ABSTRACT

Data from geotechnical boreholes and trenches, in combination with geomorphologic mapping, indicate that the Hollywood fault is an oblique, reverse—left-lateral fault that has undergone at least one surface-rupturing earthquake during latest Pleistocene to middle or late Holocene time. Geomorphologic observations show that the fault extends for 14 km along the southern edge of the eastern Santa Monica Mountains, from the Los Angeles River westward through downtown Hollywood to northwestern Beverly Hills, where the locus of active deformation steps 1.2 km southward along the West Beverly Hills lineament to the Santa Monica fault. Rupture of the entire Hollywood fault, by itself, could produce a $M_w \approx 6.6$ earthquake, similar in size to the highly destructive, 1994 Northridge earthquake, but even closer to more densely urbanized areas. Assuming a 0.35 mm/yr minimum fault-slip rate consistent with available geologic data, we calculate an average maximum recurrence interval for such moderate events of $\approx 4000$ yr. Although occurrence of such moderate events is consistent with the elapsed time since the poorly constrained age of the most recent surface rupture, the data do not preclude a longer quiescent interval suggestive of larger earthquakes. If earthquakes much larger than $M_w \approx 6.6$ occurred in the past, we speculate that they may have been generated by the Hollywood fault together with other faults in the Transverse Ranges Southern Boundary fault system.

INTRODUCTION

During the past decade ideas about the seismic hazards facing urban Los Angeles have undergone dramatic revision and refinement. Earlier earthquake scenarios for the metropolitan region focused primarily on the effects of a great ($M_w \approx 7.7$ to 7.9) earthquake generated by the San Andreas fault, which is located more than 50 km northeast of downtown Los Angeles (Fig. 1). Not until the mid-1980s (e.g., Wescoussy, 1986; Topozada, 1988) did attention turn to the potential hazards posed by faults directly beneath the metropolitan area. The 1987 $M_w \approx 6.0$ Whittier Narrows earthquake and the 1994 $M_w \approx 6.7$ Northridge earthquake clearly demonstrated the seismic hazards associated with these urban faults. More recent seismic hazard assessments incorporate the possibility of large urban earthquakes, as well as the recurrence of a major earthquake on the San Andreas fault (e.g., Working Group on California Earthquake Probabilities, 1995). Because of their proximity to metropolitan Los Angeles, moderately large to large earthquakes ($M_w \approx 7.0$ to 7.5) generated by the urban faults could cause at least as much, and possibly more damage, than a much larger earthquake occurring on the San Andreas fault (Working Group on California Earthquake Probabilities, 1995; Dolan et al., 1995; Heaton et al., 1995). At least two such large earthquakes have occurred during historic time in southern California on faults similar to those that underlie the metropolitan region: the December 21, 1812, $M \approx 7.1$ Santa Barbara Channel earthquakes (Topozada, 1981) and the July 21, 1952, $M_w \approx 7.5$ Kern County event (Hanks et al., 1975; Stein and Thatcher, 1981; Wallace, 1988; Ellsworth, 1990). Neither of these earthquakes resulted in widespread damage or major loss of life, because both regions were relatively sparsely populated at the time of the earthquakes.

Despite a heightened awareness of the potential for destructive earthquakes from faults beneath metropolitan Los Angeles, as well as numerous recent studies that have illuminated the active tectonics of the region (e.g., Hauksson, 1990; Wright, 1991; Shaw and Suppe, 1996), too little information exists about the earthquake histories and recent kinematics of these faults to construct realistic probabilistic hazard maps for the metropolitan region. Specifically, we have only sparse data concerning recurrence intervals, dates and sizes of past events, slip rates, and kinematics for many faults. Furthermore, we do not know the exact nature and surficial location of many of these faults. Knowledge of these fault parameters is essential for constructing realistic probabilistic seismic hazard models for southern California.

Over the past several years we have been studying the active tectonics and paleoseismology of the northern Los Angeles metropolitan region; the area extends from Pacific Palisades and Santa Monica on the coast, eastward through Beverly Hills, Hollywood, downtown Los Angeles, and east Los Angeles to Whittier Narrows (Fig. 1). In this paper we discuss our results from the Hollywood fault, which extends for 14 km through this densely urbanized region (Fig. 2). We first describe the results of our geomorphologic and paleoseismologic studies of the fault and then discuss the implications of these data for seismic hazard assessment in the metropolitan Los Angeles region. In addition to the implications of these results for seismic hazard analysis, data from this and similar studies of

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*Present Address: Department of Earth Sciences, University of Southern California, Los Angeles, California 90089-0740; e-mail: dolan@earth.usc.edu.
† Dolan, Sieh, and Rockwell are members of the Fault Zone Geology Group, Southern California Earthquake Center, University of Southern California, Los Angeles, California 90089-0740.

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The Hollywood fault extends east-northeast along the southern edge of the Santa Monica Mountains, the southernmost of the Transverse Ranges (Fig. 2). The range exhibits an asymmetric, south-vergent anticlinal structure, which has been interpreted as a fault-propagation fold above a gently north-dipping blind thrust fault (Fig. 3; Davis et al., 1989; Davis and Namson, 1994). The basic structure of the Hollywood area was revealed during extensive oil exploration, which began during the early 1900s and continued through the 1980s (see Wright, 1991, for a comprehensive review). These data show that the steeply north-dipping Hollywood fault juxtaposes Cretaceous quartz diorite and predominantly Miocene volcanic and sedimentary rocks of the Santa Monica Mountains against Quaternary and Tertiary sedimentary rocks to the south.

The Hollywood fault is part of a system of east-trending reverse, oblique-slip, and left-lateral strike-slip faults that extends for >200 km along the southern edge of the Transverse Ranges, an east-west belt of ranges that developed in response to north-south compression that began ca. 2.5 to 5 Ma (Fig. 1; e.g., Barbat, 1958; Davis et al., 1989; Wright, 1991; Shaw and Suppe, 1996; Schneider et al., 1996; Tsutsumi, 1996). We refer to these faults collectively as the Transverse Ranges Southern Boundary fault system. Within the fault system, left-lateral and oblique-reverse, left-lateral motion on a subsystem comprising the Raymond (Crook et al., 1987; Jones et al., 1990), Hollywood (Dolan et al., 1993; this study), Santa Monica (Dolan et al., 1992), Anacapa-Dume (Stierman and Ellsworth, 1976; Ellsworth, 1990), Malibu Coast (Drumm, 1992; Treiman, 1994), Santa Cruz Island (Patterson, 1978; Pinter and Sorlien, 1991; Pinter et al., 1995), and Santa Rosa Island faults (Colson et al., 1995) accommodates relative westward motion of the Transverse Ranges block. Paleomagnetic studies of upper Pliocene strata (1 to 3 Ma) reveal 20° of clockwise rotation of parts of the western Transverse Ranges block (Liddicoat, 1992), suggesting that left-lateral motion is accompanied by active clockwise rotation of the western Transverse Ranges.

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The fault is marked by a narrow, steeply southward-sloping gravity gradient that is most pronounced in the downtown Hollywood area (Chapman and Chase, 1979).

The Hollywood fault defines the northern edge of the 300-m-deep Hollywood basin, which extends approximately from La Brea Avenue eastward to Western Avenue and from Santa Monica Boulevard northward to the mountain front. A—bedrock fault in Elysian Park Hills (Lamar, 1970); H—eastern end of the Sunset Strip at intersection of Sunset Boulevard and Havenhurst Drive; H2O—shallow ground water along Hollywood fault (F. Denison, 1991, personal commun.); K—Kings Road—Sunset Boulevard intersection; N—intersection of Normandie and Franklin Avenues; Oil—linear oil and water seeps at Greystone Park (Crook and Proctor, 1992); SM Flt—Santa Monica fault; BC—Benedict Canyon; BrC—Brushy Canyon; GP—Greystone Park; LC—Laurel Canyon; NC—Nichols Canyon; WBHL—West Beverly Hills lineament; WeHo—West Hollywood.

Figure 2. Map of the Hollywood fault zone, showing surficial geology and major tectonic and sedimentary landforms. Major fault and fold scarps are shown in black. Faults are dotted where inferred beneath recent alluvium. Bedrock geology is from Dibblee (1991a, 1991b). Lines with opposing double arrows are crests of youthful folds on the ground surface. The word Hollywood is centered on the main business district of downtown Hollywood, which extends approximately from La Brea Avenue eastward to Western Avenue and from Santa Monica Boulevard northward to the mountain front. A—bedrock fault in Elysian Park Hills (Lamar, 1970); H—eastern end of the Sunset Strip at intersection of Sunset Boulevard and Havenhurst Drive; H2O—shallow ground water along Hollywood fault (F. Denison, 1991, personal commun.); K—Kings Road—Sunset Boulevard intersection; N—intersection of Normandie and Franklin Avenues; Oil—linear oil and water seeps at Greystone Park (Crook and Proctor, 1992); SM Flt—Santa Monica fault; BC—Benedict Canyon; BrC—Brushy Canyon; GP—Greystone Park; LC—Laurel Canyon; NC—Nichols Canyon; WBHL—West Beverly Hills lineament; WeHo—West Hollywood.
In downtown Hollywood the fault exhibits several parallel, locally overlapping south-facing scarps that indicate a wide, complex zone of surficial faulting (Fig. 4). Data from previous geotechnical and ground-water studies, in combination with our geomorphologic results, confirm that the fault comprises at least three major splays through much of downtown Hollywood (Converse Consultants, Earth Sciences Associates, and Geo/Resource Consultants, 1981; Crook and Proctor, 1992; F. Denison, 1991, personal commun.). The most prominent scarp in the downtown area, which we refer to as the Franklin Avenue strand, extends for ~2 km along and just south of Franklin Avenue, from ~250 m east of La Brea Avenue to just east of Gower Street (Figs. 2 and 4). Two 1991 foundation boreholes excavated just south of Franklin Avenue on Las Palmas Street confirm that a fault exists beneath the prominent scarp (G’ in Fig. 4; R. Slade, 1992, personal commun. in Crook and Proctor, 1992). These boreholes reveal a pronounced ground-water barrier that correlates with the prominent south-facing scarp (G in Fig. 4). Ground water on the north side of the fault was encountered at 4.6 m, whereas south of the fault it occurred at 13.7 m. The dotted and dashed lines through G in Figure 4 show the probable trace of this fault strand. Farther east, the Franklin Avenue strand is defined by pronounced scarps just east and west of Cahuenga Boulevard and by a fault mapped in Miocene bedrock near Vine Street (Fig. 4; Dibblee, 1991a).

At least two other fault strands occur in Hollywood, one to the south (Yucca Street strand) and one to the north (northern strand) of the Franklin Avenue strand (Fig. 4). West of the Cahuenga alluvial fan, the Yucca Street strand exhibits a 5–6-m-high scarp. East of the fan the Yucca Street scarp merges with the Franklin Avenue scarps. The lack of topographic scarps across the 300 m width of the fan suggests that surficial displacements on the fault have been obscured during at least the past few thousand
Figure 4. Detailed map of the Hollywood fault zone and related fault scarps, ground-water barriers, and alluvial fans in downtown Hollywood. Darkest shaded areas are inferred fault scarps. Lighter shading denotes recently active alluvial fans and drainages. Fault locations dotted where inferred, and dashed where based on ground-water barriers. Bull’s-eyes denote boreholes (Converse Report, 1981; Crook and Proctor, 1992). Location is shown in Figure 2. Bedrock fault north of Franklin Avenue from Dibblee (1991a). Ground-water barriers along fault are denoted by G (R. Slade, cited in Crook and Proctor, 1992) and G’ (F. Denison, 1991, personal commun.). Topography redrafted from Burbank and Hollywood 1:24 000 6’ USGS quadrangles (1926). Contour interval is 1.5 m (5 ft) up to the 500 ft contour, above which the interval is 7.6 m (25 ft).

Figure 5. Cross section inferred from boreholes along Cahuenga Boulevard in downtown Hollywood (data from Converse Report, 1981; see Crook and Proctor, 1992, for alternative interpretation). Location is shown in Figure 4. Crook and Proctor (1992) show a fault displacement between 28-2 and 28A. We observe no evidence for this strand, and we do not show it in the figure. Fault dip is not constrained by data; we show an arbitrary 45°N dip. See text for discussion.

years by fluvial deposition and/or erosion. Westward of a point ~300 m west of Cahuenga Boulevard the Yucca Street strand does not exhibit a surficial scarp. However, ~375 m west of Cahuenga Boulevard the fault acts as a ground-water barrier; much shallower ground-water levels are observed in building excavations north of the fault (5 m depth) than to the south (>12 m depth) (G’ in Fig. 4; F. Denison, 1991, personal commun.).

The stratigraphy of four boreholes drilled during 1981 along Cahuenga Boulevard confirms that the Yucca Street scarps mark a fault (Converse Consultants, Earth Sciences Associates, and Geo/Resource Consultants, 1981). These data indicate a major north-side-up displacement of the Miocene Topanga Formation south of borehole 28A (Figs. 4 and 5). Direct evidence for the Yucca Street strand was encountered in borehole 28B, which penetrated 3.4 m of fault breccia, composed of phacoids of Miocene sandstone and siltstone, at 37 to 40 m depth. Crook and Proctor (1992) used these data to suggest two closely spaced, north-dipping faults in this area, but we see no compelling evidence for the existence of their more northerly strand, which would project to the surface just south of Yucca Street. Because of the wide spacing of the boreholes and the absence of trench data from this site, the dip of the fault is poorly constrained. In contrast to Crook and Proctor (1992), who showed the faults as shallowly dipping (23°) thrust faults, we show the fault as dipping moderately north, on the basis of the well-determined, steep northward dip of the fault observed in three excavations 1 km to the west (discussed in the following).

The northern strand is defined by discontinuous scarps at the topographic mountain front that extend eastward from Vine Street (Fig. 4). This scarp disappears eastward beneath the Brushy Canyon fan (Fig. 2). East of the fan the well-developed scarp extends eastward along the northern edge of Franklin Avenue for ~1 km (to north in Fig. 2; Normandie Avenue intersection). The possible terminations of the northern strand near Vine Street and the Franklin Avenue strand beneath the Brushy Canyon fan may indicate that the fault exhibits an ~350-m-wide left step between the two strands in downtown Hollywood.

Although the east-northeast–trending mountain front along Los Feliz Boulevard northeast of downtown Hollywood exhibits a linear, south-facing slope (Fig. 2), we are uncertain whether this represents a surficial fault trace. The gentle southward slope of the alluvial apron there (~5° to 8°S) does not resemble the more steeply sloping scarps that we observed elsewhere along the fault, and we speculate that this slope may represent alluvial strata that have been tilted southward above a near-surface thrust fault.
West of Downtown Hollywood

West of downtown Hollywood, between La Brea Avenue and Laurel Canyon, the fault traverses an area of recent alluvial sedimentation on small, young alluvial fans that emanate from numerous small-canayon sediment sources. The lack of pronounced scarps along this reach of the fault suggests that sedimentation has buried all evidence of recent fault activity (Figs. 2 and 6). Geotechnical data from this area provide evidence to support this interpretation. Near Nichols Canyon the fault changes strike westward from N85°E to N55°–N60°E (Fig. 2). This more northeasterly trend extends for ~1.6 km between Nichols Canyon and the intersection of Sunset Boulevard and Havenhurst Drive, the far eastern end of the famed Sunset Strip (H in Fig. 2). Along the western part of the Sunset Strip, west of La Cienega Boulevard, the fault may exhibit two main strands: a weakly defined northern strand that lies approximately at the mountain front, generally north of Sunset Boulevard, and a better defined southern strand in the alluvial apron ~50 to 150 m south of Sunset Boulevard (Fig. 2).

The scarp of the southern strand is particularly well-developed where it crosses Doheny Drive ~150 m south of Sunset Boulevard. The topographic expression of the southern strand appears to die out west of Doheny Drive, although differential stream incision of the alluvial apron ~850 m west of Doheny Drive suggests recent warping and possible faulting of the fan surface. Shallow ground water was encountered in a foundation excavation ~600 m east of Doheny Drive; the clayey granitic soil there is greenish gray, in marked contrast to the beige and brown of most alluvium in the area (H2O in Fig. 2; F. Denison, 1991, personal commun.). The presence of shallow ground water suggests that there may be a fault to the south, although the absence of excavations to the south precludes assessment of whether this represents the northern part of a true ground-water barrier caused by a fault.

The hills along the north edge of Sunset Boulevard consist of quartz diorite, whereas the steep slopes along the southern edge of the road are underlain by alluvium. A 1974 borehole ~200 m east of La Cienega Boulevard and ~50 m south of Sunset Boulevard penetrated >60 m of alluvium (G. Brown, 1993, personal commun.). This borehole and outcrops of quartz diorite ~10 m south of Sunset Boulevard confirm that the main strand of the Hollywood fault lies either directly beneath or just south of Sunset Boulevard (Fig. 2). The very steep slopes of the alluvial fan apron south of Sunset Boulevard (up to 17°) are too steep to be purely depositional, and probably reflect tectonic disruption, indicating recent north-side-up displacement along the fault. About 300 m east of La Cienega Boulevard shallow ground water was encountered just south of Sunset Boulevard (K in Fig. 2; King’s Road intersection), but was not encountered in excavations 160 m to the south, suggesting that the fault forms a ground-water barrier in the steep slope along the southern edge of the boulevard (F. Denison, 1991, personal commun.). West of La Cienega Boulevard, the sharp break in slope at the southern edge of bedrock outcrops suggests the presence of a northern strand of the fault, which is probably located just north of, and sub-parallel to Sunset Boulevard. This strand is much less well defined geomorphically than the southern strand in this reach.

West of Doheny Drive a third, northernmost splay appears to split off from the main fault. This strand, which is defined by a linear zone of oil and gas seeps at the south end of Greystone Park (Oil in Fig. 2; Crook and Proctor, 1992) and discontinuous scarps, can be traced for only ~500 m. Excavations of this feature in Greystone Park encountered sheared Miocene and Mesozoic bedrock, but no evidence of recent faulting (Crook and Proctor, 1992).

The Hollywood fault zone can be traced as a nearly continuous geomorphic feature westward to the east edge of the Benedict Canyon drainage in northwestern Beverly Hills, near the corner of Sunset Boulevard and Rodeo Drive (Fig. 2). There the pronounced south-facing scarps terminate. However, the mountain front to the west of Benedict Canyon in northern Westwood and Brentwood is locally quite linear and may represent the trace of an older (or much less active) westward continuation of the Hollywood fault.

At Benedict Canyon the belt of most prominent surficial deformation steps southward ~1.2
km to the Santa Monica fault (Figs. 1 and 2). This left step in the fault system corresponds to a pronounced east-facing, north-northwest–trending topographic scarp that we refer to as the West Beverly Hills lineament (Dolan and Sieh, 1992). The lineament, which separates a region of highly dissected older alluvium to the west from the young Beverly Hills alluvial plain to the east, may represent an east-dipping normal fault associated with extension along the left step between the Hollywood and Santa Monica faults. Continuation of this feature to the south of the fault stepover, however, suggests the alternative possibility that, at least south of the stepover, the lineament is the surficial expression of a complex, oblique reverse–right-lateral, north-northwest–trending fault system, encompassing both the Newport-Inglewood right-lateral strike-slip fault system and a northern extension of the Compton blind thrust system (Dolan and Sieh, 1992). The West Beverly Hills lineament may be a fold scarp along the northern extension of the back limb of the Compton blind thrust anticline, which was identified farther to the south by Shaw and Suppe (1996). That is, the surface slope of the lineament scarp may be a dip slope along the east-dipping backlimb of a fold, the base of which is onlapped by young, flat-lying alluvium of the Beverly Hills plain (Dolan and Sieh, 1992). Another possibility is that the lineament is cut by a probable right-lateral strike-slip fault, which we have interpreted as the northernmost of a series of left-stepping, en echelon right-lateral fault segments that make up the northern Newport-Inglewood fault zone (Figs. 1 and 2; Dolan and Sieh, 1992).

East of Downtown Hollywood

East of downtown Hollywood, geomorphic data indicate that the Hollywood fault extends generally along the mountain front about to Western Avenue, where it diverges from the mountain front and continues eastward into the bedrock of the northern Elysian Park Hills (Fig. 2). Between downtown Hollywood and Western Avenue the fault exhibits a discontinuous, 8–25-m-high, south-facing scarp. The easternmost documented expression of the Hollywood fault occurs in the Elysian Park Hills northwest of downtown Los Angeles, where Lamar (1970) reported a bedrock fault that juxtaposes quartz diorite and upper Miocene (Mohnian) sandstone (A in Fig. 2). Although this bedrock fault does not displace late Quaternary strata, it is along trend with the young Hollywood fault scarp at Normandie Avenue, and thus may represent the bedrock expression of the active fault. Weber et al. (1980) reported scarps in the eastern flood plain of the Los Angeles River in the Atwater area and suggested that they represent the eastward continuation of the Hollywood fault. However, because these scarps are parallel to an east-trending reach of the main river channel just to the south, we suggest that it is likely that they are fluvial terrace risers, rather than fault scarps. We cannot trace the geomorphic expression of the Hollywood fault across the flood plain and into the hills northeast of the Los Angeles River. Gravity data, however, suggest that at least the bedrock expression of the fault extends eastward across the river toward the Raymond fault (Chapman and Chase, 1979).

Detailed Study Area West of Downtown Hollywood

Geotechnical investigations for the subway tunnel through the Santa Monica Mountains and two storm-drain trenches excavated by Los Angeles County provide detailed data on the geometry, kinematics, and earthquake history of the Hollywood fault in a 700-m-wide area just west of downtown Hollywood (Figs. 2 and 6). The study area, bounded on the east by North La Brea Avenue and on the west by Wattles Park, encompasses two small alluvial fans emanating from canyons draining the Hollywood Hills—Runyon Canyon fan, and a fan emanating from a canyon 215 m to the west (Fig. 6), which we refer to as Vista Canyon; we refer to the associated fan as the Vista fan. Downslope, the Vista and Runyon Canyon fans merge into a larger, composite fan. Sediment input from Runyon Canyon appears to dominate this composite fan, as would be expected from the much larger catchment of Runyon Canyon (Fig. 6).

The youngest significant alluvial deposition on the Runyon Canyon and Vista fans appears to be recent, and no surficial scarps of the Hollywood fault are discernible crossing these deposits. The Hollywood Hills in this area are composed of mid-Cretaceous, coarse-grained quartz diorite (Hoots, 1931; Dibblee, 1991a; Wright, 1991), and most of the strata are onlapped in boreholes and excavations into the fans consist of sand and gravel derived from erosion of the plutonic rocks. Quartz diorite crops out at the northern end of Fuller Avenue and was encountered within 1 m of the surface in excavations at the northern ends of La Brea Avenue and Vista Street.

Continuously Cored Boreholes

We completed 30 continuously cored boreholes along two north-south transects (Fig. 6). The western transect was 525 m long and consisted of 25 boreholes that extended southward from the mountain front along Camino Palermo and Martel Avenue. The eastern transect consisted of 5 closely spaced boreholes along La Brea Avenue 375 m east of the Camino Palermo transect. The boreholes along the two transects ranged from 14 to 73 m in depth and all but one was continuously cored to produce 9 cm diameter cores. The cores were hand scraped to remove the drilling rind of disturbed material.

Most of the cores were recovered using a hollow-stem auger; the deeper parts of several deep holes (B-10, B-13, B-14, SM-1, SM-1A, and SM-IB) were drilled using a rotary core-mud system. The upper ~1.5 m (5 ft) of the holes were not cored due to the friable nature of the material, but the loose sand and minor gravel from these intervals was recovered during drilling. Core recovery was generally very good in all holes, and recovery in most intervals exceeded 90%. However, isolated intervals of nonrecovery as thick as 50 cm were common throughout many cores. A few rare intervals of nonrecovery were as much as 1.5 m thick. Hole B-15 was a 70-cm-diameter bucket-auger hole, which we examined directly by being lowered by winch into the hole.

Camino Palermo–Martel Avenue Transect.

Boreholes along the Camino Palermo–Martel Avenue transect were drilled just west of the Runyon Canyon fan axis during the summer of 1992 (Fig. 6). The northernmost boreholes penetrated quartz diorite (Fig. 7). The upper surface of the quartz diorite, which dips southward 20°, more steeply than the 6° dip of the alluvial fan surface, is onlapped by young alluvial deposits.

The oldest alluvial deposits, herein referred to as unit C, consist of generally massive, beige to brown alluvial sand and minor gravel and clayey silt interlayered with several dark brown buried soils. In order to correlate these buried soils from core to core, we laid out all of the cores simultaneously in a parking lot. We correlated soils in adjacent holes on the basis of color, texture, the presence of buried A and argillic (Bt) horizons, and the thickness of these horizons relative to intervening intervals that did not exhibit any soil development. We were careful to keep track of the locations of unrecovered intervals and did not let these intervals influence our correlations. The correlations reveal that all of the buried soils dip gently southwest, parallel to the recent fan surface (Fig. 7).

In order to determine an approximate accumulation rate on the Runyon Canyon fan, we conducted detailed analyses of the six soils exposed in core B-31. These analyses, which included particle-size analysis and estimates of the mean horizon index (MHI) and soil development index (SDI) for each soil, are described in the Appendix. Our results show that the surface soil (soil 1) and the shallowest buried soil (soil 2) exhibit relatively weak soil development, whereas the lower four soils (soils 3 through 6) exhibit mod-
erate soil development. Collectively, the surface soil and the five buried soils are estimated to record ~150,000 (based on MHI) to 170,000 (based on SDI) years of soil development, providing a minimum age for the sediments at the base of B-31 at 16.6 m. These data yield an overall minimum late Pleistocene–Holocene average accumulation rate of ~0.1 mm/yr at B-31. This is a minimum estimate because: (1) there may have been minor erosion of several of the buried soils (Appendix); and (2) we assume that the duration of sediment accumulation between periods of nonsedimentation and soil development is very short, relative to the duration of periods of soil development. We consider this a reasonable assumption in this proximal alluvial fan setting, where most sediment was probably deposited very rapidly.

Accelerator mass spectrometer (AMS) radiocarbon analysis of a charcoal fragment recovered in B-31 at 6.55 m depth from the A horizon of buried soil 3 yielded an age of 19,765 \( \pm 455 /-365 \) yr B.P. (Table 1; Fig. 7; Table 1): all radiocarbon samples were prepared by Beta Analytic, Inc. and were analyzed at the Lawrence Livermore Laboratory reactor. Because the charcoal fragment was recovered from the A horizon of the buried soil, we consider it likely that it was incorporated into the soil profile during development of soil 3. The charcoal may have had a preburial age. Thus, the ca. 20,000 yr date represents a maximum burial age for buried soil 3, and the combined age of the two overlying soils (1 and 2) must be <ca. 20,000 yr. The combined preferred MHI ages for soils 1 and 2 total ca. 18,000 yr (Appendix), in very close agreement with the charcoal age. Because the combined preferred SDI ages overestimate the duration of soil 1 and 2 development at ca. 30,000 yr (Appendix), we have more confidence in the MHI method for estimating soil ages in this area. On the basis of the similar age estimates for soils 1 and 2, we estimate that the top of unit C is ca. 6000 to 10,000 yr old at B-31 (Appendix). Buried soil 2 is missing north of B-22 and may have been eroded (Fig. 7).

Unit C is overlain by two distinct alluvial units (Fig. 7). The lower, unit B, consists of moderately indurated, brown, massive, slightly clayey silty sand. Unit B is traceable from the north end of the transect southward for ~145 m. The deposit thickens downslope from 1.5 m in B-13 to more than 4.5 m in borehole B-10. The unit A–unit B contact could not be discerned in B-17. Between B-10 and B-12 unit B thins abruptly to ~2 m, in a lateral distance of only 10 m. Downslope from B-12 unit B thins gradually and is not present south of B-22 (Fig. 7).

In the area of B-12, B-10, B-17, B-15, and B-16, the uppermost alluvial deposit, unit A, consists of yellow-brown silty sand and minor gravel; it is distinguished from unit B by its more friable consistency and absence of clay. A charcoal fragment from the middle of unit A in borehole B-15 (2.1 m depth) yielded an AMS date of 3375 \( \pm 175 /-160 \) yr B.P. (Fig. 7; Table 1). The absence of soil development within unit A in the area of B-12, B-10, B-17, B-15, and B-16 is in marked contrast to the surface soil (soil 1) developed in the unit downfan at B-31 (Appendix). This suggests that the unit A surface soil 1 was eroded during relatively recently deposition of the friable, late Holocene alluvium encountered north of B-12. Furthermore, the absence of any soil development within unit A in the proximal part of the fan suggests relatively continuous deposition, without any long hiatuses characterized by soil development. Thus, the base of unit A at 4.9 m depth is probably no more than a few thousand years older than the detrital charcoal sample; deposition of the intervening 2.8 m of sediment requiring more than several thousand years would likely have produced detectable soil development. Compounding the uncertainty of the estimated age of the base of unit A is the possibility...
that the charcoal sample had a significant age at burial. On the basis of the limited available evidence, however, our best estimate of the base of unit A is ca. 4000 to 8000 yr B.P. This age is supported by our analysis of the weak surface soil developed through the top of unit A in hole B-31, which suggests that soil 1 required ~6.5 +14.8/–4.5 k.y. to develop there (Appendix).

**Evidence for Faulting.** The cores contain abundant evidence of faulting, within both the quartz diorite and the alluvium. The southern, subsurface limit of the quartz diorite is a steeply north-dipping fault contact. One fundamental observation of this transect is that, in contrast to the wide zone of active faulting in downtown Hollywood, all evidence of recently active faulting is located in a narrow zone near the mountain front; no evidence of recent faulting or tectonic warping was observed in the southern 85% of the transect.

The buried soils of unit C are traceable continuously from the south end of the transect northward for >450 m, where their continuity is interrupted between B-12 and B-10, ~105 m south of the topographic mountain front. Between these boreholes the upper surface of the unit C buried soil (soil 3 at B-31; Appendix) appears to be displaced down-to-the-north (Fig. 7). The concentration of boreholes near this zone of displacement allowed us to construct a structure contour map on the top of buried soil 3 (Fig. 8). Because the boreholes were confined to a strike-parallel zone only 10 m wide, the contours of the structure contour map are not fully constrained. In contouring the data we assumed relatively uniform spacing of contours and no abrupt changes in slope, except at the zone of north-side-down displacement. We also assumed that the contours intersect the zone of displacement at the same angle on both sides. Total north-side-down separation of the top of the buried soil 3 is ~1 m between B-12 and B-10. We interpret this separation as the result of fault rupture, rather than fluvial incision of the Runyon Canyon fan, because buried soils 3 and 4 are vertically separated down-to-the-north the same amount between B-12 and B-10 (Fig. 7). Thus, the buried, north-facing scarp cannot be ascribed to incision of only the shallowest unit C buried soil (soil 3). This fault strand coincides with a ground-water barrier, which separates a shallow (17 m deep) water table north of the fault from a deeper (27.2 m) water table to the south (Fig. 7).

Further below the ground surface, the subsurface data indicate the presence of at least four distinct fault strands within a zone ~30 m wide (Fig. 7). However, only the single strand just described exhibits any evidence for post–late Pleistocene vertical displacement. The zone of near-surface displacement projects downward into a well-defined, very steeply north-dipping fault zone observed in B-10. The upper part of B-10 penetrated alluvial units A, B, and C in normal stratigraphic succession, as well as the underlying quartz diorite. At 40.8 m depth, however, the borehole again reentered alluvium. After penetrating 12.1 m of alluvium the borehole again encountered quartz diorite at 53.9 m. Below 60 m alluvium was again encountered to a total depth of 73 m. Both of the quartz diorite alluvium contacts in B-10 are distinct faults (Fig. 7). The entire core, including both quartz diorite intervals, is intensely sheared from 28 to 59 m depth. Shear planes range in dip from 41° to 124° (opposing very steep dips occur in continuous core segments at many intervals). The predominant dip of the shear fabric is 70° to 85°, and 75% of the 200 dip measurements are ≥70°; the average dip is ~77° (Fig. 9). Because the core, which was not oriented with respect to map directions, is

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### Table 1. Radiocarbon Samples and Ages

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Lab number</th>
<th>Lawrence Livermore</th>
<th>Calendric age (2σ)</th>
<th>14C age (B.P. ± 1σ)</th>
<th>Age B.P. (A.D. 1950)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF C-2</td>
<td>Beta-57674</td>
<td>CAMS-4148</td>
<td>1,230 ± 70 yr B.P.</td>
<td>A.D. 786 (A.D. 662–979)</td>
<td>1,165 + 125–195 B.P.</td>
</tr>
<tr>
<td>HF C-3</td>
<td>Beta-57675</td>
<td>CAMS-4149</td>
<td>1,230 ± 70 yr B.P.</td>
<td>A.D. 786 (A.D. 662–979)</td>
<td>1,165 + 125–195 B.P.</td>
</tr>
<tr>
<td>HF C-4</td>
<td>Beta-57676</td>
<td>CAMS-4150</td>
<td>300 ± 70 yr B.P.</td>
<td>A.D. 1641 (A.D. 1446–1954)</td>
<td>309 + 195–315 B.P.</td>
</tr>
<tr>
<td>B-15 HF 7&quot;</td>
<td>Beta-57677</td>
<td>CAMS-4151</td>
<td>3,170 ± 70 yr B.P.</td>
<td>1,424 B.C. (1264–1599 B.C.)</td>
<td>3,375 + 175–160 B.P.</td>
</tr>
<tr>
<td>B-31 HF 21&quot;</td>
<td>Beta-57681</td>
<td>CAMS-4152</td>
<td>16,760 ± 90 yr B.P.</td>
<td>17,814 B.C. (17448–18267 B.C.)</td>
<td>19,765 + 455–365 B.P.</td>
</tr>
</tbody>
</table>

*Note: Calendric ages calculated using CALIB 3.0 (Stuiver and Reimer, 1993).*

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**Figure 8. Structure-contour map of the top of the uppermost buried soil of unit C (soil 3) in the area of the most recently active fault strand at Camino Palmero. Contours are in feet (1 ft = 0.3 m). Numbered dots indicate the locations of boreholes. Vertical separation across fault is ~5 ft (1.5 m) and is mountain-side down.**
fault as the main active strand of the Hollywood fault at Camino Palermo.

Fault gouge and the geometry of the quartz diorite reveal at least two other fault strands north of the main active strand between B-12 and B-10 (Fig. 7). Neither of these faults exhibits any vertical separation of either the youngest buried soils or the overlying Holocene alluvial units. If the upper surface of the quartz diorite unit is a planar feature with a nearly uniform dip, as it is in the Fuller Avenue trench to the east (discussed in the following), then it has apparently been displaced up-to-the-north between B-10 and B-16. This postulated fault strand projects upward to a ground-water barrier between B-10 and B-12, indicating the presence of a latest Pleistocene fault extending to within 13 m of the ground surface, the depth to ground water on the north side of the fault in B-10. This strand is ~10 m north of the main strand observed between B-10 and B-12, suggesting a recently active fault zone of at least this width. Because the northern strand exhibits no discernible vertical displacement, it either (1) has very minor displacement, sufficient to generate a fault plane capable of acting as a ground-water barrier but not to create discernible stratigraphic separation, or (2) has predominantly strike-slip motion.

The northernmost fault strand is revealed by 3 m of fault gouge in the quartz diorite penetrated by boreholes B-8 and B-14, as well as by an apparent abrupt shallowing of the upper surface of the quartz diorite between B-14 and B-16. The absence of a ground-water barrier above this strand suggests that it may not have ruptured up into the shallower parts of the overlying alluvium.

Age of Most Recent Faulting. The precise age of the most recent faulting event cannot be determined from available data. However, stratigraphic relationships observed in Camino Palermo boreholes allow us to bracket the age of most recent faulting. The ca. 20,000 yr age of the charcoal sample recovered from the faulted, buried soil 3 is a maximum age for the most recent surface displacement. At Camino Palermo we interpret the southern edge of the quartz diorite interval in the La Brea transect as the main active strand between B-12 and B-10. We therefore interpret the steeply dipping

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Figure 9. Rose diagram showing dips of shear planes in borehole B-10. Because the core was not oriented with respect to map directions, all measurements <90° have a bimodal distribution. However, we only show one of the two possible dips in order to emphasize opposing dips (>90°) observed in continuous core sections. The predominant dip of the shear fabric is ~70° to 85°.
displacement along these two fault strands. The surface of the quartz diorite is probably related to the plain downdropping of the quartz diorite between SM-1C and SM-1D. The anomalously steep, 50° dip of the upper surface of the quartz diorite projected between SM-1 and SM-1B suggests that it may record north-side-up fault displacement. A zone of abundant clay-lined shears in the quartz diorite at 25 m depth in SM-1B may be the downward continuation of the northern fault splay, suggesting a steep, northerly dip. Furthermore, a southward dip of the northern splay cannot explain downdropping of the quartz diorite between SM-1B and SM-1. The dip of the southern strand is not well constrained, although it is probably relatively steep. In Figure 10 we show both faults as steeply north-dipping, oblique-reverse faults. The probable northward dip of the northern fault lies between SM-1C and SM-1, whereas the southern strand lies between SM-1C and SM-1D. The anomalously steep, 50° dip of the upper surface of the quartz diorite projected between SM-1 and SM-1B suggests that it may reflect ground-water flow along the fault or ground water cascading over the fault.

Two additional ground-water barriers in the hanging-wall block of the main fault suggest the presence of at least two additional fault strands. Ground water in SM-1D was encountered at an elevation of 132.5 m, 6.7 m ft deeper than in SM-1C (139.2 m elevation), indicating a barrier between the two boreholes. A second ground-water barrier is between SM-1C and SM-1; ground water in SM-1 was encountered at 144.4 m elevation, 5.2 m shallower than in SM-1C. Development of the topographic depression in the buried surface of the quartz diorite is probably related to displacement along these two fault strands. The ground-water data suggest that at shallow depths the northern fault lies between SM-1C and SM-1, whereas the southern strand lies between SM-1C and SM-1D. The anomalously steep, 50° dip of the upper surface of the quartz diorite projected between SM-1 and SM-1B suggests that it may reflect ground-water flow along the fault or ground water cascading over the fault.

Figure 10. Cross section of North La Brea Avenue borehole transect shows that the Hollywood fault dips moderately steeply at depth but flattens near the surface. The main fault strand acts as a major ground-water barrier, separating a shallow water table to the north from a much deeper water table to the south. Thick vertical lines denote boreholes. Small triangles and gray lines denote ground-water levels in boreholes. Although ground water was encountered at shallow depth in SM-1, the hole was dry below the main fault plane. Modified from detailed borehole logs in Earth Technology Report (1993).

piezometer installed at the base of SM-1, screened entirely below the main fault in order to measure in situ conditions in the footwall of the fault, was found to be dry several days after installation. These observations indicate that the main fault forms an effective ground-water barrier. A thin wet zone encountered in SM-1D in the alluvium directly beneath the main fault may reflect ground-water flow along the fault or ground water cascading over the fault.

As part of a tunnel alignment investigation, MetroRail drilled six boreholes at four additional sites during winter—spring 1995. The following description is taken from R. Radwanski (1995, written commun.). Two closely spaced boreholes located along the north edge of Hillside Avenue between Fuller Avenue and La Brea Avenue, OW-34 and E-206 (located 3 m east of OW-34) penetrated alluvium (predominantly silty sand and clayey sand) to a total depth of 58 m (OW-34; E-206 td 50 m; Fig. 6). The upper surface of the quartz diorite was not encountered, indicating that the boreholes were drilled into the footwall of the fault, which must therefore lie north of the boreholes. This inference is supported by the absence of ground water in the boreholes; no ground water was encountered during drilling, although one week after drilling ground water was measured at 52 m depth in OW-34.

Four other boreholes drilled at three sites extending north from the north end of Fuller Avenue penetrated only quartz diorite. The three boreholes at the southern two sites, OW-34A (located several meters south of the gate at the north end of Fuller Avenue), OW-34B (located 3 m south of OW-34A), and OW-34C (located 90 m south of OW-34A in Runyon Canyon Park), encountered common clay gouge zones intercalated with intensely fractured and disaggregated quartz diorite. In contrast, the northernmost boreholes, OW-34D and E, which were drilled ~85 m north of OW-34C, encountered fractured, but more coherent bedrock with no clay gouge. These observations raise the possibility of a very broad Hollywood fault zone extending northward from just south of Hillside Avenue into the quartz diorite along the mountain front. Much of this faulting, however, could record late Neogene motion not directly related to the current tectonic regime (see Wright, 1991; Tsutsui, 1996).

During May 1995 MetroRail excavated a subway tunnel northward to the Hollywood fault zone approximately halfway between La Brea and Fuller Avenues (Fig. 6). The main fault zone, which was marked by a 70-cm-wide shear zone juxtaposing alluvium with quartz diorite to the north, was encountered at 52 m depth ~50 m N24°W of the centerline of Hillside Avenue. The fault dips 60° to 70° N and was marked by discontinuous clay gouge.

Data from Storm Drain Trenches

During fall 1992 and spring 1993 we examined two storm-drain trenches excavated by the Los Angeles County Department of Public Works. Although the county was extremely ac-
accommodating of our research interests, our time in the trenches, particularly the Fuller Avenue trench, was very limited because of the rapid pace of construction of the storm-drain pipeline. The Fuller Avenue trench was excavated up the Runyon Canyon fan, just east of the fan axis, whereas the Vista Street trench was excavated up the axis of the Vista fan (Fig. 6). The trenches were 3 to 4.5 m deep and 2 m wide.

**Fuller Avenue Trench.** If the main strand of the Hollywood fault extends as a continuous feature between the subway tunnel and Camino Palmero, it probably crosses Fuller Avenue just south of the Hillside Boulevard intersection (Fig. 6). We were not able to view any part of the Fuller Avenue trench south of Hillside Boulevard. We did, however, map the 60 m of trench north of Hillside Avenue (Fig. 11). The trench exposed three of the four lithologic units encountered at Camino Palmero, the basal quartz diorite and alluvial units A and B (Fig. 11). As at Camino Palmero, the upper surface of the quartz diorite dips shallowly southward at ~15°, somewhat more steeply than the 6° dip of the fan surface.

The quartz diorite is overlain by massive, clayey sand of unit B. AMS dating of a charcoal fragment from within this deposit yielded an age of 309 ⋅ 125/315 yr B.P. (Fig. 11; Table 1). This age may not represent the true age of the deposit, because it underlies beds from which older charcoal was recovered (discussed in the following).

Unit B is overlain, along a very sharp, irregular, highly erosively modified contact, by friable, well-bedded sand and pebble gravel of unit A. Two charcoal fragments from a 3–10-cm-thick clayey horizon near the base of a broad, 8-m-wide channel incised into unit B yielded identical AMS ages of 1165 ⋅ 125/195 yr B.P. (Table 1). These AMS ages are in conflict with the younger AMS age of the charcoal sample recovered from underlying unit B. On the basis of the limited number of samples, we cannot determine whether the 1165 yr old samples were reworked from an older deposit, or whether the sample with the younger age was introduced into unit B after deposition. The unit A channel trends S50°E and projects upslope toward the mouth of Runyon Canyon. The AMS ages suggest that at Fuller Avenue, along the east shoulder of the fan, the base of unit A may be considerably younger than at Camino Palmero, if the deposits at the two sites are truly correlative (Fig. 6).

**Evidence of Recent Faulting.** The Fuller Avenue trench crossed what we interpret as a secondary zone of the Hollywood fault ~35 m south of the mountain front (short black line immediately south of OW-34A in Fig. 6). The secondary fault zone, which apparently is at least 40 m north of the main fault, juxtaposes the basal quartz diorite against unit B alluvium (Fig. 11). The main fault splay strikes N59°E, and dips 74°NW at the base of the trench, although several splays of the fault zone roll over into near-horizontal dips just south of the main zone (Fig. 11). North-side-up vertical separation of the contact is ~35 cm across the main fault strand, which is characterized by a 5–15-cm-thick gouge zone composed of sheared white carbonate. Other fault strands are defined by 1–12-mm-thick beige clay seams.

The south end of the quartz diorite exposure, ~1 m south of the main fault, appears to be a vertical fault that truncates the diorite outcrop, as well as the shallowly north-dipping fault strands that splay off the main northern strand, indicating at least two periods of faulting. Although this planar surface appeared to be a fault, because of our limited time in the trench at the fault crossing (<1 hour), we could not unequivocally exclude the possibility that it was a purely erosional feature. If this feature is a fault, the minimum north-side-up vertical separation across both strands is >90 cm. The upward termination of the inferred southern fault strand could not be determined. In the east wall of the trench another fault strand, located entirely within unit B alluvium, occurs several meters south of the northern strand. On the east wall the southern strand, which appears to trend ~N85°W across the trench, may connect with the near-vertical fault strand exposed on the west wall. In the east wall it steepens from a dip of ~40°N at 2.7 m to a near-vertical dip at 3.3 m depth. This strand could not be traced above a depth of 2.7 m. The northern fault strand extends at least 1 m upward into the alluvium, but we were unable to determine its upward termination because of the massive nature of unit B. Any possible displacement of the sharply defined unit A–unit B contact was obliterated in the west wall of the trench by an earlier excavation for a lateral feeder pipe, which was unfortunately located at exactly the site of any expected displacement (Fig. 11). Compounding the problem, in the east wall of the trench a similar lateral feeder pipe was excavated directly into the northern fault zone, completely obscuring its updip termination. Thus, the evidence necessary to unequivocally determine the updip termination of the fault was destroyed during construction of the storm drain.

The geometry of the channel, however, suggests that the unit A-unit B contact has probably not been displaced vertically. At issue is whether the south-facing scarp observed in the west wall of the trench is a purely erosional feature, or whether it is a fault-modified channel edge. Along the west wall of the trench the northern channel edge corresponds exactly to the expected position of the fault, if it in fact continues upward beyond its recognized extent and displaces the unit A-unit B contact. Because the channel cuts obliquely across the fault, the south-facing channel edge on the eastern wall of the trench is exposed more than 2.5 m south of the fault zone. Although it is cut out by the lateral side pipe at the fault, the unit A-unit B contact on the eastern wall projects across the side pipe as an apparently continuous, relatively planar feature, suggesting that the contact has not been displaced vertically. We could, however, have missed minor vertical separations of the contact up to ~20 to 30 cm. The steeper, higher northern edge of the channel might at first appear to suggest that it had been steepened during faulting. However, we suggest that this is simply due to the fact that the channel has cut obliquely across the ~6° dipping fan surface. This geometry requires a higher northern channel margin, and erosion of this higher bank resulted in the steepness of the northern channel margin.

![Figure 11. Map of the west wall of the Fuller Avenue trench. Irregular, thin black lines in unit 3 denote bedding. See Figure 6 for location.](image-url)
Vista Street Trench. Although we logged the entire 425 m length of the Vista Street trench from Hollywood Boulevard to north of Hillside Avenue (Fig. 6), we observed no evidence of faulting. At Wattles Park, ~250 west of Vista Street, quartz diorite occurs within 25 cm of the surface just south of the mountain front (Q in Fig. 6; Crook and Proctor, 1992), indicating that the main fault lies south of that point. On the basis of this constraint and the discussed data above, the north-south Vista Street trench must have crossed the east-west trace of the fault, probably between Franklin and Hillside Avenues. Thus, the trench appears to have been too shallow to expose evidence of the most recent surface rupture. In Figure 12 we show only the 35-m-long section of the trench that includes the projected location of the Hollywood fault. Station numbers in the text below and in the figure refer to distance in feet north from the north edge of the sidewalk along the northern edge of Hollywood Boulevard (1 ft = 0.3 m). For example, the north edge of Franklin Avenue is at station 640, which is 640 ft (195 m) north of Hollywood Boulevard, and the south edge of Hillside Avenue is at station 1045, 1045 ft (318 m) north of Hollywood Boulevard.

As at Camino Palmero and Fuller Avenue to the east, the Vista Street trench exposed three alluvial units above the basal quartz diorite (Fig. 12). These alluvial units, however, cannot be correlated directly with any of the units in the eastern excavations. To avoid unintended correlations, we therefore refer to them as units 1 (youngest), 2, and 3 (oldest). Due to the absence of detrital charcoal in the trench, all age estimates are based upon soil analyses, which have much larger error estimates than features dated by radiocarbon methods (Appendix).

The quartz diorite is exposed only in the northern 45 m of the trench, north of Hillside Avenue. It exhibits a highly eroded, irregular upper surface that dips gently south at 2° to 12°, generally slightly more steeply than the 8° to 9° south-surface that dips gently south at 2° to 12°, generally massive, and has local channels; north and south of this part of the trench the unit is locally well-bedded and has numerous channels. Unit 1 exhibits essentially no soil development, although a surficial A horizon could have been destroyed during grading of Vista Street (Appendix). The combined unit 1-unit 2 soil data indicate that the buried soil developed in unit 1 was buried no more than ~3000 yr ago, and could have been buried as recently as ~500 to 1000 yr ago (Appendix).

The only potential direct evidence of surficial faulting that we observed in the entire Vista Street trench was a vertical carbonate vein exposed in unit 3 at the base of the trench at station 918. The vein trends ~N70°E near the west wall of the trench and bends to a more northerly orientation within the trench floor; it is not exposed in the east trench wall. Despite the highly irregular geometry of the vein, the lack of abundant carbonate in the soil suggests that this may be a fracture fill of tectonic origin, rather than a pedogenic feature. If so, then the shallowest evidence for faulting in the Vista Street trench is in unit A, although this evidence is neither abundant nor clear cut.

At station 1170 in the Vista Street trench (not shown in Fig. 12), an inactive(?), steeply south-dipping (N75°E, 73°S) fault zone separates highly weathered, orange-brown decomposed quartz diorite to the south from firmer, orange-buff quartz diorite in pods within a clay matrix to the north. The fault does not cut the overlying friable, gravelly sand of unit 1.

Age of Most Recent Surficial Faulting. The absence of faulting in the Vista trench across the presumed fault crossing (with the possible exception of the vein at station 918), suggests that the shallowest evidence of the most recent surface rupture has either been buried beneath the 3 to 4 m depth of the trench or has been obliterated by soil-forming processes in units 2 and 3. Unit 3 is exposed continuously from stations 860 to 942. Our experience observing similar, moderately well-developed, dark reddish-brown soils at Camino Palmero and Fuller Avenue suggests that faults and fractures should be readily apparent, because most of these features exhibit either a well-defined beige, 1-5-mm-thick oxidized halo, clay gouge, or carbonate shear veins. No such features were observed in unit 3, with the possible exception of the vein at station 918. Even if this vein is a fault, it projects upward into unfaulted unit 2 deposits. Although unit 2 is not exposed over a 7-m-long stretch between stations 930 and 950, we suggest that the unit has not been faulted. The only possible location where faulting of unit 2 might not be discernible is the

Figure 12. Map of the west wall of the portion of the Vista Street trench between Franklin and Hillside Avenues, which includes the presumed crossing of the main strand of the Hollywood fault zone. See Figure 6 for projected location of the Hollywood fault zone.
2.5-m-wide interval from stations 942 to 950, where neither units 2 or 3 are exposed. However, unit 2 projects across this unexposed interval with no apparent vertical displacement. Thus, the most recent surface rupture at Vista Street appears to have occurred before deposition of unit 2, and may even be older than deposition of unit 3. Alternatively, it is possible that 1000 to 2000 yr of soil development in soil 2 could have obliterated subtle traces of a surface rupture within unit 2. From this we infer that the weak unit 1 soil and at least most of the unit 2 buried soil have developed since the most recent surface rupture on the Hollywood fault, which therefore probably occurred at least ~500 to 3000 yr ago.

**DISCUSSION: KINEMATICS OF THE HOLLYWOOD FAULT**

Because of its location along the southern edge of the Santa Monica Mountains anticlinorium, and the pervasive evidence of contractional deformation in the Transverse Ranges, the Hollywood fault has generally been considered to be a north-dipping reverse fault (e.g., Barbat, 1958; Davis et al., 1989). Displacement of Cretaceous quartz diorite over Pleistocene alluvium at Camino Palmero and La Brea Avenue, and consistently south-facing scarps, confirm a long-term component of reverse motion along the fault. Recent uplift of the mountain front is also suggested by the deposition and lack of incision of the numerous small alluvial fans near the mountain front.

In addition to the north-side-up reverse component of motion, however, several lines of evidence suggest that the Hollywood fault also exhibits a significant, possibly predominant, component of left-lateral strike-slip motion.

1. The buried, mountain-side-down separation between B-12 and B-10 at Camino Palmero (Fig. 7) is incompatible with pure reverse displacement on the fault and indicates either horizontal offset of irregular topography, or pure normal or oblique-normal displacement along the north-dipping fault. At Camino Palmero the fault displaces a shallowly south-southwest–dipping alluvial surface (Fig. 8). Because the apparent right-lateral offset of the contours is clearly at odds with the abundant data showing left-lateral strike-slip motion along the Transverse Ranges Southern Boundary fault system, including both the Raymond fault to the east (Jones et al., 1990) and the Santa Monica fault to the west (Dolan et al., 1992), recent fault displacement at Camino Palmero is almost certainly not right-lateral strike slip. The geometry of the faulted surface might at first suggest pure normal faulting, possibly along a secondary normal fault formed in the hanging wall of a north-dipping, near-surface thrust fault.

However, the lack of tilting or warping of the buried soils south of the main active strand shows that no recently active contractual structures exist south of B-12. With evidence for a long-term, north-side-up component of reverse motion along the Hollywood fault, this observation indicates that the main strand at Camino Palmero cannot be explained by pure normal displacement, and that it is probably best explained as an oblique-normal, left-lateral strike-slip fault. The north-side-down sense of vertical separation at Camino Palmero is opposite to that observed in the North La Brea transect to the east. We speculate that this is related to a slightly more north-easterly strike of the fault at Camino Palmero, resulting in a local transtensional environment along a predominantly transpressional fault.

2. Although the fault exhibits recent mountain-side-down separation at Camino Palmero, at all other sites (Figs. 5, 10, and 11), as well as deeper on the Camino Palmero strand, the fault exhibits recent mountain-side-up separation (Fig. 7). Such apparently contradictory senses of vertical separation are incompatible with pure reverse displacement, but are a common feature of many strike-slip faults (Yeats et al., 1997).

3. The dip of the Hollywood fault has been directly measured at three localities. At Camino Palmero the main fault zone dips northward at ~75°N (Figs. 7 and 9). In the North La Brea transect the fault dips ~60°N at 50 m depth (Fig. 10). Because the fault steepens with depth in the North La Brea transect, the overall dip of the fault at >50 m depth may be steeper than 60°. In the MetroRail subway tunnel crossing the fault, dips are between 60° and 70°N at 50 m depth; the fault was only exposed at the tunnel crossing, and thus it is not known if it steepens with depth as it does in the North La Brea transect ~100 m to the east. On the basis of these data, we suggest that the overall dip of the Hollywood fault at depth is probably at least ~70° to the north. Such steep dips are generally not associated with pure reverse faults, whereas they are commonly associated with strike-slip and oblique-slip faults (Yeats et al., 1997).

In order to help quantify this assertion, we compared the dips and rakes from focal mechanisms for 26 Cordilleran earthquakes Mw ≥5.3 (Fig. 13; Appendix). These data reveal that faults dipping ≥65° to 70° exhibit predominantly strike-slip motion. A similar comparison based on a global catalog of 170 earthquakes yielded the same basic result—faults that dip ≥70° exhibit strike-slip:dip-slip ratios >1 (Coppersmith, 1991; Wells and Coppersmith, 1991). On the basis of these observations, we suggest that the Hollywood fault probably accommodates more strike-slip than reverse motion.

4. Inversion of earthquake focal mechanisms indicates that the maximum compressive stress in the Hollywood area is horizontal and trends N12°—N13°E (Hauksson, 1990). These data are compatible with the strike-slip component on the
north-northeast–trending Hollywood fault being left lateral. Furthermore, the orientation of the stresses indicates that the more northeast-striking parts of the fault may accommodate a larger component of left-lateral motion than the more easterly trending sections of the fault, such as the reach through downtown Hollywood (Fig. 2). The depth of the Hollywood basin is based on data from only a few wells (Wright, 1991; Hummon et al., 1994; Tsutsumi, 1996), and it is therefore impossible to correlate the depth of this basin with changes in orientation of the Hollywood fault. However, on the basis of the evidence described above for a probable component of left-lateral slip on the Hollywood fault, we speculate that the Hollywood basin has formed at least partially in response to oblique, normal to left-lateral slip along more northeasterly trending stretches of the Hollywood fault, including the ~N60°E trending Nichols Canyon–Sunset Strip releasing bend, the ~N25°E trending Benedict Canyon releasing bend at the western end of the fault, and possibly the 350-m-wide left step between the Franklin and northern strands of the Hollywood fault just east of downtown Hollywood (Fig. 2). We further speculate that extension across the West Beverly Hills lineament at least partially explains the existence of the low-lying Beverly Hills alluvial plain east of the lineament; motion through the Benedict Canyon releasing bend has resulted in increased accommodation space to the east that is filled by alluvium derived from Benedict and Laurel Canyons (Fig. 2).

Our geomorphic analysis failed to provide any direct evidence of left-lateral strike slip along the Hollywood fault, either in the form of offset drainages or displaced fans. We attribute this to rapid aggradation of the alluvial fans, which have buried all potential evidence of strike-slip offsets (e.g., offset streams), and earthquake recurrence intervals that are long relative to the rate of geomorphic activity. For example, at Camino Palmero the displaced top of buried soil 3 at 7 m depth is the shallowest well-documented faulted feature. The apparently unfaulted unit A-unit B contact there lies at a depth of almost 5 m, suggesting that at least that much deposition has occurred since the most recent surface rupture that could have generated any discernible surficial strike-slip offsets. Similarly, evidence of the most recent surface rupture may have been buried beneath trench depth by more than 3 to 4 m of sediment at Vista Street. Furthermore, our data reveal late Holocene sediment accumulation on the fans at the fault crossing, rather than deep incision of channels that might be discernible even through the urban overprint.

We speculate that the lack of discernible large-scale offsets of the fans may be due to a conveyor-belt style of sediment input from the numerous, closely spaced canyon sediment sources. In this model, strike-slip motion along the fault would continually move the alluvial apron past the sediment sources, preventing the development of very large individual fans at any single canyon input and forming an alluvial apron upon which small fans develop. Such a process may explain the relatively small sizes of the fans observed along the central reach of the Hollywood fault. This hypothesis could be tested by excavating an east-west transect of sites in the foothall of the fault. The transects would be designed to document the three-dimensional transition from fans composed predominantly of sediment eroded from Tertiary sedimentary and volcanic strata exposed in the Hollywood Hills north of downtown Hollywood, to fans composed predominantly of eroded quartz diorite exposed to the west (Fig. 2). In summary, we contend that the lack of offset geomorphologic features does not necessarily preclude a significant component of left-lateral strike-slip motion along the Hollywood fault.

Potential Interactions Between the Hollywood Fault and Nearby Faults

Both the Hollywood and Santa Monica faults are interpreted to be north-dipping, oblique-reverse, left-lateral faults (Dolan and Sieh, 1992; Dolan et al., 1992; this study). Coupled with the similar orientations of the two faults, this leads us to interpret them as closely related strands within a single fault system that might rupture together during large earthquakes (Fig. 2). However, the three northeast-trending releasing bends along the Hollywood fault could act as earthquake segment boundaries, as has been shown along other faults (e.g., Sibson, 1985).

Recognition of a component of left-lateral strike slip on the Hollywood fault also raises the possibility that it may directly connect with the left-lateral Raymond fault to the east (Fig. 1). Such a connection has long been postulated on the basis of the similar strike of the two faults (e.g., Barbat, 1958; Lamar, 1961), and gravity data, which suggest overall continuity of basement trends across the Los Angeles River (Chapman and Chase, 1979). However, the area between the southwesternmost well-established location of the Raymond fault ~5 km east of the Los Angeles River (Weber et al., 1980) and the easternmost scarps of the Hollywood fault just west of the Los Angeles River is very complex topographically, and a thoroughgoing east-northeast–trending fault trace cannot be verified on the basis of geomorphic expression (Fig. 1). Rather, it appears that the Raymond fault splays westward into several east-trending, oblique-reverse (?) faults (Weber et al., 1980; Crook et al., 1987). Although left-lateral slip on the Raymond fault may ultimately be transferred to the Hollywood fault through some unknown mechanism, the Raymond fault may act at least partially as a left-lateral tear fault transferring motion from the Sierra Madre fault to the Verdugo–Eagle Rock fault system (Fig. 1). However, the presence of Pleistocene-Holocene (?) fault scarpsof the western Raymond system west of Arroyo Seco, west of the presumed point of interaction with the Verdugo–Eagle Rock fault system, indicates that some slip on the Raymond fault system extends westward toward the Hollywood fault. Trenches excavated across one strand of the Raymond fault at the base of a drained, 5-m-deep reservoir west of Pasadena revealed numerous steeply north-dipping faults (64° to 85°) (Department of Water and Power Report, 1991). The steep dips and contradictory, but predominantly normal, vertical separations across these faults suggest that they are strike-slip faults, indicating that some left-lateral motion is transferred along the Raymond fault west of the Eagle Rock fault intersection.

Age of Most Recent Activity of the Hollywood Fault

In the absence of demonstrable evidence for Holocene displacements (Crook et al., 1983; Crook and Proctor, 1992), the Hollywood fault has not been zoned as active by the State of California. Our data indicate that the Hollywood fault has generated at least one surface rupture since latest Pleistocene time, suggesting that it is almost certainly capable of producing damaging earthquakes in the future. The ~500 to 3000 yr interval required to develop the unfaulted Vista Street soils (Fig. 12) represents the minimum interval since the most recent earthquake on the main strand. This estimate is supported by data from the Fuller Avenue trench (Fig. 11), which suggest, but do not prove, that no movement has occurred on the secondary strand of the fault exposed there in at least 1200 yr. An even older minimum age is suggested by the lack of discernible vertical displacement of the ~4000 to 8000 yr old unit A-unit B contact across the main fault zone at Camino Palmero. Although this latter age estimate is poorly constrained, recovery of an ~3500 yr old charcoal fragment from the middle of unit A, 2.8 m above the apparently unfauluted contact, suggests a long period of quiescence since the most recent Hollywood fault surface rupture.

The ca. 20,000 yr B.P. charcoal date from the faulted buried soil 3 at Camino Palmero (Fig. 7) represents a maximum age for the most recent surface displacement on the Hollywood fault. We do not know the exact depth of the upward termination of the most recent surface rupture at Camino Palmero. The shallowest displaced
marker discernible in the cores is the unit B-unit C contact. In the Fuller Avenue trench, however, rupture clearly extended well above the contact, at least 1 m up into unit B (Fig. 11). Thus, if stratigraphic units are correlative between Fuller Avenue and Camino Palmero, the most recent surface rupture may significantly postdate the <~20 000 yr old unit B-C contact. In summary, our best estimate is that the most recent surface rupture on the Hollywood fault occurred during deposition of unit B between ca. 20 000 and 4000 yr ago. Available evidence does not allow us to exclude the possibility that more than one event has occurred during this time interval.

**Constraints on the Slip Rate of the Hollywood Fault**

The dense urbanization of the Hollywood area precludes excavation of a three-dimensional network of trenches designed to assess the rate and amount of lateral slip on the Hollywood fault; virtually the entire length of the fault is either paved or covered with buildings. Consequently, the overall slip rate and the relative proportions of lateral to vertical slip have not been directly measured. Nonetheless, we can use a combination of the borehole data, soil analyses, and regional geologic and geodetic information to place constraints on the slip rate and slip vector of the fault.

Despite the mountain-side-down separation of late Pleistocene(?)–early Holocene (?) deposits at Camino Palmero, the displacement of quartz diorite over alluvium in both borehole transects suggests that the Hollywood fault exhibits a long-term component of reverse displacement. The weakly constrained ~0.1 mm/yr late Pleistocene–Holocene sediment-accumulation rate estimated from soil analyses at B-31, when extrapolated up-fan 170 m to just south of the fault crossing, yields an approximate age of ca. 660 000 to 750 000 yr for sediments at 73 m depth (correlative with the base of B-10) (Fig. 7; Appendix). The parallelism of the buried soils with the fan surface implies that the accumulation rate at the fault crossing is similar to that at B-31, and that this is therefore a reasonable extrapolation.

Because the quartz diorite was not observed in the footwall of the fault, the minimum amount of separation across the fault zone equals the vertical distance between the bottom of B-10 and the projection of the planar upper surface of the quartz diorite southward across all four known strands of the fault. Dividing this distance, ~50 m, by the sediment age yields a minimum relative uplift rate of ~0.07 mm/yr across the fault. For a local fault dip of 75°, this uplift rate yields a weakly constrained, minimum mid-Pleistocene to present dip-slip rate of ~0.075 mm/yr. We emphasize, however, that extrapolation of data on late Pleistocene–Holocene accumulation rates back several hundred thousand years introduces a potentially significant, but unquantifiable, degree of uncertainty in these age estimates, and in the accumulation rates and fault-slip rates that we derive from them.

We can also estimate an approximate maximum, long-term dip-slip rate on the basis of the thickness of Quaternary alluvium filling the Hollywood basin south of the fault. Dividing the presumed maximum 300 m depth to early Quaternary marine gravels at the base of the alluvial section by their estimated ca. 0.8 to 1.2 Ma age (Hummon et al., 1994; D. Ponti, 1995, written commun.) yields a maximum long-term uplift rate of ~0.3 to 0.4 mm/yr. An overall 70° dip for the Hollywood fault yields a similar dip-slip rate of ~0.3 to 0.4 mm/yr. This long-term rate is a maximum because: (1) the Hollywood basin probably developed at least partially, and possibly mainly, in response to motion through the Nichols Canyon–Sunset Strip and Benedict Canyon releasing bends; and (2) the bottom of basin may be shallower than 300 m over most of the length of the Hollywood fault. If any of Hollywood basin subsidence is due to strike-slip motion, and we suspect that much of it is, the true reverse dip-slip rate on the Hollywood fault must be slower than the ~0.3 to 0.4 mm/yr maximum rate. Given the maximum and minimum constraints determined above, in the following discussion we use 0.25 ± 0.15 mm/yr, the average of the minimum (~0.1 mm/yr) and maximum (~0.4 mm/yr) rate estimates, as a reasonable dip-slip rate for the Hollywood fault.

The estimated ~70° overall dip of the fault suggests that it may accommodate more strike-slip than reverse motion. In the following discussion, however, we assume a conservative strike-slip:dip-slip ratio of 1, which yields an overall oblique-slip rate of ~0.35 ± 0.2 mm/yr. This rate is probably a minimum because we suspect that the actual strike-slip rate may be higher, possibly considerably higher, than the dip-slip rate; in the far western part of the Transverse Ranges Southern Boundary fault system, the Santa Cruz Island and Santa Rosa Island faults exhibit left-lateral strike-slip rates of ~0.75 and ~1 mm/yr, respectively (Pinter et al., 1995; Colson et al., 1995).

A strike-slip rate along the Hollywood fault significantly >0.25 mm/yr is not precluded by recent geodetic data. Global Positioning System (GPS) geodetic data from four sites northwest of Hollywood (open squares in Fig. 1) show that the western Transverse Ranges, including the Santa Monica Mountains, are moving westward as a block relative to sites in the Los Angeles basin at 0 to 2 mm/yr (A. Donnellan, JPL Geodesy Group, 1996, personal commun.). These data suggest that a major strike-slip fault is between the Santa Monica Mountains and the Los Angeles basin.

The Hollywood fault is the most likely fault on which this left-lateral strike-slip motion could be accommodated. The only other near-surface fault that has been proposed in the Hollywood area is the North Salt Lake fault, which parallels the Hollywood fault ~1.5 km to the south (Fig. 3; Schneider et al., 1996; Tsutsumi, 1996). The North Salt Lake fault, however, exhibits no surface expression and may no longer be active. Available subsurface data do not clearly resolve whether the fault cuts late Quaternary strata (Tsutsumi, 1996). In contrast, the data discussed in this paper show that the Hollywood fault: (1) is well expressed at the surface; (2) has produced at least one earthquake since latest Pleistocene time; (3) is steeply dipping, which implies a strike-slip component of motion; (4) exhibits near-surface deformation at Camino Palmero indicative of strike-slip offset; and (5) has contradictory vertical separations on single strands consistent with predominantly strike-slip motion. On the basis of these observations, we suggest that most, if not all, of the left-lateral strike-slip motion between the Santa Monica Mountains and Los Angeles basin is accommodated along the Hollywood fault. Future GPS data will provide increasingly tighter constraints on the true slip rate of the Hollywood fault during the next decade.

**Size and Frequency of Future Hollywood Fault Earthquakes**

Although we have no direct information concerning the recurrence interval for Hollywood fault earthquakes, the probable long duration of the current quiescent period implies that the fault exhibits a recurrence interval measurable in terms of several thousands, rather than hundreds, of years. In the absence of direct recurrence data we can use estimates of the size of the Hollywood fault plane and minimum and maximum inferred slip rates to speculate about the size and frequency of future Hollywood fault earthquakes.

The Hollywood fault is 14 km in length. Assuming an average fault dip of 70° and a thickness of the seismogenic crust of ~17 km yields a total fault surface area of ~250 km². These data suggest that rupture of the entire Hollywood fault could produce a Mw ~6.6 earthquake with ~1.5 m of average slip across the rupture plane (Dolan et al., 1995). Assuming an oblique-slip rate for the Hollywood fault of 0.35 mm/yr, which we infer to be a probable minimum, yields a recurrence interval for a Mw 6.6 earthquake of ~4000 yr. As discussed above, this slip rate estimate is poorly constrained, and a faster rate would result in a correspondingly shorter expected recurrence interval. The Vista Street trench data indicate that it
Implications for Seismic Hazard Assessment in Northern Los Angeles Basin

The Hollywood fault appears to be capable of generating an earthquake comparable to the 1994 Mw 6.7 Northridge event, which directly caused generating an earthquake comparable to the 1994 in Northern Los Angeles Basin. Implications for Seismic Hazard Assessment (e.g., the adjacent Santa Monica and/or Raymond faults).

Southern Boundary fault system (e.g., the transpressional faults in the Transverse Ranges), involved the Hollywood fault together with other transpressional faults in the Transverse Ranges. Southern Boundary fault system (e.g., the adjacent Santa Monica and/or Raymond faults).

CONCLUSIONS

From a seismic hazard perspective, perhaps our most important result is that the Hollywood fault is probably active and capable of producing damaging earthquakes beneath the densely urbanized northern Los Angeles basin. Prior to this study no paleoseismicologic information was available for the fault, which is consequently not zoned as active by the State of California. The fault has ruptured to the surface at least once during the past 20,000 yr. Unfaulted deposits that cross the fault indicate that the most recent earthquake occurred at least ~500 to 3000 yr ago. However, stratigraphic relations in several excavations lead us to suspect that the most recent surface rupture probably occurred earlier, possibly during latest Pleistocene to early or mid-Holocene time, between ~4000 and 20,000 yr ago. Although the minimum age of the most recent surface rupture is consistent with the occurrence of moderate (Mw ~6.6) earthquakes along the Hollywood fault, the poorly constrained age of the most recent event is also consistent with the occurrence of less frequent, and therefore probably larger, earthquakes. We speculate that if such large ruptures have occurred, they may have involved simultaneous rupture of the Hollywood fault and adjacent faults of the Transverse Ranges Southern Boundary fault system.

Although it has generally been considered a reverse fault, recent mountain-side-down displacement documented at one site, coupled with the probable steep overall dip (~70°N) and north-northeast strike of the fault, suggest a significant, possibly predominant, component of left-lateral strike-slip motion along the Hollywood fault. In addition to the strike-slip component, the sparse available data suggest that the Hollywood fault exhibits a component of reverse displacement of ~0.25 mm/yr, indicating that overall motion is oblique reverse, left-lateral strike-slip.

ACKNOWLEDGMENTS

This research was supported by grants from the California Department of Transportation, the City of Los Angeles, the County of Los Angeles, and the National Science Foundation, administered by the Southern California Earthquake Center. We thank the Metropolitan Transit Authority Red Line subway project, in particular Richard Radwanski, Timothy Smirnoff, and Tony Stirbys, for helpful discussions and for allowing publication of the borehole data. We also thank the County of Los Angeles Department of Public Works, Gary Johnson in particular, for allowing us access to storm-drain trenches. Frank Denison graciously provided us with important unpublished data from numerous geotechnical studies of the Hollywood fault. We thank also Andrea Donnellan for helpful discussions about recent global positioning system (GPS) results. Anne Lilje generated digital topographic data from 1920s-vintage maps. Steve Wesnosky, Dan Ponti, Tom Wright, and Steve Wells provided useful comments.

<table>
<thead>
<tr>
<th>Soil</th>
<th>MHI</th>
<th>SDI</th>
<th>Predicted age (ka) (2σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MHI</td>
<td>SDI</td>
<td></td>
</tr>
<tr>
<td>Vista 2 (buried) (3.4 to ? m depth)</td>
<td>0.31</td>
<td>N.D.</td>
<td>12.6 +28.0/−8.7 N.D.</td>
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<tr>
<td>B−31 (surface#1)</td>
<td>0.19</td>
<td>42.2</td>
<td>6.5 +14.8/−4.5</td>
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<tr>
<td>B−31 (soil #2)</td>
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<td>47.8</td>
<td>11.3 +25.1/−7.8 14.5 +45.6/−4.6</td>
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<tr>
<td>B−31 (soil #3)</td>
<td>0.44</td>
<td>88.3</td>
<td>26.2 +57.0/−17.9 30.1 +93.9/−9.7</td>
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<tr>
<td>B−31 (soil #4)</td>
<td>0.48</td>
<td>108.3</td>
<td>32.8 +71.3/−22.5 41.4 +129.5/−13.2</td>
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<tr>
<td>B−31 (soil #5)</td>
<td>0.53</td>
<td>98.9</td>
<td>43.3 +94.8/−29.7 35.6 +111.3/−11.4</td>
</tr>
<tr>
<td>B−31 (soil #6)</td>
<td>0.46</td>
<td>90.4</td>
<td>29.3 +63.7/−20.0 31.1 +97.1/−10.0</td>
</tr>
</tbody>
</table>
| Averages (B−31) | &nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&n

Notes: MHI—maximum horizon index, SDI—soil development index, N.D.—no data
### TABLE A2. SOIL DESCRIPTIONS FROM THE VISTA STREET TRENCH AND BOREHOLE B-31

<table>
<thead>
<tr>
<th>Pedon</th>
<th>Horizon</th>
<th>Depth (cm)</th>
<th>Color</th>
<th>Text</th>
<th>Structure</th>
<th>Consistency</th>
<th>Clay films</th>
<th>Bound.</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay %</th>
<th>H.I.</th>
<th>SDI</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vista 1</td>
<td>Ab?</td>
<td>(94–144)</td>
<td>SL</td>
<td>3/4m</td>
<td>m-sg</td>
<td>n.o.</td>
<td>?</td>
<td>82</td>
<td>11.6</td>
<td>6.4</td>
<td>0.07</td>
<td>Scattered pebbles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>(144–322)</td>
<td>(195)</td>
<td>LS-SL</td>
<td>3/4m</td>
<td>m-sg</td>
<td>n.o.</td>
<td>?</td>
<td>82</td>
<td>11.6</td>
<td>6.4</td>
<td>0.07</td>
<td>Scattered pebbles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>(144–322)</td>
<td>(235)</td>
<td>LS</td>
<td>3/4m</td>
<td>m-sg</td>
<td>n.o.</td>
<td>?</td>
<td>82</td>
<td>11.6</td>
<td>6.4</td>
<td>0.07</td>
<td>Scattered pebbles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>(144–322)</td>
<td>(290)</td>
<td>SL</td>
<td>3/4m</td>
<td>m-sg</td>
<td>n.o.</td>
<td>?</td>
<td>82</td>
<td>11.6</td>
<td>6.4</td>
<td>0.07</td>
<td>Scattered pebbles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bwb?</td>
<td>(322–330+)</td>
<td>SL</td>
<td>3/4m</td>
<td>m-sg</td>
<td>n.o.</td>
<td>?</td>
<td>82</td>
<td>11.6</td>
<td>6.4</td>
<td>0.07</td>
<td>Scattered pebbles</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vista 2</td>
<td>C (undiff.)</td>
<td>0–270</td>
<td>10YR 3/4m, 5/5d</td>
<td>SL</td>
<td>3/4m</td>
<td>m-sg</td>
<td>n.o.</td>
<td>?</td>
<td>82</td>
<td>11.6</td>
<td>6.4</td>
<td>0.07</td>
<td>Scattered pebbles</td>
<td></td>
</tr>
<tr>
<td>B-31</td>
<td>Gone</td>
<td>0–1.52</td>
<td>10YR 3/4m, 4/5d</td>
<td>SL</td>
<td>3/4m</td>
<td>m-sg</td>
<td>n.o.</td>
<td>?</td>
<td>82</td>
<td>11.6</td>
<td>6.4</td>
<td>0.07</td>
<td>Scattered pebbles</td>
<td></td>
</tr>
</tbody>
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### TABLE A3. MAXIMUM HORIZONTAL INDEX (MHI) DATA FOR SOILS FROM VISTA STREET TRENCH AND BOREHOLE B-31

<table>
<thead>
<tr>
<th>Profile</th>
<th>MHI</th>
<th>Sy</th>
<th>Conf.</th>
<th>Log age</th>
<th>Error in µ of Y</th>
<th>St(y–y)</th>
<th>Conf.</th>
<th>Log age</th>
<th>Error in Y pop.</th>
<th>Age (yr)</th>
<th>95% predicted age C.I.</th>
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<tbody>
<tr>
<td>Vista 2</td>
<td>0.31</td>
<td>0.0608</td>
<td>0.1273</td>
<td>4.10</td>
<td>4.23</td>
<td>3.97</td>
<td>0.2420</td>
<td>0.5065</td>
<td>4.61</td>
<td>3.60</td>
<td>12,653</td>
</tr>
<tr>
<td>B31#1</td>
<td>0.31</td>
<td>0.0797</td>
<td>0.1667</td>
<td>3.81</td>
<td>3.98</td>
<td>3.64</td>
<td>0.2474</td>
<td>0.5178</td>
<td>4.33</td>
<td>3.29</td>
<td>4644</td>
</tr>
<tr>
<td>B31#2</td>
<td>0.29</td>
<td>0.0635</td>
<td>0.1329</td>
<td>4.05</td>
<td>4.19</td>
<td>3.92</td>
<td>0.2427</td>
<td>0.5079</td>
<td>4.56</td>
<td>3.55</td>
<td>11,313</td>
</tr>
<tr>
<td>B31#3</td>
<td>0.44</td>
<td>0.0512</td>
<td>0.1071</td>
<td>4.42</td>
<td>4.53</td>
<td>4.31</td>
<td>0.2397</td>
<td>0.5018</td>
<td>4.92</td>
<td>3.92</td>
<td>25,193</td>
</tr>
<tr>
<td>B31#4</td>
<td>0.48</td>
<td>0.0516</td>
<td>0.1079</td>
<td>4.52</td>
<td>4.62</td>
<td>4.41</td>
<td>0.2398</td>
<td>0.5020</td>
<td>5.02</td>
<td>4.01</td>
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<tr>
<td>B31#5</td>
<td>0.53</td>
<td>0.0544</td>
<td>0.1138</td>
<td>4.64</td>
<td>4.75</td>
<td>4.52</td>
<td>0.2404</td>
<td>0.5033</td>
<td>5.14</td>
<td>4.13</td>
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<tr>
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<td>0.46</td>
<td>0.0512</td>
<td>0.1071</td>
<td>4.47</td>
<td>4.57</td>
<td>4.36</td>
<td>0.2397</td>
<td>0.5018</td>
<td>4.97</td>
<td>3.97</td>
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### TABLE A4. SOIL DEVELOPMENT INDEX (SDI) DATA FOR SOILS FROM VISTA STREET TRENCH AND BOREHOLE B-31

<table>
<thead>
<tr>
<th>Profile</th>
<th>SDI</th>
<th>Sy</th>
<th>Conf.</th>
<th>Log age</th>
<th>Error in µ of Y</th>
<th>St(y–y)</th>
<th>Conf.</th>
<th>Log age</th>
<th>Error in Y pop.</th>
<th>Age (yr)</th>
<th>95% predicted age C.I.</th>
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<tbody>
<tr>
<td>Vista 2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<tr>
<td>B31#1</td>
<td>4.20</td>
<td>0.0611</td>
<td>0.1290</td>
<td>4.16</td>
<td>4.29</td>
<td>4.03</td>
<td>0.2361</td>
<td>0.4982</td>
<td>4.66</td>
<td>3.66</td>
<td>14,488</td>
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<td>B31#2</td>
<td>4.70</td>
<td>0.0590</td>
<td>0.1245</td>
<td>4.20</td>
<td>4.32</td>
<td>4.08</td>
<td>0.2356</td>
<td>0.4971</td>
<td>4.70</td>
<td>3.70</td>
<td>15,835</td>
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<tr>
<td>B31#3</td>
<td>8.80</td>
<td>0.0525</td>
<td>0.1107</td>
<td>4.48</td>
<td>4.59</td>
<td>4.37</td>
<td>0.2341</td>
<td>0.4938</td>
<td>4.97</td>
<td>3.99</td>
<td>30,120</td>
</tr>
<tr>
<td>B31#4</td>
<td>10.80</td>
<td>0.0557</td>
<td>0.1175</td>
<td>4.62</td>
<td>4.73</td>
<td>4.50</td>
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<td>0.4954</td>
<td>5.11</td>
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<td>0.1132</td>
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<td>4.67</td>
<td>4.44</td>
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<td>0.4944</td>
<td>5.05</td>
<td>4.06</td>
<td>35,641</td>
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<tr>
<td>B31#6</td>
<td>9.40</td>
<td>0.0526</td>
<td>0.1110</td>
<td>4.49</td>
<td>4.60</td>
<td>4.38</td>
<td>0.2341</td>
<td>0.4939</td>
<td>4.99</td>
<td>4.00</td>
<td>31,141</td>
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### Table A5. Parameters for Earthquakes Used in Constructing Figure 13

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Mw</th>
<th>Strike</th>
<th>Dip</th>
<th>Rake</th>
<th>References</th>
</tr>
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<tr>
<td>07-21-52</td>
<td>Kern County</td>
<td>7.5</td>
<td>50</td>
<td>63</td>
<td>49</td>
<td>Hanks et al. (1975); Stein and Thatcher (1981); Hill et al. (1990)</td>
</tr>
<tr>
<td>12-16-54</td>
<td>Fairview Peak, Nevada</td>
<td>7.1</td>
<td>350</td>
<td>60</td>
<td>-150</td>
<td>Doser (1986)</td>
</tr>
<tr>
<td>09-12-66a</td>
<td>Truxee</td>
<td>5.9</td>
<td>44</td>
<td>80</td>
<td>0</td>
<td>Hill et al. (1990)</td>
</tr>
<tr>
<td>04-09-68</td>
<td>Borrego Mtn.</td>
<td>6.5</td>
<td>132</td>
<td>90</td>
<td>180</td>
<td>Hill et al. (1990)</td>
</tr>
<tr>
<td>02-09-71</td>
<td>San Fernando</td>
<td>6.7</td>
<td>290</td>
<td>54</td>
<td>76</td>
<td>Heaton (1982)</td>
</tr>
<tr>
<td>02-21-73</td>
<td>Point Mugu</td>
<td>5.3</td>
<td>80</td>
<td>36</td>
<td>55</td>
<td>Steimer and Ellsworth (1976); Hill et al. (1990)</td>
</tr>
<tr>
<td>08-06-79a</td>
<td>Coyote Lake</td>
<td>5.7</td>
<td>150</td>
<td>84</td>
<td>180</td>
<td>Hill et al. (1990)</td>
</tr>
<tr>
<td>10-15-79b</td>
<td>Imperial Valley</td>
<td>6.5</td>
<td>146*</td>
<td>90</td>
<td>180</td>
<td>*Ekstrom and England (1989); Kanamori and Regan (1982); Hill et al. (1990)</td>
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<tr>
<td>01-24-80a</td>
<td>Livermore</td>
<td>5.8</td>
<td>157</td>
<td>160</td>
<td>0</td>
<td>Hill et al. (1990)</td>
</tr>
<tr>
<td>06-05-80b</td>
<td>Mammoth Lakes</td>
<td>6.2*</td>
<td>21</td>
<td>116</td>
<td>0</td>
<td>Hill et al. (1990)</td>
</tr>
<tr>
<td>08-04-81</td>
<td>N. Santa Barbara Is.</td>
<td>5.9</td>
<td>45</td>
<td>80</td>
<td>0</td>
<td>Hill et al. (1990)</td>
</tr>
<tr>
<td>10-25-82</td>
<td>New Idria</td>
<td>5.5</td>
<td>154</td>
<td>41</td>
<td>137</td>
<td>Ekstrom and Dziewonski (1985); Stein and Ekstrom (1992)</td>
</tr>
<tr>
<td>05-02-83a</td>
<td>Coalinga</td>
<td>6.5</td>
<td>145</td>
<td>30</td>
<td>100</td>
<td>Kanamori (1983); Eberhart-Phillips (1990); Stein and Ekstrom (1992); *Anderson et al. (1995)</td>
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<td>10-28-83b</td>
<td>Borah Peak, Idaho</td>
<td>6.9</td>
<td>151</td>
<td>52</td>
<td>64</td>
<td>Average of 6 values (with nonfixed rake angle) in Richins et al. (1985)</td>
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<tr>
<td>04-24-84</td>
<td>Morgan Hill</td>
<td>6.2</td>
<td>333</td>
<td>76</td>
<td>179</td>
<td>Ekstrom and England (1989); *Anderson et al. (1995); Wells and Coppersmith (1995)</td>
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<tr>
<td>08-04-85</td>
<td>Kettleman Hills</td>
<td>6.1</td>
<td>142</td>
<td>12</td>
<td>109</td>
<td>Ekstrom et al. (1992); Stein and Ekstrom (1992)</td>
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<tr>
<td>07-08-86a</td>
<td>N. Palm Springs</td>
<td>6.1*</td>
<td>114</td>
<td>37</td>
<td>156</td>
<td>Ekstrom and England (1989); *Wells and Coppersmith (1995); **Anderson et al. (1995)</td>
</tr>
<tr>
<td>07-21-86b</td>
<td>Chalfant Valley</td>
<td>6.3*</td>
<td>149</td>
<td>60</td>
<td>163</td>
<td>Ekstrom and England (1989); Hill et al. (1990)</td>
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<tr>
<td>10-01-87a</td>
<td>Whittier Narrows</td>
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<td>90</td>
<td>25</td>
<td>90</td>
<td>Hauksson (1990); Hartzell and Iida (1990)</td>
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<td>11-24-87b</td>
<td>Superstition Hills</td>
<td>6.7*</td>
<td>305/20</td>
<td>80</td>
<td>175</td>
<td>Bent et al. (1989); *Anderson et al. (1995);</td>
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<tr>
<td>11-18-89</td>
<td>Loma Prieta</td>
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<td>68</td>
<td>137</td>
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<td>Sierra Madre</td>
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<td>243</td>
<td>49</td>
<td>82</td>
<td>Wald (1992)</td>
</tr>
<tr>
<td>04-23-92a</td>
<td>Joshua Tree</td>
<td>6.1*</td>
<td>180</td>
<td>90</td>
<td>160</td>
<td>Hauksson et al. (1993); *Hough and Dreger (1995)</td>
</tr>
<tr>
<td>06-28-92b</td>
<td>Landers</td>
<td>7.3</td>
<td>170</td>
<td>90</td>
<td>170</td>
<td>Hauksson et al. (1993); *average of 5 in Anderson et al. (1995)</td>
</tr>
<tr>
<td>06-28-92c</td>
<td>Big Bear</td>
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<td>55</td>
<td>85</td>
<td>10</td>
<td>Hauksson et al. (1993)</td>
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<tr>
<td>01-17-94</td>
<td>Northridge</td>
<td>6.7</td>
<td>122</td>
<td>40</td>
<td>101</td>
<td>Wald, Heaton, Hudnut (BSSA in press); *average of 5 in Anderson (1995)</td>
</tr>
</tbody>
</table>

Figure A1. Regression of Maximum Horizon Index (MHI) values for undated soils in Vista Street trench and borehole B-31 against data from dated southern California soils.
APPENDIX. SOIL DESCRIPTIONS FROM BOREHOLE B-31, CAMINO PALMERO BOREHOLE TRANSECT AND FOR VISTA STREET TRENCH

We described one complete and one partial soil profile from the Vista Street trench during the storm drain pipeline excavations (Fig. 12), as well as a sequence of six soils from the core of borehole B-31 at Camino Palmero (Fig. 7). All of these soils were described according to SCS Soil Survey Staff (1975; 1992) (Tables A1 and A2) and samples were collected for particle-size analysis.

Vista Street Profiles

The partial profile we described, Vista 1, was located at stations 822-824, whereas profile Vista 2 was located at station 885 (Fig. 12). Vista 2 appeared to expose a complete profile of the soil developed in depositional unit 2. At least three depositional pulses are present in the Vista 2 profile; the upper 2.7 m (unit 1) is characterized by unweathered, essentially raw alluvium. The alluvium between 2.7 and 3.4 m depth (unit 2) appears to have been exposed to the surface for a period of time and has an A horizon developed through it. Vista 2 appeared to expose a complete profile of the soil developed in depositional unit 2. The lower part of the buried A horizon in the Vista 2 exposure graded laterally into a weakly expressed Bw horizon in the Vista 1 exposure 20 m to the south. Particle size distributions for both of these units are nearly identical, supporting their correlation. The top of a better developed buried soil (unit 3) is present at ~3.4 m depth at the Vista 2 site. There a buried A horizon overlies a weakly developed argilllic (Bt) horizon developed in this lowest stratigraphic unit exposed in the trench.

We compared the Vista 2 and borehole B-31 soils to dated soils elsewhere in southern California as the basis for age estimates. For a buried soil, the age estimate represents only the time that the sediments and soil were exposed at the surface. Thus, because there is no age control on the length of the depositional phase, the cumulative ages represented by the combined ages of the surface and buried soils should be considered a minimum age for the sediments at the base of the trench and borehole.

Vista Trench 2

The surface soil and deposit exposed in the trench has essentially no soil development, suggesting a very young age. However, an A horizon may have been present that was disturbed or graded during construction of Vista Street. If not, then the surface alluvium is probably <100 yr in age in that well-formed A horizons are usually evident within 50 to 100 yr in southern California (Rockwell et al., 1985; Harden, 1982; McFadden and Weldon, 1987). Similarly, the shallowest buried soil (unit 2) is represented by only an A horizon (albeit a thick one) in the Vista 2 exposure and possibly by a cambic (Bw) horizon in the Vista 1 exposure (Fig. 12). The presence of a cambic horizon indicates more development and time than just the presence of an A horizon. Cambic horizons without evidence of translocated clay have formed in sandy alluvium in similar environments in southern California in 500 to 5000 yr (Rockwell et al., 1985; McFadden and Weldon, 1987), although many recent data have been collected from the Los Angeles basin area showing incipient illuviation (clay film development) in fewer than 3000 yr (T. Rockwell, unpub. data). On the basis of these observations, we suggest that the unit 2 is middle to late Holocene in age.

For the lowest buried soil (unit 3) with a weak argillic horizon, the maximum horizon index (MHI) values from the field descriptions were regressed against data from soil profiles in three different chronosequences developed under a xeric (Mediterranean) climate in California. There are minor differences in parent material and climate among these chronosequences (see Rockwell et al., 1990, for a complete discussion), but they are similar enough for analysis of the Vista Street soil profiles. We also include data from dated soil profiles from within the Los Angeles basin region.

The three chronosequences used are from the Ventura basin (Rockwell, 1983; Rockwell et al., 1985), the central Valley of California (Harden, 1982), and the Cajon Pass area (McFadden and Weldon, 1987) (Figure A1). Only one criterion was used to estimate the age of...
the Vista Street trench soils: the maximum horizon index (MHI), as presented in Harden (1982), Ponti (1985), and Rockwell et al. (1994). Two other criteria, the profile mass accumulation of secondary clay, as determined by particle-size analysis, and the soil development index (SDI) of Harden (1982), are usually also used, but only the top of the argillic horizon was exposed, so there are too many assumptions that would have to be made to apply these techniques. The MHI parameter converts field description data of the best-developed horizon (usually the B0) to numerical values that allow numerical comparison to the dated profiles. We assume that this portion of the B horizon that we described is representative of this unit’s soil. We understand that such an assumption, if incorrect, could lead to wide significant errors in the age estimate of the soil. We therefore do not use our age estimate of soil 3 for any paleoearthquake calculations.

The MHI data for the three chronosequences, along with the other Los Angeles basin profiles (not presented here; these will form the focus of a future paper), define a log-linear trend with a high r² value (0.85; Fig. A1).

Regression of the Vista 2 MHI value (0.31) indicates an a log-linear trend with a high r² value (0.85; Fig. A1).


