Tectonic geomorphology of active folding over buried reverse faults: San Emigdio Mountain front, southern San Joaquin Valley, California

E. A. Keller* *Environmental Studies Program* and *Department of Geological Sciences, University of California, Santa Barbara, California 93106*

D. B. Seaver *SEPUP, Lawrence Hall of Science, University of California, Berkeley, California 94720*

D. L. Laduzinsky *Henshaw Associates, Inc., 11875 Dublin Boulevard, Suite A-200, Dublin, California 94568*

D. L. Johnson *Department of Geography, University of Illinois, Urbana, Illinois 61801*

T. L. Ku *Department of Earth Sciences, University of Southern California, Los Angeles, California 90089*

ABSTRACT

Investigation of the tectonic geomorphology of active folding over buried reverse faults at the San Emigdio Mountain front, southern San Joaquin Valley, California, provides insight concerning the tectonic and geomorphic development of mountain fronts produced by active folding and faulting. Monoclinally flexed gravels with dips as great as 50º and a minimum age of about 65 ka provide evidence of late Pleistocene deformation at the active range front. Studies of the surface folding of alluvial fans and fluvial terraces indicate a Holocene vertical deformation rate of 1.9–3.0 m/k.y. at the active range front and 0.8–1.3 m/k.y. ~2 km basinward. Geomorphic evidence also indicates that the locus of active folding and vertical deformation along the northern flank of the San Emigdio Mountains has migrated and continues to migrate basinward. This evidence includes a relict mountain front, now within the uplifted block, 5 km from the present active mountain front, and the existence of recently initiated folds in the active alluvial fan 2 km basinward from the mountain front. Northward migration of tectonic activity results in the progressive widening of the uplifted block as the location of active folding moves basinward. This migration of tectonic activity appears to occur through the onset and subsequent increase of vertical deformation along more northerly folds and faults accompanied by reduction and eventual cessation of activity along the older, more southerly structures.

*E-mail: keller@magic.ucsb.edu.

GSA Bulletin; January 2000; v. 112; no. 1; p. 86–97; 13 figures; 2 tables.

INTRODUCTION

This study was undertaken to determine the Quaternary history associated with the folding and vertical deformation of the San Emigdio Mountains. The study area (Fig. 1) is located near the boundary between two geomorphic provinces: the Transverse Ranges to the south and the San Joaquin Valley to the north. The east-west–trending San Emigdio Mountains, part of the southern Coast Ranges, cut across the structural grain of California, similar to the adjacent east-west–trending Transverse Ranges. The rocks of the San Emigdio Mountains have been deformed and uplifted ~7 km to their present elevation of ~2130 m since late Cenozoic time (Davis, 1983). The San Emigdio Mountains and the Tehachapi Mountains form the southern terminus of the San Joaquin Valley. During Quaternary time, the San Joaquin Valley has been an actively subsiding depositional basin accumulating a relatively undeformed, continuous sequence of Quaternary strata.

There are three major, active, structural elements in the study area: (1) the right-lateral San Andreas fault, striking west-northwest in what is termed the Big Bend segment of its trace; (2) the White Wolf fault, across which an undetermined amount of left slip and at least 5 km of vertical separation have occurred (Stein and Thatcher, 1981; Davis, 1983); and (3) the Pleito fault system (the focus of this study), a series of east-west–trending, south-dipping, reverse fault segments that are a consequence of the north-south compressional stress field found throughout the Transverse Ranges (Rodgers and Chinnery, 1973; Working Group on California Earthquake Probabilities, 1995).

The objectives of the research presented in this paper are: (1) investigate the tectonic framework, geometry, and range of vertical deformation rates associated with folding on upper plates of buried reverse faults, and (2) reconstruction of the Quaternary depositional and tectonic history of the north flank of the San Emigdio Mountain front.

We assume for our evaluation that tectonic activity rather than climatic change has produced the observed vertical separation of Quaternary deposits and surfaces. This is a reasonable assumption for the following reasons. (1) The southern San Joaquin Valley has been a local, closed basin for most of the past few hundred thousand years (Davis and Green, 1962), and, as such, has not been influenced by global marine base-level changes. (2) Most of the increase in topographic relief, the subject of this paper, results from uplift, folding, and faulting. (3) A growing body of evidence suggests that whereas climatic change can produce aggradation events in southern California and other areas, to produce landforms such as alluvial fan segments and fill terraces, it is local to regional tectonically induced base-level change (uplift or subsidence) that provides the stream power necessary to increase and preserve these landforms as geomorphic surfaces (Bull, 1991; Keller et al., 1998).

Geologic Setting

Rocks exposed within the study area consist of igneous and metamorphic rocks that form the core of the San Emigdio Mountains (Davis, 1983). On the northern flank of the range, these rocks are overlain by thick Cenozoic strata (Fig. 1), which generally dip northward and become subhorizontal in the San Joaquin Valley. These deposits, both

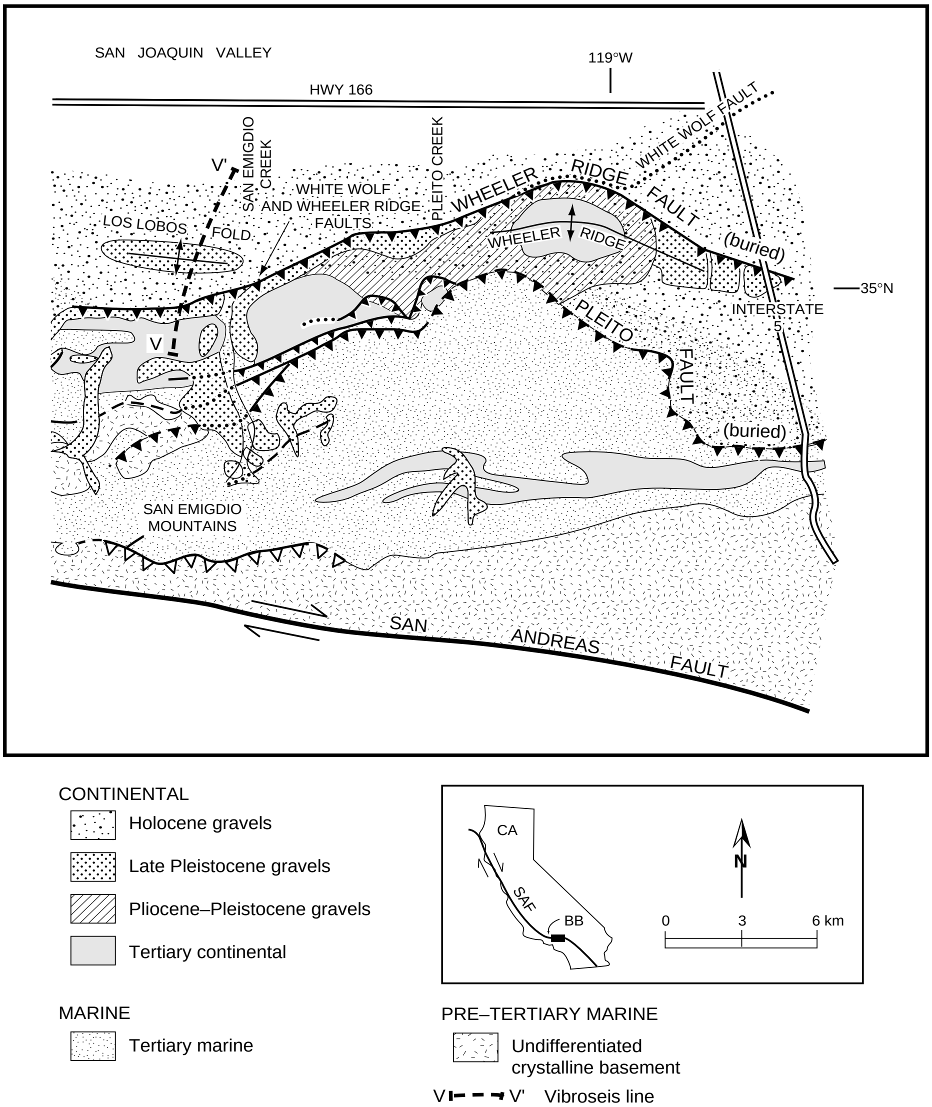

Figure 1. Index and generalized geologic map of the San Emigdio and Wheeler Ridge areas. Dashed line is location of Vibroseis line (see Fig. 3) (after Davis, 1983; Dibblee, 1973, 1974; Morton and Troxel, 1962).

surface and subsurface, have been well studied (Hoots, 1930; McGill, 1951; Foss and Blaisdell, 1968; Dibblee, 1973; Nilsen, 1973, 1987; Nilsen et al., 1973). For the most part, we use the nomenclature of Nilsen et al. (1973). Only the latest Tertiary and Quaternary deposits found at the mountain front are briefly described herein; they consist predominantly of sandstone and conglomerate beds containing clasts derived from the older rocks found within the adjacent mountain block.

The oldest of the late Tertiary range-front strata is the Pliocene San Joaquin Formation, which consists of 100–1100 m of brackish-water and lacustrine claystone, sandstone, and minor conglomerate. The overlying Pliocene-Pleistocene Tulare Formation consists of as much as 2000 m of poorly indurated conglomeratic sandstone, sandstone, and siltstone deposited as alluvial fans. The transition from lacustrine clay and fine sandstone of the San Joaquin Formation to the fluvial, coarse-grained conglomeratic sandstones of the Tulare Formation may mark the onset of uplift in the San Emigdio Mountains in late Pliocene time (Nilsen et al., 1973; Davis, 1983).

Upper Pleistocene to Holocene alluvial fan and river gravel unconformably overlie the Tulare Formation, generally truncating Tulare strata at angles of 15°–30°, but as high as 110°. These deposits are typically at least 100 m thick, and consist of thickly bedded, bouldery gravel. Clast types and sedimentary structure indicate that the San Emigdio Mountains, located to the south, were part of the source area. The oldest gravels consist of deformed terrace and/or fan deposits forming the walls of canyons near the present active range front (the modern topographic mountain front forming above the buried Wheeler Ridge fault at San Emigdio Canyon, Fig. 1), where late Pleistocene gravel is tilted as much as 50° to the north (Fig. 2).

Recent Deformation

Active faults in the area include the White Wolf fault, the Pleito and Wheeler Ridge faults of the Pleito fault system, and the newly identified Los Lobos fault. These faults form the northern boundary of the San Emigdio Mountain front. The dominant structural features of the north flank of the San Emigdio Mountains are east-west–trending folds and south-dipping, buried thrusts that are associated with the Pleito fault system, which extends the entire length of the range front from Wheeler Ridge to the Los Lobos folds (Fig. 1). Based on oil well data, the Pleito fault system consists of a series of concave-upward thrusts that have combined total dip slip of about 7 km (Davis, 1983). Cross sections by Davis (1983) suggest that these faults may connect at depth. A brief description of the Los Lobos fault-fold system follows; the other faults of the Pleito system have been studied and described (Harding, 1976; Davis, 1983; Hall, 1984; Davis and Lagoe, 1987; Namson and Davis, 1988; Medwedeff, 1988; Keller et al., 1998).

Los Lobos Folds and Fault

The Los Lobos folds, two anticlines about 2 km basinward from the buried Wheeler Ridge fault, deform Pleistocene and recent gravel. Well data (Davis, 1983) and Vibroseis records provided by Tenneco Oil Company were used to evaluate the subsurface structures. One seismic line, shot at 34 m station spacing, suggests that the monoclinal folding at the range front is caused by a fault-bend fold formed by ramping of the Wheeler Ridge fault (Fig. 3). The fault approaches the surface and cuts strata to a depth near 0.5 km, where it appears to bend into the bedding, thus placing Miocene Etchegoin Formation on top of Pliocene San Joaquin Formation. The Los Lobos folds are apparently underlain by the Los Lobos fault, which offsets some reflectors but terminates in an anticline at about 1.5 km (Seaver, 1986). This fault-fold relationship resembles a fault-propagation fold (Suppe and Namson, 1979; Boyer and Elliott, 1982; Davis, 1983; Seaver, 1986). The Wheeler Ridge and Los Lobos faults may converge at depth to form a subhorizontal decollement surface, as suggested by Davis (1983). The seismic record provides evidence for the existence of this surface at ~3 km below the surface (Seaver, 1986).

SAN EMIGDIO SOIL GEOMORPHOLOGY AND LATE PLEISTOCENE–HOLOCENE STRATIGRAPHY

Soil Chronosequence

The main objective of our soils work is to assist in the correlation of late Pleistocene and Holocene alluvial surfaces and to establish a relative chronology. On the basis of field mapping and soils analysis, four major late Pleistocene–Holocene units (Q1–Q4, youngest to oldest) were established, including stream terraces and alluvial fan segments. The distribution of Q2–Q4 surfaces and/or deposits is shown in Figure 4A, and the idealized topographic profile is shown in Figure 4B.

Soils of the San Emigdio chronosequence vary from A–C profiles on Holocene surfaces to well-developed argillic B and petrocalcic horizons on Pleistocene surfaces. With increasing age, soils thicken, colors redden, structure becomes more strongly developed, clay and $CaCO_3$ contents increase, clay-film development increases, and the stage of carbonate morphology increases (Table 1; Laduzinsky, 1989).

We described and sampled 20 soil profiles. Soils on each mappable geomorphic surface (with the exception of Q4b) were described at a minimum of three sites (see Fig. 4A for locations of sites). Generalized soil characteristics of the chronosequence are listed in Table 1. Parent material for the soils is mostly poorly consolidated, cobble-boulder gravel derived from the adjacent San Emigdio Mountains. The mineralogy of the clasts within the deposits varies slightly from canyon to canyon, but in general, parent materials can be considered uniform (Table 1; Laduzinsky, 1989).

Age Control

Numerical ages for Q2, Q3, and Q4 deposits (Table 2) are derived from radiocarbon and uranium-series analyses of buried charcoal and carbonate rinds, respectively.

Three radiocarbon dates on charcoal and wood samples from Q2 deposits (Fig. 4A) are shown in Table 2. These yield ages ranging from 0.5 to 1.0 ka.

In San Emigdio Canyon, charcoal buried in Q3 deposits 3–4 m below the surface were dated as 4.7–5.0 ka. Downstream from the active mountain front, a maximum age of 6.9–7.5 ka for Q3 is obtained from charcoal buried in a Q4 A soil horizon overlain by Q3 deposits (Table 2). Thus, our results indicate that the age of Q3 is 4.7–7.5 ka.

Samples of the innermost rinds of $CaCO_3$ formed around cobbles below stage IV laminar horizons were collected at three Q4b sites. Uranium-series dating, following Ku et al. (1979; Th^{230}-U^{234}), of pedogenic carbonate was done at the University of Southern California. The three samples yielded dates of 22 ± 3 ka; 33 ± 5 ka; and 59 ± 10 ka for the Q4 surface (Table 2). Possible climatic interpretation for the youngest date was discussed in Keller et al. (1998). Uranium-series dating provides minimum ages because the carbonate is not confined within a closed system. That is, clasts below the stage IV laminar zone may not have been completely isolated from downward-percolating waters, and the samples may have been contaminated by young carbonate. The oldest date (QF-4 Ranch House, Table 2) comes from a Q4b soil horizon that is buried by Q3 deposits at the Los Lobos folds. The buried Q4b A horizon lacks carbonate, indicating that the profile has been isolated from wetting fronts at least since mid-Holocene time. Because evidence indicates that this sample is least likely to be contaminated with younger carbonate, and assuming a 5 k.y. lag time necessary for carbonate rinds to

Figure 2. Tilted Q4 gravels unconformably overlying beds of the Tulare Formation along the San Emigdio Mountain front.

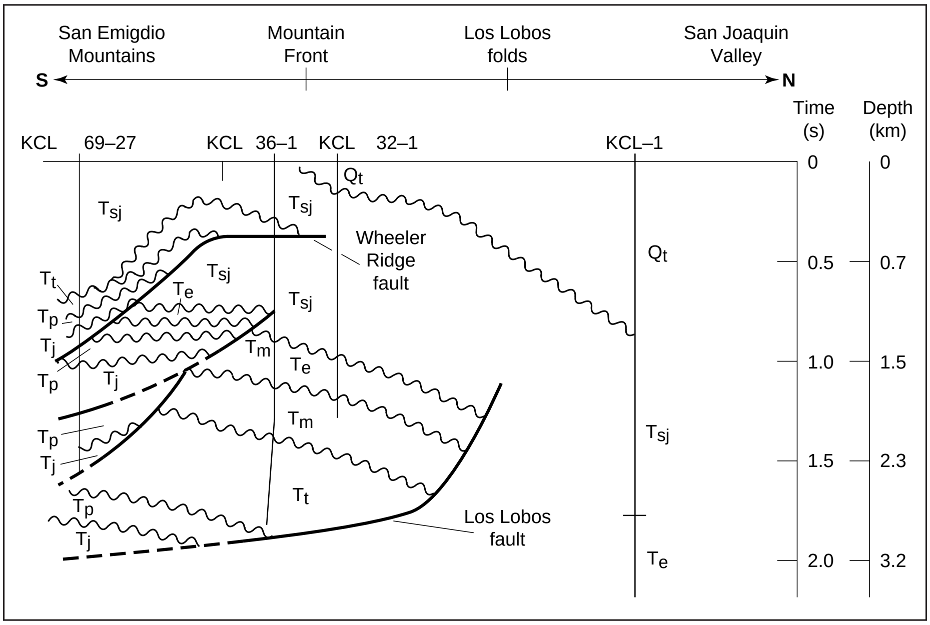

Figure 3. Interpretation of Vibroseis records donated by Tenneco Oil Company showing the buried Wheeler Ridge and Los Lobos faults. The location of line is shown in Figure 1. Qt— Pleistocene Tulare Formation; Tsj—Pliocene–Pleistocene San Joaquin Formation; Te—Miocene Etchegoin Formation; Tm—Miocene Monterey Formation; Tt—Oligocene–Miocene Temblor Formation; Tp—predominantly Oligocene Pleito Formation; Tj—Eocene Tejon Formation (after Seaver, 1986).

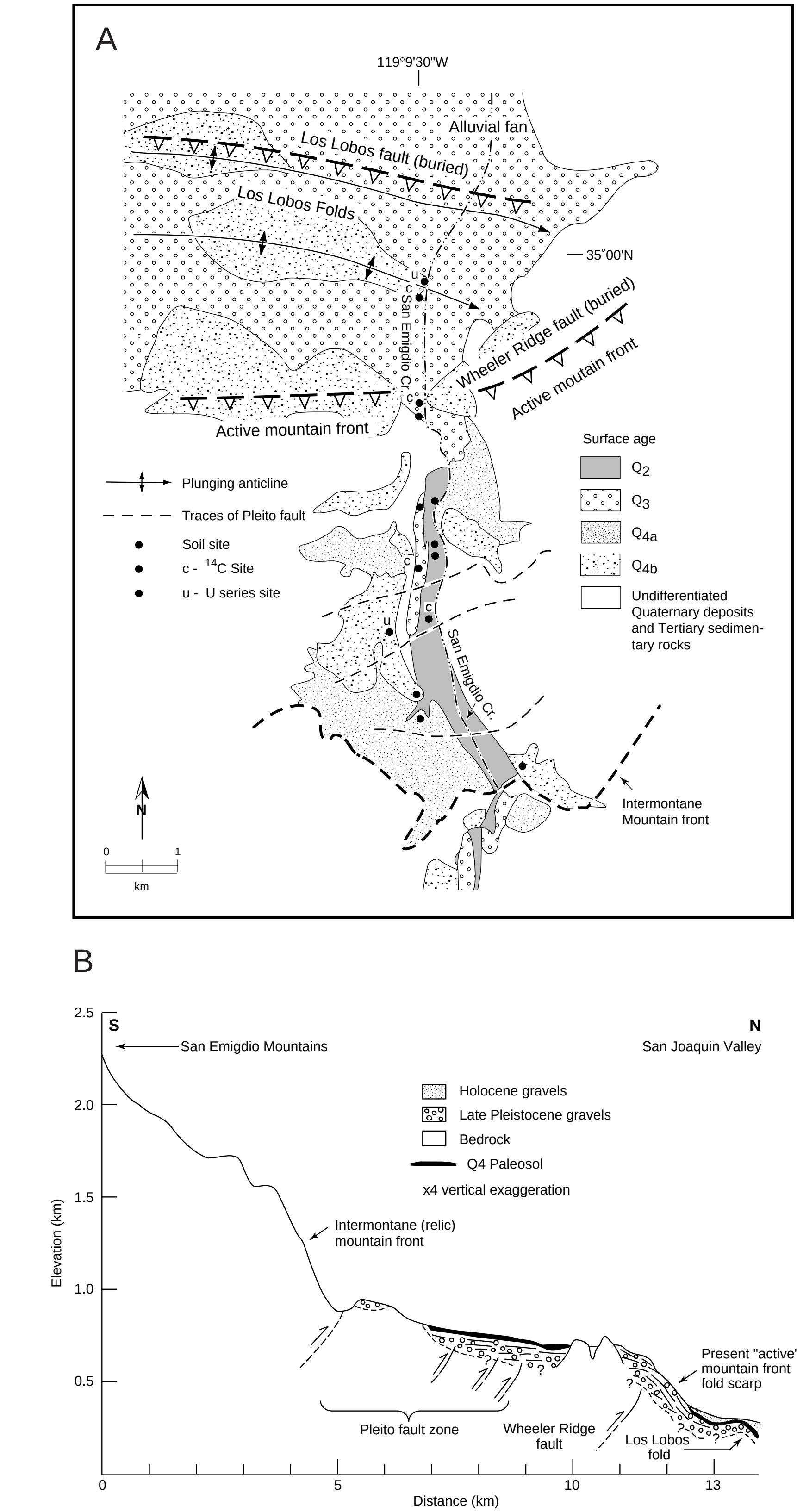

Figure 4. Generalized map of Holocene and late Pleistocene deposits (Q2–Q4) of the San Emigdio Canyon area, the buried trace of the Wheeler Ridge fault, and Los Lobos folds and sample sites (A); and idealized topographic profile constructed approximately along the crest of the west side of San Emigdio Canyon (B).

accumulate (Laduzinsky, 1989; Keller et al., 1998), we derive a minimum age of ca. 55–75 ka for the Q4b surface.

Geomorphic Surfaces

The Q1 surface is the modern flood plain of San Emigdio Creek. The surface is <1 m above the present stream channel and continues to be altered by erosion and deposition during moderate to large floods. Vegetation consists of sparse grasses and common 95–180-cm-diameter cottonwood trees, indicating that the surface has been relatively stable during recent historic time.

The Q2 surface forms an extensive terrace 2–3 m above the present stream channel in San Emigdio and adjacent canyons. The terrace has a longitudinal slope of about 2.5°, is covered by low grass, and is commonly littered with large boulders.

The Q3 surface is a stream terrace that forms a major part of the San Emigdio Canyon floor. The terrace is generally 6–7 m above the present stream channel, and deposits are composed of the same course-grained mixed alluvium that composes the Q1 and Q2 deposits.

A number of depositional surfaces similar in form, location, and pedogenic development to the Q3 surfaces are present throughout the area. They are mostly pond deposits formed when landslides from canyon walls produced temporary dams (McGill, 1951). The resulting deposits are fine-grained, thinly bedded, lacustrine sediments. Terraces are formed by rapid incision when the stream eventually cuts through the landslide dam.

Across the entire San Emigdio front, Q4 deposits are remnants of late Pleistocene alluvial fans. An extensive gently dipping surface in San Emigdio Canyon is ~100 m above the present stream channel. This surface becomes dramatically tilted toward the San Joaquin Valley, with dips to 50° north at the range front. Q4 soils are divided into two submembers, the Q4b member representing soils developed on the mixed coarse-grained alluvial fan gravel, and the somewhat less developed Q4a soils on younger erosion surfaces cut into the Q4b deposits.

GEOMORPHOLOGY OF THE SAN EMIGDIO ALLUVIAL FANS

Alluvial fans have been accumulating on the north flank of the San Emigdio Mountains since at least late Pleistocene time (Fig. 4). Because alluvial fans are the end points of an erosional-depositional system and as such are sensitive to changes within the system, geomorphologic studies of alluvial fans can be used to evaluate tectonic perturbations that occurred during and after fan deposition (Bull, 1977).

TABLE 1. GENERALIZED SOIL CHARACTERISTICS FOR THE SAN EMIGDIO CHRONOSEQUENCE AND Q4 AT WHEELER RIDGE

Geomorphic surface	Number of profiles described	Solum thickness (cm)	B Horizon Type	Moist color*	Texture	Structure	Clay films	Carbonate stage[†]	Estimated age (ka)
Q1 San Emigdio	3	50–68	A–C		With primary fluvial stratification		None	–	Modern flood plain
Q2 San Emigdio	4	100–101+	A–C		With primary fluvial stratification		None	I	0.5–1.0[§]
Q3 San Emigdio	5	130+	±Cambric	10 yr 3/3	Sandy loam	Massive	None	II	4.7–7.5[§]
Q4a San Emigdio	1	>200	Argillic	10 yr 5/6 7.5 yr	Sandy clay loam	Strong angular blocky-prismatic	Many, moderately thick	II–III	Not known
Q4b San Emigdio	5	>250	Argillic	7.5 yr 4/6	Sandy clay loam	Strong angular blocky-columnar	Many to continuous moderately thick to thick	Weak IV	55–75 (minimum)[#] 60–113**
Q4 Wheeler Ridge	5	>300	Agrillic	7.5 yr 4/6	Sandy loam	Massive breaking to fine subangular blocking	Continuous thick	III	105 or 125 Ka[††]

*Color terms follow Munsell notation.
[†]Carbonate stage terms follow Gile et al. (1966)
[§]Age based on ^{14}C dates collected in San Emigdio Canyon.
[#]Uranium series on soil carbonate.
**Based on rates of uplift.
[††]Based on uranium series, correlated with Q4a of San Emigdio (from Keller et al., 1998).

Several segments are present on the San Emigdio fan, the largest and best-formed fan (Fig. 5). Our observations suggest that the upper (folded) fan segments have a different fan head apex than the fan toe segment. Vertical deformation along the active mountain front has produced the younger fan head segments of Q2 and Q3 age, the apex of which is at the active front (Fig. 4). We infer that the segment found at the fan toe is a morphologic remnant of an older Q4 fan, the apex of which is 5 km south of the active mountain front at an intermontane mountain front (Fig. 4). Although most of the Q4 soil profiles of the fan toe deposits are thinly buried by very recent San Joaquin Valley fill or disturbed by farming, the Q4 fan toe morphology remains.

Reconstruction of the San Emigdio alluvial fan is based on the assumption that contour lines are concentric arcs having their centers of curvature at the apex of the fan. Thus, by fitting alluvial fan contours with circular arcs, one can reconstruct the radii and thus determine the location of the fan apex at the time of deposition of that portion of the fan (Seaver, 1986). Using this methodology, we found that fan toe contours project back to a different apex than mid-fan and fan head contours. We interpret this as evidence for two alluvial fans, each with a different apex (Fig. 6) and a different time of deposition (Seaver, 1986). Our fan apex reconstruction indicates that the apex of the older, larger fan (Q4) is located south (mountainward) of the active front at a distinct topographic break (Figs. 4 and 7). This topographic break is along the trace of the southernmost strand of the Pleito fault system, and most likely represents an older, intermontane (relic) front (Davis, 1983). If this is the case, then the older, Q4 fan apex is located at the former northern boundary of the San Emigdio Mountains. Additional evidence to support this hypothesis is the fact that the southern boundary of map unit Q4b coincides with the location of the topographic break and fault trace (Fig. 8).

To reconstruct the morphology of the Q4 fan, we assume that the fan toe segment of the San Emigdio fan consists of nearly undeformed Q4b gravels, which is reasonable because the toe segment is several kilometers north of any identified deformation. Using topographic measurements from the fan toe segment, we were able to reconstruct the depositional morphology of the Q4b fan using a series of equations developed by Troeh

TABLE 2. RADIOCARBON (^{14}C) AND URANIUM-SERIES (Th^{238}-U^{234}) AGE ESTIMATES, SAN EMIGDIO CANYON

Site number	Geomorphic surface	Sample number	Age (ka)	Calibrated age (ka)
SEQ-2	Q2	ISGS-1276	0.64 ± 0.07[†]	0.55–0.67[§]
SELB #1	Q2	ISGS-1249	0.73 ± 0.15[†]	0.55–0.79[§]
SE-MS 1	Q2	ISGS-1373	0.96 ± 0.08[†]	0.78–0.95[§]
SEQ-3	Q3	ISGS-1338	4.27 ± 0.11[†]	4.65–4.98[#]
QF-4* Ranch house	Buried A horizon of Q4b	ISGS-1259	6.36 ± 0.28[†]	6.9–7.5[#]**
QF-4 Lobos	Q4b	USC QF-4 Lobos	22 ± 3	
QF-4 HT-1 #1	Q4b	USC QF-4 HT-1 #1	33 ± 5	
QF-4 Ranch	Q4b	USC QF-4 Ranch	59 ± 10	

Notes: ISGS radiocarbon samples were analyzed in the laboratory of D. D. Coleman at the Illinois State Geological Survey. USC uranium-series samples were analyzed in the laboratory of T. L. Ku at the University of Southern California; the uncertainties quoted are one standard deviation derived from counting statistics.
*Provides a maximum age for Q3.
[†]To years before 1950.
[§]Stuiver and Pearson, 1986.
[#]Pearson et al., 1986.
**Linick et al., 1986.

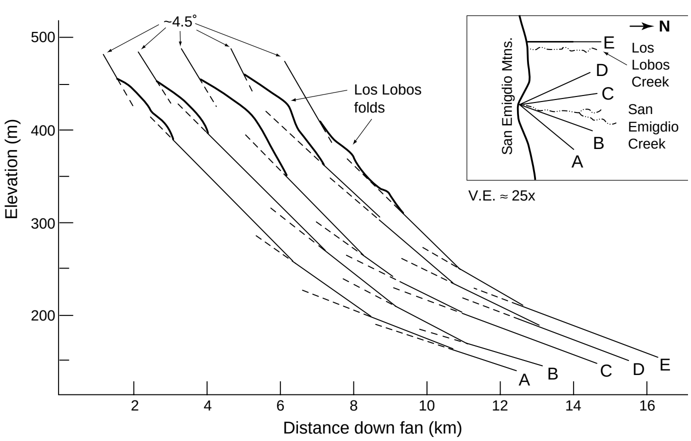

Figure 5. Radial profiles of the San Emigdio alluvial fan downstream from the present mountain front. Notice the deformation produced by the Los Lobos folds and the several segments of fans that are present.

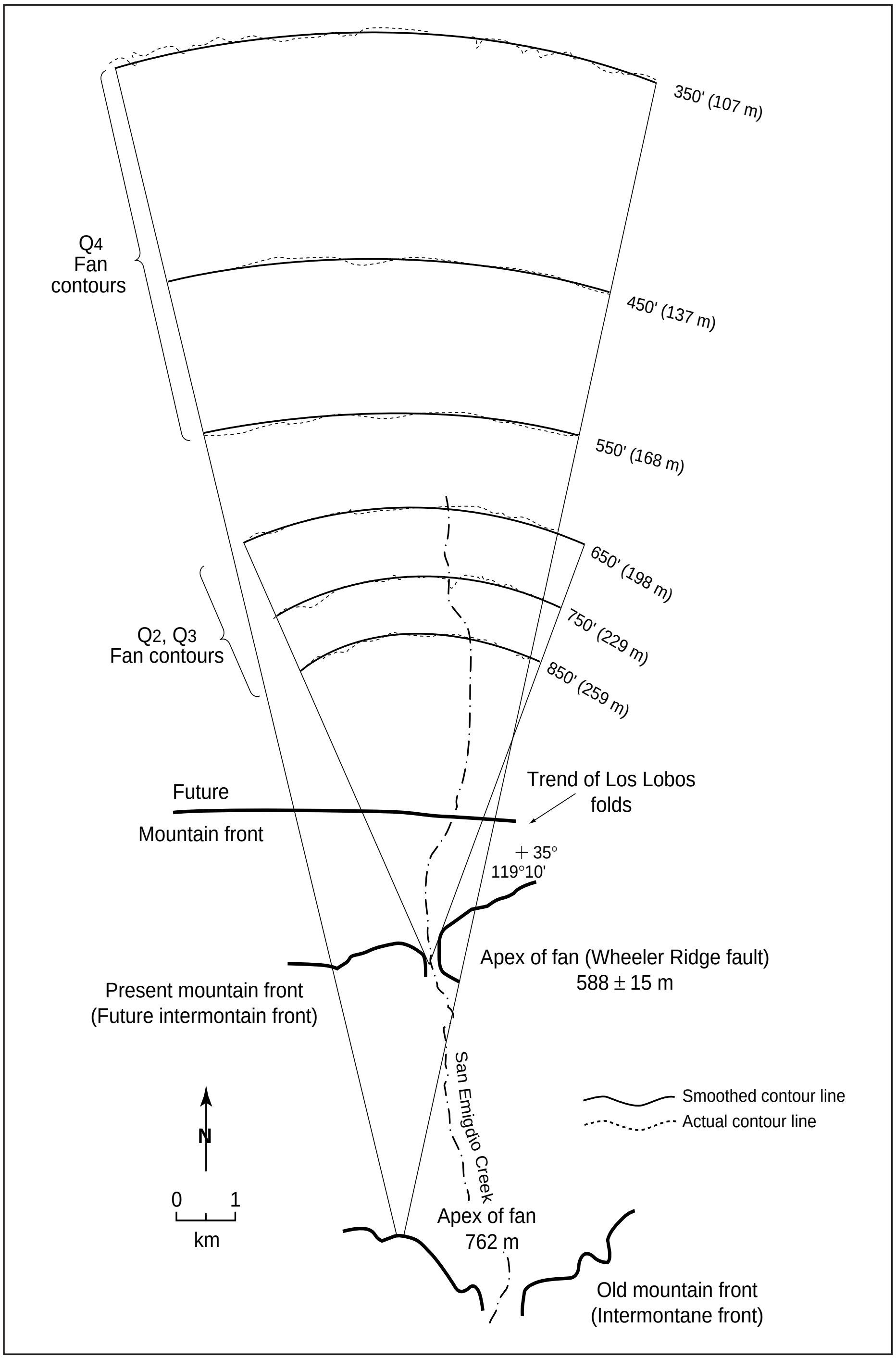

Figure 6. Selected and slightly smooth contours of the San Emigdio alluvial fan. Two different fans and associated radial profiles are present, one with an apex at the active mountain front, which is underlain by the buried Wheeler Ridge fault, and the other at an intermontane front several kilometers to the south.

(1965). These equations utilize three points of known elevation and of known radial distance from the fan apex to predict the elevation of any point on the fan. The equations are:

$$S = \frac{(Ea - Ec)(Rb^2 - Rc^2) - (Eb - Ec)(Ra^2 - Rc^2)}{(Ra - Rc)(Rb^2 - Rc^2) - (Rb - Rc)(Ra^2 - Rc^2)}$$

$$L = \frac{Ea - Ec - S(Ra - Rc)}{Ra^2 - Rc^2}$$

$$P = Ea - SRa - LRa^2$$

$$Ez = P + SRz + LRz^2,$$

where Ea, Eb, Ec = elevation of any three known points A, B, C on the fan; Ra, Rb, Rc = radial distance from apex to points A, B, C; L = 1/2 the rate of change of slope; P = elevation of fan apex; S = slope of fan at P; and Ez = elevation of any point Z at known radial distance Rz.

The reconstructed depositional morphology of the Q4 alluvial fan produced by Troeh's equations can then be applied as a landscape model to estimate vertical displacement since the time of Q4b. Using present-day data from the fan toe segment (contours at 107 m, 137 m, and 168 m) (Fig. 6), we determined that the reconstructed average elevation of the fan apex at the time of Q4b deposition is about 490 m. Because the present elevation of the apex is about 760 m (constrained by the topographic expression at the intermontane front), we infer a total vertical deformation of about 270 m for the San Emigdio Mountains since the deposition of the Q4b gravels.

Troeh's equations can be used to reconstruct an entire radial profile of an alluvial fan. We have done this for the Q4b alluvial fan using the same data points used to calculate the fan apex elevation. Figure 9 shows the reconstructed Q4 profile, as well as the present-day surface profile of Q4 and the present-day profile of San Emigdio Creek (Seaver, 1986). The figure also shows the approximate positions of the Wheeler Ridge and Los Lobos faults. Using the reconstructed profile, the amount of deformation that has occurred since Q4b gravels were deposited can be estimated. The total amount of vertical deformation of the Q4b fan above the Wheeler Ridge fault is ~270 m, and results from combined deformation on both the Wheeler Ridge and Los Lobos faults. Vertical deformation over the Los Lobos folds is ~90 m. Thus, 180 m of the vertical deformation is attributed to the Wheeler Ridge fault.

The projected location of the older fan apex is ~1.5 km west of the present stream canyon. One interpretation of this offset is that in addition to the dip-slip displacement, left-lateral displacement has occurred along the Pleito fault. The

1952 movement on the White Wolf fault produced left-lateral reverse slip (Stein and Thatcher, 1981), and this oblique displacement may have been occurring since Pleistocene time. Using the estimated minimum 75 ka age for the fan, the left-lateral component of slip would be a maximum of 20 m/k.y. Even were the Q4 fan to be twice as old, the resulting horizontal slip rate of 10 m/k.y. should produce a significant geomorphic signature and this is not present. Therefore, we believe that the left-lateral component must be much less and the position of the San Emigdio Canyon relative to the Q4b fan is primarily a left deflection of the fan head caused by erosion, rather than left-lateral fault offset.

HOLOCENE TECTONICS: SAN EMIGDIO CANYON AREA

Surveying of stream terrace surfaces in San Emigdio Canyon utilizing an engineering level indicates that Holocene deposits are deformed vertically at the active range front. The survey results show that the stream terraces from both upstream and downstream directions diverge toward the axis of uplift.

Three Holocene surfaces (terraces and fan segments, Q1, Q2, and Q3) are generally present. At the canyon mouth, however, four additional terraces are present. In contrast with terraces Q2 and Q3, which probably represent a climatically driven Holocene aggradation event (Bull, 1991), the other four terraces are more likely tectonic in origin (they are only present directly above the buried Wheeler Ridge fault), and their isolation and preservation are believed to be direct results of active vertical deformation (Laduzinsky, 1989).

The overall morphology of the folded Q2 and Q3 surfaces is such that the terrace gradients are reduced upstream from the axis and increased downstream from an assumed uniform undeformed longitudinal profile. This pattern is similar to the large-scale asymmetric folding evident at Wheeler Ridge to the east (Keller et al., 1998). Results of the survey of the 4.7–7.5 ka Q3 surface are shown in Figure 10. In the downstream direction, the terrace gradient is reduced from 2.9° to 2.4° where it crosses the Pleito fault. This reduced slope is maintained as the surface approaches the canyon mouth until the exposure is covered by younger colluvium from side canyons. The Q3 surface is also present at the canyon mouth, where it is identified on the basis of soil-profile development, but it has an increased slope of 4.2°. As the surface extends onto the San Joaquin Valley floor, the gradient again decreases, probably in response to folding at the Los Lobos folds. Projecting the terrace surface across the axis of folding delineates the deformed surface. The assumed original

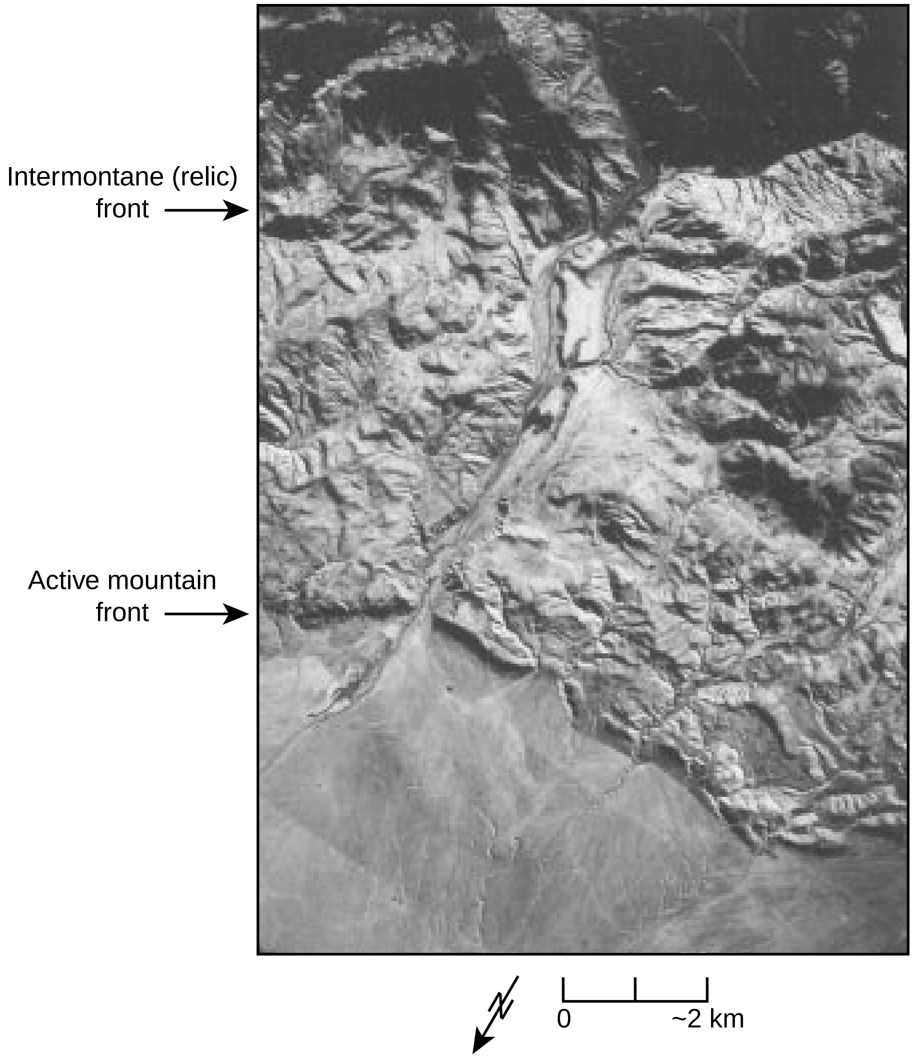

Figure 7. High-altitude aerial view of San Emigdio Canyon showing the intermontane and active mountain fronts. Courtesy of National Aeronautics and Space Administration.

Figure 8. Apex area of Q4 deposits associated with the intermontane mountain front in the San Emigdio Mountains. The mesa-like landform is the Pleistocene alluvial fan.

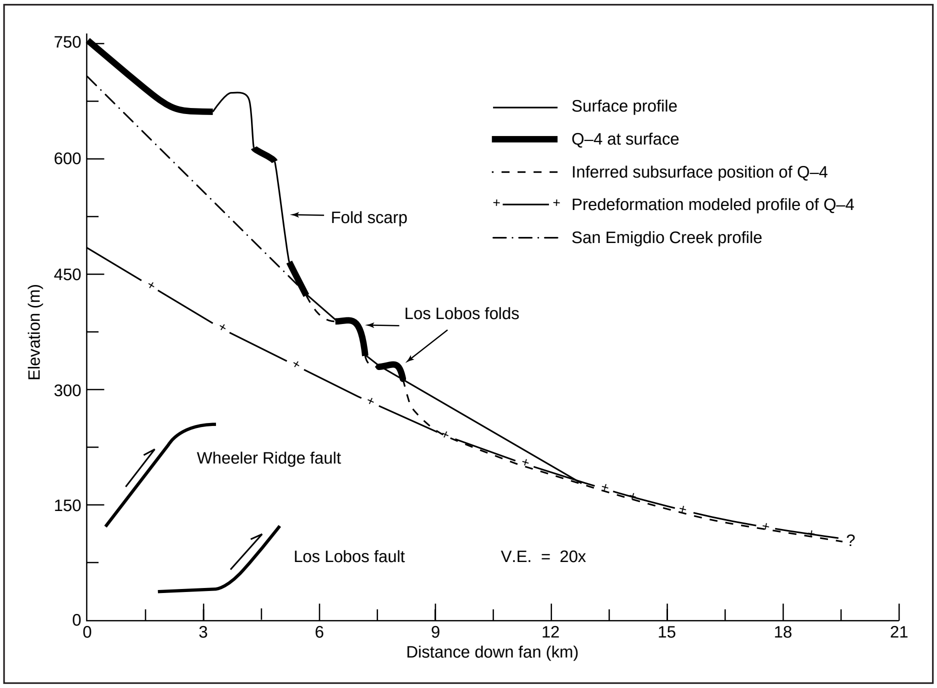

Figure 9. Reconstruction of the San Emigdio Canyon Q4b alluvial fan using Troeh's (1965) equations. Also shown is the topographic profile of the Q4b surface along the western crest of the canyon, and the profile of San Emigdio Creek. The buried Wheeler Ridge and Los Lobos faults are shown for illustrative purposes.

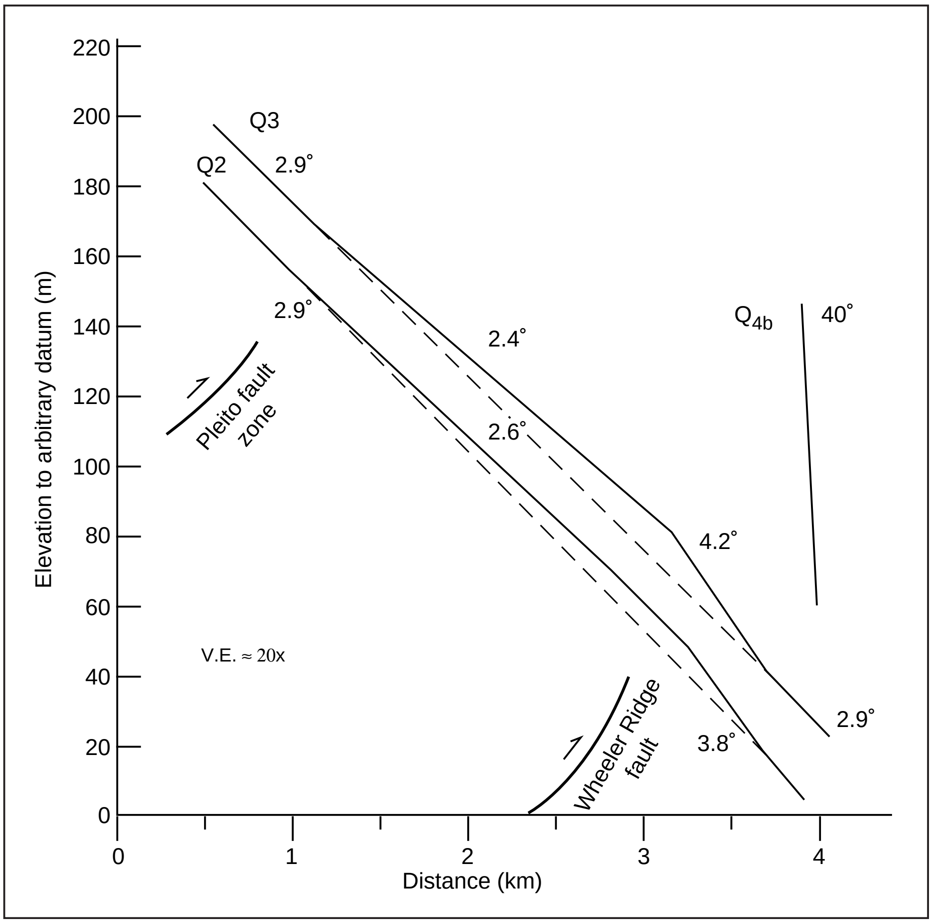

Figure 10. Profiles of Q2 and Q3 over the axis of uplift produced by the buried Wheeler Ridge fault, shown here for diagrammatic purposes. Vertical component of deformation for Q3 is ~14 m.

undeformed terrace position is defined by connecting the upstream and downstream inflection points, i.e., points where the surface gradient is reduced. Vertical deformation of 14 m as a result of folding is measured at the point of maximum difference in height between the deformed and undeformed surface for the 4.7–7.5 ka Q3 deposit (Fig. 10). Data from Q3 surfaces give a mid-Holocene to present rate of vertical deformation of 1.9–3.0 m/k.y. at the active range front. Using Q2 to estimate the rate of uplift is uncertain because portions of this surface are only a few hundred years old (see Table 2). However, as shown in Figure 10, Q2 is clearly less deformed than Q3.

At the Los Lobos folds, the Q4b surface emerges from beneath the Holocene deposits and is folded into two broad anticlines on the San Joaquin Valley floor. The Q4b soil, exposed along San Emigdio Creek, is buried by Q2 and Q3 deposits, which are in turn deformed as they cross the folds. Survey results from the Q3 surface, 6 m of vertical deformation (Fig. 11) in 4.7–7.5 k.y., gives a rate of vertical deformation of about 0.8–1.3 m/k.y. at the Los Lobos folds (Fig. 11). To determine the total rate of deformation we add the two rates, because when the Los Lobos fault ruptures, both the Los Lobos anticline and active mountain front underlain by the Wheeler Ridge fault are deformed. When the Wheeler Ridge fault ruptures the active front is deformed. Thus the total rate of vertical deformation of the north-central San Emigdio Mountains would be the combined rate of the active front and the Los Lobos folds, or 2.7–4.3 m/k.y..

Holocene deposits are not significantly deformed by the principal strands of the Pleito fault in San Emigdio Canyon. Where the Holocene surfaces cross the active mountain front, at the northernmost strand of the Pleito fault, an inflection point is present. In other words, the reduction in terrace slope due to folding at the frontal faults coincides with the position of the Pleito fault. Thus, it appears that the Pleito fault acts as a zone of weakness along which differential tilting produced by folding at the front occurs. Bull (1978) observed a similar inflection feature on older marginally active faults along the San Gabriel Mountain front.

DISCUSSION

Pleistocene Evolution of the San Emigdio Range Front

The approach we take in reconstructing the range front evolution is to apply the mid-Holocene uplift rate to the vertical component of slip on the Wheeler Ridge and Pleito faults measured from the subsurface data of Davis (1983). Assuming that Davis's estimates of deformation

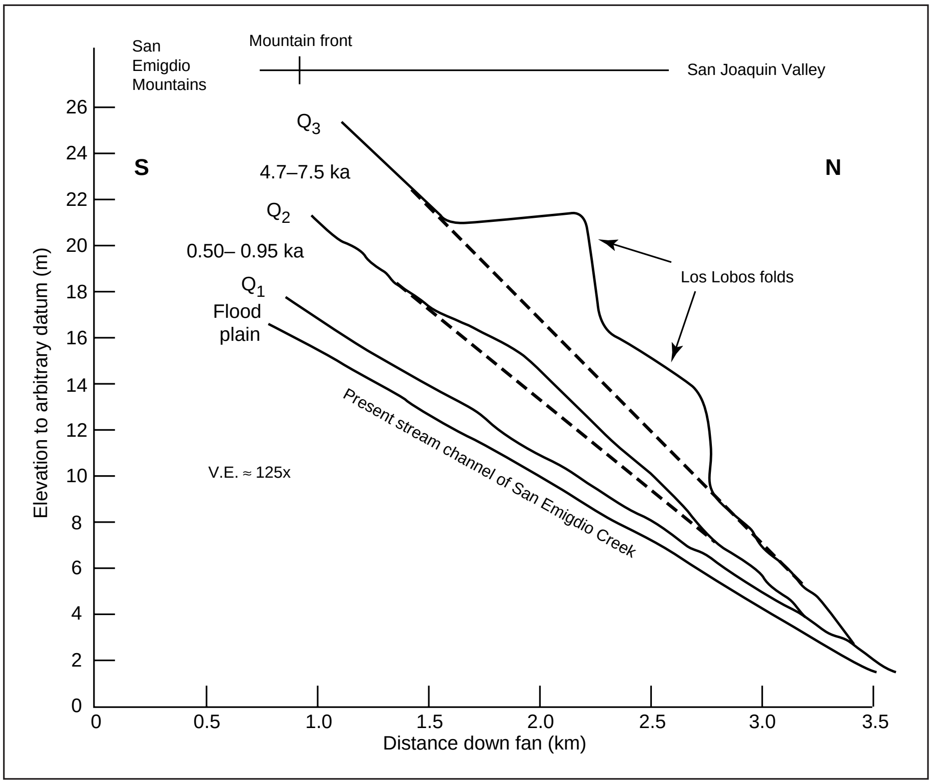

Figure 11. Profiles of Q2 and Q3 where they cross the Los Lobos folds. Vertical component of uplift for Q3 is ~6 m.

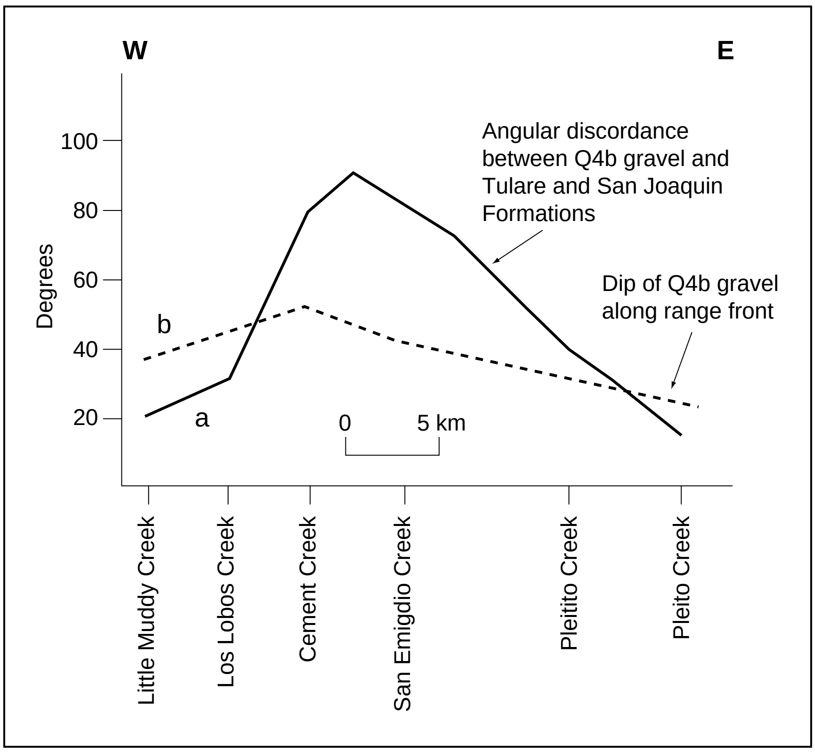

Figure 12. Discordance between Q4b deposits and the underlying San Joaquin–Tulare Formations (a) along the present range front; and present dip of Q4b gravels along the range front (b).

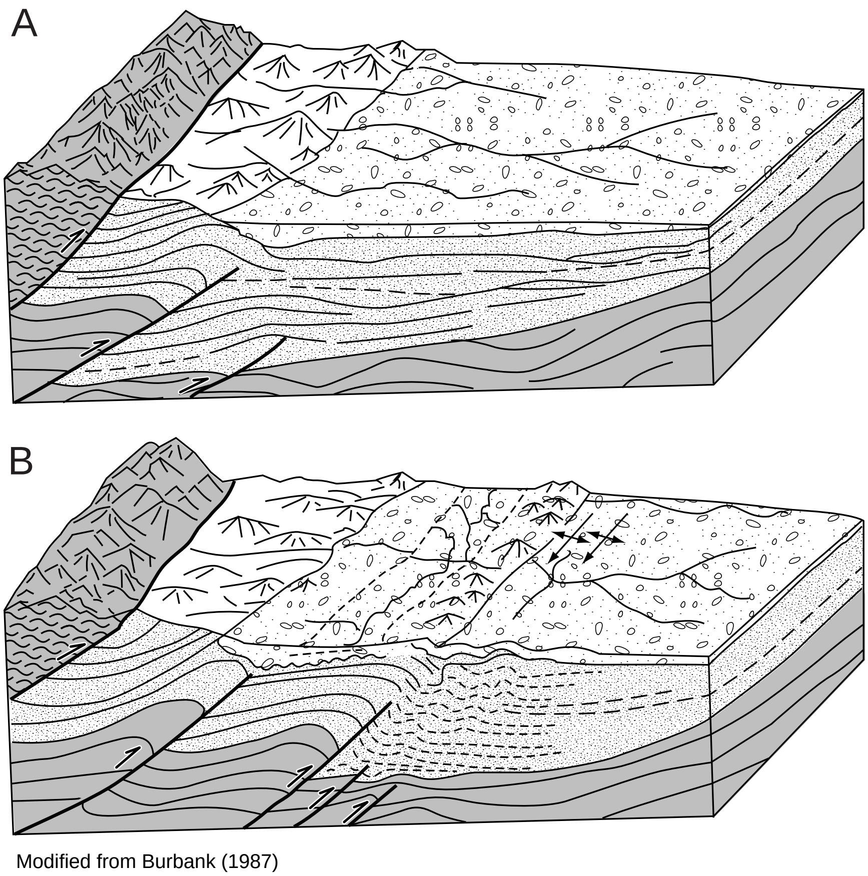

Figure 13. Idealized diagram showing how the mountain fronts at San Emigdio Canyon might have formed. (A) Time 1, illustrating several buried faults and deformation of sedimentary units. (B) Time 2, perhaps 100 k.y. later. Additional buried faults have formed and alluvial fans formed in A have incorporated into the widening fold belt that produces intermontane and currently active mountain fronts. (Modified with permission from D. Burbank, 1987, written commun.)

are accurate and assuming a constant Quaternary uplift rate, the timing of the uplift at the present range front and the mid-Pleistocene range front may be estimated.

Active Range Front

At the active range front, the buried Wheeler Ridge fault has a stratigraphic displacement of about 2.74 km (Davis, 1983) and an average dip of about 30° (Davis, 1983; Medwedeff, 1988). The vertical component of uplift is 2.74 km × sin 30° = 1.37 km. If the vertical rate of deformation is 1.9–3.0 m/k.y., ~450–700 k.y. are needed to accommodate the slip, and this time becomes the estimated age of the onset of faulting and folding at the active range front.

The 450–700 ka estimate for the age of initiation of uplift at the active front is consistent with the available geologic evidence. Between Pleito Creek and San Emigdio Creek, the Tulare Formation is clearly concordant with the underlying San Joaquin Formation, indicating that deformation did not begin until after, or at least during, the late stages of Tulare deposition, estimated to have been about mid-Pleistocene time (Croft, 1972; Davis, 1983). The present dip of the Q4b gravel varies from 20° to 50° across the range front, and the discordance between them and the underlying deposits varies from 20° to 90° (Fig. 12). The maximum dip of the Q4b gravel coincides with the maximum discordance between the deposits; discordance reaches a maximum of about 90° 1.5 km west of San Emigdio Creek (Fig. 12). This area also marks the maximum expression of the Los Lobos folds 2 km to the north, suggesting that the folding is concentrated more strongly in this central part of the range front. Restoration of the Q4b deposits to horizontal shows that at the time of Q4b deposition, the Tulare beds at this part of the range front were vertical. Thus, folding at the active range front was initiated prior to Q4b deposition. The geologic evidence requires that the vertical deformation at the active front began before 65 ka and close to or after 500 ka, which is consistent with the estimated age of 450–700 ka determined by assuming a constant rate of vertical deformation through time. Not all of the vertical component of slip on the fault is expressed as topographic relief at the range front because a great deal of the initial slip was likely lost to folding, and topographic relief is moderated by erosion and adjacent valley filling.

The variable discordance shown in Figure 12 also indicates that initial deformation was not uniform across the entire length of the range front. Pre-Q4b deformation is most intense near San Emigdio Creek, suggesting that this area may once have been an isolated highland rising from the San Joaquin Valley floor, much as Wheeler Ridge does today. This central part of the range front also marks the location of the maximum expression of the Los Lobos folds, suggesting that the basic geometry of the range front deformation has remained similar since mid-Pleistocene time.

The topographic expression of active fold-and-thrust belts is mostly produced by the ongoing thrust faulting and folding. The locus of tectonic activity commonly migrates toward adjacent sedimentary basins as the mountain range forms. That is, the locus of tectonic activity migrates away from the highlands of the range toward the adjacent flanks of ranges, and as this occurs, the fold-and-thrust belt widens with time. Interior faults of the system may become relatively inactive as the active tectonic processes are transferred to frontal fault systems (Ikeda, 1983; Yeats, 1986). This pattern of deformation has been observed in fold-and-thrust belts in various localities in the world, including Taiwan (Davis et al., 1983), Japan (Ikeda, 1983), India and Pakistan (Yeats, 1986), and in the Transverse Ranges of California (Bullard and Lettis, 1993; Davis, 1983; Keller et al., 1987; Namson and Davis, 1988). The pattern of thrust fault migration is consistent with a mechanical fold model (Davis et al., 1983), based on earlier observations by Chapple (1978) of fold-and-thrust belts that emphasize (1) the existence of a basal decollement or detachment fault that slopes toward the interior of a mountain belt below which relatively little deformation occurs; and (2) the existence of a topographic tapering wedge and tectonic shortening. The model by Davis et al. (1983) predicts that folds will migrate toward the edge of a fold-and-thrust belt.

The basic model described here appears sufficient to explain the topographic development of the fold-and-thrust belt on the northern flank of the San Emigdio Range. Figure 13 is an idealized diagram showing the widening of the fold-and-thrust belt as folding and faulting migrate toward the adjacent basin, consuming mountain-front alluvial fan deposits as a new front is developed. As illustrated in Figure 13A, a mountain front develops and alluvial fan deposits are shed into the basin. With time (Fig. 13B) new buried reverse faults form basinward and new folds and a new mountain front develop. Older alluvial fans are folded, faulted, and incorporated within the mountain range. An older, now-intermontane front is abandoned in the interior of the range, and new fans are developed basinward. The small folds closest to the basin represent the recently initiated Los Lobos folds, whereas the dominant active feature continues to be the buried Wheeler Ridge fault at the present active mountain front.

Age Estimate for Q4

Because the mid-Holocene to present rate of vertical deformation is known, this information can be used with a landscape model of the Q4b alluvial fan (Fig. 9) to better constrain and estimate the age of the Q4b gravel. The vertical component of deformation at the active mountain front resulting from both the Wheeler Ridge and Los Lobos buried faults is estimated to be 2.7–4.3 m/k.y. Thus, 63–100 k.y. would be needed to account for the estimated 270 m of uplift. Similarly, for the Los Lobos folds, the vertical component of deformation of 0.8–1.3 m/k.y. along with about 90 m of vertical deformation is used to estimate an age of 69–113 ka for the Q4b gravel. Vertical deformation of Q4b due to the Wheeler Ridge fault is about 180 m, and applying the mid-Holocene vertical deformation rate of 1.9–3.0 m/k.y. suggests that the age of Q4b is 60–95 ka. In summary, age estimates for Q4b based on rate of vertical deformation at the buried Wheeler Ridge or Los Lobos faults, as well as their combined rates of deformation, provide internally consistent results. Uranium-series analyses yield a minimum age of ca. 55–75 ka for Q4b (Table 2, with the addition of 5 k.y. for the initiation of carbonate rinds), and our estimate of maximum age based upon the rate of vertical deformation is about 113 ka. Q4b soils developed upon the most prominent geomorphic surface at San Emigdio roughly correlate with Q4 soils at Wheeler Ridge 18 km to the east (Fig. 1) (Keller et al., 1998). At Wheeler Ridge the Q4 geomorphic surface forms the most prominent late Pleistocene (oxygen isotope stage 5) alluvial fan segment. In both areas the soils have well-developed argillic B horizons with similar color, structure, clay films, and carbonate stage (Table 1; Keller et al., 1998). Thus, the available evidence supports correlation of Q4 to oxygen isotope stage 5 (82–125 ka) (Chappell and Shackleton, 1986).

CONCLUSIONS

The mid-Holocene to present rate of uplift, based on surface folding, is ~1.9–3.0 m/k.y. at the active range front above the buried Wheeler Ridge reverse fault; another 0.8–1.3 m/k.y. is a result of folding of the Los Lobos folds above the buried Los Lobos fault. Total uplift, based on surface folding, is therefore 2.7–4.3 m/k.y.

We infer that the faulting below the San Emigdio front is shallow. As a result, the vertical displacement is transferred to surface uplift, even though there is no evidence for ground rupture.

Reconstructing the active range front and adjacent alluvial fan, and applying the mid- Holocene uplift rate, suggests that ~450–700 k.y. are needed to accommodate the slip, and therefore this is a minimum time for the onset of folding and faulting at the active range front.

Reconstruction of a late Pleistocene alluvial fan, along with geomorphic, geologic, and tectonic data, suggests that the topographic position at the range front has migrated northward ~5 km during late Pleistocene time. Furthermore, the topographic front appears to be moving another 2 km north to the location of Los Lobos folds, above the buried Los Lobos fault.

ACKNOWLEDGMENTS

This work was financially supported by U.S. Geological Survey Earthquake Hazard Reduction Program grants 14-08-0001-G1165 and 14-08-0001-G1496. This is University of California Institute for Crustal Studies Contribution 0304-89TC.

Work on this project could not have been completed without permission to work on private lands in the study areas. We greatly appreciate such permission from the San Emigdio Ranch. We are also indebted to Thom Davis, whose creative work in the San Emigdio Mountains on folds with buried faults inspired our project to evaluate the tectonic geomorphic development of the fold-and-thrust belt on the northern flank of the San Emigdio Mountains. We gratefully acknowledge the useful review comments and constructive criticism by Don Easterbrook, Harvey Kelsey, and Tor Nilsen.

The views and conclusions contained in this paper are ours and should not be interpreted as necessarily representing the official policies, either express or implied, of the U.S. Government or others doing previous work in the area.

REFERENCES CITED

Boyer, S. E., and Elliott, D., 1982, Thrust systems: American Association of Petroleum Geologists Bulletin, v. 66, p. 1196–1230.

Bull, W. B., 1977, The alluvial fan environment: Progress in Physical Geography, v. 1, p. 222–270.

Bull, W. B., 1978, Final technical report south front of the San Gabriel Mountains, California: U.S. Geological Survey Contract 14-08-0001-G-394, 100 p.

Bull, W. B., 1991, Geomorphic response to climate change: New York, Oxford University Press, 326 p.

Bullard, T. F., and Lettis, W. R., 1993, Quaternary fold deformation associated with blind thrust faulting, Los Angeles Basin, California: Journal of Geophysical Research, v. 98, p. 8349–8369.

Chapple, W. M., 1978, Mechanics of thin-skinned fold-and-thrust belts: Geological Society of America Bulletin, v. 89, p. 1189–1198.

Chappell, J., and Shackleton, N. J., 1986, Oxygen isotopes and sea level: Nature, v. 324, p. 137–140.

Croft, M. G., 1972, Subsurface geology of the late Tertiary and Quaternary water bearing deposits of the southern part of the San Joaquin Valley, California: U.S. Geological Survey Water-Supply Paper 1999-H, p. H1–H29.

Davis, D., Suppe, J., and Dahlen, F. A., 1983, Mechanics of fold-and-thrust belts and accretionary wedges: Journal of Geophysical Research, v. 88, p. 1153–1172.

Davis, G. H., and Green, J. H., 1962, Structural control of interior drainage, southern San Joaquin Valley, California: U.S. Geological Survey Professional Paper 450-D, p. D89–D91.

Davis, T. L., 1983, Late Cenozoic structure and tectonic history of the western "Big Bend" of the San Andreas fault and adjacent of San Emigdio Mountains [Ph.D. dissert.]: Santa Barbara, University of California, 508 p.

Davis, T. L., and Lagoe, M. B., 1987, The 1952 Arvin-Tehachapi earthquake (M = 7.7) and its relationship to the White Wolf fault and the Pleito thrust system: Geological Society of America Abstracts with Programs, v. 19, no. 6, p. 370.

Dibblee, T. W., Jr., 1973, Geologic maps of Coal Oil Canyon, Eagle Rest Peak, Grapevine, Mettler, Pleito Hills, and Santiago quadrangles: U.S. Geological Survey Open-File map, scale: 1:24 000.

Dibblee, T. W., Jr., 1974, Geologic map of the San Emigdio quadrangle, California: U.S. Geological Survey Open-File Map, scale 1:24 000.

Foss, C. D., and Blaisdell, R., 1968, Stratigraphy of the west side, southern San Joaquin Valley, *in* S.E.P.M. Guidebook, Pacific Section, 43rd Annual Meeting, Bakersfield, California: Society of Economic Paleontologists and Mineralogists, p. 33–43.

Gile, L. H., Peterson, F. F., and Grossman, R. B., 1966, Morphological and genetic sequences of carbonate accumulation in desert soils: Soil Science, v. 10, p. 347–360.

Hall, N. T., 1984, Late Quaternary history of the eastern Pleito thrust fault, northern Transverse Ranges, California [Ph.D. dissert.]: Stanford, California, Stanford University, 314 p.

Harding, T. P., 1976, Tectonic significance and hydrocarbon trapping consequences of sequential folding synchronous with San Andreas faulting, San Joaquin Valley, California: American Association of. Petroleum Geologists Bulletin, v. 60, p. 356–378.

Hoots, H. W., 1930, Geology and oil resources along the southern border of the San Joaquin Valley, California: U.S. Geological Survey Bulletin, v. 812, p. 243–332.

Ikeda, Y., 1983, Thrust-front migration and its mechanism; evolution of intraplate thrust fault system: Tokyo University Department of Geography Bulletin, v. 15, p. 125–159.

Keller, E. A., Zepeda, R. L., Seaver, D. B., Rockwell, T. K., Laduzinsky, D. M., and Johnson, D. L., 1987, Active fold-thrust belts and the Western Transverse Ranges: Geological Society of America Abstracts with Programs, v. 19, no. 6, p. 394.

Keller, E. A., Zepeda, R. L., Rockwell, T. K., Ku, T. L., and Dinklage, W. S., 1998, Active tectonics at Wheeler Ridge, southern San Joaquin Valley, California: Geological Society of America Bulletin, v. 110, p. 298–310.

Ku, T. L., Bull, W. B., Freeman, S. T., and Knauss, K. G., 1979, ^{230}Th-^{243}U dating of pedogenic carbonates in gravelly desert soils of Vidal Valley, southeastern California: Geological Society of America Bulletin, v. 90, p. 1063–1073.

Laduzinsky, D. L., 1989, Late Pleistocene–Holocene chronology and tectonics, San Emigdio Mountains, California [Master's thesis]: Santa Barbara, University of California, 95 p.

Linick, T. W., Long, A., Damon, P. E., and Ferguson, C. W., 1986, High precision radiocarbon dating of bristlecone pine from 6554 to 5350 B.C.: Radiocarbon, v. 28, p. 943–953.

McGill, J. T., 1951, Quaternary geology of the north-central San Emigdio Mountains, California [Ph.D. dissert.]: Los Angeles, University of California, 102 p.

Medwedeff, D. A., 1988, Structural analysis and tectonic significance of late Tertiary and Quaternary compressive-growth folding, San Joaquin Valley, California [Ph.D. dissert.]: Princeton, New Jersey, Princeton University, 184 p.

Morton, K., and Troxel, B. W., 1962, Mines and mineral re-

sources of Kern County, California: California Division of Mines and Geology County Report 1, 370 p.
Namson, J. S., and Davis, T. L., 1988, Seismically active fold and thrust belt in the San Joaquin Valley, central California: Geological Society of America Bulletin, v. 100, p. 257–273.
Nilsen, T. H., 1973, Facies relations in the Eocene Tejon Formation of the San Emigdio Mountains, California, *in* Vedder, J. G., ed., Sedimentary facies changes in Tertiary Rocks—California Transverse and Southern Coast Ranges: Anaheim, California, Annual Meeting AAPG-SEPM-SEG, Field Trip Guidebook 2, p. 7–23.
Nilsen, T. H., 1987, Stratigraphy and sedimentology of the Eocene Tejon Formation, Western Tehachapi and San Emigdio Mountains, California: U.S. Geological Survey Professional Paper 1268, 110 p.
Nilsen, T. H., Dibblee, T. W., Jr., and Addicott, W. O., 1973, Lower and middle Tertiary stratigraphic units of San Emigdio and western Tehachapi Mountains, California: U.S. Geological Survey Bulletin, v. 1372-H, 23 p.
Pearson, G. W., Plicher, J. R., Baillie, M. G. L., Corbett, D. M., and Qua, F., 1986, High-precision ^{14}C measurement of Irish Oaks to show the natural ^{14}C variations from A.D. 1840 to 5210 B.C.: Radiocarbon, v. 28, p. 911–934.
Rodgers, D. A., and Chinnery, M. A., 1973, Stress accumulation in the Transverse Ranges, southern California, *in* Proceedings of the conference on tectonic problems of the San Andreas fault system: Stanford University Publications, Geological Sciences, v. 13, p. 70–79.
Seaver D. B., 1986, Quaternary evolution and deformation of the San Emigdio Mountains and their alluvial fans, Transverse Ranges, California [Master's thesis]: Santa Barbara, University of California, 116 p.
Stein, R. S., and Thatcher, W., 1981, Seismic and aseismic deformation associated with the 1952 Kern County, California, earthquake and relationship to the Quaternary history of the White Wolf fault: Journal of Geophysical Research, v. 86, p. 4913–4928.
Stuiver, M., and Pearson, G. W., 1986, High-precision calibration of the radiocarbon time scale, A.D. 1950–500 B.C.: Radiocarbon, v. 28, p. 805–838.
Suppe, J., and Nansom, J., 1979, Fault-bend origin of frontal folds of the western Taiwan fold-and-thrust belt: Petroleum Geology Taiwan, no. 16, p. 1–18.
Troeh, F. R., 1965, Landform equations fitted to contour maps: American Journal of Science, v. 263, p. 616–627.
Working Group on California Earthquake Probabilities, 1995, Seismic hazards in southern California: Probable earthquakes, 1994–2024: Seismological Society of America Bulletin, v. 85, p. 379–439.
Yeats, R. S., 1986, Active faults related to folding, *in* Active tectonics: Washington, D.C., National Academy Press, p. 63–79.

MANUSCRIPT RECEIVED BY THE SOCIETY AUGUST 12, 1997
REVISED MANUSCRIPT RECEIVED JANUARY 29, 1999
MANUSCRIPT ACCEPTED MARCH 22, 1999

Printed in U.S.A.