**Middle Miocene reconstruction of the central and eastern San Gabriel Mountains, southern California, with implications for evolution of the San Gabriel fault and Los Angeles basin**

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**ABSTRACT**

Geological mapping of basement rocks in the central and eastern San Gabriel Mountains reveals a consistent range-scale tectonostratigraphic sequence dismembered into diamond-shaped blocks by late Cenozoic strike-slip faults. These faults and contemporaneous reverse faults record brittle response of the San Gabriel block to stresses that accompanied development of the transform plate boundary in southwestern California. Sequential restoration of northwest-striking right-lateral faults and northeast-striking left-lateral faults is accomplished in map view by matching distinct Proterozoic and Mesozoic crystalline sheets that occur at similar structural levels. This procedure removes 16 km of Quaternary dextral slip on the Scotland–San Jacinto–Glen Helen fault system, variable (1–3 km) of Pliocene-Quaternary sinistral slip on the Stoddard Canyon, San Antonio Canyon, Sunset Ridge, San Dimas Canyon–Weber, and Pine Mountain faults, and 22 km of late Miocene dextral displacement on the north branch San Gabriel–Icehouse Canyon–Lytle Creek fault system. The model also incorporates 15 km of late Miocene dextral displacement on the Sawpit Canyon–Clamshell fault, feeding slip from the south branch San Gabriel fault onto the eastern segment of the north branch. Effects of late Cenozoic shortening within the San Gabriel block are not restored.

The deepest exposed portion of the tectonostratigraphy is the Pelona Schist, a polydeformed assemblage of metagraywacke, metabasalt, and metachert, structurally overlain by greenschist-facies mylonite derived from Paleoproterozoic gneiss and Mesozoic plutons. Especially conspicuous upper-plate marker units include Paleoproterozoic porphyritic granite augen gneiss, the Late Triassic Mount Lowe intrusion, and Late Cretaceous quartz diorite or granodiorite. The remarkable along-strike continuity of these crystalline sheets provides multiple piercing lines that project across the San Andreas fault into the Chocolate Mountains.

Palinspastic reconstruction incorporating 160 km restoration of the San Gabriel block along the San Andreas fault yields a middle Miocene paleogeography containing several provocative features: (1) continuity of the Vincent thrust and Mount Lowe intrusion between the San Gabriel Mountains and Chocolate Mountains (2) reassembly of the late Oligocene Telegraph Peak–Mount Barrow granite and associated rhyolite-dacite intrusions, and (3) demarcation of a broad zone of transtension within...
a right step between the early-mid Miocene Clemens Well fault and an inferred borderland transform fault. The transtensional zone contains a middle Miocene mafic intermediate dike swarm emplaced along conjugate shear fractures in San Gabriel basement rocks. This zone is bounded on the east by the ancestral San Antonio Canyon fault, the south end of which facilitated opening of the Los Angeles pull-apart basin.

INTRODUCTION

The San Gabriel Mountains (Figs. 1–2) contain a complicated assemblage of crystalline rocks disrupted by a network of brittle faults associated with late Cenozoic development of the Pacific-North American transform plate boundary. Proterozoic and Mesozoic rocks of the San Gabriel block have long been utilized as piercing points for reconstructions of the southern San Andreas fault system (Crowell, 1952, 1962; Hill and Dibblee, 1953; Ehlig, 1968, 1975; Powell, 1993; Matti and Morton, 1993; Dillon and Ehlig, 1993). All of these tectonic models position the San Gabriel Mountains somewhere near the present-day Salton Sea during middle Miocene time, east of the Frazier Mountain block and west of the Orocopia and/or Chocolate Mountains (compare Figures 1A–C). However, Miocene configuration of the San Gabriel block and its geometric relationship to the future Los Angeles basin remains controversial, largely due to differing interpretations of displacement on various branches of the San Gabriel fault (Figs. 1B and 1C, see also Powell, 1993). This paper examines details of the San Gabriel fault system within the San Gabriel Mountains, and presents a middle Miocene palinspastic reconstruction of the region. New constraints on Miocene activity of the San Gabriel fault and associated faults provide fresh insight into the kinematic development of the Los Angeles basin.

Reconstruction of the San Gabriel Mountains basement requires correlation of distinct metamorphic and plutonic sheets between multiple fault blocks. Field relationships described in this paper include mapping by Perry Ehlig (1958, 1975) north of the San Gabriel fault. Ehlig’s work is integrated with recent mapping (Nourse et al., 1998a, 1998b; Nourse, unpub.) and other studies (Morton, 1973; Dibblee, 1982; Jacobsen, 1983; May and Walker, 1989; Morton and Matti, 1991; Norum, 1997) to define a coherent tectonostratigraphy through the San Gabriel Mountains block east of Mount Wilson (Fig. 3). Unique offsets of this tectonostratigraphic sequence and crosscutting relationships involving early Miocene and middle Miocene intrusive rocks constrain the kinematics of late Cenozoic strike-slip faulting in the region.

PREVIOUS WORK IN THE SAN GABRIEL MOUNTAINS BLOCK

The San Gabriel Mountains block (Fig. 2A) preserves a protracted history of tectonism, only the latest phase of which is related to the San Andreas and the Sierra Madre–Cucamonga fault systems that form its north and south boundaries, respectively. Despite proximity to the Los Angeles metropolitan area, the range has yet to be completely mapped at 1:24,000 or even 1:50,000 scale. In addition to geologic complexity, other obstacles include rugged relief (locally >2500 m), the inherently unstable nature of slopes that have lost cohesion because of brittle cataclasis, and persistence of chaparral and poison oak at lower elevations. Fortunately, a network of highways, fire roads, and fire breaks provides good exposures that can be correlated with accessible outcrops in canyon bottoms. Figure 2A shows Perry Ehlig’s 1975 compilation of bedrock geology in the San Gabriel block. Field and geochronological studies bearing on rock unit correlations are summarized below.

The earliest descriptions of San Gabriel Mountains basement rocks are detailed by Arnold and Strong (1905) and Hershey (1912). Hershey proposed an Archean (pre-Belt Series) age for the schist of Sierra Pelona, but it is unclear whether the larger body in the eastern San Gabriel Mountains was mapped. Subsequently, Pelona Schist was reported to be truncated on the northeast by the San Andreas fault (Noble, 1926). However, the large magnitude (200+ km) of strike-slip displacement on the San Andreas fault was not postulated until much later (Hill and Dibblee, 1953; Crowell, 1962). Recognition of Pelona-type schist in the Orocopia/Chocolate Mountains played an important role in these interpretations. In the meantime, mapping in the central San Gabriel Mountains (Miller, 1934) delineated a Mesozoic(?)-batholith (Mount Wilson diorite) intruded into banded gneiss and augen gneiss of presumed Precambrian age.

Perry Ehlig devoted much of his career to mapping the eastern and central San Gabriel Mountains high country. His significant contributions include detailed descriptions of sheared rocks along the Vincent thrust (Ehlig, 1958, 1968, 1975, 1981) and definition of petrologic zones within the Mount Lowe intrusive complex (Ehlig, 1981; Barth and Ehlig, 1988). Other noteworthy publications proposed cross-fault correlations of the Pelona Schist, Mount Lowe intrusion, and middle Tertiary conglomerate to localities northeast of the San Andreas fault in the Orocopia/Chocolate Mountains region (Ehlig, 1975; Dillon and Ehlig, 1993). Of particular interest to this paper is evidence for 22 km of dextral displacement on the north branch of the San Gabriel fault and speculation for early right-lateral movements on the Sawpit Canyon fault (Ehlig, 1981; Dibblee, 1982; Dillon and Ehlig, 1993).
A growing body of geochronological data has aided correlation of basement units within the complexly faulted San Gabriel Mountains block. Preliminary U/Pb zircon work by Silver et al. (1963) established a Mesoproterozoic age for emplacement of the anorthosite body in the western San Gabriel Mountains. Later U/Pb study (Silver, 1971) reported Paleoproterozoic ages for band gneiss into which porphyritic granites (now augen gneisses) were intruded. A Triassic age was also determined for bodies of “Parker Mountain-Lowe granodiorite” (Silver, 1971), and Carter and Silver (1971) reported a Cretaceous U/Pb age for a granite body in the Josephine Mountain intrusion. Silver’s work has been refined and augmented by additional isotopic, geochemical, and geochronological studies. For example, Rb/Sr, trace element, and U/Pb analyses have demonstrated the primitive petrologic character of the Mt Lowe intrusion (Joseph et al., 1982) and verified a Late Triassic age of 218 ± 2 Ma (Barth et al., 1990). Conventional U/Pb zircon analyses coupled with ion microprobe analyses have yielded a better constrained age of 1191 ± 3.5 Ma for the anorthosite-jotonte-syenite complex (Barth et al., 1995a; 2001). Other work by Barth et al. (1995b) documented a strong degree of crustal contamination in tonalite and granite of the Josephine Mountain intrusion, which yielded discordant zircons with interpreted lower intercept ages of 76–81 Ma and 72 ± 3 Ma. Similarly, tonalite and granite intruded into the metasedimentary strata of Ontario Ridge in the eastern San Gabriel Mountains yielded discordant zircons with interpreted lower intercept ages of ca. 85 Ma and 78 ± 8 Ma, respectively (May and Walker, 1989). U/Pb zircon work on Proterozoic gneisses in the study area is limited to one analysis reported from Glendora Ridge (Ehlig, 1981).

Petrologic studies from the past two decades include detailed petrographic and geochemical data that provide the basis for correlating undated portions of plutonic and gneissic rock units of the study area. The palinspastic reconstruction presented here also aligns map-scale basement folds and homoclinal dipping sections. Foliation orientations from peripheral regions are documented by Ehlig (1958), Morton (1973), Dibblee (1982), Jacobsen (1983) May and Walker (1989), and Morton and Matti (1991).

**DEFINITION AND CORRELATION OF LITHOSTRATIGRAPHIC UNITS**

The east-central San Gabriel Mountains reveal a folded stack of crystalline sheets constituting the lower and upper plates of the latest Cretaceous-Paleocene Vincent thrust (Figs. 2 and 3). Pioneering work by Perry Ehlig (1958, 1968) characterized this gently to moderately south-dipping thrust contact along a strip of high country extending from Mount San Antonio to Mount Baden-Powell. The lower plate of the Vincent thrust system is composed of metamorphosed deep marine sedimentary and mafic volcanic rocks (Pelona Schist). The upper plate, composed of Proterozoic gneiss intruded by tabular Mesozoic plutons, is separated from Pelona Schist by a greenschist facies mylonite zone of variable thickness, derived mainly from upper-plate protoliths (Nourse, 1991; Nourse and Litzenburg, 1998), although the uppermost part of the Pelona Schist is also intensely sheared (Ehlig, 1981; Jacobson, 1983).

New mapping from the area between Mount Wilson and Middle Fork Lytle Creek is presented in Figure 3A. This work provides details not included on previously published maps (Jennings and Strand, 1969; Ehlig, 1981; Dibblee, 1982, 1998; Bortugno and Spittler, 1986; May and Walker, 1989). For example: (1) the distribution of Proterozoic units is more clearly defined, with new subdivisions (2) additional Mesozoic units are distinguished within the Proterozoic complex (3) several metaplutonic bodies of probable Triassic age are recognized (4) greenschist facies mylonite associated with the Vincent thrust is extended to several isolated regions south of the San Gabriel fault (5) foliation orientations define several new folds in the basement complex, and (6) patterns in the mapped tectonostratigraphy provide multiple piercing lines across the north branch San Gabriel fault system and across several younger northeast-striking left-lateral faults.

**Pelona Schist (map unit KTps)**

At the deepest level of the tectonostratigraphy lies Pelona Schist, composed of interlayered greenschist facies metagraywacke ("greenschist"), metabasalt ("greenschist"), and metabasalt. Primary sedimentary and volcanic structures are generally transposed. Within the upper few hundred meters of the schist penetrative foliation is oriented parallel to the Vincent thrust and upper-plate mylonitic fabric. This foliation defines map-scale open folds with subhorizontal west- or northwest-trending axes (Ehlig, 1958; Jacobson, 1983).

The Pelona Schist is believed by many to represent part of a marine basin that was subducted beneath North American basement during latest Cretaceous or Paleocene time (Haxel and Dillon, 1978; Ehlig, 1981; Jacobson et al., 2000). Ion probe analyses of individual detrital zircons in metagraywacke indicate sediment derivation from Paleoproterozoic, Triassic, Jurassic, and Middle to Late Cretaceous sources (Jacobson et al., 2000). Debate continues about the duration of sedimentation in the Pelona basin, the tectonic setting of this basin, and the polarity of subsequent subduction (Ehlig, 1968; Haxel and Dillon, 1978; Nourse and Litzenburg, 1998; Jacobson et al., 2000; Silver and Nourse, 2001).

The contact between Pelona Schist and overlying mylonite provides a structural marker useful for deducing sense and magnitude of displacement on late Cenozoic faults. Internal stratigraphic markers, such as thick layers of greenschist abundant at higher structural levels, facilitate interpretation of displacements on the San Jacinto and San Antonio Canyon fault systems in the northeastern San Gabriel Mountains (Norum, 1997).
Figure 1. Simplified geologic maps of southern California illustrating: (A) Present-day location of the San Gabriel Mountains, configuration of major strike-slip faults, and distribution of Pelona–Orocopia–Chocolate Mountains schist bodies (shown in squiggly pattern). Modified from Figure 1 in Dillon and Ehlig (1993). (B) Widely cited middle Miocene palinspastic reconstruction showing restoration of the San Gabriel Mountains along major dextral strike-slip faults. Based on Ehlig (1981) and Dillon and Ehlig (1993); modified from Figure 5 in Matti and Morton (1993). FM—Frazier Mountain, LG—Lowe Granite, LM—Liebre Mountain, SCM—southern Chocolate Mountains. Fault abbreviations as follows: SGF—San Gabriel fault, NSGF—north branch San Gabriel fault, SSGF—south branch San Gabriel fault, PBF—Punchbowl fault, SAF—San Andreas fault, SFF—San Francisquito fault, FF—Fenner fault, CWF—Clemens Well fault. This model restores 240 km on the San Andreas fault, 22 km on the north branch San Gabriel fault, and 38 km on the south branch San Gabriel fault. (C) Alternative middle Miocene palaeogeology showing San Gabriel Mountains restored along major strike-slip faults (modified from Powell, 1993, Figure 11). Fault abbreviations as follows: CF—Canton fault, NSGF—north branch San Gabriel fault, SSGF—south branch San Gabriel fault, VCF—Vasquez Creek fault. This model restores 162 km on the San Andreas fault, 22 km on the north branch San Gabriel fault, 5 km on the Vasquez Creek fault (a.k.a. south branch San Gabriel fault), and 15 km on the Canton fault.
Vincent thrust mylonite (map unit KTmy)

This unit (Figs. 4A and 4B) consists of mylonitized upper-plate granite, granodiorite, quartz diorite, diorite, gneiss, or amphibolite, retrograded and sheared during movement on the Vincent thrust. The Vincent thrust mylonite varies in thickness from 10 m to 1000 m. A characteristic green color results from chlorite and epidote alteration of hornblende- and biotite-rich protoliths.

The mylonite exhibits a penetrative foliation generally oriented parallel to the thrust contact with Pelona Schist. The thickest exposures occur in the East Fork San Gabriel Canyon between Mount San Antonio and Mount Baden-Powell. Other exposures form east-west elongate antiformal windows directly south of the north branch San Gabriel fault.

Mylonitization occurred in Late Cretaceous or Paleocene time. The older age limit is constrained by analyses of upper-plate Mount Waterman batholith, dikes of which are progressively transposed into the Vincent thrust mylonite. Granodiorite of the Mount Waterman batholith sampled 3 km west of Mount Baden-Powell yielded a U/Pb zircon age of ca. 74 Ma (Silver and Nourse, 2001), whereas a hornblende 40Ar/39Ar date of 71 ± 2 Ma is reported from another part of the batholith (Grove and Lovera, 1996). The minimum age of mylonitization is constrained by 40Ar/39Ar dates of 55.3 ± 0.4 Ma on muscovite from mylonite and 60.8 ± 0.6 Ma on muscovite from Pelona grayschist (Jacobson, 1990). Unfoliated late Oligocene Telegraph Peak granite (map unit Tgr; May and Walker, 1989) and associated rhyolite porphyry dikes and sills also intrude the schist and mylonite.

Paleoproterozoic banded gneiss (map unit PCgn)

Gneiss characterized by centimeter to millimeter scale banding and isoclinal folding constitutes the oldest upper-plate rock unit. This unit and associated intrusive sheets of augen gneiss, collectively referred to as “San Gabriel gneiss” (Miller, 1934; May and Walker, 1989), form the framework into which Mesozoic plutons were intruded. On Glendora Ridge the San Gabriel gneiss occurs as isolated 1 m to 100 m xenoliths within diorite and granodiorite.

The banded gneiss ranges in composition from felsite to amphibolite. Persistent amphibolite facies crystalloblastic fabric and local mylonitization has obscured original textures such that protolith interpretation is difficult. Abrupt compositional and textural variations along with commonly observed sheared intrusive contacts suggest that a heterogeneous accumulation of fine-grained layered protoliths was intruded prior to metamorphism and deformation by dikes or sills of gabbroic to granitic composition. Subordinate quartzite and metapelite (e.g., garnet-biotite gneiss) indicate a minor sedimentary component. Pri-
Figure 2. (A) Perry Ehlig’s geologic map of the San Gabriel Mountains basement complex, showing study area (Fig. 3B) and locations of faults and geographic features mentioned in the text. Modified from Ehlig (1975). (B) Index map of the central and eastern San Gabriel Mountains, showing geographic features mentioned in text and sources of geologic data compiled on Figures 3A and 3B.
Figure 3. Geologic maps of the central and eastern San Gabriel Mountains. Geographic locations are shown in italics: CR—Cogswell Reservoir, CP—Cucamonga Peak, MR—Morris Reservoir, MBP—Mount Baden Powell, MSA—Mount San Antonio, MW—Mount Wilson, OP—Ontario Peak, PM—Pine Mountain, SAD—San Antonio Dam, SDR—San Dimas Reservoir, SGD—San Gabriel Dam, SGR—San Gabriel Reservoir, and TP—Telegraph Peak. Fault labels as follows: CF—Cucamonga fault, DF—Duarte fault, GHF—Glen Helen fault, ICF—Icehouse Canyon fault, LF—Lytle Creek fault, MFLCF—Middle Fork Lytle Creek fault, NSGF—north branch San Gabriel fault, PMF—Pine Mountain fault, PF—Punchbowl fault, RHF—Raymond Hill fault, SCCF—Sawpit Canyon-Clamshell fault, SAF—San Andreas fault, SACF—San Antonio Canyon fault, SDCF—San Dimas Canyon fault, SJF—San Jacinto fault, SJOF—San Jose fault, SMF—Sierra Madre fault, SSGF—South Branch San Gabriel fault, SF—Scotland fault, SCF—Stoddard Canyon fault, SRF—Sunset Ridge fault, VCF—Vasquez Creek fault, VF—Verdugo fault, WF—Weber fault. A: Proposed subdivision of rock units and definition of faults in the central and eastern San Gabriel Mountains. See text for detailed rock descriptions. New mapping by this author is included from the Mount Baldy quadrangle, Glendora quadrangle, north 1/2 of Azusa quadrangle, northeast 1/4 of Mount Wilson quadrangle, east 1/2 of Crystal Lake quadrangle, south 14 of San Antonio quadrangle, south 13 of Telegraph Peak quadrangle, and northwest 14 of Cucamonga Peak quadrangle. Geologic data outside of these areas is compiled from Ehlig (1958), Jennings and Strand (1969), Morton (1973), Dibblee (1998), and Bortugno and Spittler (1986). B: Present-day geologic map of the southern and east-central San Gabriel Mountains used as template for palinspastic reconstructions of Figures 5–8. Peripheral faults and rock units not shown on Figure 3A are compiled from Jennings and Strand (1969), Dibblee (1998), and Bortugno and Spittler (1986).
Figure 4. Photographs showing rock textures and field relationships in the central and eastern San Gabriel Mountains. A: Mylonite of the Vincent thrust (KTmy) from Vincent Narrows area, showing boudinaged Late Cretaceous (?) granite in sheared quartz diorite host. View to the S25W. Hammer is 45 cm long. B: Close-up view of KTmy unit from Vincent Narrows, showing rotation of K-feldspar porphyroclast in sheared granodiorite. View to the S25W. Hammer handle is 4 cm wide.
mary contacts are generally transposed into a penetrative foliation that is axial planar to common mesoscale isoclinal folds.

A similar structurally inferior position relative to the Mount Lowe intrusion suggests that the banded gneiss is an along-strike continuation of the Mendenhall gneiss of the western San Gabriel Mountains. However, the latter unit is higher grade (commonly granulite facies), and contains a much lower proportion of interlayered augen gneiss. Felsic components of the Mendenhall gneiss have yielded discordant Mesoproterozoic U/Pb zircon ages from conventional isotope dilution methods (Silver et al., 1963; Barth et al., 1995a). Recent ion probe spot analyses (Barth et al., 2001) show that Paleoproterozoic zircons from felsic portions of the Mendenhall gneiss were isotopically disturbed during intrusion of the nearby 1191 ± 3.5 Ma anorthosite-jotunite-syenite complex.

**Paleoproterozoic granite augen gneiss (map unit PCagn)**

A medium to coarse-grained biotite granite augen gneiss with flattened or isolocinally folded K-feldspar augen occurs as concordant sheets or irregular plutons intruded into the banded gneiss or as xenoliths within Mesozoic intrusions. Most common is a dark brown weathering biotite-rich variety with 0.5–2 cm long K-feldspar augen (Fig. 4C). Coarser-grained, leucocratic varieties contain K-feldspar augen as long as 8 cm composing >60% of the rock volume (Fig. 4D). Biotite, quartz, and feldspar are pervasively recrystallized in both varieties, with concomitant development of axial planar foliation. Augen gneiss shares axial planar foliation with the banded gneiss and displays isoclinal folds of similar orientation.

Late Paleoproterozoic U/Pb zircon ages are reported by Silver (1971) from augen gneisses of the San Gabriel Mountains and Soledad basin, as well as augen gneiss exposures west of the San Gabriel fault at Frazier Mountain and east of the San Andreas fault in the Orocopia and Chuckwalla Mountains. Medium-grained augen gneiss of Glendora ridge yielded a 207Pb/206Pb age of 1670 ± 20 Ma (T. Davis, 1978, personal commun., in Ehlig, 1981). An augen gneiss layer within the Mendenhall gneiss contains zircons with oscillatory-zoned cores indicating an upper intercept U/Pb age of 1679 Ma indicating an upper intercept U/Pb age of 1679 Ma. Considering the strong degree of recrystallization and foliation development in the augen gneisses, the generally discordant Proterozoic zircons probably record an intense thermal-deformational overprint of late Paleoproterozoic granite that preceded later thermal effects of the 1191 ± 3.5 Ma anorthosite intrusion (Barth et al., 1995a; 2001).

**Pre-Cretaceous metasedimentary strata (map unit ms)**

Complexly folded masses of quartzite, marble, pelitic gneiss, phyllite, and graphitic schist form the wall rocks of Late Cretaceous intrusions on Ontario Ridge (May and Walker, 1989). Early Miocene and Pliocene movements on the San Antonio Canyon fault (see below) have sinistrally offset this unit 8–10 km to the region west of San Antonio Dam. Possibly correlative strata occur west of Pasadena (Powell, 1993).

The north-dipping metasedimentary section of Ontario Ridge is separated from structurally deeper Cretaceous Cucamonga granite (map unit Kcg; May and Walker, 1989; Morton and Matti, 1991) by “black-belt mylonite” (map unit Kny; Hsu, 1955). May and Walker interpreted the black-belt mylonite as being derived from metasedimentary rocks, Cretaceous granulite, and Cretaceous tonalite. Due to intense deformation (Fig. 4E) and amphibolite facies metamorphism, protolith age of the metasedimentary sequence is uncertain.

**Triassic Mount Lowe intrusion (map units TRqm, TRqmzd, and TRdi)**

A distinctive foliated Triassic plutonic complex intrudes Paleoproterozoic framework rocks in the upper plate of the Vincent thrust. Originally named “Lowe granodiorite” (Miller, 1934) for exposures on Mount Lowe, later studies (Ehlig, 1981; Barth and Ehlig, 1988; Barth et al., 1990) showed this pluton (map unit TRqmzd) to be compositionally zoned from a biotite quartz monzonite or granodiorite interior to a hornblende quartz monzodiorite margin. The central portion of the pluton is characterized by ovoid K-feldspar phenocrysts (“pigeon eggs”) as large as 10–12 cm. The marginal facies (“dalmationite”) displays conspicuous 0.5–1.5 cm hornblende phenocrysts (Fig. 4F).

The Mount Lowe intrusion forms a “tail” whose southwest contact with Paleoproterozoic banded gneiss constitutes a piercing point on the north branch of the San Gabriel fault (Ehlig, 1981; Dibblee, 1982, Fig. 2A). Recent mapping (Fig. 3) extends several thin sheets of quartz monzodiorite 25 km farther east to San Antonio Canyon. The eastern Mount Lowe intrusion is intimately associated with fine-grained biotite-hornblende diorite, hornblende-biotite quartz diorite, and minor coarse-grained gabbronorite (map unit TRdi). This diorite contains abundant xenoliths of banded gneiss and augen gneiss and is locally intruded by quartz monzodiorite (Fig. 4G). Foliated, medium-grained porphyritic quartz monzonite (map unit TRqm) intrudes diorite in the walls of Cogswell and San Gabriel Reservoirs. The diorite is interpreted to be an early phase of the Mount Lowe intrusion based on similarities to intrusive relationships described northwest of Mount Baden Powell (Cox et al., 1983).

**Jurassic (?) granodiorite (map unit Jgd)**

Foliated porphyritic biotite granodiorite with distinct lavendel K-feldspar phenocrysts occurs at the high levels of the synform that defines the structure of Sunset Ridge. This pluton forms discordant sheets intruded into Proterozoic and Triassic rocks. Dikes of Late Cretaceous (?) leucocratic granite and pegmatite crosscut all of these units, but share a protomylonitic
Figure 4. C: Paleoproterozoic biotite granite augen gneiss (PCagn) from lower West Fork San Gabriel Canyon. Hammer handle is 4 cm wide. D: Coarse-grained Paleoproterozoic augen gneiss (PCagn) of Glendora Ridge, showing isoclinally folded augen. Pencil is 16 cm long.
Figure 4. E: Folds in boulder of quartzite–calc-silicate gneiss, a common component of the ms unit south of Icehouse Canyon. Daypack is 40 cm wide. F: Xenolith of Triassic Mount Lowe hornblende quartz monzodiorite (TRqmzd) within Late Cretaceous quartz diorite (Kgr) host of Mount San Antonio. Narrow part of hammer is 3 cm wide.
Figure 4. G: Xenolith of Triassic quartz monzodiorite in Late Cretaceous quartz diorite of Mount San Antonio. Note also the xenolith of Triassic diorite (TRdi) surrounded by quartz monzodiorite. Pencil is 16 cm long. H: Middle Miocene basalt dike (arrows) offset by west-northwest striking dextral fault of the San Gabriel system. View to the southwest. Dike is 50 cm wide.
fabric with Jurassic (?) granodiorite probably related to the Vincent thrust (Nourse and Litzenburg, 1998). The granodiorite resembles dated Jurassic plutons of the San Gabriel Mountains, including the 164 ± 3 Ma granodiorite of Pleasant View Ridge northwest of Mount Baden-Powell (U/Pb zircon age reported in Barth, 1989; see also Cox et al., 1983).

**Late Cretaceous quartz diorite-tonalite-granodiorite-granite (map unit Kgr)**

The pre-Cretaceous upper-plate stratigraphy of the Vincent thrust is “stitched together” by several intrusive sheets of locally porphyritic, medium-grained biotite-hornblende quartz diorite or tonalite and hornblende-biotite granodiorite. These sills extend eastward from the “Wilson diorite” (Miller, 1934) to the summits of Mount San Antonio, Ontario Peak, and Cucamonga Peak. Quartz diorite and granodiorite are intruded by irregular bodies of leucocratic biotite granite and pegmatite generally too small to map on Figure 3. Quartz diorite and granodiorite of the eastern San Gabriel Mountains share a weak to moderate foliation with granite dikes (Nourse, 1991; Nourse and Litzenburg, 1998). Quartz diorite south of Cogswell Reservoir and on Mount San Antonio (Fig. 4F) contains abundant xenoliths of Mount Lowe quartz monzodiorite. These xenoliths define part of the Mount Lowe “tail” utilized to constrain dextral displacements on the San Gabriel fault.

Granite from the Josephine Mountain intrusion yielded a Late Cretaceous U/Pb zircon age (Carter and Silver, 1971). Two samples of foliated tonalite from Ontario Ridge preserve discordant U/Pb crystallization ages of 88 ± 3 Ma and ca. 85 Ma, while crosscutting granite yielded a discordant 78 ± 8 Ma age (May and Walker, 1989). Work farther west (Barth et al., 1995b) indicates that the Late Cretaceous Josephine Mountain intrusion is calc-alkaline and has assimilated a significant fraction of country rock, as recorded by inherited Paleoproterozoic components in zircon arrays.

**Late Oligocene Telegraph Peak granite (map unit Tgr)**

Both plates of the Vincent thrust system are intruded by unfoliated, medium-grained, leucocratic, porphyritic biotite granite. Exposed on Telegraph Peak, this pluto has injected rhyolite or rhyodacite porphyry sills and dikes of similar major and trace element character (Nourse et al., 1998b) into basement rocks to the west and south. A larger pluton of similar composition and texture (Mount Barrow granite) occurs on the north side of the San Andreas fault in the northern Chocolate Mountains (Miller and Morton, 1977). May and Walker (1989) report a 26 ± 1 Ma U/Pb zircon age for Telegraph Peak granite in the easternmost San Gabriel Mountains. K/Ar ages of 19 Ma and 14 Ma (Miller and Morton, 1977) probably reflect thermal disturbances related to widespread emplacement of middle Miocene dikes (see also Hsu et al., 1963).

**Middle Miocene mafic-intermediate dike swarm**

Conspicuous swarms of basalt, basaltic andesite, and andesite dikes, not mappable at the scale of Figure 3, intrude both plates of the Vincent thrust system. These dikes are generally steeply dipping, and occur in northeast and northwest-striking domains that record emplacement along conjugate strike-slip shear fractures (Nourse et al., 1998b; Nourse, 1999). The dikes tend to be most concentrated within two kilometers of the San Gabriel fault (Perry Ehlig, 1996, personal commun.). A middle Miocene age is inferred (Nourse et al., 1998b) because the dikes: (a) intrude the Telegraph Peak granite (b) are overprinted and displaced by various strands of the late Miocene San Gabriel fault (Fig. 4H), and (c) are compositionally and geochemically similar to the nearby 15–16 Ma Glendora volcanic rocks (Shelton, 1955; Nourse et al., 1998b).

**LATE CENOZOIC STRIKE-SLIP FAULTS: DISPLACEMENT AND AGE CONSTRAINTS**

Figures 3A and 3B illustrate numerous strike-slip offsets of the crystalline stratigraphy described above. A network of west- or northwest-striking dextral faults and northeast-striking sinistral faults subdivides the east-central San Gabriel Mountains into diamond-shaped blocks of various sizes. Synthetic faults with minor slip, spaced at 1–50 m intervals, commonly penetrate the interiors of these blocks. The overall effect at outcrop scale is to produce a pervasive brittle overprint that tends to obscure older structures and fabrics. In one view, the San Gabriel Mountains represent an example of “map-scale cataclasism” (S. Richard, 2000, personal commun.). Indeed, it seems amazing that the gross pre-Miocene structure and basement stratigraphy of this region has preserved its character throughout its extensive late Cenozoic history of brittle deformation.

The San Gabriel block is bounded on the northeast by the active dextral San Andreas fault and on the south by the active Cucamonga-Sierra Madre thrust; therefore the eastern San Gabriel Mountains are currently experiencing a state of transpression. Late Cenozoic reverse faulting has accompanied strike-slip faulting within the range; these shortening effects are manifested by gaps that appear between fault blocks in the palinspastic map reconstructions. The following section documents timing and displacement constraints for the major strike-slip faults identified on Figure 3B and restored on Figures 5–8. These faults are described from youngest movements to oldest, in the same sequence that the reconstruction is presented later.

**Quaternary dextral faults**

**San Andreas fault (SAF).** The San Gabriel block is truncated on the northeast by the active Mojave Desert strand of the San Andreas fault (Powell, 1993; Fig. 1A). This fault has been accumulating dextral slip for the past 5 million years. Estimates
Figure 5. Early Quaternary (ca 1.5–1.0 Ma) palinspastic reconstruction of the central and eastern San Gabriel Mountains, showing 16 km restoration along the dextral San Jacinto fault system. Rock unit patterns and fault labels same as in Figure 3B. Fault blocks have been restored along faults shown with heavy dots. Solid-line faults were active at earlier times.

of total displacement vary from 240 km (Ehlig, 1981; Dillon and Ehlig, 1993) to 160 km (Powell, 1993; Matti and Morton, 1993), however, all models (Figs. 1B–1C) restore the San Gabriel Mountains to a position in the present-day Salton Trough near the Orocopia and Chocolate Mountains. Other faults described below record dismemberment of the San Gabriel block prior to and during its northwestward translation along the San Andreas fault.

San Jacinto fault system (SJF, SF, and GHF). Pelona Schist and Telegraph Peak granite in the northeastern San Gabriel Mountains are sliced by three strands of the Quaternary San Jacinto fault system mapped on Figure 3 as the Scotland, San Jacinto, and Glen Helen faults. Microseismicity indicates that one or more of these faults is still active (Cramer and Harrington, 1987). All three fault strands appear to dextrally offset the northeast ends of the San Antonio Canyon and Weber faults (Norum, 1997). Independent constraints on displacement are derived from matching the following piercing lines: (a) a sharp northwestern intrusive contact of the Telegraph Peak granite against Pelona Schist (b) segments of a northeast-striking faults that coincide with projected traces of the San Antonio Canyon fault and Weber fault, and (c) internal stratigraphic markers (metabasalt and metachert) and foliation domains within the Pelona Schist. These cross-fault ties yield consistent dextral displacements of 3.5 km, 7 km, and 5 km on the Scotland, San Jacinto, and Glen Helen faults, respectively (compare Figures 3 and 5). All three strands of the San Jacinto fault system are interpreted to merge in the upper North Fork Lytle Creek drainage, with their combined slip feeding onto the Punchbowl fault (PF). Ongoing field studies are testing this hypothesis, which contradicts the views of Morton (1975) and Matti and Morton (1993).

Pliocene-Quaternary sinistral faults

These northeast-striking faults are described in order of geographic position, from east to west. Timing of displacement is constrained as follows: (a) all of the faults considered cause left-lateral displacements or deflections of the north branch of the San Gabriel fault, which ceased moving in earliest Pliocene time (ca. 5 Ma; see also Crowell, 1952), and (b) some of these faults are truncated by known active dextral faults such as the San Jacinto and San Andreas faults. Basement separations are consistent with sinistral offsets of the San Gabriel fault, but in one case excessive separation indicates a period of ancestral movement (pre–12 Ma) that predates San Gabriel fault activity.

Stoddard Canyon fault (SCF). This northeast-striking structure follows the axis of Stoddard Canyon and crosses Ontario Ridge west of the saddle between Cucamonga Peak and Bighorn Peak. It displaces the Icehouse Canyon fault sinistrally ~1.5 km to a position coinciding to the Middle Fork Lytle Creek. A steeply north-dipping contact between Cretaceous(?
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Figure 6. Early Pliocene (ca. 5 Ma) palinspastic reconstruction of the central and eastern San Gabriel Mountains, showing variable magnitudes of restoration along northeasterly sinistral faults. Rock unit patterns and fault labels same as in Figure 3B. Fault blocks have been restored along faults shown with heavy dots. Solid-line faults were active at earlier times.

granodiorite and metasedimentary rocks on Ontario Ridge is separated a similar distance. Sinistral displacement postdates late Miocene dextral slip on the Icehouse Canyon fault. The northeast end of the Stoddard Canyon fault appears to be truncated by the Scotland fault. To the southwest, the fault merges with and contributes slip to the San Antonio Canyon fault.

San Antonio Canyon fault (SACF). This fault, named for its location in San Antonio Canyon, records two stages of sinistral movement (Nourse et al., 1994). Pliocene and younger displacement of ~3 km is estimated from offset of the north branch San Gabriel fault (and corresponding west-trending valley) to Icehouse Canyon. This displacement value is consistent with apparent left-lateral separation of: (a) the Vincent thrust, and (b) a map pattern of open folds (antiform-synform-antiform) developed in the Pelona Schist, Vincent thrust, and upper-plate mylonite on opposite sides of the San Antonio Canyon fault (Jones, 1993). A minor splay of the San Antonio Canyon fault transects the northwest part of Ontario Ridge causing about ¼ km left-lateral offset of a Cretaceous granodiorite-metasedimentary gneiss contact and minor deflection of the Icehouse Canyon fault.

South of Icehouse Canyon, the San Antonio Canyon fault preserves evidence for sinistral displacement predating late Miocene movement on the San Gabriel–Icehouse Canyon fault (Nourse et al., 1994). A north-dipping section on Ontario Ridge consisting of (from bottom to top) quartzite, pelitic gneiss, marble, granite, and tonalite is offset left laterally 8–10 km to a position west of San Antonio Dam. Five to seven km of this displacement accumulated before the Vincent thrust and Pelona Schist were translated into the area by the San Gabriel–Icehouse Canyon fault system (compare Figures 3B, 6, and 8). Early Miocene movement on this “ancestral” San Antonio Canyon fault is demonstrated by subhorizontal fault striae that crosscut rhyolite dikes of the Telegraph Peak granite. These faults are intruded by middle Miocene mafic dikes (Nourse et al., 1998b, Nourse, 1999).

The northeast segment of the San Antonio Canyon fault appears to be inactive because it is truncated and dextrally displaced by three strands of the active San Jacinto fault system. However, Holocene activity on the southwest segment is suggested by focal mechanisms of micro earthquakes (Cramer and Harrington, 1987), and possible kinematic linkage (via a right step) to the San Jose fault, which generated left-lateral oblique reverse earthquakes in 1988 and 1990 (Hauksson and Jones, 1991).

Sunset Ridge fault (SRF). A northeast-striking fault zone
transecting the northwest side of Sunset Ridge is associated with ~0.8 km sinistral separation of an elongate augen gneiss screen in Jurassic(? ) granodiorite. Synthetic faults within this zone show minor displacements of northwest-striking middle Miocene mafic dikes. The Sunset Ridge fault appears to cut across the San Gabriel fault and disrupt basement stratigraphy to the northeast. It joins the San Antonio Canyon fault north of Icehouse Canyon, contributing sinistral displacement to the northeast segment of this fault.

**San Dimas Canyon–Weber fault (SDCF and WF).** A pronounced jog in the mountain front northeast of Glendora corresponds to an apparent left-lateral offset of the unconformity between Glendora volcanic rocks (Shelton, 1955) and crystalline basement. This offset coincides with 1.5 km sinistral separation of a moderately north-dipping basement section consisting of (from deeper to shallower): (a) Paleoproterozoic augen gneiss and banded gneiss intruded by granite (b) Cretaceous(? ) granodiorite, and (c) banded gneiss. A system of prominent north-northeast–striking faults with subhorizontal striae marks the displacement zone, which is aligned with the axis of lower San Dimas Canyon. One of these faults juxtaposes quartz diorite against banded gneiss in the east wall of San Dimas Reservoir.

Along strike to the north-northeast, the San Dimas Canyon fault is poorly exposed, but appears to connect a series of saddles and jogs in minor streams. Farther northeast, the San Gabriel fault and an antiformal window of Vincent thrust mylonite are sinistrally offset a minor amount (0.5 km), where the San Dimas fault appears to join the Weber fault, mapped by Ehlig (1975). The gently dipping Vincent thrust is apparently displaced 4 km by the Weber fault. Discrepancies in magnitude of apparent displacement on the San Dimas Canyon-Weber fault system probably reflect a transition from pure strike-slip motion in the southwest to a significant component of dip-slip (northwest side up) in the northeast.

**Pine Mountain fault system (PMF).** A series of northeast-
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Figure 8. Early late Miocene (ca. 12 Ma) palinspastic reconstruction of the central and eastern San Gabriel Mountains, showing proposed 15 km restoration along the Sawpit Canyon-Clamshell fault system. Rock unit patterns and fault labels same as in Figure 3B. Fault blocks have been restored along faults shown with heavy dots. Solid-line faults were active at earlier times. Arrows indicate residual basement offset inherited from early Miocene sinistral movement on the ancestral San Antonio Canyon fault.

striking faults with subhorizontal striae penetrate Pine Mountain. The fault shown on Figure 3 records ~1 km sinistral offset of a valley marking the main trace of the San Gabriel fault. It juxtaposes augen gneiss (on the southeast) with quartz diorite and Vincent thrust mylonite. Farther west, additional left-lateral displacement appears to be distributed along a system of north-easterly faults that coincide with sharp jogs in the West Fork San Gabriel River. These minor displacements (generally <0.5 km) were not incorporated into the palinspastic reconstruction.

Late Miocene dextral faults

North branch San Gabriel–Icehouse Canyon–Middle Fork Lytle Creek fault system (NSGF, ICF, and MFLCF). The San Gabriel fault records a complicated and controversial displacement pattern (Ehlig, 1975; Powell, 1993; Weldon et al., 1993; Matti and Morton, 1993). Mapping by John Crowell (1952) documented ~45 km late Miocene dextral displacement on the “type” San Gabriel fault between the western San Gabriel Mountains and its northwestern terminus with the San Andreas fault (Fig. 1). Northwest of Pasadena the San Gabriel fault splits into north and south branches (Fig. 2A). The south branch appears to merge with and is probably overprinted by the Sierra Madre thrust. Displacement on the north branch in the central San Gabriel Mountains is well constrained, but much debate continues about: (a) where to transfer slip on the south branch beyond the point where it “disappears,” and (b) how to balance total San Gabriel fault displacement with other late Miocene dextral faults to the southeast or possible late Miocene transtensional basin formation within the northeastern Los Angeles basin (compare Wright, 1991, Matti and Morton, 1993, Powell, 1993, Weldon et al., 1993, Kenney and Weldon, 1998).

The classic piercing point on the north branch San Gabriel fault (Ehlig, 1981; Dibblee, 1982) is a northeast-dipping contact between Proterozoic gneiss and the structurally overlying “tail” of the Mount Lowe intrusion (Figs. 2A and 3B). This contact, exposed west of Mount Wilson, is offset 22 km dextrally from a position 2 km east of Cogswell Reservoir. Additional mapping of the basement stratigraphy (Fig. 3A) confirms this value and provides new piercing lines that support a comparable amount of displacement between Pine Mountain and Mount San Antonio.
The Mount Lowe “tail” and adjacent crystalline strata, exposed continuously from the south side of Mount Wilson into the West Fork San Gabriel Canyon, provide an important cross-fault tie between the West Fork exposures and those on the south flank of Mount San Antonio. Specifically, the Pine Mountain area reveals a moderately northwest-dipping section composed of (from deepest to shallowest): (a) Vincent thrust mylonite (b) Paleoproterozoic gneiss (c) Cretaceous quartz diorite (d) Triassic quartz monzodiorite (e) Triassic (?) diorite, and (f) Triassic (?) quartz monzonite. A strikingly similar southwest-dipping succession is exposed between the summit of Mount San Antonio and the San Gabriel fault, ~20–25 km to the east. Dextral displacement on the north branch San Gabriel fault was apparently localized near the hinge of a regional west-plunging synform (see also Figure 7).

East of San Antonio Canyon, the north branch San Gabriel fault follows the axis of Icehouse Canyon, where the 50-m-thick Icehouse Canyon fault zone is intermittently exposed. Other faults of uncertain importance but similar orientation transect ridges ~1 km north of Icehouse Canyon. East of the left-lateral offset caused by the Stoddard Canyon fault, the Icehouse Canyon fault and its northerly branches follow east-trending Middle Fork Lytle Creek Canyon to the point where they are truncated by the Scotland fault. The Icehouse Canyon-Middle Fork Lytle Creek fault system records at least 22 km dextral displacement, however, analysis of another fault of the San Gabriel system (described below) suggests the possibility for 37 km total displacement.

**Sawpit Canyon–Clamshell fault system (SCCF).** The Sawpit Canyon–Clamshell fault system of Morton (1973) is an east-northeast striking crush zone as much as 300 m wide. Although some workers consider this fault to be a left-lateral structure continuous with the active Raymond Hill fault, Holocene thrust activity is indicated by seismic studies that correlate it with the 1991 M 5.8 Sierra Madre earthquake (Hauksson, 1994). Interestingly, the Sawpit–Clamshell fault may also record late Miocene dextral displacement (Dibblee, 1982; Dillon and Ehlig, 1993), an interpretation supported by analyses of small-scale brittle fault structures along certain segments (J. Evans, 1994, personal commun.). In the model proposed in this paper, the Sawpit–Clamshell fault represents an eastward continuation of the cryptic south branch San Gabriel fault, whose curved trace was sliced off and abandoned by the straighter, younger north branch San Gabriel fault. Effectively, a transpressional left jog in the early San Gabriel fault was straightened out by transfer of slip to a mechanically more efficient north branch.

A significant mismatch of basement stratigraphy across the Sawpit Canyon–Clamshell fault cannot be resolved by left-lateral or thrust restorations. Specifically, the northwest-dipping homoclinal section of Pine Mountain (described earlier) contrasts with multiple folds in a section of medium-grained augen gneiss, Triassic quartz monzodiorite, banded gneiss, and Triassic (?) diorite exposed southeast of the Sawpit Canyon–Clamshell fault. A different mismatch occurs when 22 km dextral displacement is restored on the north branch San Gabriel–Icehouse Canyon–Middle Fork Lytle Creek fault system (Fig. 7). The fault block immediately north of Icehouse Canyon and Middle Fork Lytle Creek, composed mainly of mylonitized leucogranite, granodiorite, and quartz diorite, contrasts markedly with Triassic (?) diorite, Paleoproterozoic augen gneiss and banded gneiss, and Triassic quartz monzodiorite exposed to the south.

One mechanism for reconciling these discrepancies applies 15 km of late Miocene dextral displacement to the Sawpit–Clamshell fault, adding this slip to the eastern segment of the north branch San Gabriel fault, which records 22 km of younger displacement. The resulting reconstruction (Fig. 8) juxtaposes north-dipping rock units currently exposed northeast of Monrovia with north-dipping mylonite exposed north of the Icehouse Canyon and Middle Fork Lytle Creek faults. Comparison of rock units and structures between these two areas is a focus of ongoing research (Nourse, unpub. mapping).

**MIDDLE MIocene TO RECENT PALINspastic RECONSTRUCTION**

Palinspastic reconstruction is accomplished in four steps (Figs. 5–8) that restore the sequence of fault displacements described above. The present-day geologic map (Fig. 3B) provides the main template utilized in reconstruction. The procedure assumes pure strike-slip translations of fault blocks. Resulting gaps in the map view reconstruction reflect components of reverse slip along nonvertical structures. These transpressional features are manifestations of: (a) the pronounced left jog that formed early during evolution of the late Miocene San Gabriel fault, and/or (b) Quaternary reactivation of certain faults during development of the Sierra Madre–Cucamonga fault.

First, ~16 km of Quaternary dextral displacement is restored on the San Jacinto fault system, with slip partitioned into 3.5 km, 7 km, and 5 km on the Scotland, San Jacinto, and Glen Helen faults, respectively. Figure 5 shows the Telegraph Peak granite reassembled in the resulting early Quaternary paleogeography. Second, minor Pliocene–Quaternary sinistral displacement is restored on multiple northeasterly faults that disrupt the San Gabriel fault (Fig. 6). The model assumes displacement values of 1.5 km, 3 km, 0.8 km, 1.5 km, and 1 km for the Stoddard, San Antonio, Sunset Ridge, San Dimas–Weber, and Pine Mountain faults, respectively. This procedure aligns discontinuous segments of the San Gabriel fault. Third, 22 km of dextral displacement is restored on the north branch San Gabriel fault, aligning the Mount Lowe “tail” in the west, and bringing the Pine Mountain section adjacent to similar strata on Mount San Antonio (Fig. 7). This displacement probably occurred between 9 Ma and 5 Ma. Lastly, 15 km of dextral displacement is restored on the Sawpit Canyon–Clamshell fault, contributing additional slip to the eastern segment of the north
branch San Gabriel fault. Figure 8 shows the paleogeography at ca. 12 Ma, just prior to significant right-lateral movements on the south branch San Gabriel fault.

**DISCUSSION**

**Implications for San Gabriel fault evolution**

The palinspastic reconstruction proposed above resolves a number of issues raised by Powell and Weldon (1992), Matti and Morton (1993), and Powell (1993), regarding late Miocene kinematic development of the San Gabriel fault system. In particular, it provides a new mechanism for transferring 20 km of dextral displacement on the south branch San Gabriel fault to regions farther southeast. This new reconstruction is most similar to one of the general models proposed by Powell and Weldon (1992; see their Figure 8C, p. 458), in which slip on both branches of the San Gabriel fault merges eastward with a southern strand of the early San Andreas fault. This strand was probably the Banning fault, whose possible connections to the San Gabriel fault system are developed by Matti and Morton (1993). For the most part, I concur with the Matti and Morton model, including their hypothesis that the south branch San Gabriel fault is older than the north branch. However, our interpretations differ in that dextral displacement on the south branch San Gabriel fault is shunted onto the Banning fault via the Sawpit Canyon–Clamshell–Icehouse Canyon–Middle Fork Lytle Creek fault system rather than the Stoddard Canyon–Middle Fork Lytle Creek fault system. Previously described evidence for minor sinistral slip on the Stoddard Canyon fault seems at odds with the 22 km dextral displacement utilized by Matti and Morton (1993).

Displacement discrepancies between the northwestern portion of the San Gabriel fault and the north branch of the San Gabriel fault are discussed in detail by Powell (1993). I agree with Powell’s 42 km value for total displacement on the northwest end of the San Gabriel fault, and concur that 22 km is a good number for displacement on the north branch. The 20 km difference could most easily be partitioned onto other structures such as the Vasquez Creek fault and the Canton fault (Fig. 9). Powell (1993) argued that the Vasquez Creek fault can only account for 5 km of the slip discrepancy, but his more recent work (R. Powell, 2001, personal commun.) indicates that larger displacements are possible. The 1993 Powell model assumes 5 km and 15 km displacement on the Vasquez Creek and Canton faults, respectively, and cryptically absorbs this slip farther southeast via oblique extension in the Los Angeles basin and in the San Gabriel–San Bernardino Valleys (see Powell, 1993, Figure 14B, p. 39). To reconcile fault relations in the central and eastern San Gabriel Mountains I prefer to transfer 15 km displacement on the Vasquez Creek fault onto the Sawpit Canyon–Clamshell system. In this perspective, only 5 km of late Miocene dextral displacement is absorbed by extension or transtension in the Los Angeles basin (Fig. 9). The new reconstruction offers closer continuity of the Vincent thrust system and eastern Mount Lowe intrusion between the eastern San Gabriel Mountains, Banning block, and southern Chocolate Mountains.

A variety of isolated structural features and paleodepositional patterns are explained by the geometric complexities that accompanied San Gabriel fault evolution. The early San Gabriel fault shown in Figures 8 and 9 exhibits several bends or jogs. The overall transpressional character of the San Gabriel fault was recognized by Weldon et al. (1993), who attribute formation of the Squaw Peak–Liebre Mountain thrusts, uplift of the proto-Transverse Ranges, and accumulation of several late Miocene basins (including the Ridge Basin; Fig. 9) to components of vertical displacement near restraining bends in the San Gabriel fault. Evidence supporting this transpressional model is preserved in the central and eastern San Gabriel Mountains, where late Miocene(? ) reverse slip occurred along a segment of the proposed south branch San Gabriel fault that displays a pronounced left jog (Figs. 8–9). Specifically, the Sawpit–Clamshell fault and the Icehouse Canyon fault both preserve an early system of north-dipping reverse faults cut by northeasterly left-lateral faults of inferred Pliocene age. Presence of Vincent thrust mylonite in both hanging walls indicates that deep levels of the San Gabriel basement were uplifted on the north side. These transpressional effects probably diminished after ca. 9 Ma, when transfer of slip to the straighter north branch San Gabriel fault (Matti and Morton, 1993) caused the restraining bend in the south branch to be abandoned.

Similarly, anorthosite boulders in displaced conglomerate of the Frazier Mountain block (Fig. 9) suggest that an uplifted anorthosite source in the western San Gabriel Mountains shed debris southwestward across the San Gabriel fault during Mohnian time (Crowell, 1952). In this case, however, emergence of the western San Gabriel Mountains and deposition of the anorthosite-clast conglomerate may be explained by local vertical movements driven by transtensional stress (note the apparent right jog in reconstructed San Gabriel fault in this region; Fig. 9).

**Paleogeographic implications for development of the Los Angeles basin**

The proposed middle Miocene tectonic reconstruction (Figs. 8 and 9) illuminates several intriguing paleogeographic features that bear on early development of the Los Angeles basin. The San Gabriel Mountains formed the northern boundary of this late Miocene–Pliocene marine depocenter. Especially interesting are the restored positions and geometry of the: (a) late Oligocene Telegraph Peak granite (b) ancestral (early Miocene) San Antonio Canyon fault, and (c) middle Miocene mafic-intermediate dike swarm and associated Glendora volcanic rocks.

Fault slices of the Telegraph Peak granite restore near the Mount Barrow granite of the Chocolate Mountains (Powell, 1993) forming an ovoid pluton (Fig. 9). Rhyolite-dacite sills
Figure 9. Proposed middle Miocene (ca. 18–13 Ma) paleogeography of southern California, showing the San Gabriel and Frazier Mountain blocks restored adjacent to the Orocopia Mountains and Chocolate Mountains. Elements of the palinspastic base are modified from Figure 2 in Crowell (1952), Figures 14a and 14b in Powell (1993) and Figures 7b and 7c in Matti and Morton (1993). Fault abbreviations as in Figure 1C and Figure 3B. The model hypothesizes genetic relations between middle Miocene faults, igneous intrusions, volcanic rocks, and future development of the Los Angeles and Ventura pull-apart basins. Note the broad region of transtension in step-over zone between the Clemens Well and offshore borderland faults. In this model, north-northeast sinistral or oblique-normal faults such as the ancestral San Antonio Canyon fault, Raymond Hill fault, and Santa Monica/Malibu Coast fault connect a right step between the Clemens Well and Offshore Borderland faults. The middle Miocene Glendora and Conejo volcanic rocks are extruded near these boundary structures. Northeast and northwest-striking mafic-intermediate dikes are emplaced into conjugate shear fractures developed within the eastern San Gabriel Mountains basement.

Emanating from the pluton intrude both plates of the Vincent thrust, whereas less common steep-dipping dikes strike south-southwest and west-northwest (Nourse et al., 1998b). Dikes on Glendora Ridge probably connected the Mount Barrow–Telegraph Peak granite with the Mountain Meadows dacite of the Pomona Valley. This isolated dacite exposure, which underlies the Glendora volcanic rocks and Puente Formation and overlies Late Cretaceous(?), quartz diorite (Shelton, 1955), has yielded a biotite 40Ar/39Ar date of ca. 27 Ma (G. Hazelton, 1998, personal commun.). Hence, basement underlying the northeastern Los Angeles basin was adjacent to the eastern San Gabriel Mountains during late Oligocene time.

Another interesting feature of the middle Miocene reconstruction is a residual 6 km sinistral offset of basement stratigraphy across the north-northeast striking ancestral San Antonio Canyon fault (Fig. 8). As described earlier, displacement occurred during early Miocene time. Interestingly, this fault zone marks the eastern limit of a mid Miocene dike swarm, and its southward projection into the Pomona Valley forms the eastern boundary of the middle Miocene Glendora volcanic rocks. As shown on Figure 9, the ancestral San Antonio Canyon fault does not connect with the sinistral Raymond Hill-Malibu Coast fault as implied by Matti and Morton (1993). Instead, the San Antonio, Raymond Hill, and Malibu Coast faults appear to be
Implications for evolution of the San Gabriel fault and Los Angeles basin

Separate conjugate faults associated with a right step between the early Miocene Clemens Well fault and a dextral transform fault located in the California borderland (see also Powell and Weldon, 1992, Figure 7, p. 455). The transtensional geometry implied by this reconstructed fault configuration strongly supports a pull-apart origin for the Los Angeles and Ventura basins.

A third intriguing feature of the middle Miocene reconstruction is distribution of the middle Miocene mafic-intermediate dike swarm and its presumed surface expression, the Glendora volcanic rocks (Nourse et al., 1998b). The dike swarm was intruded along a preexisting (early Miocene) network of northeast- and northwest-striking conjugate shear fractures (Nourse, 1999) developed throughout much of the San Gabriel Mountains west of San Antonio Canyon. These dikes occur within a right step between the Clemens Well fault and an inferred borderland fault (Fig. 9). The model proposes that the middle Miocene Glendora volcanic rocks and middle Miocene Conejo-Zuma volcanic rocks (Weigand, 1982) mark the bottoms of separate pull-apart basins located west of the ancestral San Antonio and Santa Monica–Malibu Coast faults respectively. Hence, a right-stepping Clemens Well fault system was the driving mechanism for the early-mid Miocene extension recorded by basal strata of the Los Angeles and Ventura basins. The main phase of Los Angeles basin subsidence coincided with late Miocene–Pliocene movements on the San Gabriel fault (Wright, 1991; Ingersoll and Rumelhardt, 1999), during which minor splays such as the Canton–Verdugo–Whittier–Elsinore fault and offshore borderland faults formed northwest-striking boundaries of active pull-aparts. Complicating this scenario is coincident clockwise rotation of the western Transverse Ranges (Nicholson et al., 1994). Pliocene to Holocene phases of this rotation may have been facilitated by dextral displacements on the Newport–Inglewood, Palos Verdes, and California borderland faults.

CONCLUSIONS

The central and eastern San Gabriel Mountains basement complex is reconstructed to a 12 Ma configuration by sequential restoration of late Cenozoic strike-slip faults. Unique offsets of basement stratigraphy constrain the magnitude and timing of fault displacements. Particularly useful marker units include the Late Triassic Mount Lowe intrusion and Late Cretaceous quartz diorite or granodiorite, intruded as extensive sheets into a framework of Paleoproterozoic banded gneiss and augen gneiss. The reconstruction restores 16 km of Quaternary dextral displacement on the Scotland–San Jacinto–Glen Helen fault system, minor Pliocene-Quaternary sinistral slip on the Stardard Canyon, San Antonio Canyon, Sunset Ridge, San Dimas Canyon–Weber, and Pine Mountain faults, 22 km of late Miocene dextral displacement on the north branch San Gabriel–Icehouse Canyon–Middle Fork Lytle Creek fault system, and 15 km of early-late Miocene dextral displacement on the Sawpit Canyon–Clamshell fault system. The resulting paleogeography resolves issues regarding disposition of the south branch San Gabriel fault and its relationship to early strands of the southern San Andreas fault system. Also implied are genetic relationships between Los Angeles basin development, the ancestral (early Miocene) San Antonio Canyon fault, and the middle Miocene mafic-intermediate igneous rocks.

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