Active Faults in the Los Angeles Metropolitan Region

Southern California Earthquake Center Group C*

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Introduction

Group C of the Southern California Earthquake Center was charged with an evaluation of earthquake fault sources in the Los Angeles Basin and nearby urbanized areas based on fault geology. The objective was to determine the location of active faults and their slip rates and earthquake recurrence intervals. This includes the location and dip of those faults reaching the surface and blind faults that are expressed at the surface by folding or elevated topography.

Slip rate determinations are based on several timescales. The tectonic regime of the Miocene was generally extensional, and the north-south contractional regime came into being in the early Pliocene with the deposition of the Fernando Formation (Wright, 1991; Yeats and Beall, 1991; Crouch and Suppe, 1993). The longest timescale for slip-rate estimates, then, is the time of imposition of the north-south contractional regime, the past 5×10^6 years. Another timescale is the early and middle Quaternary ($\sim 2 \times 10^6$ years), the time of deposition of the upper Pico member of the Fernando Formation plus the shallow-marine to nonmarine San Pedro Formation. Information for the first two timescales is derived from the subsurface using oil-well and water-well logs, multichannel seismic profiles, and surface geology. A third timescale is the late Quaternary (10^2-10^5 years), information for which is obtained through trench excavations, boreholes, and high-resolution seismic profiles and ground-penetrating radar augmented by the 232-year-long record of historical seismicity in the Los Angeles area. The shortest timescale (10 yrs) is that afforded by repeated GPS observations.

The late Quaternary rate is the most representative long-term rate in forecasting future behavior because it provides a geologically- and statistically-significant averaging time but is unlikely to be contaminated by Pliocene and early Pleistocene geologic processes no longer active today. Two examples illustrate this problem. (1) The post-Miocene slip rate on the Las Cienegas blind fault was estimated as 2.1-2.3 mm/yr by Schneider et al. (1996) based on Fernando and San Pedro growth strata, but only as 0.09-0.13 mm/yr by Ponti et al. (1996) based on thickness changes of late Quaternary strata between the upthrown and downthrown blocks of the Las Cienegas fault. (2) The late Quaternary displacement on the Whittier fault is almost purely by strike slip (Rockwell et al., 1992), yet the total lateral displacement is too small to be expressed in offset facies changes of members of the Miocene Puente Formation (Bjorklund and Burke, in review).

The late Quaternary rate may be different from the rate based on GPS observations. For example, the GPS rate across the Eastern California Shear Zone (Sauber et al., 1994; Thatcher et al., 1999; Miller et al., 2001; Dixon et al., 2000) is considerably higher than the late Quaternary geologic estimates. In California, similar differences between GPS and geology may occur on the Garlock fault. In this instances, the GPS rate may not be steady state but may represent a short-term strain transient.

This report summarizes the evidence for slip rates across faults of the Los Angeles metropolitan region and calculates the north-south component of shortening to compare with the convergence rates of about 4.4 mm/yr between downtown Los Angeles and the San Gabriel Mountains based on GPS (Bawden et al., 2001). The references are largely those that summarize recent SCEC-supported work, and they should be consulted for earlier references such as Hoots (1931), Yerkes et al. (1965), Ziony (1985), and Wright (1991) that made important contributions to an understanding of active faulting in Los Angeles.

Transverse Ranges Southern Boundary Fault System

Santa Monica fault

The Santa Monica fault is part of the Transverse Ranges Southern Boundary fault system, a west-trending system of reverse, oblique-slip, and strike-slip faults that extends for more than 200 km along the southern edge of the Transverse Ranges (Dolan et al., 1997, 2000a). Other faults in this system, included in this review, are the Hollywood and Raymond faults. The Anacapa-Dume, Malibu Coast, Santa Cruz Island, and Santa Rosa Island faults to the west are also part of this system, but are not included in this report.

The Santa Monica fault extends east from the coastline in Pacific Palisades through Santa Monica and West Los Angeles and merges with the Hollywood fault at the West Beverly Hills Lineament in Beverly Hills, west of the crossing of Santa Monica Boulevard and Wilshire Boulevard, where its strike is northeast. The surface expression of the fault is a series of left-stepping en échelon, south-facing scarps with an overall southward-convex map pattern. Onshore, the fault offsets the surface 2-3.5 km south of the Santa Monica Mountains range front; the range front itself is marked by the inner edge of the Stage 5e marine terrace (Dolan et al., 2000a). Accordingly, the fault traverses alluvium that allows the Quaternary history of the fault to be characterized based on geomorphology, stratigraphy, and seismic reflection characteristics (Dolan and Pratt, 1997; Dolan et al., 2000a).

Uplift of an alluvial-fan surface north of the fault requires a reverse-slip rate of ~0.5 mm/yr (Dolan and Pratt, 1997). The inner-edge altitude of the Stage 5e marine terrace at Potrero

Canyon in Pacific Palisades requires an overall uplift rate of 0.6-0.7 mm/yr and a reverse-slip rate on the fault of about 0.6 mm/yr (McGill, 1989; Dolan et al., 2000a).

A trench excavation on the grounds of the Veteran's Administration hospital at Sawtelle (here called the VA trench), west of I-405, supplemented by a high-resolution seismic profile (Dolan and Pratt, 1997), provided evidence for at least six surface ruptures in the past 50 ky, and at least two and probably three events after the burial of a prominent paleosol dated as 16-17 ka (Dolan et al., 2000a). According to these authors, a well-documented surface rupture occurred between10 and 17 ka, although a more recent earthquake probably occurred in the vicinity of the trench 1-3 ka. This leads to an average earthquake recurrence interval of 7-8 ky, which is much longer than the ~1.9-3.3 ky recurrence interval for earthquakes of M_w 6.9-7.0 that would be expected if the entire Santa Monica fault ruptured at once. The longer recurrence interval may be explained by the Santa Monica fault rupturing along with other faults to the west (Anacapa-Dume fault) or east (Hollywood fault), resulting in greater slip per event.

In the subsurface, the active Santa Monica fault is shown to be the youngest of several faults, the oldest of which sustained major left-lateral strike-slip of basement rocks and Eocene strata prior to the deposition of alluvial strata south of the range front (Yeats, 1968; Tsutsumi, 1996; Tsutsumi et al., 2001). The South strand of the Santa Monica fault underwent normal separation in the late Miocene as documented by a thick sequence of Mohnian strata north of the fault relative to a thinner sequence to the south. The separation changed to south side down in the Delmontian and continued through the deposition of the Fernando Formation. The South strand cuts strata as young as the Middle Pico Member of the Fernando Formation. Thickness differences in the Upper Pico Member indicate that the South strand continued to be active as a blind fault throughout the deposition of the Upper Pico (age 2.5-0.9 Ma, Tsutsumi et al., 2001). The Quaternary San Pedro Formation shows no variation in thickness across the upward projection of the South strand, evidence that it post-dates this strand.

The out-of-sequence North strand of the Santa Monica fault underwent all of its dip separation of 180-200 m during and after deposition of the San Pedro Formation, or in the last ~1 my (D, Ponti in Hummon et al., 1994). If the 0.6 mm/yr dip separation rate characterizes the entire history of the fault, then the North strand of the fault became active at about 300 ka (Dolan et al., 2000a).

The Santa Monica fault has not yielded direct evidence for its strike-slip rate. Evidence for left-lateral strike slip includes the left-stepping pattern of en-échelon faulting, numerous small strike-slip faults in the VA trench (Dolan et al., 2000a), and left-lateral stream offsets on the Malibu Coast fault north of Point Dume (Drumm, 1992; Treiman, 1994). The abrupt changes of dip with depth: steep close to the surface, low-angle at depth (Tsutsumi et al., 2001), suggest a major component of strike slip, possibly a flower structure, with the high-angle strike-slip fault beneath the range front at depth. Treiman (1994) estimated that the strike-slip rate north of Point Dume is currently < 0.5 mm/yr, diminished from a longer-term Quaternary rate of up to 2 mm/yr.

Santa Monica Mountains blind thrust

Davis and Namson (1994) suggested on the basis of a balanced cross section that the Santa Monica Mountains are uplifted along a north-dipping blind thrust with a slip rate of 3.9-5.9 mm/yr over the past 2-3 my. However, Johnson et al. (1996) indicated that this blind fault has a slip rate < 1 mm/yr based on the uplift of marine terraces along the Malibu coast. The 120-ka terrace at Point Dume and Pacific Palisades is being uplifted at a rate of 0.1-0.2 mm/yr (Dolan et al., 2000a). Uplift of the footwall block of the Santa Monica fault at Potrero Canyon (McGill, 1989) is taking place at a rate of < 0.2 mm/yr along the coast (Dolan et al., 2000a). Meigs et al. (1999) show that the south flank of the Santa Monica Mountains has been uplifted over the past several million years at an average rate of 0.5 +/- 0.4 mm/yr, and the north flank has been uplifted at a rate of 0.24 +/- 0.1 mm/yr.

It is unclear if the Santa Monica fault and the blind thrust are the same fault, or if the two faults represent strain partitioning. If the 0.6 mm/yr dip-slip rate is the same as that on the blind thrust, then north-south shortening on the entire structure is 0.4 mm/yr (Dolan et al., 2000a).

Hollywood fault

The Hollywood fault extends ENE for a distance of 14 km through Beverly Hills, West Hollywood, and Hollywood to the Los Angeles River and Interstate 5. It is truncated on the west by the NNW-striking West Beverly Hills Lineament (WBHL), which marks a left step of 1.2 km between the Santa Monica fault and Hollywood fault (Dolan et al., 2000a). The lineament, located in Beverly Hills immediately east of the Los Angeles Country Club, is on trend with, and may be the northwest continuation of the Newport-Inglewood fault. The WBHL is a topographic scarp separating highly-dissected older alluvium to the west from young alluvium of the Beverly Hills plain to the east (Dolan et al., 2000a). Subsurface well control shows that the WBHL has normal separation, with its east side down (Tsutsumi et al., 2001).

The Hollywood fault is marked by a steep gravity gradient (Chapman and Chase, 1979) that extends to and beyond the Los Angeles River in the direction of the Raymond fault. However, the Hollywood fault has not been documented as a young fault even as far east as the Los Angeles River, although a south-facing slope in alluvium north of Los Feliz Boulevard may have been produced by a strand of that fault (Dolan et al., 1997; J.F. Dolan, in prep.). A bedrock fault between Mesozoic granitic rocks and Miocene strata south of Los Feliz Boulevard and west of Interstate 5 is probably the Hollywood fault, but evidence for late Quaternary activity has not been found there (Dolan et al., 1997).

Subsurface evidence for late Quaternary faulting is found in Hollywood, including a borehole transect along Cahuenga Boulevard and trenches and borehole transects at La Brea Avenue, Fuller Avenue, Camino Palmero Avenue, and Vista Street, with the clearest evidence for timing at the Camino Palmero borehole transect (Dolan et al., 1997; 2000b). The most recent faulting at Camino Palmero occurred after deposition of ~9 ka sediments and prior to deposition of sediments dated as ~6 ka (Dolan et al., 1997; 2000b). However, a pronounced ground-water barrier at Highland Ave, between La Brea Avenue and Cahuenga Boulevard, suggests that steeply north-dipping faults extend upward into late Holocene deposits there (Lindvall et al., 2001). The fault dips northward 70°-85° at Camino Palmero based on shear fabric in the fault zone and 60°-70° north dips at the Metrorail subway tunnel between Fuller and La Brea avenues. Quartz diorite is consistently on the north side, faulted against Quaternary alluvium, but at Camino Palmero, separation of soil horizons shows north-side-down separation, suggestive of an unknown component of strike slip (Dolan et al., 1997; 2000b).

Based on sediment accumulation rates determined by radiocarbon dating, the dip separation rate is slow, but is at least 0.075 mm/yr. The narrow Hollywood Basin, filled by Quaternary deposits parallel to and south of the Hollywood fault, contains strata as old as 0.8-1.2 Ma (D. Ponti in Hummon et al., 1994). Dolan et al. (1997) estimate that the strike separation rate on the Hollywood fault is greater than 0.25 mm/yr.

The Hollywood Basin was modeled as the backlimb of a blind thrust generating the Wilshire arch, the axis of which generally follows Wilshire Boulevard (Hummon et al., 1994). However, Tsutsumi et al. (2001) suggest that the Hollywood Basin is a pull-apart basin related to the left step between the Santa Monica and Hollywood faults. Not only is the WBHL characterized by normal separation, but the southern boundary of the basin is the North Salt Lake normal-separation fault of Wright (1991) and Schneider et al. (1996), a fault that is parallel to the Hollywood fault. The thickness of shallow-marine Quaternary San Pedro Formation is greater in the Chevron Laurel Core Hole in the western part of the Hollywood Basin than it is in the central Los Angeles trough (Hummon et al., 1994; Schneider et al., 1996). A pull-apart origin of the Hollywood basin strengthens the case for left-lateral strike slip on the Hollywood fault, although the slip rate is as yet unknown.

In Hollywood, where the fault was studied in detail by Dolan et al. (1997; 2000b), the active fault is close to the Santa Monica Mountains range front. Farther west, however, near the intersection of Sunset and La Cienega boulevards in West Hollywood, the active fault lies near the base of a pronounced south-facing alluvial apron along the mountain front (Dolan et al., 1997; Lindvall et al., 2001). Several south-dipping and north-dipping normal faults displace a marine abrasion platform overlain by marine sands that are estimated as 400-900 ka in age (Lindvall et al., 2001). Unfaulted soil horizons >100 ka in age provide an upper bound to the age of most of these hangingwall faults. The alignment of bedrock outcrops along a topographic scarp at Sunset Boulevard, previously assumed to be the active trace of the fault, is apparently a Pleistocene beach cliff; the active fault trace must lie farther south (Lindvall et al., 2001). These authors compare the altitudes of the 400-900-ka hangingwall terrace in West Hollywood to the Pleistocene marine terrace identified by Quinn et al. (2000) south of the fault in La Brea Plain, and they conclude that the differential uplift rate across the Hollywood fault is less than 0.14 mm/yr.

Raymond fault

The Raymond fault extends 25 km from the Los Angeles River east of Griffith Park east to east-northeast across the San Gabriel Valley through South Pasadena, Pasadena, San Marino, Arcadia, and Monrovia to a junction with the Sierra Madre fault at the foot of the San Gabriel Mountains. A sharp gravity gradient connects the western end of the Raymond fault across the Los Angeles River floodplain with the eastern end of the Hollywood fault, but this connection is not confirmed by geological evidence except for local air-photo lineations. The fault is convex southward, consisting of a western section that strikes east-west and an eastern section that strikes east-northeast. Left-deflected drainages, shutter ridges, sagponds, and pressure ridges in right-stepping restraining bends indicate that the Raymond fault is predominantly a left-slip fault (K. Sieh in Jones et al., 1990), although south-facing scarps along the central reach of the fault indicate a component of dip slip due to motion around a 25° restraining bend (Crook et al., 1987; Weaver and Dolan, 2000). One kilometer west of the change in strike, the Raymond fault has a poorly-defined intersection with the Eagle Rock fault. The Eagle Rock fault is much more poorly defined geomorphically than the Raymond fault, suggesting that it is less active, hence the kinematics of the fault intersection remains obscure. The Raymond fault joins the Sierra Madre fault south of Santa Anita Wash and south of the Clamshell-Sawpit fault in the foothills of the San Gabriel Mountains (Weaver and Dolan, 2000) on which the 1991 Sierra Madre earthquake of M_W 5.8 occurred (Hauksson, 1994). The 1988 Pasadena earthquake of M_L 4.9 probably occurred on the Raymond fault based on the fault-plane solution of the mainshock and the distribution of aftershocks (Jones et al., 1990); this earthquake sequence delineated a fault dipping 80° north.

Trenches excavated by Crook et al. (1987) and Weaver and Dolan (2000) show that the most recent earthquake occurred 1000-2000 years ago (Weaver and Dolan, 2000). Between 5 and 8 earthquakes occurred between 40 and 2 ka, a maximum average recurrence interval of 5.7 to 10 k.y. (Crook et al., 1987; Weaver and Dolan, 2000). Between 3 and 5 of these events occurred between 41.5 and 31.5 ka, an average recurrence interval equal to or less than 3300 yrs (Weaver and Dolan, 2000). This may indicate a cluster of earthquakes, or it may signify undetected events.

A site in east Pasadena yielded a best-estimate left-lateral strike-slip rate of 4 +1/-0.5 mm/yr based on left offset of a gravel-filled channel of 44 m, with 0.5 m vertical component. This rate is based on sediments within and below the channel dated by radiocarbon and by optically-stimulated luminescence (Marin et al., 2000; Dolan et al., in review). An apparent 3.4-km left-lateral offset of a crystalline basement ridge at the east end of the fault may represent the total slip on the fault (Weaver and Dolan, 2000).

Santa Susana and Sierra Madre Fault Systems

The western Transverse Ranges are crossed obliquely by a set of north-dipping reverse faults extending from the Santa Barbara Channel east to an intersection with the San Jacinto fault near Cajon Pass. These faults include, from west to east, the Red Mountain, San Cayetano, Santa Susana, Sierra Madre, and Cucamonga faults. The San Cayetano and Santa Susana faults have the highest documented long-term reverse slip rates in southern California. The Santa Susana and Sierra Madre faults are within the Los Angeles metropolitan area and are described here. The San Gabriel fault is characterized by Quaternary reverse-oblique slip in the east Ventura basin; it traverses the foothills of the San Gabriel Mountains north of the San Fernando Valley and is also described here, even though its long-term history is predominantly that of a strike-slip fault.

Santa Susana fault

The Santa Susana fault extends 28 km west-northwest from the northwest edge of the San Fernando Valley into Ventura County and is at the surface high on the south flank of the Santa Susana Mountains. The fault ends near the point where it overrides the south-side-up South strand of the Oak Ridge fault. The fault has a low dip near the surface, locally becoming horizontal. This may in part be due to a distortion of the stress field by the steep topographic gradient on the southern slope of the Santa Susana Mountains (Butler, 1977) as well as to uplift from a blind, south-dipping fault, part of the Oak Ridge fault system (described below).

The fault has two left-stepping lateral ramps (Yeats, 1987). The Gillibrand Canyon ramp on the west is the smaller of the two but is the best documented by subsurface geology. The Pliocene Frew fault (Yeats, 1987) ends or changes strike westward to another fault, also named the Frew fault of the Santa Susana and Tapo Canyon oil fields, and the pre-Saugus Torrey fault also changes strike there, indicating that this ramp influenced Pliocene structures in the Santa Susana footwall (Yeats, 1987). The east Ventura Basin fold belt changes its structural character across a northeast projection of this lateral ramp (Yeats, 1987), leading Yeats et al. (1994) to call it a segment boundary. The ramp had an effect on the distribution of aftershocks of the Northridge earthquake of 1994. The zone of major moment release in the 1994 earthquake was southeast of the Gillibrand Canyon ramp (Wald et al., 1996). Immediately southeast of the ramp, a zone of 1994 aftershocks "lit up" the Santa Susana fault (Pujol, 1996, cross section A-A' of his fig. 4). Northwest of the ramp, aftershocks in the Santa Susana footwall defined rupture planes that are more steeply dipping than they are southeast of the ramp. (See website of Sara Cavena, geoweb.princeton.edu/students/Cavena/ImageGallery/ImgGallery.html)

The larger ramp at the western edge of the San Fernando Valley is called the San Fernando or Chatsworth ramp (Yeats, 1987; Yeats et al., 1994); this ramp may be influenced by the Miocene Chatsworth set of faults marking the western margin of the San Fernando Valley (Tsutsumi and Yeats, 1999; Yeats, 2001a). The mainshock and a large number of the aftershocks of the 1971 Sylmar (San Fernando) earthquake were located on or close to this ramp; focal mechanisms showed a large component of left slip (Whitcomb et al., 1973). However, the rupture plane of the 1994 earthquake as defined by aftershocks went across this ramp.

The Pico Canyon earthquake of 4 April 1893, of M 5.5-5.9 (Toppozada, 1995), which might have occurred on the Santa Susana fault, caused damage in Newhall, Saugus, Castaic, and the now-vanished oil town of Mentryville (Richter, 1973), in addition to Los Angeles, Pasadena, and Fillmore.

The Santa Susana fault cuts the Quaternary Saugus Formation, and clasts in the Saugus contain evidence for the age of uplift of the Santa Susana Mountains. Most of the Saugus at Horse Flats, south of the Aliso Canyon Oil Field in the Santa Susana Mountains, contains conglomerate clasts largely derived from basement rocks of the San Gabriel Mountains and other crystalline ranges, evidence for deposition prior to uplift of the Santa Susana Mountains (Saul, 1975). In contrast, conglomerate in the uppermost Saugus of Saul (1975) at Horse Flats is dominated by locally-derived Modelo and Towsley clasts, evidence of uplift of the Santa Susana Mountains, presumably by upward movement of the hangingwall of the Santa Susana fault. Similar relations are found on the north side of the range near Magic Mountain amusement park (Treiman and Saul, 1986; Levi and Yeats, 1993, their fig. 3), where the deformed, locally-derived Saugus is called Pacoima Formation, following Oakeshott (1958). Paleomagnetic stratigraphy by Levi and Yeats (1993) permits the estimation of the ages of the base of the Saugus Formation, of the appearance of locally-derived clasts in the Saugus, and of the top of the Saugus as 2.3 Ma, 600-700 ka, and 500 ka, respectively. The age of initiation of the Santa Susana fault is thus constrained to have begun between 2.3 Ma and 600 ka (Huftile and Yeats, 1996).

The total dip-slip displacement on the Santa Susana fault is based on the offset of the base of the Fernando Formation in a balanced cross section (Huftile and Yeats, 1996). The displacement is 4.9 to 5.9 km, giving a dip-slip rate of 2.1 to 9.8 mm/yr. The horizontal component of displacement is 4.1 km, giving a horizontal shortening rate of 5.7 +/- 2.5 mm/yr (Huftile and Yeats, 1996).

An additional constraint on the age of initiation of the Santa Susana fault is based on the age of initiation of clockwise rotation of the Saugus Formation in its hangingwall at Magic Mountain. Most of the Saugus in the Magic Mountain section is rotated clockwise approximately 30°, whereas the Van Norman Dam section in the footwall of the Santa Susana fault is not rotated at all (Levi and Yeats, 1993). The uppermost part of the Magic Mountain section is rotated only about 15°, and the age of initiation of rotation of the Saugus Formation can be estimated at about 1 Ma (Levi and Yeats, 1993; S. Levi and R.S. Yeats, in prep.). If the rotation is evidence that the displacement on the Santa Susana hangingwall is not a translation but a rotation about a pivot point at the Santa Susana fault tip, then the age of initiation of the fault can be estimated as 1 Ma. Using 1 Ma to accumulate 4.9 to 5.9 km of displacement, the long-term slip rate is 4.9-5.9 mm/yr, and the horizontal shortening rate is about 4.1 mm/yr (S. Levi and R.S. Yeats, in prep.).

A trench across the fault at Limekiln Canyon at the northern edge of Horse Flats yielded no evidence of Holocene displacement (Lung and Weick, 1987). However, this trench was across the Older strand of the Santa Susana fault, which has been abandoned for the Younger strand within the Santa Susana Mountains (Yeats, 1987). Lung and Weick (1987) also exposed the fault in a sidehill cut near Tapo Canyon, west of the Gillibrand Canyon lateral ramp; this trench also yielded no evidence for Holocene rupture. As mapped by Ricketts and Whaley (1975) and Yeats (1977; cf. fig. 9.2 of Yeats, 1987), the Santa Susana fault is a single strand bringing Miocene Modelo Formation over Saugus Formation and late Quaternary fan deposits containing debris from the hangingwall. Fan deposits unconformably overlying the fault were undated, but are considered to be Pleistocene because they are extensively dissected by erosion. In a nearby flat-bottomed canyon, older alluvium interpreted by Lung and Weick (1987) as younger than these fan deposits includes peat with an age of 10,010 +/- 580 radiocarbon years. These results appear to be inconsistent with the high long-term slip rate on the Santa Susana fault and with the high north-south shortening rate based on GPS (Argus et al., 1999). Possibly the Holocene displacement is distributed among north-dipping bedding planes in bedrock in the hangingwall, but this cannot be confirmed. Because the Santa Susana fault crops out on the steep southern slopes of the Santa Susana Mountains rather than at the base of the range, age-diagnostic trenching sites are difficult to find, as pointed out by Lung and Weick (1987).

Sierra Madre fault (west)

The Santa Susana fault strikes northeast at the Fernando lateral ramp and turns east at the northern margin of the Sylmar Basin to become the Sierra Madre fault. This fault is exposed near the base of the San Gabriel Mountains for 75 km from San Fernando Pass at the Fernando lateral ramp east to its intersection with the San Antonio Canyon fault in the eastern San Gabriel Mountains (Crook et al., 1987), east of which the range front is formed by the Cucamonga fault. Exhumation of the San Gabriel Mountains began about 7 Ma based on fission-track and (U-Th)He geochronology; this may date the time of initiation of the Sierra Madre fault (Blythe et al., 2000). We describe the Sierra Madre fault in two sections, with their boundary the intersection of the Sierra Madre fault with the Raymond and Clamshell-Sawpit faults. A short distance west of this intersection, the Vasquez Creek fault (the Southern strand of the San Gabriel fault of Ehlig, 1975) intersects the Sierra Madre fault at a low angle to strike. East of this intersection, the Sierra Madre fault, like the Cucamonga fault farther east, is a zone of deformation close to the base of the San Gabriel Mountains. To the west, however, the Sierra Madre fault is the northernmost of several north-over-south faults including the Mission Hills, Verdugo, and Northridge Hills faults, all of which appear to be active.

The Sierra Madre fault differs from the Santa Susana fault in that it lies at the base of the range, whereas the Santa Susana fault crops out high on the south slopes of the Santa Susana Mountains. It differs also in its complexity, including a series of boomerang-shaped faults characterized by a west-northwest-striking section of reverse slip and a northeast-striking section of apparent left slip (Oakeshott, 1958). These include the Lopez-Limerock and Sunland faults and possibly the Buck Canyon-Watt faults of Oakeshott (1958). The Saugus Formation in Kagel Canyon and Lopez Canyon is rotated clockwise approximately 34° (Levi and Yeats, 2001), suggesting that these boomerang-shaped blocks are rotating clockwise in a broad system of right-lateral shear related to the San Gabriel fault a short distance to the north (S. Levi and R.S. Yeats, in prep.). It is more difficult to determine the slip and slip rate of a rotating block because these rates would increase from zero at the pivot point to a maximum at the edge of the block. Furthermore, the rotations pertain only to slip rates over the past million years; these faults are not known to have tectonic geomorphic expression or to offset late Quaternary deposits younger than Saugus. Electron-spin resonance plateau dating of fault gouge shows that the most recent movement on the Limerock fault took place at 346 +/- 23 ka (Lee and Schwarcz. 1996).

Crook et al. (1987) concluded that the Sierra Madre fault between the 1971 San Fernando earthquake rupture and the Cucamonga fault is less active than segments to the east and west, based on degree of dissection of fault scarps and the relative age of fan surfaces cut by the fault based on geomorphology and soil development. Following criteria established by Bull (1964), Crook et al. (1987) noted that alluvial fan heads in the vicinity of the 1971 earthquake, such as the Pacoima and Little Tujunga Canyon fans, are incised to a lesser degree and hence are more active than the Arroyo Seco and Eaton Canyon fans in the Pasadena area farther east. A minimum long-term slip rate on this westernmost part of the fault can be obtained from the intersection of the base of the Saugus, which is 2.3 Ma in age, with the fault at the northern edge of the Sylmar basin. This intersection is at least 5 km below the surface, a minimum slip rate of 2.2 mm/yr. The rate would be larger depending on how much erosion of basement rocks had taken place in the hangingwall after deposition of the Saugus.

In that part of the Sierra Madre fault east of the 1971 earthquake rupture, Crook et al. (1987) were unable to identify any fault scarps or displaced strata involving sediments younger than late Pleistocene, and they concluded that this section of the fault had not produced large earthquakes in several thousand years and possibly not in the Holocene. Rubin et al. (1998) trenched a site in Altadena and found evidence that the most recent earthquake there had occurred in the past 10,000 years. Two earthquakes in the past 18,000 years had resulted in 10.5 m of slip, a minimum slip rate of 0.6 mm/yr. Displacements on these two earthquakes are large enough that Rubin et al. (1998) concluded that they were produced by earthquakes of M 7.2 to 7.6, much larger than the M 6.7 Sylmar earthquake of 1971 involving the western end of the fault.

The north-dipping rupture plane defined by aftershocks of the 1971 earthquake is probably the Sierra Madre fault at depth (Mori et al., 1995; Tsutsumi and Yeats, 1999). But the Sierra Madre range-front fault east of Big Tujunga Canyon did not rupture at the surface (Barrows, 1975; Kahle, 1975; Weber, 1975). The fault plane delineated by 1971 aftershocks passes south of the Sierra Madre fault in the direction of active reverse faults to the south: the Mission Hills and Northridge Hills fault (Mori et al., 1995; Tsutsumi and Yeats, 1999).

Mission Hills fault

The Mission Hills fault strikes east-west for about 9 km along the southern edge of the Mission Hills and Granada Hills, which are apparently uplifted by long-term reverse displacement of the hangingwall of this fault. The fault is mapped eastward to the eastern end of the hills near the Golden State Freeway, where it appears to turn southeastward toward the Verdugo fault (Tsutsumi and Yeats, 1999). The fault branches westward into two strands. The northern strand dips 60°-70° north in the Mission Oil Field and juxtaposes Modelo Formation against Fernando Formation. The southern strand extends along the base of the Santa Susana Mountains to Limekiln Canyon, where it brings upper Saugus on the south against lower, marine Saugus on the north. The fault may be linked with the Devonshire fault. Tsutsumi and Yeats (1999) argue that this fault does not join the Simi fault of the Simi Valley, as some maps have done. The active, north-side-up Simi fault ends where its geomorphic expression ends at the northeastern corner of the Simi Valley (Hanson, 1983).

Dip separation of the base of the Saugus Formation across the Mission Hills fault yields a dip separation rate of 0.6-0.7 mm/yr. The thickness of the Fernando Formation is about the same on both sides of the fault, indicating that slip began after Fernando deposition (Tsutsumi and Yeats, 1999).

Balboa Boulevard follows Bull Canyon, a drainage antecedent to Mission Hills uplift that is now filled with alluvial-fan deposits, some of which developed a large lateral spread during the 1994 earthquake (Holzer et al., 1999). CPT borings show that unfaulted Holocene sediments overlie a fault, considered by R.S. Yeats to be the Mission Hills fault, near Rinaldi Street at the southern edge of the Mission Hills based on a ground-water cascade and stratigraphic changes across the fault (Holzer et al., 1999). A slip rate on the fault could not be determined because the fault was not directly observed in the field.

Northridge Hills fault

A series of discontinuous low hills that extend from near the town of Chatsworth east-southeast to the San Diego Freeway marks the crest of a south-vergent fault-propagation fold above the blind, north-dipping, 15-km-long Northridge Hills thrust (Tsutsumi and Yeats, 1999). Well data in the western part of the fault show a dip of 70 degrees, but farther east, growth triangles in a seismic profile along Balboa Boulevard show that the fault is thin-skinned, with a moderate dip. Dip separation across the fault of a sandstone within the Miocene Modelo Formation gives a long-term dip separation rate as high as 0.3 mm/yr.

Baldwin et al. (2000) excavated a trench, several test pits, and several boreholes across a 2-m-high scarp on a probable Holocene terrace adjacent to Aliso Canyon Wash. A gravel bed with a soil age estimate of 6 to 30 ka shows 6 +/- 1 m vertical separation, and an unconformity on the top of the Saugus Formation is warped into a monocline with 13 +/- 2 m of relief. These relations provide a reverse-slip rate of 1.0 +/- 0.7 mm/yr on the blind Northridge Hills thrust (Baldwin et al., 2000).

The fault has no topographic expression east of the San Diego Freeway, where its presence is based on subsurface oil-well data (Tsutsumi and Yeats, 1999) and a steep gradient in the groundwater table (Weber et al., 1980). The fault intersects and either merges with or is truncated by the Verdugo fault at the Pacoima Oil Field (Tsutsumi and Yeats, 1999).

Verdugo fault

Both the Mission Hills and Northridge Hills faults appear to merge with the southeast-striking Verdugo fault, which lies on the southwest side of the Pacoima Hills and the Verdugo

Mountains. Vertical separation across this fault is at least 1000 m based on the structural relief between the valley floor and the crest of the Verdugo Mountains and the intersection of the base of the Saugus Formation with the fault in the Pacoima Oil Field (Tsutsumi and Yeats, 1999). The fault at the southwest edge of the Verdugo Mountains is marked by a pronounced gravity gradient (Weber et al., 1980) that is best modeled as a normal-separation fault (Langenheim et al., 2000). Pujol et al. (2001) , using seismic tomography, image the Verdugo fault with a nearly vertical dip. Adjacent to the Pacoima Hills, however, the gravity gradient is more consistent with a thrust-fault geometry (Langenheim et al., 2000), an interpretation supported by subsurface oil-well data around the Pacoima Oil Field (Tsutsumi and Yeats, 1999).

Weber et al. (1980) reported southwest-facing scarps 2-3 m high in alluvial-fan deposits in the Burbank-west Glendale area. In the Sun Valley area, they found minor faults 40 m below the surface in sand and gravel deposits in a gravel pit. Also in Sun Valley, groundwater-bearing alluvial deposits of Big Tujunga Wash are displaced, and in Glendale, there is a groundwater cascade in Verdugo Wash.

The Verdugo fault is on trend to the southeast with the Eagle Rock fault, but Weber et al. (1980) were not able to find evidence of late Quaternary offset. Weaver and Dolan (2000) observed that the Eagle Rock fault, especially its southeastern reach, is much more subdued geomorphically than the Raymond fault farther south.

San Fernando fault

The 1971 Sylmar (San Fernando) earthquake produced about 15 km of surface rupture south of the Sierra Madre fault (Sharp, 1975; Barrows, 1975; Weber, 1975); this rupture became known as the San Fernando fault. Slip vectors showed about equal amounts of reverse slip, north side up, and left-lateral strike slip, with the horizontal component of net slip as large as 2.5 m (Sharp, 1975). The Tujunga segment of the San Fernando fault occurred at the range front, evidence of pre-1971 faulting. Trench excavations also showed that the 1971 rupture followed older, prehistoric ruptures (Heath and Leighton, 1973). Bonilla (1973) reported that the most recent prehistoric rupture occurred less than 200 years prior to 1971, although the sample providing the radiocarbon date might be historic. Fumal et al. (1995) excavated trenches on both side of Bonilla's trench and found evidence for only two surface ruptures in the past 3.5-4 ky, including the 1971 break.

Tsutsumi and Yeats (1999, their figs 4f, 4g, and 7) showed that the San Fernando fault did not follow any major fault zone but occurred on the south flank of the Mission Hills syncline and Merrick syncline. Slip vectors measured by Sharp (1975) were parallel to bedding, and Tsutsumi and Yeats (1999) concluded that the San Fernando fault was a flexural-slip fault, formed during folding of the synclines.

Lindvall et al. (1995) described a set of fault scarps, north side up, near Pacoima Wash in the Sylmar Basin west of the Tujunga segment of the 1971 rupture. These faults, which did not rupture in 1971, offset terraces of Pacoima Wash, with an older terrace covered by soils estimated to be 20-30 ka and a younger terrace with a soil age estimated as 8-15 ka. The height of the fault scarps gives a minimum reverse-separation rate of 1 mm/yr across this zone of faulting If these faults are secondary to a master fault dipping 45° north (a non-flexural-slip origin), the master fault would have a reverse-slip rate of 2 mm/yr.

Sierra Madre fault (east)

The Sierra Madre fault lies at or south of the range front of the San Gabriel Mountains east of its intersection with the Raymond and Sawpit-Clamshell faults (Crook et al., 1987), passing through the cities of Arcadia, Monrovia, Bradbury, Duarte, Azusa, Glendora, San Dimas, and Claremont. This section of the fault terminates eastward at the northeast-striking San Antonio Canyon left-lateral fault, where the Sierra Madre fault steps left to the Cucamonga fault. This left-lateral fault, together with subsurface left-lateral faults that were the source of the 1988 and 1990 Upland earthquakes (Hauksson and Jones, 1991) lead to the assumption that the Cucamonga fault would have a higher dip-slip rate than the Sierra Madre fault, as suggested by their comparative geomorphic expression (Crook et al., 1987). The Cucamonga fault has a dip-slip rate of 2-5 mm/yr (Dolan et al., 1996), which serves as an upper bound to the slip rate on the eastern Sierra Madre fault. The Sierra Madre fault is expressed as a series of southward-convex lobes, and at several localities, the most active strrand is south of the range front, which is itself marked by less-active or inactive older strands (Crook et al., 1987; Tucker and Dolan, 2001).

Crook et al. (1987) located the fault in several trenches, but they were unable to obtain age control because of the lack of availability of AMS radiocarbon dating. Tucker and Dolan (2001) excavated a trench and several large-diameter boreholes in Horsethief Canyon in San Dimas, near the Glendora Tunnel, where extensive geotechnical observations are available. They found evidence for at least 14 m of slip on the Sierra Madre fault between 24 and 8 ka, and no surface rupture since 8 ka. This leads to a minimum slip rate of 0.6 mm/yr since 24 ka and a minimum of 0.9 mm/yr between 24 and 8 ka. Surface rupture at Horsethief Canyon was the result of earthquakes with $M > 7$, consistent with the interpretation by Rubin et al. (1998) of large surface displacements during the two most recent surface ruptures in their trench at Altadena along the western part of the fault. The most likely scenario is that the entire Sierra Madre fault ruptures at the same time (Tucker and Dolan, 2001). The Raymond fault could also rupture during Sierra Madre events, but the Raymond fault has undergone at least one and possibly several ruptures since the most recent rupture at Horsethief Canyon. Similarly, trench data suggest that the Cucamonga fault has ruptured at least twice and possibly several times since the most recent surface rupture on the eastern Sierra Madre fault (Dolan et al., 1996, and in prep.).

San Gabriel fault

The San Gabriel fault is the westernmost member of the San Andreas strike-slip fault system to cut across the Transverse Ranges (the others to do so are the San Jacinto fault and the San Andreas fault itself). A precursor fault, the Canton fault, underwent displacement in middle Miocene time and may have crossed the San Fernando Valley to an intersection with the Raymond fault (Powell, 1993; Yeats and Stitt, 2001). This strand was abandoned in the late Miocene, and activity shifted to the present trace of the San Gabriel fault, which crosses the southern foothills of the San Gabriel Mountains to an intersection with the left-lateral San Antonio Canyon fault in the eastern San Gabriel Mountains. The Miocene slip rate on this fault system was 6.6-9.2 mm/yr (Yeats et al., 1994) or even faster (Yeats and Stitt, 2001), but this rate slowed drastically in the Pliocene in the Castaic Lowland and eastward. The fault became inactive in the Ridge Basin, where it is overlain unconformably by the upper part of the Hungry Valley Formation (Crowell, 1982), and the fault is overridden by a south-side-up reverse fault, possibly the eastern extension of the Santa Felicia fault, at the mouth of Violin Canyon (Yeats et al., 1994; Yeats and Stitt, 2001). In both the Ridge Basin and Castaic Lowland, the San Gabriel fault dips moderately to steeply east.

The fault is active east of a segment boundary near the Honor Rancho Oil Field in the Castaic Lowland, an area now largely covered by the city of Santa Clarita. At this segment boundary, the fault changes strike southeastward from southeast to east-southeast and changes separation from normal to the northwest (northeast side down) to reverse to the southeast (northeast side up). The segment boundary is northeast of and on trend with the Gillibrand Canyon lateral ramp on the Santa Susana fault (discussed above). A line connecting these features separates contrasting geologic structures in the east Ventura Basin: the Holser-Del Valle fault system and Newhall-Potrero anticline to the northwest and the Pico anticline and Oat Mountain syncline to the southeast.

The fault has geomorphic expression in Santa Clarita, including linear ridges, trenches, hillside benches, and ponded alluvium along the fault trace (Kahle, 1986). Cotton (1986) showed that the fault cuts Holocene alluvium in trenches near Castaic Junction, and Swanson (2001) found that undated stream terrace material in the fault zone in a railroad cut at Bouquet Junction has a vertical separation of 3 to 5 meters, and an overlying soil zone is offset vertically 1 m. The Pacoima Formation, which overlies the Quaternary Saugus Formation unconformably, has a dip separation of more than 10 m across a secondary reverse fault in this railroad cut

(Swanson, 2001). Distinctive clast assemblages in the Saugus Formation are offset right-laterally about 500 m (Weber, 1982).

If the age of the top of the Saugus Formation is about 500 ka, as estimated from paleomagnetic evidence (Levi and Yeats, 1993), the 500 m of offset would have accumulated at a right-lateral strike-slip rate of 1 mm/yr. Kahle (1986), largely on the basis of geomorphic evidence, estimated the slip rate as less than 1 mm/yr. Yeats et al. (1994) argued for a long-term slip rate of 2.5-3 mm/yr based on reverse separation of the base of the Saugus Formation in the Saugus Oil Field, where dip separation is greatest (Yeats and Stitt, 2001). Estimates of long-term slip rate are larger than those for late Quaternary slip rate, suggesting that the slip rate has slowed with time.

The late Quaternary activity of the San Gabriel fault in the San Gabriel Mountains has not been studied. Electron-spin resonance plateau dating of San Gabriel fault gouge in the Little Tujunga area shows that the most recent movement occurred at 39 +/- 6 ka (Lee and Schwarcz. 1996), although this result is inconsistent with evidence for Holocene displacement farther west in Santa Clarita. The fault splays into a northern and southern branch (Ehlig, 1975), renamed by Powell (1993) the San Gabriel fault *sensu stricto* and the Vasquez Creek fault, respectively. In the eastern San Gabriel Mountains, the San Gabriel fault *sensu stricto* is cut off by the left-lateral San Antonio Canyon fault, suggesting that this is the less active strand. We suggest that the major part of the activity shifts to the Vasquez Creek fault, which merges to the southeast with the Sierra Madre fault. The long-term slip rate on the Vasquez Creek fault, based on offsets of basement rocks, is no more than 5 mm/yr (Powell, 1993), but the Quaternary rate must be much less, based on analogy with the San Gabriel fault farther west (cf. Yeats and Stitt, 2001).

South-dipping Reverse Faults

The most damaging earthquake in the history of the United States, the 1994 Northridge earthquake, struck a previously-unknown south-dipping blind reverse fault beneath the eastern Santa Susana Mountains and western San Fernando Valley. Aftershocks of this earthquake terminated updip at the base of the north-dipping 1971 rupture zone (Mori et al., 1995). The Quaternary long-term slip rate on the blind fault was estimated as 1.7 mm/yr (Davis and Namson, 1994; Huftile and Yeats, 1996) based on thickness changes in the Saugus Formation in the Castaic Lowland, a foredeep with respect to the blind fault contributing to uplift of the Santa Susana Mountains and warping of the Santa Susana fault. Only the Saugus Formation appears to have responded to growth of the foredeep (Yeats et al., 1994; Huftile and Yeats, 1996), indicating that faulting began at or after about 2.3 Ma, the age of the base of the Saugus, earlier than the age of initiation of the faster-moving north-dipping Santa Susana fault (Levi and Yeats, 1993; S. Levi and R.S. Yeats, in prep.). The Saugus is even thicker in the Sylmar Basin, which also acted as a foredeep, but a slip rate based on the Sylmar Basin has not been worked out (Tsutsumi and Yeats, 1999).

Small-scale flexural-slip faulting was recognized by Treiman (1995) in Santa Clarita, where bedding slip in folded Saugus Formation broke the surface of building pads in the Stevenson Ranch housing development during the 1994 Northridge earthquake.

The 1994 earthquake uplifted the footwall of the Santa Susana fault , with the maximum coseismic uplift at Oat Mountain in the hangingwall (Hudnut et al., 1996). The Santa Susana fault occurs high on the south flank of the Santa Susana Mountains rather than at the base of the mountains as the San Cayetano fault does, evidence that uplift of the Santa Susana footwall in 1994 was part of the long-term uplift of the footwall in the late Quaternary accompanying earlier earthquakes on the blind south-dipping fault (Yeats and Huftile, 1995). Other faults with footwalls uplifted by blind faults dipping in the opposite direction are the western San Cayetano fault, underlain by the Sisar fault, and the Red Mountain fault, underlain by the Padre Juan fault (Yeats and Huftile, 1995). The correlation between footwall uplift and blind south-dipping reverse fault is not perfect, however. The fault as illuminated by 1994 aftershocks continues east of the Santa Susana Mountains beneath the San Fernando Valley, and the only uplift is that of the Mission Hills, which could also be explained by uplift on the north-dipping Mission Hills reverse fault. Pujol et al. (2001), using seismic tomography, imaged a south-dipping thrust beneath the north-dipping Northridge Hills thrust.

Yeats and Huftile (1995) interpreted the 1994 south-dipping earthquake fault as the eastern blind continuation of the Oak Ridge fault, which reaches the surface in the Ventura Basin. They proposed that the Oak Ridge fault curves from an east-west strike to east-southeast, following changes in strike in the pre-Saugus Frew and Torrey faults. The long-term slip rate on the Oak Ridge fault is 3.7-4.5 mm/yr near the point where the fault is overridden by the Santa Susana fault (Huftile and Yeats, 1996), a rate at least twice as fast as that of the 1994 blind thrust. The cause of the eastward decrease in slip rate is unclear, unless part is taken up by the south-side-up Holser and Del Valle faults in the east Ventura Basin (Yeats et al., 1994; Yeats, 2001). Long-term slip rate on each of these faults is estimated as not more than 1 mm/yr, but this is poorly constrained because the Saugus is eroded away where fault displacements are largest.

Farther east, in the southeastern San Fernando Valley east of Universal Studios, Weber et al. (1980) mapped a sharp photo lineament south of the Los Angeles River close to a sharp gravity gradient. They correlated this structure to the Benedict Canyon bedrock fault of Hoots (1931), which has left separation where it crosses the Santa Monica Mountains and has its north side down farther east along the northern base of the range. At the eastern end of the Santa Monica Mountains, where the Los Angeles River turns to the south, the bottom of the alluvial basin appears to be displaced relatively downward 170 m on the north side, near where faceted spurs have been identified on the flanks of the range. However, Weber et al. (1980) were unable to find evidence that this fault displaces Quaternary deposits; the faceted spurs could be caused by fluvial erosion and not fault displacement.

Los Angeles fold-and-thrust belt

Introduction

The M 5.9 Whittier Narrows earthquake of October 1, 1987, occurred on a previously-unrecognized blind thrust fault in the eastern part of the Los Angeles Basin, leading to a paradigm shift in geological understanding of the active tectonics of the basin. This earthquake provided evidence that anticlines housing the great oil fields of the Los Angeles Basin overlie seismogenic source faults. The previous belief had been that Los Angeles is primarily a strike-slip province. The appearance of an earthquake in the Los Angeles Basin with a reverse-fault signature similar to those in the Transverse Ranges led to a reappraisal of the anticlines of the Los Angeles Basin for their earthquake potential. This reappraisal used the tools of the petroleum geologist: oil-well data and seismic profiles, as well as ground-water data (Dept. of Water Resources, 1961) and tectonic geomorphology.

The folds extend from the Newport-Inglewood fault eastward to the Elysian Park, Montebello, Santa Fe Springs, West Coyote, East Coyote, Richfield, and Kraemer anticlines, all housing oil fields except the Elysian Park anticline. Davis et al. (1989) constructed balanced (retrodeformable) cross sections across the Los Angeles Basin and concluded that the blind fault generating the Whittier Narrows earthquake is part of a thrust ramp they called the Elysian Park thrust. The anticlinal feature overlying the thrust ramp was referred to by them as the Santa Monica Mountains anticlinorium, uplift of which produced the Santa Monica Mountains, the Elysian, Repetto, and Montebello Hills, and the Puente Hills. (An anticlinorium is a major anticlinal structure that consists of several smaller anticlines.) The folds were drawn as fault-propagation folds, that is, slip on faults is consumed updip by folding, following Suppe and Medwedeff (1990). The long-term slip rate on the Elysian Park thrust was estimated by Davis et al. (1989) as 2.5-5.2 mm/yr.

Shaw and Suppe (1996) also constructed balanced cross sections across the Los Angeles Basin using a relatively high-quality 2D seismic data set, but in contrast to Davis et al. (1989), they interpreted their folds to be generated by fault-bend folding, following Suppe (1983). The blind thrust consists of thrust flats and thrust ramps, and the folds are generated as a result of the non-planar geometry of the thrust surface. In the Shaw and Suppe model, the thrust ramps generate dip panels that they called trends, and the thrust flats make up the lowlands, principally the central Los Angeles Basin lowland. These make up one very large fault called the Compton-

Los Alamitos thrust. They decoupled their northwest-trending Elysian Park trend from the east-west-trending Santa Monica Mountains anticlinorium of Davis et al. (1989). The slip rate on the thrust ramp beneath the Elysian Park trend was estimated as 1.7 +/- 0.4 mm/yr. Here we discuss the Elysian Park trend within the Los Angeles Basin as limited by Shaw and Suppe (1996). In this summary, we discuss the individual structures making up the Elysian Park trend separately, although the possibility exists that several of these structures might rupture together in a cascade, an implication of the models of both Davis et al. (1989) and Shaw and Suppe (1996).

Las Cienegas fault

The last oil-exploration and development campaign in Los Angeles took place in the downtown area in the 1960s, largely on the Las Cienegas structural shelf between the deep central trough and the Santa Monica Mountains. Hummon et al. (1994) showed that the base of shallow-marine Pleistocene gravels, 0.8-1.0 Ma in age (D. Ponti in Hummon et al., 1994) is upwarped along a broad arch in Hollywood and West Hollywood called by them the Wilshire arch because its axis approximately follows Wilshire Boulevard. The south side of the arch leads into the central trough, and the north side into an elongate low called the Hollywood Basin.

Hummon et al. (1994) proposed that the arch is formed by the blind, north-dipping Wilshire thrust dipping 10°-15° north. If the Hollywood Basin is the backlimb of this arch, a fault-bend fold model yields a dip-slip rate of 1.5-1.9 mm/yr over the past 0.8-1.0 m.y. They also located the fault using an elastic-dislocation model of the wavelength (10 km) and amplitude (400 m) of the Wilshire arch, following King et al. (1988), who showed that the wavelength of a fold associated with an active fault can be compared to the wavelength of coseismic folding. This model locates a fault dippng 30°-35° north, with the fault tip 2.0 to 2.8 km below the surface, consistent with a diffuse zone of seismicity. This yields a right-oblique slip rate of 2.6-3.2 mm/yr.

These models depend on the Hollywood Basin being the backlimb of the fault generating the Wilshire arch. However, Tsutsumi (1996) and Tsutsumi et al. (2001) showed that the Hollywood Basin is a pull-apart basin related to the left step between the Santa Monica and Hollywood faults, hence a strike-slip feature in contrast to the dip-slip backlimb of the Wilshire arch. Schneider et al. (1996) used Pliocene and younger growth strata between the Las Cienegas structural shelf and the central trough to model the blind fault generating the boundary between the central trough and the structural shelf. The vertical component of displacement is the difference in thickness of coeval strata between the shelf and the trough, backstripped to obtain pre-compaction thicknesses. The horizontal component is the difference in shortening by line-length balancing of horizons of different ages. Analysis of growth strata show that the folds grew through progressive limb rotation, with fault dip of 61° at East Beverly Hills Oil Field and

62° at Las Cienegas Oil Field. The slip rates on the fault over the past 5 m.y. were1.1-1.3 mm/yr at East Beverly Hills and 1.3-1.5 mm/yr at Las Cienegas, with horizontal convergence rates 0.5-0.6 mm/yr at East Beverly Hills and 0.6-0.7 mm/yr at Las Cienegas.

Ponti et al. (1996) and Quinn et al. (2000) compared relative vertical displacement between the structural shelf and the central trough for the past 330 ky and found a vertical uplift rate no more than 0.09-0.13 mm/yr, about an order of magnitude lower than the slip rate of Schneider et al. (1996). Although the uplifted side of the Las Cienegas blind fault is still active based on topographic expression (Dolan and Sieh, 1992; M. Oskin, pers. commun., 2000), it is clear that the long-term rate is much higher than the late Quaternary rate. Analysis of additional cross sections eastward in the Boyle Heights and East Los Angeles districts near the Pomona Freeway between Las Cienegas and Bandini oil fields (R.S. Yeats and G.J. Huftile, see R.S. Yeats website) shows that the vertical changes of the Pleistocene San Pedro Formation across the Las Cienegas blind fault are considerably less eastward and essentially non-existent south of Bandini Oil Field (Yeats et al., 1999).

This eastern edge of the Los Angeles trough was depicted in a cross section by Shaw and Suppe (1996, their cross section Y-Y') as the Las Cienegas trend, a fault-bend fold generated by a thrust ramp of their Las Cienegas thrust. Growth triangles imaged on their seismic profiles showed that displacement on the blind thrust took place during deposition of the upper Pico (latest Pliocene) and continued into the Quaternary. Shaw and Shearer (1999) named this structure the Los Angeles segment of their Puente Hills thrust.

Elysian Park anticlinorium

The Elysian Park anticlinorium *sensu stricto* is a southward-verging anticline 20 km long with a curved, southward-convex axis, lying between the left-lateral(?) Hollywood fault on the northwest through the Silver Lake district and the cities of South Pasadena and Alhambra to the right-lateral East Montebello fault on the east in the city of San Gabriel. Uplift of the structure has produced the Elysian, Repetto, and Monterey Park Hills. From the Los Angeles River eastward, the southern range front of the hills is formed by the active axial surface between the south limb of the anticlinorium and the nearly-flat dips of the Las Cienegas structural shelf (R.S. Yeats and G.J. Huftile, work in progress).

Oskin et al. (2000) studied parasitic minor folds in the vicinity of the axial surface, the largest being the Coyote Pass escarpment and monocline close to the range front. Bullard and Lettis (1993) concluded that these folds provide evidence for a southward migration of deformation. Deformed late Quaternary deposits across the Coyote Pass escarpment and related structures allowed Oskin et al. (2000) to estimate a contraction rate across the structure of 0.6-1.1 mm/yr and a late Quaternary slip rate on the blind Elysian Park reverse fault of 0.8-2.2 mm/yr.

The dip of the blind fault was determined by analysis of growth strata, similar to the method of Schneider et al. (1996).

The late Quaternary slip rate on the Elysian Park fault is similar to the long-term slip rate on the Las Cienegas fault, suggesting that convergence is shifting northeastward from the Las Cienegas fault to the Elysian Park fault (Yeats et al., 1999). Unlike the Las Cienegas fault, with structural growth taking place throughout the Pliocene and early Pleistocene, the Elysian Park anticlinorium shows no significant decrease in thickness of the Repetto and early Pico members of the Fernando Formation between the structural shelf and the south limb of the anticlinorium, based on oil-well data. However, Soper and Grant (1932), based on surface geology, concluded that this structure was active in the Pliocene based on an unconformity between the Pico and Repetto members of the Fernando Formation. A possible western continuation of the Elysian Park fault in downtown Los Angeles, the San Vicente fault of Schneider et al. (1996) has relatively small reverse separation superposed on a much larger normal separation during the Miocene. However, the San Vicente fault north of East Beverly Hills Oil Field shows evidence of Pliocene growth, earlier than that at the Elysian Park axial surface (Schneider et al., 1996, their fig. 4) and consistent with observations of Soper and Grant (1932).

An unresolved problem is the origin of the MacArthur Park escarpment southwest of the Hollywood Freeway and several minor folds in alluvium on the crest of the Wilshire arch mapped by Dolan et al. (1997) along Wilshire Boulevard and La Brea Avenue to the north. The MacArthur Park lineament is the northwest-trending range front between southwest-dipping strata of the Elysian Park anticlinorium and Quaternary deposits atop the Wilshire arch, which are cut off at the range front. Oskin et al. (2000) show the MacArthur Park escarpment as the continuation of the Coyote Pass escarpment, based on uplifted fluvial terraces. However, the MacArthur Park escarpment does not correspond to the same axial surface between low-dipping strata of the Las Cienegas structural shelf and southwest-dipping strata of the anticlinorium. Cross sections constructed by R.S. Yeats and G.J. Huftile across the Los Angeles Downtown Oil Field and the Jefferson pool of the Las Cienegas Oil Field (see R.S. Yeats website) show that the range front is northeast of the active axial surface.

Whittier Narrows earthquake source fault

The fault-plane solution for the 1987 Whittier Narrows earthquake showed a moderately-dipping fault plane with an east-west strike (Hauksson and Jones, 1989). Releveling after the earthquake showed an uplifted area extending from the Santa Fe Springs anticline northward across the intervening La Habra syncline to the Montebello anticline (Lin and Stein, 1989). Shaw and Shearer (1999) relocated the mainshock and aftershocks of the earthquake, illuminating a fault plane dipping about 25° north, a dip consistent with fault-plane reflections on a seismic profile west of the crest of the Santa Fe Springs anticline between -3 and -7 km below sea level. The fault tip is located beneath the south side of the Santa Fe Springs anticline based on a trishear kinematic model (Allmendinger and Shaw, 2000). The long-term slip rate was estimated as 0.5 to 2.0 mm/yr, with the faster limit based on GPS evidence (Argus et al., 1999); a minimum long-term slip rate is 0.5-0.9 mm/yr (Shaw et al., 2000).

High-resolution seismic profiles across the updip projection of the active axial surface between the Santa Fe Springs anticline and low-dipping strata to the south provide structural data within 15 m of the surface, with south dips of 20° to 25° north of the axial surface and horizontal dips to the south (Williams et al., 2000; Christofferson et al., 2000 and in prep.). If these dipping sediments can be dated through borehole traverses and trench excavations, a short-term slip rate could be calculated.

The fault is part of the Puente Hills thrust of Shaw and Shearer (1999), with the Santa Fe Springs segment stepped to the right from their Los Angeles segment farther west. The cloud of aftershocks of the 1987 earthquake is limited to the Santa Fe Springs segment (Hauksson and Jones, 1989).

The Montebello anticline to the north is a separate structure from the Las Cienegas, Elysian Park, or Santa Fe Springs structure. It is described below as part of the Whittier fault system.

Coyote folds

The Puente Hills thrust steps right east of the Santa Fe Springs anticline to a north-dipping reverse fault beneath the Coyote Hills (Shaw and Shearer, 1999). The Whittier earthquake of July 8, 1929, with intensities as high as VII, had its epicenter close to this stepover, with meizoseismals oriented north-south (Richter, 1958).

The Coyote Hills in the cities of La Mirada, La Habra, Fullerton, and Placentia are uplifted along a string of doubly-plunging anticlines. From west to east, these are the West Coyote anticline, housing the West Coyote Oil Field, and the Hualde and Anaheim domes of the East Coyote Oil Field. Farther to the southeast in the cities of Yorba Linda and Orange, the Richfield and Kraemer anticlines converge with the Whittier fault north of the Santa Ana River in the foothills of the Puente Hills. The south-verging Coyote folds each include an axial reverse fault, the South Flank fault of West Coyote and the Stern fault of East Coyote (Wright, 1991). Myers (2001) showed that the Stern fault underwent 1200 m of left-lateral strike slip, when the fault was nearly vertical, and became inactive prior to folding in the Quaternary. This strike-slip fault was traced westward across the Leffingwell Oil Field and must extend eastward south of the Anaheim dome of the East Coyote Oil Field. Folding began during deposition of the Pico member of the Fernando Formation.

Myers (2001) and D. Myers, J. Nabelek, and R. Yeats (in prep.) used dislocation modeling to locate the blind fault generating the Coyote folds, yielding dips consistent with those observed using aftershocks and fault-plane reflections beneath the Santa Fe Springs anticline (Shaw and Shearer, 1999), although there is large uncertainty in fault dip. Several dated horizons were projected into the East Coyote fold: the Brunhes-Matuyama boundary from a water well in Pico Rivera south of the Montebello anticline (D. Ponti, pers. commun., 2000), an age estimate of 1.4 +/- 0.4 Ma of a mollusc in the San Pedro Formation in the West Coyote Hills (Powell and Stevens, 2000), and the dated Nomlaki Tuff (3.4 +/- 0.3 Ma, Sarna-Wojcicki et al., 1991) near the Meyer shale in the Santa Fe Springs Oil Field (A. Sarna-Wojcicki and T.H. McCulloh, pers. comm., 2000). This leads to a slip rate on the blind thrust of 1.2 +1.4/-0.5 mm/yr.

Dislocation modeling was also applied to the Santa Fe Springs anticline, resulting in a slip rate slightly higher than that at East Coyote and a fault dip consistent with that obtained by fault-plane reflections and distribution of 1987 mainshock and aftershocks (D. Myers, J. Nabelek, and R. Yeats, in prep.).

Peralta Hills thrust

South of the Coyote folds, Burruel Ridge and the Peralta Hills project westward into the Los Angeles Basin from the Santa Ana Mountains, possibly deflecting the course of the Santa Ana River westward. This feature is a southward-vergent anticline with the thrust on the south side; west of the Santa Ana River, the anticline projects into the Olive Oil Field. Bryant and Fife (1982) suggested that bedrock structures are thrust southward against Pleistocene terrace deposits, although subsequent geotechnical work by others suggests that they may have mapped a landslide. West of the Costa Mesa Freeway in Orange, immediately south of the Olive anticline, a scarp in alluvial deposits of the Santa Ana River adjacent to Lincoln Avenue appears to be active. A contractional structure, if extended eastward across the northern Santa Ana Mountains, could explain the difference in slip rate between the Elsinore fault at Glen Ivy and the Whittier fault at Santa Ana Canyon.

Northwest-striking faults in the northernmost Peninsular Ranges

Introduction

The southern part of the Los Angeles metropolitan area is tectonically a part of the Peninsular Ranges, with northwest-striking right-lateral faults that are part of the southern San Andreas fault system. Slip rates on these faults are highest on the San Andreas fault itself, lower on the San Jacinto fault, and still lower on the Whittier-Elsinore and the Newport-Inglewood faults (Yeats, 2001b). Davis et al. (1989) and Shaw and Suppe (1996) pointed out that these are not simple strike-slip faults; reverse slip is also important and locally may be dominant. Davis et al. (1989) even suggested that the Whittier fault may be relatively unimportant compared to the regional blind thrust that underlies the Puente Hills. It seems likely that strain partitioning is an important element in the earthquake evaluation of these faults, just as it is in the central Coast Ranges, affected by reverse-fault earthquakes in 1983 (Coalinga) and 1985 (Kettleman Hills) as well as the great Fort Tejon strike-slip earthquake of 1857 and several Parkfield earthquakes from then until 1966.

Here we discuss those northwest-striking local faults that strongly impact the Los Angeles metropolitan region: the Whittier-Elsinore, Newport-Inglewood, and Palos Verdes faults. The San Jacinto fault is important to the San Bernardino-Riverside metropolitan area, and the San Andreas fault is important to the entire Los Angeles metropolitan region, but these faults are not discussed here. Offshore faults in the California Continental Borderland, in particular the San Diego Trough-San Pedro fault and the San Clemente fault, have an impact on the Los Angeles region, but too little is known about their slip rates to include them in this discussion.

Also included in this section are the east-northeast-striking San Jose fault and the north-northwest-striking Chino fault and a consideration of the active-tectonic significance of the Santa Ana Mountains and San Joaquin Hills.

Whittier-Elsinore fault

The Whittier and Elsinore fault is marked by a band of diffuse seismicity, although this is much less pronounced than the seismicity marking the San Jacinto fault to the east.

The late Pleistocene to Holocene strike-slip rate on the Elsinore fault at Glen Ivy Marsh south of Corona is 5.3-5.9 mm/yr (Millman and Rockwell, 1986), with evidence for 4 to 5 earthquakes of M 6-7 since about 1060 AD (Rockwell et al., 1986). The most recent event was probably the Temescal Valley earthquake of M 6 on May 15, 1910, with about 15 km of surface rupture (Rockwell, 1989). Northwest of Glen Ivy, the fault divides into two subpararallel strands, with the northeastern strand becoming the Chino fault and the southwestern strand, following the northeastern range front of the Santa Ana Mountains, becoming the Whittier fault. East of Santa Ana Canyon, the Whittier fault turns west-northwest into the northern end of the Santa Ana Mountains, where digital terrain images suggest right-lateral stream offsets. At Santa Ana Canyon, the Whittier fault has a right-lateral strike-slip rate of 2-3 mm/yr based on a 400-m offset of terraces of the Santa Ana River that are 140 ka in age (Gath, 1997; Gath et al., 1998; Rockwell et al., 1988). Farther west, at Olinda Creek, one strand of the Whittier fault has a right-lateral strike-slip rate of about one mm/yr. The stream offset by this strand is offset the same amount by another strand, and Gath et al. (1992) assigned a strike-slip rate on both strands of at least 2 mm/yr. The two strands are part of a positive flower structure, with Miocene Puente

Formation thrust over alluvial deposits; however, the displacement is mainly by strike slip (Gath et al., 1992). In addition, the tectonic geomorphic expression of the fault is characteristically strike slip, including right-deflected streams and shutter ridges (Rockwell et al., 1988).

The slip rate difference led Rockwell et al. (1992) to conclude that about 2.6 mm/yr of strike slip escapes along the Chino fault. However, some of this difference can be accounted for by the Coyote folds that intersect the Whittier fault at Santa Ana Canyon. The slip rate on the blind thrust generating the East Coyote folds (Myers, 2001) is enough to account for part of the difference between the strike-slip rate at Glen Ivy Marsh and that at Olinda Creek. Additional displacement could take place on the Peralta Hills thrust and on a footwall anticline beneath the Whittier fault between Turnbull Canyon (Herzog, 1998) and Yorba Linda (see fig. 17 in Myers, 2001, and R.S. Yeats website), including the 304 and 184 anticlines of the Whittier Oil Field (Herzog, 1998) and the Brea anticline of the Brea-Olinda Oil Field. This anticline (locally an anticlinorium) is considered to be active due to footwall uplift east of Turnbull Canyon; west of Turnbull Canyon, the Whittier fault lies at the Puente Hills range front (Herzog, 1998).

At the Whittier Narrows of the San Gabriel River, the Whittier fault turns more northerly to become the East Montebello fault. At Alhambra Wash in Rosemead, Gath et al. (1994) and Gath and Gonzalez (1995) trenched a strand of the East Montebello fault and found a slip rate of only 0.2 +/- 0.1 mm/yr; a second, larger scarp to the west was not investigated. This suggests a lower slip rate than that measured at Olinda Creek, which could be accounted for by growth of the Montebello anticline, which is truncated on the east by the East Montebello fault. The Montebello anticline was not uplifted separately from the Santa Fe Springs anticline during the 1987 Whittier Narrows earthquake (Lin and Stein, 1989), suggesting that its uplift history is controlled by strike slip on the Whittier fault instead of (or in addition to) reverse slip on the blind Santa Fe Springs segment of the Puente Hills thrust.

Despite the evidence for late Quaternary strike slip, the total right slip on the Whittier fault is relatively small. Part of the difficulty in establishing piercing-point offsets is that the modern Whittier fault reactivated a Miocene normal fault with the north side down (Yeats and Beall, 1991; Bjorklund and Burke, in review). McCulloh et al. (2000) estimate the right separation as 8-9 km based on offset facies and isopachs of Paleogene strata. This estimate faces the difficulty that north of the fault, Paleogene facies boundaries turn abruptly westward in the southeastern Puente Hills. The Santa Rosa basalt dated at 10.6 Ma is offset across the Elsinore fault no more than 15 km (Hull and Nicholson, 1992). Bjorklund and Burke (in review) are able to construct isopachs of the late Miocene Sycamore Canyon member of the Puente Formation without any offset, although the isopachs south of the fault are parallel to it, and an undetermined amount of strike slip is permitted by the isopach data.

Throughout most of its length on the south side of the Puente Hills, the fault has reverse separation, north side up, with maximum vertical separation of 4267 m in the northwest Puente Hills (McCulloh et al., 2000). This separation is less to the southeast, and near the Horseshoe Bend of the Santa Ana River, the sense of separation in bedrock (although probably not in late Quaternary deposits) changes to south side up, and the dip is vertical (Bjorklund and Burke, in review; McCulloh et al., 2000). Nonetheless, northwest of Horseshoe Bend of the Santa Ana River, the dominant expression is reverse slip, with a dip of 60° to 75° north. At Rideout Heights at the northwestern end of the Whittier fault, the late Pleistocene-Quaternary uplift rate is 0.6 +/- 0.1 mm/yr, and the dip separation rate is 0.97 +/- 0.1 mm/yr (Herzog, 1998), about the same as the strike-slip rate.

Puente Hills, San Jose Hills, and the San Jose fault

Davis et al. (1989) implied that the uplift of the Puente Hills is dominated by the Elysian Park blind thrust. Shaw and Shearer (1999) named the regional blind thrust generating the 1987 Whittier Narrows earthquake the Puente Hills thrust, although the topographic expression of the Puente Hills thrust is the Santa Fe Springs anticline and the Coyote Hills, not the Puente Hills. Herzog (1998) observed that the Puente Hills are restricted to the region between the Santa Ana and San Gabriel rivers, where the west-northwest-striking Whittier fault is a restraining bend between the northwest-striking Elsinore fault and north-northwest-striking East Montebello fault. Bjorklund and Burke (in review, based on structure contours of the La Vida member of the Puente Formation, map the structure of the Whittier fault hangingwall as a south-vergent anticline with its culmination west of Brea Canyon, next to the Brea-Olinda Oil Field. The uplifted footwall of the fault between Turnbull Canyon and Yorba Linda, related to a footwall anticline, attests to dip-slip on part of the Whittier fault system, evidence of partitioning between strike slip, as seen in the geomorphology and trench excavations, and dip slip, as seen in anticlines in both the footwall and hangingwall.

In contrast to the southern Puente Hills, the northern Puente Hills and San Jose Hills appear to be structurally more complex, and folding dominates (Olmstead, 1950). The San Jose Hills trend east-northeast and are uplifted along a west-southwest-plunging anticline underlain by the La Vida member of the Puente Formation, the Glendora Volcanics, and Cretaceous granitic rocks. The San Jose fault lies at the southern range front, steps left where the anticlinal axis steps left (Tan, in press a, b), and dies out at the surface farther west in the south limb of the anticline. Farther south, the Amar syncline is in an alluviated lowland, and still farther south, the Puente Hills anticline, housing the Walnut Oil Field, is also expressed as tectonic topography in the Little Puente Hills (Tan, in press a, b). This leads to the suggestion by R.S. Yeats that these folds, along with the Glendora South Hills farther north (Shelton, 1955), may be previously-unrecognized reverse-fault earthquake sources with a Transverse Ranges trend.

This implies that the Upland strike-slip earthquakes of 1988 and 1990 (Hauksson and Jones, 1991) may not have originated on the northeastern continuation of the San Jose fault. However, their source could have been the continuation of a strike-slip fault farther northwest, such as the Walnut Creek fault mapped by Tan (in press a, b) along the southwestern margin of the San Gabriel Valley or the Indian Hill fault mapped in the San Gabriel Valley farther northwest (Dept. of Water Resources, 1966; 1970; located on maps by Hauksson and Jones, 1991). A difficulty in evaluating these sources is that the youngest bedrock is Puente Formation; the thick Pliocene of the western San Gabriel Valley is absent. The Indian Hill fault appears to offset the base of water-bearing sediments, with the north side up (Dept. of Water Resources, 1970).

Chino fault

The Chino fault has been regarded as a strike-slip member of the Elsinore fault system (Rockwell et al., 1992). An earthquake of M 4.3 in February, 1989, with its epicenter southwest of the surface trace of the fault, had a fault-plane solution consistent with right-lateral strike slip on the Chino fault (Hauksson and Jones, 1991). A strike-slip fault with a more northerly strike than that of the Elsinore fault should be transtensional; indeed, small depressions are found at right stepovers along the fault (E.M. Gath, in prep.). On the other hand, the Chino fault has reverse separation throughout its length, with the southwest side up (Gray, 1961; Durham and Yerkes, 1964; Castro, 1975; Schoellhamer et al., 1981). In the Chino Hills, the Mahala anticline in the hangingwall of the Chino fault has topographic expression, following the Chino Hills drainage divide. McCulloh et al. (2000) suggested that the total right slip on the Chino fault can be no greater than a few kilometers, based on isopachs of Paleogene strata. R.S. Yeats (in prep.) suggests that the Mahala-Chino structure might comprise an active fold-reverse fault pair that is propagating north-northwestward toward the San Jose Hills, although the 1989 earthquake provided evidence that this fault can generate strike-slip earthquakes. Alternatively, the Chino fault could bend to a more northerly strike, cutting off the San Jose Hills on the east.

Heath et al. (1982) estimated a slip rate of 0.06 mm/yr horizontal and the same rate vertical near Prado Dam. Their slip rate was based on the 8-m vertical separation of a paleosol, the age of which was estimated as 125 ka. This separation was both by faulting and downwarping. They had no independent evidence for horizontal offset of this paleosol or of younger deposits; they simply assumed that the horizontal offset would be no larger than the vertical. Chris Walls and Eldon Gath suggest that the fault is active and is predominantly right lateral, based on northeast-facing fault scarps, deflected drainage, and beheaded drainage in the

Chino Hills and northeast-facing fault scarps and vegetated lineaments in the alluvium near and southeast of Prado Dam (see also Weber, 1977). Walls and Gath salvage-logged a trench excavation in the Chino Hills in which an organic colluvial layer overlying Puente Formation is offset 4.2-5.6 m right laterally with 10-15 cm apparent vertical separation. Charcoal from this colluvium was dated by Chris Walls as 11,219 +/- 331 and 9543 +/- 55 radiocarbon years.

To the east, the Central Avenue fault may be a right stepover from the Chino fault, based on photo lineations and geomorphic features being studied by J.A. Treiman (in prep.).

Newport-Inglewood fault and the Compton-Los Alamitos trend

Like the Whittier-Elsinore fault, the Newport-Inglewood fault, 70 km long onshore, is marked by a band of diffuse seismicity. Several earthquakes have struck the fault zone, including the March 10, 1933 "Long Beach" earthquake of M 6.4, with its epicenter off Newport Beach, and smaller earthquakes at Inglewood on June 20, 1920 (M 4.9), Gardena on October 22, 1941 (M 4.9), and Torrance-Gardena on November 14,1941 (M 5.4; Hauksson, 1990). Many microearthquakes are characterized by right-lateral strike-slip focal mechanisms, as was the 1933 earthquake (Hauksson, 1987; 1990). No historical earthquake is known to have been accompanied by surface rupture (Barrows, 1974).

The Newport-Inglewood fault continues offshore to the southeast (Fischer and Mills, 1991) and makes landfall in La Jolla as the Rose Canyon fault, which has evidence of Holocene right-lateral strike slip and a slip rate of 1.5 mm/yr (Lindvall and Rockwell, 1995). It is not a continuous surface fault like the Whittier fault, but instead is marked by a series of uplifts and anticlines including Newport Mesa, Huntington Beach Mesa, Bolsa Chica Mesa, Alamitos Heights and Landing Hill, Signal Hill and Reservoir Hill, Dominguez Hills, Rosecrans Hills, and the Baldwin Hills (Barrows, 1974). Farther northwest, it is on trend with the Cheviot Hills and the West Beverly Hills Lineament, the latter marking the left stepover between the presumably left-lateral Santa Monica and Hollywood faults (Dolan et al., 1997; 2000b). The right-lateral stress field is evident from the predominance of reverse faults in the west-trending Dominguez anticline, the coincidence of Signal Hill with a short, northeast step (Pickler fault) in the Long Beach segment of the fault, and normal separation on north-striking faults in Sunset Beach and Huntington Beach oil fields (Yeats, 1973; Harding, 1973).

Freeman et al. (1992) worked out long-term strike-slip rates on the fault by correlating electric-log facies of strata of 6 to 2.3 Ma on one side of the fault to a best match on the opposite side. At Seal Beach and Huntington Beach oil fields, this gave a slip rate of 0.49-0.52 mm/yr. At Long Beach Oil Field, the slip rate is 0.5 mm/yr, and at Inglewood Oil Field, at the northwest end of the zone, the slip rate is 0.31 mm/yr. With error bars, the approximate slip rate can be estimated as about 0.5 mm/yr. Slip rates can also be determined from offset anticlines at Seal

Beach and Inglewood oil fields, and offset isopachs (Freeman et al. (1992). Maximum displacement measured is about 4 km for strata about 7 Ma at Huntington Beach Oil Field. The maximum displacement at Inglewood Oil Field is 1.4 km for strata of 4 Ma (Wright et al., 1973), indicating that strike slip at Inglewood did not start until the Pliocene, later than it started at Huntington Beach. Freeman et al. (1992) estimated the ratio of vertical to horizontal slip to be 1:20. Grant et al. (1997) estimated a minimum Holocene right-lateral strike-slip rate of 0.30-0.55 mm/yr for the southern Newport-Inglewood fault zone in the Huntington Beach Oil Field.

Yet a purely strike-slip history, even taking into account restraining bends such as the one at Dominguez Hills and a transfer of strike slip to folds west of the fault at Sawtelle Oil Field (Tsutsumi et al., 2001), cannot explain the Central Uplift, the name applied by the petroleum industry to the elevated structure of the Newport-Inglewood trend with respect to the central trough to the northeast and the Wilmington structural shelf to the southwest. Davis et al. (1989) accounted for the Central Uplift by a blind thrust. Shaw and Suppe (1996) described the northeast-dipping flank of the Central Uplift as the Compton-Los Alamitos trend, a fault-bend fold that overlies a thrust ramp with 4 km of slip, based on upward-narrowing growth triangles of sedimentary strata above the ramp. The base of the growth triangle, marking the age of initiation of thrusting, was estimated as 2.5 Ma, near the top of the Repetto Member of the Fernando Formation. With this information, the long-term dip-slip rate was calculated as 1.4 +/- 0.4 mm/yr.

T.K. Rockwell and K.J. Mueller excavated a trench, and K.J. Mueller acquired CPT borings across the surface projection of the Compton-Los Alamitos axial surface (Mueller, 1997), showing that this surface does not deform peat deposits dated as 1.9 ka or the Gaspur aquifer (cf. Dept. of Water Resources, 1961) dated as 15-20 ka. Additional work (K.J. Mueller and T.K. Rockwell, in prep.), including structure contours on five aquifers ranging in age from 15-20 ka to 730 ka tied into the global eustatic sea level curve (D.J. Ponti, in prep.), additional trenching and CPT profiles on the Los Alamitos air base, and analysis of a digital elevation model shows no folding of the Gaspur aquifer on the air base. But the Sunnyside (720 ka), Lynnwood (650 ka), and Gage (330 ka) aquifers are folded consistent with the Shaw and Suppe (1996) model but at a slower rate, about 0.5 mm/yr.

Grant et al. (1997) showed that a splay of the North branch of the Newport-Inglewood fault at Huntington Beach has a vertical separation rate of 0.2 mm/yr. They found evidence of five earthquakes, with the oldest shortly after 11.0-12.3 ka. Events younger than 4.4-5.0 ka may be present but are unresolvable with their data.

San Joaquin Hills

Adjacent to the Newport-Inglewood fault where it crosses the shoreline, the San Joaquin Hills are uplifted at a rate of 0.21-0.27 mm/yr, based on mapping and dating late Quaternary shorelines (Grant et al., 1999; in press). The relations are best explained by a southwest-dipping blind thrust with a slip rate of 0.42-0.79 mm/yr. Rivero et al. (2000) consider this southwest-dipping thrust to be part of a larger structure extending offshore to the south and dipping 23°. In their view, the southwest-dipping thrust is a hangingwall structure in their east-dipping Oceanside thrust, a Miocene low-angle normal fault reactivated in the Quaternary. They described a similar thrust farther west, the Thirtymile Bank fault, which is too far offshore to be included in this summary.

Coseismic coastal uplift of the San Joaquin Hills may have generated the largest historical earthquake in the Los Angeles region, an earthquake experienced by the Portolá expedition on July 28, 1769. Late Holocene marsh deposits and shorelines are elevated 1 m to 3.6 m above the active shoreline in a pattern that is best explained by tectonic uplift accompanying an earthquake of M>7. Radiocarbon dating and pollen analysis constrain the date of the earthquake as between 1635 and 1855 A.D., with the strong possibility that this was the earthquake reported by Portolá (Grant et al., in revision).

Palos Verdes fault

The Palos Verdes fault follows the northeastern range front of the Palos Verdes Hills between Redondo Beach and San Pedro, extending across Los Angeles Harbor onto the continental shelf to the southeast. The Palos Verdes Hills are etched by a flight of marine terraces with their ages estimated as 0.45 to 1.5 Ma, leading to an uplift-rate determination of 0.7 +/- 0.2 mm/yr (Ward and Valensise, 1994). The uplift pattern of the Palos Verdes terraces enabled Ward and Valensise (1994) to model the uplift of the Palos Verdes anticlinorium, 15 km long and 8 km wide, as due to a restraining bend on an oblique reverse-right slip fault dipping to the southwest with a long-term slip rate of 3.0-3.7 mm/yr. The uplift rate of Ward and Valensise (1994), and therefore the slip rate on the fault, is controlled by the correlation of the marine terraces; more recent work by D.J. Ponti suggests a slower uplift rate, 0.3-0.5 mm/yr.

Northwest of San Pedro, high-resolution seismic profiles show that the channel of the ancestral Los Angeles River, dated as 120-80 ka, is deflected 300 m, leading to an intermediate-term slip rate of 2.5-3.8 mm/yr, with strike slip predominating (Stephenson et al., 1995). To the southeast, in Los Angeles Harbor, McNeilan et al. (1996) showed that an early Holocene paleochannel has been deflected 21-24 m, indicating a slip rate of 2.7 mm/yr for the past 7.8-8 ka, with the ratio of horizontal to vertical slip 7:1 to 8:1.

In contrast, Davis et al. (1989) interpreted the Palos Verdes anticlinorium and fault along with the Torrance-Wilmington-Belmont (TWB) anticlinorium to the northeast, as overlying a décollement. Shaw and Suppe (1996) considered the Palos Verdes anticlinorium as the hangingwall of a backthrust related to a fault-bend fold, with uplift of the anticlinorium the same as that calculated by Ward and Valensise (1994). The slip rate of the fault underlying the TWB anticlinorium was calculated as 1.2 +/- 0.4 mm/yr. 3D seismic data suggest that the TWB anticlinorium is a tip-line fold developed above a northeast-dipping thrust ramp that offsets and folds basement; the forelimb of this fold contains deformed Pliocene strata (J. Shaw, in prep.).

Well data show that the TWB anticlinorium stopped growing in middle Pico time and is overlain unconformably by undeformed strata (Wright, 1991). This argues against the TWB being linked to the Palos Verdes fold, dated by younger uplifted marine terraces. However, J. Shaw (in prep.) has found that the unconformity and overlying strata in the TWB anticlinorium are, indeed, folded gently about the axial surface bounding the southern edge of the forelimb, consistent with reverse-fault seismicity described by Hauksson (1990), although the slip rate on this structure has slowed down in the Quaternary. The two models linking the Palos Verdes and Compton-Los Alamitos structures (Shaw and Suppe, 1996) are (1) the Compton structure refolds part of the Palos Verdes fault (favored by J. Shaw, in prep.) and (2) the Palos Verdes fault is offset by the Compton ramp, or is a backthrust above the Compton ramp (Davis et al., 1989).

The Palos Verdes fault extends offshore to the southeast, where it is clearly mapped by sidescan sonar (M.V. Gardner, in prep., C. Goldfinger et al., in prep.) and high-resolution seismic-reflection profiles (Francis et al., 1999 and in prep.). At a point about 10 km southeast of the breakwater, the fault bends southward (releasing bend) and breaks up into several youthful traces that cut through the Beta Oil Field (Fischer et al., 1977; Kelsch et al., 1998). The fault appears to bend into a more northerly trend (transtensional) that controls the location of San Gabriel submarine canyon, as shown by multibeam bathymetry of Gardner et al. (2000). The fault splits into two major faults around Lasuen Knoll, a restraining-bend pop-up structure. The principal trace of the Palos Verdes fault lies along the southwest flank of Lasuen Knoll, where it is clearly expressed in seismic profiles (Bohannon et al., 1998; Mallory et al., 2000). The Palos Verdes fault zone continues southeast as the Coronado Bank fault zone with alternating regions of transpressional pop-up structures and broad transtensional sags (Legg, 1985; Legg and Kennedy, 1991; M. Legg and C. Goldfinger, in prep.) Overall, the Palos Verdes-Coronado Bank fault zone is complex and segmented, commonly with two sub-parallel faults. Uplift at left bends and sags at right bends show the right-slip character. The eastern fault zone from Lasuen Knoll to La Jolla submarine canyon is poorly known and may be tied to the Oceanside detachment/thrust fault system (M. Legg, C. Sorlien, and C. Nicholson, in prep).

To the northwest, off Redondo Beach, the fault is not as easy to trace on sidescan sonar (C. Goldfinger, M. Legg, R.S. Yeats, and G.J. Huftile, in prep.). The shelf is cut by the Redondo and Santa Monica submarine canyons (Nardin and Henyey, 1978); uplifted areas on the shelf bring Miocene strata to the surface (Junger and Wagner, 1977). Some authors extend the Palos Verdes fault northwest as a strike-slip fault to an intersection with the Dume fault. An alternative is for various "horsetail" strands to splay westward, including the Redondo Canyon fault. These western splays should have reverse separation and consume slip in Santa Monica Bay on the north side of the Shelf Projection anticline of Nardin and Henyey (1978). Hauksson (1990; see also Davis et al., 1989) showed this region as the northwestern continuation of their Torrance-Wilmington fold and thrust belt. A north-trending graben near the head of Redondo submarine canyon suggests a pull-apart origin at a right stepover on the Palos Verdes fault where it extends offshore. Numerous fault traces have been mapped on the shelf in Santa Monica Bay (Vedder, 1986) although possible nearshore fault traces are presently unknown due to lack of data in the immediate coastal area. The coast-parallel trend of ancient Ballona Creek (Los Angeles River channel) immediately offshore Playa del Rey to Manhattan Beach may be fault-controlled (M. Legg and D. Francis, in prep.).

Earthquakes in Santa Monica Bay with reverse-fault focal mechanisms, with the largest the Malibu earthquakes of January 1, 1979 and January 19, 1989, each with magnitude 5.0 (Hauksson and Saldivar, 1989; Hauksson, 1990), are too far south to be attributed to the Dume fault. These earthquakes may be related to the western splays of the Palos Verdes fault. However, there are also many strike-slip earthquakes in this region, so the northern end of the Palos Verdes fault still remains poorly located.

The overall pattern of a segmented Palos Verdes fault, with alternating areas of extension and contraction, continues in Santa Monica Bay. The predominance of west to west-northwest trending anticlinoria along the southwest flank of the Palos Verdes fault is consistent with a reduction of strike slip northwestward toward the Transverse Ranges, with slip taken up by shortening on folds and horsetail splays.

Discussion: Problems for SCEC II

Introduction

The main purpose of this report is to synthesize what we know about the earthquake geology of the Los Angeles metropolitan area rather than analyze the data with respect to conflicting tectonic hypotheses. However, it is possible to see where we stand at the end of SCEC I and point out the major unsolved problems for SCEC II. The questions that we raise today could not have been posed at the time SCEC I began.

Convergence rate discrepancy between late Quaternary geology and GPS

Walls et al. (1998) compared the convergence rates across the Los Angeles metropolitan area with convergence rates based on geologically-determined slip rates on individual faults.

These rates appeared to be in agreement when the higher rates of Davis et al. (1989) and Davis and Namson (1994) were used (Argus et al., 1999), but recent studies of late Quaternary slip rates, summarized above, suggest that the geological rates in the Los Angeles and San Gabriel basins are slower than the GPS rates would predict. Bawden et al. (2001), after removing GPS sites contaminated by groundwater- and oil-pumping effects, determined an average southward shortening across the Los Angeles Basin of 4.4 +/- 0.8 mm/yr in a direction N35° +/- 5° E. The GPS rates could be a temporary velocity transient, as has been suggested for parts of the Great Basin, but this is less likely in Los Angeles because the GPS and geological rates appear to be in agreement in the Ventura Basin (Huftile and Yeats, 1995; 1996) and opposite the Cucamonga fault east of the San Jose Hills. In fact, the geologically-determined rates are higher than GPS rates in the western Ventura basin.

The principal problem is the unexplained lower slip rate on the Sierra Madre fault between the 1971 rupture zone and the Cucamonga fault (Crook et al., 1987, reinforced by more recently-determined late Quaternary slip rates, discussed above). The shortening across the Sierra Madre, Elysian Park, and Puente Hills faults, together with a contractional component across the Raymond and Whittier strike-slip faults, sums to 3-3.5 mm/yr. The discrepancy could be accounted for by the San Jose fault and a blind reverse fault beneath the northern Puente Hills anticline at Walnut, but this is not yet known. West of the San Fernando Valley, the Santa Susana, San Cayetano, and Oak Ridge faults have slip rates that are high enough to be consistent with GPS results (Huftile and Yeats, 1995; 1996), and this may be the case also for the Cucamonga fault. The Verdugo fault in the eastern San Fernando Valley could take up some of the strain, but the Eagle Rock fault between the Verdugo and Raymond faults has poor geomorphic expression and probably hase a low slip rate.

Some of the shortening could be taken up by folding. The blind Santa Monica Mountains thrust was thought to have a high slip rate by Namson and Davis (1994), but studies of the marine terraces along the Malibu coast show that the slip rate of that thrust is much lower, possibly an order of magnitude lower.

This is a major problem for SCEC II because of the possibility of other faults, as yet unidentified, that take up the missing horizontal convergence indicated by GPS. We don't want to be surprised by another Northridge blind thrust.

Short-term vs long-term slip rates

In the western Ventura Basin, the short-term rates are somewhat faster than the long-term rates but are in a general way consistent in that they involve the same faults. In the Los Angeles Basin, the long-term slip rates (2-5 x 10^6 yrs) on the Las Cienegas and Compton-Los Alamitos faults are much higher than the short-term rates measured in 10^4-10^5 yrs. Strike slip on the

Newport-Inglewood fault appears to have started earlier in the southeastern Los Angeles Basin than farther northwest. High slip rates on both the Raymond and Whittier faults must be considered in light of low total displacement on these faults, evidence that the presently-operating strike-slip phase is relatively young. The northwest-striking right-slip faults of the Peninsular Ranges may have propagated into the Los Angeles metropolitan area only in the Quaternary, implying that slip rates on these faults might approach zero as the Transverse Ranges boundary is approached.

If confirmed by additional work, this leads to a higher weighting of slip rates based on late Quaternary offsets than longer-term rates in probabilistic hazard analyses.

Offshore faults

The Newport-Inglewood, Palos Verdes, Santa Monica, and Malibu Coast faults extend offshore, where their geology is poorly understood compared to onshore faults. Newly-emerging technology of side-scan sonar, high-resolution swath bathymetry, high-resolution seismic profiling, and remotely-operated submersibles is expensive, but these techniques, together with piston cores, are necessary to characterize the offshore portions of onshore faults. For example, high-resolution multibeam bathymetry offshore from metropolitan Los Angeles (Gardner et al., 2000; Marlow et al., 2000) has provided a new understanding of the geometry and recency of movement on major offshore faults, including the San Pedro Basin and Avalon Knoll fault zones, both of which have prominent seafloor expression and likely Holocene activity. In addition, some faults are completely offshore, but close enough to metropolitan areas that they will impact the Los Angeles and San Diego metropolitan areas, just as a modern repetition of the December 21, 1812 earthquake would impact coastal cities around the Santa Barbara Channel.

Offshore paleoseismology is possible based on the analysis of turbidites in submarine channels, as has already been shown by work by C. Goldfinger, H. Nelson, and Gorsline et al. (2000). Turbidites at the mouth of Noyo Canyon off the northern California coast have been age-calibrated by AMS dating of foraminiferal tests, giving a paleoseismological record of the northern San Andreas fault for the past 13,000 years, a record consistent with the shorter record available from trench excavations (C. Goldfinger and H. Nelson, in prep.). Gorsline et al. (2000) concluded that the larger, more areally extensive turbidites in Santa Monica Basin were generated by earthquakes. These turbidites were dated using ^{210}Pb and AMS ^{14}C and by counting varves. The most recent turbidite might have recorded the 1812 earthquake in the western Transverse Ranges. Recurrence frequency of these large turbidites is 470 years. Submarine fans and turbidite-filled channels in the Borderland can be surveyed with high-resolution seismic imagery combined with piston cores to provide information on fault displacements during individual earthquakes and strong shaking generating turbidites.

The present Group C team comprises terrestrial geologists, with a few notable exceptions, and terrestrial geology has dominated most of the funding. A major problem is the expense of gathering data, but this can be alleviated by forming partnerships with other agencies, including NOAA, NSF, and USGS Marine Geology Branch.

Strain partitioning

The early days of SCEC were characterized by lively debate between those advocating a dominance of dip-slip faulting, especially blind thrusting, vs those suggesting that strike-slip faulting is important also. In part, the two camps were using two different time scales. Slip rates based on blind thrusting are based on growth strata deposited over several million years whereas slip rates on strike-slip faults are based on trench excavations and late Quaternary tectonic geomorphology, including stream deflections and shutter ridges.

It appears that both camps are partly correct. Strike slip on the Newport-Inglewood fault does not explain the Central Uplift, atop which the Newport-Inglewood oil fields are located, and strike slip on the Whittier fault does not explain footwall uplift between the Whittier and Brea-Olinda oil fields, nor does it explain uplift of the Coyote Hills. A clue may be seen in examining focal-mechanism solutions in Santa Monica Bay (Hauksson and Saldivar, 1989), which show both strike-slip and reverse-slip solutions. The mainshock of the 1987 Whittier Narrows earthquake was a reverse fault, but the largest aftershock was strike slip, probably on the East Montebello fault. The 1986 Oceanside earthquake (Hauksson and Jones, 1991) had a northwest-trending thrust mechanism although it took place on a restraining bend of the San Diego Trough fault (Legg, 1985). Alternatively, this earthquake may have been related to the blind, low-angle Thirtymile Bank fault (Rivero et al., 2000).

A problem for SCEC II is the question of how dip-slip earthquakes relate to strike-slip earthquakes. Would a Los Angeles cascade include both dip-slip and strike-slip events? Does the fast-moving Raymond strike-slip fault sometimes rupture alone and at other times rupture with the Sierra Madre or Hollywood fault, or with the San Andreas fault? Would a dip-slip event on the Sierra Madre fault reduce strain buildup on the Raymond fault across strike from it, or would a dip-slip event on the Puente Hills blind thrust reduce or add to strain buildup on the Whittier fault?

A corollary to this problem is the accommodation of north-south convergence. Is convergence accompanied by east-west escape-block tectonics, as proposed by Walls et al. (1998) or by crustal thickening, as favored by Argus et al. (1999). Part of the debate in these two papers is influenced by how the right-lateral shear strain on the San Andreas fault is factored out to get at the convergence signal, but the late Quaternary geology is important, too.

Most of the useful late Quaternary slip rate data in Los Angeles have been published in the past five years, as AMS radiocarbon dating has become more widely available. SCEC II has the opportunity of following up on this breakthrough in a focused late Quaternary dating project, including attempts to do paleoseismology on blind thrusts, as has already been accomplished in the San Joaquin Hills (Grant et al., in revision) and is currently being attempted for the Puente Hills blind thrust. A key to the success of this endeavor is a better age-calibrated stratigraphy for the late Quaternary, already begun by the USGS on the Las Cienegas structural shelf and in the Los Angeles Basin west of the Newport-Inglewood fault (Ponti et al., 2001). East of the Newport-Inglewood fault, late Quaternary marine deposits have been dated in the San Joaquin Hills (Grant et al., 1999) and are currently being correlated with marine faunas (Powell et al., submitted). In addition, with the availability of higher-quality imaging and digital elevation models, including TOPSAR, there is a need to quantify tectonic geomorphology to the point that it can contribute to an estimate of slip rates.

Paleoseismology of blind thrusts

Study of multichannel seismic profiles and petroleum-industry well data has resulted in the delineation of blind thrusts in the Los Angeles Basin, including the source fault for the 1987 Whittier Narrows earthquake (Dolan et al., 1995; Shaw and Suppe, 1996, Schneider et al., 1996; Shaw and Shearer, 1999; Tsutsumi et al., 2001), but little progress has been made in determining slip rates and recurrence intervals on these faults. High-resolution seismic profiles (Williams et al., 2000; Christofferson et al., 2000), trenching, and analysis of water-well logs (Mueller, 1997; K.J. Mueller and T.K. Rockwell, in prep.) and high-resolution late Quaternary stratigraphy (Ponti et al., 1996; D.J. Ponti, in prep.) are necessary to obtain a paleoseismic history of blind thrusts comparable to that obtained by trenching of surface faults.

Dates of most recent large earthquakes

Research by SCEC geologists has demonstrated that many active faults are potentially very hazardous to the Los Angeles metropolitan region because of their proximity to densely-populated areas. The slip rates of many metropolitan faults are difficult to measure because the faults are blind, the slip rates are low, or the data have been destroyed by urbanization. Therefore, it may be difficult to reconcile geologically-derived slip rates with geodetically-measured deformation. However, it would be useful to learn where Los Angeles is in the seismic cycle of potentially-hazardous urban faults. Two historical earthquakes have been correlated to local faults: the 1769 earthquake reported by the Portolá expedition (Grant et al., in revision) and the May 10, 1910 Temescal Valley earthquake on the Elsinore fault (Rockwell, 1989). More paleoseismic data are needed for time-dependent hazard calculations, analysis of deformation rates, and studies of triggered earthquakes and strain partitioning.

The Los Angeles metropolitan area needs a focused study comparable to BAPEX in the San Francisco Bay area. This would include study of the late Quaternary history of the San Jose, Walnut Creek-Indian Hill, Chino, Peralta Hills, and Newport-Inglewood faults, and the Palos Verdes fault northwest of Los Angeles Harbor.

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