Tectonics of the San Gabriel Basin and surroundings, southern California

Robert S. Yeats[†]
Department of Geosciences, Oregon State University, Corvallis, Oregon 97331, USA

ABSTRACT

The San Gabriel Basin is a Pliocene–Pleistocene Transverse Ranges structure bounded by the San Gabriel Mountains on the north, the San Jose and Puente Hills on the east, and the Repetto and Montebello Hills on the west. A basement boundary between gneissoid rocks of San Gabriel Mountains aspect and Peninsular Ranges rocks strikes east across the basin and connects with the San Jose fault. This boundary may represent the eastward continuation of the Canton fault, a middle Miocene precursor of the San Gabriel fault system with up to 30 km of right slip. Canton fault displacement is largely canceled by ~22.5 km of left slip on a precursor to the Raymond fault such that an Oligocene dacite in the San Jose Hills and clasts derived from it show little evidence of large horizontal displacement between the San Gabriel Mountains and Puente Hills. Clockwise rotation in the middle Miocene probably influenced the distribution of lateral slip. The fill in the northeast-trending Pliocene–Pleistocene San Gabriel Basin is a basal shallow-marine sequence overlain by the nonmarine Duarte Conglomerate, in contrast to the deep-water Fernando Formation of the Los Angeles Basin. The paleoslope trends south in the direction of the Repetto and Puente Hills, evidence that uplift of these hills postdated deposition. The triangular San Gabriel Basin is currently a stable block bounded by the right-slip, northwest-striking East Montebello fault on the west and the left-slip(?), northeast-striking Walnut Creek fault on the east. Farther east, the San Jose and Puente Hills are underlain by an east-trending active fold belt, including the San Jose reverse fault and anticline, the Walnut anticline, and the Puente Hills anticline adjacent to the right-lateral Whittier fault. The East Montebello fault is bounded on the west by the Elysian Park anticlinorium, a fold belt in downtown Los Angeles. The left-slip Holocene Raymond fault joins the Sierra Madre reverse fault at its segment boundary marked by the Clamshell-Sawpit fault. The triangular stable block between east-trending fold belts is bounded on the south by the Puente Hills blind thrust and on the north by the Sierra Madre fault, documenting north-south Quaternary convergence. East-west extension is also indicated, although not confirmed by geodetic measurements.

Keywords: tectonics, urban geology, earthquake hazards, well data, strike-slip faults, blind reverse faults.

INTRODUCTION

The heart of the California Transverse Ranges is an east-trending chain of basins including, from west to east, the Santa Barbara Channel, the Ventura Basin, the San Fernando Valley, the Los Angeles Basin, and the San Gabriel Basin (Fig. 1). Most of these basins are well known in three dimensions because of extensive exploration for and production of oil and gas (see, for example, Tsutsumi and Yeats, 1999; Tsutsumi et al., 2001; Wright, 1991, and Yeats et al., 1994). The synthesis of the geology and tectonics of the Los Angeles Basin by Wright (1991) included a few observations about the San Gabriel Basin, but for the most part, this discussion was limited to the Los Angeles Basin. The Los Angeles Basin and San Gabriel Basin are transitional between the east-trending Transverse Ranges on the north, dominated by reverse faulting, and the northwest-trending Peninsular Ranges on the south, dominated by right-lateral strike-slip faulting (Fig. 2A).

An extensive set of well data and seismic reflection profiles permits the geology of the Ventura and Los Angeles Basins to be portrayed in three dimensions and allows seismogenic source faults to be characterized even where they are blind, that is, where they do not reach the surface (for example, Shaw and Shearer, 1999; Shaw et al., 2002). The San Gabriel Basin, on the other hand, is not a major producer of hydrocarbons, although there are small oil fields around its southern edge. But enough oil-exploratory wells have been drilled that the three-dimensional geology can be compared with that of adjacent basins and highlands. I analyzed the original well data (see Acknowledgments for sources), although I also consulted Yerkes (1972), Sorensen (1985, 1988), and McCulloh et al. (2001, 2002) for interpretations of basement, Oligocene, and Miocene rocks. Industry seismic reflection data of relatively low resolution have remained proprietary, but the LARSE-1 deep-crustal seismic profile crossed the basin (Fig. 2B; Fuis et al., 2001), and the gravity and magnetic signatures have been studied in detail (Langenheim and Jachens, 1996; Langenheim, 1999).

The San Gabriel Basin is a triangular region, bounded on the north by the San Gabriel Mountains and the Raymond fault, on the southeast by the San Jose Hills and Puente Hills, and on the southwest by the Repetto Hills and Montebello Hills (Figs. 2A, 2B). The geology of the San Gabriel Mountains was described by Ehlig (1975, 1981), May and Walker (1989), and Nourse (2002), and the structure of the range-front Sierra Madre fault system, including the Duarte fault, was described by Crook et al. (1987) and Tucker and Dolan (2001). The Puente Hills and San Jose Hills were described and mapped by Woodford et al. (1944, 1946), Daviess and Woodford (1949), Olmsted (1950), Shelton (1955), Durham and Yerkes (1964), Yerkes (1972), West and Redin (1991), Bjorklund et al. (2002), and Bjorklund and Burke (2002), studies that included subsurface well data. The geology of the Repetto Hills and Elysian Park area has most recently been summarized by Oskin et al. (2000), building on earlier work by Lamar (1970), Davis et al. (1989), and Bullard and Lettis (1993). The geology of aquifers in the San Gabriel Basin is discussed in a report by the California Department of Water Resources (1966), and the Raymond groundwater basin north of the Raymond fault was described by Buwalda (1940). The surface geology is included in recent maps by Dibblee (1989a, 1989b, 1998, 1999, 2001, 2002a, 2002b), Tan (2000a, 2000b, 2000c), and Nourse (2002). An analysis including the San Gabriel Basin focusing on Miocene and older rocks was published by McCulloh et al. (2001).

[†]E-mail: yeatsr@geo.oregonstate.edu.

GSA Bulletin; September/October 2004; v. 116; no. 9/10; p. 1158–1182; doi: 10.1130/B25346.1; 11 figures; 2 tables.

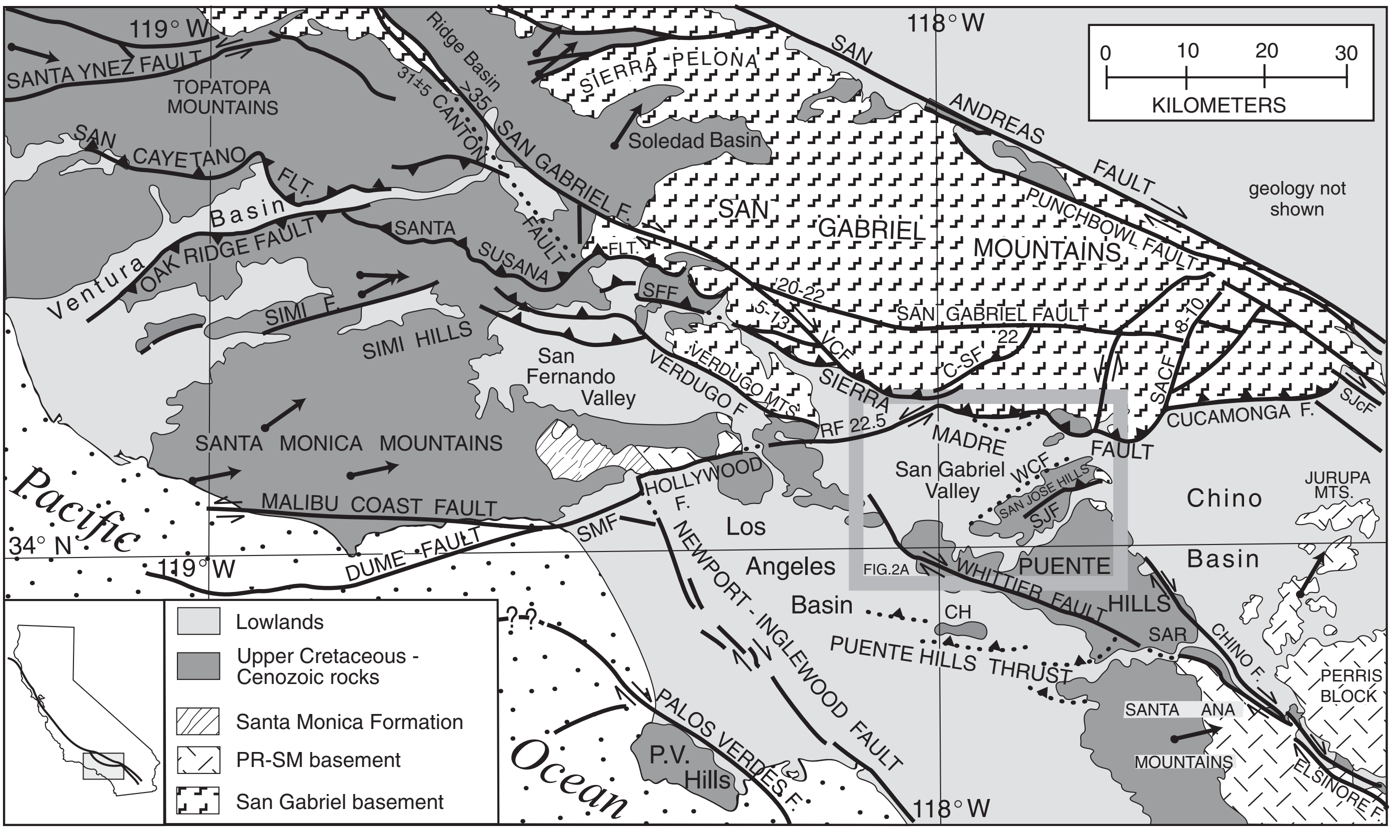


Figure 1. Map of part of central Transverse Ranges locating San Gabriel Valley and surrounding regions. Faults shown in heavy lines, dotted where covered or blind; numbers refer to strike-slip offset, in kilometers, based on McCulloh et al. (2001), Nourse (2002), Yeats and Stitt (2003), and this paper. Abbreviations: C-SF—Clamshell-Sawpit fault; CH—Coyote Hills; PV Hills—Palos Verdes Hills; RF—Raymond fault; SACF—San Antonio Canyon fault; SAR—Santa Ana River; SFF—San Fernando fault; SJF—San Jose fault; SJcF—San Jacinto fault; SMF—Santa Monica fault; VCF—Vasquez Creek fault; WCF—Walnut Creek fault. PR-SM basement refers to basement rocks of the Peninsular Ranges and Santa Monica Mountains; San Gabriel basement refers to heterogeneous basement of San Gabriel Mountains, including Pelona Schist. Arrows not associated with faults show paleomagnetic declination of Miocene and older rocks based on Liddicoat (2001), Luyendyk et al. (1980), Prothero et al. (1996), Prothero and Lopez (2001), Prothero and Vance (1996), and Prothero and Vacca (2001). Base map from Jennings (1977). Rectangle locates Figure 2A.

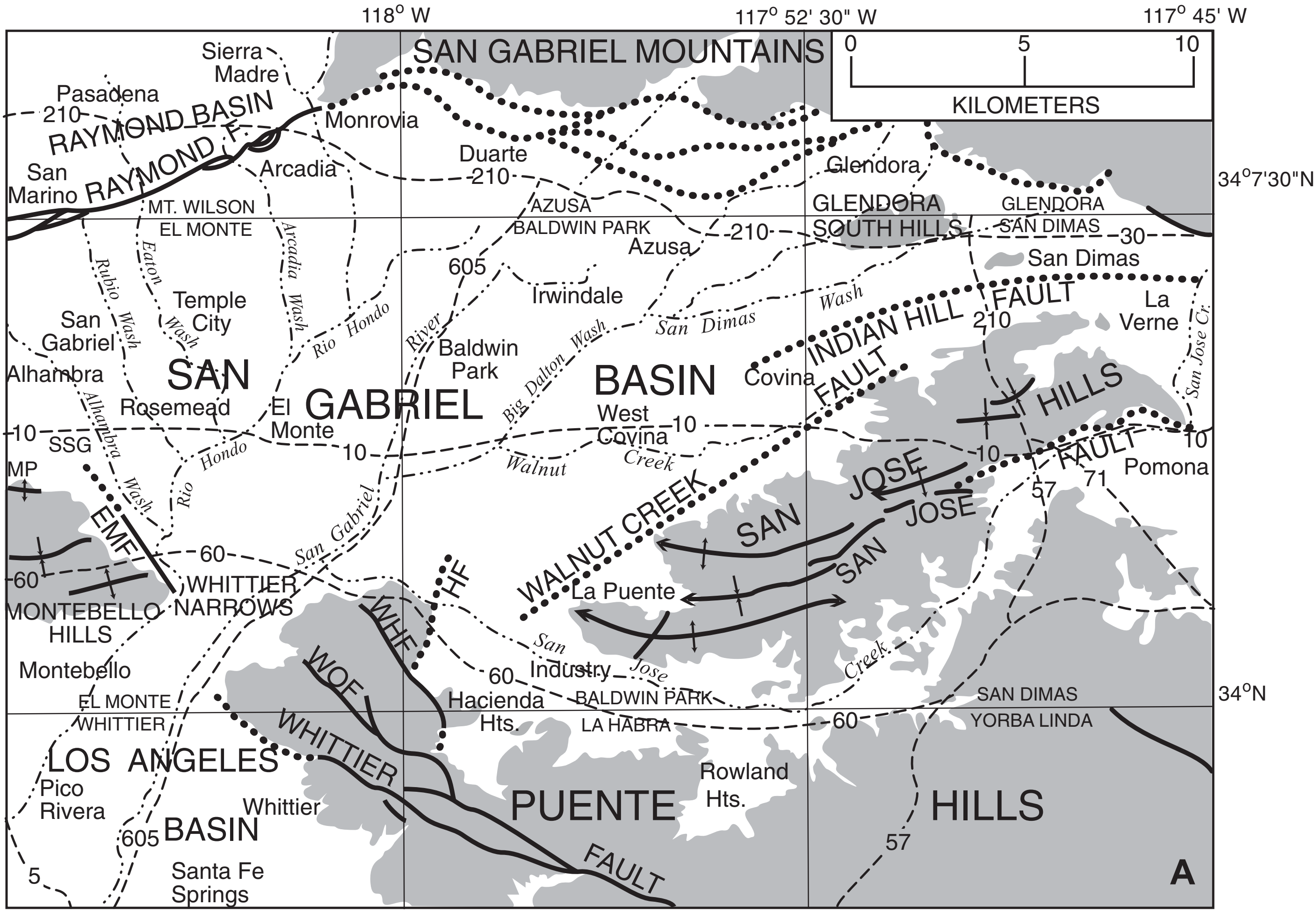
The instrumental seismicity of the San Gabriel Basin is relatively low, but the margins of the basin were struck by five moderate-size earthquakes in a five-year period (Fig. 2B): the 1987 Whittier Narrows earthquake (M5.9) on the east-striking Puente Hills blind thrust (Hauksson and Jones, 1989; Shaw and Shearer, 1999), the 1988 Pasadena earthquake (M4.9) on the east-northeast–striking left-lateral Raymond fault (Jones et al., 1990), the 1988 and 1990 Upland earthquakes (M4.6 and M5.2, respectively) on a left-lateral fault northeast of the San Jose Hills (Hauksson and Jones, 1991), and the 1991 Sierra Madre earthquake (M5.8) on the Clamshell-Sawpit reverse fault in the foothills of the San Gabriel Mountains (Hauksson, 1994). These earthquakes reflect the transitional nature of the San Gabriel Basin. The Sierra Madre and Whittier Narrows earthquakes occurred on east-striking reverse faults on the northern and southern edges of the basin, respectively, whereas the Pasadena and Upland earthquakes occurred on strike-slip faults, left-lateral rather than the more dominant northwest-striking right-lateral faults of the Peninsular Ranges.

A major goal of this study is to describe the subsurface geology of the San Gabriel Valley and to relate it to exposures in adjacent ranges: basement rocks to exposures in the San Gabriel Mountains, Santa Monica Mountains, and San Jose and Puente Hills; Miocene rocks to the Puente Hills, San Jose Hills, and the Elysian Park region; and Pliocene and Pleistocene strata to the Los Angeles Basin. A second goal is to resolve the tectonic evolution of the region, in particular the extension, rotation, and volcanism of the Miocene and the early history of the San Gabriel fault system. In addition, this study evaluates the blind and surface faults of the region as to their earthquake potential. How are these fault systems related to the Miocene faults that preceded them, and how are they related to the subsidence of the San Gabriel Basin?

BEDROCK UNITS

Pre-Tertiary Basement Rocks

A profound nonconformity separates middle Tertiary rocks from pre-Tertiary rocks of two distinctive terranes. On the north is the crystalline basement of the San Gabriel Mountains: Early Proterozoic gneiss, a Proterozoic layered anorthosite-syenite-gabbro complex, Paleozoic(?) metasedimentary rocks, a Triassic monzodiorite-granodiorite pluton, Jurassic granodiorite, and Cretaceous quartz diorite, tonalite, granodiorite, and granite (Ehlig, 1981; May and Walker, 1989; Nourse, 2002). A heterogeneous crystalline rock assemblage is found



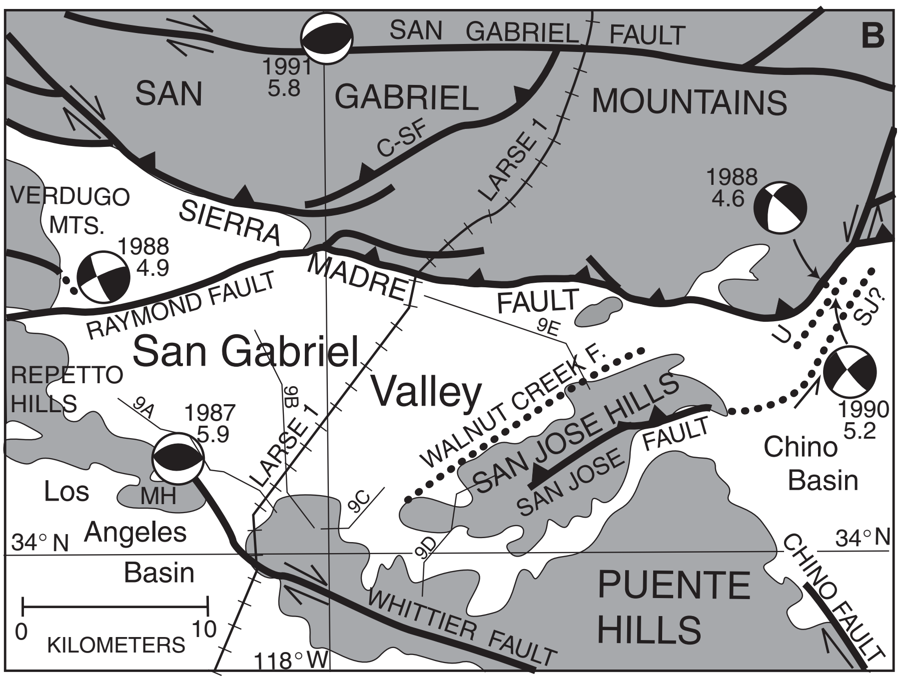


Figure 2. (A) Index map of San Gabriel Valley showing uplands (shaded), faults (heavy lines, dotted where covered), freeways (numbered dashed lines), drainages (dash-dot lines), and cities. EMF—East Montebello fault; HF—Handorf fault; MP—Monterey Park; SSG—South San Gabriel; WHF—Whittier Heights fault; WOF—Workman Hill fault. U.S. Geological Survey 7½-minute quadrangles identified with latitude boundaries. This map is the base map for Figures 3, 4, and 8. (B) Locations of five recent earthquakes around the San Gabriel Valley. Fault-plane solutions: 1987 Whittier Narrows—Hauksson and Jones (1989), Bent and Helmberger (1989); 1988 Pasadena—Jones et al. (1990); 1988 and 1990 Upland—Hauksson and Jones (1991); 1991 Sierra Madre—Hauksson (1994). Lower-hemisphere focal mechanisms show compressional quadrants in black and dilational quadrants in clear. Location of LARSE-1 seismic line from Fuis et al. (2001). Location of cross sections in Figures 9A–9E in thin solid lines. Hilly areas shaded. Faults in heavy lines, dotted where covered. C-SF—Clamshell-Sawpit fault; MH—Montebello Hills; SJ—extension of San Jose fault.

TABLE 1. BASEMENT ROCKS IN WELLS IN THE SAN GABRIEL VALLEY, SAN JOSE HILLS, AND PUENTE HILLS

Number	Well name	Operator	L†	S§	R#	Description
1	Bartolo rd	Shell	SG	Mo	OSo	Slate, silver-gray
2	Cordova	Occidental	SG	E	O	Santa Monica fractured schist, slate
3	El Monte	Am. Petrofina	SG	F	O	Gneiss
4	Ferris	Chevron	SG	F	OM	Gneissoid granodiorite, quartz diorite, 156 Ma
5	Gapco B1	Great American	PH	S	DM	Granite
6	Garnier	Texaco	SJ	V	S	Quartz diorite, protomylonite
7	Kraemer-Backs	Stella	PH	K?	W	Biotite granite and aplite
8	LeGrand	Marathon	SJ	M	Ol,S	Pink granite gneiss; albite granite
9	Live Oak	Chevron	SG	F	OM	Banded gneiss
10	Los Nogales		PH	?	OW	Red and gray granite
11	Menchego 6	Shell	PH	F	Yr	Schistose metavolcanic rocks
12	Pellissier	Shell	SG	C?	Y	Sheared granodiorite
13	Pomona 1		PH	S	M	May have bottomed in granite
14	Puente A-1	Shell	PH	F	Yr	Metavolcanic rocks
15	Puente A-3	Shell	PH	F	YrM	Schistose meta-andesite; $^{87}Sr/^{86}Sr$ = 0.70422
16	Puente A-6	Shell	PH	F	Yr	Schistose metavolcanic rocks
17	Puente B-8	Shell	PH	D?	Yr	Metavolcanic rocks
18	Puente D-2	Shell	PH	D?	Yr	Metavolcanic rocks
19	Puente D-10	Shell	PH	D?	Yr	Metavolcanic rocks
20	Puente CH 3	Shell	PH	V	O	Basement
21	Puente CH 4	Shell	PH	S	M	Biotite quartz diorite
22	Rosemead oh, rd	Exxon	SG	E	O	Black metasiltstone with chlorite schist (oh); chlorite schist (rd)
23	Rosemead	Harry Riskas	SG	E?	O	Green and gray-green schist
24	Rowland Est. 3-1	Morton and Sons	PH	V	O	Aplite, alaskite, quartz porphyry
25	Sansinena 8B2	Unocal	PH	F?	YrM	Schistose meta-andesite
26	S. San Gabriel 1-2	Exxon	SG	E	So	Pelitic schist, amphibolite
27	S. Pacific CH	Chevron	SG	Mo	OSo	Dark gray schist, quartzite, quartz veins
28	Walnut Creek	McMillan	SJ	V	S	Pink mylonitic gneiss

†Locality: SG—San Gabriel Basin; SJ—San Jose Hills; PH—Puente Hills.
§Stratigraphy: unit overlying basement: K—Upper Cretaceous; M—Mountain Meadows Dacite; S—"Sespe" Formation; F—Topanga (Division F; Luisian–Relizian); V—volcanic rocks (Glendora); Mo—Mohnian; A–E—Divisions A, B (Delmontian), C, D, E (Mohnian); oh—original hole; rd—redrilled hole.
#Source reference: D—Durham and Yerkes (1964); M—McCulloh et al. (2001); O—operator; Ol—Olmsted (1950); S—Shelton (1955); So—Sorensen (1985, 1988); W—Woodford et al. (1944); Y—Yeats and Beall (1991); Yr—Yerkes (1972). Caution: Basement rocks identified only by operator may be described by a geologist inexperienced in igneous or metamorphic petrology.

in the Verdugo Mountains and in the ranges north of the Soledad and Ridge Basins. Rocks immediately north of the Cucamonga fault in the southeastern San Gabriel Mountains include Early Cretaceous granulitic gneiss associated with mylonite. These crystalline rocks make up several tectonostratigraphic terranes that were amalgamated by ductile faulting and folding and plutonism during the Late Cretaceous (Alf, 1948; May and Walker, 1989) and subsequently thrust over the Pelona Schist, continental-margin strata metamorphosed at ca. 65–60 Ma (Ehlig, 1981; Jacobson, 1990; Nourse, 2002).

In contrast, the basement rocks of the Santa Monica Mountains consist of the Santa Monica Formation, metasedimentary rocks of Late Jurassic (late Oxfordian to middle Kimmeridgian) age (Imlay, 1963). These rocks are predominantly slate, but in their easternmost exposures, where they have been intruded by granodiorite and quartz diorite dated as 102 ± 10 Ma (L.T. Silver in Dibblee, 1982), they are metamorphosed to spotted slate, phyllite, and schist (Hoots, 1931, p. 89; McCulloh et al., 2001). In the northern Santa Ana Mountains, the Bedford Canyon Formation is older than the Santa Monica Formation (Middle to early Late Jurassic according to Imlay, 1963). The Bedford Canyon Formation is overlain with angular unconformity by the Santiago Peak Volcanics of latest Jurassic (Tithonian) age on the basis of fossils reported by Fife et al. (1967); zircon ages are 134–123 Ma (Anderson, 1991). These rocks are intruded by the Peninsular Ranges batholith, which has ages ranging from 140 to 105 Ma (L.T. Silver in Howell et al., 1987). Potassium-argon ages of the northwestern edge of the batholith east of the Chino fault are 108 Ma, becoming younger eastward, and zircon ages on one pluton in this area are 109.5 and 112.6 Ma (Gray et al., 2002). The western plutons of the Peninsular Ranges batholith are more mafic than their eastern counterparts and have $^{87}Sr/^{86}Sr$ ratios of <0.706. The Santiago Peak Volcanics are not known from the Santa Monica Mountains; however, basal nonmarine Upper Cretaceous strata contain large clasts of Santiago Peak lithology (Dibblee, 1982, p. 98), demonstrating that similar volcanic rocks were originally present nearby prior to intrusion of Cretaceous plutons and dismemberment by Cenozoic faulting.

Except for limited exposures in the easternmost San Jose Hills and northernmost Puente Hills (Shelton, 1955), the basement rocks of the eastern Los Angeles Basin, San Gabriel Basin, and Puente and San Jose Hills are known only from wells (Table 1; Fig. 3). The Santa Monica Formation underlies Miocene strata in the northern Los Angeles Basin, the Repetto Hills, and the western San Gabriel Basin, where it is contact-metamorphosed (wells 2, 22, 23, 26, and 27, Table 1) and intruded on the east by granitic rocks (well 12, Table 1). The Santa Monica Formation is offset 14.2–22.5 km left-laterally across the Raymond fault from a comparable piercing point in the San Gabriel Basin (McCulloh et al., 2001, their Fig. 9).

The correlation of the granitic rocks in wells beneath most of the San Gabriel Valley with granitic exposures is less clear, in part because the basement rocks in wells 3, 4, and 9 (Fig. 3, Table 1) are gneissoid, allowing a possible correlation with gneissoid rocks of the San Gabriel Mountains (Fig. 3; Table 1). The basement rocks in the Chevron Ferris well (well 4) were dated by Geochron Laboratories as 156 ± 6 Ma (first reported as 153 ± 3 Ma by Yerkes, 1972, p. C5), older than the Peninsular Ranges batholith, but close to a U-Pb age of 164 ± 2 Ma for granodiorite northwest of Mount Baden-Powell in the San Gabriel Mountains (Barth, 1989; Nourse, 2002). In the San Jose Hills, basement rocks in the Texaco Garnier well (well 6, Fig. 3) include quartz diorite and ultramylonite, and the Ohio LeGrand well (well 8, Fig. 3) reached granitic gneiss (Olmsted, 1950; McCulloh et al., 2001). Gneissoid granite (Shelton, 1955) and tonalite exposed at the eastern end of the San Jose Hills yielded a questionable K-Ar age of 96.4 Ma on biotite (F.K. Miller in McCulloh et al., 2001, p. 7), younger than the Peninsular Ranges batholith but close to a U-Pb age of 88 ± 3 Ma on tonalite intruding the Cucamonga and San Antonio terranes of May and Walker (1989, p. 1260) and an age of 78 ± 8 Ma for posttectonic granite

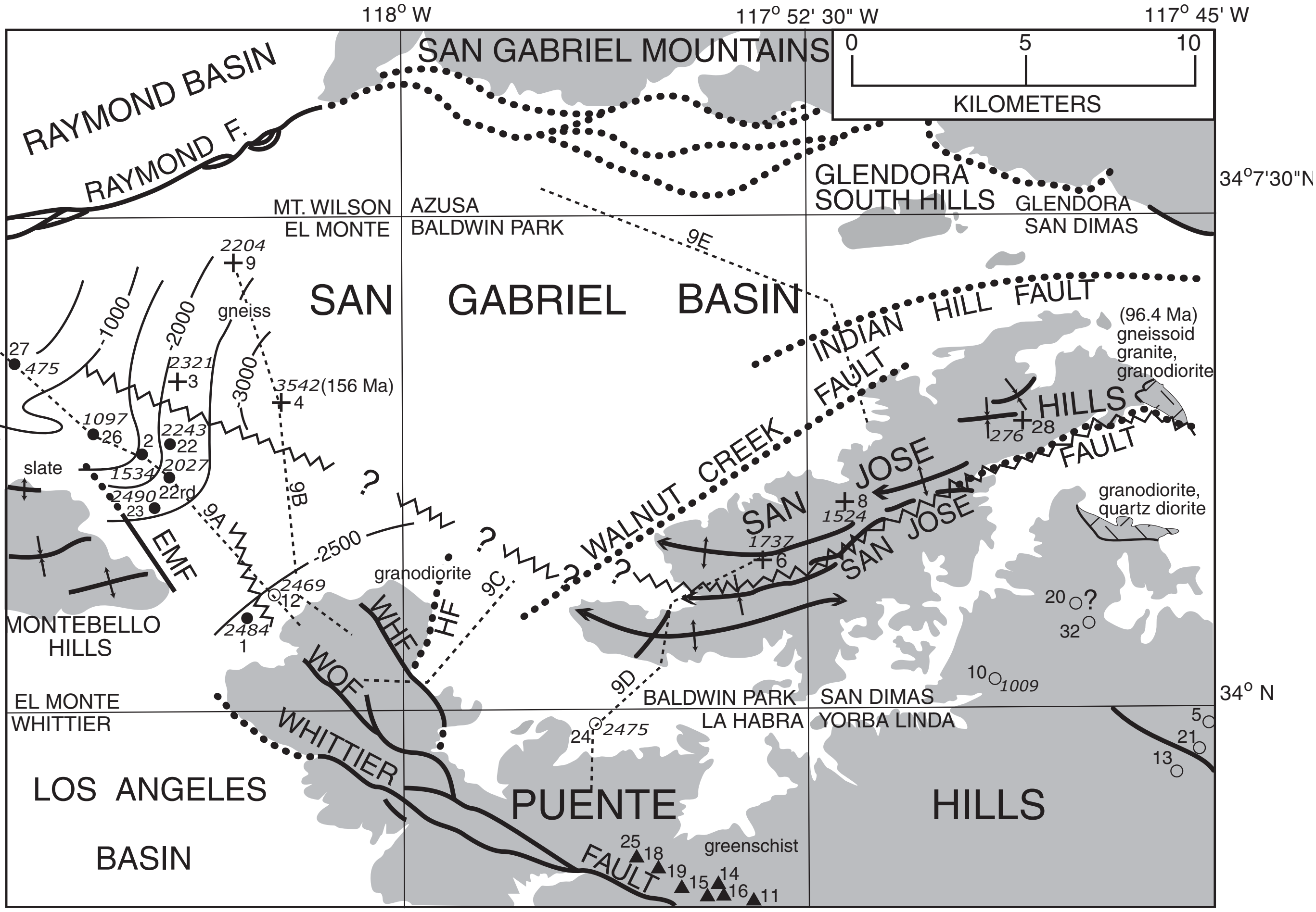


Figure 3. Basement rocks in the San Gabriel Basin and vicinity. Filled circles—Santa Monica Formation; open circles—Peninsular Ranges batholithic rocks; triangles—greenschist correlated to Santiago Peak Volcanics; plusses—gneiss and mylonite. Well numbers refer to Table 1; not all wells in Table 1 included in figure. C—Continental Monterey Park 1-1; oh—original hole; rd—redrilled hole. Descriptions of surface exposures in San Jose Hills and Puente Hills from Shelton (1955). Jagged lines show proposed basement boundaries. The southern boundary of gneiss follows the alternate southern boundary of the San Gabriel amalgamated terrane proposed by McCulloh et al. (2001). Structure contours, in meters subsea, on top of basement in western San Gabriel Basin; location of basement accounts for directionally drilled wells. Basement depths not shown for wells in greenschist and for wells in Yorba Linda quadrangle. Lines of cross sections in Figure 9 are shown. See Figure 2A caption for fault abbreviations.

(May and Walker, 1989). The San Jose pluton has a high $^{87}Sr/^{86}Sr$ ratio of 0.70824 (D.M. Morton in McCulloh et al., 2001), inconsistent with plutonic rocks of the western margin of the Peninsular Ranges batholith to the southeast, which have lower $^{87}Sr/^{86}Sr$ ratios. This discrepancy led McCulloh et al. (2001, their Fig. 4) to consider the possibility that the basement rocks of the San Jose Hills and northern San Gabriel Basin could be related to rocks in the San Gabriel Mountains, although their preferred southern boundary of the San Gabriel Mountains amalgamated basement terrane is the Sierra Madre fault system. Their alternate boundary (Fig. 3) extends across the western San Gabriel Basin, where it separates gneiss on the north from Santa Monica Formation and granodiorite on the south. If this interpretation is correct, the northern extension of the contact between metamorphosed Santa Monica Formation and intrusive granodiorite between wells 1 and 11 would be truncated by a tectonic boundary and would not extend to a piercing point at the Raymond fault, as suggested by McCulloh et al. (2001). The metamorphic aureole in the Santa Monica Formation could serve as a piercing point for left-lateral offset on the Raymond fault, but the contact between the Santa Monica Formation and granitoid rocks would not.

Farther south in the Puente Hills, the basement rocks in wells are granitic, similar to those in the Peninsular Ranges (Fig. 3; Table 1, wells 5, 10, 13, 20, 21, 24). Pre-Tertiary metavolcanic rocks in the Puente pool of the Brea-Olinda Oil Field, in the hanging wall of the Whittier fault, are probably correlated to the Santiago Peak Volcanics (Yerkes, 1972; Table 1, wells 11, 14–19, 25).

Pre-Tertiary Unmetamorphosed Strata

Upper Cretaceous strata of the eastern Santa Monica Mountains and the Santa Ana Mountains show evidence of derivation from a nearby source terrane similar to the basement rocks of the Peninsular Ranges, including large blocks of Santiago Peak Volcanics in basal nonmarine deposits in both ranges. East of the basal nonmarine Cretaceous exposures in the Santa Monica Mountains, the basement rocks are overlain directly by Miocene and younger rocks in the northeastern Los Angeles Basin,

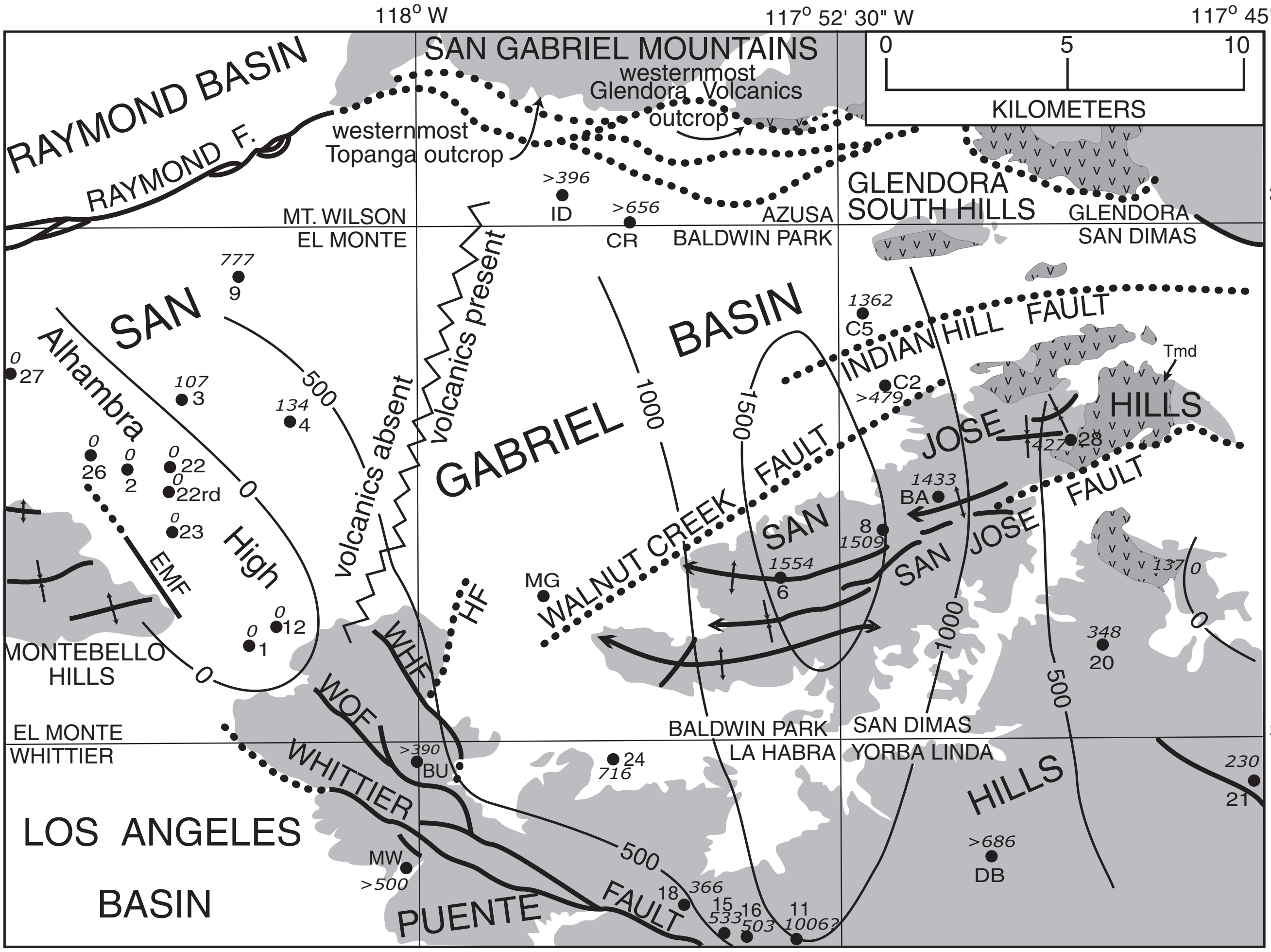


Figure 4. Isopachs, in meters, of Topanga Group, including the Topanga Formation of Durham and Yerkes (1964) and Glendora Volcanics of Shelton (1955). Dots indicate well control; numbers are identified in Table 1. Other wells: BA—Bayly (Conoco); BU—Buehler (Conoco); CR—Consolidated Rock Products (Chevron); C2—Covina 27-1 (Texaco); C5—Covina 5-1 (Texaco); DB—Diamond Bar (Western Gulf); ID—Irwindale-Duarte (Unocal); MG—McGinnis (Texaco); MW—Murphy-Whittier 304 (Chevron). V pattern—exposures of Glendora Volcanics; Tmd—Mountain Meadows Dacite. Isopachs not extended south of Whittier fault. Zero isopach turns west into Montebello Hills to accommodate well control in Montebello Oil Field (see Fig. 5). Well control in La Habra quadrangle from Yerkes (1972), in Yorba Linda quadrangle from Durham and Yerkes (1964); well MW from Herzog (1998). See Figure 2A caption for fault abbreviations.

the San Gabriel Basin, and much of the Puente Hills. Marine Paleogene rocks are found in the southeastern Puente Hills, Coyote Hills, and the southeastern Los Angeles Basin (Schoellhamer et al., 1981; McCulloh et al., 2000, their Fig. 3); these strata correlate with exposures in the Santa Ana Mountains and along the Elsinore fault.

Mountain Meadows Dacite

Small intrusions of biotite dacite porphyry are found in the eastern San Gabriel Mountains and in the San Jose Hills. This distinctive rock unit is a light gray to tan porphyry with phenocrysts of euhedral biotite and rounded quartz bipyramids and subordinate crystals of oligoclase and potassium feldspar (McCulloh et al., 2001). The quartz phenocrysts contain microscopic trains of fluid inclusions that allow these phenocrysts to be identifiable as clasts in younger strata. Biotite from a core in the Continental Bayly well in the San Jose Hills near the type locality of the dacite has a K-Ar age of 27.6 ± 0.4 Ma (V. Frizzell in McCulloh et al., 2001, p. 8). Biotite separates, assumed to be from the type locality, are dated by $^{40}Ar/^{39}Ar$ as 28.0–27.5 Ma (G. Hazelton in Nourse et al., 1998). These dates are consistent with other dates in the southeastern San Gabriel Mountains, including a U-Pb zircon date of 26 ± 1 Ma for the Telegraph Peak Granodiorite (May and Walker, 1989; Nourse, 2002). Igneous rocks of this age have not been found in the San Gabriel Basin or in the Puente Hills south of the San Jose fault, although they have been reported from the Verdugo Mountains northwest of the San Gabriel Basin (McCulloh et al., 2001).

"Sespe" Formation

Nonmarine fluvial strata in the Santa Ana Mountains and in the subsurface of the Puente Hills, correlated to the Eocene–Oligocene Sespe Formation of the Ventura Basin, were mapped as "Sespe-Vaqueros" by Schoellhamer et al. (1981) in the Santa Ana Mountains, where marine and nonmarine strata are interbedded. Vaqueros interbeds are unknown north of the Santa Ana River (McCulloh et al., 2001), where the nonmarine strata overlap marine Eocene rocks and rest directly on crystalline basement in Shell Puente core hole 4 (well 21, Fig. 3;

McCulloh et al., 2000, their Fig. 8). Vertebrate fossils in the "Sespe" of the Santa Ana Mountains are correlated to the early Hemingfordian Vertebrate Stage by Prothero and Donohoo (2001); these strata have been referred to the paleomagnetic chron C5Er to C5Cr (19–17 Ma) by Prothero and Donohoo (2001). The "Sespe" contains clasts of Mountain Meadows Dacite, indicating that the dacite intrusions had been uplifted and eroded prior to "Sespe" deposition (McCulloh et al., 2001). These strata are the same age as nonmarine strata in the central Santa Monica Mountains that both overlie and underlie the Vaqueros Formation and underlie the Topanga Formation (Yerkes and Campbell, 1979, p. E10–E11).

In this region, the nonmarine strata are more appropriately regarded as the oldest members of the Topanga and Puente depositional sequence rather than the youngest member of the Paleogene depositional sequence. However, unlike the Topanga, the "Sespe" is not found in the San Jose Hills or San Gabriel Basin.

Topanga Group

The Glendora Volcanics of Shelton (1955) and the Topanga Formation of Durham and Yerkes (1964) and Yerkes (1972) compose the Topanga Group of Wright (1991; see McCulloh et al., 2001, 2002, for discussion of nomenclature). The Glendora Volcanics were described by Shelton (1955, p. 45) as "massive and autobrecciated basalt, calcic andesite, andesite, dacite(?), and rhyolitic lavas, and an approximately equal volume of interbedded tuffs and tuff breccias." These rocks are widespread in the San Jose Hills and northern Puente Hills and are found also in the southern Puente Hills, the eastern San Gabriel Basin, and the adjacent foothills of the San Gabriel Mountains, where numerous mafic to intermediate dikes in pre-Tertiary crystalline rocks are assigned to the Glendora Volcanics on the basis of geochemical evidence (Nourse et al., 1998). The andesite was radiometrically dated by McCulloh et al. (2002), using $^{40}Ar/^{39}Ar$, as 15.08 ± 0.11, 15.28 ± 0.05, and 15.32 ± 0.16 Ma; a basalt was dated as 17.2 ± 0.5 Ma.

The volcanic rocks follow a northeast trend in the San Jose Hills and western Puente Hills and have a maximum thickness of 1130 m in the Texaco Garnier well (well no. 5, Fig. 3; Bjorklund et al., 2002). Volcanic rocks are found in the eastern San Gabriel Basin (Union Irwindale Duarte and Chevron Consolidated Rock Products wells, located in Fig. 4) but are absent in the central and western San Gabriel Basin (Fig. 4; McCulloh et al., 2002). The western boundary of the volcanic field (Fig. 4) trends more northerly than that shown by Bjorklund et al. (2002) to accommodate volcanic rocks in the Irwindale Duarte and Consolidated Rock Products wells in the San Gabriel Basin, west of which the Topanga Formation lacks associated volcanic rocks. Bjorklund et al. (2002) found a northwest-striking high-velocity anomaly based on crustal P- and S-wave tomography that might be a pluton that supplied magma to the Glendora volcanic center.

The volcanic rocks are overlain by and interbedded with the Topanga Formation of Relizian and Luisian age, 17.1–13.6 Ma according to the Miocene time-scale correlation of Barron and Isaacs (2001; see also Blake, 1991; stage names from Kleinpell, 1938). Strata with Relizian and Luisian microfossils overlie Glendora Volcanics in the Texaco Garnier well (Olmsted, 1950). In the Texaco Covina 5-1 core hole, a nannofossil flora assigned to zone CN 3, 18.3–15.6 Ma, is succeeded by a flora of zone CN 3-4, which could be as young as 13.6 Ma, the age of the top of the Luisian Stage (McCulloh et al., 2001; Barron and Isaacs, 2001). In the San Jose Hills, the Topanga strata include the Buzzard Peak Conglomerate of Woodford et al. (1946), found also in the Conoco Bayly and Ohio LeGrand wells to the west. For the most part, the Topanga of the San Gabriel Basin is sandstone and shale, including organic "Monterey Shale" lithologies with fish scales. The combined Topanga and Glendora thickness is as great as 1554 m in the Texaco Garnier well in the western San Jose Hills, decreasing to zero at the outcrop in the northeasternmost Puente Hills, where Puente Formation directly overlies granitic basement (Fig. 4; Shelton, 1955; Tan, 2000c). Topanga thickness decreases to zero southwest of wells 3 and 4 (Fig. 4), where Puente strata directly overlie Santa Monica Formation and Peninsular Ranges granodiorite, a feature called the Alhambra High by Wright (1991, his Fig. 5). The zero isopach marking the Alhambra High must turn to the west at Whittier Narrows to accommodate Topanga Formation in the deep Argo East Montebello Unit 1 well in the Montebello Oil Field (West et al., 1988; Fig. 5 herein).

McCulloh et al. (2001, their Fig. 6) also show a zero Topanga isopach, but they assumed that the Topanga was originally present there but subsequently removed by erosion. They showed an eastern Topanga shoreline, following Woodford et al. (1946), extending from the front of the San Gabriel Mountains southeast through the eastern San Jose Hills and Puente Hills close to the Chino fault. Woodford et al. (1946) showed that clasts in Topanga conglomerates could have been derived from the eastern San Gabriel Mountains. Topanga Formation in the Consolidated Rock Products well in the northern San Gabriel Basin and in an exposure in the San Gabriel Mountains foothills contains clasts derived from Mountain Meadows Dacite (McCulloh et al., 2001).

The north-to-northwest strike of Topanga Group isopachs (Fig. 4), as also mapped by Wright (1991) and McCulloh et al. (2001), is strongly divergent to the present-day geomorphology of the San Gabriel Basin and adjacent San Jose, Puente, and Montebello Hills, indicating that those topographic features formed later. The presence of eastern San Gabriel Mountains clasts in Topanga strata indicates that the San Gabriel Mountains were a sediment source in the middle Miocene, although the absence of coarse clastic Topanga Formation close to the range front in the San Gabriel Basin suggests that the configuration of that range in the middle Miocene was far different than today. In addition, Topanga conglomerate overlying Glendora Volcanics in the San Jose Hills contains only Glendora Volcanics clasts and dacite clasts (Nourse et al., 1998).

Puente Formation

The Puente Formation was named by Eldridge and Arnold (1907) for a clastic sequence of predominantly late Miocene age in the Puente Hills. They divided the Puente into a lower shale, a middle sandstone, and an upper shale, which were named by Schoellhamer et al. (1954) the La Vida, Soquel, and Yorba Members, respectively. The La Vida Member is lower Mohnian in the biostratigraphy of Kleinpell (1938), corresponding to Division E of Wissler (1943, 1958) (Fig. 5). The Soquel and Yorba Members are upper Mohnian of Kleinpell (1938); the Soquel corresponds approximately to Division D and the Yorba to Division C of Wissler (1943, 1958). Daviess and Woodford (1949) found an upper Miocene member overlying the Yorba Member in the western Puente Hills that was named the Sycamore Canyon Member, with fossils of the Delmontian Stage of Kleinpell (1938) and Divisions A and B of Wissler (1943, 1958). In his maps of the Puente Hills, Dibblee (1999, 2001) retained the La Vida, Soquel, and Yorba Members but placed these in the Monterey Formation rather than the Puente. The Sycamore Canyon Member was raised by Dibblee to formation status. In the subsurface of the Los Angeles Basin, Blake (1991) retained the Puente Formation, but not its members, which could not be correlated on the basis of lithology away from the Puente Hills. The correlations in Figure 5 are based on benthic foraminifera (Kleinpell, 1938; Wissler, 1943, 1958) as calibrated by Blake (1991) and Barron and Isaacs (2001) using pelagic microfossils and radiometric dates.

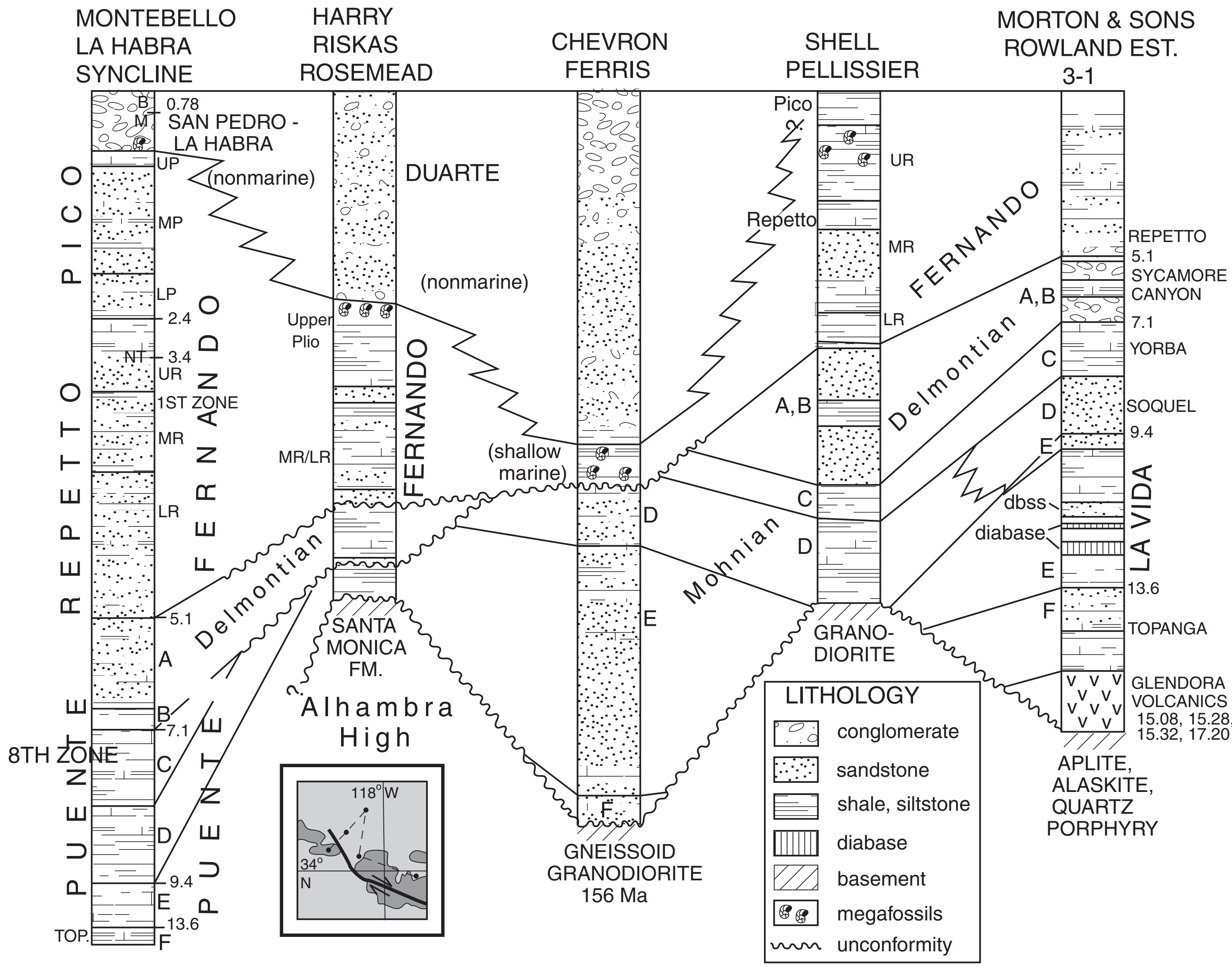


Figure 5. Stratigraphic relationships among San Gabriel Basin (Riskas and Ferris wells), Los Angeles Basin (Montebello, La Habra syncline), and Puente Hills (Pellissier and Rowland Estates wells). Stratigraphic sections located in inset. Sources of data: Montebello and La Habra syncline sections from Union Howard & Smith 3, Argo E. Montebello Unit 1, and Shell Pansini wells. B/M—Brunhes/Matuyama magnetic chron boundary from a water well from D. Ponti, U.S. Geological Survey; for location, see Myers (2003). Montebello, Riskas, and Ferris sections use data from West et al. (1988). Pellissier and Rowland Estates well from Yeats and Beall (1991); Rowland Estates section also uses data from Yerkes (1972), including exposures in nearby Industry syncline. Numbers are ages in millions of years based on magnetostratigraphy (D. Ponti, 2000, personal commun.), correlation of benthic foram zones to radiometric time scale (Barron and Isaacs, 2001; Blake, 1991), and radiometric ages of volcanic rocks (Nourse et al., 1998; McCulloh et al., 2002). Well files curated at Los Angeles Basin Repository at California State University at Long Beach. Abbreviations: dbss—Diamond Bar sandstone; A–F—benthic foraminiferal zones of Wissler (1943, 1958); Delmontian and Mohnian defined by Kleinpell (1938); UP—upper Pico; MP—middle Pico; LP—lower Pico; UR—upper Repetto; MR—middle Repetto; LR—lower Repetto, as used by Blake (1991).

Yerkes (1972) pointed out that these members represented facies and that lateral gradation from sandstone to shale was to be expected. He recognized an eastern facies, which included coarse clastic strata and which he called the Puente Formation sensu stricto, and an unnamed western facies composed mainly of organic shale, diatomite, siltstone, and mudstone.

The La Vida Member is lower Mohnian, Division E, which represents a time range of >4 m.y., almost as long as the time taken to deposit the other three members of the Puente Formation. Its equivalent farther west in the Los Angeles Basin is the "Nodular shale," largely fine-grained, highly organic strata that accumulated slowly (Wright, 1991). In the Puente Hills, the La Vida includes the Diamond Bar sandstone, named for its presence in the Western Gulf Diamond Bar well in the central Puente Hills (located in Fig. 4). The sandstone lenses out southward toward the Whittier fault but is still present in the Morton and Sons Rowland Estates 3-1 well (Fig. 5; Yeats and Beall, 1991, their section J). The First Walnut and Second Walnut producing sandstones in the Walnut Oil Field are interbedded with shales with a Division E fauna, indicating that this field produces oil from the La Vida Member (Ingram, 1960). Sandstone in the western San Jose Hills and northern Puente Hills was mapped as Soquel by Tan (2000a, 2000b) and Dibblee (1999), but microfossils in overlying shales are, for the most part, early Mohnian (Olmsted, 1950), indicating that this sandstone also is an interbed in the La Vida Member. Division E strata in the San Gabriel Basin are interbedded sandstone and shale, and it is not possible to break out a separate La Vida Member on the basis of lithology (see Ferris section in Fig. 5). The clast content suggests derivation from the San Gabriel Mountains (Woodford et al., 1946; Critelli et al., 1995).

Bjorklund et al. (2002) produced an isopach map of the La Vida Member and found that it is thickest north of and close to the Whittier fault, evidence that the La Vida was deposited in a half graben, with a boundary normal fault later reactivated in the opposite sense as the Whittier fault. Formation of this half graben was accompanied by magmatism, based on the presence of diabase sills in outcrop (Yerkes, 1972) and in wells, for example, the Rowland Estates 3-1 well in Figure 5.

The Soquel Member is predominantly deep-water sandstone in the Puente Hills, most likely derived from the San Gabriel Mountains to the north (Woodford et al., 1946; Critelli et al., 1995). In the northern Puente Hills and San Jose Hills, the Soquel is conglomeratic; it has boulders as large as 4 m across (Woodford et al., 1946), locally overlapping the La Vida and Topanga to rest directly on Cretaceous basement. In the western Puente Hills, the Soquel sandstone is relatively thin north of the Whittier Oil Field (Yerkes, 1972; Dibblee, 2001), and in the Shell Pellissier well near the San Gabriel River, the Division D interval is entirely shale (Fig. 5). Farther northwest in the San Gabriel Basin, Division D strata, like those of Division E, include sandstone and shale (Fig. 5).

The Yorba Member, with a Division C fauna, is largely shale in the Puente Hills. Shale referred to the Yorba in the northern Puente Hills by Dibblee (1999) and Tan (2000a, 2000b) commonly contains an early Mohnian fauna (Olmsted, 1950) and is more likely equivalent to the La Vida. Division C shale is mapped as far west as the edge of the San Gabriel Basin (Texaco McGinnis and Shell Pellissier wells), but farther northwest within the basin, Division C strata are absent owing to overlap by the Sycamore Canyon Member and the Pliocene Fernando Formation.

The Sycamore Canyon Member is conglomeratic at its type locality in the westernmost Puente Hills (Daviess and Woodford, 1949; Yerkes, 1972), but farther northwest near Whittier Narrows, Delmontian strata are largely interbedded sandstone and shale. Within the San Gabriel Basin, equivalent strata are fine grained in the Riskas Rosemead well (Fig. 5), northwest of which the Delmontian sequence is overlapped by the Pliocene Fernando Formation, which rests directly on Division D and E strata. Delmontian strata are also fine grained in the Repetto Hills (Lamar, 1970) and in the Walnut anticline east of the type locality. The fine-grained Delmontian indicates that the conglomerate facies in outcrop gives way northwestward, eastward, and down-dip to finer-grained strata, and the submarine turbidite fan discussed by Critelli et al. (1995) does not extend into the San Gabriel Basin. Yeats and Beall (1991) noted that isopachs of the Division A, B, and C strata of the Los Angeles Basin defined a sand-rich trough that trends northeast, at right angles to the northwest trend of the post-Miocene Los Angeles trough. The thick sandstones constituting the Fifth through Eighth zones of the Montebello Oil Field are probably continuous with the conglomerate and sandstone of the type Sycamore Canyon Member of the western Puente Hills. However, the presence of fine-grained Delmontian strata to the northwest in the San Gabriel Basin and Repetto Hills indicates that the center of this fan is in the northwest Puente Hills, not the San Gabriel Basin.

Yeats and Beall (1991) produced an isopach map of a second Delmontian–uppermost Mohnian fan parallel to and south of the Whittier fault with an entry point at an ancestral Santa Ana River. Bjorklund and Burke (2002) produced an isopach map of the Delmontian sequence separately and concluded that the fan emanating from the Santa Ana River is the source of the conglomerate of the type Sycamore Canyon as well as the sandstones of Montebello Oil Field. However, Critelli et al. (1995) pointed out that some clasts in the Sycamore Canyon are mineralogically similar to the Lowe Granodiorite in the San Gabriel Mountains, which is not part of the drainage basin of the modern Santa Ana River. On the basis of provenance, the Sycamore Canyon conglomerate of the western Puente Hills is more likely derived from the north (Woodford et al., 1946; Yerkes, 1972), even though its upstream equivalent was eroded prior to deposition of Pliocene strata. However, the head of this fan has not been found in wells.

Fernando Formation and Duarte Conglomerate

The Fernando Formation of Eldridge and Arnold (1907) was subdivided in the Los Angeles Basin into the Repetto and Pico Members (cf. Blake, 1991). This sequence can be correlated as far east as the Montebello Oil Field, Repetto Hills (where the type Repetto is located), westernmost Puente Hills, and the footwall of the Whittier fault. The marine Pico is overlain by the shallow-marine San Pedro Formation (Powell and Stevens, 2000) and nonmarine Coyote Hills and La Habra Formations, exposed in the Coyote Hills and eastern part of the La Habra syncline (Yerkes, 1972). However, a major facies change takes place in the southwestern San Gabriel Basin (Fig. 5). As first shown by West et al. (1988), the deep-water basin-plain sequence of the Los Angeles Basin changes facies northeast of the Montebello Oil Field and Repetto Hills to nonmarine sandstone, conglomerate, and claystone; conglomerate becomes dominant in the upper part of the sequence. This nonmarine sequence, nearly 1800 m thick in the Chevron Ferris well in the center of the basin, is referred to here as the Duarte Conglomerate of Shelton (1946), although the upper part may include the older part of the San Dimas Formation of Eckis (1928). The Duarte Conglomerate is exposed only at the base of the San Gabriel Mountains, where it is at least 450 m thick (Shelton, 1955). This nonmarine sequence is underlain by a shallow-marine, fossiliferous, largely fine-grained sequence that is not dated more closely than Pliocene, although various industry paleontologists have referred to fossil assemblages as “Pico” or “Repetto.” The benthic foraminiferal assemblages established for the Fernando by Natland (1952) and Natland and Rothwell (1954) reflect water depth more than age (Blake, 1991). In the Los Angeles Basin, where the Fernando was deposited largely in deep water, the Pico and Repetto have been age-calibrated by using radiometric dates and pelagic microfossil assemblages. It is not possible to correlate the shallow-water sequence in the San Gabriel Basin to the deep-water sequence in the Los Angeles Basin other than to refer to the former as shallow-water Fernando Formation.

The facies change also takes place between the San Gabriel Basin and the Puente Hills. The nonmarine Duarte Conglomerate is not exposed at the surface in the Puente Hills, just as it is not exposed in the Repetto and Montebello Hills. The Fernando Formation in the westernmost Puente Hills consists of marine siltstone, sandstone, and conglomerate (Daviess and Woodford, 1949), and there is uncertainty in locating the Fernando/Sycamore Canyon contact (compare Dibblee, 1999, and Tan, 2000b, 2000c). Farther east, in the reentrant occupied by the City of Hacienda Heights, the Fernando is finer grained, consisting of sandy siltstone and fine-grained sandstone with a basal conglomerate (Yerkes, 1972, p. C14). The facies change between the Fernando of the western Puente Hills, including in the subsurface in the Lapworth Oil Field, and the Duarte Conglomerate takes place in the San Gabriel Basin; the base of the Duarte Conglomerate subcrops beneath alluvium of the San Gabriel River.

Late Quaternary Deposits

Fan deposits of several ages overlie the Duarte Conglomerate at the foot of the San Gabriel Mountains (Crook et al., 1987). The San Gabriel Basin includes an uplifted deposit of late Quaternary age referred to as older alluvium; this deposit has well-developed soils. Younger alluvium occupies the modern stream drainage courses. The hills contain extensive landslide deposits.

DISCUSSION

The San Gabriel Basin is bounded on the north by the Sierra Madre fault system, which brings predominantly crystalline rocks of the San Gabriel Mountains over the Duarte Conglomerate and contains slices of Glendora Volcanics and Topanga and Puente sedimentary rocks (Crook et al., 1987). The Sierra Madre system, including the Duarte fault, is divided into western and eastern sections bounded by the Clamshell-Sawpit fault, which extends into the San Gabriel Mountains toward the San Gabriel fault sensu stricto. On the south, the Raymond fault joins the Sierra Madre fault near this boundary. The Raymond fault is predominantly left slip (Crook et al., 1987; Jones et al., 1990; Weaver and Dolan, 2000), whereas the Sierra Madre system is predominantly dip slip, although the latter may contain a component of strike slip on the eastward continuation of the Vasquez Creek fault (Fig. 1).

On the southeast, the San Gabriel Basin gives way eastward to anticlinal hills of the northern Puente Hills and San Jose Hills, including the Walnut and San Jose anticlines, both of which plunge westward toward the basin. The anticlinal hills are separated from nearly flat-lying strata of the San Gabriel Basin by the left-lateral(?) Walnut Creek fault, discovered through analysis of water-well data (California Department of Water Resources, 1966). The Walnut Creek fault does not continue southwest across the northwest Puente Hills (Daviess and Woodford, 1949). This part of the Puente Hills may be anticlinal, too, but most of the south flank of the anticline is truncated at the Whittier fault (Yerkes, 1972; Herzog, 1998; Bjorklund and Burke, 2002). The northwest Puente Hills are cut by the northwest-striking Workman Hill and Whittier Heights faults and the north-striking Handorf fault, all of which lose dip separation northward in the San Gabriel Basin.

The Whittier fault extends across the southern foothills of the Puente Hills to the San Gabriel River at Whittier Narrows, where it turns more northwesterly to become the East Montebello fault of Wright (1991). Like the Walnut Creek fault farther east, the East Montebello fault separates active folds uplifting the Montebello and Repetto Hills from flat-lying strata of the San Gabriel Basin.

The San Gabriel Basin itself contains nearly flat-lying strata and is crossed by major drainages (Rio Hondo, San Gabriel River, Big Dalton Wash) flowing southwestward to collect at Whittier Narrows (Fig. 2A). North of Rio Hondo, streams flow south-southeast across the Raymond fault. Two streams, Walnut Creek and Alhambra Wash, flow close to but on the basin side of the Walnut Creek and East Montebello faults, respectively. The San Gabriel Basin is deepest in the south and shallows northeastward to bedrock ridges, the largest of which are Glendora South Hills.

Miocene History of the San Gabriel Fault System

The middle Miocene tectonics of the western Transverse Ranges was characterized by volcanism (Campbell and Yerkes, 1976), in contrast with today's contractional deformation and an absence of volcanism. Examples of Miocene normal faults reactivated in the opposite sense are the Santa Susana fault (Yeats, 1987; Yeats et al., 1994) and the Whittier fault (Bjorklund et al., 2002). Because the Miocene and modern stress fields are so different, only those Miocene faults that continue to be oriented close to a plane of high shear stress in the present strain regime are likely to be reactivated. Other faults such as the basement boundary in the San Gabriel Basin would simply be overlain unconformably by younger strata. The orientation of Miocene faults is a consideration in tracking the Miocene San Gabriel fault system through the Transverse Ranges.

The San Gabriel fault diverges from the San Andreas fault northwest of the Ridge Basin and converges on the San Jacinto and San Andreas faults at the east end of the San Gabriel Mountains (inset, Fig. 1). The 16–20 Ma basal beds of the Caliente Formation near the northern end of the outcrop of the San Gabriel fault contain anorthosite clasts from the San Gabriel Mountains, indicating right-lateral displacement of the basal Caliente from the Mint Canyon Formation of the Soledad Basin by as much as 75 km (Crowell, 2003; lower estimates of 70 km are from Ehlert, 1982, 2003, and 60 km from Bohannon, 1975; see Yeats and Stitt, 2003, for location). In contrast, Powell (1993) reached a right-slip estimate of 42 km in the San Gabriel Mountains, similar to the 42–44 km estimated by Matti and Morton (1993). The Devil Canyon submarine fan on the southwest side of the San Gabriel fault is offset at least 35 km from its most likely source in the San Gabriel Mountains (Crowell, 2003; Yeats and Stitt, 2003).

In the San Gabriel Mountains, the San Gabriel fault divides into a north strand, or San Gabriel fault sensu stricto, and a south strand, called the Vasquez Creek fault by Powell (1993). Ehlig (1981) documented 22 km right offset of the Permian–Triassic Lowe Granodiorite across the San Gabriel fault sensu stricto, similar to offset of the western edge of a field of small intrusions correlated to the Mountain Meadows Dacite (McCulloh et al., 2001) and the offset of basement terrane contacts matched by Nourse (2002). Powell (1993) found evidence for no more than 5 km of right slip on the Vasquez Creek fault, although McCulloh et al. (2001) found that this offset could be as large as 13 km on the basis of offset of the west edge of the field of small intrusions correlated to the Mountain Meadows Dacite. R. Powell ([2003] in a personal commun. to J. Nourse) now considers the larger value possible. The Vasquez Creek fault merges to the southeast with the Sierra Madre fault, although Nourse (2002) proposed that the right-lateral displacement might continue eastward, not along the Sierra Madre fault but along the Clamshell-Sawpit fault with 15 km of right-lateral displacement. This interpretation requires that both strands of the San Gabriel fault join eastward in the easternmost San Gabriel Mountains. The sum of the displacements on the San Gabriel fault sensu stricto and the Vasquez Creek–Clamshell–Sawpit fault are consistent with the estimate of displacement on the San Gabriel fault farther west by Powell (1993) and the offset of the late Miocene Tarzana fan in the San Fernando Valley from a source in the San Gabriel Mountains (Sullwold, 1960; Fig. 6).

Powell (1993) and Yeats and Stitt (2003) resolved the discrepancy between (1) the large offsets of the basal Caliente from the Mint Canyon (Ehlert, 2003), and (2) the smaller offsets of the Devil Canyon fan from its source in the San Gabriel Mountains and of basement offsets within the San Gabriel Mountains by proposing that the Canton fault, west of the San Gabriel fault, takes up some of the slip. The Canton fault diverges from the San Gabriel fault west of the Ridge Basin (Fig. 1) so that the 60–75 km offset of the basal Caliente Formation as well as of bodies of anorthosite would take place on the combined Canton and San Gabriel faults (Yeats and Stitt, 2003). However, the offset of the Devil Canyon fan from its source and the offset of basement terranes within the San Gabriel Mountains would be measured only on the San Gabriel fault because the Devil Canyon fan unconformably overlies the Canton fault in the east Ventura Basin and heads at the San Gabriel fault (Yeats and Stitt, 2003). Yeats and Stitt (2003) proposed that the Paleogene section of the northeast Ventura Basin, west of the Ridge Basin, may be offset 31 ± 5 km from Paleogene strata in the subsurface northeast of the Santa Susana fault (Winterer and Durham, 1962; Yeats et al., 1994). This offset is permissive but not diagnostic—like the basal Caliente offset—in that it does not match unique stratigraphic units or basement clast types.

Powell (1993) proposed that the Canton fault continues into the San Fernando Valley, and Yeats and Stitt (2003) suggested that the fault might follow the active Verdugo fault marking the southern range front of the Verdugo Mountains. The Verdugo fault separates contrasting basement rocks: Paleozoic(?) metasedimentary rocks, gneiss, migmatite, and granitic rocks on the north (Ehlig, 1975) and more uniform granitic rocks in wells in the San Fernando Valley and in exposures in the Santa Monica Mountains to the south (Yeats, 2001; Wright, 2001). The southeast continuation of the Verdugo fault is the Eagle Rock fault, which intersects the Raymond fault where McCulloh et al. (2001) suggested it might be offset left laterally to the Sierra Madre fault (but see discussion below).

The timing of the shift from the Canton fault to the San Gabriel fault is established in the east Ventura Basin and in the basal Caliente Formation farther north (Yeats and Stitt, 2003). Right-lateral strike-slip began after the deposition of the basal Caliente with anorthosite clasts and Hemingfordian vertebrate fossils, and prior to or during deposition of overlying Caliente with only local clasts (Ehlert, 1982, 2003). This change in sediment source dates the beginning of right slip as 20–16 Ma, about the same time as right-lateral strike-slip along the Clemens Well–Fenner–San Francisquito fault, a precursor to the San Andreas fault (Powell, 1993; Nourse, 2002). The San Gabriel fault established itself in its present position at the edge of the Ridge Basin in the early Mohnian (13.6–9.4 Ma, according to Barron and Isaacs, 2001), on the basis of the presence of the Violin Breccia in the Ridge Basin, additional bodies of breccia in the Mint Canyon Formation in the subsurface, and early Mohnian microfossils within the Devil Canyon conglomerate (Yeats and Stitt, 2003).

In the eastern San Gabriel Mountains and San Gabriel Basin, does the Miocene Canton fault follow the Sierra Madre fault, or does it continue farther south? Either way, a paradox is encountered. Continuity of Paleogene strata between the eastern Puente Hills and the northern Santa Ana Mountains in conjunction with right slip of 8–9 km on the Whittier fault (McCulloh et al., 2000) precludes a strike-slip fault with larger displacement south of the eastern Puente Hills. McCulloh et al. (2001) suggested further that the Mountain Meadows Dacite, dated as 28–27.5 Ma, can be correlated directly to similar rocks in the eastern San Gabriel Mountains and that quartz clasts from the dacite, with distinctive trains of microscopic fluid inclusions, are found in younger strata in the Puente Hills south of the dacite type locality in the San Jose Hills. McCulloh et al. (2001) used these relationships to argue against major strike slip on faults between the San Gabriel Mountains and southern Puente Hills, although the dacite dikes are so widespread in the San Gabriel Mountains that they are questionable piercing points (J. Nourse, 2003, personal commun.).

The Miocene Canton fault, now reactivated as the Verdugo fault, might connect across the Raymond fault to the possible tectonic boundary between gneissoid rocks similar to those in the San Gabriel Mountains and granitic rocks correlated to the Peninsular Ranges batholith; this boundary is reactivated in its eastern reach as the San Jose fault (Fig. 7A). This structure separates contrasting basement, as does the Verdugo fault, with definite Peninsular Ranges basement only to the south. However, the separation of the Miocene Verdugo fault and the basement boundary in the San Gabriel Basin across the Raymond fault is too small to match the 15–13 km left-lateral offset of the eastern, metamorphosed phase of Santa Monica Formation proposed by McCulloh et al. (2001). These observations raise the question: How well controlled is this offset?

The 13–15 km displacement is based on a 14.2 km separation of "spotted slate," part of the metamorphic aureole between the Santa Monica Formation and granitic rocks to the east, 16 km separation of the late Miocene Tarzana fan (Wright, 1991, p. 101–103; Redin, 1991), 13.2 km offset between the Verdugo–Eagle Rock fault and eastern Sierra Madre fault, and 22.5 km offset of the intrusive contact between the Santa Monica Formation and granitic rocks (McCulloh et al., 2001). Tsutsumi (1996, p. 71), using facies equivalents of the Tarzana fan in

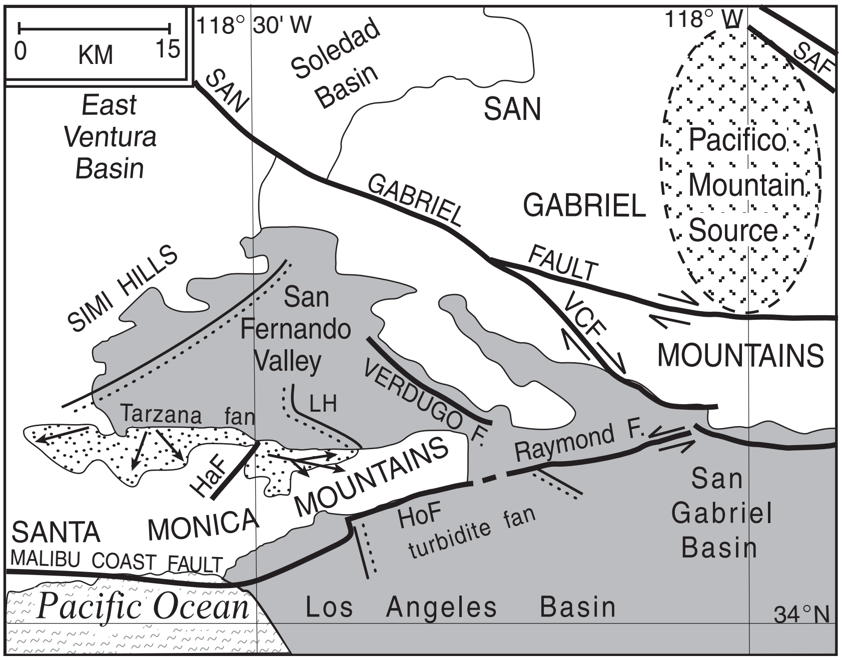


Figure 6. Constraints on Miocene tectonics provided by the late Miocene Tarzana fan of Sullwold (1960). LH—Leadwell high of Wright (2001); HaF—Hayvenhurst fault of Sullwold (1960); HoF—Hollywood fault; VCF—Vasquez Creek fault. Dot pattern shows Tarzana fan outcrop in the Santa Monica Mountains; light line with dot pattern shows edges of fan where controlled by subsurface well data; control south of the Hollywood fault from Redin (1991) and Wright (1991). Miocene paleogeography precludes the use of the Tarzana fan as a piercing point across the Hollywood-Raymond fault. Pacifico Mountain area in the San Gabriel Mountains is the probable source of the Tarzana fan (Sullwold, 1960).

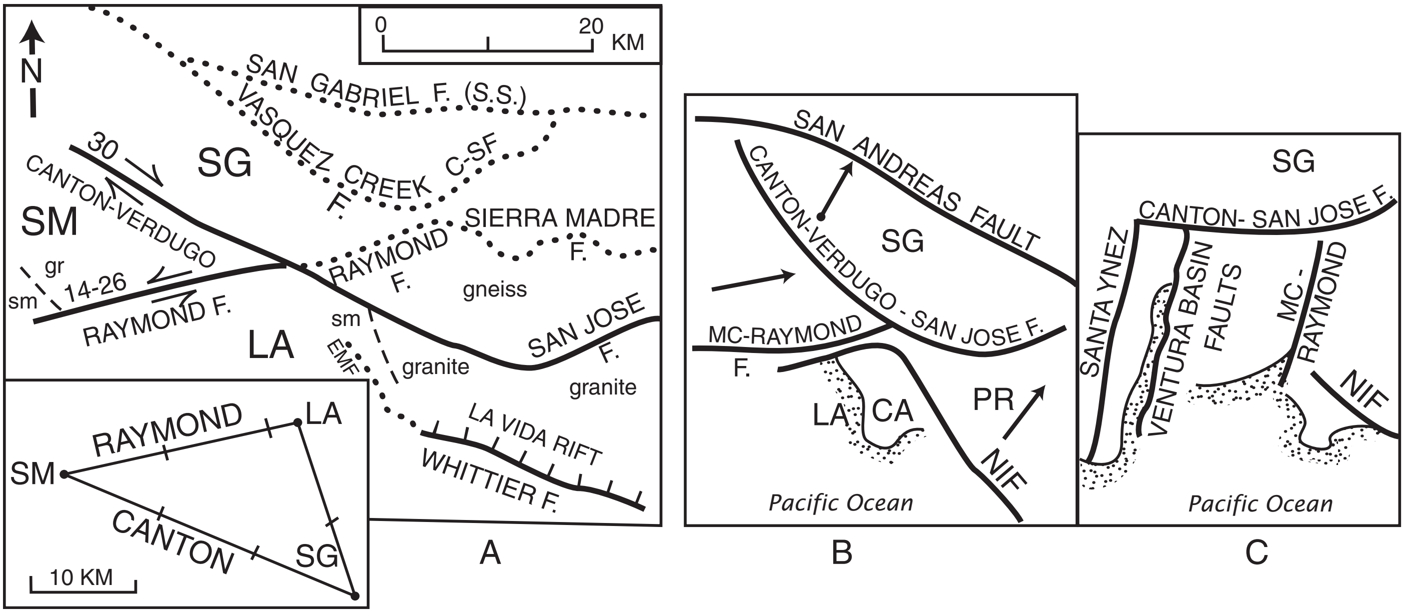


Figure 7. Tectonic models. (A) Proposed middle Miocene faulting to account for 30 km right slip on the Canton fault in the San Gabriel Basin, involving only translation. Canton-Verdugo fault, separating metamorphic rocks of San Gabriel block (SG) from plutonic and low-grade metasedimentary rocks of the Santa Monica Mountains (SM), continues across San Gabriel Basin to connect with San Jose fault. Piercing points across Raymond fault show offset between Santa Monica Mountains and Los Angeles block (LA); sm—Santa Monica Formation; gr—Peninsular Ranges granitic rocks. Inset: Vector diagram with 30 km right slip on Canton fault and 22.5 km left slip on Raymond fault results in 17 km convergence between San Gabriel block and Los Angeles block but little or no strike slip. Convergence would be less if some convergence were accommodated across Miocene Raymond and Canton-Verdugo faults or if the Miocene Canton fault were oriented east-west or east-northeast–west-southwest to account for clockwise rotation of both the San Gabriel and Santa Monica Mountains blocks. Dotted lines show future (post–middle Miocene) faults; EMF—East Montebello fault. La Vida rift of Bjorklund et al. (2002) shown for reference. (B) Paleomagnetically defined rotated blocks of Luyendyk (1991) modified to show Canton–Verdugo–San Jose fault as southern boundary of San Gabriel block (SG) and to show 26° clockwise rotation of northwest Peninsular Ranges determined by Teissere and Beck (1973). Thin line with dots shows shoreline at Palos Verdes Hills in Los Angeles–Catalina block (LA-CA). NIF—Newport-Inglewood fault; MC—Malibu Coast fault. (C) 14–13 Ma reconstruction of Luyendyk (1991) modified to show boundaries in B and to show Canton fault with 30° clockwise rotation restored; other parts of coastline added. In this restoration, the Canton–San Jose fault forms the eastern boundary of the strongly rotated Western Transverse Ranges block of Luyendyk (1991).

the northern Los Angeles Basin, was unable to confirm the offset of the Tarzana fan proposed by Wright (1991) and Redin (1991) because paleocurrent directions in the Tarzana fan measured by Sullwold (1960) are locally parallel to the Santa Monica Mountains owing to a Miocene structural high in those mountains and the Leadwell high of Wright (2001) in the San Fernando Valley, thereby precluding a piercing-point determination (Fig. 6). The eastern edge of a thick turbidite sandstone fan in downtown Los Angeles (Redin, 1991, his Fig. 8) could connect with east-directed paleocurrents in the Tarzana fan with only a few kilometers left-lateral offset (Sullwold, 1960; Fig. 6). The Verdugo–Sierra Madre offset correlation requires that these faults were continuous prior to left slip on the Raymond fault, an assumption that appears unlikely because of their different fault histories. The 22.5 km offset of the intrusive contact depends on how the slate-granite contact between wells 1 and 12 near the base of the northwestern Puente Hills (Fig. 3) is projected across the gneiss terrane to the Raymond fault. Tsutsumi (1996) estimated 24 km, and it could be as high as 26 km.

Suppose that the Miocene Raymond fault terminated at the Miocene Verdugo (= Canton) fault, resulting in its 22.5–26 km left slip annihilating most of the 30 km right slip on the Canton fault documented in the east Ventura Basin (Fig. 7A). This circumstance would reduce strike slip on the basement boundary beneath the San Gabriel Basin to no more than a few kilometers, which could explain the apparent absence of large-scale strike slip between the San Gabriel Mountains and the Puente Hills (McCulloh et al., 2001), including the offset of the Topanga isopachs and the western edge of the Glendora Volcanics. In this scenario, only the western part of the Raymond fault has a Miocene ancestor; the active fault has reactivated the Miocene fault and has propagated east to a junction with the Sierra Madre fault. A vector diagram (Fig. 7A, inset) showing 30 km right slip on the Canton-Verdugo fault and 22.5 km left slip on the proto-Raymond fault would require ~17 km of Miocene convergence between the San Gabriel Mountains and Puente Hills, but relatively little strike slip. The gravity data suggest that the San Jose Hills are underlain by low-density rock, which could be explained by thrusting lower-density sedimentary and volcanic rocks beneath the granitic rocks exposed at the eastern end of the hills (Langenheim and Jachens, 1996, p. 10). Convergence would be less if part of it was accommodated across the Miocene Canton-Verdugo fault.

This discussion is limited to translation, yet Luyendyk et al. (1980) showed through paleomagnetic observations that much of southern California rotated as large discrete blocks beginning in the Miocene (Luyendyk et al., 1985; Fig. 7B). A Miocene reconstruction by Luyendyk (1991) envisioned a Western Transverse Ranges block, bounded to the north

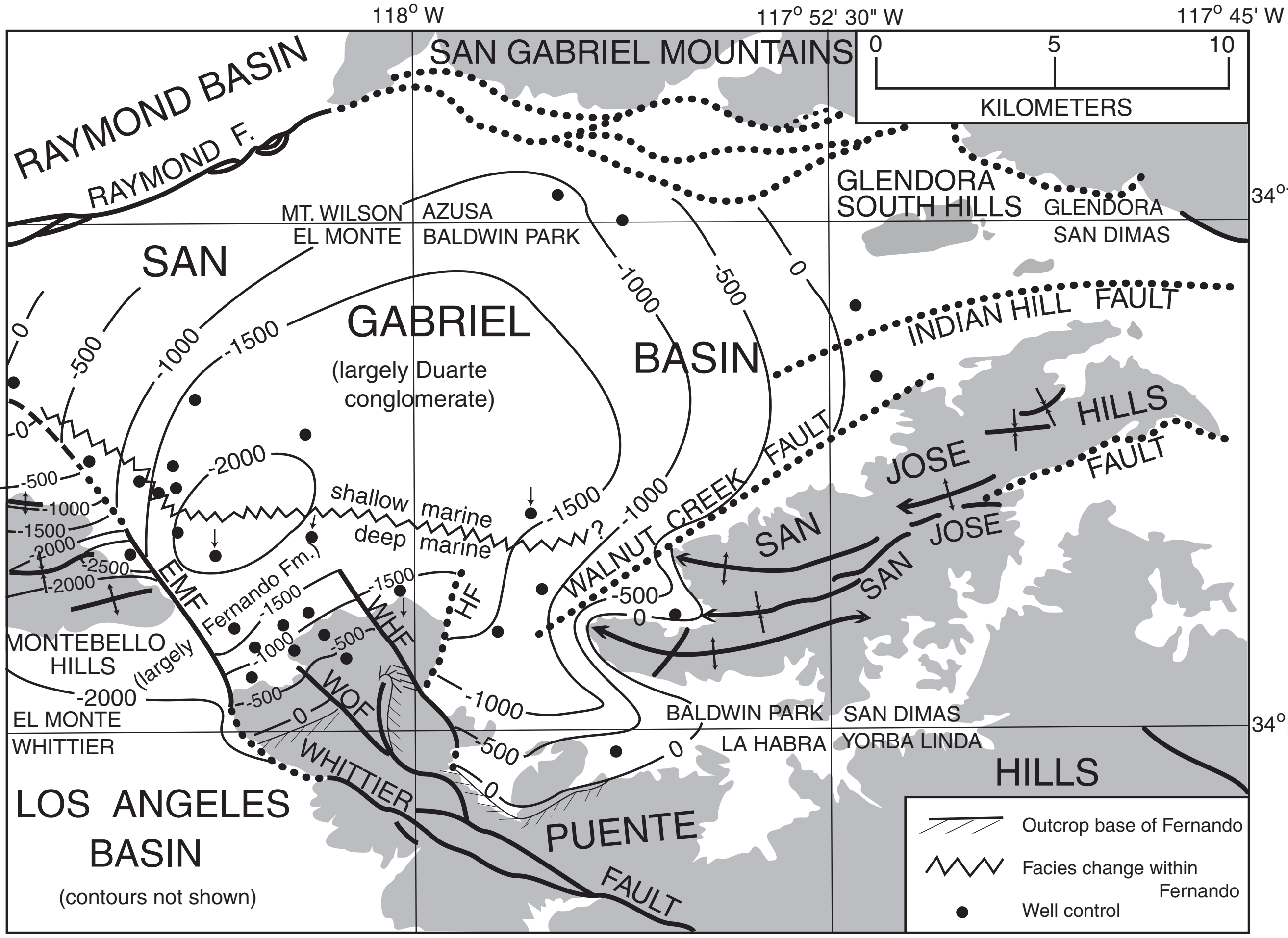


Figure 8. Structure contours, in meters, of the base of the Fernando Formation. South of Whittier fault, structure modified from Bjorklund (2002, his Plate 1). Dots show well control; dot with arrow indicates well did not reach the base of the Fernando. In San Gabriel Basin, structure developed during Fernando deposition; south and west of Whittier and East Montebello faults and in northern Puente Hills and San Jose Hills, structure is at least in part postdepositional. Stratigraphic separation decreases northwest across HF—Handorf fault, WHF—Whittier Heights fault, WOF—Workman Hill fault, and EMF—East Montebello fault; the –1500 m contour is not offset across the Workman Hill fault. Facies boundary is between a sequence of Duarte Conglomerate underlain by basal shallow-marine deposits and a Los Angeles Basin sequence including deep-water Repetto and Pico Members.

and south by the Santa Ynez fault and the Malibu Coast–Santa Monica–Hollywood–Raymond fault, respectively, with 95° clockwise rotation, a San Gabriel Mountains block with about half that amount of clockwise rotation, and an unrotated Peninsular Ranges block (but see following discussion). As I interpret Luyendyk's reconstruction, the Western Transverse Ranges block could be further subdivided into slats bounded by the Red Mountain–San Cayetano fault and the Oak Ridge fault (shown diagrammatically as Ventura Basin faults in Fig. 7C).

In my reconstruction, the San Gabriel block of Luyendyk (1991) is bounded on the south not by the Sierra Madre fault but by the Miocene Canton–Verdugo–San Jose fault (Fig. 7C). In contrast to an unrotated Peninsular Ranges block (Luyendyk, 1991), Teissere and Beck (1973) showed that the Southern California batholith in the Peninsular Ranges is rotated ~26° clockwise from its expected Cretaceous direction. Prothero and Lopez (2001) showed even larger clockwise rotation of upper Paleocene strata in the Santa Ana Mountains. According to these results, this part of the Peninsular Ranges, at least, is tectonically rotated about as much as the San Gabriel Mountains block (SG, Fig. 7B) but significantly less than the Western Transverse Ranges block west of the Canton-Verdugo fault. The 14–13 Ma reconstruction of Luyendyk (1991, Fig. 5) is consistent with 30 km right slip between the San Gabriel block and the Western Transverse Ranges block, although I would place the block boundary at the southern edge of gneissoid rocks in the San Gabriel Basin rather than at the Sierra Madre fault. The Canton–Verdugo–San Jose fault would mark the eastern end of the strongly rotated Western Transverse Ranges block (Fig. 7C).

Pliocene–Pleistocene Syndepositional Tectonics

The structure of the San Gabriel Basin is shown in a structure-contour map of the base of the Fernando-Duarte sequence (Fig. 8), the "Base of Repetto" of Wright (1991, his Fig. 9). Contours south of the Whittier, East Montebello, and Walnut Creek faults reflect postdepositional folding and are not discussed here. The San Gabriel Basin is a broad depression plunging to the southwest toward the Montebello and Repetto Hills. The deepest part of the basin is about one-third as deep as the center of the Los

Angeles trough (Wright, 1991); indeed, the base of the Fernando in the syncline north of the Montebello anticline, on the Los Angeles side of the East Montebello fault, is at least 500 m deeper than the deepest part of the San Gabriel Basin. The orientation of the San Gabriel Basin is at right angles to the orientation of the syndepositional Los Angeles trough (Yeats and Beall, 1991, their Figs. 5, 6), approximately parallel to the Raymond fault to the northwest and the Walnut Creek fault to the southeast. The basin slopes upward toward the Raymond fault.

Two northwest-striking faults in the northwest Puente Hills northeast of the Whittier fault are syndepositional. Daviess and Woodford (1949) showed that the Workman Hill and Whittier Heights faults cut the Repetto (lower Fernando) but not the Pico (upper Fernando). Structure contours of the base of the Fernando (Fig. 8) show no displacement of the –1000 m and –1500 m contours across the Workman Hill fault, indicating a decrease in separation northwestward. The –1500 m contour is offset across the Whittier Heights and Handorf faults, but there appears to be no offset of the deepest part of the basin. I find no evidence to support the continuation of these faults northwestward to the Raymond fault, as shown by McCulloh et al. (2001). Just south of the San Bernardino Freeway between El Monte and Rosemead, a tonal and vegetation lineament near a linear reach of Rubio Wash mapped by Treiman (1991), on trend with the Workman Hill fault, is the northernmost feature that might be related to one of those faults.

The North Whittier Heights Oil Field (Hunter, 1959) and Turnbull Oil Field (Mefferd, 1962) provide well control indicating that the Whittier Heights fault has normal separation, down to the east. A downward decrease in fault dip suggests that this fault may be listric. The Whittier Heights fault merges with the Workman Hill fault, which also has normal separation (Mefferd, 1962; Yerkes, 1972). The age relationships of these faults are established in outcrop (Daviess and Woodford, 1949); these normal faults formed during Fernando deposition.

A third normal fault, the Handorf fault (Fig. 9C; Table 2), intersects the Whittier Heights fault (Hunter, 1959) but strikes northerly. This fault comprises the eastern range front of the northwestern Puente Hills. Farther north, on the north side of San Jose Creek, an area of older alluvium terminates eastward at the northward projection of the Handorf fault. I interpret this as evidence that the Handorf fault cuts older alluvium and that San Jose Creek is antecedent to uplift of the west side of the fault. However, as for the other faults, there is no evidence for this fault north of the exposures of older alluvium.

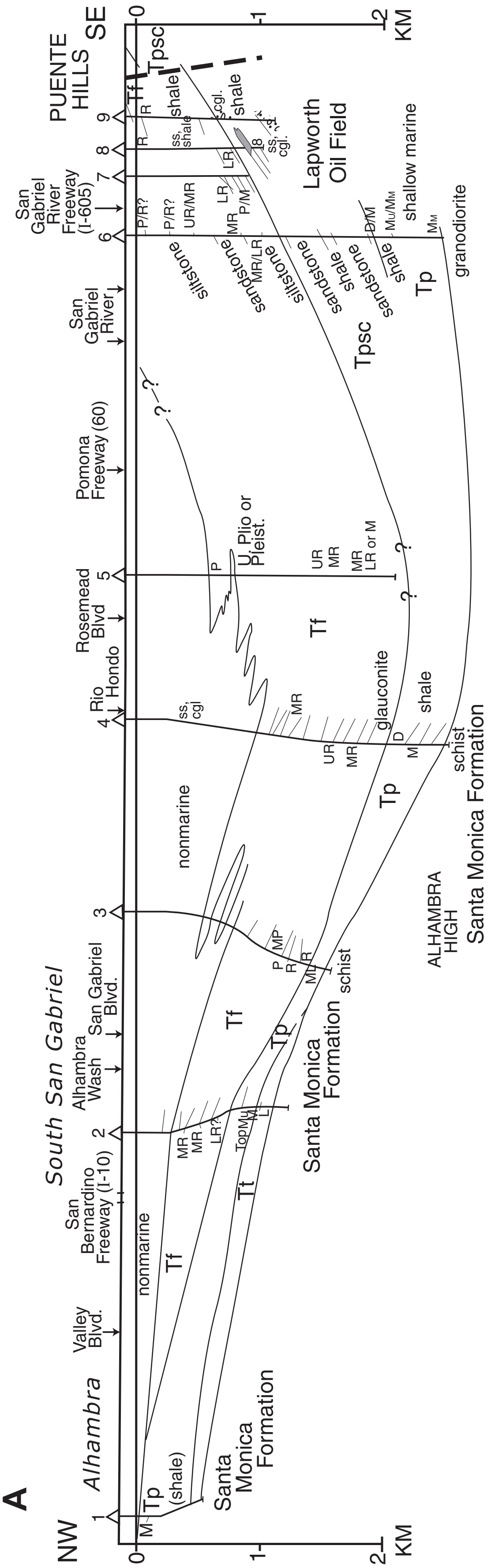
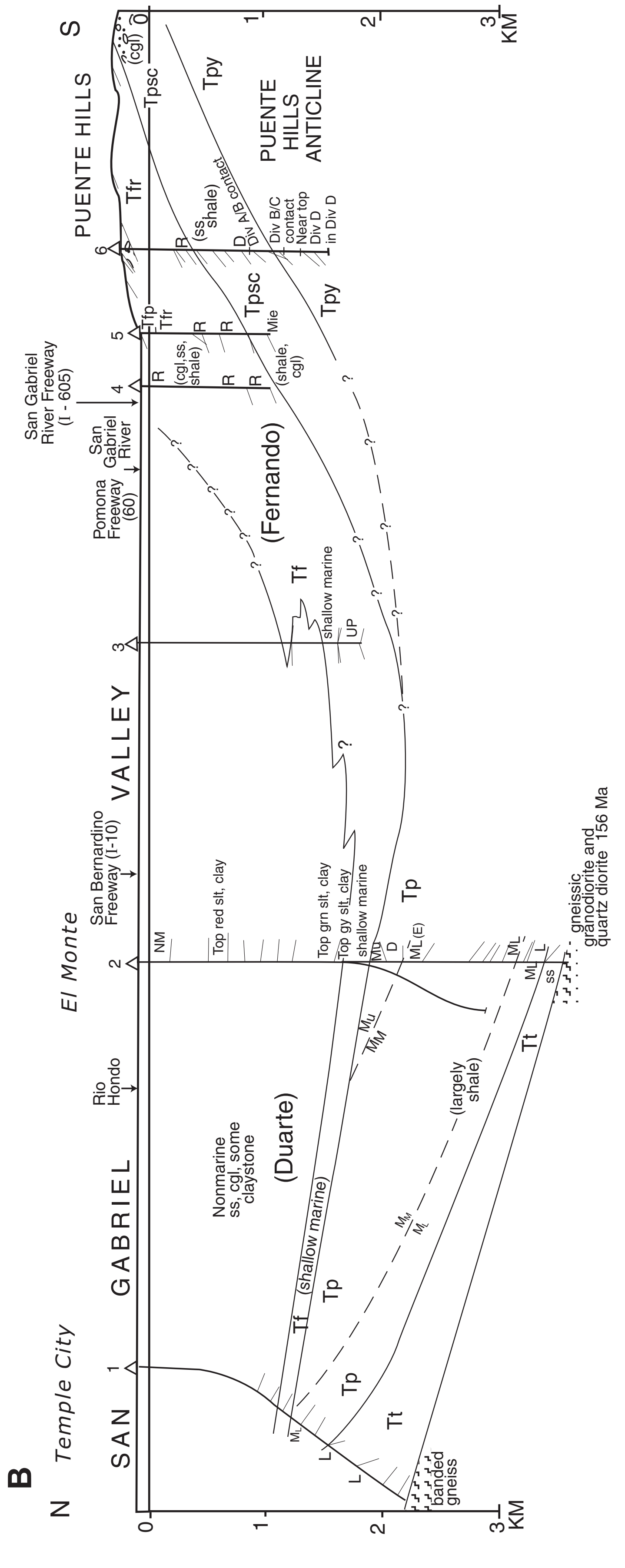


Figure 9. Cross sections, based on well data, from west to east through San Gabriel Basin and adjacent parts of the Puente and San Jose Hills. No vertical exaggeration; scale in kilometers. For well names, see Table 2. Abbreviations for all sections: L—Luisian; M—Mohnian; M_L—lower Mohnian; M_U—upper Mohnian; D—Delmontian; MM—middle Miocene; UM—upper Miocene; P/M—Pliocene/Miocene boundary; for other abbreviations, see Figure 5. (A) Western San Gabriel Basin parallel to East Montebello fault, showing gradation between deep-water Fernando Formation at edge of Puente Hills (right) and nonmarine strata in Alhambra (left). Transition from shallow- to deep-water facies toward northwest Puente Hills indicates postdepositional uplift of Puente Hills and imposes a north dip on the Fernando Formation. In Lapworth Oil Field, oil is trapped in deep-water turbidites that had an oil source to the north, in the San Gabriel Basin. Section shows no downdip evidence for Workman Hill fault. (B) Central San Gabriel Basin to northwest Puente Hills. Sycamore Canyon Member in outcrop is overlapped downdip by Fernando Formation. Pliocene–Pleistocene nonmarine strata (NM) give way to deep-water strata in direction of Puente Hills. (C) Northwest Puente Hills to southern San Gabriel Basin, showing normal-separation Whittier Heights and Handorf faults. Presence of nonmarine strata to right suggests section is northwest of Walnut Creek fault. (D) Central Puente Hills to San Jose Hills, showing fold belt. Walnut anticline housing Walnut Oil Field is referred to as Puente Hills anticline by Dibblee (1999) and Puente Hill anticline by Tan (2002b). w1, w2—First and Second Walnut oil-producing zones. (E) Eastern San Gabriel Basin to San Jose Hills, showing eastward shallowing of basin. Walnut Creek fault separates Topanga in well 5 from La Vida Member in outcrop. Glendora Volcanics are present in this section but are absent in sections A and B (to west).



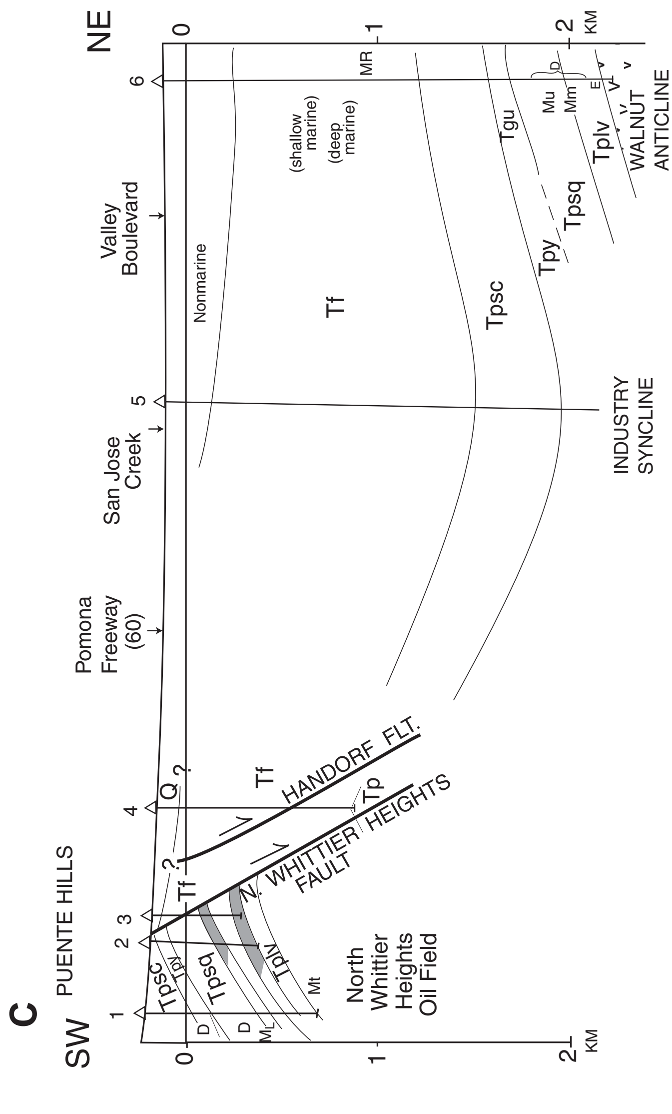


Figure 9 (*continued*).

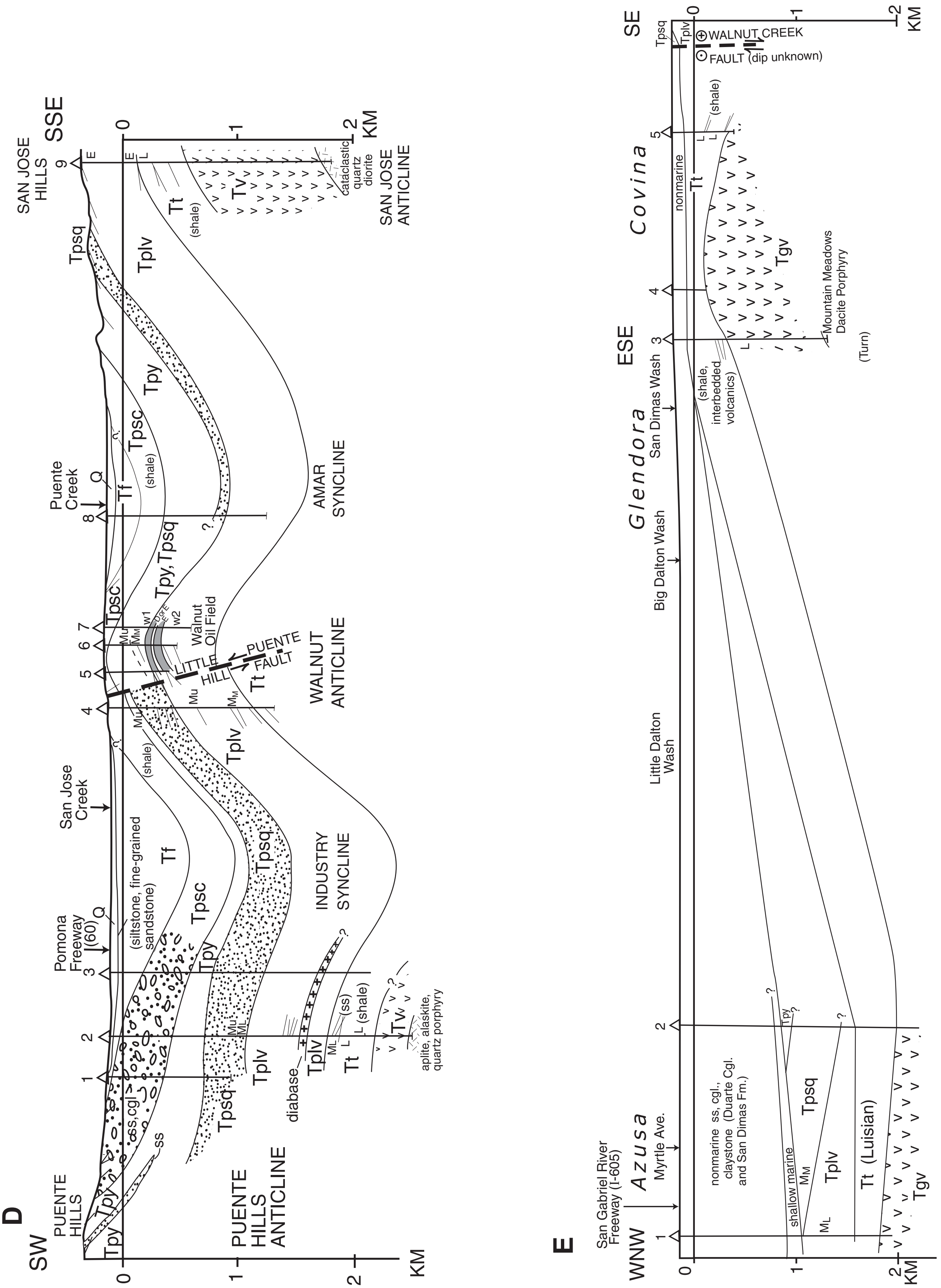


Figure 9 (*continued*).

The facies boundary between the area of thick Duarte Conglomerate with a thin basal shallow-marine section (Ferris section, Fig. 5) and the thick deep-water Repetto and Pico Members of the Los Angeles Basin (all other sections in Fig. 5 except that the strata of the Riskas Rosemead section is gradational between the two facies) provides insights into the timing of uplift of surrounding ranges (Figs. 8, 9A, 9B, 9E). The San Gabriel Basin deepened southward in the direction of the Repetto, Montebello, and Puente Hills, indicating that those hills were uplifted after deposition of the Pliocene–lower Pleistocene sequence. In the Los Angeles Basin, uplift of the Puente Hills postdated deposition of the nonmarine Pleistocene Coyote Hills Formation, which contains clasts of basement rocks with a provenance beyond the Puente Hills, and predated and accompanied deposition of the overlying La Habra Formation, which contains abundant clasts of Puente Hills provenance (Yerkes, 1972, p. 24–25). This is evidence that these hills were uplifted during contractional deformation on folds and faults south of the San Gabriel Basin. On the other hand, the San Gabriel Mountains must have been elevated enough to supply clasts to the Duarte Conglomerate. Blythe et al. (2000) showed, on the basis of apatite fission-track and (U-Th)/He analyses, that the most recent cooling of the San Gabriel Mountains accompanied uplift and denudation beginning at ca. 7 Ma and possibly accelerating at 3 Ma, the time of deposition of the Duarte Conglomerate.

The East Montebello fault in the Montebello Oil Field has reverse separation of Fernando horizons, southwest side down. This fault was probably syndepositional, with the southwest block subsiding more than the northeast block. This ancestor to the active East Montebello fault, discussed below, might have continued northwest to the Raymond fault, as shown by McCulloh et al. (2001), but well data do not require it.

Earthquake Sources

The earthquake sequence of 1987–1991 indicates that the heavily populated San Gabriel Basin is subject to earthquake hazard. Here the major earthquake sources are identified and characterized in a clockwise direction, beginning with the Raymond fault.

Raymond Fault

This fault comprises part of the Transverse Ranges Southern Boundary fault system, a west-trending system of reverse, oblique-slip, and strike-slip faults that extends for >200 km along the southern edge of the Transverse Ranges (Fig. 1; Dolan et al., 1997, 2000). Other members of this system are the Malibu Coast, Santa Monica, and Hollywood faults.

The Raymond fault extends 25 km from the Los Angeles River east to east-northeast across the San Gabriel Valley to a junction with the Sierra Madre fault at the foot of the San Gabriel Mountains. A sharp gravity gradient connects the western end of the Raymond fault across the Los Angeles River floodplain with the eastern end of the Hollywood fault (Chapman and Chase, 1979), although an active, through-going fault connection between the Hollywood fault and the Raymond fault has not been documented (Dolan et al., 1997). It was suggested above that the Miocene ancestor of the active Raymond fault was responsible for the large-scale offset of the intrusive contact between the Santa Monica Formation and granitic rocks and that this ancestral fault extended only to the intersection with the Verdugo–Eagle Rock fault, so that movement along the Raymond fault east of this junction began much later.

The fault is convex southward, consisting of a western section that strikes east and an eastern section, adjacent to the San Gabriel Basin, that strikes east-northeast. Left-deflected drainages, shutter ridges, sag ponds, and pressure ridges in right-stepping restraining bends (Weaver and Dolan, 2000) indicate that the Raymond fault is predominantly a left-slip fault, although south-facing scarps along the central reach of the fault indicate a component of dip slip due to motion around a 25° restraining bend (Crook et al., 1987; Weaver and Dolan, 2000). The 3.5 km left separation of a basement-cored ridge may represent total displacement on the eastern part of the fault (Weaver and Dolan, 2000). The Raymond fault joins the Sierra Madre fault south of Santa Anita Wash and south of the Clamshell-Sawpit fault in the foothills of the San Gabriel Mountains (Weaver and Dolan, 2000). The 1988 Pasadena earthquake of M_W 4.9 probably occurred on the Raymond fault, on the basis of the fault-plane solution of the main shock and the distribution of aftershocks (Jones et al., 1990), which delineated a fault dipping 80° north.

Trenches excavated by Crook et al. (1987), Weaver and Dolan (2000), and Marin et al. (2000) show that the most recent previous earthquake on the Raymond fault occurred 1000–2000 yr ago (Weaver and Dolan, 2000). Between five and eight earthquakes occurred between 40 and 2 ka, a maximum average recurrence interval of 5.7–10 k.y. (Crook et al., 1987; Weaver and Dolan, 2000). Between three and five of these events occurred between 41.5 and 31.5 ka, an average recurrence interval of ≤3300 yr (Weaver and Dolan, 2000). These data may indicate a cluster of earthquakes, or they may be a sign of undetected events.

TABLE 2. WELLS USED IN CROSS SECTIONS

	Well name
Figure 9A	
1	Chevron SP Core Hole
2	Exxon South San Gabriel 1-2
3	Occidental Cordova
4	Harry Riskas Rosemead
5	Potrero Newman
6	Shell Pellissier
7	R.R. Bush Pellissier
8	J. Herley and P. Kelley Lapworth
9	Exxon Pellissier
Figure 9B	
1	Chevron Live Oak Park
2	Chevron Ferris
3	Hillman Long Mulholland
4	Hilo Bishop Hilo Pellissier
5	Bradford Bishop Baldwin
6	Continental Baldwin
Figure 9C	
1	Barnsdall Baldwin
2	Capital Harry Kline 2-1
3	Capital Harry Kline 1-2
4	Capital 3-1
5	Jergins Handorf
6	Texaco McGinnis
Figure 9D	
1	McVicar Rowland Estate 1
2	McVicar Rowland Estate 3-1
3	McVicar Rowland Estate 2-1
4	Ark Hurley A-1
5	Greuter Guerrieri
6	Lautenbach
7	Vanderhoof 2
8	D and B Dietzel
9	Texaco Garnier
Figure 9E	
1	Unocal Irwindale Duarte
2	Chevron Consolidated Rock Products
3	Texaco Covina 27-1
4	Goodwin Charter Oaks
5	Texaco Covina 5-1

Sierra Madre Fault System

This fault is part of a set of north-dipping reverse faults extending from the Santa Barbara Channel east to an intersection with the San Jacinto fault northeast of the Chino Basin (Fig. 1). The Sierra Madre fault is exposed near the base of the San Gabriel Mountains for 75 km from its merger with the Santa Susana fault in the northern San Fernando Valley east to the San Antonio Canyon fault, east of which the range front is formed by the Cucamonga fault. The fault may be divided into western and eastern sections, bounded by its intersection with the Raymond fault on the south and the Clamshell-Sawpit fault on the north

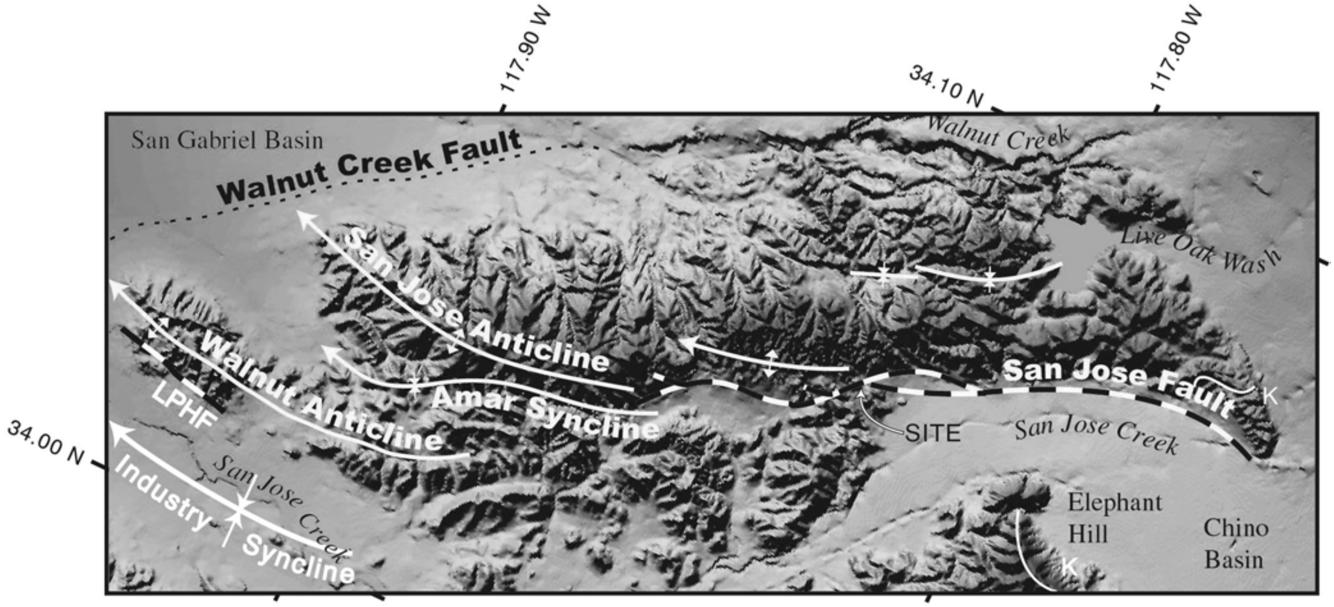


Figure 10. Digital elevation model of San Jose Hills and adjacent northern Puente Hills, created by using RiverTools. San Jose fault marks southern range front of San Jose Hills, but becomes blind westward. San Jose and Walnut anticlines create topography on the west, adjacent to San Gabriel Basin. Note en echelon step of San Jose anticline adjacent to a left bend in San Jose fault and in drainage divide. Geocon fault study area on California State Polytechnic University, Pomona, is labeled SITE. K—exposures of Cretaceous plutonic rocks. LPHF—Little Puente Hill fault. North of San Jose Hills, Walnut Creek fault cuts a steep canyon in older alluvium. Structure follows Tan (2000b, 2000c) modified by Geocon (2001).

(Crook et al., 1987). West of this intersection, the Vasquez Creek fault (the southern strand of the San Gabriel fault of Ehlig [1975]) intersects the Sierra Madre fault at a low angle to strike. Nourse (2002) suggested that the Vasquez Creek fault connects with the Clamshell-Sawpit fault rather than (or in addition to) connecting with the eastern Sierra Madre fault.

From the rupture zone of the 1971 San Fernando earthquake east to the Cucamonga fault, the Sierra Madre fault appears on the basis of geomorphic expression to be less active than the westernmost Sierra Madre fault or the Cucamonga fault (Crook et al., 1987). Following criteria established by Bull (1964), Crook et al. (1987) noted that alluvial-fan heads in the vicinity of the 1971 rupture are incised to a lesser degree and hence are more active than fans farther east in the Pasadena area. In addition, Crook et al. (1987) were unable to identify any fault scarps or displaced sediments east of the 1971 rupture younger than late Pleistocene. Rubin et al. (1998) excavated a trench east of the 1971 rupture and documented two earthquakes in the past 18 k.y. resulting in 10.5 m slip, yielding a minimum slip rate of 0.6 mm/yr.

East of the Raymond fault, the Sierra Madre fault, including the Duarte fault, is expressed as a series of southward-convex lobes, and at several localities, the most active strand is south of the range front, which is itself marked by less active or inactive older strands (Crook et al., 1987; Tucker and Dolan, 2001). Crook et al. (1987) located the fault in several trenches, but were unable to obtain age control because of the lack of availability of AMS (accelerator mass spectrometry) radiocarbon dating. Tucker and Dolan (2001) excavated a trench and several large-diameter boreholes in San Dimas, near the Glendora Tunnel, where extensive geotechnical observations are available (Proctor et al., 1992). Tucker and Dolan (2001) found evidence for at least 14 m of slip on the Sierra Madre fault between 24 and 8 ka, but no surface rupture since 8 ka. These data lead to a minimum slip rate of 0.6 mm/yr since 24 ka and a minimum of 0.9 mm/yr between 24 and 8 ka, in contrast to a slip rate of 2–5 mm/yr on the Cucamonga fault to the east (Dolan et al., 1996; Morton and Matti, 1987). Surface rupture near the trench site was the result of earthquakes with M >7, consistent with the interpretation by Rubin et al. (1998) of two surface displacements with total slip of 10.5 m during the two most recent surface ruptures observed in their trench across the western Sierra Madre fault north of Pasadena. The most likely explanation of M >7 events on a fault with such a low slip rate is that the entire Sierra Madre fault could rupture at the same time (Tucker and Dolan, 2001). The Raymond or Cucamonga faults could also rupture at the same time, but it is clear that the Raymond fault has ruptured at least once and possibly several times and the Cucamonga fault has ruptured several times since the most recent surface rupture on the eastern Sierra Madre fault (Dolan et al., 1996; Weaver and Dolan, 2000, and 2003, personal commun.).

San Jose Fault and Related Anticlines

The Upland strike-slip earthquakes of 1988 and 1990 northeast of the San Jose Hills were attributed to the San Jose fault by Hauksson and Jones (1991), whose kinematic model assumed that the San Jose fault is predominantly left-lateral strike slip. A groundwater barrier extends from the eastern tip of the San Jose Hills to the vicinity of the Upland earthquakes (California Department of Water Resources, 1970; Cramer and Harrington, 1987), and Hauksson and Jones (1991) concluded that this barrier is the northeast continuation of the San Jose fault.

However, the San Jose fault lies at the southern range front of the east-northeast–trending San Jose Hills (Fig. 10). Geotechnical investigations on the campus of California State Polytechnic University at Pomona (Geocon, 2001) indicated that the San Jose is an active reverse-separation fault. Prior to the Geocon investigations, Herber (1999) estimated a slip rate on the San Jose fault of 0.4–0.8 mm/yr based on soil development on a scarp 1.4 m high on the campus. Because of the lack of success in previous trench excavations, Geocon (2001) based its conclusions on a series of closely spaced boreholes along several traverses across a subtle topographic bench on the campus. They discovered two shallowly to moderately north-dipping thrust faults in an anastomosing pattern; the most recent displacement is ~1 m and occurred since 3500 yr B.P. on the basis of radiocarbon dating of faulted alluvium. This finding shows that the San Jose fault is active, but is a reverse-separation fault south of the San Jose Hills. The change in strike from southwest at the site of the Upland earthquakes to west-southwest at the south edge of the San Jose Hills might account for the change southwestward from left slip to reverse slip (Fig. 2B).

The San Jose Hills are underlain by a west-southwest–plunging, south-vergent anticline (Fig. 10; Olmsted, 1950) that deformed the La Vida Member of the Puente Formation, the Topanga Formation, Glendora Volcanics, and Cretaceous plutonic rocks (Tan, 2000c). The anticlinal axis steps left where the San Jose fault bends left. Uplift of the San Jose Hills appears to be related to anticlinal folding; the anticlinal axis is expressed in topography (Fig. 10). The San Jose fault dies out westward at the surface and is a blind thrust farther west. A cross section through the western end of the anticline (Fig. 9D) shows that the Fernando Formation is involved in the folding in the down-plunge direction. The lack of thinning of strata toward the anticlinal axis is evidence that folding postdates all stratigraphic units involved in the folds.

The San Jose fault is succeeded southward by the Amar syncline and the Walnut anticline (Fig. 9D). The Walnut anticline (the Puente Hills anticline of Dibblee, 1999, and Puente Hill anticline of Tan, 2000b) is also south vergent (Olmsted, 1950) and west plunging, creating topography, and the Little Puente Hill fault follows the southern range front of the Little Puente Hills (Tan, 2000b), in the same relationship that the San Jose fault has to the San Jose Hills. The Walnut anticline is separated from north-dipping strata in the Puente Hills proper by the Industry syncline, the axis of which follows San Jose Creek (Figs. 9D, 10). The next anticline to the south is strongly asymmetric. Its axis consists of several en echelon segments, and most of its south flank is cut off by the Whittier fault (Durham and Yerkes, 1964; Yerkes, 1972). Despite the appearance of a fold-thrust belt (Fig. 9D), the ratio of length to width (aspect ratio) of these folds is much lower than in a typical Appalachian Valley and Ridge or Canadian Rockies fold-thrust belt. None of the folds continues westward past the San Jose and Puente Hills, suggesting that they do not continue past the Walnut Creek fault.

In conclusion, the north-dipping San Jose fault and the blind fault underlying the Walnut anticline are separate structures, although they could merge into a single fault at seismogenic depths. They are reverse-fault sources, not strike-slip fault sources; however, the en echelon, left-stepping pattern might indicate a component of left slip on the Walnut Creek fault to the west. Both faults are north dipping.

Walnut Creek Fault

This fault was first reported by California Department of Water Resources (1966) on the basis of analysis of water-well data. The fault is nowhere exposed, and it does not have tectonic geomorphic expression. The fault separates folded strata of the San Jose and Puente Hills from nearly flat-lying strata in the San Gabriel Basin. The western range front is not strongly linear because of the presence of anticlinal ridges, but the northwestern end of the outcrop, taking into account the anticlinal ridges, is strongly linear, especially in the western San Jose Hills in Covina, where Walnut Creek flows close to the range front and cuts a gorge 30–40 m deep in older alluvium.

The Walnut Creek fault may be the on-strike continuation of the source fault of the left-lateral, strike-slip Upland earthquakes. The San Jose and Walnut anticlines die out eastward away from the fault, suggesting that these are transpressional structures related to the Walnut Creek fault. Accordingly, some left slip between the San Gabriel Basin and the San Jose Hills may be accommodated on this fault, together with the Indian Hill fault to the north (California Department of Water Resources, 1966) and the San Dimas Canyon fault in the foothills of the San Gabriel Mountains (Tucker and Dolan, 2001; Nourse, 2002). These faults may account for the difference in slip rate between the Cucamonga and Sierra Madre faults. However, the slip rate on the Walnut Creek fault must be low on the basis of its lack of tectonic geomorphic expression on predevelopment aerial photographs. In addition, the fault appears to die out between the Walnut anticline and the northwesternmost Puente Hills.

Whittier and East Montebello Faults

The Elsinore fault is one of the major right-lateral strike-slip faults of the Peninsular Ranges. The Elsinore fault bifurcates northwestward into the Chino fault, with a more northerly strike, and the Whittier fault, with a more westerly strike (Fig. 1). The Puente Hills are limited to the region where the Whittier fault strikes west-northwesterly, suggesting that uplift of the hills may be related to the restraining bend marked by the more westerly strike of the Whittier fault. The Whittier fault may have an anomalous strike because it has reactivated a zone of weakness, a Miocene normal fault with its north side down (Bjorklund et al., 2002). In addition, much of the Pliocene and early Pleistocene displacement may be by reverse slip (Yeats and Beall, 1991; Bjorklund et al., 2002). The fault dips north with reverse separation along most (but not all) of its length. However, the late Quaternary evidence is for nearly pure strike slip (Gath, 1997). Part of the uplift of the Puente Hills may accompany reverse faulting. This interpretation implies strain partitioning.

The total right separation on the Whittier fault is 8–9 km on the basis of offset facies and isopachs of Paleogene strata (McCulloh et al., 2000). This estimate faces the difficulty that north of the Whittier fault, Paleogene facies boundaries turn abruptly westward in the southeastern Puente Hills, subparallel to the fault. However, the Santa Rosa Basalt, dated at 10.6 Ma, is offset across the Elsinore fault by no more than 15 km (Hull and Nicholson, 1992), providing an upper bound for displacement on the Whittier fault. Bjorklund and Burke (2002) constructed isopachs of the Sycamore Canyon Member of the Puente Formation without any horizontal offset, although the isopachs south of the fault are parallel to the fault, permitting an undetermined amount of strike slip.

The late Pleistocene to Holocene strike-slip rate on the northern Elsinore fault is 5.3–5.9 mm/yr (Millman and Rockwell, 1986), whereas it is only 2–3 mm/yr at Santa Ana Canyon (separating the Puente Hills from the Santa Ana Mountains in Fig. 1) on the basis of offset of dated terraces (Gath, 1997; Gath et al., 1988; Rockwell et al., 1988, 1991). Farther west, the strike-slip rate is at least 2 mm/yr (Rockwell et al., 1988; Gath et al., 1992). The Whittier fault could accumulate 8–9 km of right slip in 3–4 m.y. at a rate of 2.5 mm/yr.

At Whittier Narrows, the Whittier fault turns more northwesterly to become the East Montebello fault, and at Alhambra Wash, a strand of the East Montebello fault has a strike-slip rate of only 0.2 ± 0.1 mm/yr. A second, larger scarp to the west was not studied in detail (Gath et al., 1994; Gath and Gonzalez, 1995). The slip rate decreases westward because part of the slip escapes along other structures, including the Chino fault, the Coyote folds that mark the surface expression of the Puente Hills blind thrust (Shaw et al., 2002; Myers et al., 2003), and the Montebello and Repetto Hills anticlines.

McCulloh et al. (2001) suggested that the East Montebello fault extends northwest to an intersection with the Raymond fault. The subsurface geology offers no support for an active fault northwest of the Repetto Hills. Treiman

(1991) examined old topographic maps and air photographs and summarized existing geotechnical studies on faulting in the vicinity of the East Montebello fault. He mapped a locally prominent east-facing scarp, vegetation lineaments, a break in slope, and a low linear ridge and swale that extend >6 km northwest from Rio Hondo toward Alhambra. These features merge northwest into a gentle warp that can be traced north to the San Bernardino Freeway (Interstate 10) but no farther. The East Montebello fault in the subsurface in the Montebello Oil Field has reverse separation and has trapped an oil accumulation (East area) against the fault, providing well control (Wright, 1991, p. 88–89). The northeast-side-up subsurface relationships at Montebello, similar to those at the Whittier fault adjacent to the Puente Hills, are in contrast to the active structure, which is northeast-side-down. This difference may be due to a greater component of strike slip in the late Quaternary.

The largest aftershock of the 1987 Whittier Narrows earthquake was located near the East Montebello fault with a fault-plane solution consistent with right slip on a northwest-striking fault (Bent and Helmberger, 1989).

I conclude that the East Montebello fault is the northern end of the Whittier fault and that Whittier fault displacement is absorbed by the Montebello and Elysian Park anticlines, the latter as defined by Oskin et al. (2000). The lineations and broad topographic features observed by Treiman (1991) north of the Repetto Hills may represent an incipient northwest propagation of a reactivated fault, but there is no evidence that the active fault continues to the Raymond fault. The relatively flat gravity and aeromagnetic fields reported by Langenheim and Jachens (1996) and Langenheim (1999) show no lineations that might correspond to the East Montebello, Workman Hill, or North Whittier Heights faults.

Puente Hills Blind Thrust

The 1987 Whittier Narrows earthquake highlighted the significance of a zone of north-dipping blind thrusts in the northern Los Angeles Basin, expressed at the surface as anticlines. Davis et al. (1989) used balanced cross sections and subsurface well data to delineate a thrust ramp called by them the Elysian Park blind thrust. The anticlinal feature overlying the thrust was called the Santa Monica Mountains anticlinorium, which Davis et al. (1989) interpreted as a fault-propagation fold that was uplifted to produce the Santa Monica Mountains, the Elysian, Repetto, and Montebello Hills, and the Puente Hills. They estimated the long-term slip rate on the blind thrust as 2.5–5.2 mm/yr. Shaw and Suppe (1996), using a relatively high quality two-dimensional seismic data set, also constructed balanced cross sections and interpreted the anticlines to have been generated by fault-bend folding, following Suppe (1983). Their blind thrust consists of thrust flats and ramps, and the folds are generated as a result of the nonplanar geometry of the thrust surface. Their thrust ramps produce dip panels that they called trends, and their thrust flats underlie the lowlands, principally the central Los Angeles Basin. The long-term slip rate on the thrust ramp beneath their Elysian Park trend was estimated as 1.7 ± 0.4 mm/yr.

The fault-plane solution for the Whittier Narrows earthquake showed a moderately north-dipping fault plane with an east strike (Hauksson and Jones, 1989). Releveling after the earthquake showed an uplifted area extending from the Santa Fe Springs anticline northward across the intervening La Habra syncline to the Montebello anticline (Lin and Stein, 1989). Shaw and Shearer (1999) relocated the main shock and aftershocks of the earthquake, illuminating a fault plane dipping ~25° north, a dip consistent with the fault-plane solution and with fault-plane reflections on a seismic reflection profile west of the crest of the Santa Fe Springs anticline between 3 and 7 km below sea level. The fault tip is located beneath the south side of the Santa Fe Springs anticline on the basis of a trishear kinematic model (Allmendinger and Shaw, 2000; Shaw et al., 2002) and an elastic dislocation model (Myers et al., 2003). The long-term slip rate was estimated as 0.44–1.7 mm/yr (0.62–1.28 mm/yr preferred) by Shaw et al. (2002) and 1.3 ± 0.5 mm/yr for the past 1.2 m.y. by Myers et al. (2003). High-resolution seismic reflection profiles across the updip projection of the active axial surface between the Santa Fe Springs anticline and low-dipping strata to the south provide structural data within 15 m of the surface (Pratt et al., 2002). Dolan et al. (2003) used geotechnical borehole data to demonstrate that the central section of this fault has generated at least four large-magnitude earthquakes in the past 11,000 yr.

The age of initiation of thrusting is based on the age of the oldest strata that show thinning across the anticline. For the East Coyote anticline, the oldest strata showing growth are upper Repetto (Myers et al., 2003), implying an age of initiation of thrusting of 4–3.5 Ma (see left-hand stratigraphic section in Fig. 5 for age control).

In the shallowest few kilometers, the thrust is segmented, and fault-plane reflections confirm that the blind thrust beneath the Santa Fe Springs anticline is offset from the thrust beneath the Coyote Hills to the east and also from the thrust beneath downtown Los Angeles to the west (Shaw and Shearer, 1999; Shaw et al., 2002). The 1987 Whittier Narrows aftershock distribution and the coseismic uplift were limited to that segment of the thrust beneath and adjacent to the Santa Fe Springs anticline. Uplift in 1987, based on releveling, was centered on the La Habra syncline between the Montebello and Santa Fe Springs anticlines (Lin and Stein, 1989), suggesting that the Montebello anticline and La Habra syncline may be more related to strike-slip events on the Whittier fault, whereas the Santa Fe Springs anticline is part of a larger structure that was uplifted during blind-thrust earthquakes like the one in 1987.

The blind thrust is generally assumed to pass beneath the San Gabriel Basin as a décollement (e.g., Ryberg and Fuis, 1998; Fuis et al., 2001). If so, there does not appear to be a close correlation between the blind thrust and uplifted terrain east and west of the San Gabriel Basin. Uplift accompanying the blind thrust affects the Coyote Hills and Santa Fe Springs anticline, but not the Puente Hills, which are more likely to owe their uplift to the restraining bend in the Whittier fault.

Active Tectonics

Figure 11 shows the active faults in and around the San Gabriel Basin. The Puente Hills thrust is blind and is expressed at the surface as a series of anticlines, including the Coyote Hills. The San Jose fault is partly blind. All sources are discussed above except for the Chino fault, which is from C. Walls and E. Gath (2001, personal commun. in Treiman, 2002) and Hauksson and Jones (1991).

The Sierra Madre fault marks the most pronounced geomorphic boundary in the region, between the basin and the San Gabriel Mountains, yet its convergence rate based on trenching and on geomorphology is <1 mm/yr. The convergence rates on the Cucamonga fault to the east and the Elysian Park anticline to the west (0.8–2.2 mm/yr from Oskin et al., 2000) are higher than the rates on dip-slip faults between them. The strike-slip rates on the Whittier fault and possibly on the Raymond fault are also higher than the dip-slip rates on the Sierra Madre or Puente Hills faults. A complete analysis of these rates and a comparison with satellite-derived rates (Bawden et al., 2001) are premature because of a lack of information about slip rates on the San Jose fault, the blind fault beneath the Walnut anticline, and the reverse-slip component of the Whittier fault that is producing uplift of the Puente Hills.

The inset of Figure 11 shows a tectonic model of the San Gabriel Basin and Puente–San Jose Hills bounded by right-lateral faults striking northwest (East Montebello fault and Chino fault) and a left-lateral fault striking northeast (Walnut Creek fault). The San Gabriel Basin and Chino Basin are stable, unfolded blocks with low topographic relief separated by a more mobile block, the Puente–San Jose Hills, that has active folding. West of the East Montebello fault is downtown Los Angeles, another mobile block containing the Elysian Park anticline. These blocks are bounded on the north and south by active reverse faults (Sierra Madre fault, Puente Hills fault). This geometry suggests escape-block tectonics (Walls et al., 1998), although the satellite data of Bawden et al. (2001) suggest uniaxial convergence without east-west extension. The left-lateral Raymond fault and the right-lateral Whittier fault are superimposed on this system, and Walls et al. (1998) considered these faults to contribute to escape-block tectonics and east-west extension. The combination of strike-slip and dip-slip faulting may be expressed on a finer scale in seismicity, including reverse-fault and strike-slip-fault earthquakes reported by Cramer and Harrington (1987) and the September 2002 M 4.8 strike-slip earthquake on a northeast-trending fault near the Whittier fault (Hauksson et al., 2002).

Although active faults constitute the margins of the San Gabriel Basin, the cities in the interior of the basin are not underlain by active earthquake sources. The Puente Hills blind thrust may continue beneath the San Gabriel Basin as a thrust flat (Ryberg and Fuis, 1998), but this fault plane was not reactivated seismically in the 1987 Whittier Narrows earthquake, and it may lie beneath the seismogenic zone. The surface-rupture hazard for cities within the San Gabriel Basin is lower than that for downtown Los Angeles, the location of the Elysian Park anticline, or the area south of the Whittier fault, within the thrust ramp of the Puente Hills thrust. However, the presence of active faults on all sides of the San Gabriel Basin and the existence of soft sediments at the surface indicate that the seismogenic hazard is still high.

SUMMARY AND CONCLUSIONS

Study of subsurface well data provides insights about a largely unknown basin in the Transverse Ranges that is part of metropolitan Los Angeles, unknown because it is entirely covered by flat-lying Quaternary deposits. This analysis permits the relationship of the basin to adjacent highlands to be worked out, resulting in a better understanding of Cenozoic tectonics of the Transverse Ranges.

Pre-Tertiary basement rocks are divided into gneissoid rocks on the north, similar to rocks in the San Gabriel Mountains, and Jurassic Santa Monica Formation intruded on the east by granitic rocks related to the Peninsular Ranges batholith. The boundary between these terranes appears to be tectonic and suggests that the San Gabriel composite terrane extends into the San Gabriel Basin and that the present range front of the San Gabriel Mountains, marked by the Sierra Madre fault, is a younger structure. The contact between the Santa Monica Formation

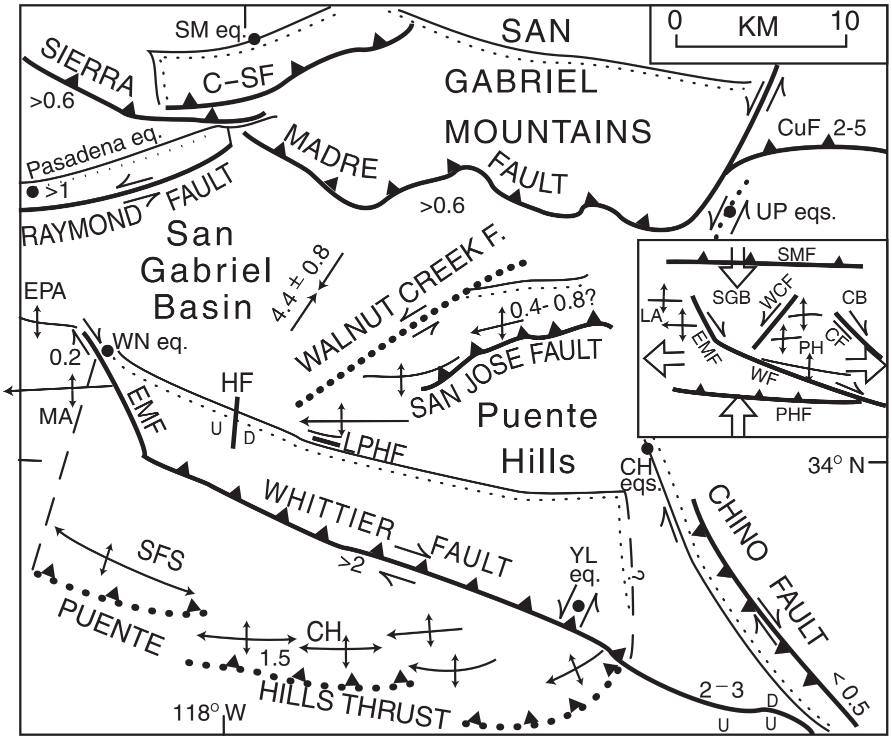


Figure 11. Earthquake sources in and near San Gabriel Basin. Heavy lines—surface traces of active faults (dotted where covered or blind); polygons with lighter lines and dots—map projections of dipping earthquake sources. The downdip boundaries of the Chino, Clamshell-Sawpit, Puente Hills, and Raymond faults are located on the basis of the location of moderate-size earthquakes that are presumed to nucleate near the base of the seismogenic zone. Whittier fault not projected; base of seismogenic zone is probably north of the Yorba Linda earthquake location and may merge with base of Puente Hills seismogenic zone. Solid circles locate significant earthquakes: CH eq.—1989 earthquake possibly related to Chino fault from Hauksson and Jones (1991); SM eq.—1991 Sierra Madre earthquake on Clamshell-Sawpit fault; UP eqs.—Upland earthquakes; dotted line shows orientation of aftershocks; WN eq.—1987 Whittier Narrows earthquake on Puente Hills blind thrust; YL—3 September 2002 Yorba Linda earthquake (M 4.8) on a northeast-striking fault based on aftershock distribution (Hauksson et al., 2002). Other abbreviations: CuF—Cucamonga fault; CH—Coyote Hills anticline; C-SF—Clamshell-Sawpit fault; EPA—Elysian Park anticline (source area not shown; see Oskin et al., 2000); HF—Handorf fault; LPHF—Little Puente Hill fault; MA—Montebello anticline; SFS—Santa Fe Springs anticline. Numbers by faults are late Quaternary slip rates (in mm/yr) where known; Chino fault from C. Walls and E. Gath (2001, personal commun., in Treiman, 2002). Slip rates across San Jose, Walnut Creek, and reverse component of Whittier fault not known. Opposing arrows in San Gabriel Basin show convergence rate across the Los Angeles Basin based on uncontaminated GPS (Global Positioning System) sites and interferometric satellite radar imagery (Bawden et al., 2001). Inset: Tectonic model of active faulting showing stable blocks of low topographic relief and no active folding (SGB—San Gabriel Basin; CB—Chino Basin) and folded blocks of moderate relief (PH—Puente–San Jose Hills and downtown LA—Los Angeles). These are separated by strike-slip faults: EMF—East Montebello fault; WF—Whittier fault; WCF—Walnut Creek fault; CF—Chino fault. North-south compression occurs across SMF—Sierra Madre fault and PHF—Puente Hills fault. The result is north-south shortening and east-west extension (open arrows), although the extension is not confirmed by satellite data.

and intrusive rocks is offset left laterally at least 22.5 km across the Raymond fault.

Pre-Miocene unmetamorphosed strata are absent in the San Gabriel Basin and the adjacent northern Puente Hills and Repetto Hills. The Oligocene Mountain Meadows Dacite, found in the San Jose Hills, appears to be correlated with intrusive rocks in the eastern San Gabriel Mountains, implying no large-scale strike slip since that time. Rocks mapped as Sespe Formation postdate the Mountain Meadows Dacite and are Miocene in age on the basis of the presence of Mountain Meadows Dacite clasts and paleomagnetic and vertebrate fossil evidence. As such, the Sespe of this area may be considered to be the basal part of the Miocene sequence that follows.

The Glendora Volcanics follow a north trend and are thickest in the western San Jose Hills. The western edge of the volcanic field crosses the San Gabriel Basin and the westernmost Puente Hills. The volcanic rocks are interbedded with and overlain by the middle Miocene Topanga Formation, which is thickest in the northern Puente Hills and San Jose Hills, thinning eastward to a shoreline and westward to zero on the Alhambra High in the western San Gabriel Basin. A conglomerate member in the western San Jose Hills is probably derived from the San Gabriel Mountains, but for the most part, the range front in middle Miocene time was not as prominent as it is today, on the basis of the facies of the Topanga. The upper Miocene Puente Formation is correlated from the Puente Hills westward into the San Gabriel Basin, where much of the formation was deposited in deep water. The thickest Puente is in the Puente Hills, which occupy a former basin axis. The youngest member of the Puente, the Sycamore Canyon Member, is conglomeratic in the western Puente Hills but finer grained in the San Gabriel Basin, indicating that this proximal turbidite fan has its axis in the outcrop, not in the present basin to the west. The Pliocene–Pleistocene Fernando Formation of the Los Angeles Basin changes facies in the western San Gabriel Basin to a basal transgressive deposit overlain by a thick, largely nonmarine sequence including conglomerate, referred to here as the Duarte Conglomerate.

New information from the San Gabriel Basin provides a solution to the “San Gabriel fault problem,” in which a 60–75 km offset of middle Miocene deposits between Lockwood Valley and the Soledad Basin is contrasted with an offset of 42–44 km across the San Gabriel fault between the east Ventura Basin and the San Gabriel Mountains. The apparent contradiction is resolved by a middle Miocene Canton fault that diverges from the San Gabriel fault west of the Ridge Basin and extends into the San Fernando Valley, probably on the south side of the Verdugo Mountains. But this solution raises the problem of how to account for right slip of up to 30 km on the Canton fault in the San Gabriel Basin because the distribution of Mountain Meadows Dacite and clasts derived from it appears to preclude large offset. Furthermore, the Raymond fault, on which 22.5 km left offset of the eastern end of the Santa Monica Formation has occurred, must join the Verdugo fault, on which up to 30 km right offset has occurred, thereby canceling out most of the strike slip and implying that the Raymond fault did not extend east to the San Gabriel Mountains in the Miocene. If Miocene displacement on the Canton and Raymond faults is by pure strike slip, the San Jose Hills must converge on the Puente Hills with ~17 km of shortening, an interpretation favored by low-density rocks beneath the San Jose Hills revealed by gravity data. An alternate solution involves clockwise rotation, in which the Peninsular Ranges must rotate along with, but separately from, the San Gabriel Mountains block and the Western Transverse Ranges block (cf. Teissere and Beck, 1973; Prothero and Lopez, 2001). Convergence would be much less if the middle Miocene strike of the Canton fault were east to east-northeast.

The syndepositional Pliocene–Pleistocene San Gabriel Basin trends east-northeast, a Transverse Ranges trend, in contrast to the northwest trend of the Los Angeles trough, which reflects a Peninsular Ranges trend. The facies boundary between thick Duarte Conglomerate and deep-water Fernando Formation trends east and indicates that the Puente Hills and Repetto Hills were not yet emergent. Northwest-striking normal faults in the westernmost Puente Hills were formed during Fernando deposition.

The Puente and San Jose Hills currently form a triangular elevated and folded block flanked by the right-slip Chino fault on the east and the left-slip(?) Walnut Creek fault on the west. The San Gabriel Basin is an unfolded, stable block of low relief to the west, bordered by the right-slip East Montebello fault, west of which is the folded Elysian Park block that includes downtown Los Angeles. This configuration, together with the east-trending Sierra Madre fault to the north and the Puente Hills blind thrust to the south, is consistent with north-south shortening and east-west extension, although satellite data suggest that the present-day convergence is uniaxial. Higher slip rates are found on the left-lateral Raymond fault and right-lateral Whittier fault. The triangular Puente Hills uplift may be related to the restraining bend in the Whittier fault when compared with the more northwesterly Elsinore fault to the southeast and the East Montebello fault to the northwest. There are no independent earthquake fault sources within the San Gabriel lowland, but all the lowland boundaries are controlled by active faults, so the hazard is still severe.

ACKNOWLEDGMENTS

This project was supported by Award 00HQGR0070 from the Earthquake Hazards Reduction Program of the U.S. Geological Survey. Additional support was received from the Southern California Earthquake Center, which is funded by National Science Foundation Cooperative Agreement EAR-0106924 and USGS Cooperative Agreement 02HQAG0008. The California Geological Survey made available advance copies of their geologic maps of the Baldwin Park, El Monte, and San Dimas quadrangles, and Tom Wright provided me with additional subsurface well data. Gary Huftile worked on the East Montebello fault and Montebello Oil Field. Data repositories at California State University at Long Beach, University of California at Santa Barbara, and California State University at Bakersfield supplemented well data from the California Department of Oil, Gas, and Geothermal Resources, which lacked directional surveys and paleontological reports. Discussions with Eldon Gath, Tania Gonzalez, David Herzog, Gary Huftile, Dan Myers, Tom Rockwell, Siang Tan, Jerry Treiman, Hiroyuki Tsutsumi, Chris Walls, and Tom Wright were especially helpful. The paper was reviewed critically by James Dolan, Jon Nourse, and Associate Editor Martha Gerdes. Figure 10 was created by Sam VanLaningham and Chris Krugh; other illustrations were prepared by Kristi Weber. SCEC Contribution No. 756.

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Manuscript Received by the Society 25 February 2003
Revised Manuscript Received 31 October 2003
Manuscript Accepted 30 November 2003

Printed in the USA