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Review

Fault Slip Rates and Earthquake Histories for Active Faults in Southern California

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Abstract Within the context of the historical record of seismicity, we review the geological data bearing on the Quaternary slip rates and paleoearthquake histories of active faults in southern California.

Introduction

Fault slip rate and paleoearthquake data now commonly form the foundation for seismic hazard analysis. As part of the Southern California Earthquake Center's effort to characterize seismic hazard in southern California, we have compiled published information bearing on the Quaternary slip rate and paleoearthquake histories of active faults in southern California. Reports of such data are scattered among a myriad of sources, ranging from brief abstracts and little-reviewed guidebook articles to the more rigorously reviewed professional reports and articles. As a result, the data are not always conveniently accessed by the interested investigator. Toward both precluding a duplication of effort by others and providing a benchmark of progress in paleoearthquake and fault slip rate studies to date, we present our compilation here and place it within the context of the historical record of seismicity along each of the faults considered.

The location of each fault slip rate or paleoearthquake study is indicated in Figure 1. The label at each site corresponds to the abbreviated description in Table 1 of both the results of the study and reference to the original report describing the site. Table 1 lists the location of the study, the geologic feature offset by the fault, the method used to date the offset feature, the amount of offset and the respective investigator's estimate of the fault slip rate, and, when available, dates of paleoearthquakes. For convenience of presentation, studies along the San Andreas, San Jacinto, Whittier–Elsinore, Newport–Inglewood, Palos Verdes, and Rose Canyon faults and active faults within the Transverse Ranges, Mojave Desert, and Continental Borderlands are grouped and accorded separate discussions. For each fault or region, discussion of the fault slip rate and paleoearthquake studies is accompanied by a description of historical seismicity, including maps and cross sections of the past 50 yr of seismicity and aftershock zones of the largest historical earthquakes.

The Southern San Andreas Fault

Mojave Segment

Historical Seismicity. For convenience of presentation, we define the 150-km section of the fault between Tejon Pass and Cajon Pass as the Mojave segment (Figs. 2 and 3). Surface ruptures during the great 1857 earthquake extended from northwest of Tejon Pass to a point between Wrightwood and Cajon Pass. The amount of coseismic offset during 1857 ranged between about 3 and 4 m along this section of the fault (Sieh, 1978b), although up to 6 m was found near Pallett Creek when the effects of paleomagnetically determined warping were included (Salyards, 1989; Salyards *et al.*, 1987, 1992). Tree ring analysis near Wrightwood also suggests that an *M* 7.5 earthquake ruptured part of the Mojave section of the San Andreas in 1812 (Jacoby *et al.*, 1988). Recent seismicity (1932 through 1992), however, is quite sparse along the Mojave segment [e.g., Hill *et al.*, 1990; Fig. 2]. Cross sections of seismicity since 1981 along the fault indicate that earthquakes extend to depths of about 15 km (Fig. 4).

Fault Slip Rate Data. A slip rate of about 9 mm/yr was initially reported by Sieh (1984) for the Mojave segment based upon stratigraphic offsets observed across the fault in a trenching study. Later paleomagnetic studies at the same site by Salyards *et al.* (1987, 1992) and Salyards (1989) indicate that the 9 mm/yr significantly underestimates the fault slip rate at this site because it does not take into account warping of the sediments adjacent to the trench. After correcting for warping of the sediment by analysis of paleomagnetic rotations, Sal-

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yards *et al.* (1992) reinterpreted the Sieh (1984) study to indicate 36 ± 7 mm/yr of slip. Schwartz and Weldon (1987) reference another study in abstract form of an offset stream channel near Little Rock that was used to place a limit of 16 to 38 mm/yr of slip along the Mojave segment during the past 3,500 yr.

For comparison, alignment array surveys dating back to the mid-1960s indicate a segment of the fault near Parkfield, located north of the Mojave segment, creeps seismically at about 32 mm/yr (Burford and Harsh, 1980). Sieh and Jahns (1984) also studied the offset of Wallace Creek to estimate a 33.9 ± 2.9 mm/yr late Holocene slip rate within the Carrizo Plain: In addition, geodetic studies of the Los Padres–Tehachapi network indicate a slip rate of 30 ± 6 mm/yr near Tejon Pass (Eberhart-Phillips *et al.*, 1990).

Paleoearthquake Data. Examination of stratigraphic and structural relationships exposed in trenches has resulted in recurrence interval estimates for the San Andreas fault near Pallett Creek. At Pallett Creek, Sieh *et al.* (1989) place the average recurrence interval between the latest 10 episodes of faulting at 132 yr, although the variability about the mean is quite large and indicates an irregular recurrence pattern. Ongoing studies at Wrightwood, only 30 km along strike from Pallett Creek, also show a similar average recurrence interval since about 1470 A.D. but suggest that Wrightwood and Pallett Creek may not always rupture simultaneously during the same earthquake (Weldon, 1991; Weldon *et al.*, 1989; Fumal *et al.*, 1993).

Southern San Andreas

Historical Seismicity. The southern San Andreas is defined here as that section extending from near Cajon Pass in the north to Bombay Beach in the south (Figs. 2 and 3). The trace of the San Andreas is complex where it splays into the subparallel strands of the Mission Creek, San Gorgonio Pass, and Banning faults. At least 10 $M > 5.0$ events have occurred in the vicinity of San Gorgonio Pass since 1935 (Richter *et al.*, 1958), the largest being the 12 December 1948 Desert Hot Springs earthquake (M_L 6.5) and the 3 July 1986 North Palm Springs

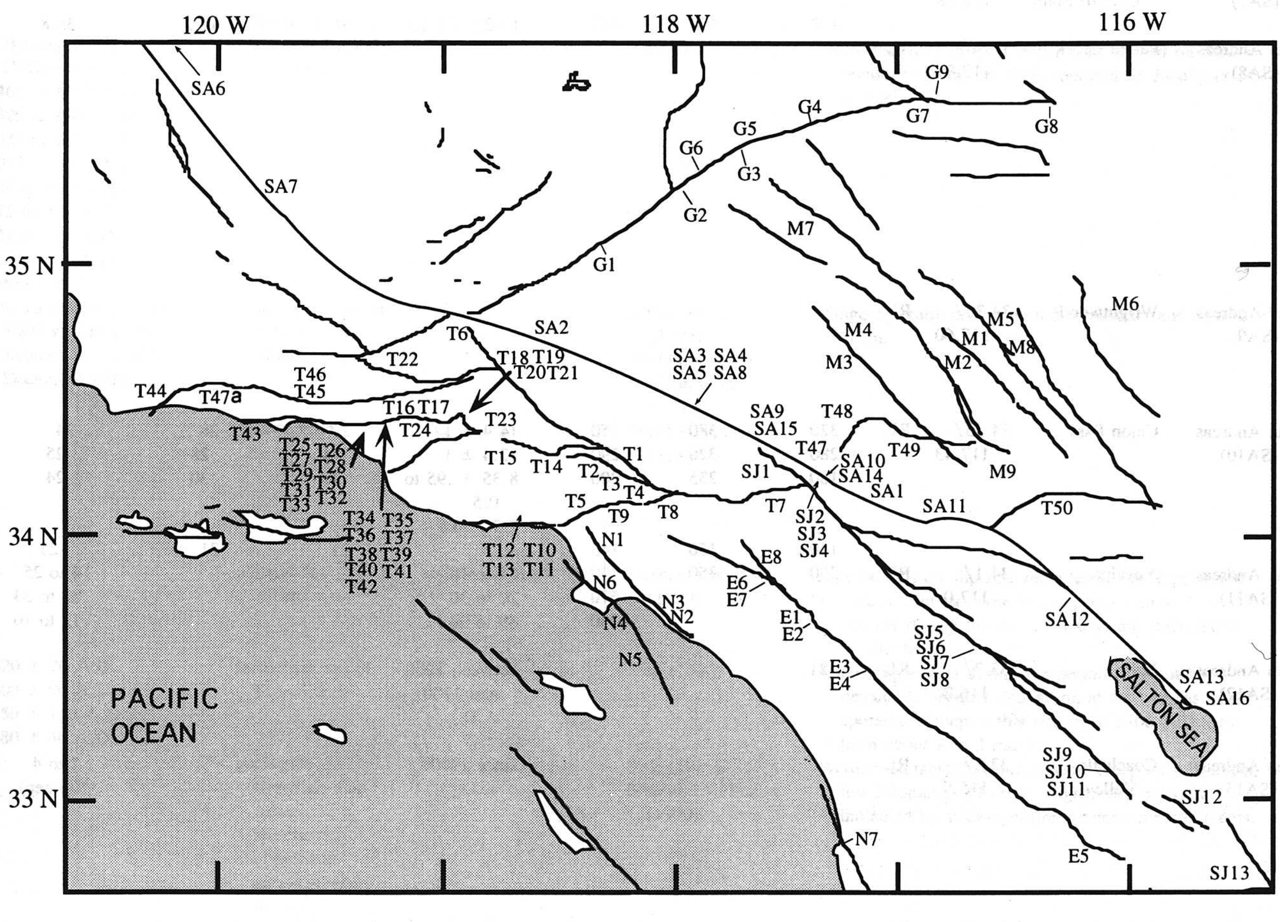


Figure 1. Map showing sites of slip rate studies in southern California for the San Andreas (SA1-14), San Jacinto (SJ1-13), Elsinore–Whittier (E1-8), Newport–Inglewood (N1-3), Palos Verdes (N4-6), Rose Canyon (N7), Transverse Ranges (T1-50), Mojave (M1-6), and Garlock (G1-9) faults.

Table 1. Onshore Southern

Fault	Location	Lat/Lon	Fault Type	Slip (m) Mn	Slip (m) Mx	Slip (m) Pr	Age of Offset (kyr)	Slip Rate (mm/yr) Mn	Slip Rate (mm/yr) Mx	Slip Rate (mm/yr) Pr
San Andreas Fault Zone										
San Andreas (SA1)	Elder Gulch	34.13/ 117.17	RL	30	50		?		25	
San Andreas (SA2)	Three Points	34.74/ 118.56	RL	14	123		1.84 to 2.4	5.8	67	48
San Andreas (SA3)	Pallett Creek	34.46/ 117.89	RL	10			period between 735 and 1857 A.D.			9
San Andreas (SA4)	Pallett Creek	34.46/ 117.89	RL	15.9	20.8	18.0	period between 1346 ± 17 A.D. and 1857 A.D.	30.1	42.1	35.2
San Andreas (SA5)	Little Rock	34.5/ 118.0	RL			19	1.0 to 1.2	16 to 19		
					<130		3.5 ± 2.2		38	
San Andreas (SA6)	Bitterwater Valley	36.4/ 121.0	RL				1967 to 1970 A.D.			33
San Andreas (SA7)	Wallace Creek/ Carrizo Plain	35.27/ 119.83	RL	127	129	128	3.7 ± .16	31	36.8	33.9
				472	478	475	13.25 ± 1.65	31.7	41.2	35.8
San Andreas (SA8)	Pallett Creek	34.46/ 117.89	RL							
San Andreas (SA9)	Wrightwood	34.35/ 117.60	RL							
San Andreas (SA10)	Cajon Pass	34.25/ 117.43	RL	320	380	350	14.4 ± 1	20	28	24
				280	320	290	12.4 ± 1	21	28	25
				180	235	200	8.35 + .95 to 0.5	19	30	24
							5.9 ± 0.9			
				140	150	145		21	31	25
San Andreas (SA11)	Yucaipa	34.1/ 117.0	RL	250	350	300	14 to 18			14 to 25
						670	20 to 30			22 to 34
						1040	69 to 90			12 to 16
San Andreas (SA12)	Indio	33.7/ 116.2	RL	21			between 1000 and 1700 A.D.	30		
San Andreas (SA13)	Coachella Valley	33.4/ 115.8	RL				since 1700 A.D.			2 to 4 (creep)
San Andreas (SA14)	Cajon Pass	34.25/ 117.43	RL							

California Slip Rates

Historical and Paleo Earthquakes	Offset Feature	Dating Method	Reference	Comments
	stream channels	soil development	Clark *et al.* (1984)	Reported from Rasmussen (1982). Geologic, stratigraphic, and soil age data are not documented in the Rasmussen study.
	landslide	^{14}C	Clark *et al.* (1984)	Reported from Rust (1982a, b)
	stream and marsh deposits	history and ^{14}C	Sieh (1984)	Rate is considered a minimum by authors because of considerable folding of sediments observed adjacent to fault trace.
	stream and marsh deposits	^{14}C	Salyards *et al.* (1987) Salyards (1989) Salyards *et al.* (1992)	Paleomagnetism used to account for slip accommodated by warping rather than faulting (Sieh, 1984).
	stream offset	^{14}C	Schwartz and Weldon (1987)	Only documented in abstract form.
	channel fill deposit	^{14}C		
	alignment array	calendar	Burford and Harsh (1980)	Displacement of alignment arrays from 30 to 200 m in length. Arrays located between endpoints of 1906 and 1857 surface ruptures. Lesser values of creep recorded at points closer to the 1906 and 1857 ruptures.
	offset stream	^{14}C	Sieh and Johns (1984)	
	alluvial fan offset	^{14}C		
9 January 1857, 8 December 1812 1465 to 1495 A.D. 1329 to 1363 A.D. 1035 to 1165 A.D. 1015 to 1081 A.D. 981 to 1013 A.D. 775 to 919 A.D. 721 to 747 A.D. 658 to 684 A.D. before 529 A.D.	stream and marsh deposits	^{14}C	Sieh *et al.* (1989)	Note that date of 1812 earthquake argued on basis of evidence from tree rings reported by Jacoby *et al.* (1988).
7 to 10 events during last 1300 yr, including 9 January 1857 and 8 December 1812	peat, sand, gravel and debris flows	^{14}C	Fumal *et al.* (1993) Weldon (1991) Weldon *et al.* (1989)	Ongoing study only reported in abstract and summary form.
	terrace risers	^{14}C	Weldon and Sieh (1985)	
	alluvial fan offsets	soil development	Harden and Matti (1989)	The bounds on slip rate recorded here are preferred values. Authors note that slip rates up to 35 to 65 mm/yr during the last 14,000 yr are permissible by the data.
1020 ± 20 A.D. 1300 ± 90 A.D. 1450 ± 150 A.D. 1680 ± 40 A.D.	lacustrine and fluvial beds	^{14}C	Sieh (1986)	Other slip events during the period may not be detectable because deposition at the site has been sporadic. Creep at this site since 1700 A.D. has been about 2 to 3 mm/yr.
	geological deposits, man made structures, alignment arrays, creep meters	history	Sieh (1986) Sieh and Williams (1990)	Authors suggest that rate reflects creep only in upper few kilometers of crust. Higher slip rates are indicated by wide-aperture geodetic measurements.
2 to 4 events between 1290 and 1805 A.D.	marsh deposits, scarp breccias		Weldon and Sieh (1985)	Evidence is cited as tentative, but suggests 1.5 to 2 century return time. Several places in mapped area where ~4 m of offset can be measured on young geomorphic features.
6 events in past ~1000 yr				

Table 1—*Continued.* Onshore

Fault	Location	Lat/Lon	Fault Type	Slip (m) Mn	Slip (m) Mx	Slip (m) Pr	Age of Offset (kyr)	Slip Rate (mm/yr) Mn	Slip Rate (mm/yr) Mx	Slip Rate (mm/yr) Pr
San Andreas (SA15)	Wrightwood	34.35/ 117.6	RL							
San Andreas (SA16)	Indio	33.7/ 116.2	RL			700	20 to 70	10	35	23 to 35
San Jacinto and Imperial Fault Zones										
San Jacinto (SJ1)	Lower Lytle Creek	34.20/ 117.43	RL V		125 5		50 to 60		2 to 2.5 0.04 to 0.1	
San Jacinto (SJ2)	San Bernardino	34.10/ 117.28	RL	3.5	6		≤1931 ± 109 B.P.	1.7	3.3	
San Jacinto (SJ3)	near San Bernardino	34.03/ 117.25	RL			0.6 to 0.7 km	50 to 100			0.6 to 1.3
San Jacinto (SJ4)	near San Bernardino	34.0/ 117.2	RL	12 km			0.7 ± .2 m.y.	>13	>24	>17
San Jacinto (SJ5)	Anza	33.5/ 116.7	RL	85 ± 10			9.5 ± 1			>9.2 ± 2
				120	180	150	14^{+7}-5	6	20	11
				180	230	210	17^{+9}-6	7	21	12
				580	660	620	50^{+9}-6	7	23	13
San Jacinto (S16)	Anza	33.5/ 116.7	RL				28.65 ± 0.98	7	18	
				48			4.29 + 0.51/ −0.32	10		
							9.5	7	11	9
San Jacinto (SJ7)	Anza Valley	33.57/ 116.65	RR	5.7 km			<730	8		>12
San Jacinto (SJ8)	Hog Lake near Anza	33.5/ 116.7	RL				$<1.2^{+6}$-1.8 kyr A.D.			
San Jacinto (SJ9)	Lower Borrego Valley	33.1/ 116.05	RR	10.9	11.1		4.5 to 6.5	1.4	2.0	
San Jacinto (SJ10)	Lower Borrego Valley	33.1/ 116.05	RR			1.3	265 to 500 yr	2.7	5.0	
San Jacinto/ Coyote Creek (SJ11)	Old Kane Spring Road	33.1/ 116.1	RL				3080 ± 600 to 860 ± 200 A.D.			
San Jacinto/ Superstition Hills (SJ12)	Imler Road	33.0/ 115.7	RL	1.06	1.16	1.11 m	330 yr (since 1663 ± 22 A.D.)	1.7	6.1	2 to 6 ± 1
Imperial (SJ13)	U.S./Mexico International border	32.70/ 115.35	RL					15	20	

Southern California Slip Rates

Historical and Paleo Earthquakes	Offset Feature	Dating Method	Reference	Comments
9 January 1857 8 December 1812 1700 (1680 to 1730 A.D.) 1610 (1500 to 1650 A.D.) 1470 (1450 to 1490 A.D.)	debris flows and stream deposits	^{14}C	Fumal *et al.* (1993)	Evidence for five paleoearthquakes is based on fault scarps, colluvial wedges, fissure infills, upward termination of ruptures, and tilted and folded deposits. These data indicate that the average recurrence interval for large earthquakes is about 100 yr near Wrightwood.
	alluvial fan	soil profile	Keller *et al.* (1982a) Bonkowski (1981)	Estimation of slip rate and identification of paleoseismicity for the San Andreas fault in the Indio Hills is difficult. Age of offset fan may be 70,000 yr old but is more likely between 20,000 and 30,000 yr old.
	fluvial terrace	soils and stratigraphic correlation	Metzger and Weldon (1983)	Offset is across Lytle Creek fault (the western branch of the San Jacinto fault. Hence, estimate is not indicative of entire slip rate across San Jacinto.
	buried stream channel	^{14}C	Wesnousky *et al.* (1991)	Study did not encompass all active strands of the fault at the site. Slip rate is a minimum.
	stream offsets	soils and U-series	Prentice *et al.* (1986)	Documented only in abstract form.
	fluvial conglomerate	paleontology correlation	Morton *et al.* (1986)	Documented only in abstract form.
	alluvial fan	soil chronosequence	Rockwell *et al.* (1990a, b)	
	stream channel	calibrated to ^{14}C		
	stream channel			
	beheaded channel			
	shutter ridge	^{14}C	Merifield *et al.* (1991)	These dates bracket the slip rate on the Clark fault north of Anza at 10 to 18 mm/yr for the last 30,000 yr. Data from one trench indicate a recurrence interval for ground-breaking events of 300 ± 200 yr. The slip rate for the stream gravels are dendrochronologically corrected years.
	gravels in channel	^{14}C		
	ponded sediments	^{14}C		
	gravel bed	K-Ar on a tuff	Clark *et al.* (1984) Sharp (1981)	
2 to 3 events	peat layers and allvium	^{14}C	Klinger and Rockwell (1989)	Documented only in abstract form. Authors interpret 2 to 3 earthquakes occurred during last 750 yr based on vertical offsets of sediments exposed in a trench. The data suggest a maximum recurrence interval of 250 yr.
1968	buried channel	^{14}C	Clark *et al.* (1984) Sharp (1981)	
1968	vertical component of lake bed	^{14}C and historical record	Clark *et al.* (1984) Sharp (1981)	Strike slip is inferred from ratio of vertical to horizontal slip during 1968 earthquake. Time elapsed since 1968 and slip during 1969 event not used in determining slip rate (see Clark *et al.* (1984).
1968	Lake Cahuilla sediments	^{14}C on shells	Clark (1972)	Authors estimate recurrence interval of about 200 yr for tectonic events like that of the 1968 Borrego Mountain earthquake by comparing vertical components of displacement in 1968 with earlier movements recorded in offset sediments of ancient Lake Cahuilla. In light of subsequent observations by Sharp (1981), these observations are consistent with a lesser repeat of between 100 and 200 yr.
1987 A.D. 1660 to 1915 A.D.	Lake Cahuilla highstand shoreline	^{14}C combined with historical accounts	Hudnut and Sieh (1989)	Maximum rate includes interpretation of off-fault warping and minor faulting. Slip rate includes components of both creep and co-seismic offset. Authors further estimate the average interval between large surface slip events on this fault is between 150 and 300 yr.
1 event 1670 A.D.	Lake Cahuilla sediments	^{14}C	Thomas and Rockwell (1993)	These data suggest that the slip rate for the past 300 yr is less than that expected from geodetic measurements and regional structural models.

Table 1—*Continued.* Onshore

Fault	Location	Lat/Lon	Fault Type	Slip (m) Mn	Slip (m) Mx	Slip (m) Pr	Age of Offset (kyr)	Slip Rate (mm/yr) Mn	Slip Rate (mm/yr) Mx	Slip Rate (mm/yr) Pr
Elsinore Fault Zone										
Elsinore (E1)	Glenn Ivy North Strand, Temescal Valley	33.7/ 117.4	RL	0	85	—	5 to 600	0	17	—
				85	244	143	20 to 30	2.8 to 4.3	8.1 to 12.2	4.8 to 7.2
				152	335	213	30 to 40	3.8 to 5.1	8.4 to 11.2	5.3 to 7.1
				256	933	594	100 to 200	1.3 to 2.6	4.7 to 9.3	3.0 to 5.9
							overlap in rates	2.6 to 4.3	8.4 to 9.3	5.3 to 5.9
Elsinore (E2)	Glenn Ivy North Strand, Temescal Valley	33.7/ 117.4	RL							
Elsinore (E3)	Agua Tibia Mountains	33.50/ 117.25	RL			1035 ± 20	130 to 600	1.7	8.1	2.9 ± 1.3
						895 ± 20	130 to 600	1.5	7.0	2.6 ± 1.1
						1130 ± 20	130 to 600	1.9	8.9	3.2 ± 1.4
						245 ± 20	15 to 240	1.0	17.7	4.9 ± 1.7
						140 ± 20	20 to 82	1.5	8.0	4.6 ± 2.3
						345 ± 20	50 to 240	1.4	7.3	3.5 ± 1.7
						880 ± 20	130 to 600	1.5	6.9	2.5 ± 1.1
						245 ± 20	50 to 240	1.0	5.3	2.5 ± 1.3
						70	15 to 70	0.7	10.4	
						135 ± 20	50 to 600	1.0	12.7	3.0 ± 0.6
						615 ± 20	50 to 600	1.3	15.6	3.7 ± 0.7
						760 ± 20	50 to 240	1.8	9.5	4.6 ± 2.2
						455 ± 20				
Elsinore (E4)	Wildomar fault, Murrieta, California	33.50/ 117.25	RL	9	11	10	2.358 + 0.371/ −0.029	3.3	4.7	4.2
Elsinore (E5)	Coyote Mountains	32.8/ 116.2	RL			40	Holocene			4.0 ± 1
Whittier (E6)	Brea, California	33.80/ 117.60	RL	8.6			10			0.95 ± 0.1
				14.5			14			
Whittier (E7)	Yorba Linda	33.75/ 117.60	RL					2.5	3.0	
						18	14			1.3
Chino (E8)	near Prado Dam	33.90/ 117.65	R.Rev			7.6	125			0.06
Newport–Inglewood, Palos Verdes, and Rose Canyon Fault Zones										
Newport-Inglewood (N1)	Baldwin Hills	34.05/ 118.37	RR?	60			100 to 500	0.1	0.6	
Newport-Inglewood (N2)	Bolsa Chica Mesa	33.71/ 118.05	RR?	12			10 to 126	0.1	1.2	
Newport-Inglewood (N3)	Bolsa Gap	33.71/ 118.03	RR?	6			1 to 11	0.6	6	0.6

Southern California Slip Rates

Historical and Paleo Earthquakes	Offset Feature	Dating Method	Reference	Comments
	alluvial fan surfaces	soil correlation	Millman and Rockwell (1986)	Soil chronosequence developed by comparison of 75 soil profiles in Temescal Valley to dated soils in Ventura Basin. Authors assume overlap rates are representative of long-term slip rate. Rates are only for horizontal separation. Horizontal to vertical ratio of slip may be 2:1 in Temescal Valley [see Rockwell et al. (1986)].
post 1660 A.D. 1360 to 1660 A.D. ~1300 A.D. 1260 to 1275 A.D. ~1060 A.D.	marsh deposits	^{14}C	Rockwell *et al.* (1985, 1986)	Paleoearthquakes produced 2 to 30 cm of apparent vertical offset in trench exposures. Authors interpret maximum recurrence of 250 yr for surface rupturing events. Note that preferred estimate of horizontal slip rate at site Millman and Rockwell (1986) is 5 to 6 mm/yr, which suggests horizontal slip events of (<250 × 5 to 6 mm/yr) 1.25 to 1.5 m.
	alluvial fan, landslide, and fluvial terrace deposits.	soil correlation	Vaughan and Rockwell (1986)	Soil chronosequence developed by comparison to soil development in southern and central California, as no datable material found in any of older deposits. Minimum ages for late Holocene deposits placed by radiocarbon dates of archaeological sites. Offsets are horizontal separation only. Authors quote "horizontal offset seems to be best bracketed by a slip rate range of 1.5 to 7 mm/yr, with an average best estimate of about 3–6 mm/yr."
	channel	^{14}C	Bergman *et al.* (1993)	This rate could be higher if the Willard fault, the Murrieta Creek fault, or the Murrieta Hot Springs fault have experienced significant slip in the late Holocene.
	alluvial fan	soil correlation	Rockwell and Pinault (1986)	
	single system of nested feeded channels	^{14}C	Gath *et al.* (1992)	This data suggests a minimum dextral slip rate of 0.95 ± 0.1 mm/yr for one strand of the Whittier fault. Based on the similarity in the amount of right-deflection of the creek across both faults, a minimum slip rate of about 2 mm/yr is reasonable for the Whittier fault zone at Brea, California.
	alluvial fan	^{14}C	Rockwell *et al.* (1992a)	Two strands display similar deflection of the channel deposits suggesting that they carry similar amounts of late Quaternary slip. Therefore, the two strands may distribute about 2.6 mm/yr of dextral slip. The slip rate for the Whittier fault is about half that estimated for the Elsinore fault. Therefore, Rockwell *et al.* (1992) suggest that 2.6-mm/yr slip rate may be accommodated by the Chino fault.
	channel deposits	dated paleosol	Heath *et al.* (1982)	Surface and subsurface geologic mapping. Subsurface studies included six trenches excavated across photo lineament east and southeast of Prado Dam spillway and a line of eight borings were drilled across the zone in this same area.
	alluvial terrace	soil correlation	Clark *et al.* (1984)	Rates based on vertical separation. Horizontal slip may be greater.
	land surface	topo map correlation	Clark *et al.* (1984)	Rates based on vertical separation. Horizontal slip may be greater.
		water well correlations	Clark *et al.* (1984)	Rates based on vertical separation. Horizontal slip may be greater.

Table 1—*Continued.* Onshore

Fault	Location	Lat/Lon	Fault Type	Slip (m) Mn	Slip (m) Mx	Slip (m) Pr	Age of Offset (kyr)	Slip Rate (mm/yr) Mn	Slip Rate (mm/yr) Mx	Slip Rate (mm/yr) Pr
Palos Verdes (N4)	San Pedro Shelf	33.70/ 118.23	RR7	3			>10			0.3
Palos Verdes (N5)	San Pedro Shelf	33.58/ 118.11	RR?	3			30 to 130	0.02	0.1	
Palos Verdes (N6)	Palos Verdes Peninsula	33.75/ 118.35	RR/							3.0
Rose Canyon (N7)	San Diego	32.7/ 117.1	RL	8.7			8.159 + 0.23/ −0.20	1.07 ± 0.03		
Transverse Ranges Faults										
San Gabriel Range Front										
Sierra Madre (T1)	Sunland to Glendora	34.25/ 118.25	R				Pleistocene			
Sierra Madre (T2)	Dunsmore Canyon	34.25/ 118.25	R			4	1 to 11	0.36	4.0	
Sierra Madre (T3)	Gould Mesa	34.21/ 118.19	R			600	200 to 500	1.2	3.0	
Sierra Madre (T4)	Jet Propulsion Laboratory	34.2/ 118.17	R			244	200 to 500	0.5	>1.2	
San Fernando (T5)	Oak Hill	34.1/ 118.4	R							
San Gabriel (T6)	northwestern terminus	34.8/ 118.9	RR	500	1000		1000 to 5000 late Pliocene to mid Pliestocene	0.5	1	
Cucamonga (T7)	Day Canyon	34.17/ 117.53	R			36	10 to 13	4.5 to 5.5		
Raymond (T8)	Sunnyslope reservoir	34.13/ 118.09	LR					0.10	0.22	0.13
Western Transverse Ranges										
Hollywood (T9)	Atwater School	34.12/ 118.30	LR?	2	3		4 to 6	0.33	0.75	
Santa Monica (T10)	Portrero Canyon	34.03/ 118.53	LR?	34	47		122 to 126	0.27	0.39	

Southern California Slip Rates

Historical and Paleo Earthquakes	Offset Feature	Dating Method	Reference	Comments
	seismic reflector	correlation with nearby cores	Clark *et al.* (1984) Darrow and Fisher (1983)	Rates based on vertical separation. Horizontal slip may be greater. Reflector assumed to be base of Holocene Gaspar formation.
	seismic reflector	correlation with nearby cores	Clark *et al.* (1984) Darrow and Fisher (1983)	Rates based on vertical separation. Horizontal slip may be greater.
	terrace on flank of Palos Verdes anticline	age of terrace and absolute dating of deformed rock	Valensise and Ward (1992)	The slip rate of the Palos Verdes fault was independently calculated based on the age of one of the best investigated terraces and on absolute dating of the deformed bedrock.
	gravel-filled channel	^{14}C	Rockwell *et al.* (1992)	Trenches demonstrate a minimum of 8.7 m of right-lateral slip and less than 1 m of dip slip. Other strands of the Rose Canyon fault zone are mapped to the east and west of this site and if they carry slip than the rate determined may substantially underestimate the total seismic slip rate for the entire fault zone.
	alluvial fan deposits	^{14}C	Crook *et al.* (1987)	Study of 33 trench exposures along the fault zone between Sunland and Glendora revealed no evidence of Holocene movement, leading authors to speculate a recurrence time >5000 yr for individual sections of the fault zone.
	alluvial fan surface	soil development	Clark *et al.* (1984)	Reinterpretation of data presented in Crook *et al.* (1987). The rate calculation assumes vertical separation approximates vertical displacement. Horizontal component may be present.
	alluvial deposits	soil development	Clark *et al.* (1984)	Reinterpretation of data presented in Crook *et al.* (1987). The rate calculation assumes vertical separation approximates vertical displacement and is for entire width of fault zone.
	alluvial deposits	soil development	Clark *et al.* (1984)	Reinterpretation of data presented in Crook *et al.* (1987). The rate calculation assumes vertical separation approximates vertical displacement and is across Bridge strand only. Horizontal component may be present.
1971 A.D. 100 to 300 yr B.P.	colluvium	^{14}C	Bonilla (1973)	Radiocarbon date of 100 to 300 yr b.p. on wood recovered in displaced pre-1971 scarp colluvium is basis to interpret two large events during last 100 to 300 yr. Trench across subsidiary fault strand which also broke in 1971. Penultimate offset greater than 1971.
	alluvial, fan, and landslide deposits		Weber (1979)	Based on Pleistocene subunits of Saugus Formation in Honor Rancho area (dated 1 to 5 m.y.)
see comments	alluvil fan surface	soil development and ^{14}C	Morton and Matti (1987)	Vertical component of slip (36 m) is cumulative across 3 strands. Uncertainty in slip rate reflects both uncertainty in fault dip and time period over which slip occurred. Authors also interpret age of offset distribution on individual fault strands to interpret a 684-yr repeat time for 2-m ground-rupture events.
evidence for at least eight events during last 36,000 yr interpreted from sequence of trench exposures. Youngest event Holocene.	sag pond deposits	^{14}C	Crook *et al.* (1987)	Assumes sedimentation rates based on ^{14}C dates in sequence of sag pond deposits are equal to rates of vertical separation during the last 36,000 yr. Rates of sedimentation based on mean values from nine samples from different depths. Horizontal component may also be present.
	river terrace surface	soil correlation	Clark *et al.* (1984)	Assumes that degraded scarps on terrace are fault-produced and that vertical separation approximates vertical offset. Rate determined by Clark *et al.* (1984) from data in Weber (1980).
	marine wave-cut platform	paleontology, amino acids, geomorphology, and dated sea level curve	Clark *et al.* (1984)	Assumes that vertical separation approximates vertical offset. Rate determined from data in McGill (1981, 1982).

Table 1—*Continued.* Onshore

Fault	Location	Lat/Lon	Fault Type	Slip (m) Mn	Slip (m) Mx	Slip (m) Pr	Age of Offset (kyr)	Slip Rate (mm/yr) Mn	Slip Rate (mm/yr) Mx	Slip Rate (mm/yr) Pr
Santa Monica-Malibu Coast (T11)		34.03/ 118.53	LR	100 16,000			20 4 to 5	3	5	
Malibu Coast (T12)	Marie Canyon	34.04/ 118.71	R	8.5	16.3		185 to 200	0.04	0.09	
Malibu Coast (T13)	Corral Canyon	34.04/ 118.73	R			5	185 to 200	0.03	0.03	
Santa Susana (T14)	Aliso Canyon	34.32/ 118.55	R			>4000	500 to 2000	>2	>8	
Santa Susana (T15)	Tapo Canyon area	34.36/ 118.71	R							
San Cayetano (T16)	Sisar Creek	34.45/ 119.13	R			13	15 to 20	>0.85	>1.25	
San Cayetano (T17)	Bear Canyon	34.44/ 119.12	R	8 129	10 141	9 135	8 to 12 80 to 200	0.95 1.85	1.75 2.45	1.35 2.15
San Cayetano North Strand (T18)	Mud Creek	34.42/ 119.01	R	29	35		15 to 20	1.8	2.9	2.35
San Cayetano (T19)	Timber Canyon	34.43/ 119.01	R	16 1375	20 1675		<5 160 to 200	>3.2 6.8	>4.0 10.6	8.7
San Cayetano (T20)	Fillmore	34.40/ 118.86	R			9000	1000			9
San Cayetano (T21)	Fillmore	34.40/ 118.86	R							7
Big Pine (T22)		34.65/ 119.30	L			13,000 16,000	1800 to 6,000	2	7	4
Oak Ridge (T23)	Fillmore	34.38/ 118.86	R			3500	1000			3.5
Oak Ridge (T24)	Santa Paula	34.35/ 119.05	R	2375	2490		200 to 400	5.9	12.5	
Red Mountain main strand (T25)	Javos Canyon	34.35/ 119.40	R?			27.4	45 to 60	0.5	>0.7	
Red Mountain South Strand (T26)	Punta Gorda	34.26/ 119.44	R?	22.8	26.3		45 to 60	0.4	0.6	
Red Mountain South Strand (T27)	Punta Gorda	34.37/ 119.45	R?	60	69		45 to 60	1.1	1.5	
Red Mountain North Strand (T28)	Punta Gorda	34.37/ 119.44	R	29.5	34.1		45 to 60	0.5	0.8	
Red Mountain (T29)	Lake Casitas	34.34/ 119.34	R	200	3500		250 ± 50	0.7	18	
Ventura (T30)	Ventura	34.28/ 119.25	LR?	12	13.9		5.7 to 15	0.8	2.4	

Southern California Slip Rates

Historical and Paleo Earthquakes	Offset Feature	Dating Method	Reference	Comments
	stream courses slate		Molnar (1991)	
	marine wave-cut platform	correlation	Clark *et al*. (1984)	Assumes that vertical separation approximates vertical offset. Rate determined by Clark *et al*. (1984) from Yerkes and Wentworth (1965) and other unpublished data.
	marine wave-cut platform	paleontology, amino acids, geomorphology	Clark *et al*. (1984)	Assumes that vertical separation approximates vertical offset. Rate determined by Clark *et al*. (1984) from Yerkes and Wentworth (1965) and other unpublished data.
	Modelo formation	correlation	Yeats (1987)	Offset is stratigraphic separation. True offset likely much larger.
Probable age of last movement > 10,000 yr B.P.		^{14}C is peatlike layers	Lung and Weick (1987)	Fault not observed in trench presumably emplaced over fault trace. Inferred that any fault movement predated age of unbroken "peatlike layers."
	fluvial terrace	soil development	Rockwell (1988)	Rate determined from vertical offset measurement and assuming fault dips at 45°.
	alluvial fan surfaces	soil development	Rockwell (1988)	Rate determined from vertical offset measurement and assuming fault dips at 45°.
	alluvial fanhead	soil development	Rockwell (1988)	Rate determined from vertical offset measurement and assuming fault dips at 53°.
	alluvial fan surfaces	soil development and ^{14}C	Rockwell (1988)	
	base of Saugus	correlation	Yeats (1983)	Interpreted by author based on Figure 11 of Yeats (1983).
			Molnar (1991)	Interpreted cross sections of Yeats (1983) and Rockwell (1988) so that the cross section is taken perpendicular to the strike of the structure and obtains a slightly lower slip rate then they did.
	Ozena fault and Maldulce Syncline	fault displaces late Pliocene sediments	Molnar (1991)	Rate determined by looking at maps of Hill and Dibblee (1953).
	base of Saugus	correlation	Yeats (1983)	Interpreted by author based on Figure 11 of Yeats (1983).
	top of Saugus formations	correlation	Yeats (1988)	
	marine platform	amino-acid and U-series	Clark *et al*. (1984)	Slip rate based on interpretation of a number of reports: Lajoie *et al*. (1982); Lee *et al*. (1979); Sarna-Wojcicki *et al*. (1979); Yeats, 1982; Yerkes and Lee (1979), and Yeats *et al*. (1987).
	marine platform	amino-acid and U-series	Clark *et al*. (1984)	Slip rate based on interpretation of a number of reports (Lajoie *et al*., 1982; Lee *et al*., 1979; Sarna-Wojcicki *et al*., 1979; Yeats, 1982; Yerkes and Lee, 1979; and Yeats *et al*., 1987).
	marine platform	amino-acid and U-series	Clark *et al*. (1984)	Slip rate based on interpretation of a number of reports (Lajoie *et al*., 1982; Lee *et al*., 1979; Sarna-Wojcicki *et al*., 1979; Yeats, 1982; Yerkes and Lee, 1979; and Yeats *et al*., 1987).
	marine platform	amino-acid and U-series	Clark *et al*. (1984)	Slip rate based on interpretation of a number of reports (Lajoie *et al*., 1982; Lee *et al*., 1979; Sarna-Wojcicki *et al*., 1979; Yeats, 1982; Yerkes and Lee, 1979; Yeats *et al*., 1987).
	Casitas formation	correlation	Huftile and Yeats (1992)	Slip rate reflects interpreted shortening rate, assuming that Red Mountain fault flattens to horizontal at depth.
	alluvial fan surface	^{14}C and amino-acid racemization	Clark *et al*. (1984)	Rate calculated from observations in a number of reports (Gardner and Stahl, 1977; Lee *et al*. 1979; Sarna-Wojcicki *et al*. 1976; Sarna-Wojcicki and Yerkes, 1982; Yeats, 1982; Yerkes and Lee, 1979). Rate calculation assumes fault dip of 60° to 90°. May be a nonseismogenic bending moment to fault (Yeats, 1982), although evidence considered inconclusive (Clark *et al*., 1984).

Table 1—*Continued*. Onshore

Fault	Location	Lat/Lon	Fault Type	Slip (m) Mn	Slip (m) Mx	Slip (m) Pr	Age of Offset (kyr)	Slip Rate (mm/yr) Mn	Slip Rate (mm/yr) Mx	Slip Rate (mm/yr) Pr
Javon Canyon (T31)	Javon Canyon	34.34/ 119.40	R			4	3.5			1.1
				42	49		45	>0.9	>1.1	
Padre Juan (T32)	Javon Canyon	34.34/ 119.39	R?			61	45 to 60	1.0	>1.4	
Padre Juan (T33)	Javon Canyon	34.34/ 119.40	R?			24	45 to 60	0.4	0.5	
Villanova (T34)	Ventura River	34.43/ 119.28	R			11 ± 0.3	28.5 to 30.9			0.37 ± .02
						14 ± 0.3	36.5 to 39.5			0.37 ± .02
La Vista (T35)	Ventura River	34.42/ 119.29	R(v)			11 ± 0.3	28.5 to 30.9	0.35	0.40	0.37 ± .02
						15 ± 3	36.5 to 39.5	0.37	0.42	0.39 ± .02
						41 ± 3	44 to 64	0.59	1.0	0.76
						98 ± 3	79 to 105	0.90	1.27	1.07
Devil's Gulch (T36)	Ventura River	34.41/ 119.30	R			18 ± 0.3	36.5 to 39.5			0.47 ± .02
				47	59	37 ± 3	44 to 64	0.73	1.34	0.69
Oak View (T37)	Ventura River	34.41/ 119.28	R(v)	23	33	19 ± 3	44 to 64	0.25	0.50	0.35
Thorpe (T38)	Timber Canyon	34.41/ 119.01	N	3.0	10.6		4.5 to 5	0.6	2.4	
				13	24		25 to 30	0.43	0.96	
				116	141		160 to 200	0.58	0.88	
Culbertson (T39)	Timber Canyon	34.40/ 119.01	N	0	6		4.5 to 5		0 to 1.3	
				1.6	9.1		25 to 30		0.05 to 0.36	
				37	49		160 to 200		0.19 to 0.31	
Rudolf (T40)	Orcutt Canyon	34.39/ 119.04	R	3	9		4.5 to 5	0.6	2	
				23	29		25 to 30	0.77	1.2	
				60	64		80 to 100	0.6	0.8	
Orcutt (T41)	Orcutt Canyon	34.40/ 119.05				?				
Arroyo Panda-Santa Ana (T42)	Ventura River	34.43/ 119.29	R?			11 ± .3	29.7 ± 1.25			0.37 ± .02
						14 ± .3	38 ± 1.5			0.37 ± .02
More Ranch (T43)	Goleta	34.42/ 119.88	R?			10	40 to 60	0.2	>0.3	>0.3
South Santa Ynez (T44)	Alegria Canyon	34.49/ 120.27	LV			3	5 to 15	0.2	>0.6	0.4
Santa Ynez North Strand (T45)	Blue Canyon	34.49/ 119.60	LV			34	10 to 700	0.05	3.4	0.3
Santa Ynez South Strand (T46)	Blue Canyon	34.49/ 119.60	LV			67	10 to 700	0.1	6.7	0.7
Santa Ynez South Strand (T47a)	near Blue Canyon	34.5/ 119.6	LV			5	80 to 105			0.1
Eastern Transverse Range										
Cleghorn (T47)	Cleghorn Road	34.29/ 117.38	IL				Quaternary	1.5	18.0	3.0
Ord Mountain (T48)	northwest flank	34.41/ 117.20	R(v)				Quaternary		1.2	0.1
Sky High Ranch (T49)	Fifteen Mile Valley	34.4/ 117.0	RL				Quaternary	0.3	15.0	1.3
Pinto Mountain (T50)		34.1/ 116.3	LL				Miocene	0.3	5.3	1.0

Southern California Slip Rates

Historical and Paleo Earthquakes	Offset Feature	Dating Method	Reference	Comments
3500 B.P. 2975 B.P. 1830 B.P. 1475 B.P. 425 B.P.	stream terrace platform marine terrace	^{14}C correlation, U-series, ^{14}C	Sarna-Wojcicki *et al.* (1987)	Fault shows stratigraphic evidence of five rapid displacements with throw ranging from 0.4 to 1.3 m, respectively, during the last 3500 yr but inferred to be flexural slip fault and, hence, nonseismogenic by Yeats (1982). However, Sarna-Wojcicki *et al.* (1987) indicate that whether or not fault is bedding-plane fault is irrelevant to hazard potential.
	marine platform	amino-acid and U-series	Clark *et al.* (1984)	Reported from Sarna-Wojcicki *et al.* (1979) and Yeats (1982). Rate reflects vertical component only.
	marine platform	amino-acid and U-series	Clark *et al.* (1984)	Reported from Sarna-Wojcicki *et al.* (1979) and Yeats (1982). Rate reflects vertical component only.
	river terrace surface	soil development and ^{14}C	Rockwell *et al.* (1984)	Fault parallels bedding and may represent flexural slip along overturned limb of fold.
	river terrace surfaces	soil development and ^{14}C	Rockwell *et al.* (1984)	Fault parallels bedding and may represent flexural slip along overturned limb of fold.
	river terrace surfaces	soil development and ^{14}C	Rockwell *et al.* (1984)	Fault parallels bedding and may represent flexural slip along overturned limb of fold.
	river terrace surface	correlation	Rockwell *et al.* (1984)	Fault parallels bedding and may represent flexural slip along overturned limb of fold.
	alluvial fan surfaces	soil development, dendrochronology and ^{14}C	Clark *et al.* (1984)	Reported from Rockwell (1983). Fault parallels bedding and may represent flexural slip along overturned limb of fold.
	alluvial fan surfaces	soil development and ^{14}C	Clark *et al.* (1984)	Reported from Rockwell (1983). Fault parallels bedding and may represent flexural slip along overturned limb of fold.
	alluvial fan surfaces	soil development, dendrochronology and ^{14}C	Clark *et al.* (1984)	Data and interpretation reported from Rockwell (1983). Fault parallels bedding and may represent flexural slip along overturned limb of fold.
	river terrace surfaces	soil development	Rockwell *et al.* (1984)	Fault progressively offsets four terraces of the Ventura River. Dip of fault not known. Vertical separation assumed to equal vertical displacement. Horizontal slip may also be present.
	marine wave-cut platform	paleontology and amino acids	Clark *et al.* (1984)	Assumes vertical separation equals displacement. Horizontal component may be present.
	fluvial gravels	geomorphology and sea-level curve	Clark *et al.* (1984)	Vertical component only. Horizontal component is small (<50 m).
	river terrace surface and incised stream channels	inferred	Clark *et al.* (1984)	Rate calculated from observations in Keaton (1978).
	river terrace surface and incised stream channels	inferred	Clark *et al.* (1984)	Rate calculated from observations in Keaton (1978).
	terrace deposits		Rockwell *et al.* (1992b)	This is a vertical slip rate. The strike-slip rate is inferred to be as great but not greater than the vertical slip rate.
	stream offsets		Meisling (1984)	Information from Wesnousky (1986).
			Meisling (1984)	Information from Wesnousky (1986).
			Meisling (1984)	Information from Wesnousky (1986).
			Anderson (1979)	Information about Wesnousky (1986).

Table 1—*Continued*. Onshore

Fault	Location	Lat/Lon	Fault Type	Slip (m) Mn	Slip (m) Mx	Slip (m) Pr	Age of Offset (kyr)	Slip Rate (mm/yr) Mn	Slip Rate (mm/yr) Mx	Slip Rate (mm/yr) Pr
Mojave Faults										
Calico-Blackwater (M1)	Rodman Mountains	34.73/ 116.58	RL	8500	9600		2000 to 20,000	0.43	4.8	2.6
Camp Rock (M2)	Newberry Mountains	34.73/ 116.78	RL	1600	4000		2000 to 20,000	0.08	2	1.0
Helendale (M3)	Interstate 15	34.68/ 117.22	RL			3000	2000 to 20,000	0.15	1.5	0.8
Lenwood (M4)	Newberry Mountains	34.75/ 117.22	RL	1500	3000		2000 to 20,000	0.05	1.5	0.8
Rodman-Pisgah (M5)	Lava Bed Mountains	34.65/ 116.45	RL	6400	14,400		2000 to 20,000	0.32	7.2	3.8
Bristol Mountain (M6)		34.86/ 116.0	Rl	6000			2000 to 20,000	>0.3	>3.0	1.7
Gravel Hills-Harper (M7)		35.19/ 117.4	RL		3200		2000 to 20,000	<0.16	<1.6	0.9
Pisgah (M8)	Sunshine Cone lava field	34.6/ 116.4	RL				late Quaternary			0.8
Homestead Valley (M9)		34.1/ 116.4	RL			3	late Pleistocene-Holocene	0.4	0.6	
Emerson (M9)		34.1/ 116.4	RL	2	6		9	0.2	0.7	
Northern Johnson Valley (M9)		34.1/ 116.4	RL							
Garlock Fault										
Garlock (G1)	Oak Creek	35.04/ 118.40	LL	200	300		90 to 190	1	3	2
Garlock (G2)	Koehn Creek	35.37/ 117.85	LL	75	85		11 to 15	5	8	7
Garlock (G3)	Mesquite Canyon	34.43/ 117.72	LL	16,000	20,000		<650 to 3000	5	>30	11
Garlock (G4)	Christmas Canyon	35.52/ 117.37	LL	7000	9000		8 to 10	0.7	1.1	1
Garlock (G5)	Searles Valley	35.48/ 117.65	IL	81.6	105.6	90.3	10 to 13.8	4	9	5 to 7

Southern California Slip Rates

Historical and Paleo Earthquakes	Offset Feature	Dating Method	Reference	Comments
	Kane Springs fault	fossils and K-Ar	Dokka (1983) Dokka and Travis (1990a, b)	Dokka and Travis (1990a, b) preferred age for initiation of faulting in 6 to 10 m.y.b.p. Preferred slip rate based on mean of the minimum and maximum slip rates.
	Kane Springs fault	fossils and K-Ar	Dokka (1983) Dokka and Travis (1990a, b)	Dokka and Travis (1990a, b) preferred age for initiation of faulting in 6 to 10 m.y.b.p. Preferred slip rate based on mean of the minimum and maximum slip rates.
	pluton	inferred	Dokka (1983) Dokka and Travis (1990a, b) Miller and Morton (1980), Miller (1980)	Dokka and Travis (1990a, b) preferred age for initiation of faulting in 6 to 10 m.y.b.p. Preferred slip rate based on mean of the minimum and maximum slip rates.
	Kane Springs fault	fossils and K-Ar	Dokka (1983) Dokka and Travis (1990a, b)	Dokka and Travis (1990a, b) preferred age for initiation of faulting in 6 to 10 m.y.b.p. Preferred slip rate based on mean of the minimum and maximum slip rates.
	Kane Springs fault	fossils and K-Ar	Dokka (1983) Dokka and Travis (1990a, b)	Dokka and Travis (1990a, b) preferred age for initiation of faulting in 6 to 10 m.y.b.p. Preferred slip rate based on mean of the minimum and maximum slip rates.
			Dokka (1983) Dokka and Travis (1990a, b)	Dokka and Travis (1990a, b) preferred age for initiation of faulting in 6 to 10 m.y.b.p. Preferred slip rate based on mean of the minimum and maximum slip rates.
			Dokka (1983) Dokka and Travis (1990a, b)	Dokka and Travis (1990a, b) preferred age for initiation of faulting in 6 to 10 m.y.b.p. Preferred slip rate based on mean of the minimum and maximum slip rates.
	Sunshine Cone lava field		Hart *et al.* (1988)	In addition, Late Quaternary geomorphic features just north of Hidalgo Mountain suggest a slip rate for the West Calico fault that is comparable to the Pisgah fault (about 0.5 to 1 mm/yr).
1992 5.7 to 8.5 ka 12.5 to 14 ka	alluvial fan and playa deposits	^{14}C	Hecker *et al.* (1993)	Site is located where slip in the 1992 Landers earthquake was 3 m and vertical slip was 0.4 m. Apparent vertical displacement for the penultimate event is 35 to 40 cm, similar to the 1992 diplacements.
1992 9 ka 14.8 to 24.1 ka	soils	^{14}C	Rubin and Sieh (1993)	The previous event had similar displacement to the 1992 offset at the site they studied.
1992 9.1 to 9.4 ka 9.4 to 9.5 ka	soils	^{14}C	Herzberg and Rockwell (1993)	The previous event produced a scarp and rupture over a 15-m-wide zone, similar to the width of the 1992 rupture. However, the event between 9.4 and 9.5 ka is only represented by minor displacement and may have been caused by triggered slip or a much smaller event.
post 890 ± 195 yr B.P.	stream channels	correlation	Clark *et al.* (1984) LaViolette *et al.* (1980)	Reported from La Violette *et al.* (1980) although Clark *et al.* (1984) note that 200 to 300 m of offset may be estimated from Figure 2 of the article.
9 to 17 events in past 15 ka yr	lake bar	^{14}C on tufa and shell	Clark *et al.* (1984)	Based on data published in abstract form only (Burke and Clarke, 1978; Clark and Lajoie, 1974). Clark *et al.* (1984) note that soil on bar suggests older age for bar deposit than used for slip rate calculation.
	alluvial gravels	fossils	Clark *et al.* (1984)	Based on data from Carter (1980, 1982).
	former stream channel	^{14}C and correlation	Clark *et al.* (1984)	Rate based on data from Smith (1975).
post 1490 A.D.	Pleistocene lake shoreline	^{14}C	McGill and Sieh (1991)	Rate estimate incorporates (Bard *et al.* 1990) calibration of radiocarbon timescale. Offset geomorphic features indicate past several earthquakes involved 2 to 3 m slip. Using slip rate of 4 to 9 mm/yr they suggest a recurrence interval of 200 to 750 yr for large earthquakes.

Table 1—*Continued.* Onshore

Fault	Location	Lat/Lon	Fault Type	Slip (m) Mn	Slip (m) Mx	Slip (m) Pr	Age of Offset (kyr)	Slip Rate (mm/yr) Mn	Slip Rate (mm/yr) Mx	Slip Rate (mm/yr) Pr
Garlock (G6)	El Paso Mountains	35.37/ 117.84	LL				Holocene	4	7	
Garlock (G7)	Pilot Knob Valley	35.60/ 116.96	LL				Holocene	3	9	
Garlock (G8)	Leach Lake and Avawatz Mtns.	35.60/ 116.45	LL				Holocene	1	9	
Garlock (Owl Lake) (G9)	Quail Mountains	35.62/ 116.90	LLN	43	80		30 to 34	1	3	

earthquake (M_L 5.9) that ruptured the Mission Creek and Banning faults, respectively (Richter *et al.*, 1958; Jones *et al.*, 1986; Nicholson, 1992). In addition, the highest background seismicity in southern California is also located in the vicinity of San Gorgonio Pass, where the seismicity is diffuse and does not clearly identify any particular fault (Fig. 2; Hill *et al.*, 1990). Seismicity extends to depths between 15 and 22 km along this section of the southern San Andreas (Fig. 4).

Fault Slip Rate Studies. Immediately south of the junction of the San Andreas and San Jacinto faults and within Cajon Pass (Fig. 2), Weldon and Sieh (1985) obtained four independent estimates of the slip rate. Their work limits slip on the San Andreas at this site to 24.5 ± 3.5 mm/yr for the past 14,400 yr. Farther to the south near Yucaipa, along the Mission Creek and San Gorgonio Pass fault zones, Harden and Matti (1989) used soil age estimates and offset alluvial fans to interpret a slip rate of 14 to 25 mm/yr over the last 14,000 yr, but admit minimum and maximum estimates of 11 mm/yr and 35 mm/yr. Yet, farther to the south, near Indio, Keller *et al.* (1982a) interpret a 0.7-km cumulative offset of an alluvial fan, whose age is estimated by soil profile development to range between 20,000 and 70,000 yr. From these observations, they suggest a slip rate for the southern San Andreas between 10 and 35 mm/yr with a best estimate of between 23 and 35 mm/yr. Bonkowski (1981) also indicated that numerous earthquakes have occurred during the latest Pleistocene, each of which were associated with displacements of at least several meters. In that same region, Sieh (1986) interpreted displaced lacustrine beds to reflect a 30 mm/yr slip rate during the period of about 1000 to 1700 A.D. Further study of the Indio region by Sieh and Williams (1990), however, indicates that slip has occurred by creep along the fault between Indio and Bombay Beach and averaged only 2 to 4 mm/yr during the last 300 yr or so. They interpret the creep to reflect motion in only the upper few kilometers of the crust, and note that wide-aperture geodetic measurements over the past 2 decades indicate higher rates of strain more consistent with the 30 mm/yr slip rate found for the period 1000 to 1700 A.D. (Prescott *et al.*, 1987; Savage *et al.*, 1981).

Paleoearthquake Data. Direct evidence of paleoearthquakes is limited to sites at Cajon Pass and Indio. Excavations at Cajon Pass provided Weldon and Sieh (1985) tentative evidence for six earthquakes during the past 1000 yr and led them to suggest an average recurrence interval for large earthquakes of 1.5 to 2 centuries. Similarly, Sieh and Williams (1990) observed evidence of dextral slip events of > 2 m and recurrence of large earthquakes on average every 2 to 3 centuries in trenches across the San Andreas near Indio.

A synopsis of the fault slip rate and paleoearthquake

Southern California Slip Rates

Historical and Paleo Earthquakes	Offset Feature	Dating Method	Reference	Comments
			McGill and Sieh (1991)	Used Clark and Lajoie (1974) value of slip rate and calibrated it from 5 to 8 mm/^{14}C-yr to 4 to 7 mm/yr. Offset geomorphic features indicate past several earthquakes involved 4 to 7 m slip. Using a slip rate of 4 to 7 mm/yr they suggest a recurrence interval of 600 to 1200 yr for large earthquakes.
			McGill and Sieh (1991)	Used slip rate upper bound of 9 mm/yr and lower rate of 3 mm/yr from offset Pleistocene shoreline (McGill and Sieh, 1991). The lower bound is reduced from 4 to 3 mm/yr since some slip may be accommodated by a nearby active fault. Offset geomorphic features indicate past several earthquakes involved 2 to 4 m slip. Using a slip rate of 3 to 9 mm/yr they obtained a recurrence interval of 200 to 1300 yr for large earthquakes.
			McGill and Sieh (1991)	Used slip rate upper bound of 9 mm/yr and lower rate of 1 mm/yr from offset Pleistocene shoreline (McGill and Sieh, 1991). The lower bound is reduced from 4 to 1 mm/yr since some slip may be accommodated by nearby active faults. Offset geomorphic features indicate past several earthquakes involved 2 to 3 m slip. Using a slip rate of 1 to 9 mm/yr they suggest a recurrence interval of 200 to 3000 yr for large earthquakes.
	channel wall	^{14}C	McGill (1993)	Dated weathering rind beneath varnish.

data for the entire southern San Andreas is provided in Table 1 and locations are shown in Figure 1.

San Jacinto and Imperial Faults

The San Jacinto and Imperial faults comprise a 300-km-long zone that is composed of several subparallel fault strands, separated by en-echelon steps as large as 4 to 8 km (Fig. 5). Fault slip is primarily right lateral, although significant vertical motion may contribute up to 10% of the net slip (Brown, 1990). In addition, the zone is intersected by several left-lateral faults that trend northeast (Nicholson *et al.*, 1986; Hudnut *et al.*, 1989a; Petersen *et al.*, 1991). The cumulative offset across the zone is reported as 24 km (Sharp, 1967).

Historical Seismicity. Extensive summaries, interpretations, and earthquake history of the San Jacinto fault are given by Thatcher *et al.* (1975), Sanders and Kanamori (1984), Wesnousky (1986), Sanders (1989), Doser (1990), and Bent and Helmberger (1991a), and of the Imperial fault by Doser and Kanamori (1986). Seismicity between 1932 and 1992 is generally distributed along the entire length of the zone, and extends to depths ranging from about 12 km near the Superstition Hills fault, to about 18 km along the Coyote Creek and Clark faults (Fig. 5). The general decrease in the maximum depth of seismicity as one continues south along the fault has been attributed to higher heat flow near the southern portion of the fault (Doser and Kanamori, 1986).

The occurrence rate of moderate to large earthquakes is greater along the San Jacinto than any other fault zone in southern California (Fig. 5). The 25 December 1899 (*M* 7.1); 22 July 1899 (*M* 6.5), 23 July 1923 (*M* 6.3), and 21 April 1918 (*M* 6.8) earthquakes ruptured along or near the northernmost reach of the zone (Sanders and Kanamori, 1984; Sanders *et al.*, 1986; Thatcher *et al.*, 1975). It has been interpreted that the 1918 earthquake produced rupture along the Claremont strand, whereas the 25 December 1899 (*M* 7.1) produced offset along the Casa Loma strand of the fault zone (Sanders and Kanamori, 1984; Sanders *et al.*, 1986), but no firm evidence of surface rupture is known for any of these events. The 22 July 1899 and 1923 events may have ruptured the San Jacinto fault; however, the large uncertainties associated with locating historical events do not preclude the possibility that one or more of these earthquakes were the result of slip on other nearby faults (Sanders *et al.*, 1986).

Farther to the south, a relocation of the 1937 (M_L 5.9) epicenter and aftershocks places the event between the Buck Ridge and Clark faults, possibly along a northeast-striking cross-fault (Sanders *et al.*, 1986). The 1954 (M_L 6.2) event is located at the southeast end of the mapped trace of the Clark fault (Sanders *et al.*, 1986). The Borrego Mountain section of the fault ruptured in an M_L 6.8 earthquake in 1968, and produced surface ruptures along virtually the entire length of the segment (Clark, 1972). The 1968 earthquake (e.g., Hamilton, 1972) was followed by the smaller M_L 5.8 Coyote Creek earthquake, located immediately to the north, which did not produce surface rupture and which Petersen *et al.* (1991) suggest may have occurred along a northeast-trending fault. The 1942 M_L 6.5 earthquake has been relocated southwest of the southern end of the Coyote Creek fault (Sanders *et al.*, 1986), off the main traces of the San Jacinto fault zone. Doser (1990) suggests that this earthquake may also have occurred as a result of displacement on a northeast-striking cross-fault. Most recently, both the Superstition Hills segment as well as an intersecting cross-fault ruptured in M_L 6.6 and M_L 6.2 events, respectively, during November of 1987 (e.g., Hanks and Allen, 1989; Bent *et al.*, 1989; Sharp *et al.*, 1989).

The Imperial fault strikes southeastward from a point near Brawley to about 30 km beyond the Mexican border. Historical surface-rupturing events occurred in 1940

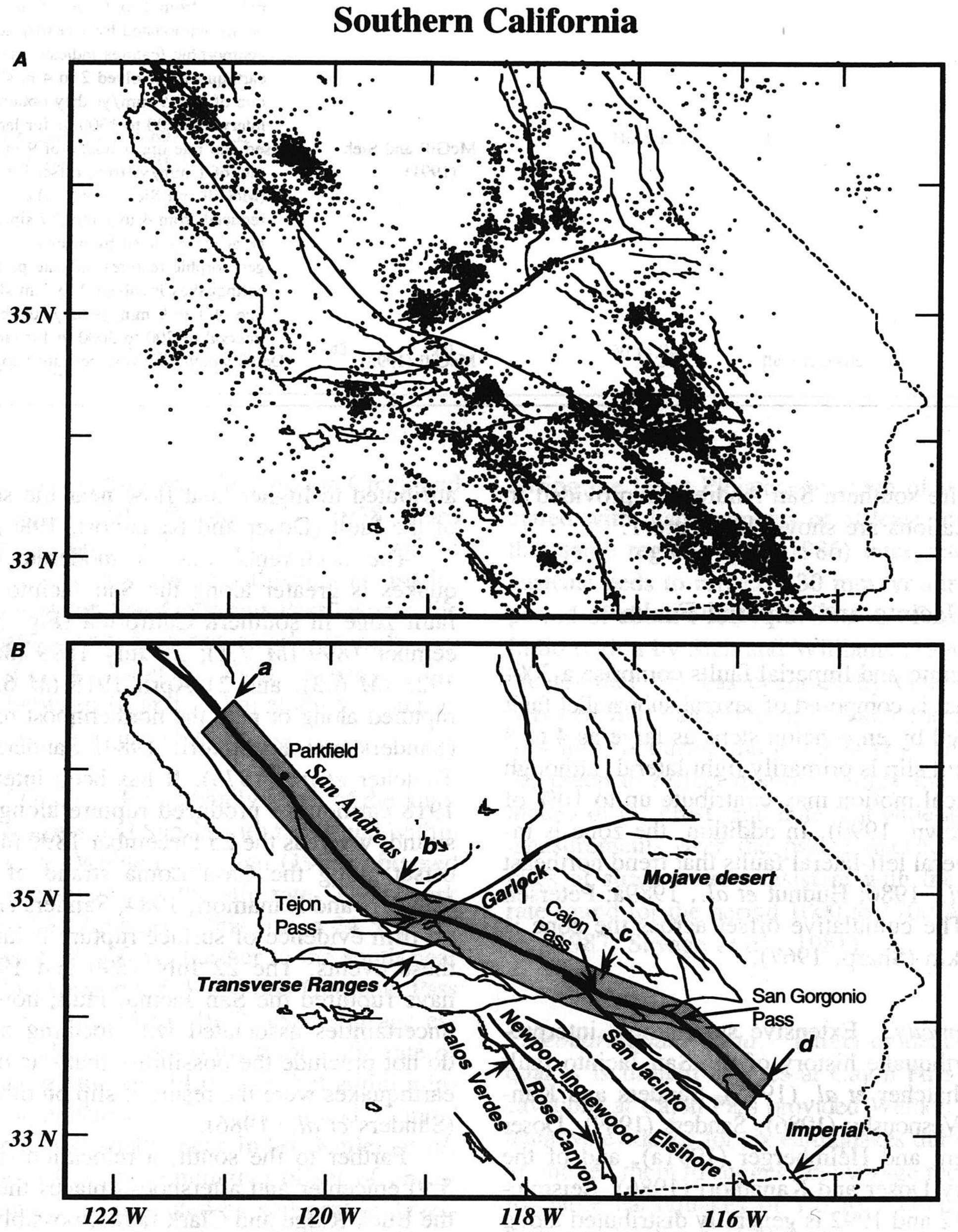


Figure 2. Maps showing (a) southern California seismicity (1932 through 1992 $M > 1.75$) recorded by CIT/USGS southern California network with faults and state outline, and (b) boxes showing regional faults, names used in text, and locations of earthquakes used for constructing cross sections between points a, b, c, and d (Fig. 4).

(M_L 7.1) and in 1979 (M_L 6.9) (Sharp *et al.*, 1982; Larsen and Reilinger, 1991) and a third event may have produced surface rupture at the northern end of the fault near Brawley in 1915 (Toppozada and Park, 1982). The 1940 earthquake produced surface rupture both north and south of the border, whereas the 1979 earthquake produced surface rupture just north of the border even though its epicenter was also located south of the border. This is consistent with the larger moment magnitude of the 1940 event (Trifunac, 1972).

Fault Slip Rate Data. Near San Bernardino the San Jacinto fault is composed of several subparallel strands. Mezger and Weldon (1983) interpreted offset terrace deposits to indicate a maximum horizontal slip rate of 2.5 mm/yr across the Lytle Creek fault (a northern extension and splay of the Claremont fault). This rate, however, probably does not reflect the entire deformation rate across this latitude of the San Jacinto fault zone (Morton, 1975). Within San Bernardino, an offset and buried stream channel has been interpreted to indicate a minimum slip rate of 1.7 to 3.3 mm/yr, but, again, the rate does not reflect offset across the entire fault zone (Wesnousky *et al.*, 1991). Immediately south of San Bernardino, Morton *et al.* (1986) interpret a displaced Pleistocene conglomerate to indicate an average of 17 mm/yr during the last 0.7 m.y. Also, in proximity of the Morton *et al.* study, Prentice *et al.* (1986) estimate 6 to 13 mm/yr of slip based on stream channels that are offset 0.6 to 0.7 km and are incised into a surface interpreted to be 50,000 to 100,000 yr old.

Near Anza, in the central portion of the San Jacinto fault, Sharp (1981) placed a minimum limit of 8 to 12 mm/yr along the fault zone during the last 0.73 m.y., based on the offset of alluvial fan deposits. A more recent study by Rockwell *et al.* (1990a) of displaced Holocene alluvial fan and fluvial deposits indicates a similar minimum slip rate during the last 9500 yr of about 9.2 mm/yr near the same locality. In addition, Merifield *et al.* (1991) interpreted an offset shutter ridge, stream channel, and fine-grained alluvial deposits observed in trenches near Anza to indicate slip rates of 7 to 18, 10, and 9 ± 2 mm/yr, respectively, for the Clark fault.

South of Anza, along the segment of the fault that ruptured during the 1968 Borrego Mountain earthquake, Sharp (1981) interpreted geologic relations to show that slip has averaged 2.8 to 5.0 mm/yr and 1.6 to 2.2 mm/yr during about the last 40 and 6000 yr, respectively. Sharp interpreted these latter slip rates to suggest that the rate of slip has varied through time on the San Jacinto. The hypothesis of variable slip rate through time, however, conflicts with the just-mentioned Holocene measurements of slip rate near Anza reported by Rockwell *et al.* (1990) and may simply reflect slip rate measurements that did not account for slip across the entire San Jacinto fault zone.

Yet, farther to the south, Hudnut and Sieh (1989) investigated the recent prehistoric behavior of the Superstition Hills fault, which ruptured in 1987. They calculated a slip rate for the Superstition Hills segment of the San Jacinto fault zone, averaged over the past 330 yr between 2 and 6 mm/yr. A significant component of this slip may, however, represent motion by aseismic creep. In addition, Hudnut *et al.* (1989b) attributed offsets of the Lake Cahuilla shoreline to a 0.5 to 1.5 mm/yr slip rate along the northeast-trending Elmore Ranch fault; this is the only information we could find on the paleoseismic history of any of the left-lateral faults along the San Jacinto fault zone.

Seismological and geodetic observations also pro-

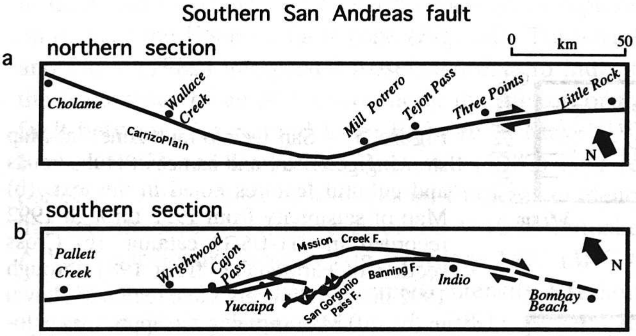


Figure 3. Strip maps showing the southern San Andreas fault with geometry and cultural features mentioned in the text.

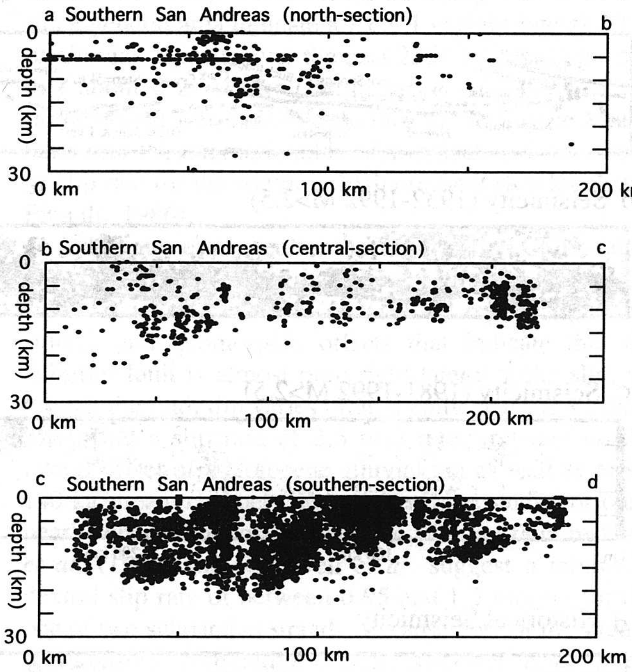


Figure 4. Cross sections of seismicity (1981 through 1992 $M > 2$) near the San Andreas fault. Endpoints a, b, c, and shown in Figure 2b.

vide information regarding the recent slip rate of the San Jacinto fault zone and are in general accord with geological studies. Thatcher *et al.* (1975), for example, determined and summed the seismic moments of earthquakes along the entire fault zone since about 1890 to estimate a seismic slip rate of about 8 mm/yr along the San Jacinto fault zone. Geodetic and trilateration measurements spanning the fault south of San Bernardino are also consistent with 11 to 18 mm/yr of slip being stored elastically in a 10 to 15-km-thick crust (King and Savage, 1983; Savage and Prescott, 1976; Savage *et al.*, 1981).

Trilateration and triangulation studies between 1941 and 1987 provide an average displacement of 35 to 43 mm/yr across the Imperial fault and other nearby faults (Prescott *et al.*, 1987; Snay and Drew, 1982). Larsen and Reilinger (1991) used a slip rate of 40 mm/yr to obtain a 25-yr recurrence interval. However, this recurrence rate assumes that the 1.0-m offset in both 1940 and 1979 is entirely co-seismic and characteristic of this fault. Cohn *et al.* (1982) have documented as much as 5 mm/yr of creep on the Imperial fault prior to the 1979 event as well as significant afterslip. Therefore, a more reasonable estimate of earthquake recurrence may be about 50 to 75 yr (Larsen and Reilinger, 1991). Displaced Lake Cahuilla shoreline deposits were studied by Thomas and Rockwell (1993) near the southern Imperial fault and indicate a 15 to 20-mm/yr slip rate for the past 300 yr, significantly less than obtained by the geodetic studies described above.

Paleoearthquake Data. On the basis of trenching studies, Sieh *et al.* (1973) documented evidence of at least two paleoearthquakes on the San Jacinto fault zone near San Bernardino, although major flooding and rapid urban development along the fault precluded successful dating of those events. Near Hog Lake in the Anza seismic gap, Klinger and Rockwell (1989) interpreted an average recurrence interval of 220 to 320 yr for the fault, based on structural and stratigraphic relations exposed in trenches. Although the frequency of prehistoric earthquakes on the Clark fault is uncertain, Merifield *et al.* (1991) observed stratigraphic offsets in a trench near Anza that may indicate a recurrence interval of 300 ± 200 yr for large ground-rupturing events. Along the Borrego Mountain section of the fault zone, Clark (1972) estimated an average recurrence interval of about 200 yr for tectonic events similar to the 1968 earthquake by comparing vertical components of displacement in 1968 with earlier movements recorded in offset sediments of ancient Lake Cahuilla that ranged in age from 860 to 3080 yr.

Along the Superstition Hills fault segment that ruptured in 1987, Hudnut and Sieh (1989) and Hudnut *et*

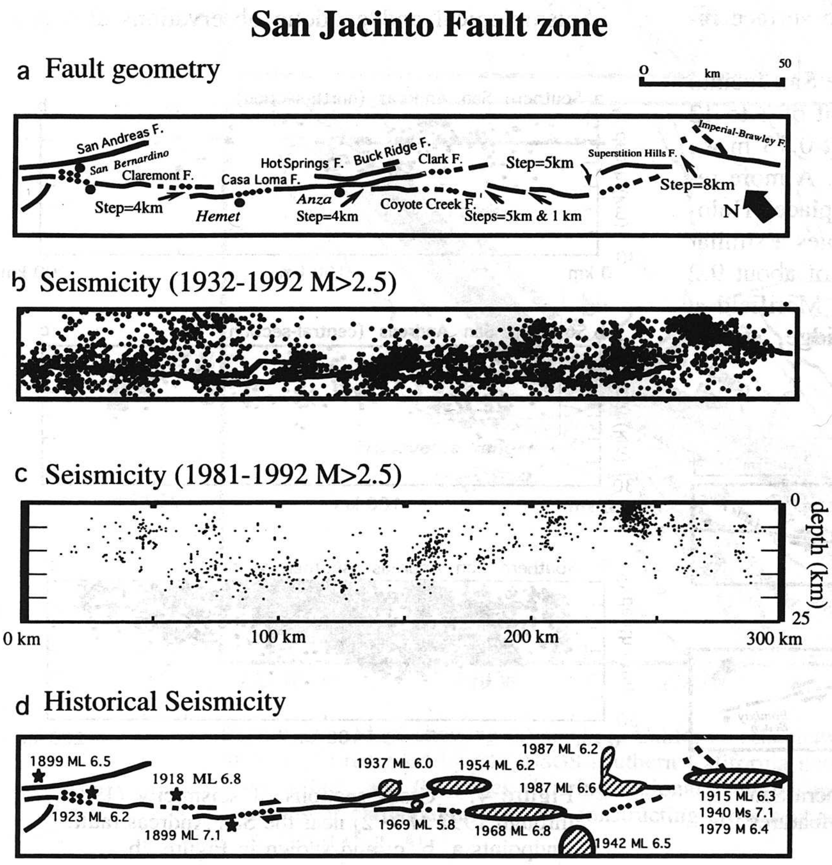


Figure 5. San Jacinto fault zone. (a) Map showing geometry and names of fault strands and cultural features noted in the text. (b) Map of seismicity from 1932 through 1992 recorded in CIT-USGS catalog. (c) Cross section of earthquakes from 1981 through 1992 in approximately same region as shown in (b). (d) Map showing the approximate location of historical earthquakes (stars) and aftershock zones (hachured) described by Sanders *et al.* (1986) and Petersen *et al.* (1991).

al. (1989b) place the repeat time of large surface slip events between about 150 and 300 yr for both the mainstrand as well as for the intersecting Elmore Ranch fault. Lindvall *et al.* (1989) also examined offset geomorphic features to determine the slip distribution of the penultimate and earlier events and found that the slip distribution of the penultimate event was similar to that observed in 1987. They further noted, however, that this similarity in slip distribution may be fortuitous if afterslip continues to increase the total slip for the 1987 earthquake.

The estimates of earthquake recurrence along the Imperial fault are primarily based on the past three historical large earthquakes shown in Figure 5. Sykes and Nishenko (1984) estimate a 32-yr recurrence interval for the Imperial fault based on the 39-yr interval between the 1940 and 1979 earthquakes as well as the 25-yr period between the 1915 and 1940 earthquake sequences. This implies a 20-mm/yr slip rate and that strain released during the 1979 earthquake had accumulated since the 1940 earthquake.

A synopsis of the fault slip rate and paleoearthquake data is provided in Table 1 and Figure 1.

Elsinore, Whittier, and Chino Faults

The Elsinore–Whittier fault zone strikes northwest from the Mexican border, a distance of about 250 km, and shows principally right-lateral displacement (Fig. 6; Hull and Nicholson, 1992). Although a considerable number of geological studies bearing on the fault slip rate have been completed, references are primarily limited to reports, guidebooks, and abstracts. A recent summary of geological reports related to the Holocene slip rate of the fault zone was provided by Anderson *et al.* (1989). Studies indicate cumulative offsets along the Elsinore fault zone between 5 and 40 km (e.g., Hull and Nicholson, 1992), whereas others (e.g., Lamar, 1990) have interpreted up to 30 km of offset along the Whittier fault.

Historical Seismicity. Historical records indicate that at least two large ($M >\sim 6$) earthquakes have ruptured on or near the Elsinore fault zone (Fig. 6d). Toppozada and Parke (1982) interpreted isoseismal data to indicate the occurrence of an M 6 event along the section of the fault between Corona and Lake Elsinore in May 1910. Brake (1987) and Brake and Rockwell (1987) later reported the observation of a displaced flume as evidence that the Elsinore was the source of the 1910 earthquake. A large earthquake occurred in February 1892 (M 7 to 7.5) and produced Modified Mercalli intensity VII damage in San Diego (Toppozada *et al.*, 1981). Several investigators have suggested that this event may have occurred along the Laguna Salada fault, which is the portion of the Elsinore fault south of the Coyote Mountains (Fig. 6d; Strand, 1980; Anderson *et al.*, 1989). That event produced up to 5 m of dip slip and probably 4 m of right-lateral slip over at least 22 km of the fault, suggesting a magnitude of 7.1 (Meuller and Rockwell, 1993).

Recent seismicity does not sharply delineate the trace of the fault, but rather marks a broad zone with a concentration of seismicity to the northeast of the fault (Fig. 6b). The largest earthquake that has been recorded by the seismic network and directly attributed to the Elsinore fault zone is an M_L 5.2 event in 1938. The 1990 Upland (M_L 5.3) and the 1987 Whittier Narrows (M_W 5.9) earthquakes are responsible for the two distinct clusters of seismicity observed in cross-sectional view at the northern end of the fault zone. The seismicity extends to a depth of nearly 20 km along most of the zone (Fig. 6c).

Fault Slip Rate Studies. A summary of all slip rate studies for the fault zone is provided in Table 1 and Figure 1. Slip rate estimates along the Elsinore fault vary between about 2 and 9 mm/yr. A chronosequence development and recognition of offset alluvial fans led to a slip rate estimate of between 2.6 and 9.3 mm/yr, with an interpreted best estimate of between 5.3 and 5.9 mm/yr, during the last 250,000 yr for the section of the Elsinore fault located between Corona and Lake Elsinore (Millman and Rockwell, 1986). Similar palinspastic reconstructions of offset drainages at a site farther to the south near Agua Tibia Mountain indicate a 1.5- to 7-mm/yr slip rate for the fault, with a best estimate of 3 to 6 mm/yr, over the last 600,000 yr (Vaughan and Rockwell, 1986). More recent trenching studies in that same general area indicate a 10 ± 1 m right-lateral offset of alluvial deposits over the past 2358 yr, yielding a slip rate about 4.2 mm/yr (Bergmann *et al.*, 1993). Even farther south, offset Holocene fans in the Coyote Mountains near the international border indicate a 4- to 6-mm/yr slip rate for the southern Elsinore fault (Rockwell and Pinault, 1986).

Slip rates estimated for the Whittier and Chino faults are considerably lower than those estimated for the Elsinore fault. Rockwell *et al.* (1992a) reports trenching studies and geomorphic offsets that indicate that the Whittier fault is almost pure right-lateral strike slip, although the fault dip varies dramatically near the surface. They find a slip rate of 2.5 to 3 mm/yr based on the lateral offset of a Holocene alluvial fan as well as offset 140 ka stream channels. Recent trenching studies of other nearby channel deposits across the Whittier fault by Gath *et al.* (1992) and Rockwell *et al.* suggest a minimum dextral slip rate of between 0.95 and 1.3 mm/yr for the one of two subparallel strands. Because both of the strands show similar cumulative offsets, Rockwell *et al.* interpret a probable minimum slip rate of about 2.6 mm/yr across both of these two strands.

Displacements observed across the Chino fault are right reverse (Heath *et al.*, 1982). Heath *et al.* concluded that the Chino fault is not the principal extension of the Elsinore fault zone. Reported values of slip rate on that fault are low, ranging from 0.02 to 0.2 mm/yr. Rockwell *et al.* (1992a), however, suggest that since the slip rate for the Whittier fault is only half of the rate of the Elsinore fault, located just to the south, the slip transferred northward from the Elsinore fault may be accommodated equally by the Chino and Whittier faults.

Recent paleoearthquake studies suggest that several large earthquakes have occurred along the Elsinore fault zone. Rockwell *et al.* (1985, 1986) trenched along the Glen Ivy North strand between Corona and Lake Elsinore, and identified stratigraphic evidence within trenches excavated across the trace to interpret the occurrence of five magnitude 6 to 7 events since about 1060 A.D. On this basis, they suggest a maximum ground-breaking earthquake recurrence interval of about 250 yr. Gath *et al.* (1992) trenched offset channels on the Whittier fault and identified at least two events between 10 and 14 ka. Geomorphic features are offset along the southern Elsinore fault near the Coyote Mountains and indicate that six large earthquakes (M 6.5 to 7) have ruptured the southern Elsinore with average slip per event of about 1.45 m (Rockwell and Pinault, 1986). Furthermore, recent geomorphic studies by Rockwell and Pinault indicate offsets of 2.8, 2.2, and 3.2 m for the past three large earthquakes. Pinault and Rockwell (1984) suggest that these large events have a recurrence interval of about 350 yr, whereas Rockwell *et al.* (1990) update these estimates to between 600 and 1000 yr.

Newport–Inglewood Fault

The Newport–Inglewood fault strikes southeast from the Santa Monica fault, which defines the southern border of the Transverse Ranges, to near Newport Beach where it continues offshore (Bryant, 1988; Fig. 7). The 70-km onshore fault trace is discontinuous and not well expressed at the surface, but is clearly marked by a distinct series of hills and anticlines (Ziony and Yerkes, 1985). Right-lateral displacement of 1 to 2 km in lower Pliocene strata and more than 1 km of apparent vertical separation in basement rock have been documented along the zone (Yerkes *et al.*, 1965).

Historical Seismicity. The fault is not clearly delineated by the historical distribution of seismicity but, rather, is marked by a broad epicentral distribution of seismicity about the trace (Fig. 7b). A plot of $M > 2$ events re-

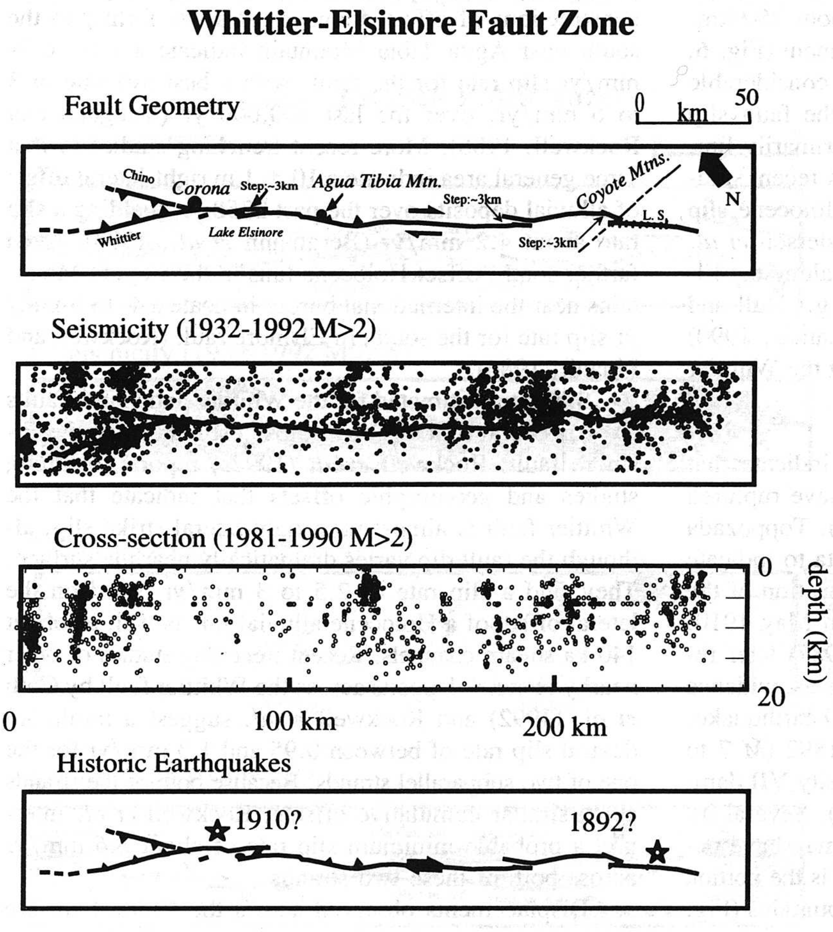


Figure 6. Whittier fault zone. (a) Map of fault geometry and sites mentioned in text. (b) Seismicity from 1932 through 1992. (c) Depth section of earthquakes recorded for a 10-yr period from 1981 through 1990 in the same area as (1). (d) Map showing approximate location of the largest two historical earthquakes.

corded in the CIT-USGS catalog shows seismicity extending to depths of nearly 20 km (Fig. 7c). Hauksson (1987), however, indicates that depths of about 16 km more accurately describe the deepest extent of seismicity along the zone, with the greatest concentration located at depths between 6 and 11 km.

The largest earthquakes recorded by the seismic network in the vicinity of the Newport–Inglewood fault include the 1933 Long Beach (M_L 6.3; e.g., Hauksson and Gross, 1991) and the 1941 Torrance–Gardena earthquakes (M_L 5.0 and 5.4; e.g., Richter, 1958). Hauksson and Gross recently reanalyzed the 1933 earthquake sequence, finding the event to be characterized by a seismic moment of 5×10^{25} dyne-cm (M_W 6.4) and pure right-lateral offsets in the subsurface of about 85 to 120 cm. Aftershocks of the 10 March 1933 event were concentrated along an approximately 30-km segment (Fig. 7d) of the fault that extended northwest of the epicenter (Hauksson and Gross).

Fault Slip Rate Studies. Right-lateral slip along the Newport–Inglewood fault has reportedly averaged 0.3 to 0.8 mm/yr since the Late Miocene to Pliocene (Guptil and Heath, 1981; Bird and Rosenstock, 1984; Ziony and Yerkes, 1985; Anderson *et al.*, 1989). Estimates of slip rate from offset features of Holocene to Pleistocene age range between 0.1 and 6.0 mm/yr, with average and better-limited values equal to about 0.6 mm/yr (Clark *et al.*, 1984). These latter values, however, reflect only the vertical component of slip, and hence, the total rate, including the horizontal component, may be greater. A synopsis of slip rate studies reported along the fault is provide in Table 1 and Figure 1.

Palos Verdes Fault

Historical Seismicity. The Palos Verdes fault extends from about 10 km north of the Palos Verdes peninsula southward at least 75 km (Fig. 8a). Recent seismicity along the fault zone has been concentrated near the northern portion of the fault (Fig. 8b) and is primarily located at depths shallower than 15 km (Fig. 8c). Although numerous small events are located near the Palos Verdes fault trace, we are aware of no historical moderate to large earthquakes along this fault.

Fault Slip Rate Studies. The fault zone is composed of several en-echelon strands that strike about 130° and dip about 70° southwest beneath the peninsula (Ziony and Yerkes, 1985). Uplifted terraces indicate that vertical motion has continued through the Pleistocene (e.g.,

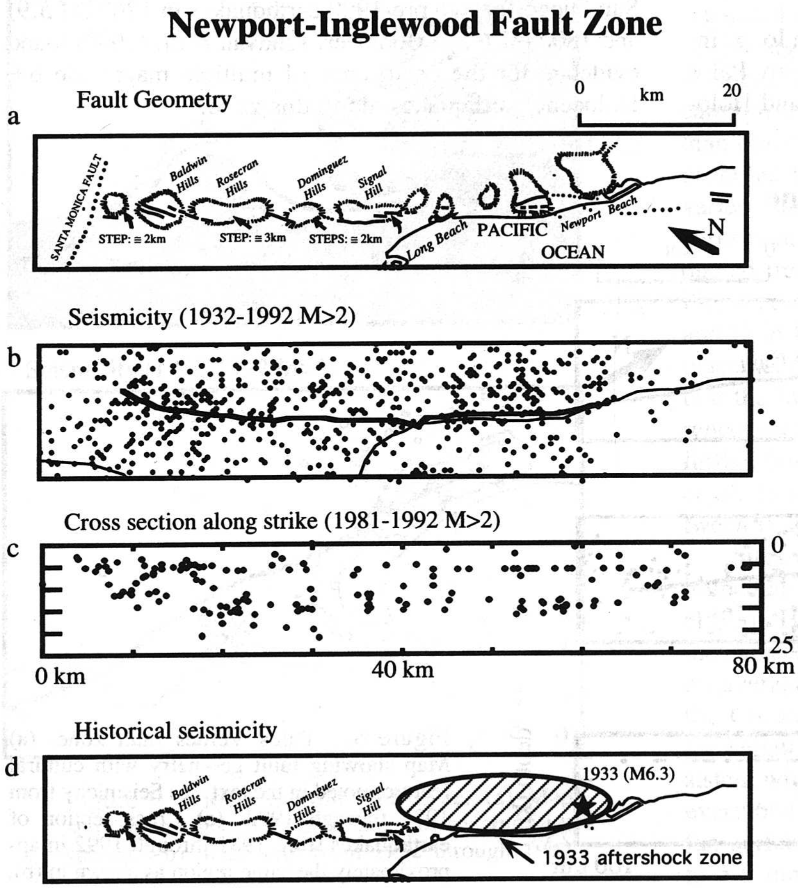


Figure 7. Newport–Inglewood fault zone. (a) Map showing fault geometry and cultural features noted in text. (b) Seismicity from 1932 through 1992 (c) Cross section of earthquakes from 1981 through 1992 in approximately the same location as shown in (1). (d) Map showing the approximate location of the 1933 earthquake and aftershock zone.

Woodring *et al.*, 1946; Valensise and Ward, 1992). Yerkes *et al.* (1965) reported a 1.8-km vertical separation, southwest side up, of Catalina Schist basement rock.

Marine reflection data indicates that beds considered of Holocene age have been offset by the fault (Clarke *et al.*, 1985; Darrow and Fisher, 1983), but these data provide no clear evidence for horizontal offset along the fault. Clark *et al.* (1984) interpreted the observations of Darrow and Fisher (1983) to indicate a vertical fault slip rate between 0.02 and 0.7 mm/yr. More recently, Valensise and Ward (1992) attributed the uplift of several marine terraces (235 to 668 ka) on the flanks of the Palos Verdes peninsula to be the result of 3.0 mm/yr of dip-slip motion along the Palos Verdes fault.

Subsidiary Faults. In close proximity to the Palos Verdes fault are two subsidiary faults, the Cabrillo and Redondo Canyon faults (Nardin and Henyey, 1978). The 18-km-long Cabrillo fault displaces Miocene strata but apparently does not displace the sea floor (Clarke *et al.*, 1985). The fault strikes about 155° and dips 65° to the east (Ziony and Yerkes, 1985). Darrow and Fisher (1983) report that the portion of the Cabrillo fault that extends offshore has a slip rate of about 0.7 mm/yr. Valensise and Ward (1992), however, suggest that the Cabrillo fault displaces the youngest emergent terraces by only a few tens of meters, which leads to a slip rate of about 0.1 mm/yr, and that it may root in the Palos Verdes mainstrand at relatively shallow depth.

The Redondo Canyon fault is about 13-km long, intersects the Palos Verdes fault on the northern Palos Verdes peninsula, and cuts both the sea floor and Holocene deposits on the shelf (Nardin and Henyey, 1978; Clarke *et al.*, 1985). The fault strikes about 80°, subparallel with the Redondo submarine canyon, but the dip is unknown (Ziony and Yerkes, 1985). Clarke *et al.* summarize two views regarding the slip distribution north of Palos Verdes peninsula; one in which the northern portion of the Palos Verdes fault accommodates most of the slip and another in which the Redondo Canyon fault accommodates the slip through south-over-north reverse faulting. Slip rate and paleoearthquake data for the Palos Verdes fault are tabulated in Table 1 and Figure 1.

Rose Canyon Fault

The Rose Canyon fault cuts San Diego in southernmost California and extends offshore (Fig. 9). The fault has a complicated geometry with strands that display normal, reverse, and right-lateral motion (Treiman, 1993). Several associated splays extend offshore and displace seafloor sediments of the Holocene age (Greene and Kennedy, 1987) including the Silver Strand, Coronado, and Spanish Bright faults (Fig. 9).

Seismicity is quite low and diffuse along the zone with most of the seismicity located near the San Diego bay, along the southern portion of the fault. However, earthquake swarms in 1985 and 1986 included three $M = 4$ earthquakes (Treiman, 1993). Toppozada *et al.* (1981) also found evidence from historical reports of damage in San Diego for two pre-1900 earthquakes in 1862 (*M* 5.9) and 1800 (*M* 6.5). Moreover, Lindvall *et al.* (1990) found evidence for the occurrence of multiple magnitude 6+ Holocene earthquakes along this zone.

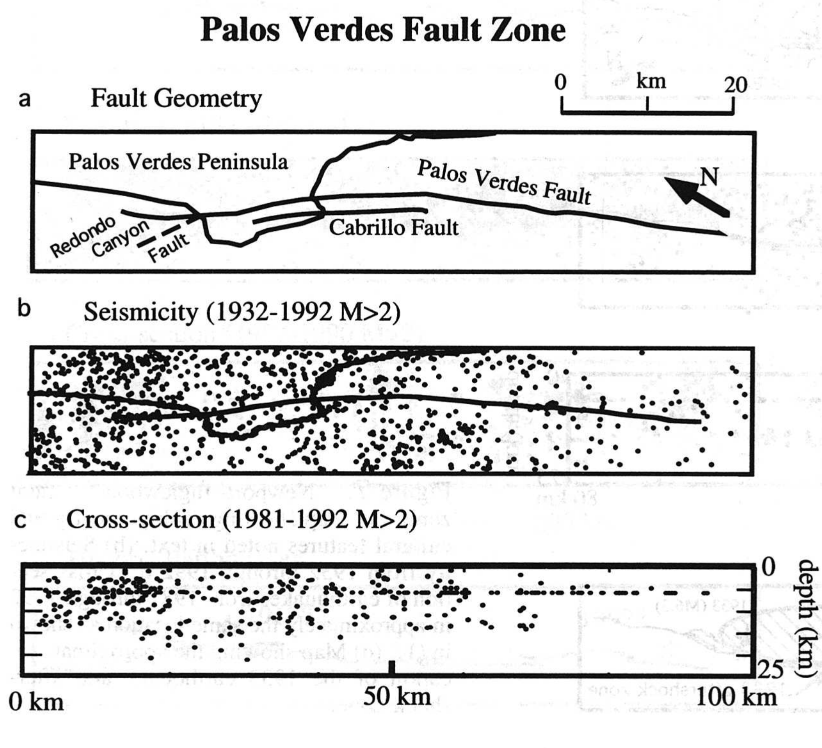


Figure 8. Palos Verdes fault zone. (a) Map showing fault geometry with cultural features noted in the text. (b) Seismicity from 1932 through 1992. (c) Cross section of earthquakes from 1981 through 1992 in approximately the same region as shown in (b).

Trench studies across the principal strand of the Rose Canyon fault zone give evidence of a minimum 8.7 m of dextral slip and less than 1-m dip-slip offsets of strata about 8200 yr old (Rockwell *et al.*, 1991). The minimum offset and the maximum age yield a minimum slip rate estimate of 1.07 ± 0.03 mm/yr for this strand of the Rose Canyon fault. Other mapped faults, located to the east and west of this principal strand, may also have Holocene activity and, therefore, this slip rate may substantially underestimate the total seismic slip rate for the entire fault zone (Rockwell *et al.*). Slip rate and paleoearthquake data for the Rose Canyon fault are tabulated in Table 1 and Figure 1.

Transverse Ranges

Central Transverse Ranges

Historical Seismicity. The central Transverse Range is taken here to encompass those Quaternary faults shown in Figure 10a, several of which have ruptured in moderate to large earthquakes. A large thrust event produced clear surface rupture in the M_W 6.7 San Fernando earthquake of 9 February 1971 (Fig. 10a; Wyss, 1971). The Clamshell–Sawpit Canyon fault produced a moderate (M_L 5.8) reverse-type earthquake on 28 June 1991 (Hauksson, 1992). Focal mechanisms and aftershocks of the M_L 5.3 event of 28 February 1990 and the M_L 5.0 event of 3 December 1988 showed principally strike-slip displacements along the San Jose and Raymond faults, respectively (Hauksson and Jones, 1991; Jones *et al.*, 1990). The 1987 M_L 5.9 Whittier Narrows earthquake produced reverse motion on what has since been known as the Elysian Park thrust system (Hauksson). More recently, the M_S 6.8 Northridge earthquake of 17 January 1994 ruptured on a south-dipping thrust fault located just southwest of the 1971 rupture (Fig. 10a; Petersen, 1994). But for the clustered seismicity marking the aftershocks of these earthquakes, seismicity is rather distributed and does not clearly delineate any particular fault planes (Fig. 10b). Slip rate and paleoearthquake data for the major faults of the region are discussed below and tabulated in Table 1 and Figure 1.

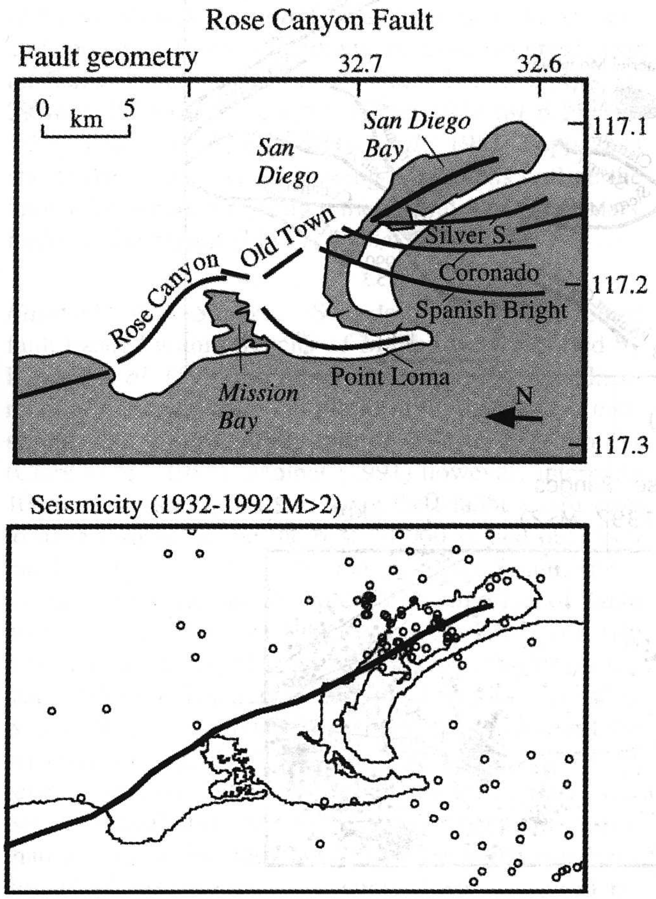


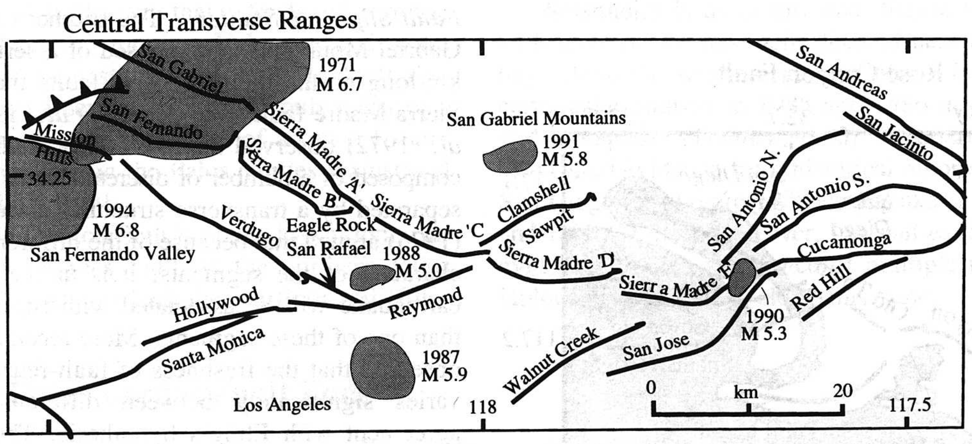
Figure 9. Rose Canyon fault zone. (a) Map showing the geometry and names of several fault strands. (b) Seismicity from 1932 through 1992 along the fault zone.

Fault Slip Rate Studies. The southern base of the San Gabriel Mountains is composed of a series of 13 to 20-km-long north-dipping reverse faults that comprise the Sierra Madre fault zone (Crook *et al.*, 1987). Proctor *et al.* (1972) observed that the Sierra Madre fault zone is composed of a number of discrete arcuate segments, each separated by a transverse structural discontinuity. Ehlig (1975) argued that because of the difference in structural character of the segments, it is unlikely that a single earthquake will be associated with rupture along more than one of these segments. More recently, Crook *et al.* observed that the freshness of fault-related morphology varies significantly between different segments, in agreement with Ehlig's hypothesis. They further conducted trenching studies and observed evidence of late Pleistocene faulting along those segments labeled B, C and D in Figure 10a, but no evidence of Holocene displacement. These observations were the basis to suggest that the individual segments are characterized by recurrence intervals of 5000 yr or more. Clark *et al.* (1984) further interpreted the mapping and trench data of Crook *et al.* to place the slip rate across these strands at between 0.36 and 4 mm/yr.

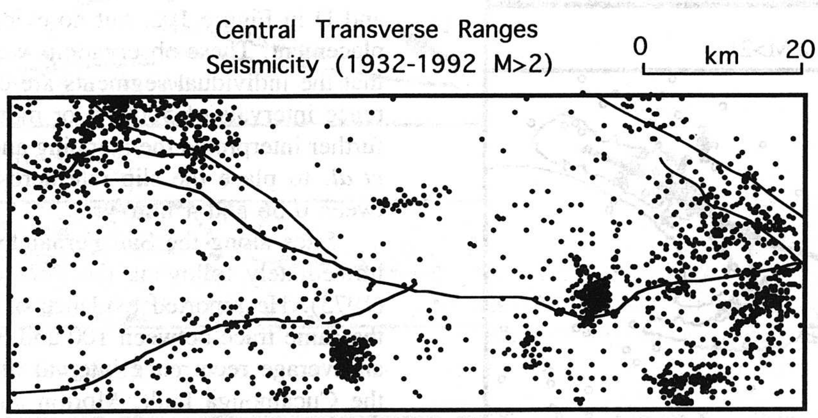
Sites along the San Fernando fault were excavated immediately following the 1971 earthquake by Bonilla (1973). He reported evidence of a prior rupture along the same trace between 100 and 300 yr ago, suggesting an average recurrence interval of about 200 yr. Along the Cucamonga fault, Morton and Matti (1987) found the height and age distribution of fault scarps to be consistent with an average repeat time of 2-m displacements every 684 yr. Morton and Matti also interpreted alluvial fan surface offsets to place a minimum slip rate of 4.5 to 5.5 mm/yr during the last 13,000 yr. They suggest that the Cucamonga fault has been seismically more active for the past 4000 yr than the remainder of the Sierra Madre fault zone.

The San Gabriel fault is 90-km long and has accumulated as much as 60 km of right-lateral offset (Weber, 1979; Yeats *et al.*, 1992), although the total offset may be significantly lower along certain portions of the fault (Weber). Evidence of Holocene displacements has been reported (Hart *et al.*, 1988) and Weber also reported offsets of latest Quaternary terrace, fan, and landslide deposits. Geologic surface mapping, geomorphic studies, and construction of detailed cross sections by Weber and Yeats *et al.* place the right-lateral slip rate since Miocene time at between 0.5 and 6.6 mm/yr. Because latest Quaternary offsets are principally vertical and show little or no right-lateral offset, the Quaternary rate of movement along the fault is generally considered to be less than 0.5 to 1 mm/yr (Weber; Yeats *et al.*).

The Raymond, Hollywood, and Santa Monica fault zones mark the northern limit of the Los Angeles basin. (Fig. 10a). Real (1987) indicates that displacement, as inferred from earthquake mechanisms, is primarily reverse with a significant left-lateral component along this fault trend. Crook *et al.* (1987) interpret rates of sedimentation in a faulted sag pond to infer a vertical slip rate along the Raymond fault of 0.10 to 0.22 mm/yr. They suggest that the Raymond fault has an average recurrence time for large earthquakes of 3000 yr. Observations from trenches emplaced across the fault further indicate the occurrence of eight events with an average displacement of 0.4 m/event during the last 36,000 yr. An offset river terrace surface is reported by Clark *et al.* (1984) as the basis for interpreting the vertical component of slip across the adjacent Hollywood fault to equal 0.33 to 0.75 mm/yr. An offset marine wave-cut platform implies a 0.27 to 0.39 mm/yr vertical slip rate for the Santa Monica fault (Clark *et al.*). Dibblee (1982) estimates 16 km of left-lateral offset along the Santa Monica fault based on the presence of Santa Monica slate observed in three drill holes south of the fault and from



(a)



(b)

Figure 10. Central Transverse ranges faults. (a) Map showing faults and extent of aftershock zones (shaded) of large earthquakes. (b) Seismicity 1932 through 1992.

outcrops of the same rock located north of the fault. This estimated 16-km offset of Santa Monica slate has been used by Molnar (1991) to infer a much higher left-lateral slip rate of 3 to 4 mm/yr for the Santa Monica fault averaged over the last 4 to 5 m.y.

Western Transverse Range

Historical Seismicity. Quaternary faults of the western Transverse region are shown in Figure 11a. The faults have not been the source of any major earthquakes during historical time, although several magnitude 5 to 6 events have been recorded in the area (Fig. 11a). The M_L 6.0 Pt. Mugu earthquake of 21 February 1973 produced reverse motion on a fault that extends westward from the Santa Monica fault (Bent and Helmberger, 1991b). Moderate earthquakes of about magnitude 5 also occurred within Santa Monica bay on 30 August 1930; 1 January 1979; and 19 January 1989 (Hauksson, 1992). The M_W 6.0 earthquake of 4 September 1981 occurred offshore and showed strike-slip offset with aftershocks that trend northwest (Hauksson). Examination of an epicentral map for the region shows that concentrations of seismicity are generally limited to the aftershock zones of the events just mentioned (Fig. 11b). In addition, several moderate to large earthquakes have occurred near the Santa Barbara channel on 21 December 1812 (*M* 7.1), 29 June 1925 (*M* 6.3), 4 November 1927 (*M* 6.2), and 1 July 1941 (*M* 5.5; Toppozada *et al.*, 1981; Toppozada and Parke, 1982). The following paragraphs outline the known information regarding the slip rates of Quaternary faults in the region (Fig. 1; Table 1).

Fault Slip Rate Studies. Strands of the Malibu Coast fault located within the city of Malibu were reported by Rzonca *et al.* (1991) to offset Holocene soils. Displacement of a marine wave-cut platform by that fault is consistent with a vertical slip rate of 0.04 to 0.09 mm/yr (Clark *et al.*, 1984). Molnar (1991) however, interprets 100-m offset stream courses along the Malibu Coast fault to have formed during the past 20,000 yr and obtains a much higher left-lateral slip rate of about 5 mm/yr for the fault zone. He also interprets a 16-km offset of Santa Monica slate (Dibblee, 1982) to infer a left-lateral slip rate of 3 to 4 mm/yr for the Malibu Coast fault over the last 4 to 5 m.y. The Santa Cruz Island fault may possibly be a westward continuation of the Malibu fault, and the sense of slip is probably left lateral with a component of reverse (Molnar; Dibblee). Sorlien and Pinter (1991) report a vertical slip rate for the Santa Cruz fault of less than 1 mm/yr, but they admit that the strike-slip component of motion remains unconstrained. The most recent rupture on the fault is no older than 11.78 ± 0.1 ka, based on offsets of dated terrace gravels (Pinter and Sorlien, 1991).

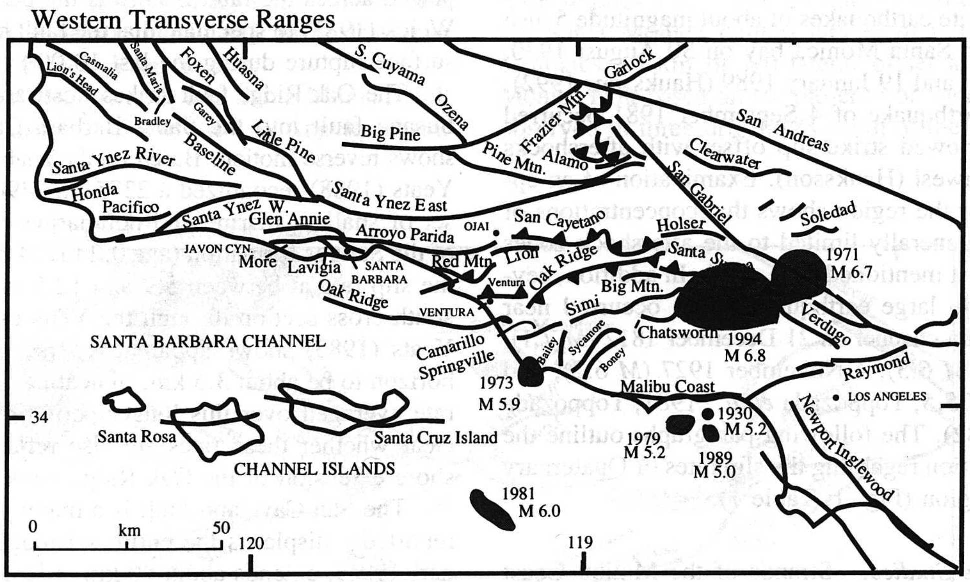
The Santa Susana fault dips north and offsets strata with reverse motion. The displacement history has been discussed by Yeats (1979, 1986, 1987). There is no reported evidence of Holocene movement except for a small segment located near the 1971 San Fernando earthquake (Yeats, 1987). This lack of Holocene uplift data may be related to the stratigraphic relationships in which the rocks of the hanging wall are much older than the faulting (Yeats, 1987). The slip rate of the fault during the last 0.5 to 2.0 m.y. has averaged greater than 2 to 8 mm/yr, based on a 4-km stratigraphic separation of the Modelo formation in the subsurface (Yeats, 1987). Molnar (1991) noted, however, that slight contrasts in stratigraphy across the fault limits the determination of vertical offsets, and therefore, the reported 4-km offset of the Modelo formation may be an overestimate. A trench emplaced across the fault zone was the basis for Lung and Weick (1987) to speculate that the fault has not produced surface rupture during the last 10,000 yr.

The Oak Ridge fault strikes westward from the Santa Susana fault into the Santa Barbara Channel and also shows reverse motion. Based on the analysis of well logs, Yeats (1988) recognized a 2375- to 2490-m vertical offset of shallow marine and nonmarine clastic sediments of the Saugus formation (age 0.2 to 0.4 m.y.) and placed the slip rate at between 5.9 and 12.5 mm/yr. A north–south cross section through the Ventura basin shown in Yeats (1983) shows apparent reverse slip of a 1 m.y. horizon to be about 3.5 km, indicating a 3.5-mm/yr slip rate averaged over this longer period of time. It is not clear whether these rates are also reflective of the offshore extension of the Oak Ridge fault.

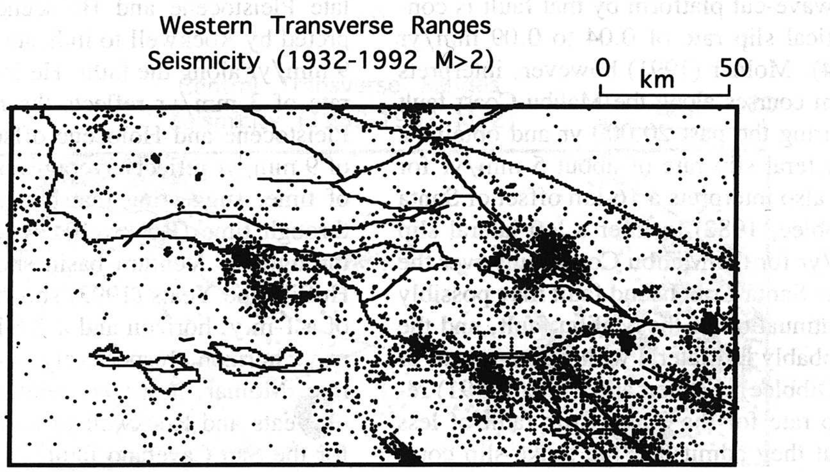
The San Cayetano fault is a major reverse fault that reportedly displaces the entire seismogenic layer (Molnar, 1991), extends about 40 km in length, and is divisible into two principal parts marked near its center by a distinct lateral ramp (Rockwell, 1988). Evidence of both late Pleistocene and Holocene offsets has been interpreted by Rockwell to indicate a slip rate between 3 and 9 mm/yr along the fault. He indicates that the lower slip rate of 3 mm/yr reflects the rate determined by upper Pleistocene and Holocene offsets, whereas the slip rate of 9 mm/yr reflects averages over a much longer period of time, suggesting that the rate of slip has decreased through time (Rockwell). A north–south cross section through the Ventura basin shown in Yeats (1983) and Huftile and Yeats (1992) shows an apparent 9-km offset of a 1-m.y. horizon and a 2.6-km offset of a 0.3 ± 0.1-m.y. horizon, respectively, indicating a 9-mm/yr slip rate. Molnar, however, reinterpreted the cross sections of Yeats and Rockwell to indicate a 7-mm/yr slip rate for the San Cayetano fault.

The Red Mountain fault is a west-striking reverse fault that dips to the north and is located adjacent to the San Cayetano fault. Seismicity ($M < 3.0$) along the fault indicates a fault dip of 60° and extends to 12-km depth (Yeats *et al.*, 1987). Unlike the San Cayetano fault, neither the Fernando nor the Saugus formations are preserved on the hanging-wall of this fault; therefore, a direct determination of slip in the last few hundred thousand years from well-log data is problematic (Yeats, 1988). Yeats (1988) assumes the slip rate is in the same general range as determined for the Oak Ridge fault (5.9 to 12.5 mm/yr). More recently, the observations of Huftile and Yeats (1992) loosely constrain the slip rate at between 0.7 and 18 mm/yr during the last 250 ± 50 ka y, based on the interpretation of subsurface well-log data. However, Clark *et al*. (1984) report observations from Lajoie *et al*. (1982), Lee *et al*. (1979), Sarna-Wojcicki *et al*. (1979), Yerkes and Lee (1979), and Yeats (1982) bearing on the offset of marine platforms to interpret a cumulative reverse slip rate for the fault equal to 0.9 to 2.3 mm/yr during the last 45,000 to 60,000 yr.

The Javon Canyon and Ventura faults are also north-dipping thrusts and cut the California coast between the Red Mountain and Oak Ridge faults. Clark *et al*. (1984) report investigations of a displaced alluvial fan to place the slip rate of the Ventura fault at between 0.8 to 2.4 mm/yr during the last 5700 to 15,000 yr. Sarna-Wojcicki *et al*. (1987) interpret offset stream and marine terraces to indicate a relatively steady 1.1 mm/yr slip rate across the Javon Canyon fault during the last 45,000 yr. They also report evidence of five paleoearthquakes across the fault during the last 3500 yr, with throw ranging from 0.4 to 1.3 m in each event. The Padre Juan fault, also



(a)



(b)

Figure 11. Western Transverse ranges faults. (a) Map showing faults and extent of aftershock zones (shaded) of large earthquakes. (b) Seismicity 1932 through 1992.

within Javon Canyon, offsets a marine platform, and is interpreted to have a vertical slip rate between >1.4 and 0.5 mm/yr during the last 45,000 to 60,000 yr (Clark *et al.*).

Yeats (1982) and Yeats *et al.* (1981) suggest that the Javon Canyon and Ventura faults may reflect slip along bedding planes in response to flexural slip during folding, and hence, may not constitute a seismic shaking hazard because they do not extend downward to rocks of high shear strength. Sarna-Wojcicki *et al.* (1987) and Sarna-Wojcicki and Yerkes (1982) argue, however, that evidence supporting such an interpretation for these faults is at best inconclusive. This controversy may also be applicable to the other numerous flexural-slip faults within the Ventura Basin, most of which are limited to about 5-km length in map view. In particular, the Santa Ana (south branch), Villanova, La Vista, Devil's Gulch, and Oak View faults, located just south of the Arroyo Parida–Santa Ana fault (Yeats, 1982 Keller *et al.* 1982b), were determined by Rockwell *et al.* (1984) to have vertical slip rates ranging between about 0.3 to 0.4 mm/yr during the last 38,000 ± 500 yr. The Thorpe, Orcutt, Culbertson, and Rudolf faults, just south of the central San Cayetano fault, represent the same style of deformation (Keller *et al.*, 1982b; Yeats *et al.*, 1981). Clark *et al.* (1984) interpreted data reported in Rockwell (1983) to indicate the slip rates of these faults have been 0 to 2.5 mm/yr during the last 5000 yr.

The Arroyo Parida fault is a thrust fault that extends westward to the coast from an intersection with the San Cayetano fault. A suite of progressively offset river terraces place the vertical slip rate of the fault at 0.37 ± 0.02 mm/yr during the last 38,000 yr (Rockwell *et al.*, 1984). An offset marine platform is the basis for Clark *et al.* (1984) to report a vertical slip rate greater than 0.3 mm/yr for the More Ranch fault, a shorter thrust that splays off the Arroyo Parida fault in the vicinity of Santa Barbara.

Subparallel and north of the Arroyo Parida–Santa Ana fault is the Santa Ynez fault. This fault is 160 km in length and is, therefore, one of the longest faults west of the San Andreas. The fault has not been thoroughly studied, and hence, the total offset and sense of slip related to this fault remain enigmatic. Dibblee (1987), however, indicates that a left-slip component is strongly suggested by the oblique west-northwest trend of associated fold axes and by offset draining canyons of the Santa Ynez Range. He notes that the Santa Ynez fault is also composed of a younger south-dipping thrust that offsets sediments just south of the main strand. Near the fault intersection with the coast, offset fluvial gravels are interpreted to indicate a 0.4-mm/yr vertical slip rate (Clark *et al.*, 1984). In addition, Darrow and Sylvester (1984) excavated a series of trenches across the fault and observed 5 to 10-m left-lateral separation of a buried stream bank. They indicate that the displaced stream terraces are late Pleistocene to Holocene in age. Along strike and farther inland, however, the best estimate of the vertical slip rate is about 1 mm/yr (Clark *et al.*). Rockwell *et al.* (1992b) studied the southern strand of the Santa Ynez fault and described 5-m vertical offset terraces with ages of about 80 to 105 ka. This yields a vertical slip rate of about 0.05 mm/yr for the southern strand of the Santa Ynez fault. These observations allow a similar, but not greater, strike-slip component.

The Big Pine fault is primarily a left-lateral fault located near the northern boundary of the Transverse Ranges (Hill and Dibblee, 1953). The Big Pine fault offsets the Ozena fault, which has displaced late Pliocene sediments up to 13 km (Molnar, 1991). In addition, the Maldulce Syncline located just northwest of the Ozena fault is offset about 16 km by the Big Pine fault (Molnar). From these offset features, Molnar suggests a slip rate of 4 ± 3 mm/yr for the Big Pine fault. However, recent geodetic analyses of the Los Padres–Tehachapi trilateration networks indicate left-lateral slip of 15 ± 6 mm/yr on the Big Pine faults (Eberhart-Phillips *et al.*, 1990), although they admit that this slip rate may include motion on more than a single vertical fault.

Eastern Transverse Range

The eastern Transverse Range consists principally of the San Bernardino Mountains (Fig. 12a). Seismicity along the eastern Transverse Ranges is quite scattered, as with seismicity along other parts of the range, but appears to be primarily associated with the San Andreas, San Jacinto, and faults associated with the 1992 Landers earthquake sequence (Fig. 12b). Nicholson *et al.* (1986) indicate that earthquakes extend to 22-km depth and have mechanisms that indicate primarily oblique slip with a large component of reverse motion. Published slip rate data are summarized in Table 1 and Figure 1.

Meisling (1984) and Miller (1987) have documented Quaternary displacements across the major faults that bound the San Bernardino Mountains to the north. We were only able to find slip rate estimates for the Cleghorn, Ord Mountain, and Sky High Ranch faults (Meisling). The left-lateral Cleghorn fault has reportedly slipped at a rate of 2 to 4 mm/yr during the last 50,000 to 100,000 yr (Meisling and Weldon, 1982a, b). Whereas the preferred Quaternary slip rate along the Ord Mountain fault is 0.1 mm/yr, estimates of slip along the Sky High Ranch fault are greater than 1.3 mm/yr (Meisling and Weldon). Farther to the east, the only reported slip rate for the Pinto Mountain fault is 0.3 to 5.3 mm/yr and is based on the offset of Miocene rocks (Anderson, 1979).

Mojave Faults

A number of faults with Quaternary displacement strike northwest across the Mojave desert, show right-lateral displacements, and are characterized by anastomosing and en-echelon segments (Fig. 13a). Evidence from recent seismicity, geodetic strain measurements, and ground rupture indicate that the regional shear east of the San Andreas fault is concentrated between the Helendale and Ludlow faults of the Mojave Desert (Dokka and Travis, 1990b). Dokka and Travis suggest that these Mojave faults, known collectively as the eastern California or Mojave shear zone, accommodate between 9 and 23% of the total relative motion between the Pacific and North American plates.

Several moderate to large earthquakes have ruptured Mojave faults, including the following: the 1975 Galway Lake (*M* 5.2), the 1979 Homestead Valley (*M* 5.6), and the 22 April 1992 Joshua Tree (*M* 6.1) earthquakes (California, 1992). In addition, on 28 June 1992 the Landers earthquake (*M* 7.5) ruptured to the surface along about 80 km of several right-lateral faults and was followed about 3 hr later by the Big Bear earthquake (*M* 6.5) that ruptured a left-lateral fault located about 40 km to the east (California). Recent seismicity between 1932 and 1992, shown in Figure 13b, indicates that most of the

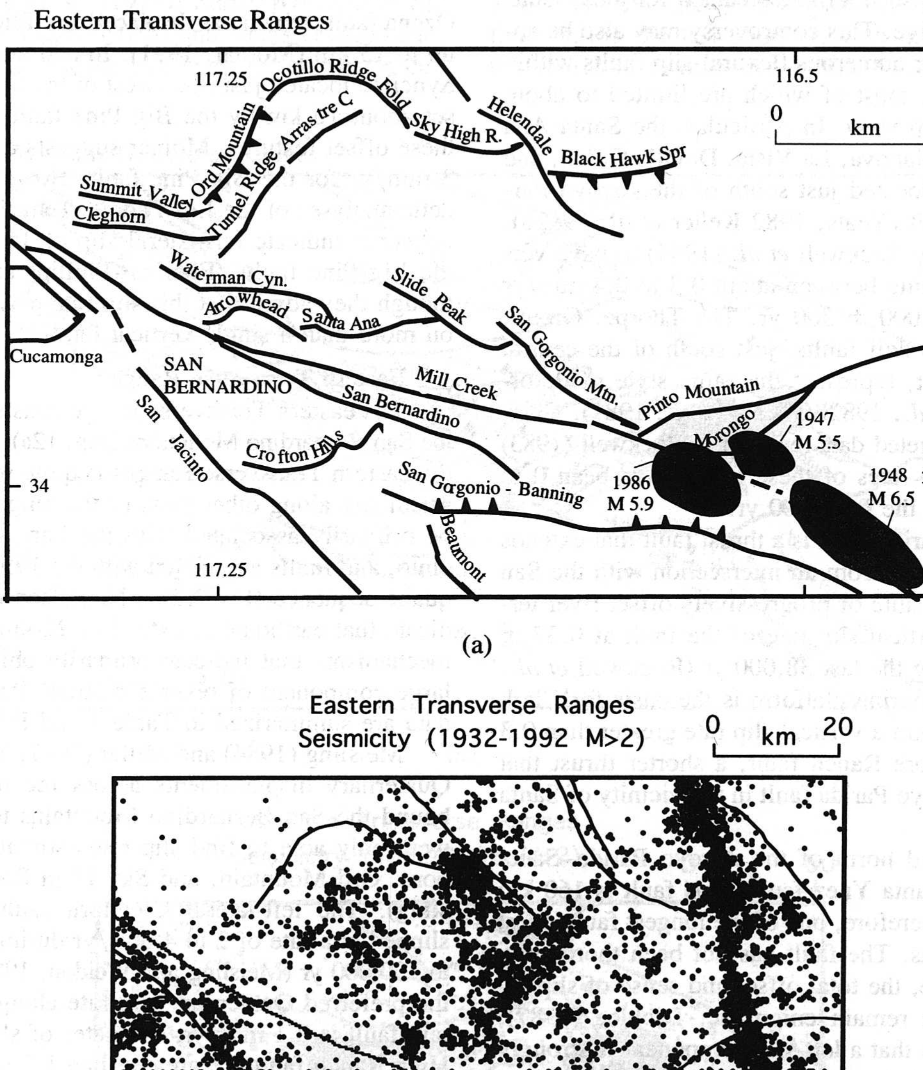
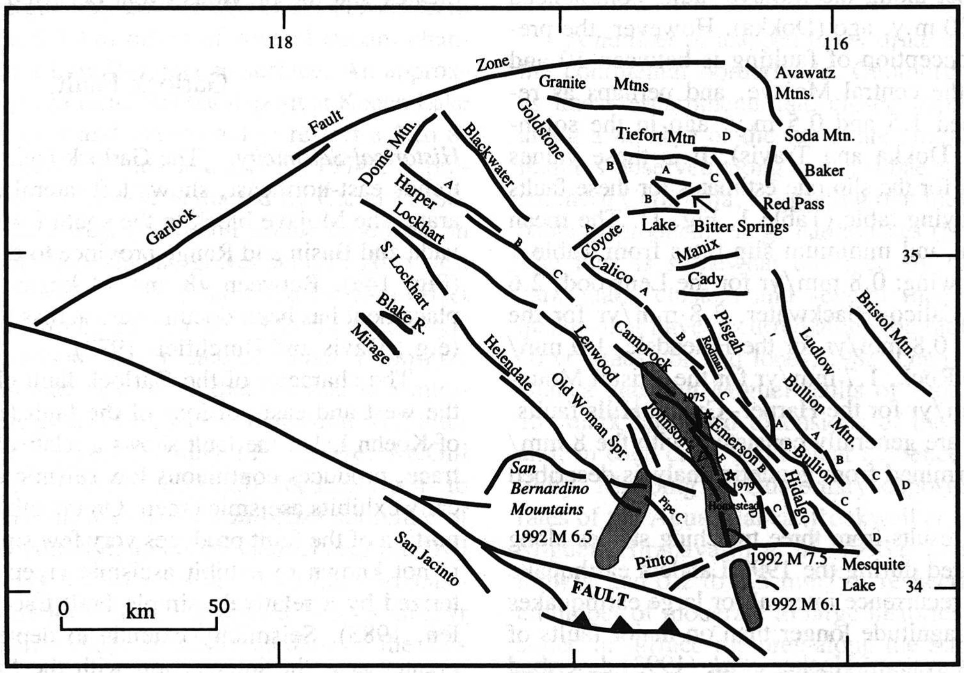


Figure 12. Eastern Transverse ranges faults. (a) Map showing faults and extent of aftershock zones (shaded) of large earthquakes. (b) Seismicity 1932 through 1992.

seismicity does not clearly delineate movement along specific faults, with the exception of aftershocks of the 1992 Landers sequence aftershocks.

Analyses of geodetic networks across the region are consistent with about 8 mm/yr of cumulative right-lateral shear being distributed across the northwesterly striking suite of faults (Sauber *et al.*, 1986; Savage *et al.*, 1990). This rate is similar to the long-term rate of 6 to 12 mm/yr for the past 10 m.y. that has been suggested from the observed geologic offsets across the fault zone (Dokka and Travis, 1990b).

Hart *et al.* (1988) mapped Holocene fault scarps, truncated spurs, closed depressions, and also the offset of a late Quaternary lava field associated with the Pisgah



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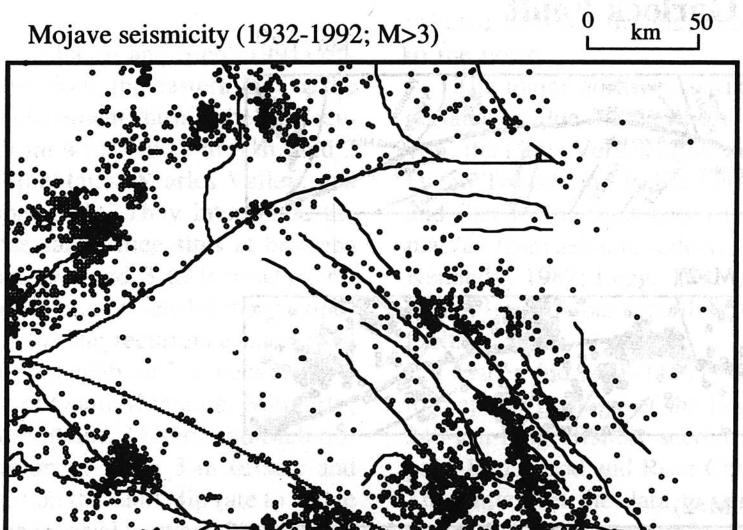

(b)

Figure 13. Mojave desert faults. (a) Map showing faults and extent of aftershock zones (shaded) of large earthquakes. (b) Seismicity 1932 through 1992.

fault. They interpret these offsets to indicate a slip rate of about 0.8 mm/yr. In addition, they observed offset late Quaternary geomorphic features along the Calico fault that suggest a slip rate similar to that observed along the Pisgah fault. Dokka (1983) and Dokka and Travis (1990a) document cumulative right-lateral displacements along the Lenwood (1.5 to 3.0 km), Calico–Blackwater (8.5 to 9.6 km), Rodman–Pisgah (6.4 to 14.4 km), Helendale (3.0 km), Camp Rock (1.6 to 4.0 km), Bristol Mountain (>6.0 km), and Harper–Gravel Hills (<3.2 km) faults. Offset along the Mojave faults commenced between 2 and 20 m.y. ago (Dokka). However, the preferred age of conception of faulting is between 10 and 6 m.y. ago in the central Mojave, and perhaps as recently as between 1.5 and 0.5 m.y. ago in the south-central Mojave (Dokka and Travis). It is these values that are the basis for the slip rate estimates for these faults in the accompanying table (Table 1, Fig. 1). The mean of the maximum and minimum slip rates from Table 1 include the following: 0.8 mm/yr for the Lenwood, 2.6 mm/yr for the Calico–Blackwater, 3.8 mm/yr for the Rodman–Pisgah, 0.8 mm/yr for the Helendale, 1.0 mm/yr for the Camp Rock, 1.7 mm/yr for the Bristol Mountain, and 0.9 mm/yr for the Harper–Gravel Hills faults. These slip rates are generally consistent with the 8 mm/yr slip rate determined from geodetic analysis described above.

Preliminary results from three trenching studies along faults that ruptured during the 1992 Landers earthquake suggest that the recurrence interval for large earthquakes is an order of magnitude longer than on major faults of the San Andreas system. Hecker *et al.* (1993) described evidence from trenching for three pre-1992 events across the section of the Homestead Valley fault that ruptured during the 1992 Landers earthquake. Assuming an offset of between 3 and 3.75 m for the penultimate event that occurred 5.7 to 8.5 ka, they obtain a slip rate of 0.4 to 0.6 mm/yr. Other trenching studies along the Emerson fault (Rubin and Sieh, 1993) suggest a slip rate of 0.2 to 0.7 mm/yr with the last earthquake occurring about 9000 ka. Moreover, trenching along the northern Johnson Valley fault (Herzberg and Rockwell, 1993) also indicates that the previous event occurred about 9 ka.

Garlock Fault

Historical Seismicity. The Garlock fault is 250-km long, trends east-northeast, shows left-lateral offset, and separates the Mojave block to the south from the Sierra Nevada and Basin and Range province to the north and east (Fig. 14a). Between 48 and 64 km of left-lateral displacement has been documented across the Garlock fault (e.g., Davis and Burchfiel, 1973).

The character of the Garlock fault changes between the west and east portions of the fault (Fig. 14b). West of Koehn Lake, the fault shows a relatively complex fault trace, produces continuous low seismic activity, and locally exhibits aseismic creep. On the other hand, the east portion of the fault produces very few small earthquakes, is not known to exhibit aseismic creep, and is characterized by a relatively simple fault trace (Astiz and Allen, 1983). Seismicity extends to depths of 25 km or greater near the intersection with the San Andreas, al-

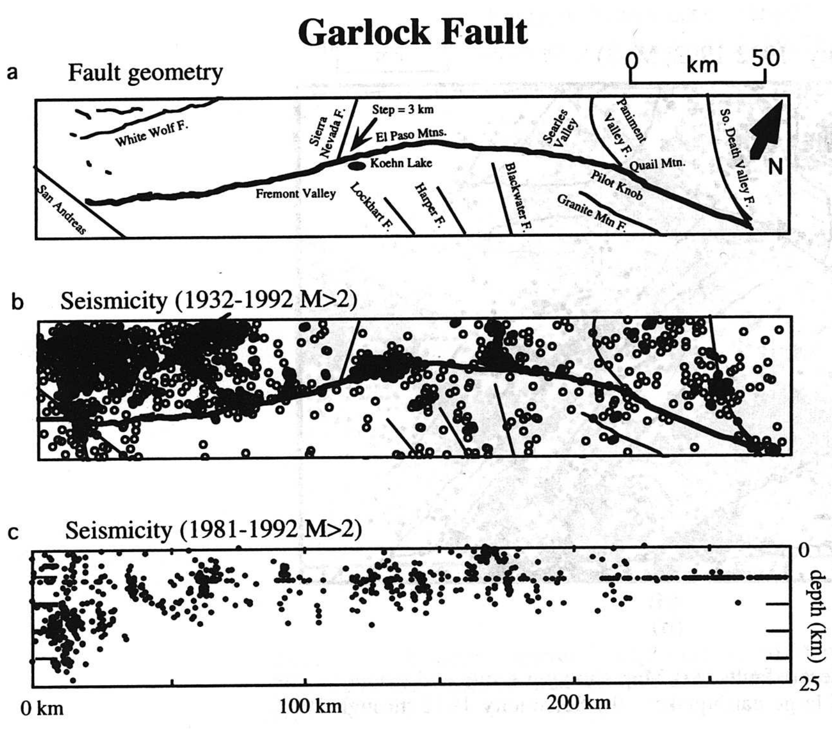

Figure 14. Garlock fault. (a) Map showing fault geometry, adjacent faults, and cultural features. (b) Seismicity 1932 through 1992. (c) Cross section of seismicity 1981 through 1992 in approximately the same region as shown in (b).

though it generally appears limited to depths of less than 15 km elsewhere (Fig. 14c). No events sufficient to produce surface rupture have occurred along the fault historically.

Fault Slip Rate Studies. The Garlock has been the subject of numerous slip rate studies during the last 2 decades. Summaries of these studies have been put forth by both Astiz and Allen (1983) and McGill and Sieh (1991). A 1- to 3-mm/yr slip rate for the western portion of the fault is argued by La Violette *et al.* (1980) from observation of a 0.3-km offset of several stream channels incised into a Late Pleistocene surface. An approximately 11,000-yr-old lacustrine bar deposit at Koehn Lake is offset by the fault and interpreted to reflect a 5 to 8-mm/^{14}C-yr rate of slip (Clark and Lajoie, 1974). A preferred estimate of 11 mm/yr is quoted by Carter (1980, 1982) for the fault west of Koehn Lake, based on an observation of an offset alluvial gravel deposit. Also west of Koehn Lake, Smith (1975) interpreted the 8-m offset of a former stream channel on an 8000- to 10,000-yr-old surface to indicate a slip rate of about 1 mm/yr, although McGill and Sieh argue that the rate is a minimum because the channel may reflect incision well after deposition of the gravel forming the surface. McGill (1992b) and McGill and Sieh (1993) document a 4- to 9-mm/yr slip rate on the basis of an offset shoreline of Searles Lake. In addition, an offset channel near the Owl Lake fault, a splay that extends about 19 km northeastward from the Garlock fault, suggests a 1- to 3-mm/yr slip rate (McGill, 1993). Geodetic studies of the Los Padres–Tehachapi trilateration networks indicates 11 ± 2 mm/yr of left-lateral motion below a depth of 10 km for the Garlock fault (Eberhart-Phillips *et al.*, 1990).

Paleoearthquake Studies. McGill and Sieh (1991) observed geomorphic features along the eastern half of the fault and suggest that displacement during the last several earthquakes ranged from 4 to 7 m, 2 to 3 m, and 2 to 4 m near the El Paso Mountains, Searles Valley, and the Pilot Knob area, respectively. They interpreted the Holocene slip rate at those same three sites at between 4 to 7 mm/yr, 4 to 9 mm/yr, and 3 to 9 mm/yr, respectively. Dividing the observed offsets by the range of slip rates led them to estimate the recurrence interval of events of magnitude greater than about 7 at between 200 and 1300 yr at points west of Quail Mountain. Similarly, to the east of the Quail Mountains, McGill and Sieh observe geomorphic expression of 2- to 3-m offsets and place a 1- to 9-mm/yr limit on the fault slip rate to arrive at bounds on the recurrence interval between 200 to 3000 yr. More direct identification and dating of paleoearthquakes has been problematic and is limited to paleoseismic investigations to the west (La Violette *et al.*, 1980) and east (McGill, 1992a, b) of Koehn Lake; these results suggest that the maximum age of surface rupture events equals about 980 ^{14}C yr B.P. and 1490 A.D., respectively. McGill (1993) indicates a 150 to 590 A.D. maximum age of the most recent surface rupture within 2 km from the easternmost end of the fault. The paleoearthquake and fault slip rate data are summarized in Table 1 and Figure 1.

Continental Borderland

A number of mapped faults strike northwesterly along the continental borderlands. Geomorphic features such as linear escarpments and closed depressions observed along a number of the faults are similar to geomorphic features observed along active subaerial wrench faults in southern California, suggesting that they may also be capable of producing large earthquakes (Legg *et al.*, 1989). The idea is somewhat enforced by the occurrence of earthquake clusters and several moderate-sized earthquakes that have occurred along the faults during the last 50 yr (Hauksson and Jones, 1988; Legg, 1980). The Agua Blanca and San Miguel faults of Baja California (Fig. 15) mark landward extensions of the borderland faults and, in each case, show clear evidence of Holocene activity. Mapping of Quaternary deposits places the slip rates of the Agua Blanca (Rockwell *et al.* 1987) and San Miguel (Hirabayashi *et al.* 1993a, b) faults at about 6 mm/yr and 0.2 to 0.5 mm/yr, respectively. Moreover, a number of moderate to large historical earthquakes resulted in surface ruptures along the San Miguel fault in 1956 (Shor and Roberts, 1958; Doser, 1992). In a kinematic sense, it is reasonable to extrapolate the 4 to 6 mm/yr of slip observed on the Agua Blanca to be distributed between the major system of borderland faults to the north.

The major northwest-striking fault zones of the borderland include the Newport–Inglewood and Rose Canyon, the Palos Verdes Hills and Coronado Bank, the San Diego Trough and Bahia Soleda, and the San Clemente and San Isidro fault zones (Fig. 15). Although clearly marked from seismic reflection studies (e.g., Greene and Kennedy, 1987; Legg, 1991), little direct information is currently available regarding the slip rates of any of the faults.

Fisher and Mills (1991) used seismic reflection data to map the geology of the inner coastal margin near the 240-km-long offshore section of fault between the Newport–Inglewood and Rose Canyon fault zones (Fig. 15). They interpret the data to suggest a late Holocene slip rate of 1.3 to 2.1 mm/yr for the northern 43-km offshore segment, 0.8 mm/yr for the 32-km central segment, and 1.3 mm/yr for the 34-km southernmost portion of the fault, which is immediately north of the Rose Canyon fault. We are not aware of any other information bearing directly on the Quaternary slip rate of borderland faults.

Blind Thrusts

Another aspect of seismic hazard that has come to light in the last decade is the seismic potential of blind thrusts, low-angle detachment faults that do not reach the surface but often produce folded sediments at the surface. Recent examples of earthquakes occurring on such structures are the 21 May 1983 M_L 6.5 Coalinga earthquake in central California and the more recent 1 October 1987 M_L 5.9 Whittier Narrows earthquake (Fig. 10) in the Los Angeles Basin (Stein and Ekstrom, 1992; Hauksson and Jones, 1989). Because the surficial expression of blind thrusts is generally more subtle than that manifested by major faults that cut the entirety of the seismogenic layer, information regarding the spatial extent and rate of movement on these structures arises principally from the study of subsurface structural geology. An approximate picture of the surface extent of the major blind thrust faults thus far identified in southern California from interpretation of seismic reflection and borehole observations is shown in Figure 15. The figure is adapted primarily from the work of Shaw (1993). The distribution of blind thrust systems shown in Figure 15 is likely not complete. For example, it has been speculated that similar thrust systems also underlie the northern coastline of the Santa Barbara Channel and the Ventura basin (Namson and Davis, 1988; Shaw).

The Elysian Park fold and thrust belt was recognized by mapping of fold axes near the flanks of the Los Angeles basin and observation of earthquakes showing thrust-type mechanisms, of which the 1987 Whittier Narrows earthquake is the primary example (Davis *et al.*, 1989; Hauksson, 1990). Analysis of structural cross sections provided Namson and Davis (1988) and Davis *et al.* evidence to suggest that the Elysian Park thrust has slipped at an average rate of 2.9 to 5.2 mm/yr during the last 2 to 4 m.y. Shaw (1993) used a fault-bend model to interpret seismic data and arrived at a similar 1.7-mm/yr rate for the same structure and time period. Detailed mapping of Quaternary deposits and geomorphic surfaces by Bullard and Lettis (1991), however, has been used to interpret much lower slip rates along the Elysian Park anticlinorium of only 0.1 mm/yr, although they admit that this slip rate is based on terrace ages that are as yet poorly constrained. It has been noted that the high 2.9 to 5.2-mm/yr rate should produce events of similar size to Whittier narrows every 5.6 to 11.6 yr along the thrust, which is more frequent than observed during the last 50 yr of instrumental recording (Namson and Davis, 1988; Davis *et al.*, 1989). The contradiction with the

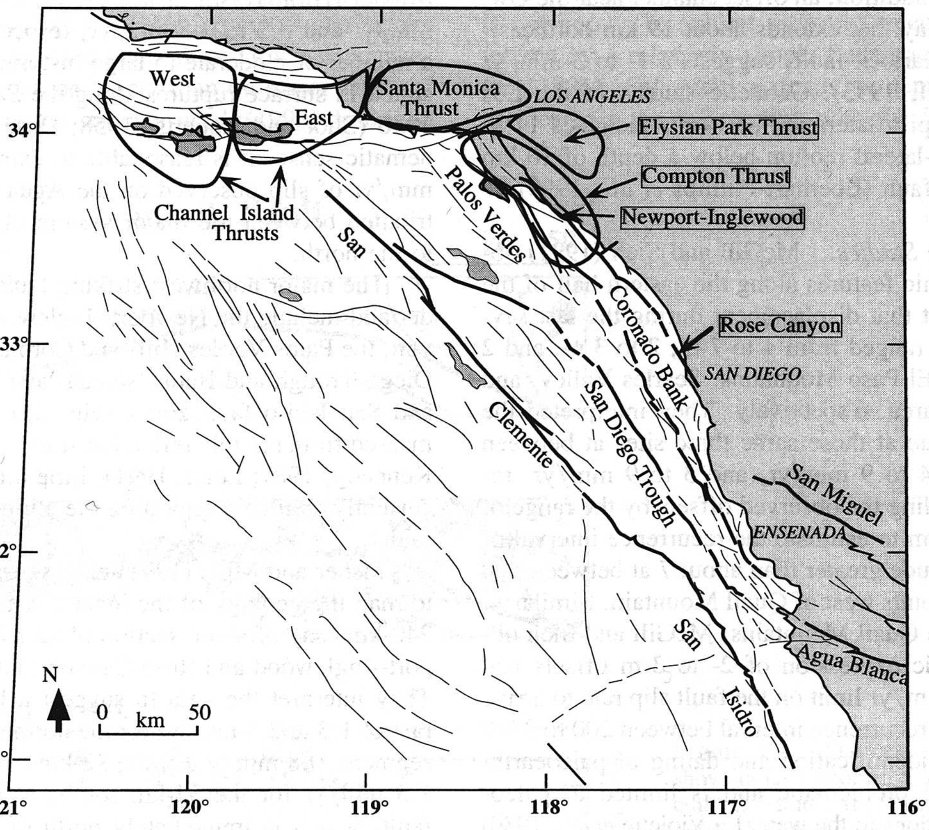

Figure 15. Map showing faults of continental borderland and blind thrust faults in southern California.

historic record may be only apparent if slip on the thrust is more characteristically released in very large events with longer repeat times.

The Compton fold and thrust belt extends beneath the Newport–Inglewood and Palos Verdes faults (Fig. 15). The structure is manifested by the location and trend of the Compton and Torrance–Wilmington fold systems (Shaw, 1993) and may represent more than a single seismogenic source (Hauksson, 1992; Davis *et al.*, 1989). Construction and interpretation of retrodeformable cross sections have resulted in an estimated slip rate of 1.9 to 3.5 mm/yr for the past 2.2 to 4.0 m.y. (Davis *et al.*). Based on an analysis of syntectonic deformed sediments, Shaw (1993) further estimates a 1.4-mm/yr slip rate for the structure during late Pliocene and Quaternary time and a recurrence time of 800 to 2000 yr for M_S 6.4 to 7.2 earthquakes on the structure.

The Santa Monica blind thrust system has been inferred from both the presence of fold trends and aspects of historical seismicity (Hauksson, 1992; Shaw, 1993), but we are aware of no information bearing on the slip rate characterizing the system. Westward and offshore of the Santa Monica blind thrust system, Shaw (1993) has interpreted subsurface data to define two buried thrust systems in the Santa Barbara Channel; the west and east Channel Island thrusts (Fig. 15). The slip rate across the structures since late Pliocene is reportedly 1.3 mm/yr (Shaw).

The study of blind thrusts and their relationship to seismic hazard is still in its infancy. Recognition of the seismic potential of such events dates back only about 10 yr to the 1983 Coalinga earthquake (e.g., Stein and Ekstrom, 1992). Current structural studies, although tremendously enlightening, are limited because the slip rate estimates reflect motion averaged over millions of years, rather than a period of thousands or tens of thousands of years generally considered in the study of late Quaternary and Holocene deposits along active fault traces. The question thus arises of whether or not the rates averaged over millions of years are reflecting the current rate of motion on the structures. Also, it should be noted that unknown uncertainties arise in the use of retrodeformable cross sections to estimate slip rates on buried thrusts in regions also characterized by active strike-slip tectonics (e.g., Hill, 1989; Weldon and Humphreys, 1989). Moreover, more than one interpretive cross section will generally explain available subsurface data (e.g., Yeats and Huftile, 1989; Namson and Davis; 1989). Continued analysis of subsurface data holds the potential to refine knowledge of the spatial extent of the broad buried thrusts outlined in Figure 15 and, hence, place limits on the location and potential size of future earthquakes. With respect to the slip rate analysis, it seems clear that future effort will necessarily focus on determining the late Quaternary and Holocene rate of slip on these structures through the study of Quaternary and Holocene deposits that overlie and are deformed by the active fold structures.

Summary

The above compilation and accompanying Table 1 represent a comprehensive survey of the published literature describing fault slip rate and paleoearthquake studies along the active faults of southern California. The earliest of the studies bearing directly on paleoearthquake history and slip rate of a fault during the Holocene dates back to Clark's (1972) study of the Borrego Mountain section of the San Jacinto fault, which ruptured in the *M* 6.4 earthquake of 9 April 1968. The bulk of the studies postdate Sieh's (1978a) study of Pallet Creek, which to date still ranks as one of the longest and most detailed paleoearthquake histories of any fault in the world. The extreme success of that study, unraveling a paleoearthquake history extending >1000 yr back in time, clearly emphasized the potential value of such studies and was virtually responsible for the creation of a cottage industry of investigators conducting similar studies in California and around the globe. Ironically, the very success the Pallet Creek study, in comparison to the generally less extensive and more limited histories provided by subsequent studies, points to a fundamental limitation of paleoearthquake as well as fault slip rate studies. More specifically, the potential success of paleoearthquake and fault slip rate studies is dependent on the creation and presentation of a unique set of stratigraphic, geomorphic, and structural relations along and across a fault zone. Hence, although there is most certainly much more data to be gleaned from the geology along faults, the very scattered nature of sites in Figure 1 that have yielded useful paleoearthquake and fault slip rate data reflects the distributed and limited nature of preservation of such sites. Indeed, the slip rates inferred along any given fault zone generally require extrapolation in regions between the limited slip rate data and, hence, assumptions regarding the behavior of the fault elsewhere along strike. Nonetheless, the benefit of geologic data to seismic hazard analysis is now well accepted and proven. With that, the summary of results and source of reference recorded here should prove beneficial to the interested investigator and mark the progress of paleoearthquake and slip rate studies to date.

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