = Santa Rosa Island. SYR = Santa Ynez Range.



## 14-29 m.y. (EARLY MIOCENE)

Figure 2. Paleomagnetic declinations from early Miocene sampling sites within and around the western Transverse Ranges. Data sources: PR and SB, Terres (1984); SMM and ANI, Kamerling and Luyendyk (1979); SCIN, SCIS, SRI, and SMI, Kamerling and Luyendyk (1985); mean of HB, TB, EC, and DP, Hornafius (1985); all other sites, Hornafius (1984) and Table A. Error calculated from  $\Delta D = \sin^{-1} [\sin \alpha_{95} / \cos I]$ . Demarest (1983) has shown that this value of  $\Delta D$  is approximately the 99% confidence level. Numbers in circles indicate the number of units averaged to obtain the mean.



vicinity. Kamerling (1980) and Kamerling and Luyendyk (1979, 1985) have studied the paleomagnetism of the lower and middle Miocene volcanic rocks in the Santa Monica Mountains and Northern Channel Islands. Terres (1984) and Terres and Luyendyk (1985) conducted a paleomagnetic investigation of volcanic rocks in the Oligocene-Miocene basins in the central Transverse Ranges. Hornafius (1984, 1985) studied the paleomagnetism of the middle and upper Miocene Monterey Formation throughout the western Transverse Ranges and the Santa Maria basin. The following summary is a compilation from these sources. We computed rotations relative to the reference poles of Irving (1979) using the method of Beck (1980), which gives uncertainties at approximately the 99% confidence level (Demarest, 1983).

#### Santa Ynez Range

Paleomagnetic results from the Monterey Formation and the Tranquillon Volcanics in the Santa Ynez Range suggest that  $95^\circ \pm 9^\circ$  of clockwise rotation has occurred within the range (west of Santa Barbara) since early Miocene time (Tables A<sup>1</sup> and 1). Paleomagnetic data from the lower part of the Monterey Formation

along the southern flank of the Santa Ynez Range show a consistent decrease in magnetic declination with decreasing age, from  $92^\circ \pm 7^\circ$  in rocks 15 m.y. old to  $36^\circ \pm 7^\circ$  in rocks 10 m.y. old (Hornafius, 1985). This finding is corroborated by widely scattered sites from throughout the range (Figs. 2-4), which also show a consistent decrease in magnetic declination with decreasing age (Fig. 5). The entire Santa Ynez Range is therefore inferred to have rotated  $56^\circ \pm 10^\circ$  clockwise during the middle Miocene. Paleomagnetic data from the upper part of the Monterey Formation suggest that the Santa Ynez Range rotated  $31.3^\circ \pm 16.8^\circ$  clockwise during the Pliocene-Pleistocene (Table 1). The amount of late Miocene rotation in the Santa Ynez Range is poorly constrained but is probably small ( $4.6^\circ \pm 17.3^\circ$  clockwise).

#### Santa Maria Basin

Paleomagnetic data from dolomite beds in the Lion's Head stratigraphic section of the Monterey Formation (Woodring and Bramlette, 1950) suggest that  $9.4^\circ \pm 27.1^\circ$  of clockwise rotation has occurred in the Santa Maria basin since the early Miocene (Table A). A single site from the Obispo Volcanics (site TS) along the northern margin of the Santa Maria basin also does not show significant clockwise rotation (Table A). The northern boundary of regional tectonic rotation in the Santa Ynez Range is therefore in-

ferred to lie along the southern margin of the Santa Maria basin. Because the northwest-trending splays of the Hosgri fault terminate against the east-west-trending Santa Ynez River fault (Fig. 1, Sylvester and Darrow, 1979), this fault is inferred to be the boundary between the rotated and nonrotated terrain. Highly variable declination anomalies from volcanic plugs and domes that intrude the Franciscan Formation to the north of the Santa Maria basin ( $20^\circ$ - $70^\circ$  clockwise) could be due to local "ball-bearing" rotations within the Franciscan mélangé between the Los Osos and Hosgri faults (Greenhaus and Cox, 1979, Fig. 1) or to a local block rotation between these faults (Luyendyk and others, 1985).

#### Eastern Ventura Basin Area

Sparse paleomagnetic data from dolomite beds in the Monterey Formation and the Rincon Shale between Santa Barbara and the San Gabriel fault suggest that the amount of post-early Miocene rotation experienced by the Santa Ynez Range decreases to  $60^\circ$  near Ventura (site CS) and further decreases to  $40^\circ$  near Fillmore (sites FB and FD; Table A and Fig. 2). A single site from the Modelo Formation to the south of the Oakridge fault is also rotated  $60^\circ$  clockwise (site GC; Fig. 3). Paleomagnetic data from the upper part of the Modelo Formation at Piru Lake suggest that no tectonic rotation has oc-

<sup>1</sup>Table A may be obtained free of charge by requesting Supplementary Data 86-27 from the GSA Documents Secretary.

11-14 m.y. (MIDDLE MIOCENE)

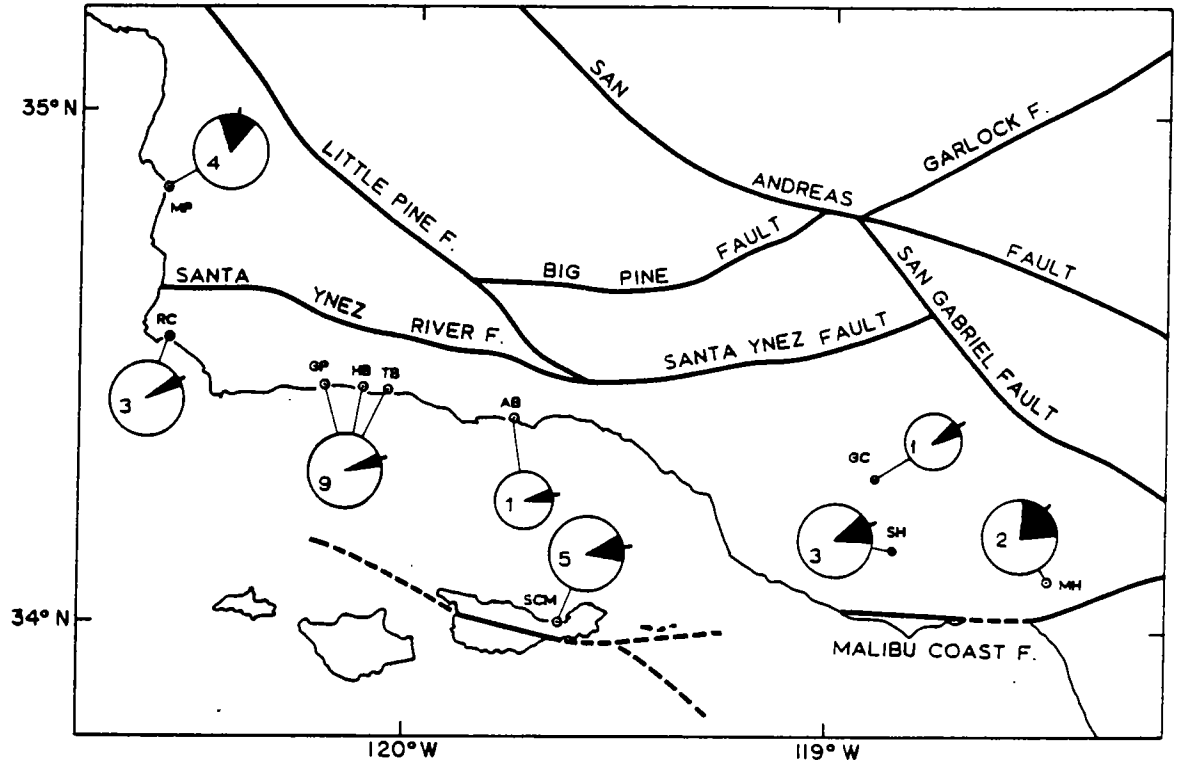


Figure 3. Paleomagnetic declinations from middle Miocene sampling sites within the western Transverse Ranges and the Santa Maria basin (site MP). Data sources: mean of GP, HB, and TB, Hornafius (1985); all other data, Hornafius (1984) and Table A. Symbols as in Figure 2.

5-11 m.y. (LATE MIOCENE)

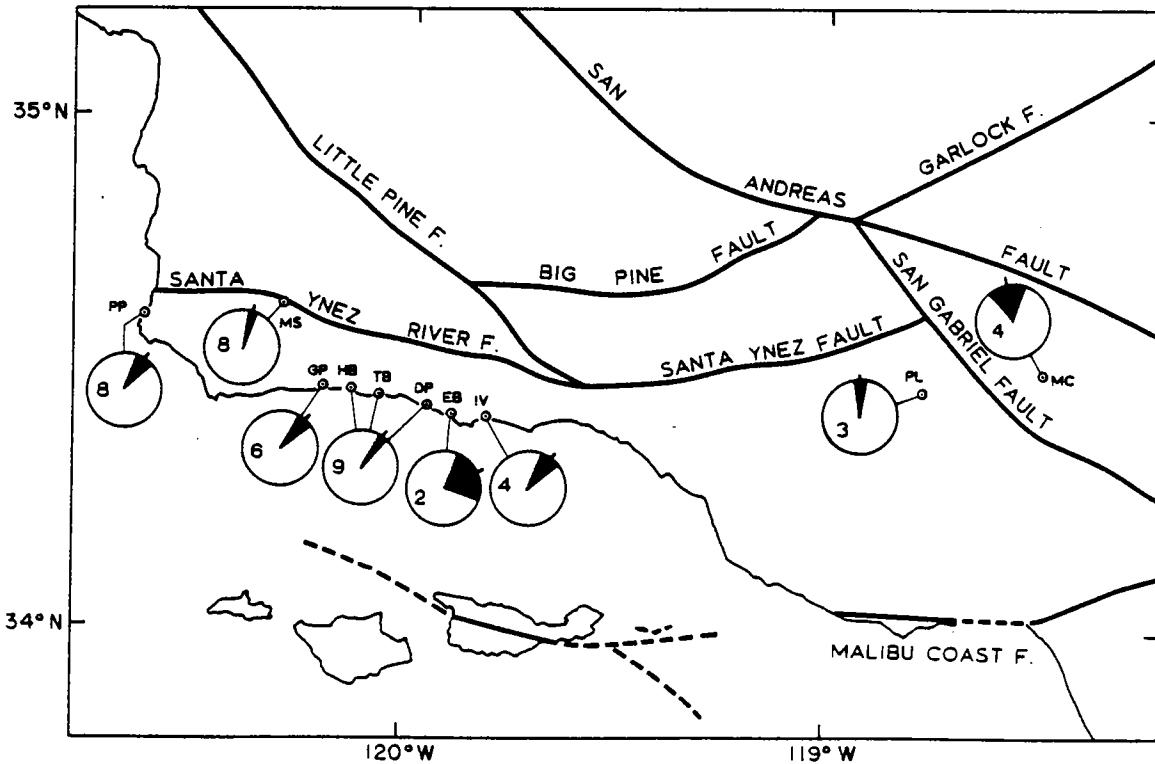


Figure 4. Paleomagnetic declinations from late Miocene sampling sites in the western Transverse Ranges and San Gabriel block (site MC). Data sources: MC, Terres (1984); PP, MS, GP, and IV, Hornafius (1984); mean of HB, TB, and DP, Hornafius (1985); EB and PL, Hornafius (1984) and Table A. Symbols as in Figure 2.

TABLE 1. REGIONAL MEAN PALEOMAGNETIC DIRECTIONS FROM THE WESTERN TRANSVERSE RANGES

Region	Age (m.y.)	No. of units	J	D	$\alpha_{95}$	VGP		$r \pm \Delta r^*$	$f \pm \Delta f^*$	Source
						lat	long			
Western Santa Ynez Range (34.4°N, 120.0°W)	15-16	12	44.8	91.7	4.9	13.3°N	53.2°W	95.2 ± 9.2 <sup>†</sup>	10.0 ± 7.0 <sup>†</sup>	Hornafius, 1985
	8-11	9	47.7	35.9	4.9	59.0°N	29.5°W	35.9 ± 9.5 <sup>‡</sup>	6.2 ± 7.1 <sup>‡</sup>	Hornafius, 1985
	5-8	4	52.4	31.3	9.5	63.8°N	36.2°W	31.3 ± 16.8 <sup>‡</sup>	1.5 ± 10.8 <sup>‡</sup>	Hornafius, 1985
Eastern Ventura basin area (34.4°N, 119.0°W)	11-23	4	49.2	52.3	9.1	46.1°N	38.4°W	55.8 ± 15.3 <sup>†</sup>	5.4 ± 10.4 <sup>†</sup>	Table A
San Gabriel block (34.5°N, 118.4°W)	23-25	7	53.2	33.5	6.7	62.4°N	36.4°W	37.1 ± 12.2 <sup>†</sup>	1.3 ± 7.8 <sup>†</sup>	Terres and Luyendyk, 1985
	10-11	4	39.8	344.3	22.9	71.8°N	114.9°E	-16.0 ± 30.0 <sup>‡</sup>	14.0 ± 23.0 <sup>‡</sup>	Terres and Luyendyk, 1985
Santa Monica Mountains (34.1°N, 118.9°W)	13-16	13	45.0	74.7	6.3	26.5°N	44.3°W	78.2 ± 10.8 <sup>†</sup>	9.3 ± 8.1 <sup>†</sup>	Kamerling and Luyendyk, 1979
Northern Santa Cruz Island volcanics (34.0°N, 119.6°W)	16-19	14	30.3	76.9	12.5	19.7°N	36.6°W	80.3 ± 15.7 <sup>†</sup>	24.0 ± 13.5 <sup>†</sup>	Kamerling and Luyendyk, 1985
Northern Santa Cruz Island Monterey (34.0°N, 119.6°W)	11-14	5	45.3	77.2	13.9	24.6°N	46.4°W	80.7 ± 20.9 <sup>†</sup>	9.0 ± 14.8 <sup>†</sup>	Table A
Northern Channel Islands (34°N, 120°W)	14-32	52	36.1	72.6	5.1	25.2°N	37.6°W	76.1 ± 8.8 <sup>†</sup>	18.2 ± 7.1 <sup>†</sup>	Kamerling and Luyendyk, 1985 (WTR)

\*From the equations of Beck, 1980; uncertainties are approximately the 99% confidence level (Demarest, 1983).

<sup>†</sup>20 Ma reference pole, 87°N, 167°E,  $\alpha_{95} = 5$  (Irving, 1979).

<sup>‡</sup>Referred to spin axis with  $\alpha_{95}$  assumed 5°.

currant at the extreme eastern end of the western Transverse Ranges since the end of late Miocene time (site PL; Table A and Fig. 4). Two units from the Pine Mountain block between the Big Pine and Santa Ynez faults suggest a clockwise rotation of 30° to 70° (SC in Fig. 2; Table A). A 40° to 60° clockwise rotation of the Ventura basin area is therefore inferred to have occurred during middle to late Miocene time (Fig. 6).

### San Gabriel Block

The San Gabriel block is bounded on the southwest by the San Gabriel fault and on the northeast by the San Andreas fault (Fig. 1). Paleomagnetic data from volcanic flows in the Vasquez Formation in the Soledad basin suggest that the central San Gabriel block has experienced a  $ner$  37° ± 12° clockwise rotation since the earliest Miocene (Terres, 1984; Terres and Luyendyk, 1985; SB sites, Fig. 2). Paleomagnetic data from the upper part of the Mint Canyon Formation (10-11 m.y. old) suggest that 16° ± 30° of *counterclockwise* rotation has occurred in the central San Gabriel block since middle Miocene time (Terres, 1984; Terres and

Luyendyk, 1985; MC sites, Fig. 4). A 53° ± 32° clockwise rotation of the San Gabriel block is therefore suggested during early or middle Miocene time (Fig. 7).

Clockwise rotation of the San Gabriel block is assumed to be mostly middle Miocene in age on the basis of geologic relationships. The timing of initiation of clockwise rotation in the San Gabriel block can be constrained by the timing of initiation of displacement on the northern San Andreas fault because clockwise rotation in the San Gabriel block would have occurred simultaneously with right-lateral strike slip on the San Andreas fault in central California (Luyendyk and others, 1980). Wrench folds adjacent to the San Andreas fault in the San Joaquin Valley began to form at the Saucasian-Relizian stage boundary (Harding, 1976), which is estimated to be between 15.3 and 16.7 Ma (Turner, 1970; Howell, 1976). It is therefore inferred that tectonic rotation in the San Gabriel block did not start until approximately 16 Ma (Fig. 7). Clockwise rotation was accompanied by left-lateral strike-slip displacement on the presently east-northeast-trending faults within the central San Gabriel block (Terres, 1984). The east-

northeast-trending faults in the central San Gabriel block cut the lower part of the Mint Canyon Formation (11-14 Ma) but are overlapped by the upper part of the Mint Canyon Formation (10-11 Ma). This observation suggests that the clockwise rotation was completed by 10 Ma (Fig. 7). The 16° ± 30° post-middle Miocene counterclockwise rotation of the San Gabriel block is probably due to bending of the San Andreas fault during the Pliocene-Pleistocene (Garfunkel, 1974; J. Morton and J. Hillhouse, unpub. data).

### Santa Monica Mountains and Northern Channel Islands

Paleomagnetic data from the Conejo Volcanics suggest that the western Santa Monica Mountains have rotated 78° ± 11° clockwise since early Miocene time (Kamerling and Luyendyk, 1979, 1985; Table 1 and Fig. 2). Three dolomite beds from a site in the Modelo Formation (11.3-13.3 Ma) in the western Santa Monica Mountains yielded a mean declination of 66° ± 24° (site SH; Table A and Fig. 3), corroborating this result. Two dolomite beds

25 - 49 @  
(-14) - 46 G

11 - 95  
84

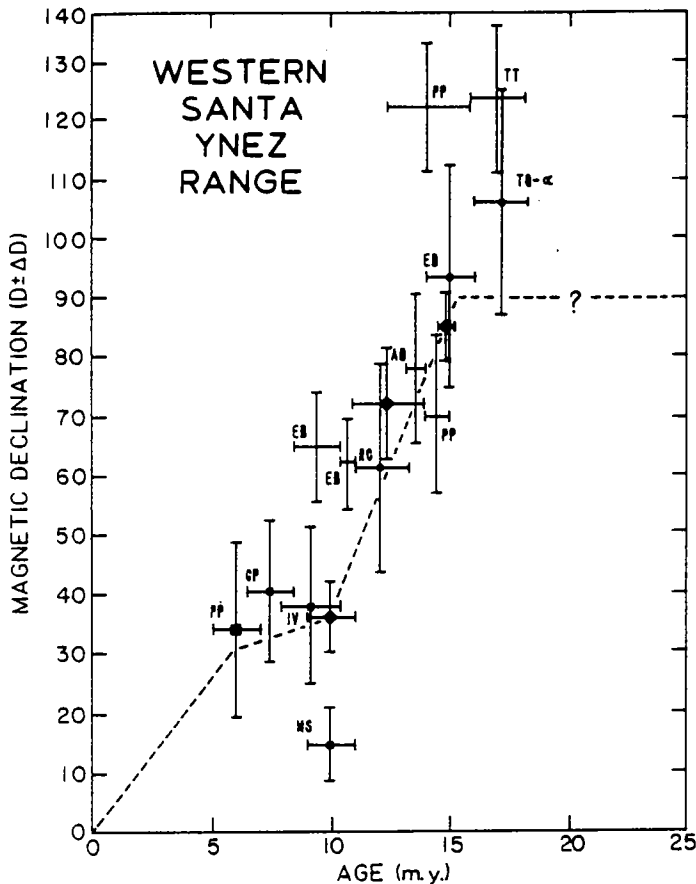


Figure 5. Declination-versus-age curve for the western Santa Ynez Range. Large symbols indicate the means of eight or more beds; small symbols indicate the means of two to seven beds; error bars without symbols are results from only one bed. Data sources: diamonds from Hornafius (1985); squares from Hornafius (1984); all other data from Hornafius (1984) and Table A. Declination error bars calculated from  $\Delta D = \sin^{-1} [\sin \alpha_{95} / \cos I]$ , which is approximately the 99% confidence level (Demarest, 1983).

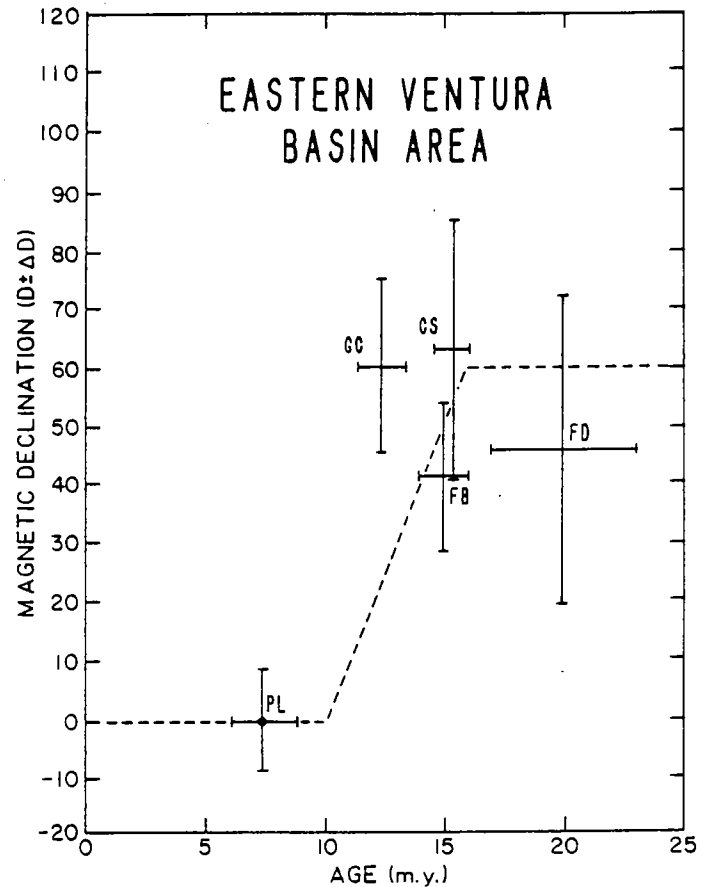


Figure 6. Declination-versus-age curve for the eastern Ventura basin area. Symbols as in Figure 5. Data sources: Hornafius (1984) and Table A.

from the base of the Modelo Formation in the eastern Santa Monica Mountains ( $11.5 \pm 1.2$  Ma; Obradovich and Naeser, 1981) yielded paleomagnetic declinations of  $37^\circ$  and  $38^\circ$  and passed a reversal test (site MH; Table A and Fig. 8).

Paleomagnetic data from upper Oligocene and lower Miocene volcanic rocks suggest that the Northern Channel Islands have rotated  $76^\circ \pm 9^\circ$  clockwise since the early Miocene (Kamerling and Luyendyk, 1985). Paleomagnetic data from the Monterey Formation on northern Santa Cruz Island (site SCM; Fig. 3) have the same mean magnetic declination as do the volcanic rocks on the northern half of the island ( $77^\circ$ ; Table 1). The magnetic inclinations from the Monterey Formation on Santa Cruz Island, however, are  $15^\circ$  steeper than are the inclinations from the volcanics (Table 1). This finding

supports Kamerling and Luyendyk's (1985) contention that the shallow inclinations recorded by the volcanics may be due, in part, to problems involved in applying an accurate tilt correction to the volcanic flows.

#### Southern Channel Islands

Paleomagnetic data from lower and middle Miocene volcanic rocks on San Nicholas Island, Santa Barbara Island, and San Clemente Island indicate that no significant rotation has occurred in the outer California borderland since the early Miocene (Kamerling and Luyendyk, 1981). Paleomagnetic data from volcanic rocks on Catalina Island suggest that the inner southern California borderland may have rotated  $\sim 100^\circ$  clockwise since the early Miocene (Luyendyk and others, 1980). This result is interpreted

either as a ball-bearing rotation of the Catalina pluton within the Catalina Schist matrix during Neogene dextral shear in the inner borderland (Hornafius, 1984) or as a larger block rotation of the entire Santa Catalina Island platform (Luyendyk and others, 1980). In either case, the southern boundary of regionally coherent tectonic rotation in the western Transverse Ranges is inferred to be the Malibu Coast fault system and other unspecified faults to the south of the Northern Channel Islands.

#### Summary of Paleomagnetic Data

The simple-shear model for tectonic rotation in the western Transverse Ranges predicts that the boundaries of the rotated terrain are the northern and southernmost east-west-trending faults bounding the western Transverse Ranges. These faults are the Santa Ynez River fault and the Big Pine fault on the north and the Malibu Coast fault system to the south. The paleomagnetic data presently available largely confirm this prediction.

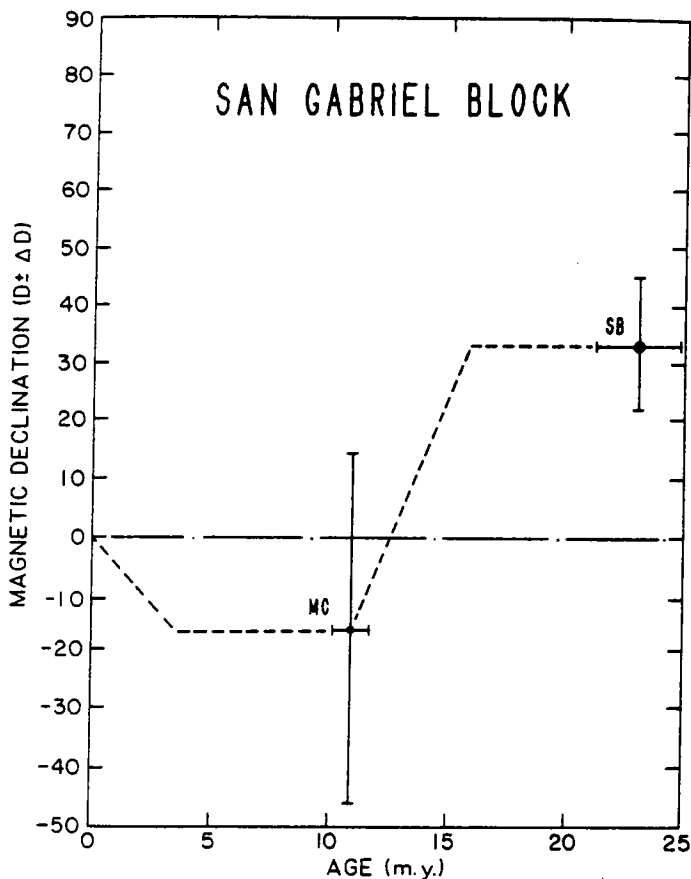


Figure 7. Declination-versus-age curve for the San Gabriel block. Symbols as in Figure 5. Data source: Terres (1984).

The declination-versus-age data from throughout the western Transverse Ranges and the San Gabriel block (Figs. 5–8) suggest that rapid clockwise rotation occurred in these areas during middle Miocene time (10–16 m.y.). The systematic decrease in magnetic declination with decreasing age over wide areas in the western Transverse Ranges also suggests that the clockwise rotation was due to coherent rotation of large crustal blocks (>100 km long) rather than to local ball-bearing rotations involving small crustal blocks (<10 km across). The amount of rotation experienced by the western Transverse Ranges and the San Gabriel block during the middle Miocene appears to be between 50° and 60° clockwise.

The *net* amount of clockwise rotation experienced by the western Transverse Ranges since early Miocene time increases westward, from 37° in the San Gabriel block to 95° in the western Santa Ynez Range (Fig. 2). Because the entire western Transverse Ranges Province, including the San Gabriel block, appears to have rotated 50°–60° clockwise during the middle Miocene, the discrepancy in the net amount of clockwise rotation between the east and west is

interpreted to result from differential rotation within the province during the late Miocene to Recent (Fig. 4). Counterclockwise rotation of the western Mojave Desert and the San Gabriel block during formation of the "Big Bend" in the San Andreas fault reduced the amount of clockwise rotation observed in the central Transverse Ranges (Terres, 1984), whereas concurrent clockwise rotation at the western end of the Transverse Ranges increased the amount of rotation observed in the western Santa Ynez Range (Hornafius, 1984). It is therefore suggested that oroclinal bending of the western Transverse Ranges since late Miocene time has produced the westward increase in magnetic declination observed within the province. The maximum paleomagnetic declinations obtained from the province parallel the change in trend of the faults within the province from east-northeast in the San Gabriel block to west-northwest in the western Santa Ynez Range (Fig. 2). This observation suggests that fault trends in the San Gabriel block and Santa Ynez

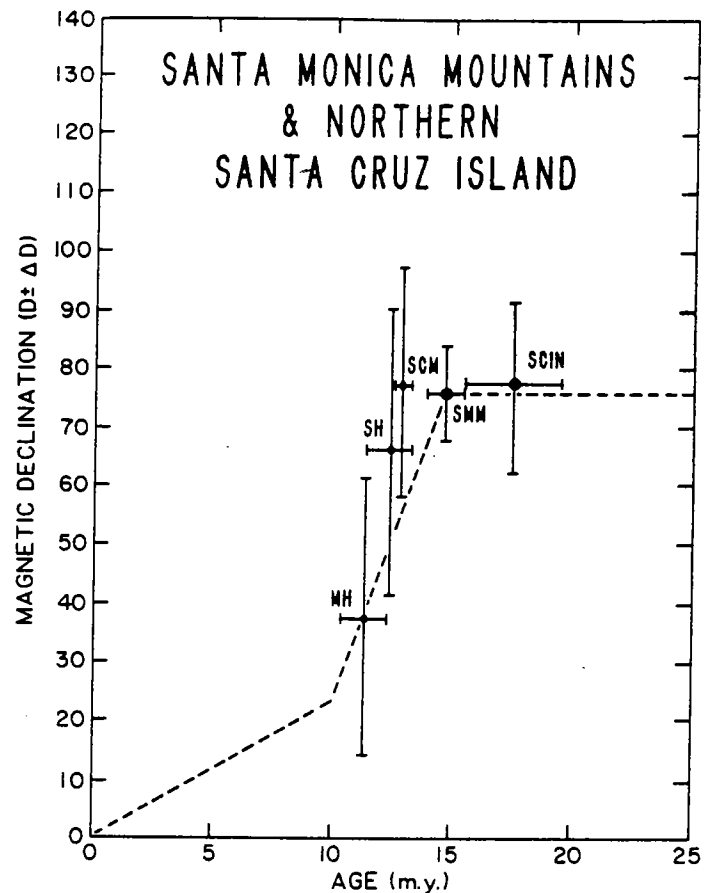


Figure 8. Declination-versus-age curve for the Santa Monica Mountains and northern Santa Cruz Island. Symbols as in Figure 5. Data sources: SCIN and SMM, Kamerling and Luyendyk (1979, 1985); SCM, SH, and MH, Hornafius (1984) and Table A.

Range were initially more linear and that the arcuate (concave-to-the-north) trends of the faults are due to oroclinal bending of the province during the Pliocene-Pleistocene.

The paleomagnetic data discussed by Luyendyk and others (1985) and the new data presented herein generally show an anomalous flattening of inclinations, suggesting northward transport of parts of what is now the southwestern United States and the western Transverse Ranges (for example, see Table 1). Two facts preclude the use of these data to constrain palaeospastic reconstructions. First, the flattening anomalies are scattered and have significant error; they lack resolution. Second, areas from cratonic North America show flattening anomalies of the same order as those for coastal southern California; this implies Neogene-age northward transport for a large part of the southwest or a widespread nondipole field effect. In the following reconstructions, removal of regional shear and rotation in the western Transverse Ranges Province can account for 3°

or 4° of flattening anomaly, leaving 5° to 10° to be explained by undetected northward transport, improper structural correction, or nondipole effects (see Luyendyk and others, 1985).

**PALINSPASTIC RECONSTRUCTIONS OF THE WESTERN TRANSVERSE RANGES**

Neogene palinspastic reconstructions of the western Transverse Ranges must take into account both the evidence for tectonic rotations and the documented strike-slip displacements on faults in southern California. The amounts of extension and compression experienced by the crust in southern California must also be considered. The Miocene palinspastic reconstructions presented in Figures 9-11 are based on the simple-shear geometric model for crustal rotation in southern California. The palinspastic reconstructions were arrived at through a rigid geometrical analysis of fault trends within the western Transverse Ranges. The length of the faults bounding the rotated blocks was assumed to be invariant, and the fault trends were then rotated as straight line segments (see Hornafius, 1984, p. 182-186).

The amount of strike-slip displacement on northwest-trending faults that terminate against the boundaries of the western Transverse Ranges was assumed to be related to the amount of tectonic rotation experienced within the western Transverse Ranges, following Luyendyk and others (1980). This assumption enables the amount of distributed dextral shear experienced by the continental margin during any given time interval to be calculated from the declination-versus-age curves in Figures 5-8 and is the basis for the minimum amounts of dextral shear calculated in Table 2. In addition, it was assumed that the amount of right-lateral distributed shear experienced by the plate boundary to the north of the Transverse Ranges is equal to the amount of distributed shear to the south of the Transverse Ranges. This assumption was used to construct a balance sheet of fault offsets in southern California (Table 3) from the amounts of strike-slip displacement suggested by the geologic evidence and the minimum amounts of dextral shear calculated from the declination-versus-age curves (Table 2).

**Early Miocene**

In order to arrive at the early Miocene palinspastic reconstruction presented in Figure 9, the Santa Ynez River fault was backrotated 95°, and the eastern Santa Ynez and Big Pine faults were backrotated 55°. The Malibu Coast fault

TABLE 2. MINIMUM AMOUNTS OF DEXTRAL SHEAR EXPERIENCED BY THE CALIFORNIA CONTINENTAL MARGIN TO THE NORTH AND SOUTH OF THE WESTERN TRANSVERSE RANGES

Crustal block	l (km)	r = Δr (deg) <sup>a</sup>	θ (deg)	D = ΔD (km)	
Post-early Miocene (0-16 m.y.)					
North of	western Santa Ynez Range	100	95 = 9	45	147 = 10
	eastern Santa Ynez Range	80	56 = 15	60	75 = 19
	San Gabriel block	40	53 = 32	65	36 = 19
	Total				258 = 29
South of	Santa Monica Mountains	110	78 = 11	45	138 = 18
	Northern Channel Islands	110	76 = 9	60	134 = 12
	Total				272 = 22
Middle Miocene (10-16 m.y.)					
North of	western Santa Ynez Range	100	56 = 10	45	90 = 17
	eastern Santa Ynez Range	80	56 = 15	60	75 = 19
	San Gabriel block	40	53 = 32	65	36 = 19
	Total				201 = 32
South of	Santa Monica Mountains	110	58 = 10 <sup>†</sup>	45	102 = 19
	Northern Channel Islands	110	56 = 10 <sup>†</sup>	60	103 = 17
	Total				205 = 25
Post-middle Miocene (0-10 m.y.)					
North of	western Santa Ynez Range	100	39 = 10	101	57 = 11
	Total				57 = 11
South of	Santa Monica Mountains	110	20 = 10 <sup>†</sup>	103	36 = 17
	Northern Channel Islands	110	20 = 10 <sup>†</sup>	116	31 = 14
	Total				67 = 22

Note: calculated from  $D = l [\cos \theta - \cos (r + \theta)]$  and  $\Delta D = l \sin (r + \theta) \Delta r$  (99% confidence limits used; Δr in radians), where D is the amount of distributed right-lateral displacement (or shear) across the block length, l is the length of the rotating block, r is the amount of rotation, and θ is the initial angle between the northwest-trending faults and the boundary of the rotated block. This equation gives the amount of displacement experienced between opposite ends of a lever arm, in a direction parallel to the shear direction (assumed to be oriented N40°W in these calculations). It also assumes that no overthrusting or shortening occurs along the length of rotated blocks (see Hornafius, 1984, p. 254).

<sup>a</sup>Data from Table 1 or estimated from Figures 5 through 8.  
<sup>†</sup>Estimated 99% limits.

TABLE 3. BALANCE SHEET OF FAULT OFFSETS USED IN THE PALINSPASTIC RECONSTRUCTIONS

Fault	0-6 m.y.	6-10 m.y.	10-16 m.y.	0-16 m.y.	
Displacements to the north of the western Transverse Ranges	Northern San Andreas	185 <sup>a</sup>	55	60 <sup>†</sup>	300 <sup>‡</sup>
	San Juan-Chimines	15 <sup>***</sup> ††	0	0	15 <sup>***</sup> ††
	Rinconada	20 <sup>†††</sup>	5	30	55 <sup>†††</sup>
	Sur-Obispo belt	50	10	130	190 <sup>§§§</sup>
	Total	270	70	220	560 <sup>***</sup>
Displacements to the south of the western Transverse Ranges	Southern San Andreas	240 <sup>†††</sup>	0	0	240 <sup>†††</sup>
	San Gabriel	0	40 <sup>§§§</sup>	20 <sup>§§§</sup>	60 <sup>§§§</sup>
	California Borderland <sup>****</sup>	30 <sup>††††</sup>	30 <sup>††††</sup>	200 <sup>††††</sup>	260 <sup>††††</sup>
	Total	270	70	220	560 <sup>***</sup>

Note: offsets in kilometres.  
<sup>a</sup>Post-Miocene offset on the northern San Andreas fault equals ~200 km since 6.7 = 0.5 m.y. (Dickinson and others, 1972; Graham, 1976) minus 15 km of Pliocene slip on the San Juan-Chimines fault (Bartow, 1974; Dibblee, 1976).  
<sup>†</sup>Huffman, 1972.  
<sup>‡</sup>Total post-early Miocene slip on the northern San Andreas fault is 315 km since 23.5 m.y. (Matthews, 1976) minus 15 km of slip on the San Juan-Chimines fault (Bartow, 1974; Dibblee, 1976).  
<sup>\*\*\*</sup>Bartow, 1974.  
<sup>††</sup>Dibblee, 1976.  
<sup>§§</sup>Includes displacement on the Hogri fault (Graham and Dickinson, 1978) and on the Nacimiento fault (Page, 1970) and distributed shear between these faults (Greenhaus and Cox, 1979).  
<sup>†††</sup>Total includes 260 km of distributed shear predicted from Table 2 plus 300 km of throughgoing fault displacement on the San Andreas fault system.  
<sup>††††</sup>Ehlig and others, 1975; includes 24 km of right slip on the San Jacinto fault (Sharp, 1967).  
<sup>§§§§</sup>60 km of slip on the San Gabriel fault between 12 and 6 m.y. ago (Ehlig and others, 1975) was partitioned between periods of 6-10 m.y. and 10-16 m.y. by assuming a constant slip rate of 10 km/m.y.  
<sup>\*\*\*\*</sup>Includes displacements on the Elsinore fault (Lamar, 1961; Sage, 1973), the Newport-Inglewood fault (Yeats, 1973; Harding, 1973), and the San Pedro basin, San Clemente, and Santa Rosa-Cortes Ridge fault zones (Junger, 1976) as well as distributed shear.  
<sup>††††</sup>Estimated from Table 2 and Figure 8.

and Dume fault, which bound the Santa Monica Mountains block on the south, were backrotated 78°, and the Santa Cruz Island and Santa Rosa Island faults were backrotated 76° (Kamerling and Luyendyk, 1985). Sixty kilometres of left slip was removed from the Malibu Coast fault

system, following Truex (1976). In addition, a total of 60 km of left slip was removed from the San Cayetano fault and Oakridge fault, based on the constraints of the simple-shear model (Luyendyk and others, 1980). Displacement on the left-lateral Santa Ynez fault system, how-



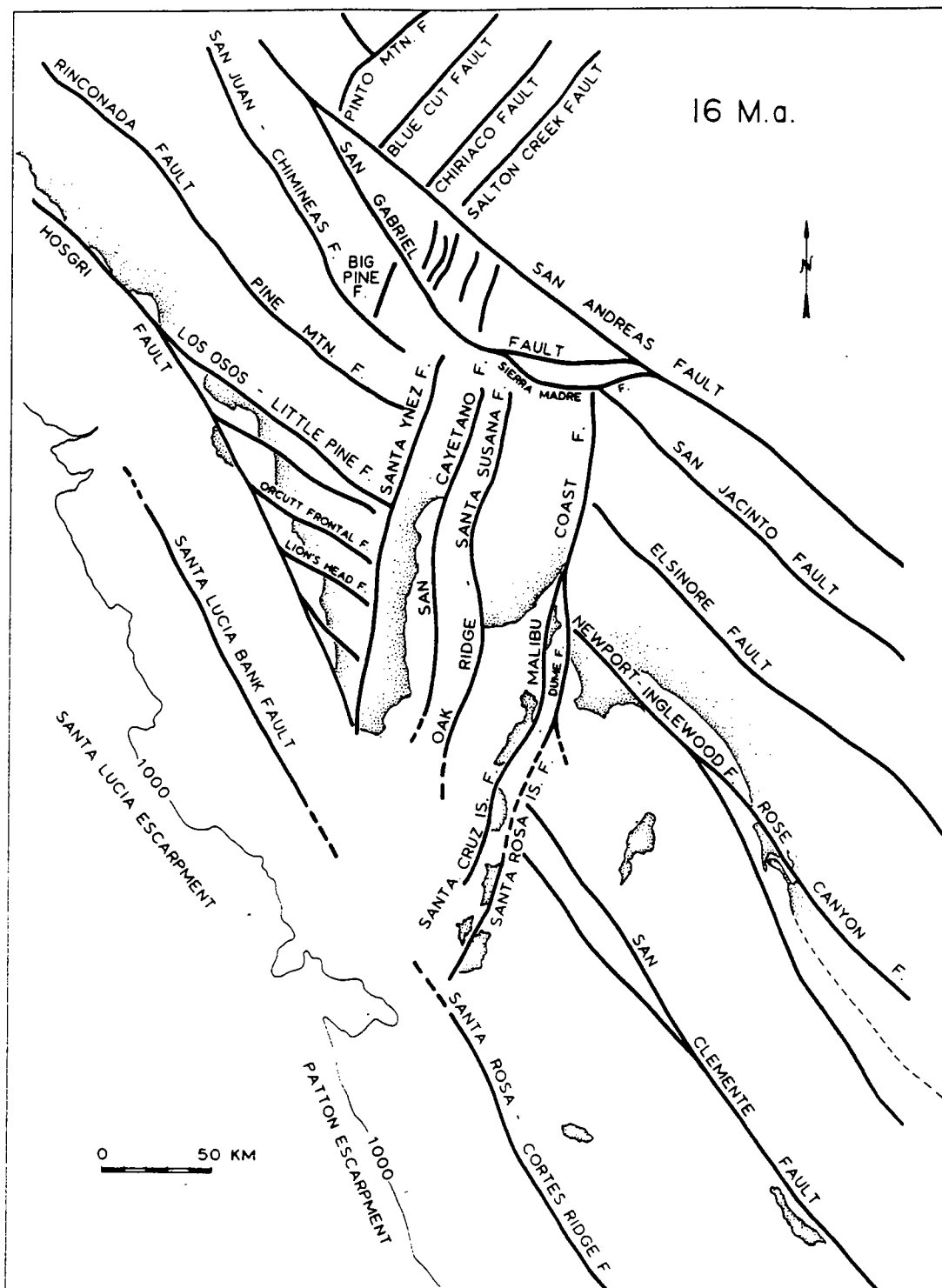


Figure 9. Palinspastic reconstruction of southern California at 16 Ma. Present-day shorelines are shown for geographical reference.

ever, was assumed to be small, following Dibblee (1982).

A  $16^\circ$  counterclockwise rigid-body rotation was removed from the San Gabriel block, which restores the bend in the San Andreas fault to a more northwesterly orientation. In addition, a  $53^\circ$  clockwise simple-shear rotation was removed from the faults internal to the block. The net result is that presently east-northeast-trend-

ing faults in the San Gabriel block are restored to initially north-northeast trends (Terres, 1984). The San Gabriel block was also backslipped 240 km along the San Andreas fault (Ehlig and others, 1975; Table 3). The eastern Santa Ynez Range and Santa Monica Mountains were backslipped an additional 60 km along the San Gabriel fault. A total of 260 km of predicted right-lateral strike-slip displacement and contin-

uum shear was then removed from the north-west-trending faults to the north and south of the rotated terrain (Tables 2 and 3; 260 km approximates 258 and 272 km in Table 2).

#### Middle Miocene

During middle Miocene time, the entire western Transverse Ranges and San Gabriel block



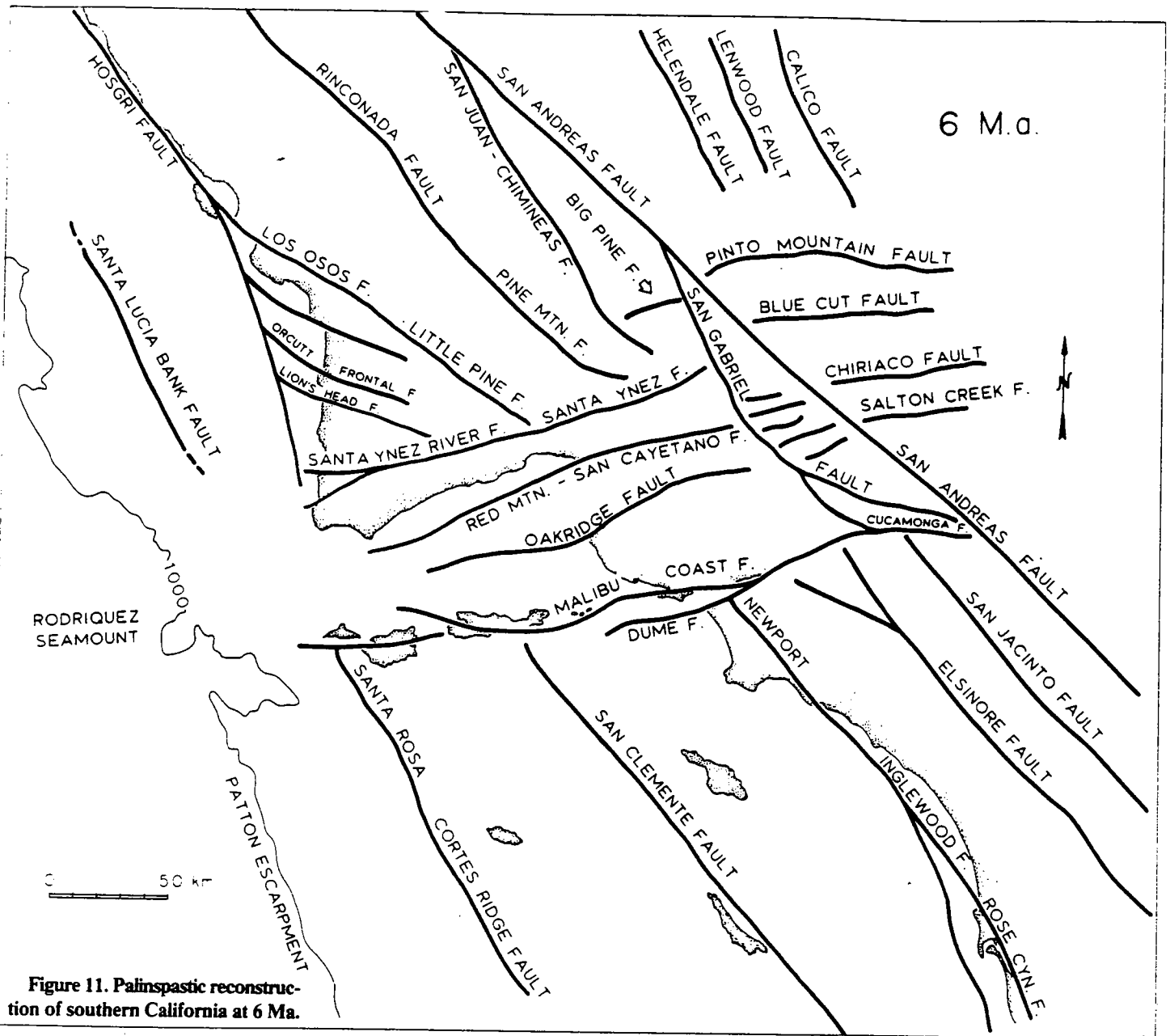


Figure 11. Palinspastic reconstruction of southern California at 6 Ma.

others, 1986). A clockwise rotation of this magnitude requires that ~100 km of dextral shear occurred on the northwest-trending faults in the Mojave Desert since 10 m.y. ago. In the palinspastic reconstructions (Figs. 10 and 11), it was assumed that a significant amount of Pacific-North American plate-boundary shear occurred to the east of the San Andreas fault during the late Miocene, resulting in clockwise rotation of the eastern Transverse Ranges between 10 and 6 m.y. ago.

#### Pliocene-Pleistocene

During the past 6 m.y., the San Andreas fault in southern California has experienced 240 km of right-lateral displacement (Ehlig and others, 1975; Table 3). The fault formed with an ~50-

km bend (Fig. 11), which was accentuated to a 160-km bend during the Pliocene-Pleistocene by a 15° counterclockwise rotation in the western Mojave desert (Burke and others, 1982; J. Morton and J. Hillhouse, unpub. data) and as much as 60 km of left slip on the Garlock fault (Fig. 1). The sinistral shear couple driving counterclockwise rotation of the Mojave block and left slip on the Garlock fault is due to a northward increase in the amount of east-west extension which has occurred in the Basin and Range Province since the Miocene (Garfunkel, 1974; Davis and Burchfiel, 1973). The resulting 100-km westward displacement of the Sierra Nevada Range was accommodated to the west of the San Andreas fault by 30% shortening in the Coast Ranges (Crouch and others, 1984).

Counterclockwise rotation also occurred in

the San Gabriel block, as the block was translated into the growing bend in the San Andreas fault. In contrast, clockwise rotation occurred in the western Transverse Ranges during the Pliocene-Pleistocene, due to continued distributed dextral shear between the Pacific and North American plates. The combination of counterclockwise rotation to the east and clockwise rotation to the west resulted in oroclinal bending of the western Transverse Ranges during the Pliocene-Pleistocene.

#### CONCLUSIONS

Paleomagnetic data from Neogene rocks in the Santa Ynez Range, the Santa Monica Mountains, the Northern Channel Islands, and the San Gabriel block suggest that large clockwise rota-

tions of these areas have occurred since early Miocene time. The coherence of the declination data with age over large crustal areas suggests that the rotation was due to coherent rotation of large crustal blocks rather than to local rotations of smaller crustal domains. The northern and southern boundaries of the coherent tectonic rotation appear to be the presently east-west-trending faults bounding the western Transverse Ranges on the north and south.

The net amount of tectonic rotation increases westward from 37° in the San Gabriel block to 95° in the western Santa Ynez Range. The declination-versus-age data from these areas suggest that the entire western Transverse Ranges and San Gabriel block rotated uniformly 50°–60° clockwise during the middle Miocene (10–16 m.y. B.P.). This rapid middle Miocene clockwise rotation resulted from distributed dextral shear along a diffuse Pacific–North American transform boundary. Clockwise rotation of the crustal block constituting the western Santa Ynez Range continued during the late Miocene to Recent, due to continued dextral shear between the Pacific and North American plates. Simultaneously, late Miocene to Recent counterclockwise rotation occurred in the San Gabriel block, due to distributed sinistral shear oriented east-west across the Mojave desert. Consequently, the net amount of post-early Miocene clockwise rotation observed in the Transverse Ranges was increased to 95° in the western Santa Ynez Range and decreased to 37° in the San Gabriel block. The resulting oroclinal bending of the western Transverse Ranges may account for the arcuate (concave-to-the-north) fault trends within the province.

The minimum amount of distributed shear experienced by the Pacific–North American transform boundary can be determined from the amount of clockwise rotation experienced by the Transverse Ranges. Since the early Miocene, the minimum amount of distributed shear experienced by the continental margin to the west of the San Andreas fault is 260 km. The declination-versus-age data suggest that the majority of this dextral shear occurred during the middle Miocene (~200 km). The majority of Neogene strike-slip displacement experienced by the northwest-trending faults in the Coast Ranges and southern California borderland that terminate against the boundaries of the western Transverse Ranges is therefore predicted to be middle Miocene in age.

## ACKNOWLEDGMENTS

The authors gratefully acknowledge discussions and comments from Tanya Atwater, John Crowell, Thomas Dibblee, Michael Fuller, and Donald Weaver. Laboratory assistance was provided by Robert Dunn and Mark Stein. Duane Champion and Richard Schweickert reviewed an earlier version of the manuscript. This research was supported in part by Grant EAR 83-05872 from the National Science Foundation.

## REFERENCES CITED

- Atwater, T., and Molnar, P., 1973. Relative motion of the Pacific and North American plates deduced from sea-floor spreading in the Atlantic, Indian, and South Pacific Oceans: Stanford University Publications in Earth Sciences, v. 13, p. 136–148.
- Barrow, J. A., 1974. Sedimentology of the Simmler and Vaqueros Formations in the Caliente Range–Carrizo Plain area, California (Ph.D. thesis): Palo Alto, California: Stanford University, 163 p.
- Beck, M. E., 1980. Paleomagnetic record of plate-margin tectonic processes along the western edge of North America: *Journal of Geophysical Research*, v. 85, p. 7115–7131.
- Burke, D. B., Hillhouse, J. W., McKee, E. H., Miller, S. T., and Morton, J. L., 1982. Cenozoic rocks in the Barstow basin area of southern California—stratigraphic relations, radiometric ages, and paleomagnetism: U.S. Geological Survey Bulletin 1529-E, 16 p.
- Carter, J. N., Luyendyk, B. P., and Terres, R. R., 1986. Neogene clockwise rotation of the eastern Transverse Ranges, California, suggested by paleomagnetic vectors: *Geological Society of America Bulletin*, in press.
- Crouch, J. K., Bachman, S. B., and Shay, J. T., 1984. Post-Miocene compressional tectonics along the central California margin. In Crouch, J. K., and Bachman, S. B., eds., *Tectonics and sedimentation along the California margin*: Society of Economic Paleontologists and Mineralogists, Pacific Section, Los Angeles, California, p. 37–54.
- Crowell, J. C., 1975. The San Gabriel fault and Ridge basin, southern California: California Division of Mines and Geology Special Report 118, p. 208–219.
- Davis, G. A., and Burchfiel, B. C., 1973. Garlock fault: An intra-continental transform structure, southern California: *Geological Society of America Bulletin*, v. 84, p. 1407–1422.
- Demarest, H. H., Jr., 1983. Error and analysis for the determination of tectonic rotation from paleomagnetic data: *Journal of Geophysical Research*, v. 88, p. 4321–4328.
- Dibblee, T. W., 1976. The Rinconada and related faults in the southern Coast Ranges, California, and their tectonic significance: U.S. Geological Survey Professional Paper 981, 55 p.
- , 1982. Geologic structure and tectonics along the eastern Santa Ynez fault, western Transverse Ranges, California: *Geological Society of America Abstracts with Programs*, v. 13, p. 159.
- Dickinson, W. R., Cowan, D. S., and Schweickert, R. A., 1972. Test of the new global tectonics: Discussion: American Association of Petroleum Geologists Bulletin, v. 56, p. 375–384.
- Ehlig, P. L., Ehler, K. W., and Crowe, B. M., 1975. Offset of the upper Miocene Caliente and Mint Canyon Formations along the San Gabriel and San Andreas faults: California Division of Mines and Geology Special Report, v. 118, p. 83–92.
- Gartunkel, Z., 1974. Model for the late Cenozoic tectonic history of the Mojave Desert, California, and for its relation to adjacent regions: *Geological Society of America Bulletin*, v. 85, p. 1931–1944.
- Graham, S. A., 1976. Tertiary sedimentary tectonics of the central Salinian block of California (Ph.D. thesis): Palo Alto, California: Stanford University, 510 p.
- Graham, S. A., and Dickinson, W. R., 1978. Apparent offsets of onland geologic features across the San Gregorio–Hogri fault trend: California Division of Mines and Geology Special Report 137, p. 13–23.
- Greenhaus, M. R., and Cox, A., 1979. Paleomagnetism of the Morro Rock–Island Hill Complex as evidence for crustal block rotations in central coastal California: *Journal of Geophysical Research*, v. 84, p. 2393–2400.
- Hall, C. A., 1975. San Simeon–Hogri fault system, coastal California: Economic and environmental implications: Science, v. 190, p. 1291–1294.
- Harding, T. P., 1973. Newport–Inglewood trend, California—An example of wrench style of deformation: American Association of Petroleum Geologists Bulletin, v. 57, p. 97–116.
- , 1976. Tectonic significance and hydrocarbon trapping consequences of sequential folding synchronous with San Andreas faulting, San Joaquin Valley, California: American Association of Petroleum Geologists Bulletin, v. 60, p. 356–378.
- Hornafius, J. S., 1984. Paleomagnetism of the Monterey Formation in the western Transverse Ranges, California (Ph.D. thesis): Santa Barbara, California: University of California, 442 p.
- , 1985. Neogene tectonic rotation of the Santa Ynez Range, western Transverse Ranges, California, suggested by paleomagnetic investigation of the Monterey Formation: *Journal of Geophysical Research*, v. 90, p. 12503–12522.
- Howell, D. G., 1976. A review of the estimates for the radiometric ages for the Relizian Stage of the Pacific Coast, in Fritsche, A. E., ed., *The Neogene symposium*: Society of Economic Paleontologists and Mineralogists Special Publication.
- Huffman, O. F., 1972. Lateral displacement of upper Miocene rocks and Neogene history of offset along the San Andreas fault in central California: *Geological Society of America Bulletin*, v. 83, p. 2913–2946.
- Irving, E., 1979. Paleopoles and paleolatitudes of North America and speculations about displaced terranes: *Canadian Journal of Earth Science*, v. 16, p. 669–694.
- Junger, A., 1976. Tectonics of the southern California borderland. In Howell, D. G., ed., *Aspects of the geologic history of the California continental borderland*: Pacific Section American Association of Petroleum Geologists Miscellaneous Publications 24, p. 486.
- Kamerling, M. J., 1980. Paleomagnetism of middle Miocene volcanics and tectonic rotation of the Santa Monica Mountains region, western Transverse Ranges, California (M.A. thesis): Santa Barbara, California: University of California.
- Kamerling, M. J., and Luyendyk, B. P., 1979. Tectonic rotations of the Santa Monica Mountains region, western Transverse Ranges, California, suggested by paleomagnetic vectors: *Geological Society of America Bulletin*, v. 90, p. 331–337.
- , 1981. Paleomagnetism and tectonics of the islands of the southern California continental borderland (abst.): EOS (American Geophysical Union Transactions), v. 62, p. 855.
- , 1985. Paleomagnetism and Neogene tectonics of the Northern Channel Islands, California: *Journal of Geophysical Research*, v. 90, p. 12485–12502.
- Lamar, D. L., 1961. Structural evolution of the northern margin of the Los Angeles basin (Ph.D. thesis): Los Angeles, California: University of California, 162 p.
- Luyendyk, B. P., Kamerling, M. J., and Terres, R., 1980. Geometric model for Neogene crustal rotations in southern California: *Geological Society of America Bulletin*, v. 91, p. 211–217.
- Luyendyk, B. P., Kamerling, M. J., Terres, R. R., and Hornafius, J. S., 1985. Simple shear of southern California during Neogene time suggested by paleomagnetic declinations: *Journal of Geophysical Research*, v. 90, p. 12454–12466.
- Matthews, V., III, 1976. Correlation of Pinnacles and Neenach volcanic formations and their bearing on San Andreas fault problem: American Association of Petroleum Geologists Bulletin, v. 60, p. 2128–2141.
- Obradovich, J. D., and Naeser, C. W., 1981. Geochronology bearing on the age of the Monterey Formation and siliceous rocks in California, in Garrison, R. E., and others, eds., *The Monterey Formation and related siliceous rocks of California*: Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 87–95.
- Page, B. M., 1970. Sur-Nacimiento fault zone of California: Continental margin tectonics: *Geological Society of America Bulletin*, v. 81, p. 667–690.
- Sage, O. G., 1973. Paleocene geology of southern California (Ph.D. thesis): Santa Barbara, California: University of California, 250 p.
- Sharp, R. V., 1967. San Jacinto fault zone in the Peninsular Ranges of southern California: *Geological Society of America Bulletin*, v. 78, p. 705–729.
- Stewart, J. H., 1983. Extensional tectonics in the Death Valley area, California: Transport of the Panamint Range structural block 80 km northwest: *Geology*, v. 11, p. 153–157.
- Stewart, J. H., Albers, J. P., and Poole, F. G., 1968. Summary of regional evidence for right-lateral displacement in the western Great Basin: *Geological Society of America Bulletin*, v. 79, p. 1407–1414.
- Sylvester, A. G., and Darrow, A. C., 1979. Structure and neotectonics of the western Santa Ynez fault system in southern California: *Tectonophysics*, v. 52, p. 389–405.
- Terres, R. R., 1984. Paleomagnetism and tectonics of the central and eastern Transverse Ranges, southern California (Ph.D. thesis): Santa Barbara, California: University of California, 325 p.
- Terres, R. R., and Luyendyk, B. P., 1985. Neogene tectonic rotation of the San Gabriel region, California, suggested by paleomagnetic vectors: *Journal of Geophysical Research*, v. 90, p. 12467–12484.
- Trues, J. N., 1976. Santa Monica and Santa Ana Mountains—relation to Oligocene Santa Barbara basin: American Association of Petroleum Geologists Bulletin, v. 60, p. 65–86.
- Turner, D. L., 1970. Potassium-argon dating of Pacific Coast Miocene foraminiferal stages. In Bandy, O. L., ed., *Radiometric dating and paleontological zonation*: Geological Society of America Special Paper 24, p. 91–129.
- Woodring, W. P., and Bramlett, M. N., 1950. Geology and paleontology of the Santa Maria district, California: U.S. Geological Survey Professional Paper 222, 185 p.
- Yeats, R. S., 1973. Newport–Inglewood fault zone, Los Angeles basin, California: American Association of Petroleum Geologists Bulletin, v. 57, p. 117–135.

MANUSCRIPT RECEIVED BY THE SOCIETY SEPTEMBER 20, 1985

REVISED MANUSCRIPT RECEIVED JUNE 5, 1986

MANUSCRIPT ACCEPTED JUNE 6, 1986