A Day in the Field With Tom Dibblee

Late Cenozoic Magmatism, Faulting, Uplift, Flooding, and Erosion in the Eastern San Gabriel Mountains and Pomona Valley

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Copies of the Mt. Baldy, San Dimas, Mt. San Antonio, and Glendora 7.5 minute geological quadrangle maps may be ordered ($15 folded, $20 rolled) from:

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Tectonic Genesis of the San Gabriel Mountains

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ABSTRACT

The San Gabriel Mountains north of Los Angeles are eroded from Mesozoic and older metamorphic and plutonic rocks elevated between the San Andreas, San Gabriel, and South Frontal faults. Remnants of Tertiary sedimentary and volcanic rocks occur on the margins. The major petroliths of this terrane are Precambrian (?) gneiss and mixtures of Mesozoic quartz diorite. In the western part the gneiss is intruded by a Precambrian laccolithic pluton of anorthosite, syenite, and gabbro and an overlying pluton of Permo-Triassic granodiorite. Elsewhere there are five Mesozoic granitic plutons and one dioritic pluton. All of these rocks are allochthonous along the Vincent Thrust mylonite, on late Mesozoic (?) mica (Pelona) Schist exposed in the eastern part, intruded by a small Tertiary pluton of granodiorite. From great depth, the autochthonous mica schist petrolith was compressed into an antiform that involved the Vincent Thrust and overlying allochthon. This occurred by Miocene time, when the schist was first exposed. Within the adjacent San Andreas fault zone another petrolith of mica schist was tightly compressed into an antiform and exposed at the same time. This antiform was juxtaposed along a southwest strand of the San Andreas fault from the Sierra Pelona 30 mi (48 km) to the northwest. The greatest amount of uplift of the San Gabriel Mountain terrane is at its eastern part where the San Gabriel and San Andreas faults converge. This is attributed to conversion of dextral shear stress into compressive stress where these faults converge and to dextral compressive uplift of the antiform of autochthonous mica schist petrolith.

INTRODUCTION

Scope and Purpose

This report describes the geology of the San Gabriel Mountains, as summarized in Dibblee (1982) and other references listed therein, and updated from more recent and more detailed geologic mapping and with greater focus on the geology of the critical eastern part of this mountain terrane. The geology of the entire San Gabriel Mountain range is now assembled in color by the Dibblee Geologic Foundation on 7.5-minute 24,000-scale topographic base maps of the U.S. Geological Survey. The geology is from the writer's geologic mapping mostly from 1953 to 1959 supplemented by additional field work in the 1960s and 1996-1998 with H. E. Ehrenspeck and others. Additional geologic mapping since 1975 by B. A. Carter, D. M. Morton, and J. C. Nourse is included. All of these maps are now published except those of the four easternmost quadrangles that are now in press. Figure 1 is an index to maps of the Dibblee Geologic Foundation that include the San Gabriel Mountains. This report is based on the geologic mapping indicated above.

Geologic Setting and Overall Geology

The San Gabriel Mountains are the south-easternmost, highest, and most mountainous part of the central Transverse Ranges. They are about 50 mi (80 km) long east-west and as wide as 20 mi (32 km) north-south in the central part. The geologic setting of this range is as shown on Figure 2. This range is a lenticular block in large part, bounded by the San Andreas and San Gabriel faults and located between the Los Angeles coastal plain on the south and western Mojave

Desert on the north. The west and east ends of this mountain terrane are narrow wedges.

The geology of the San Gabriel Mountains is shown on Figure 3. The mountains are eroded from Mesozoic to Precambrian crystalline basement rocks and elevated between the San Andreas fault zone along its northeast margin and a series of north-dipping frontal thrust faults along its south margin. This terrane is transected by internal faults, such as the southeast- to east-striking San Gabriel fault and its south branch and several northeast-striking cross faults (Figure 3).

The gneissic metamorphic and plutonic rocks of the major part of this mountain terrane are part of a deep seated thick allochthonous crustal slab on an autochthonous base of mica schist exposed only near and along the San Andreas fault zone at the northeast margin of the range. Both of these rock masses were elevated from great depth to the surface by intense compressive dextral shear stress along and within the San Andreas fault system. These transpressive crustal movements started as early as Oligocene time, if not earlier, and continued in stages during the Cenozoic era, accelerated by the late Cenozoic Coast Range orogeny.

While the terrane of the San Gabriel Mountains was intensely compressed within the San Andreas fault zone and deeply eroded, detritus accumulated rapidly as sediment in the adjacent lowlands of the Los Angeles coastal plain and Mojave Desert, where depression occurred contemporaneously by isostacy, compressive down-folding, or regional subsidence (Dibblee, 1995).

Geomorphology

The San Gabriel Mountains, the main central Transverse Range, is the highest and most rugged of the Transverse Ranges. This range is eroded from a mass of crystalline basement rocks, elevated largely on faults, into several ridges of mostly east-west trends. The ridge summits are somewhat subdued, but the intervening canyons are steep-sided, V-shaped, and deeply incised. This condition indicates that this range is in the early maturity stage of the present erosion cycle and is being actively elevated.

Physiographic features of this range are shown in Figure 4. The San Gabriel Mountains, as outlined above, will be designated tectonically as the "San Gabriel uplift" (Dibblee, 1982).

The San Gabriel Mountains uplift is highest in its eastern part, where it narrows and wedges out eastward into an alluvial plain. This part includes its highest point, Mount San Antonio (Mt. Baldy), 10,080 ft (3,010 m) above sea level.

The main mass of the eastern half of the San Gabriel uplift is abruptly bounded on the south side by a zone of north-dipping frontal thrust faults and on the northeast side by the Punchbowl fault and the San Jacinto fault zone along Lytle Canyon. This uplift is transected in its central part, west of San Antonio Canyon, by a west-trending rift-like depression along the west and east forks of San Gabriel Canyon. This canyon and its tributaries drain the major part of the central San Gabriel Mountains north of this depression.

San Antonio Canyon, which drains southward from Mount Baldy, separates the mountain terrane described above from the high rugged mountains terrane to the east that includes Cucamonga Peak (Figure 4). Southeastward from upper San Gabriel Canyon, the main crest of the eastern San Gabriel Mountains trends southeastward (Figure 4), but between Mt. Baldy and Telegraph Peak this crest is notched into two high northeast-trending ridges by cross-faults. The crystalline rock terrane of the San Gabriel uplift is moderately coherent but is severely shattered by tectonic stress, so that it is not very resistant to erosion. The terrane of (Pelona) schist of the northeast part of this uplift is even less resistant and is eroded to lower relief. The eastern San Gabriel Mountain uplift is flanked on the northeast by a lower ridge of schist known as Blue Ridge between the Punchbowl and San Andreas faults (Figure 3). Northeast of the San Andreas fault is an alignment of low ridges, including Table Mountain, that extend northwest across Cajon Canyon from the San Bernardino

Mountains. This alignment, along with the Inface Bluffs of Cajon Pass and the northern part of the San Gabriel uplift, forms the drainage divide between the Pacific Ocean to the south and the Mojave Desert to the north.

ROCK UNITS AND TERRANES

Rock Units

The rock units of the San Gabriel Mountains are as described by Dibblee (1982, p. 138-139), Morton (1975 - eastern part), Ehlig (1981), Carter (1982 - western part), and on the geologic maps of the Dibblee Geological Foundation. The aerial extent of the rock units is shown on Figures 2, 3, and 8.

Basement Terranes

The metamorphic and plutonic rocks of the San Gabriel Mountains were formerly thought to be indigenous to this region. However, numerous investigations, including detailed mapping, petrologic studies, and radiometric age determination, indicate that these rocks are parts of several distinctive geologic terranes, apparently exotic to each other, juxtaposed from probable distant areas and now accreted, as interpreted by Ehlig (1975, 1981). As now recognized (defined in Dibblee, 1982, p. 131-132, and shown on Figure 5), these geologic terranes and their rock units are described below.

San Gabriel Terrane: This terrane consists of Precambrian gneiss and plutonic rocks such as Precambrian anorthosite, syenite, and gabbroic rocks, Permo-Triassic Lowe Pluton, and late Mesozoic intrusives such as hornblende diorite, quartz diorite, and leucogranitic rocks. This is the most widespread terrane of the San Gabriel Mountains and is bounded by the Nadeau-Punchbowl faults of the San Andreas fault zone on the northeast and the San Antonio Canyon fault on the east. This terrane is allochthonous on the underlying autochthonous Pelona Schist terrane exposed in the eastern San Gabriel Mountains.

Tujunga terrane: This terrane is named for exposures in lower Tujunga Canyon southwest of the San Gabriel fault zone in the western San Gabriel Mountains; there are also exposures in the Verdugo Mountains to south. This terrane of gneiss, which contains layers of marble, includes the Placerita Formation of Oakeshott (1958) of unknown age and late Mesozoic plutonic rocks (quartz diorite, granodiorite, and quartz monzonite), is somewhat similar to the San Antonio terrane of the eastern San Gabriel Mountains.

San Antonio Terrane: This terrane is named for exposures on both sides of San Antonio Canyon in the eastern San Gabriel Mountains. Paleozoic (?) metasedimentary rocks and late Mesozoic quartz diorite and leucogranitic intrusions are bounded on the south by cataclastic quartz diorite (Black Belt mylonite of Alf, 1948), on the north by the eastern extension of the San Gabriel fault, and on the northeast by the San Jacinto fault zone in Lytle Canyon.

San Sevaine Terrane: This terrane is named for exposures in San Sevaine Canyon in the southeastern San Gabriel Mountains. It includes Paleozoic (?) or older granulite gneiss with layers of marble and late Mesozoic plutonic rocks, mostly quartz diorite and granitic rock which are exposed along the south front of the mountains from San Antonio Canyon to Lytle Canyon and northward to cataclastic quartz diorite.

Pelona Schist Terrane: This terrane is composed of late Mesozoic or older Pelona mica schist and the overlying Vincent thrust mylonite. It is exposed in the northeastern San Gabriel Mountains, including Blue Ridge. Southwest of the Punchbowl fault, it is intruded by mid-Tertiary granitic rocks and structurally underlies the allochthonous San Gabriel Terrane.

Green Valley Terrane: The inconspicuous terrane of gneiss and mixtures of quartz diorite to granodiorite in the Juniper Flats-Pinyon Ridge area between the San Andreas fault and the Punchbowl-Fenner fault is the same as that more extensively exposed far to the northwest in the low mountains around Green Valley between the San Andreas and San Francisquito faults, north of the Sierra Pelona. In the Green Valley area, it has been shifted northwest some 30 mi (48 km) with respect to the Juniper Flats – Pinyon Ridge segment of this terrane by right slip on the Punchbowl-Nadeau faults.

Cajon Terrane: The low terrane northeast of San Andreas fault, from Palmdale to Cajon Canyon including Table Mountain, composed of gneiss and quartz diorite to granodiorite-quartz monzonite, with lenses of white marble, and bodies of black hornblende diorite-gabbro, is designated as the Cajon Terrane for Cajon Canyon. This terrane extends eastward into the western San Bernardino Mountains.

Sedimentary Terranes: Sedimentary formations of mostly Tertiary age exposed on the fringes of the San Gabriel Mountains are described in Dibblee (1982) and on maps of the Dibblee Geological Foundation. These formations include the Vasquez, Tick Canyon, and Mint Canyon Formations (Oligocene-Miocene) of the Soledad basin, the San Francisquito (marine Paleocene) and Punchbowl (Miocene) Formations of the Valyermo area (Figures. 5 and 10), the Cajon and Crowder (Miocene to Pliocene) Formations of the Cajon Pass area, and the Glendora Volcanics (Miocene) of the Glendora area (Figures. 5 and 16).

PLUTONS

The metamorphic rocks of the San Gabriel Mountains are intruded by major plutons as well as by numerous leucocratic bodies, pods, dikes, and sills, many too small and complex to map. Much of the gneissic rocks are intruded by, converted to, or migmatized with quartz diorite (Wilson Diorite of Miller, 1934) throughout the San Gabriel Mountains; the gneiss and quartz diorite are so intricately mixed that they are difficult to differentiate. At least eight distinctive major plutons are recognized and mapped in these mountains (Figure 6). They range in age from Precambrian to mid-Cenozoic. From west to east and oldest to youngest these are San Gabriel Pluton, Lowe Pluton, Echo Granite Pluton, Waterman Pluton, pluton of Tujunga Canyon, two plutons of San Dimas Canyon area, and Telegraph Peak Pluton. The two oldest are laccoliths emplaced in gneiss; two others are emplaced in synforms in gneiss, and the others are cross-cutting intrusions.

San Gabriel Pluton

The western San Gabriel Mountains expose a pluton of very old, unusual igneous rocks, devoid of quartz, composed of anorthosite, syenite and gabbroic rocks, all of Precambrian age and intrusive into gneiss. These rocks were collectively designated as the San Gabriel anorthosite-syenite body by Carter (1980, 1982) and Carter and Silver (1982). They are designated here as the San Gabriel Pluton (Figure 6).

The geology of the San Gabriel Pluton is shown on Figure 7. It is bounded on the northeast and southwest by a roof of granulite gneiss (Mendenhall gneiss of Oakeshott, 1958), which is very thin on the northeast side adjacent to the Lowe Pluton. The base of the San Gabriel Pluton is not exposed because this pluton is part of a large allochthonous sheet that is floored by a zone of unusual cataclastic gneiss exposed in Mill Canyon (Carter, 1982, p. 2; Figure 7), a tributary of Soledad Canyon. The contract between the anorthosite of this pluton and the underlying gneiss, exposed only in that canyon, is interpreted as a major thrust fault, possibly related to the Vincent thrust (Carter, 1982).

The rocks of the San Gabriel Pluton are described in detail by Oakeshott (1958), Crowell and Walker (1962), Carter (1980, 1982), and Carter and Silver (1972). Their aerial distribution is shown on Figure 7. Nearly 60% of the San Gabriel pluton is composed of anorthosite, a massive pale bluish gray rock composed almost entirely of andesine plagioclase feldspar that weathers snow-white. It was radiometrically dated as 1,220 Ma and is intrusive into gneiss dated about 1,440 Ma (Carter, 1982). Barth et al. (1995b) reported a U-Pb zircon date of 1,190 Ma. Included in the anorthosite are many, mostly tabular, bodies of massive to compositionally layered leucogabbro and norite-jotunite-gabbros, a large body of hornblende gabbro through Mt. Gleason, and massive syenite at the western part of the pluton (Figure 7). All of these rocks are described in detail by Carter (1980, 1982).

The sequence of emplacement of these Precambrian rocks from oldest to youngest is anorthosite, leucogabbro, norite-gabbro, syenite, and hornblende gabbro (Ehlig, 1981;Carter, 1982). The San Gabriel pluton must have been emplaced in the gneiss somewhat as a laccolithic lens in Precambrian time, probably when the gneiss was flat-lying.

The structure of this pluton, as interpreted by Carter (1980, 1982, p. 43) is antiformal in the anorthosite in the northern eastern area and synformal in the syenite and gabbroic rocks in the southwestern area. However, this is not apparent because the anorthosite is massive with no structure and the tabular gabbroic bodies within it are generally vertical. At its southeast end, this pluton pinches out into the gneiss.

Lowe Pluton

The thin strip of gneiss along the east border of the San Gabriel Pluton separates the latter from the Lowe Pluton (Joseph et al., 1982) of late Permian-Triassic age (ca. 220 Ma; Joseph et al., 1982; Barth et al., 1990) in the western San Gabriel Mountains. (Figures. 6 and 7)

The pluton, named the Lowe Granodiorite by Miller (1934), was described in detail by Ehlig (1981) and Barth and Ehlig (1988). It is a distinctive leucocratic white rock with large phenocrysts of K-feldspar and in part mottled with black hornblende anhedra. It is moderately to vaguely gneissoid due to parallel orientation of hornblende. It was divided by Ehlig (1981) into four petrologic zones with no definite contacts. The lowest zone, on the southwest side of the pluton, is more mafic, is gneissoid due to more abundant hornblende and biotite, and contains less quartz, while the thick upper zone of the northeast side of the pluton is more leucocratic with little or no hornblende, massive, and difficult to differentiate from the massive granitic rock of the adjacent Waterman Pluton to the east.

The Lowe Pluton is exposed most extensively in the northwestern San Gabriel Mountains in the vicinity of Pacifico Mountain and Little Rock Canyon southeast of Soledad Pass (Figures 3 and 6). In that large area, the granodiorite includes several bodies of black hornblende gabbro of mostly north to northeast orientation. These bodies may be pendants recrystallized from pre-existing mafic (?) rocks. The Lowe Granodiorite of this area is in contact, to the east, with gneiss that dips steeply west (Figures 3 and 6), which is interpreted to underlie the granodiorite. To the west, the granodiorite is in contact with a thin strip of gneiss that dips steeply east and is in turn in contact with anorthosite of the San Gabriel Pluton (Figure 7).

Southeastward from the Pacifico Mountain area to the San Gabriel fault, the Lowe Pluton is exposed as a strip as wide as 4 mi (6 km), with structural attitudes that all dip steeply northeast toward the adjacent Waterman Pluton. This strip of Lowe Pluton is underlain by the strip of gneiss that dips steeply northeast under the Lowe Pluton (Figures 3 and 6); thus the gneiss must be the platform of the Lowe Pluton. Southeastward the pluton narrows toward the San Gabriel fault. The Lowe Pluton is bounded on the northeast by the leucogranitic Waterman Pluton of late Mesozoic age. The northeastern margin of the Lowe Pluton is exposed east of the Waterman Pluton in the Crystal Lake area north of the San Gabriel fault. In that area, the Lowe Pluton dips low to the southwest and intertongues to the southeast with intrusive quartz diorite associated with southwest-dipping gneiss. All those rocks are part of the allochthon above the Vincent thrust mylonite (Figures 3 and 6). South of the San Gabriel fault, the Lowe Pluton is exposed as a thin strip within the gneiss-quartz diorite complex on both sides of Santa Anita Canyon but is displaced westward from exposures north of the fault by some 12 mi (19km) of right slip on the fault. East of Santa Anita Canyon the Lowe Pluton pinches out (Figures 3 and 6).

The inferred structure of the Lowe Pluton throughout this area is that of a synform, in part plunging northwest, as suggested from the orientation of the gabbro bodies and scattered structural attitudes within the granodiorite. The Lowe Pluton was interpreted as a laccolith (Ehlig, 1981) emplaced at great depth in flat-lying Precambrian gneiss. If so, the gneiss and emplaced Lowe Pluton laccolith were subsequently involved in the development of the major synform structure in which the granitic Waterman Pluton was eventually emplaced.

Echo Granite Pluton

The Echo Granite, mapped by Miller (1934) and described in more detail by Smith (1986), is a small, elongated pluton adjacent on the southwest to the Lowe Pluton, between strands of the San Gabriel fault where the south branch diverges from the main fault north of Pasadena. The rock is light pinkish tan, massive, and composed of about 30% quartz, 65% microcline, and minor biotite. It is interpreted by Smith (1986) as Paleozoic or Precambrian (?) age and by Barth et al. (1997) as Triassic. Its position adjacent to the Lowe Pluton suggests it may be related to that pluton.

Waterman Pluton

The southwest-dipping rocks of the San Gabriel terrane above the Vincent Thrust mylonite are intruded on the southwest by massive granitic rock, mostly quartz monzonite, of a pluton, roughly 4 mi (6 km) wide that extends southeast from Little Rock Canyon through Mt. Waterman to the San Gabriel fault (Figure 6). This pluton is designated as the Waterman Pluton, for Mt. Waterman, and is of Cretaceous age. Part of this pluton is exposed south of the San Gabriel fault in the vicinity of upper Santa Anita Canyon, some 12 mi (19 km) west of the exposure north of the fault (Figures 3 and 6).

To the southwest and at Little Rock Canyon to the northwest, the Waterman Pluton is intrusive into and terminates against the older Lowe Pluton (Figures 3 and 6). In upper Santa Anita Canyon south of the San Gabriel fault, the Waterman pluton is intrusive southward into quartz diorite, that includes a strip of Lowe Granodiorite that dips north (Figures 3 and 6). Southeast of Mt. Waterman, the Waterman Pluton includes pendant remnants of quartz diorite with suggestive dips to the northwest. From the structural relations described above it is evident that the Waterman Pluton was emplaced into rocks of the allochthonous San Gabriel terrane where their structure is that of a synform which plunges northwest.

Josephine Pluton

A small pluton of granitic rocks (the Josephine Granodiorite of Carter, 1982) and Carter and Silver, 1972) of Cretaceous age (81 to 76 Ma; Carter and Silver, 1972; Barth et al., 1995a) is exposed in the vicinity of Mt. Josephine and upper Tujunga Canyon just north of the San Gabriel fault in the western San Gabriel Mountains. This pluton, designated the Josephine Pluton (Figure 6), is about 3 mi (5 km) wide and 6 mi (10 km) long and is truncated on the southwest by the San Gabriel fault. To the north, it is intrusive into gneiss and rocks of the San Gabriel Pluton, and on the east, into gneiss (Figures 6 and 7). All intrusive contacts with those rocks are cross cutting. Part of the Josephine Pluton is exposed within and just south of the San Gabriel fault zone west of the main mass of this pluton due to right slip on this fault zone. This pluton is about the same age as the Waterman Pluton to the east and is probably related to it.

Plutons of San Dimas Canyon Area

The gneiss-quartz diorite complex of the San Dimas Canyon area in the eastern San Gabriel Mountains enclose a small leucocratic pluton of granodiorite about 4 mi (6 km) long and as wide as 1 mi (1.6 km) elongated about east-west (Figure 6 and 8). This small pluton of late Mesozoic age is emplaced into the gneiss-quartz diorite complex where it is deeply down folded into a synform. This relation is similar to that of the Waterman Pluton to the northwest where leucocratic rock was emplaced in the same gneiss-quartz diorite and deeply depressed as a synform. There conditions suggest that this granitic pluton of the San Dimas Canyon area may be structurally related to the Waterman Pluton but separated from it by the complex structure of the gneiss-quartz diorite complex of the Morris Reservoir area northwest of the San Dimas Pluton and synform into which this pluton is emplaced.

Pluton of Dalton Canyon

In the vicinity of lower Dalton Canyon east of Morris Dam in San Gabriel Canyon, the gneiss-quartz diorite complex is intruded by a small, ovate hornblende diorite pluton (Figure 6) nearly 3 mi (4 km) long east-west. The age of this rock is presumably late Mesozoic. This intrusion cross-cuts the structure of the gneiss-quartz diorite complex. Several small intrusions of this rock occur to the east in San Dimas Canyon.

Telegraph Peak Pluton

In the eastern San Gabriel Mountains in the vicinity of Telegraph Peak and lower Lytle Canyon, southwest-dipping Vincent Thrust mylonite and cataclastic gneiss are intruded by granodiorite (Figure 6). This granodiorite is designated as the Telegraph Peak Pluton for Telegraph Peak. It was radiometrically dated as about 26 Ma (May and Walker, 1989; Nourse et al., 1998; Morton and Matti, 2001) or early Miocene-Oligocene. This pluton extends from Telegraph Peak, where it is about 1.5 mi (2 km) wide, eastward some 12 mi (19 km) down Lytle Canyon to the easternmost foothills of the San Gabriel Mountains (Figure 6 and 8). However, it is cut into slices by right lateral displacements on three strands of the San Jacinto fault (Figure 8), so that its aerial extent along Lytle Canyon is several times its original extent. Its intrusive contact with the Pelona Schist to the north strikes east-west but is offset by right slip on the faults (Figure 3).

Offshoots from this small pluton extend as numerous sills and some dikes of fine grained granodiorite porphyry or granophyre intrusive into the Pelona Schist almost throughout the San Gabriel antiform south of the Punchbowl fault and into some of the overlying mylonite. The small Telegraph Peak Pluton is the youngest in the San Gabriel Mountains. The very young age of this medium grained plutonic rock must indicate emplacement at great depth and rapid uplift of the San Gabriel antiform of Pelona Schist to the surface soon after this pluton was emplaced.

GEOLOGIC STRUCTURE

The overall geologic structure of the crystalline basement rocks is shown on Figures 3, 8, and 9. The structure of the Pelona Schist of the footwall on both sides of the Punchbowl fault is antiformal. The structure of the metamorphic rocks of the allochthon is more complex and somewhat obscured by plutonic intrusions is described in Dibblee (1982) based on intensive geologic mapping.

San Gabriel Antiform

The most remarkable structure in the San Gabriel Mountains is the great anticlinal structure of the Pelona Schist in the eastern part of the mountains, between the Punchbowl fault and the San Gabriel fault as shown on Figures 8 and 9. In this large fold structure, designated as the San Gabriel antiform (Dibblee, 1982, p.139), the anticlinal structure of the Pelona Schist is amazingly simple, as exposed in the upper East Fork of San Gabriel Canyon, where this structure plunges northwest. This antiform structure extends south of eastward into Lytle Canyon, where it is disrupted by right slip movements in the San Jacinto fault zone and is intruded by Tertiary granodiorite to the south. The northeast limb of this antiform is steepened and truncated against the Punchbowl fault zone that includes remnants of the overlying Vincent Thrust mylonite.

Prior to its uplift to the surface, the Pelona Schist must have been at great depth beneath the enormously thick allochthonous San Gabriel Terrane. This is indicated by its intrusion by the Telegraph Peak Pluton of Oligocene (26 Ma) age. This intrusion occurred after the schist was anticlinally folded. Then both rocks were uplifted to the surface. Accordingly, the Pelona Schist originally may have been flat lying, then compressed into an antiform upward to involve the overlying Vincent Thrust mylonite and allochthonous San Gabriel rock terrane, without piercing them during the Cenozoic Era.

Structure West of the Gabriel Antiform

It is astounding that the San Gabriel antiform structure of Pelona Schist involves the structurally overlying rocks such as the Vincent Thrust mylonite and gneissic and plutonic rocks of the overlying allochthon for some distance to the west in the north central San Gabriel Mountains (Figure 8). It is noteworthy that in the vicinity of Crystal Lake in the allochthon, the gneiss-quartz diorite complex with southwest-dipping foliation is injected by a sill-like mass of gneissoid Lowe Pluton with southwest-dipping foliation. In that area and westward the rocks are intruded by granitic rock of the Waterman Pluton as described under Plutons (Figures 6 and 8). Southwest of that pluton, the gneiss and other rocks dip steeply northeast (Figure 8), indicating that the Waterman Pluton was emplaced in a synform of those rocks.

Structure of Morris Reservoir - San Dimas Canyon Area

The structure of the gneiss and quartz diorite south of the San Gabriel fault is complex and not well understood east of where the south branch joins the main San Gabriel fault at the forking of San Gabriel Canyon. This is especially so in the area east of the Morris Reservoir of lower San Gabriel Canyon, where gneissic rocks strike and dip in different directions and are injected by a mass of augen gneiss. In much of this area and eastward, the gneissic rocks dip steeply southeast and east, whereas farther east near lower San Antonio Canyon, a large segment of gneiss dips west, northwest, and north (Figure 8). Structural relations described above indicate a closed synform structure with a northeast- to east-trending axis in upper San Dimas Canyon. Near the axial area, the gneiss is near vertical, and along that area the gneiss is intruded by the small San Dimas granodiorite pluton (Figure 8). Accordingly, this structure in the San Dimas Canyon area is similar to the larger synformal structure north of the San Gabriel fault and may be related to it.

In much of the area between San Dimas Canyon and Glendora Ridge to the northwest, the gneiss quartz diorite complex is cut by numerous dikes of rhyolite to andesite of northeasterly trends. These dikes are radiometrically dated at about 26 Ma (Oligocene; Nourse et al., 1998).

Structure of Area East of San Antonio Canyon

All of the structures described above are west of the San Antonio Canyon fault in San Antonio Canyon. Between the two splays of this fault near the mouth of this canyon, the metasedimentary rocks, mostly quartzite, are nearly vertical with a probable dip to the northwest and are intruded by granite (Figure 8). East of the main San Antonio Canyon fault, the granulite gneiss of the San Sevaine terrane is structurally overlain by cataclastic quartz diorite (“black belt”) and pendants of metasedimentary rocks in quartz diorite to the north. All of these rocks dip roughly 50° to the north. This structure is terminated on the north by the east extension of the San Gabriel fault and on the northeast by the San Jacinto fault zone (Figure 8).

Blue Ridge Antiform

The antiform structure of the Pelona Schist on Blue Ridge, between the San Andreas and the Punchbowl-Fenner faults, is another astounding structural feature in the eastern San Gabriel Mountains. This antiform structure is adjacent to the Pelona Schist of the San Gabriel antiform across the Punchbowl fault.

The Pelona Schist of Blue Ridge is tightly compressed into an antiform, designated as the Blue Ridge antiform. The axis is mapped just south of the Fenner fault and Fenner Canyon near Vincent Pass. This structure plunges slightly west. Eastward it becomes overturned northward toward the Fenner fault and then is truncated by the San Andreas fault at Wrightwood. Southeastward from there to Cajon Canyon, only the south limb is exposed (Figure 8). The Pelona Schist of this antiform was squeezed up on and south of the Fenner fault against the lowest part of the San Francisquito Formation on gneiss-quartz diorite basement (Figure 8). To the west down Big Rock Canyon, all of these rocks and the fault are unconformably overlain by basal red conglomerate of the upper Miocene Punchbowl formation (Dibblee, 2002b; Figures 8 and 10). It is not known whether or not the Blue Ridge antiform of schist pierced the overlying allochthon because this structure is bounded by the San Andreas and Punchbowl-Fenner faults.

The Pelona Schist and its structure, and rocks and the structure northwest of the Fenner fault, described above and shown on Figure 3, are amazingly similar to those of Sierra Pelona, some 30 mi (48 km) to the northwest, on the southwest side of where the Punchbowl and Nadeau faults merge northwest into the San Andreas fault (Figure 2). At Sierra Pelona, the Pelona Schist is tightly compressed into an antiform like that of Blue Ridge. It is elevated on and south of the San Francisquito fault, the possible original continuation of the Fenner fault. The schist is against south-dipping San Francisquito Formation on gneiss-quartz diorite (Greenville Terrane) basement, exactly as at Blue Ridge. To the west, all of those rocks and the San Francisquito fault are unconformably overlain by the upper Miocene Mint Canyon Formation, the probable equivalent of the Punchbowl Formation. The antiform structure of the Pelona Schist of Sierra Pelona and Blue Ridge are amazingly simple, even though tightly compressed. This anticlinally folded mica schist must have been squeezed up from great depth into the overlying allochthon of plutonic and gneissic rocks as a piercement fold by intensive compressive stress within the San Andreas fault zone.

The aerial distribution of the Pelona Schist near the San Andreas fault led Ehlig (1968) to postulate that the schist may have accumulated as sediments in a narrow, deeply subsiding belt now traversed by the San Andreas fault, as well as one traversed by the Garlock fault northwest of the Mojave Desert, then thrust over by an allochthon of crystalline rocks from great depth and metamorphosed to mica schist, all in late Cretaceous time. He also postulated that the faults might have originated along those belts. That theory is based on the assumption that the Pelona Schist is present only in the vicinity where it is now exposed. However, its concealed extent is unknown. Geophysical investigations to determine its subsurface extent in the western Mojave Desert have not provided any additional answers. An alternative theory, based on the assumption that the Pelona Schist may extend at great depth under an allochthonous crystalline petrolith far from its exposures, proposes that the schist was squeezed upward to the surface by very intensive dextral compressive stress generated along the San Andreas Fault system. The structural evidence in support of this theory is the antiform structure of the Pelona Schist in the San Gabriel Mountains, Blue Ridge and Sierra Pelona, as well as their proximity to the San Andreas fault zone.

FAULTS

As indicated under Geologic Setting, compressive uplift of the San Gabriel Mountains between faults of the San Andreas fault system in the Cenozoic Era was preceded by great deep seated thrust movements on the Vincent Thrust during or near the end of the Mesozoic Era. This great event is little understood because this thrust is exposed only in a small area in the San Gabriel Mountains. In that exposure, it is a sheet of mylonite between mica schist below as an autochthonous petrolith, with affinities to oceanic crust, and the complex of plutonic and intensely metamorphosed rocks above as typical continental crust as an allochthonous petrolith.

These conditions suggest that the Vincent Thrust mylonite may be a subduction plane along which the allochthon of the continental plate petrolith that makes up the major bulk of the San Gabriel Mountains was thrust over the oceanic (?) petrolith of mica schist. If so, these petroliths have long since been accreted to make up the basement complex of the San Gabriel Mountains. This ancient inactive thrust has nothing to do with uplift of the basement complex of these mountains on high angle faults that bound them. The uplifted basement complex of the San Gabriel Mountains is now bounded on the northeast by faults of the San Andreas fault zone such as the San Andreas, Punchbowl, and San Jacinto faults, and on the south by north-dipping frontal faults. This uplift is transected by internal faults such as the San Gabriel fault and its south branch, and northeast-striking cross faults (Figure 8). All these faults are of late Cenozoic age and potentially active.

Vincent Thrust

The Vincent thrust (Figure 8), first recognized by Ehlig (1952) who named it for Vincent Pass west of Wrightwood, is a layer of mylonite rock along which the allochthon of plutonic and gneissic metamorphic rocks of the San Gabriel rock terrane (Precambrian to Mesozoic) structurally overlies the Pelona Schist footwall autochthon terrane (late Mesozoic). Mylonite is a streaked rock formed by shearing at great depth in a metamorphic environment. The rock is hard, dark gray to black, thin layered, non-crystalline and contains whitish augen-like rolled grains of feldspar aggregate. The mylonite probably formed in late Cretaceous or early Tertiary time after emplacement of the latest plutonic rocks (Cretaceous) of the hanging block (Ehlig, 1981).

At Vincent Pass the Vincent Thrust mylonite is as thick as 1,500 ft (450 m). Astoundingly, the layer structure of the mylonite is concordant with that of the overlying cataclastic gneiss and with the foliation of the underlying Pelona mica schist. The contacts of the mylonite with the overlying gneiss of the allochthon and the schist of the footwall autochthon are gradational so that they are difficult to map accurately. These structural relations persist throughout the aerial extent of the Vincent Thrust mylonite exposed in the eastern San Gabriel Mountains, although the mylonite is thinner elsewhere. Similar conditions are apparent at Sierra Pelona. The astounding lack of discordance along the Vincent Thrust mylonite make it impossible to determine the direction of movement of the allochthon over the autochthon of schist.

The Vincent Thrust mylonite is one of the most astounding and baffling features of California geology. It is most astounding that the allochthon of old Precambrian gneiss rocks metamorphosed at enormous depth and extensively intruded by plutonic rocks are structurally underlain by mica schist of the autochthon, much less metamorphosed at a comparatively shallow depth and nowhere intruded by Mesozoic plutonic rocks. It is more amazing that the mica schist must have been flat-lying when overthrust by the allochthon of gneissoid and plutonic rocks of which the gneissoid rocks must have been flat-lying also, as indicated by the lack of structural discordance.

The Vincent Thrust mylonite and its structural relations are significant because if the mica schist of the allochthon is on a platform of mafic igneous rocks as presumed may be the oceanic plate that was subducted along the Vincent Thrust mylonite under the allochthon of deep-seated gneissic and plutonic rocks. The other reason that the Vincent Thrust mylonite is significant is that the mica schist, together with the overlying mylonite and adjacent gneissic and plutonic rocks, are together folded into a large antiform, and the schist is exposed in areas only along or near the San Andreas fault zone. This condition indicates that the schist is exposed as windows (fensters) near the fault and deeply buried elsewhere. Accordingly, the schist must have been squeezed up to the surface from great depths by intense compressive movement along the San Andreas fault zone.

San Andreas Fault

The San Andreas fault (Figures 2, 3, and 8) essentially forms the northeast border of the eastern San Gabriel Mountain uplift and southwest border of the San Bernardino Mountains uplift, as if these two mountain uplifts were displaced or separated from each other by right slip on this master fault. These uplifts may have been adjacent when the San Bernardino uplift evolved in Pleistocene time, but the San Gabriel uplift probably evolved earlier along this fault, probably in Pliocene time or earlier.

This segment of the San Andreas fault is a single strand striking about S60^{o}E, with a slight curve convex northeast. The fault forms a prominent rift zone through the eastern San Gabriel Mountains, where it is as high as 6,000 ft. (2,800 m) above sea level at a saddle northwest of Wrightwood. Much of this rift segment forms a long narrow valley for some 15 mi (22 km) from Wrightwood to Cajon Creek; northwest of the Wrightwood saddle, the rift zone is followed by canyons that drain northwest toward Valyermo. This long rift zone along this fault through mountainous terrane indicates this fault to be active, but there are few if any stream channels that cross the fault and that are offset laterally by strike slip on this fault segment.

The magnitude of right lateral shifting on this segment of the San Andreas fault is controversial and speculative. Southeast from the Fenner fault, the Cajon Terrane on the northeast side is juxtaposed against Pelona Schist terrane of Blue Ridge on the southwest side (Figure 8) of the San Andreas fault, which suggests a large amount of lateral displacement. In the Cajon Pass area, the Cajon basement terrane on the northeast side of the San Andreas fault is similar in lithology and structure to that in the Sawmill Mountain area on the southwest side of the fault near Lake Hughes, about 45 mi (72 km) to the northwest. If those basement terranes were once continuous, that much dextral shift on the San Andreas fault would be indicated. That magnitude would be much less than the 105 mi (163 km) of dextral shift of a distinctive 218-Ma porphyritic quartz monzonite at Liebre Mountain on the southwest side of the fault from the same rock in the San Bernardino Mountains on the northeast side (Frizzell et al., 1986).

In the Cajon Pass area, the Cajon basement terrane on the northeast side of the San Andreas fault is overlain by the middle Miocene (Barstovian) terrestrial Cajon Formation and bits of marine lower Miocene Vaqueros and Paleocene (?) San Francisquito Formation. It was formerly thought that the Cajon Formation was shifted southeastward some 25 mi (30 km) southeastward from the similar Punchbowl Formation, on the southwest side (Noble, 1954), but this unit contains a vertebrate fauna of upper Miocene (Clarendonian Age), so these units are not correlative. Therefore it is not known where the Cajon Formation was shifted from its equivalent on the southwest side of the San Andreas fault because there is no terrestrial unit of middle Miocene age on that side of the fault closer than the Lockwood Valley area, some 90 mi (134 km) to the northwest.

Punchbowl Fault

The Punchbowl fault, mappable for about 37 mi (59 km), is about 2.5 mi (4 km) southwest of the San Andreas fault. The Punchbowl fault was named and mapped by Noble (1954 a, b) as the north strand of the San Jacinto fault zone as shown by Jenkins (1938). The southwest strand was mapped as the San Jacinto fault by Noble (1954, a, b). In the Devils Punchbowl area, these strands are 0.3 mi (0.4 km) apart, dip steeply southward, and bound a strip of crushed plutonic and gneissic rocks. Southeastward toward Vincent Pass these strands nearly merge. However, I found that these strands are not part of the San Jacinto fault zone but extend as a single fault east-southeast to join the San Andreas fault near the blue cut in Cajon Canyon (Dibblee, 1968). Therefore, in the Devils Punchbowl area, both strands are mapped as the Punchbowl fault. The Punchbowl fault, as now mapped, was active probably in Plio-Pleistocene time, with no evidence of late movements. It must now represent an inactive strand of the San Andreas fault.

The Punchbowl and San Andreas faults bound a narrow slice roughly 2 mi (3 km) wide. Near Vincent Pass west of Wrightwood this slice is transected diagonally by the east-striking Fenner fault (Figure 8). This fault is traceable for only 5 mi (8km) but is important because it separates very different rock terranes within this fault slice, as will be discussed later. The most obvious part of the Punchbowl fault ("San Jacinto" fault of Noble, 1953, 1954) is conspicuous from Vincent Pass to just west of Juniper Hills, where it abruptly bounds the high central San Gabriel Mountains to form an imposing northeast facing escarpment. This segment is a reverse fault dipping steeply southwest, apparently generated by compressive stress. Northwestward this fault is buried by alluvial sediments for about 3 mi (4 km) and is not exposed, but is believed to extend into the Nadeau fault (of Noble, 1953), a younger strand of the San Andreas fault within 0.6 mi (1 km) of that fault.

From Vincent Pass for 20 mi (32 km) southeast to and beyond the blue cut at Cajon Creek, the Punchbowl fault is barely expressed. Southeast from the Fenner fault, the Punchbowl and San Andreas faults bound a ridge of Pelona Schist known as Blue Ridge, where the schist is tightly compressed into the Blue Ridge antiform as described under Geologic Structure. The anticlinal squeezed Pelona Schist of Blue Ridge is adjacent to the southwest along the Punchbowl fault to the Pelona Schist of the San Gabriel antiform described under Geologic Structure, so that along this fault segment the Pelona Schist is severely compressed into a tight synform. This condition accounts for the thin slice of Vincent Thrust mylonite along the fault, and at the blue cut at Cajon Creek a thin slice of quartz diorite. This is the best place to see the Punchbowl fault and where it is especially significant because the slice of quartz diorite is a slice of the allochthon that structurally overlies the autochthonous Pelona Schist.

The presence of Pelona Schist terranes on both sides of the Punchbowl fault seems to indicate no lateral movement on this major strand of the San Andreas fault. However, the Pelona Schist rocks on opposite sides of the Punchbowl fault are not the same. That of the San Gabriel antiform contains much biotite, no actinolite, and is intruded by the Tertiary granodiorite of Telegraph Peak and many sills of fine grained offshoots of that rock, whereas the Pelona Schist of Blue Ridge contains no granitic intrusions and is exactly similar to the type Pelona Schist of Sierra Pelona, some 30 mi (48 km) to the northwest, that contains actinolite and quartz veinlets. These conditions suggest that the Pelona Schist of Blue Ridge was separated from that of Sierra Pelona by that much dextral shift on the Punchbowl fault (Dibblee, 1967, 1968, Figure 2). If so, the Pelona Schist of Blue Ridge was juxtaposed against the dissimilar Pelona Schist of the eastern San Gabriel Mountains, a strange coincidence. The eastern extent of the Punchbowl fault beyond the San Andreas fault has not been found nor recognized. Presumably, it and the Pelona Schist of Blue Ridge have been shifted by dextral movement on the San Andreas fault far to the southeast to an unknown position.

Fenner Fault

The east-striking Fenner fault, located between the Punchbowl and San Andreas faults (Figure 3, 8, 11, and 12), was named for Fenner Canyon (Noble, 1954). Although traceable for only 5 mi (8 km), it is a major fault or a remnant of one. Along the Fenner fault the Pelona Schist of Blue Ridge is juxtaposed upward on the south against the Paleocene marine clastic San Francisquito Formation, which is unconformable on gneiss-quartz diorite basement (Figures 10 and 11). This fault is similar to the San Francisquito fault along the north border of the Pelona Schist of Sierra Pelona some 30 mi (48 km) northwest, where the rock units involved and their structural relations are exactly similar. Accordingly, the Fenner fault must have been the eastern extension of the San Francisquito fault (Figure 3). If so, it has been separated from that fault by some 30 mi (48 km) of dextral shift on the Punchbowl–Nadeau fault (Figure 10).

Near the Punchbowl fault, the Fenner fault is buried by red conglomerate of the upper Miocene Punchbowl Formation (Figure 10). This condition indicates that the Fenner and the San Francisquito faults, if originally continuous, are older than late Miocene. The marine Paleocene San Francisquito Formation in the Valyermo area and north of the Fenner fault (Figure 10), and north of the San Francisquito fault north of the mica schist of Sierra Pelona (Figures 3 and 12), contains conglomerate with clasts mostly of porphyritic metavolcanic rocks, similar to those (Sidewinder Volcanics; Dibblee, 1967) exposed in the central Mojave Desert, the probable source; it contains no clasts of Pelona Schist nor of rocks from the San Gabriel Mountains.

In the Valyermo area, the unconformably overlying upper Miocene Punchbowl Formation (Figure 10) contains some Pelona Schist detritus in its basal red conglomerate where it overlies the schist at Vincent Pass. Clasts in the major part of this formation are derived mostly from the Green Valley basement terrane, others from Pelona Schist, San Francisquito sandstone, and Vasquez volcanic rocks; none originated from the San Gabriel Mountains to the south. Conditions described above suggest that the terrane that includes those formations in the Valyermo area was juxtaposed southeastward along the Punchbowl fault against what is now the San Gabriel Mountains by a large amount of dextral shift along this fault, in accordance with dextral shift of the Pelona Schist of Blue Ridge from that of Sierra Pelona (Figure 12).

San Jacinto Fault Zone

The San Jacinto fault, one of the faults of the San Andreas fault system, extends northwest from the southwest margin of the San Jacinto Mountains diagonally across the valley of San Bernardino into and along the northeast margin of the eastern San Gabriel Mountains in the vicinity of Lytle Canyon and its tributaries. In that area the fault splays into several northwest-trending strands within a strip about 2 mi (3 km) wide, toward the Punchbowl fault, where they seem to die out as shown on Figure 8. Evidence of right slip on each strand is indicated by southeastward displacement of southwest-dipping Pelona Schist and the Tertiary Telegraph Peak Pluton that intrudes the schist, on the northeast side of each strand (Figure 8). On the easternmost strand, the Glen Helen fault, right slip displacement of this intrusive contact exceeds 5 mi (8 km). Northwestward, right slip on this fault juxtaposes Pelona Schist that dips southwest on the southwest side of the fault against the schist that dips northeast on the northeast side of the fault.

To the northwestward, all the strands of the San Jacinto fault zone extend into the Pelona Schist where it dips northeast on the northeast flank of the San Gabriel antiform so that those strand segments are not evident from the rocks. About the only evidence of their existence are the long straight narrow valleys of Lytle Creek (Figure 8). Near the Punchbowl fault, one of them may die out into up-ended north-dipping Pelona Schist. The southwest strands were mapped by Morgan (1975) as abruptly bending southwest into the eastern San Gabriel Mountains as left slip faults. This interpretation is unexplainable and unlikely, but if valid it would involve abrupt counter-clockwise rotation of the rock terrane involved to change the fault trends from northwest to southwest. This condition will be discussed later.

San Gabriel Fault

The San Gabriel fault, another strand of the San Andreas fault system (Figure 2), extends from the southwest margin of the Ridge Basin southeastward, probably under the Santa Clara River Valley, into the San Gabriel Mountains. In the Ridge Basin area, the San Gabriel fault (which dips steeply northeast) was intensely active as a right lateral strike slip fault in late Miocene-early Pliocene time, so intensively that it might have been the San Andreas fault during that time (Crowell, 1973). However, it may have been an active strand that co-existed with the San Andreas fault, as both dextral transcurrent faults may be required to create pull-apart conditions where they diverge southeast to generate the enormous amount of subsidence of the Ridge basin, filled with sediment eroded from adjacent areas contemporaneously elevated (Figure 13).

Active right slip on the San Gabriel fault appears to have essentially ceased in early Pliocene time, as the fault is buried by sediments younger than early Pliocene in the northwestern Ridge basin. In the Santa Clara Valley area to the southeast, the fault is buried by the Pliocene Pico and Plio-Pleistocene Saugus Formations. These formations were cut, with very small displacements, by this fault in only a few places.

To the southeast, in the San Gabriel Mountains, this fault curves eastward for at least 40 mi (64 km) to San Antonio Canyon and includes a south branch. The south branch of the San Gabriel fault (Sierra Madre fault zone of Jennings and Strand, 1969) splays southeastward from the main San Gabriel fault at Tujunga Canyon in the western San Gabriel Mountains. It diverges as much as 6 mi (9 km) from the main fault to the base of the mountains at Pasadena and Sierra Madre. From there it curves eastward and north of eastward as the Sawpit Canyon fault (of Bortugo and Spittler, 1986) back to the main fault and dies out where the forks at San Gabriel Canyon join, for a total distance of 24 mi (38 km) (Figure 3). Above Pasadena, the south branch fault is composed of several strands; however, the Sawpit Canyon fault is largely a single strand marked by a north-dipping gouge streak high up several canyons.

Movement in the south branch is mostly, if not entirely up on the north side, so it is a steep north-dipping fault. The high mountain terrane on both sides of Santa Anita Canyon is thrust up on this fault zone against the alluvial fan terrane of Pasadena and Sierra Madre on the beveled basement rock surface. Where the south branch curves eastward, it is very near the south frontal fault zone that extends eastward from the Raymond Hill fault. It does not extend into that fault zone (Figure 3) as erroneously interpreted on some maps (i.e. Ehlig, 1981). In the San Gabriel Mountains, the main San Gabriel fault extends from Tujunga Canyon eastward 30 mi (48 km) to San Antonio Canyon (Figure 3). This segment forms a rift-like depression followed or nearly followed by the west and east forks of San Gabriel Canyon. The fault is marked by a gouge zone in basement rocks that dips steeply north to vertical. Several faults, such as the Coldwater Canyon fault, extend southwest into this segment with small left slip displacement of rock units involved.

Within the San Gabriel Mountains, the San Gabriel fault, as far east as San Antonio Canyon, is within the San Gabriel basement terrane of gneiss-quartz diorite and granitic rocks. However, the terrane on the north side of the fault includes gneiss with Lowe Pluton, Vincent Thrust mylonite, and underlying Pelona Schist, all anticlinally folded on the San Gabriel antiform (Figure 8 and 9). This terrane is in contact with a structurally higher terrane of gneiss-quartz diorite on the south side of this fault. The lack of height difference of the mountain terrane on either side of the main San Gabriel fault indicates no major vertical displacement. Therefore, movement on this fault must have been mainly strike slip. This is indicated by displacement of rock terranes. North of the west fork of San Gabriel Canyon the rock terrane is composed of gneiss and the Lowe Pluton that dip northeast toward the granitic quartz monzonite of the Waterman pluton. On the south side of this fault segment, this same rock terrane, exposed in and west of upper Santa Anita Canyon, is about 12 mi (19 km) west, indicating that much right lateral displacement on this fault segment.

The main San Gabriel fault is traceable eastward to where it intersects the northeast-striking San Antonio Canyon fault near Mt. Baldy Village in upper San Antonio Canyon. In this area the geology is confused and in large part obscured by extensive coarse alluvial detritus resembling glacial till derived from the high mountain terrane to the east and north (Figure 8). The San Gabriel fault may extend eastward under this alluvium to the San Antonio fault on the east side of the canyon (Figure 8). If so, it may be offset on that fault to its inferred position up Icehouse Canyon by 1.7 mi (2 km), presumably by that amount of left slip on the San Antonio Canyon fault. Another alternative is that the San Gabriel fault veers northeastward as two faults of very minor displacement toward the mouth of Icehouse Canyon 1 mi (1.6 km) northeast of Mt. Baldy Village, with no offset on the San Antonio Canyon fault. Eastward from that fault the identity of the San Gabriel fault is uncertain.

The east extension of the San Gabriel fault is now inferred to be the fault up Icehouse Canyon some 5 mi (8 km) to the San Jacinto fault zone in Lytle Canyon (Figure 8). Much of this segment is covered by coarse alluvial, landslide and talus debris from this high mountain terrane, so it is difficult to map or even recognize. Accordingly, this segment is somewhat obscure; however, it is significant because it separates two very different rock terranes. The terrane on the north side is the terrane of Pelona Schist and structurally overlying Vincent Thrust mylonite and gneiss-quartz diorite complex, all dipping southwest and intruded by Tertiary granodiorite of Telegraph Peak. This terrane is juxtaposed on this fault against the San Antonio terrane, as described on the south side, that includes Paleozoic (?) metasedimentary rocks all dipping north and intruded by Mesozoic quartz diorite and granitic rocks (Figures 8 and 9, section D-D). A cross section shows the great contrast of these rock terranes separated by this fault segment (Figure 8), indicating this fault to be of great magnitude, but there is no evidence that it is now active. Due to this great magnitude, this fault, sometimes locally called the Icehouse fault, is now interpreted to be the eastern extension of the San Gabriel fault (Figure 8). If this interpretation is valid, then this segment is displaced from the main segment west of the San Antonio Canyon fault by about 1.7 mi (2 km) of left slip on the San Antonio Canyon fault.

It is noteworthy that the rock terranes juxtaposed along the east extension of the San Gabriel fault are somewhat similar to those juxtaposed along the San Antonio Canyon fault south of this juncture; that is, the San Antonio rock terrane on the east side of this fault is juxtaposed against the San Gabriel terrane of gneiss-quartz diorite complex (Figure 5). Accordingly, the east extension of the San Gabriel ("Icehouse") fault could be part of the San Antonio Canyon fault. But the eastward strike of this San Gabriel fault segment is in accordance with that segment west of the San Antonio Canyon fault and somewhat anomalous to the normal northeastward strike of the San Antonio Canyon fault.

If the San Gabriel fault in the San Gabriel Mountains is or was part of the San Andreas fault system with right slip movement, its original strike must have been northwest southeast, but now it curves eastward (Figure 3). This anomalous strike must indicate counter-clockwise rotation of the rock terranes that include this fault in the eastern San Gabriel Mountains. The amount of rotation would have been 30 to 45º counter-clockwise. This is astounding because it is in contrast to the evident clockwise rotation in and just north of the western San Gabriel Mountains as mentioned later. The counter-clockwise rotation of the wedge-shaped eastern San Gabriel Mountains is accompanied by an enormous amount of uplift, more so than any other part of this range. The uplift is north of the north-dipping Cucamonga fault zone at the south margin of this uplift, adjacent to the valley area to the south that is a sedimentary basin. This valley area is the depressed northwest margin of the Perris block that must be underthrusting this mountain terrane with such force as to create the counter-clockwise rotation.

The eastern segment of the San Gabriel fault extends to the San Jacinto fault zone in Lytle Canyon where it presumably terminates (Figure 8). If once continuous beyond eastward, and displaced by right slip on the San Jacinto fault zone, the position of this offset segment to the east is unknown. Perhaps the inactive Banning fault on the San Andreas fault zone is a possibility that may be of the same age. The age of the main San Gabriel fault in the San Gabriel Mountains is probably about the same as its segment by the Ridge basin, or late Miocene-early Pliocene. In this mountain terrane, there is no convincing evidence of late movement, such as, offset stream channels, shutter ridges or scarplets. Therefore, this segment, like the segment by the Ridge basin, must be old and inactive.

San Antonio Canyon Fault and Other Cross Faults

The San Antonio Canyon fault is the largest of several northeast-striking cross faults in the San Gabriel Mountains (Figure 3 and 8). This fault transects the entire range. It extends up San Antonio Canyon in the eastern part of the range and through the northwesterly of the two deep notches on the main crest and into the San Jacinto fault zone in Lytle Canyon. Southwestward in lower San Antonio Canyon it splays into two branches that curve westward into the south frontal fault zone (Figure 8). In many places the San Antonio Canyon fault is covered by Pleistocene and older alluvial deposits, so it is not active. Major movement is probably left lateral, but the amount is uncertain. Along this fault, the San Gabriel gneiss-quartz diorite rock terrane on the west-northwest side is juxtaposed against the San Antonio terrane that includes north-dipping meta sedimentary rocks as described on the east-southeast side (Figure 5). This condition indicates a large amount of probably left lateral displacement.

Southward along the west branch of the San Antonio Canyon fault, north and northwest-dipping gneiss-quartz diorite of the San Gabriel terrane on the northwest side is thrust up against metasedimentary rocks intruded by plutonic rocks on the southeast side (Figure 8). On the main strand, these rocks are juxtaposed against quartz diorite with metasediments dipping north (Figure 8). Along the (ski-lift) notch at the head of San Antonio Canyon the southwest dipping Vincent Thrust mylonite is offset nearly 4 mi (6,km) by left slip on the San Antonio Canyon fault. Other northeast-striking cross faults occur east of lower San Antonio Canyon such as the Stoddard and West Lytle Creek faults (Figure 8), with small left-slip displacements. Just northwest of Mt. San Antonio, the upper segment of the San Antonio Canyon fault is nearly paralleled by the Coldwater Canyon fault about 3 mi (4 km) northwest (Figure 8). Along this fault the Vincent Thrust mylonite is displaced by about 2.5 mi (3.5 km) of left slip movement.

The central and northwestern San Gabriel Mountains and Soledad Canyon area are transected by several cross faults that strike northeastward from the main San Gabriel fault (Figures 3 and 8). All are high angle faults mostly in the San Gabriel rock terrane with small amounts of left-slip displacement. Most die out northeastward toward the San Andreas-Punchbowl fault zone. Some extend as much as 12 mi (19 km). Genesis of these faults is attributed to small clockwise rotation of the rigid block of crystalline basement bounded by the right-slip San Gabriel fault and the Punchbowl-San Andreas fault.

South Frontal Fault Zone

The San Gabriel Mountains are abruptly bounded on the south by a complex zone of north-dipping thrust/reverse faults along which this range is elevated. The western San Gabriel Mountains were elevated on a zone of thrust faults, sometimes called the Sierra Madre fault zone (Cooke et al., 1989), that extends from Tujunga east-southeast to Pasadena, where this fault zone merges into the south branch of the San Gabriel fault (Figure 3). Along some faults of this zone, basement rocks are thrust over alluvial fan gravel, indicating active uplift on these faults. The central San Gabriel Mountains, from Sierra Madre to Claremont, were thrust up on a complex zone of frontal faults that extends from the Raymond Hill fault near Monrovia eastward to San Dimas and San Antonio Canyon (Figure 8). Most of these faults are buried by alluvial fan gravel, but on one fault, just west of the mouth of San Dimas Canyon, Miocene shale and volcanics are thrust up over alluvial gravel as indicated in shallow drill holes.

The eastern San Gabriel Mountains east of San Antonio Canyon are thrust up on the Cucamonga fault zone that breaks alluvial fans to form south-facing scarps (Cooke et al., 1989). At and near San Sevaine Canyon in the eastern part of this mountain terrane, basement rocks are thrust up along this fault zone against upended upper Tertiary sedimentary rocks of the San Bernardino basin (Figure 8). From these relations it is evident that the Cucamonga fault zone is the most active part of the south frontal fault zone along which the eastern San Gabriel Mountains are being actively elevated.

ORIGIN AND GENESIS OF THE SAN GABRIEL MOUNTAINS

Cenozoic Orogenic Episodes

The central Transverse Ranges, including the San Gabriel Mountains, evolved from Cenozoic orogenic episodes (of Dibblee, 1995) as shown on Figure 14 and described below.

<u>The Alisan Orogeny</u> exposed crystalline basement rocks following deposition of marine clastic sediments of the San Francisquito Formation in late Cretaceous-Paleocene Eocene time.

<u>The Ynezan Orogeny</u> was a great surge of compressive mountain uplift in Oligocene-early Miocene time, including widespread 25- to 23-Ma volcanic eruptions in inland areas associated with sedimentary detritus from uplifted areas deposited in adjacent lowlands that were depressed contemporaneously. The Vasquez Formation was deposited in a valley now the Soledad basin during this orogeny.

<u>The Lompocan Orogeny</u> was a recurrent surge of the Ynezan orogeny with renewed compressive mountain uplift in early middle Miocene time and widespread 18- to 15-Ma

volcanic eruptions associated with marine deposition.

The Rafaelan Orogeny in late Miocene time produced intense local mountain uplifts and basin subsidence related to movements on the San Gabriel fault.

The Coast Range Orogeny in late Cenozoic (Plio-Pleistocene) resulted from the effect of increasing dextral-compressive stress associated with the San Andreas fault system, in which the present Coast and Transverse Ranges are evolving in stages and from which eroded detritus is accumulating in adjacent lowlands and submerged areas depressed contemporaneously.

Genesis of the San Gabriel Mountains Prior to the Inception of the San Gabriel Fault

Prior to the inception of the San Gabriel fault, probably during the middle Miocene Lompocan Orogeny, the San Gabriel Mountain uplift evolved during the Oligocene Ynezan orogeny as the southeast continuation of the Alamo-Pine Mountain uplift, west of what is now the Ridge basin. Uplift of this mountain belt must have been the effect of intensive, compressive stress. Also elevated during that event were Sierra Pelona and the Sawmill-Liebre Mountain uplift (Figure 3) near the San Andreas fault, if it then existed.

During the Ynezan Orogeny, the area between the San Gabriel and Sierra Pelona uplifts was depressed as the Soledad basin; likewise the area north of the Alamo-Pine Mountain uplift was depressed as the Lockwood-Cuyama basin. These basins probably connected prior to onset of the San Gabriel fault. The Sierra Pelona uplift of Pelona Schist extends westward under Miocene sediments, probably to the present San Gabriel fault. West of this fault, the Pelona Schist of the Mount Pinos Range may be its western continuation (Figure 15). If all these matching structural features were originally continuous, they have been displaced or separated by some 30 to 35 mi (50 km) of right slip on the San Gabriel fault during the late Miocene early Pliocene Rafaelan Orogeny (Figure 15).

Genesis of the San Gabriel Mountains within the San Andreas Fault System

Since the San Gabriel uplift was shifted away from the Alamo-Pine Mountain uplift on the San Gabriel fault in late Miocene time, it with the other central transverse ranges and the Soledad-Ridge basin developed largely within the lenticular block between the San Andreas and San Gabriel faults (Figure 2 and 13). All of these tectonic features are the effects of dextral compressive shear stress that prevailed along the San Andreas fault system. Within this lenticular block, compressive uplift of the San Gabriel Mountains accelerated in the southeastern part of the block where the San Gabriel and San Andreas faults converge (Figure 13). When the San Gabriel fault became inactive after late Miocene time, possibly due to its eastward bending, uplift of the mountain block involved the terrane to the south with uplift on the zone of south frontal faults as well as the south branch of the San Gabriel fault. While the San Gabriel Mountains were elevated at the southeastern part of this lenticular block, the Ridge basin was depressed at the northwestern part, where the San Gabriel and San Andreas fault diverge (Figure 13).

It is significant that the highest part of the San Gabriel mountain uplift is its eastern segment, where it wedges out eastward against lowlands, This part includes its highest peaks, Mt. San Antonio and Cucamonga Peak, and is higher than any part of the central Transverse Range terrane within the block between the San Andreas and San Gabriel faults (Figure 2). It is more significant that this segment is where the autochthonous Pelona Schist and overlying allochthonous San Gabriel crystalline terrane have been antiformally compressed upward during the late Cenozoic Coast Range orogeny (Figure 9). The highest part of this uplifted segment is the allochthonous crystalline terrane, just above the Pelona Schist, which is eroded down to lower relief due to its weaker resistance to erosion. Uplift of the southeastern San Gabriel Mountain terrane, including Cucamonga Peak, may be in part attributed to northward underthrusting of the Perris block of the Peninsular Range province, as mentioned under faults. South of where this block is underthrusting the San Gabriel Mountains it is depressed as a subsiding sedimentary basin under the valley of Cucamonga and San Bernardino.

TECTONIC HISTORY OF THE SAN GABRIEL MOUNTAIN UPLIFT

Latest Cretaceous to Eocene

Widely scattered exosures of marine clastic sediments of latest Cretaceous, Paleocene, and Eocene ages in the central Transverse Ranges region indicate this area was submerged during that time. These sediments, including the San Francisquito Formation, accumulated on gneiss-quartz diorite basement, but conglomerates of these sediments contain no detritus of that basement rock nor of Pelona Schist.

Oligocene

The Vasquez Formation of Oligocene to early Miocene age of the Soledad basin (Figure 3) rests on a platform of anorthosite-syenite of the San Gabriel Pluton; therefore, that basement terrane was exposed at the surface prior to Oligocene time. The Vasquez Formation does not overlie the Pelona Schist, nor does it contain any detritus from it, indicating the schist was not yet exposed. North of the Pelona Schist of Sierra Pelona, the Vasquez Formation overlies the San Francisquito Formation; however, that formation is absent in the Soledad basin area. That must indicate that either the San Francisquito Formation was never deposited there, or if it was, it has been removed prior to deposition of the Vasquez Formation.

Deposition of the Vasquez Formation in the evolving Soledad basin during and after the Oligocene Ynezan orogeny started with eruption of basaltic-andesitic lavas about 25 Ma ago (Frizzell and Weigand, 1993). This is a local example of widespread inland volcanic eruptions, mostly in the Mojave Desert, northeast of the San Andreas fault. Other igneous activity of this episode occurred in the area now the eastern San Gabriel Mountains where granodiorite of the Telegraph Peak Pluton and its offshoots were intruded about 24 Ma into the Pelona Schist of the San Gabriel Antiform. Also, the swarm of andesite-dacite dikes in the San Dimas Canyon area was emplaced at that time. The volcanic flows, along with minor sediments of the Vasquez Formation, were deposited on a platform of the San Gabriel and Lowe Plutons, indicating that basement terrane was exposed prior to Oligocene time. Following the volcanic eruptions, the Vasquez Formation accumulated in the Soledad basin as coarse alluvial fans derived from those plutonic rocks uplifted to the south (Dibblee, 1996a; Figures 7 and 8). That occurred during the Ynezan Orogeny and is the earliest record of uplift of the San Gabriel Mountains.

Additional evidence of the ancestral San Gabriel Mountains in Oligocene time is indicated from conglomerate clasts in the Oligocene Sespe Formation of red beds exposed in the Piru-Carston Canyon area of the eastern Ventura basin. These clasts are of granitic and gneissic rocks and distinctive rock types such as anorthosite, gabbro, syenite and Lowe granodiorite (Crowell, 2003) derived from those rocks now exposed in the western San Gabriel Mountains northeast of the San Gabriel fault. This source terrane has since been shifted some 32 mi (45 km) southeastward by right slip on the San Gabriel fault from the Sespe Formation.

This condition suggests that in Oligocene time the area now the western San Gabriel Mountains were elevated adjacent to and shed detritus into the eastern Ventura basin in Oligocene time, probably prior to inception of the San Gabriel fault.

Miocene

The early middle Miocene Tick Canyon Formation, deposited during the Lompocan Orogeny over the Vasquez Formation in Soledad basin, is in part likewise an alluvial fan deposit of detritus derived from the San Gabriel and Lowe Plutons, indicating continued uplift of that terrane. To the southwest the middle Miocene Tick Canyon Formation laps directly onto the San Gabriel pluton (Dibblee, 1996 a, b). The mostly upper Miocene Mint Canyon Formation that overlies the Tick Canyon Formation in Soledad basin also includes in its conglomerates detritus derived from the San Gabriel and Lowe Plutons, indicating continued uplift of that terrane during that time.

The Mint Canyon Formation also includes Pelona Schist detritus at its base in northern exposures near Sierra Pelona and overlaps northwest the Vasquez Formation and granite onto the Pelona Schist of Sierra Pelona (Dibblee, 1996b, 1997b). This is the earliest record that the Pelona Schist was elevated to and exposed at the surface, during or soon after the Lompocan Orogeny. Similar conditions prevail at Vincent Pass (Figure 10), where the Miocene Punchbowl Formation overlies the Pelona Schist and contains schist detritus in its basal conglomerate. As described previously, the Punchbowl Formation was deposited after the Pelona Schist was uplifted on the Fenner fault and exposed in Miocene time, as at Sierra Pelona.

In the Devils Punchbowl area near Valyermo, the upper Miocene Punchbowl Formation contains clasts of mostly granitic plutonic rocks derived from the a source to the east. At Vincent Pass near Wrightwood, the basal red conglomerate of the Punchbowl Formation is unconformable on the Pelona Schist of Blue Ridge and its contact along the Fenner fault with the Paleocene San Francisquito Formation on gneiss-quartz diorite. This dates the Fenner fault as pre-late Miocene (Noble, 1954a; Dibblee, 2002b).

In the eastern margin of the Ventura basin southwest of the San Gabriel fault near Castaic, the middle and upper Miocene Monterey Formation includes thick lenses of coarse conglomerate, (Devil Canyon Conglomerate of Crowell 1982, 2003) of detritus of anorthosite, syenite, and gabbroic rocks (Crowell, unpub.; Dibblee, 1997a) derived from the San Gabriel Pluton of the western San Gabriel Mountains on the northeast side of the fault; this source area is now some 22 mi (35 km) to the southeast. This indicates that the western San Gabriel Mountain terrane was being elevated in middle and late Miocene time, during and following the Lompocan orogeny, and that the Ventura basin area that includes those conglomerates must have been shifted from their source terrane by some 22 mi (35 km) of right slip on the San Gabriel fault.

On the south margin of the central San Gabriel Mountains near Glendora, the San Gabriel basement terrane is overlain by the middle Miocene Glendora Volcanics (Shelton, 1946; Dibblee, 2002c) (Figures 16 and 17). These rocks, which erupted 16 to 15 Ma (Nourse et al, 1998; McCulloh et al., 2003), are the local effect of widespread volcanic eruptions during the Lompocan Orogeny. They were erupted on a platform of basement rocks uplifted prior to and since they were erupted.

In the Cahuenga Mountain area, foothills west of Pasadena, and northern Puente Hills of the Los Angeles basin, the Miocene Topanga and Monterey Formations include lenses of coarse conglomerate of quartz diorite to granitic and some gneissic detritus derived from the San Gabriel Mountain uplift (Dibblee, 1989), which indicates that terrane must have been elevated in Miocene time. The Monterey Formation that includes this conglomerate on the southwest side of the San Gabriel fault may have been shifted by some 30 mi (48 km) of right slip on the fault from its original position of its source in the western San Gabriel Mountains, on the northeast side of the fault. This again indicates uplift of the San Gabriel Mountains in Miocene time.

Late Cenozoic

As uplift of the San Gabriel Mountains accelerated in stages during the late Cenozoic Coast Range Orogeny, they shed an enormous amount of detritus. Along the northern border with the western Mojave Desert, this uplift shed detritus of plutonic, gneissic, and Pelona Schist debris as north-sloping piedmont alluvial fans. On the south and southwest side this uplift shed coarse alluvial fan detritus into the Los Angeles basin and as the Saugus Formation (Plio-Pleistocene) into the San Fernando area and eastern Ventura basin.

CONCLUSION

It is concluded that the San Gabriel Mountain uplift is basically a slice of deep-seated continental crust of crystalline basement rocks squeezed up by intense dextral transpressive stress within and adjacent to the San Andreas fault system in stages during the Cenozoic Era. Uplift of this thick crust has been so intense that it has revealed that it is allochthonous and that it is structurally underlain by a crust of low-grade mica schist that my be oceanic crust and which was squeezed up with the overlying continental crust from great depth. Whether this condition is regional or local is unknown, but similar conditions along the Garlock fault across the western Mojave Desert suggest that it may be regional.

The intensity of dextral transpressive stress along the San Andreas fault segment in the central Transverse Ranges may be attributed to its unusual N70°W strike, which is partly athwart to the prevailing northwest southeast dextral sheer stress along the usual NW-striking San Andreas fault elsewhere. Resistance to this stress along the N70°W trending segment partly converted it to compressive stress that generated uplift of the central Transverse Ranges such as the San Gabriel Mountains. The intensity of this compressive force along the San Andreas fault system must be what squeezed up the oceanic? crust of mica schist to the surface, which is further indicated by the anticlinal structure of the mica schist in all four areas mentioned.

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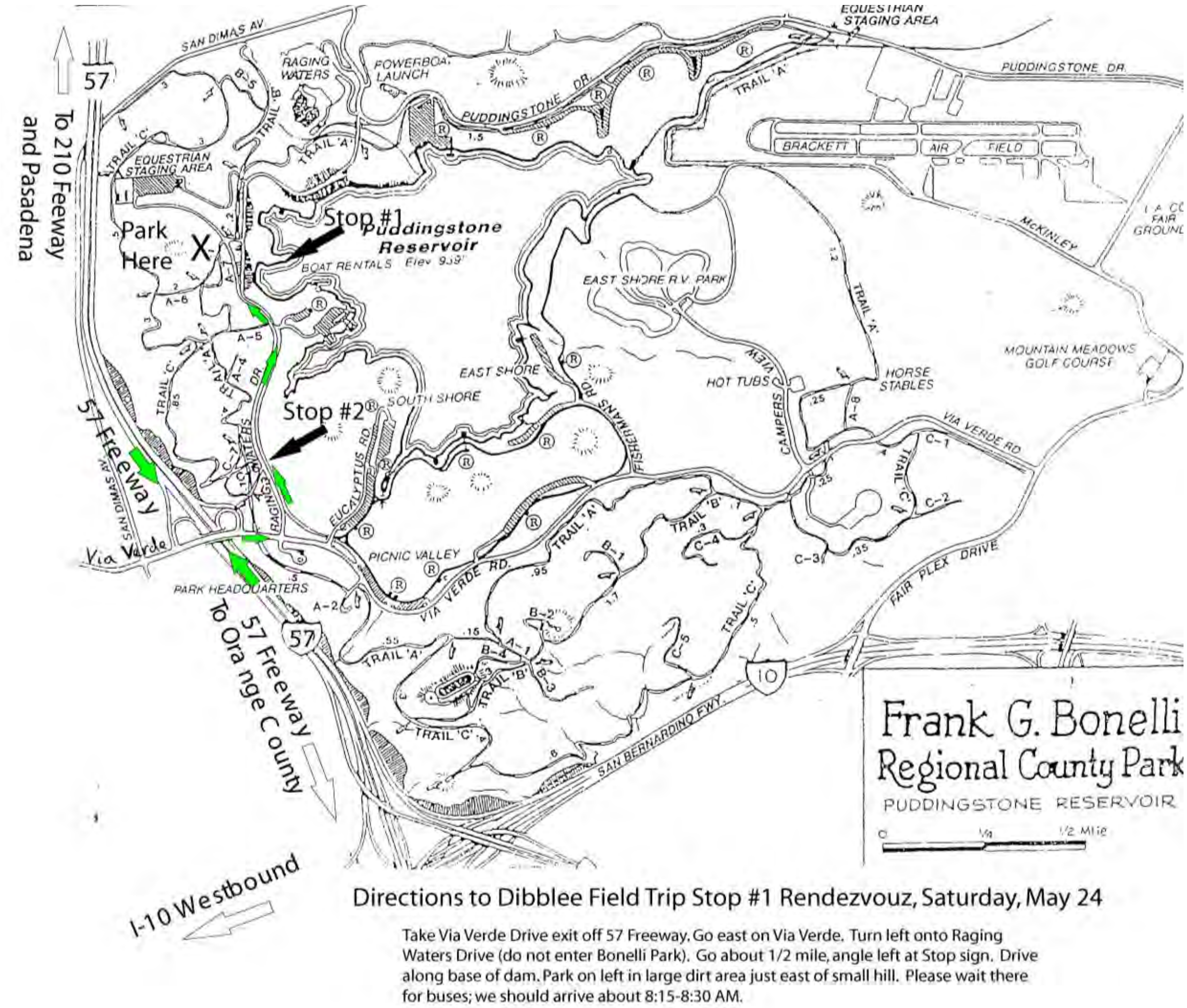

Figure 1. Location Map for Puddingstone Reservoir Stops #1-#2

Introduction

Welcome to Bonelli Park. This site was chosen to introduce the field trip because of a geologic connection between the Neogene section exposed here and a distinct assemblage of basement rocks and structures exposed in the eastern San Gabriel Mountains, where we will spend much of the day (Figure 2; see also front cover). Specifically, the area surrounding Puddingstone Reservoir is underlain by Middle Miocene volcanic rocks that were probably extruded during the time that a mafic-intermediate dike swarm was emplaced into the San Gabriel Mountains.basement (Weigand et al., 1994; Nourse et al., 1998). Furthermore, an upper Middle Miocene to Lower Pliocene conglomerate-bearing marine sequence south of Puddingstone Reservoir contains an inverted clast stratigraphy that records uplift and erosion of the eastern San Gabriel Mountains coincident with important movements on strike-slip and dip-slip faults.

The plan for today is to briefly inspect elements of the Neogene section (Figures 3 and 4), and then proceed to the San Gabriel Mountains where basement rocks and structures are superbly exposed. We shall also view field evidence of floods and landslides that have resulted from interplay between steep topography, severe weather conditions, and (probably) major earthquakes. Historical impacts on human structures such as roads and buildings will become apparent as we work our way up the Mt. Baldy Road. Depending on the clarity of today's weather conditions, views from the peninsula on Puddingstone Reservoir offer an ideal setting to discuss the connectivity between the geology of Bonelli Park and the eastern San Gabriel Mountains.

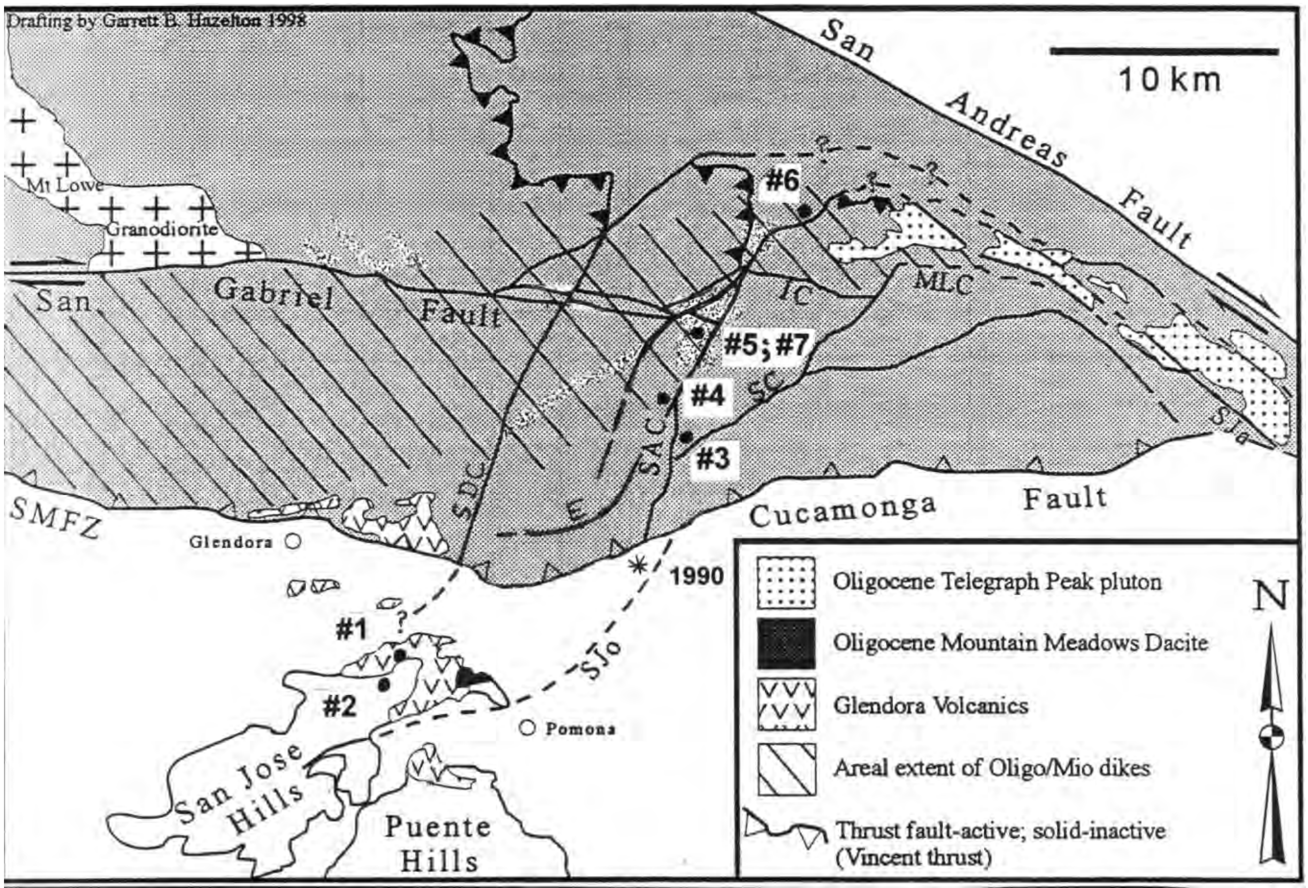

Figure 2. Schematic geologic map of the Pomona Valley and eastern San Gabriel Mountains showing distribution of Neogene igneous rocks and location of field trip stops (black dots). Solid bold lines indicate Late Cenozoic strike-slip faults. Star denotes epicenter of the 1990 M=5.4 Upland earthquake. Modified from Figure 1 of Nourse et al, (1998).

Stop #1: Glendora Volcanics

This area of Bonelli Park preserves several subunits of a Middle Miocene extrusive igneous complex named the "Glendora Volcanics" by Shelton (1955). Glendora Volcanics are exposed between the foothills of the eastern San Gabriel Mountains and the northern Puente Hills (Figure 2; see also Tom Dibblee's geologic map of the San Dimas quadrangle, 2002). This heterogeneous assemblage of flows, flow breccias, volcaniclastic conglomerates, and tuffs exhibits a compositional range between olivine basalt and rhyolite (Mull, 1934; Shelton, 1955; Higgins, 1976; Roberts, 1995). Andesite breccia is the most volumetrically abundant lithology. Outcrops near Puddingstone Reservoir were originally mapped by Mull (1934) before Puddingstone Dam was constructed. Three or four km to the southeast of Stop #1 the Glendora Volcanics rest unconformably upon Late Cretaceous plutonic rocks, and locally overlie the Late Oligocene Mountain Meadows dacite (Shelton, 1955; Figure 3). Directly south of Stop #1, a volcanic-clast conclomerate probably correlative with the upper Middle Miocene Topanga Formation separates the Glendora Volcanics from overlying Puente Formation (Nourse et al., 1998; Figure 4b). Contact relations between the Glendora Volcanics, Topanga Formation, and Puente Formation have been studied recently by McLarty (2000) and members of the Cal Poly Pomona Engineering Geology class.

As we traverse southeast from the parking area please note an outcrop of vesicular basalt flow breccia exposed beneath the fill of Puddingstone Dam (Figure 4a). Then cross the upper paved road that traverses the dam crest, pass through a gap in the chain link fence, and walk downhill to the southeast toward a peninsula.

Small outcrops of dark gray-weathering basalt breccia and purple-weathering porphyritic andesite are encountered in low areas before the peninsula. The andesite represents a common and abundant component of Glendora Volcanics that forms flow breccias in hills to the east and south of Puddingstone Reservoir. Walk east to the end of the peninsula, crossing tan and light gray fine-grained dacite and andesite flows that may be hydrothermally altered to a bright red color.

Several components of the Glendora Volcanics have yielded Middle Miocene radio-metric ages. Andesite and dacite sampled from southeast of Puddingstone Reservoir yielded whole rock K/Ar dates of 19.6±1.1 Ma and 18.2±1.1 Ma and plagioclase $^{40}Ar/^{39}Ar$ dates of 16.3 ±1 Ma and 15.9±0.3 Ma, respectively (Nourse et al., 1998). McCulloh and others (2002) have recently augmented this work with additional $^{40}Ar/^{39}Ar$ analyses. They obtained plagioclase ages of 15.08±0.11, 15.28±0.05, and 15.32±0.16 Ma from three samples of hypersthene andesite collected along Fairplex Drive and a whole-rock age of 17.2±0.5 Ma from basalt. Farther south at Elephant Hill, whole-rock K/Ar dates of 18.8±1.2 Ma and 13.2±0.4 Ma were obtained from andesite and rhyolite, respectively (L. Herber, unpublished data, reported in Nourse et al., 1998), but the degree to which these analyses have been affected by hydrothermal alteration is uncertain. The most reliable data suggest that volcanism was active from 16.3 to 15.1 Ma.

The Glendora Volcanics and approximately coeval extrusive igneous rocks of the eastern Santa Monica Mountains (McCulloh et al., 2002) represent the basal unit of the Los Angeles basin. They record an important pulse of igneous activity along the southern California coast that presum-ably occurred in an extensional or transtensional tectonic setting (Wright, 1991; Crouch and Suppe, 1993; Weigand et al., 1994; Weigand et al., 2002; Nourse, 2002, McCulloh et al., 2002). Analyses of plate motions (Nicholson et al., 1994; Atwater, 1998) and paleomagnetism (Luyendyk, 1991) indicate that this region was affected by extension, dextral translation, and rotation during much of the Middle and Late Miocene as an offshore transform fault attempted to move onto land. Much of this activity was taking place near the latitude of the Mexican border prior to major strike-slip displacements on the San Andreas fault.

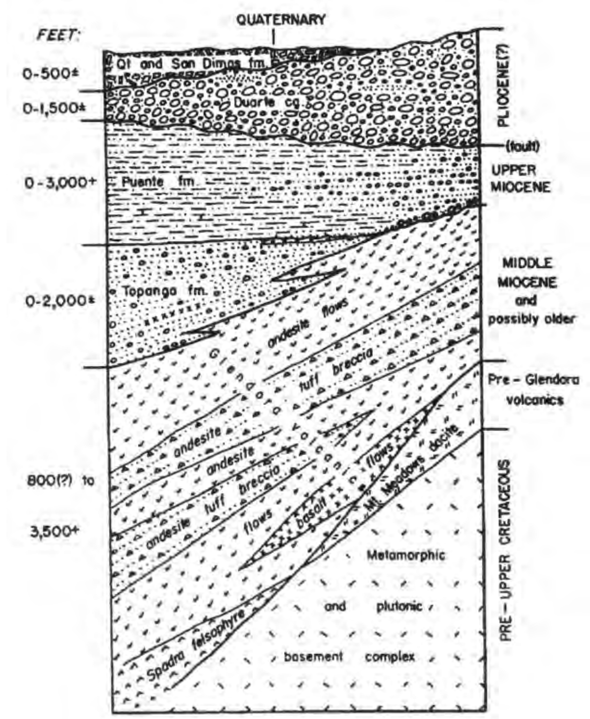

Figure 3. Stratigraphic column of the Pomona-Glendora area (from Shelton, 1955).

The Glendora Volcanics and temporally related Conejo Volcanics in the Santa Monica Mountains were generated in an extensional environment. Using a variety of geologic, geographic, and petrologic constraints, Weigand et al. (2002) proposed the following tectono-magmatic history for these volcanic suites: Clockwise rotation and rifting of the western Transverse Ranges block caused by Pacific plate capture of the partially subducted Monterey microplate began at ~20 Ma. Continued rotation and rifting of the overlying continental crust in response to transtensional Pacific plate motion of the captured microplate led to the attenuation and uplift of the underlying oceanic mantle. Decom-pression melting of this mantle source produced primitive basaltic magmas that repeatedly intruded the overlying crust, where they underwent fractional crystallization and assimilation, possibly of Catalina Schist. Starting ~17 Ma, these more evolved magmas erupted along the now-southern edge of the western Transverse Ranges block as it

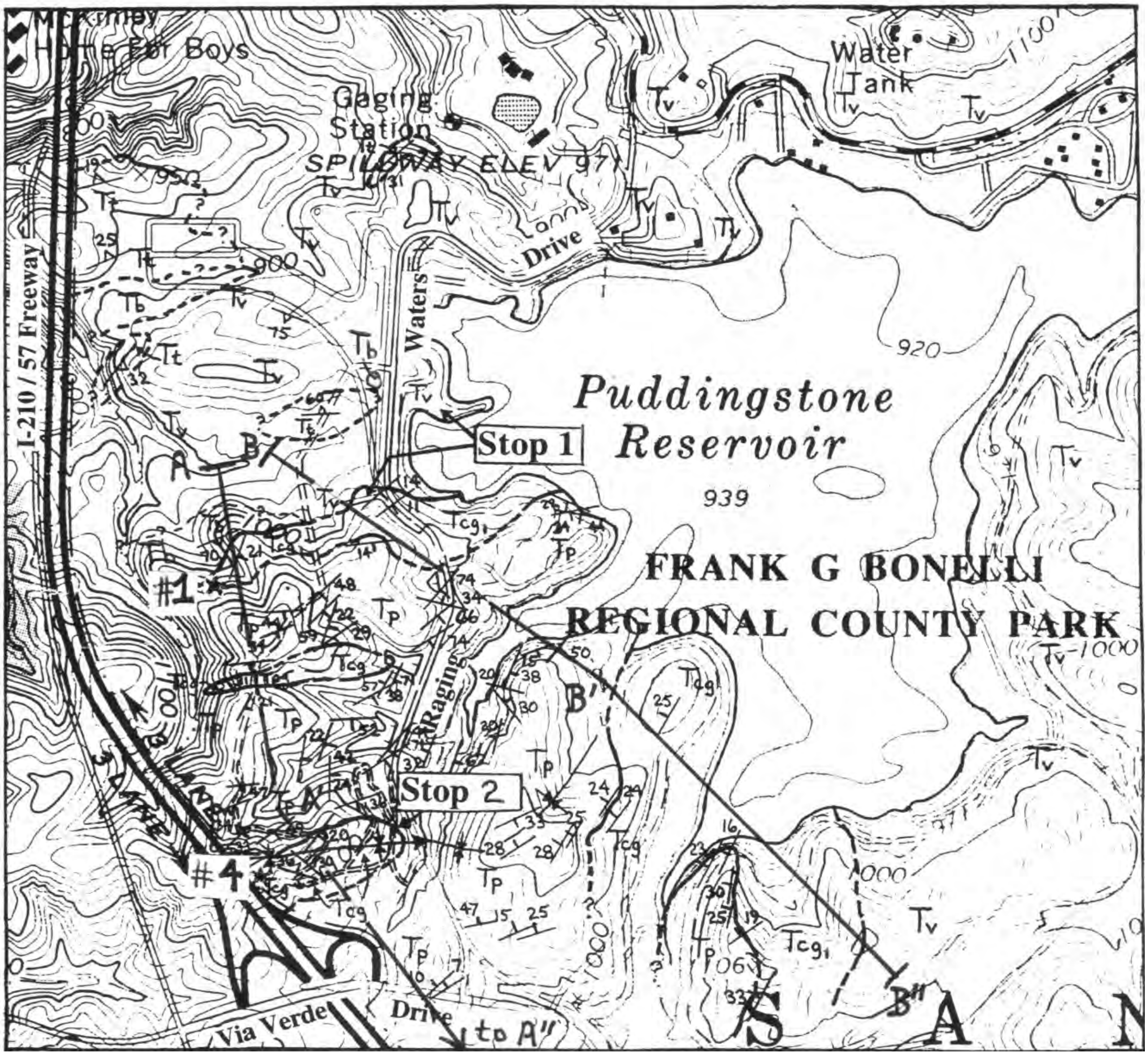

Figure 4a. Geologic map of the Puddingstone Lake area, modified from Nourse et al., 1998. Rock units as follows: **Tv** = intermediate to felsic component of Glendora Volcanics; **Tb** = basalt flow breccia component of Glendora Volcanics; **Tt** = lacustrine tuff or siltstone; **Tcg_1** = volcaniclastic conglomerate and sandstone of the Topanga Formation; **Tp** = siltstone or shale of the Puente Formation; **Tcg** = conglomerate horizons within the Puente Formation. Note locations of cross section lines A-A'-A" and B-B'-B" from McLarty (2000), shown in Figure 4b. Stars indicate conglomerate clast count localities #1 and #4 of McLarty (2000), described in Figures 5 and 6. Map scale is 1:12,000.

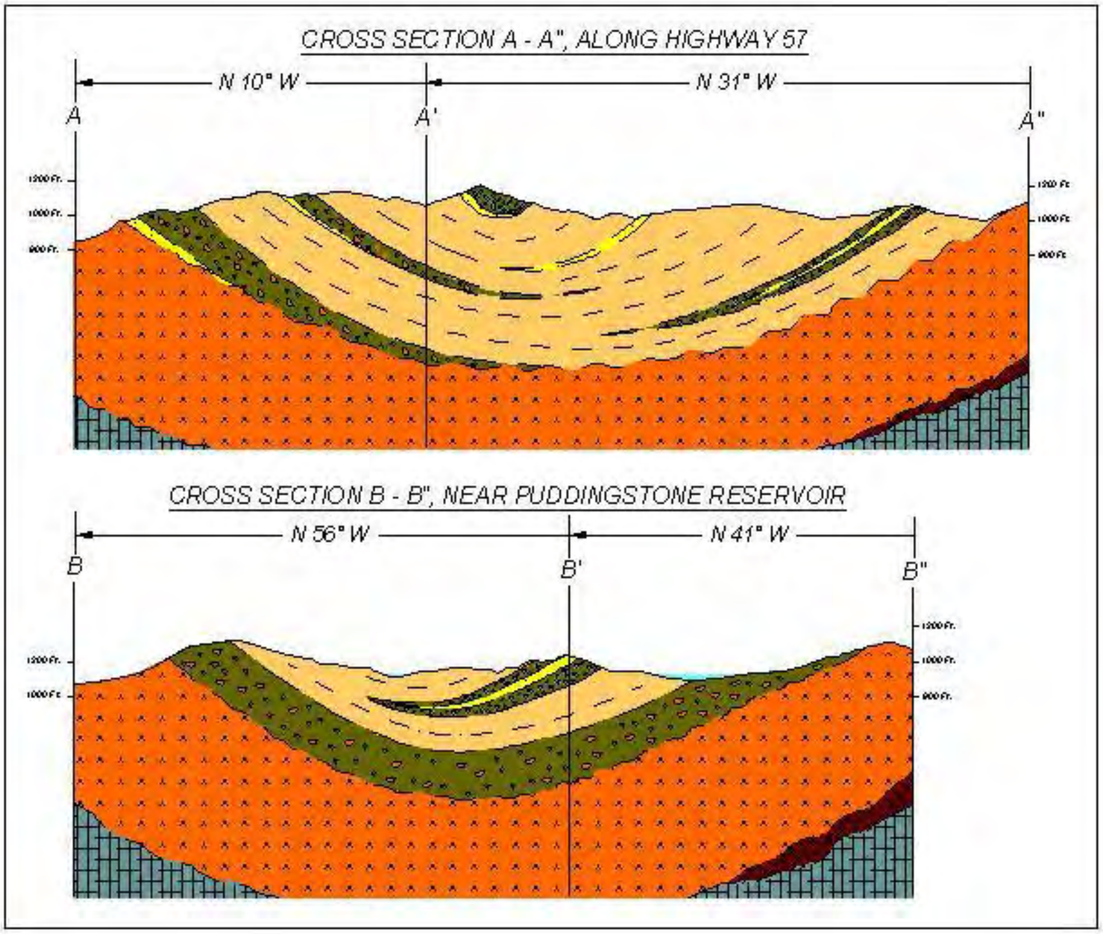

Figure 4b. Cross sections through the folded Neogene section southwest of Puddingstone Reservoir. Reproduced from McLarty (2000). See Figure 4a for location of section lines. Vertical ruled pattern represents Cretaceous basement (locally overlain by Mountain Meadows dacite. Glendora Volcanics are represented by x's. Basal conglomerate unit is the Topanga Formation. Higher level conglomerate lenses within the Puente Formation contain clasts derived from the eastern San Gabriel Mountains.

rotated off the captured Monterey microplate (Conejo Volcanics) as well as on the autochthonous edge of the rift (Glendora Volcanics).

Upper layers of the Glendora Volcanics are locally interstratified with sandstone and conglomerate beds of the Topanga Formation that contain Luisian and Relizian foraminifera (Shelton, 1955). In the Puddingstone Lake area, the Topanga Formation is overlain by Lower Mohnian siltstone, shale, and sandstone of the Puente Formation (Mull, 1934). Tongues of conglomerate that interfinger with these marine beds record the episodic uplift of San Gabriel Mountains basement and other sources during Late Miocene and Pliocene time (Woodford et al., 1946; Rumelhart and Ingersoll, 1997; McLarty, 2000).

From the scenic vantage of Stop #1, one may view prominent basement exposures of the San Gabriel Mountains to the northeast, whereas low hills to the south and southwest are underlain by marine sedimentary strata composing the Topanga and Puente Formations (Figure 4a). These sedimentary rocks stratigraphically overlie the Glendora Volcanics and record dynamic depositional conditions that accompanied filling of the northeastern Los Angeles basin. The portion of the section visible from the peninsula dips away from us to the southeast. Late Pliocene to Recent compression has folded the section into a major syncline (Figure 4b) such that outcrops of Glendora Volcanics exposed near the I-10 / 57 Freeway interchange dip northwest toward us. Our next stop will briefly inspect exposures of Topanga conglomerate and Puente Formation close to Raging Waters Drive.

Highlights en route to Stop #2

Return to bus and proceed about 0.2 mi south on Raging Waters Drive. The first outcrops at the southwest abutment of Puddingstone Dam represent the upper Middle Miocene Topanga Formation. Time permitting, we may examine these exposures, composed of gently southwest-dipping medium and coarse grained sandstone interbedded with volcaniclastic pebble-cobble conglomerate. Although at this site the contact with underlying Glendora Volcanics is obscured by dam fill, a spectacular unconformity is preserved along a fire road 400 m to the south (Figure 4a). To access this roadcut, walk a dirt road south-southwest from the Stop #1 parking area, turn right after crossing a drainage, then turn left at a T in the road. The road climbs uphill for about 250 m. Just before a sharp right bend, one may view a pristine depositional contact between cobble conglomerate and sandstone of the Topanga Formation and a deeply weathered yellow-orange vesicular basalt flow of the Glendora Volcanics.

Clast counts were carried out by McLarty (2000) on two outcrops of conglomerate from the Topanga Formation at places where it clearly separates Glendora Volcanics from overlying Puente siltstone. Results from the fire-road outcrop are shown in Figure 5. In general, this basal conglomerate unit is dominantly composed of volcanic or hypabyssal igneous clasts. Most of the clasts resemble sub-units of the Glendora Volcanics known to be exposed locally (within 10 km). A few clasts of dacite probably were derived from the Late Oligocene Mountain Meadows Dacite (Shelton; 1955; Nourse et al., 1998), whose sole surface exposure occurs 3 km to the east.

Continue south along Raging Waters Drive. After 0.3 mi, look for a yellow gate on the right that marks a dirt access road. Park on the right just north of the gate.

Stop #2: Puente Formation

The Topanga Formation is overlain by moderately southeast-dipping, light brown shale and siltstone of the Upper Miocene Puente Formation (Mull, 1934). These basinal marine strata are interstratified with 5- to 20-m thick conglomerate lenses. A short hike of ~300 m up the dirt road crosses representative sub-units of the Puente Formation, including siltstone, shale, and conglomerate containing boulders and cobbles derived from bedrock sources of the eastern San Gabriel Mountains.

Adjacent to the yellow gate is an accessible outcrop of siltstone interstratified with fine sandstone and shale. Roadcuts farther up the hill to the southwest reveal that siltstone is overlain by a ridge-forming unit composed of polymict conglomerate and coarse sandstone. The conglomerate contains boulders and cobbles of "Black Belt mylonite" (Alf, 1948; Hsu and Edwards, 1963) derived from the southeastern San Gabriel Mountains. Also present are distinctive clasts of granite, diorite, gabbro, isoclinally folded gneiss, and quartzite, all of which resemble present-day exposures in the southern front of the eastern San Gabriel Mountains (McLarty, 2000). Some boulders are as large as 1 m in diameter. In addition, a substantial component (38%) of volcanic detritus, possibly reworked from stratigraphically deeper volcaniclastic conglomerate horizons, is evident from clast counts (Figure 6). Deep levels of the San Gabriel Mountains basement were thus exposed and shedding debris into the northeastern Los Angeles basin during Late Miocene time.

A similar northwest-dipping stratigraphic section containing mollusc-bearing sandstone beds occurs about 1 km to the east. These units define the southeast limb of the a major syncline mapped on Figure 4. Good exposures occur near the southern shoreline of Puddingstone Reservoir, accessible through Frank G. Bonelli Regional Park (free of charge on winter weekdays).

The clast-composition stratigraphy preserved in conglomerate beds of the Topanga and Puente Formations is consistent throughout the folded section near Puddingstone Reservoir. This observation led to a hypothesis by McLarty

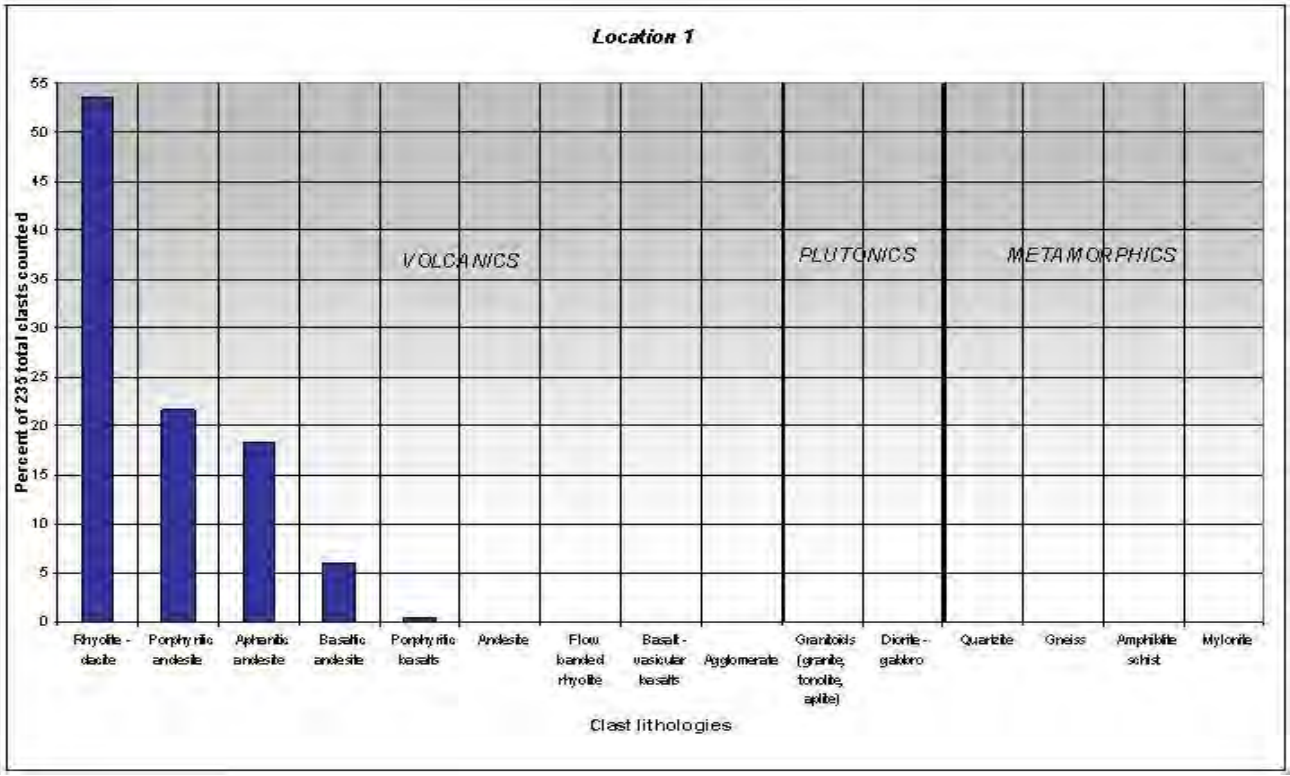

Figure 5. Statistical clast counts from the basal conglomerate member of the Topanga Formation southwest of Puddingstone Dam. Data reproduced from McLarty (2000).

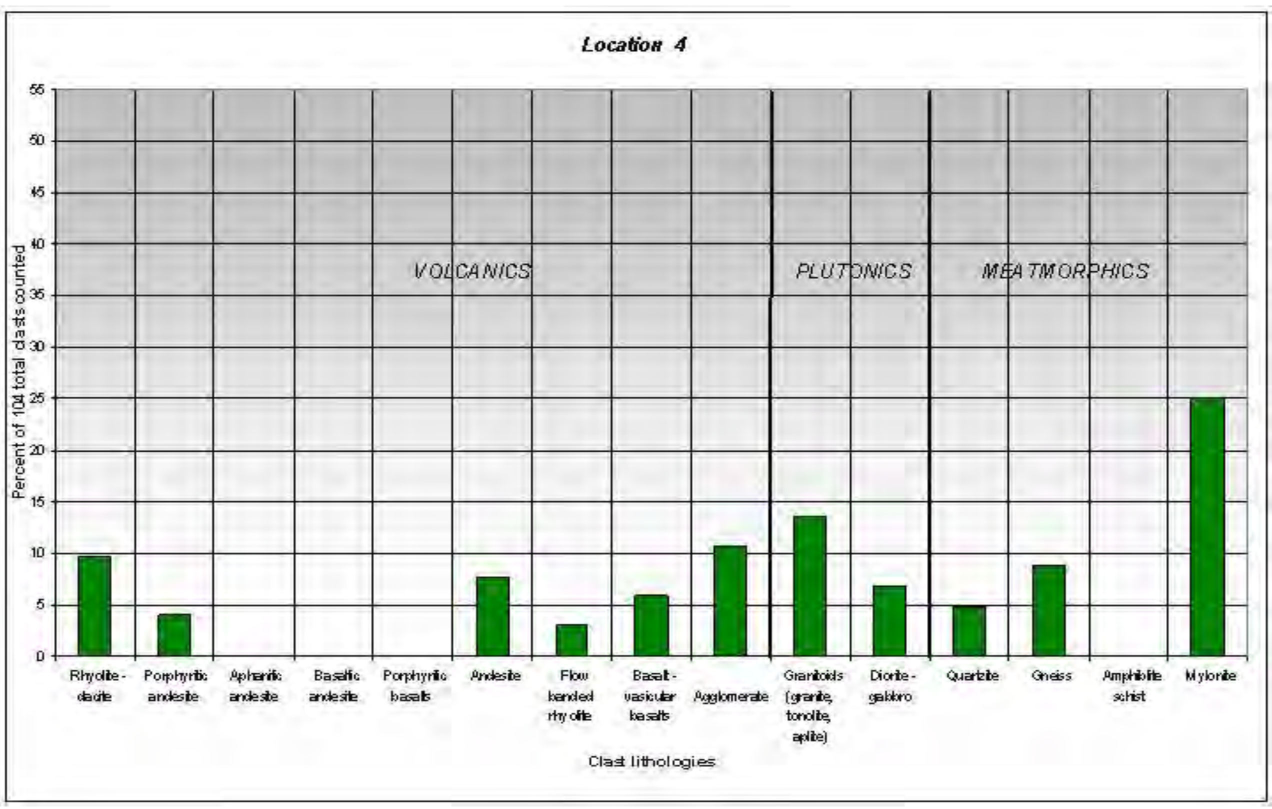

Figure 6. Statistical clast counts from the polymict conglomerate member of the Puente Formation north of Via Verde Drive. Data reproduced from McLarty (2000).

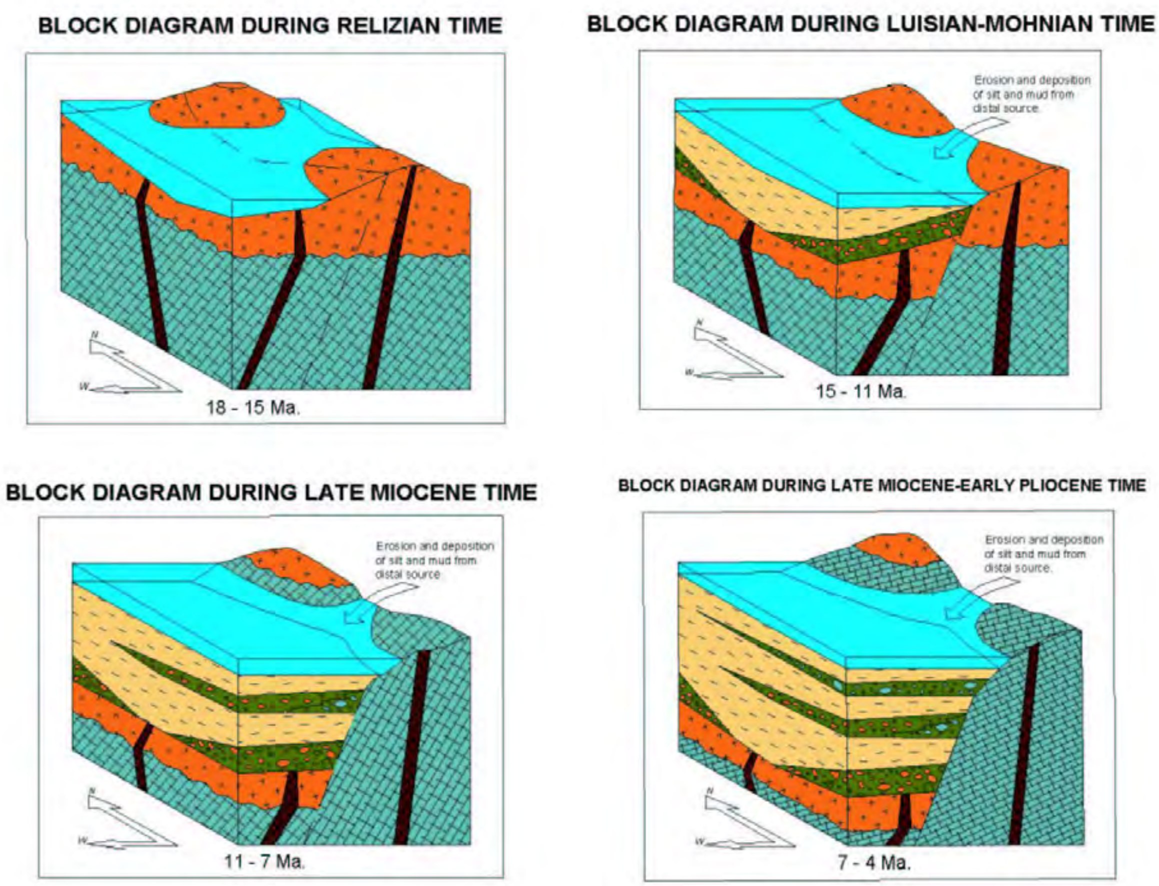

Figure 7. Block diagrams illustrating hypothetical development of the inverted clast stratigraphy in the Puddingstone Lake area. Reproduced from McLarty (2000). Patterns are the same as in Figure 4b.

(2000) that these clasts record progressive unroofing of Glendora Volcanics and underlying southeastern San Gabriel Mountains basement during late Middle Miocene and Late Miocene time (Figure 7). One implication of McLarty's model is that the Glendora Volcanics may have originally covered part of the eastern San Gabriel Mountains. The reader will be reminded of this idea at Stop #5, when we view dikes in the San Gabriel Mountains that may have provided feeders to the Glendora Volcanics.

Highlights en route to Stop #3

Continue south on Raging Waters Drive. Turn right onto Via Verde Drive. After about 0.2 mi, turn right onto the northbound 57 Freeway (this may be marked "I-210 West to Pasadena). Drive about 3 mi, stay in the right-hand lanes, then take the 210 Freeway east (toward Claremont and San Bernardino). Continue east to Baseline Road, exit there. Get in the left-turn lane. Basement exposures of the eastern San Gabriel Mountains are straight ahead to the north. Alluvial fan deposits derived from San Antonio Canyon are exposed in excavations in the foreground to the northeast. Turn left onto Baseline Road (west-bound), get into the right lane. Turn right onto Padua Avenue. Proceed north for 1.8 mi. At the four-way intersection, turn right onto the Mt. Baldy Road. We have now entered the Mt. Baldy Quadrangle (Dibblee, 2002). Please also refer to the companion article in this guidebook (Dibblee, 2003) that describes the tectonic genesis of the San Gabriel Mountains.

Drive east along the approximate trace of the Cucamonga/Sierra Madre reverse fault (Crook et al., 1987). The Mt. Baldy Road begins to climb steeply, passing San Antonio Dam (on the right) after 1.3 miles. This earth-fill dam was built by the Army Corps of Engineers in 1956 for purposes of flood control and groundwater recharge. It played a crucial role in reducing damage during the 1969 flood. To the left are outcrops of quartzite and pelitic gneiss that reside in the hanging wall of the Sierra Madre fault. The steep slopes across the canyon to the east are underlain by the Cucamonga granulite (May and Walker, 1989), which dips beneath the "Black Belt "mylonite (Alf, 1948; Hsu and Edwards, 1963).

Approximately 1.2 mi beyond San Antonio Dam is an intersection with Shinn Road (to Upland and Ontario). Turn right and follow Shinn Road down hill to a bridge crossing of San Antonio Creek. Park on the right just past the bridge.

Stop #3: Lower San Antonio Canyon--Erosional Remnants of the 1969 Flood and Pleistocene Deluges

The hairpin turn we are situated upon is a rebuilt segment of the road that was washed out during the flood of January 25-26, 1969. As shown in Figure 8, the entire flood plain in front of us was inundated by San Antonio Creek. Boulders the size of small cars were transported during this event. Peak flow at the now defunct USGS gauge 3 mi upstream was 16,400 cfs on January 25, 1969. Water impounded behind San Antonio Dam rose to an elevation of about 2193 ft, not quite high enough to flow over the spillway (elevation 2238 ft). It was necessary to let 8420 cfs through the dam outlets to keep the water below this level (Herber, 2001).

The 1969 flood was induced by a series of warm tropical storms in middle to late January that followed a December 25-26 storm that dropped 18 in of snow at Mt. Baldy Notch (elevation 7900 ft). Daily precipitation records indicate that 51.25 in of rain fell at Mt. Baldy Notch between January 18 and 28, while 39.82 in fell at Sierra Powerhouse, located at 3110 ft elevation on lower San Antonio Creek. Of these totals, 32.3 in were recorded between January 24 and 26 at the Notch, while 22.5 in fell at the Sierra station. Thunder Mountain (elevation 8600 ft, located at the top of the Mt. Baldy Ski Lifts) recorded 62.76 in of precipitation during the month of January, and 120 in during the whole season. For comparison, the famous flood of March 2, 1938 produced a peak stream flow of 21,400 cfs on Lower San Antonio Creek. That flood was partly due to heavy snow pack melting during a four-day deluge that dumped 32.2 in of rain at Kelly's Camp, elevation 8300ft.

Prior to 1969, a paved road (Mountain Avenue) diverged from this site and followed the approximate axis of San Antonio Canyon northeastward to Mt. Baldy Village (Figure 9). This road crossed San Antonio Creek in several places. Today, only isolated segments of the road remain. Five bridges were washed out during the 1969 flood. The remains of one bridge are preserved about 250 m upstream from the parking site of Stop #3.

Carefully make your way down into the wash, crossing the reinforced concrete road base (watch out for loose gravel and broken glass!). Follow the trail leading north. As we walk along this stretch of the flood plain, note the diversity of igneous and metamorphic rock types present in the assemblage of stream-transported boulders. Many of these represent bedrock units mapped on the Mt. Baldy geologic map (Dibblee, 2002; Figure 10; see also back cover). For example: (1) abundant quartzite and biotite gneiss were derived from his **mq** and **msg** units, (2) white crystalline marble represents his **ml** unit, (3) chloritized quartz diorite is **qd**, (4) leucocratic biotite granite is **gr**, and (5) foliated diorite and quartzo-feldspathic gneiss are mapped as **gn**. Other clast types have bedrock sources farther up the canyon in the Mount San Antonio and Telegraph Peak quadrangles. The most abundant clast type is medium-grained biotite-hornblende sphene-bearing quartz diorite derived from the upper slopes of Mt. San Antonio. A very distinctive clast is foliated, coarse-grained black-spotted hornblende quartz monzodiorite of the Mt. Lowe intrusion, informally named "dalmationite" by Perry Ehlig (1981), and dated with U-Pb zircon at 220±10 Ma (Silver, 1971) and 218±3 Ma (Barth et al., 1990). Also present are clasts of Pelona schist (described at Stops #6A and #6B). Diligent search will yield clasts of unfoliated rhyodacite porphyry,

Figure 8. Photograph of lower San Antonio Creek taken January 25, 1969. View is to the south toward San Antonio Dam. Old Mt. Baldy Road is in the left foreground; Shinn Road bridge is to the right. Photo provided by John Flores, U. S. Forest Service.

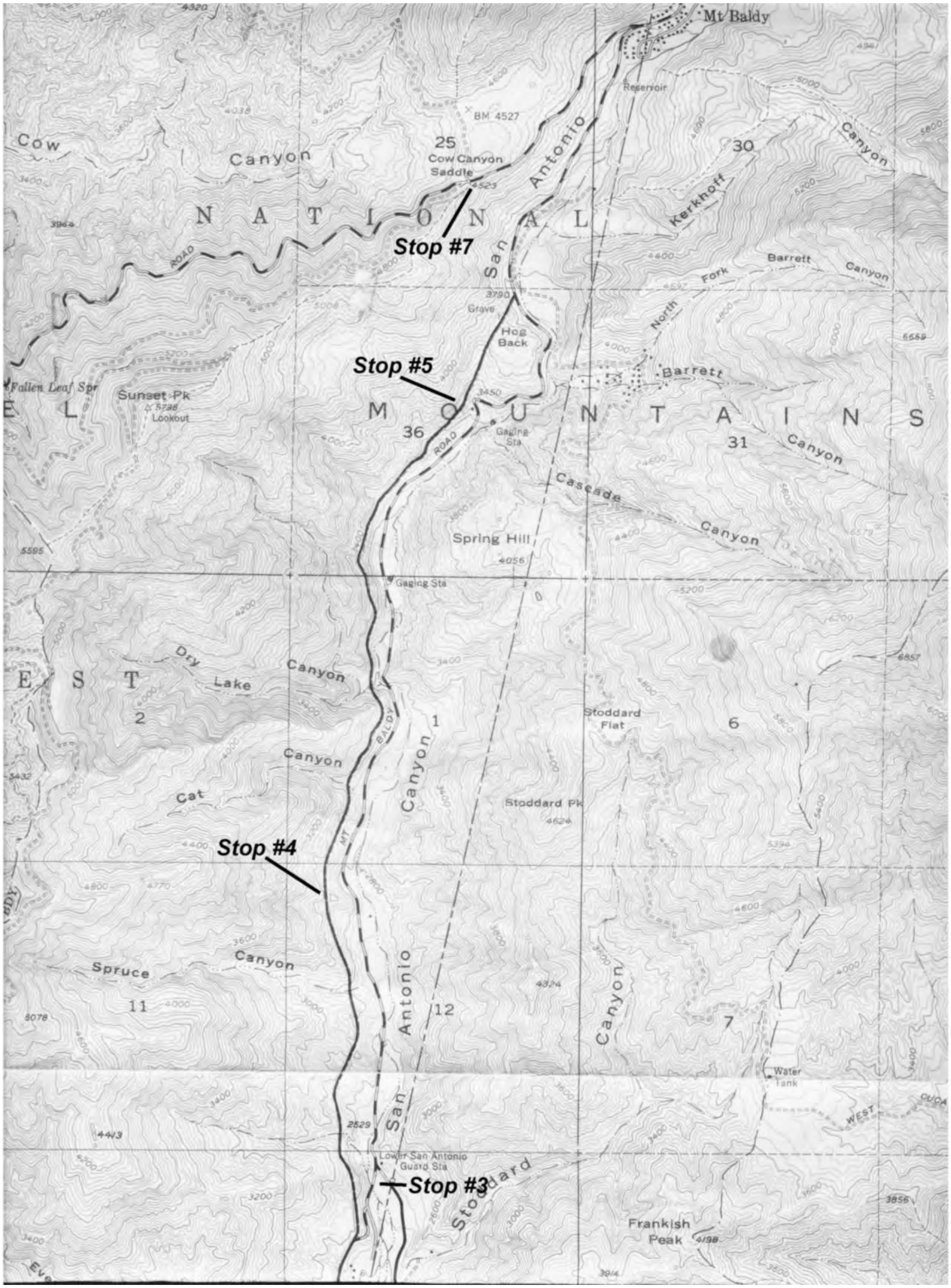

Figure 9. 1958 topographic map of lower San Antonio Canyon showing position of the Old Mt. Baldy Road (dashed pattern), now mostly washed away. Note locations of Stops #3 through #5 and #7. The present-day Mt. Baldy Road is marked with a solid line.

Figure 10. Geologic map of lower San Antonio Canyon. Reproduced from Tom Dibblee's geologic map the Mt. Baldy 7.5' quadrangle (Dibblee, 2002). Note location of Stops #3 through #5 and #7.

andesite porphyry, and aphanitic basalt, derived from Late Oligocene and Middle(?) Miocene dikes. Leucocratic biotite granodiorite or monzogranite derived from Telegraph Peak is from Late Oligocene and Middle(?) Miocene distinguished from Dibblee's **gr** unit by its lack of foliation.

The trail follows the east side of San Antonio Creek into a stand of deciduous trees, where eroded remnants of Old Mount Baldy Road are stranded about 3 m above stream level. Notice the primitive character of the road base exposed where the pavement straddles the contact between a substrate of flood deposits and foliated quartz diorite bedrock (unit **qd**). Farther upstream, a battered concrete abutment is all that remains of the bridge that was washed out in 1969. Note the poorly graded concrete aggregate, not exactly up to current building code!

As we walk back to the bus along the disintegrating pavement, observe an exposure of light orange-brown terrace gravels on the slope to the east. This represents a channel deposited by San Antonio Creek during Pleistocene(?) time. A transverse profile is evident in a view to the southeast. At the bus, take another look upstream. On the west side of San Antonio Canyon are several prominent stream terraces (Tom Dibblee's **Qoa** unit; Figure 10) revealed in cuts along the modern Mt. Baldy Road. From this vantage, it is clear that the original base level of San Antonio Creek has been elevated greater than 80 m in recent times, probably due to uplift along the Sierra Madre-Cucamonga fault and/or the San Antonio Canyon fault.

Highlights en route to Stop #4

Return to Mt Baldy Road and turn right. The road approximately follows the trace of the left-lateral San Antonio Canyon fault (Nourse et al., 1994; Nourse, 2002). San Antonio Creek incises the steep canyon to the right. Pleistocene stream terraces exposed in road cuts record youthful uplift of the area. Smaller vehicles may have room to pull off the road at several places where nonconformities with underlying quartz diorite and granite basement are preserved. Approximately 1.3 mi above Shinn Road cutoff, pull off on the left into a wide dirt parking area.

Stop #4: Roadcut Exposure of the Evey Fault Zone

The Evey fault (also called the "West San Antonio fault" on Figure 10) is a northeast-striking splay of the left-lateral San Antonio Canyon fault that cuts Late Cretaceous(?) quartz diorite along the west side of the Mt. Baldy Road. This fault is named for exposures along the Evey Canyon Road, where sheared marble and phyllite are juxtaposed against quartz diorite. At the Mount Baldy Road, the Evey fault is clearly marked by a northwest-dipping plane separating greenish and purplish sheared rock (Figure 11).

Figure 11. Evey fault exposure along the Mt. Baldy Road. View is to the southwest; fault plane dips 70^{o} to the northwest.

To the northeast, the Evey fault appears to merge with the main branch of the San Antonio Canyon fault near the axis of San Antonio Creek (Figure 10). Several ledges and saddles on the east slopes of San Antonio Canyon mark this latter fault. The San Antonio Canyon fault records a two-stage movement history (Nourse et al., 1994). Offset basement units preserve a cumulative left-lateral displacement of 8 to10 km since early Miocene time (Nourse, 2002). Relationship to the 1988 and 1990 Upland earthquakes (Figure 2) is speculative. In one interpretation, the San Antonio fault makes a left step near San Antonio Dam, forming a pull-apart basin there. In this perspective, the Upland earthquakes occurred on an active stepped segment of the San Antonio Canyon fault that may coincide with the northeast end of the San Jose fault.

The trace of the Evey fault zone curves systematically to an east-west strike as one traverses southeast toward the front of the San

Gabriel Mountains. Geomorphic considerations suggest that much of the Evey fault records reverse slip. For example, a prominent escarpment occurs on its northwest side, and thick alluvial terrace and fan deposits (unit **Qoa** on Figure 10) are restricted to its southeastern and presumed down-thrown side. However, the degree of activity is uncertain. In this author's viewpoint, the Evey fault represents an early strand of the Sierra Madre fault system. Currently, the block situated southeast of the Evey fault is being uplifted in the hanging wall of the Sierra Madre fault, and the San Antonio Canyon fault may be inducing sinistral drag and rotation of the Evey fault.

Highlights en route to Stop #5

Continue driving up Mt. Baldy Road, passing through two tunnels. Roadcuts above tunnels expose predominantly southwest-dipping San Gabriel gneiss (here composed of interlayered Paleoproterozoic and Triassic(?) orthogneisses). The road bends sharply left approximately 1.9 mi above Stop #4. The roadcut on the inside of this dangerous curve displays Late Cretaceous(?) quartz diorite concordantly overlain by San Gabriel gneiss. A 2-m-thick mylonite zone containing slices of garnetiferous biotite schist marks the contact. Proceed about 0.2 mi farther and pull of on the right just before Hogback saddle, about 2.1 miles beyond Stop #4.

Stop #5: Neogene Dikes and Faults at Hogback Roadcut

This stop displays Late Oligocene and Middle(?) Miocene dikes that represent possible feeders to Mountain Meadows dacite and Glendora Volcanics of the Pomona-Glendora region. Crosscutting field relations demonstrate an intrusive sequence that is consistent throughout the eastern and central San Gabriel Mountains. These two intrusive units bracket movements on two families of brittle faults that predated major dextral displacement on the nearby San Gabriel fault (Nourse, 1999).

The roadcut on the west side of the Mt. Baldy Road displays a moderately northwest-dipping dike of rhyolite or rhyodacite porphyry sharply intruded into southwest-dipping well-foliated Mesozoic quartz diorite. Steeply dipping, subhorizonatlly striated, slickensided fault surfaces with north and west-northwest strikes pervade the rhyodacite and its quartz diorite host (Figure 12). Brittle fault kinematic indicators on these conjugate fault surfaces record sinistral and dextral shear senses, respectively (Figure 12). These faults represent an episode of Early Miocene sinistral displacement on the N10^{o}E striking ancestral San Antonio Canyon fault (Nourse, 1999, 2002).

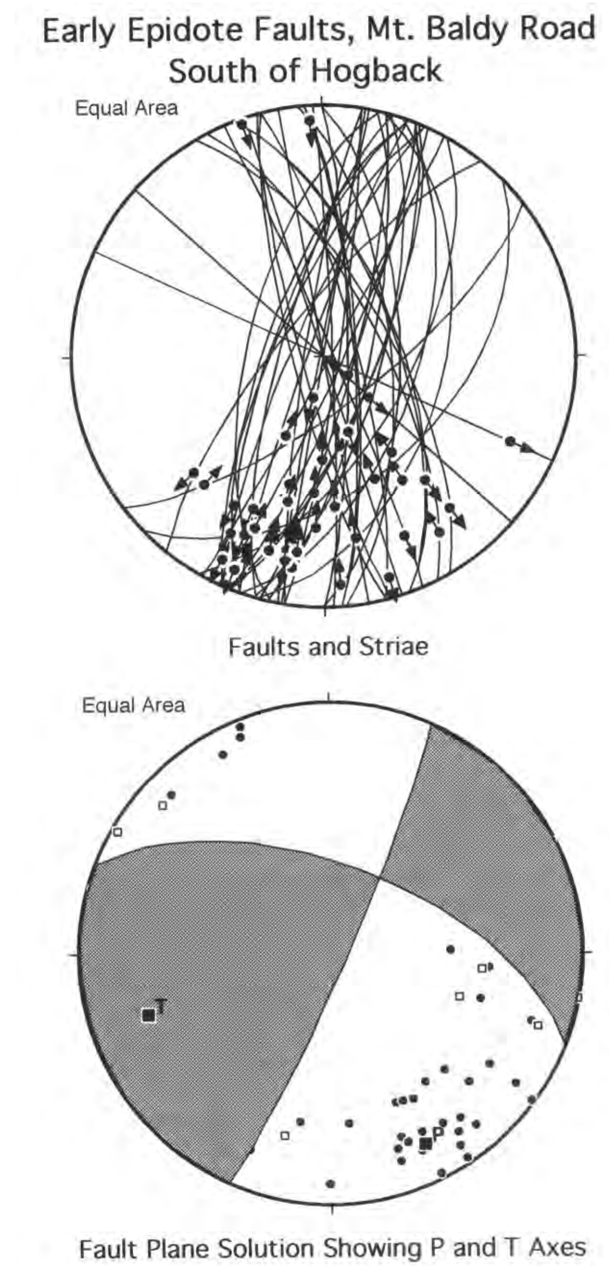

Figure 12. Equal area stereonet plots showing conjugate strike-slip fault planes and the fault-plane solution for Early(?) Miocene microfaults at Stop #5.

A second family of northwest-striking faults marked by weakly striated hematite surfaces and white breccia or gouge zones (Figure 13) cuts the strike-slip faults described above. These steep to moderately dipping faults display dip-slip striae and consistent normal offsets of both the rhyolite dike and pegmatite sills in the quartz diorite. Kinematic analysis indicates extension in a N50°E direction (Figure 13).

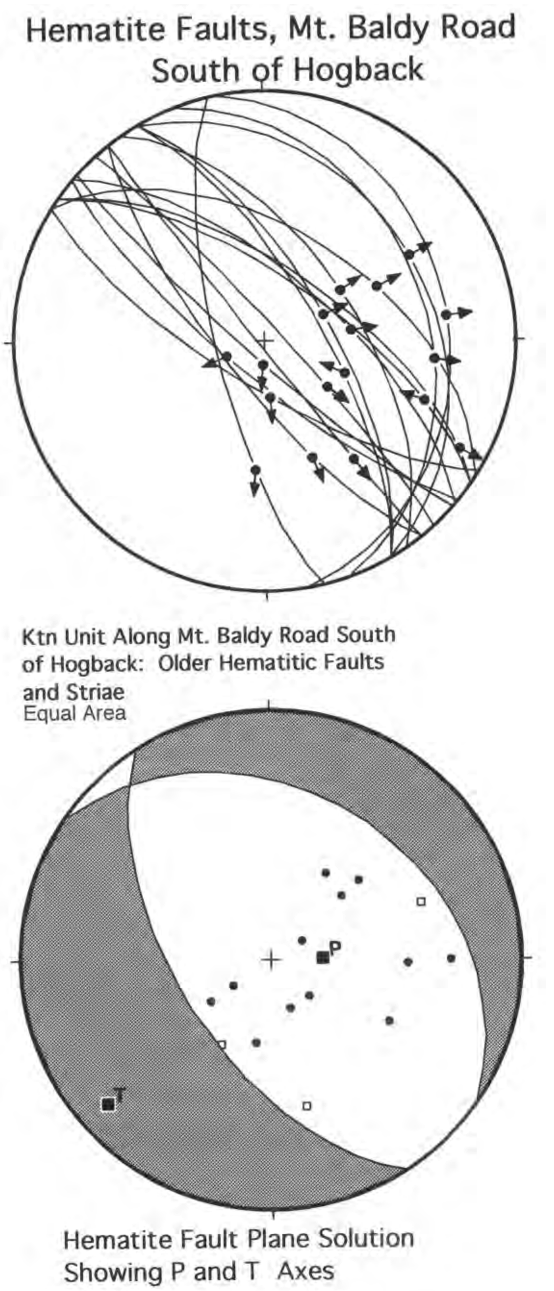

Figure 13. Equal area stereonet plots showing conjugate normal fault planes and the fault-plane solution for Middle(?) Miocene microfaults at Stop #5.

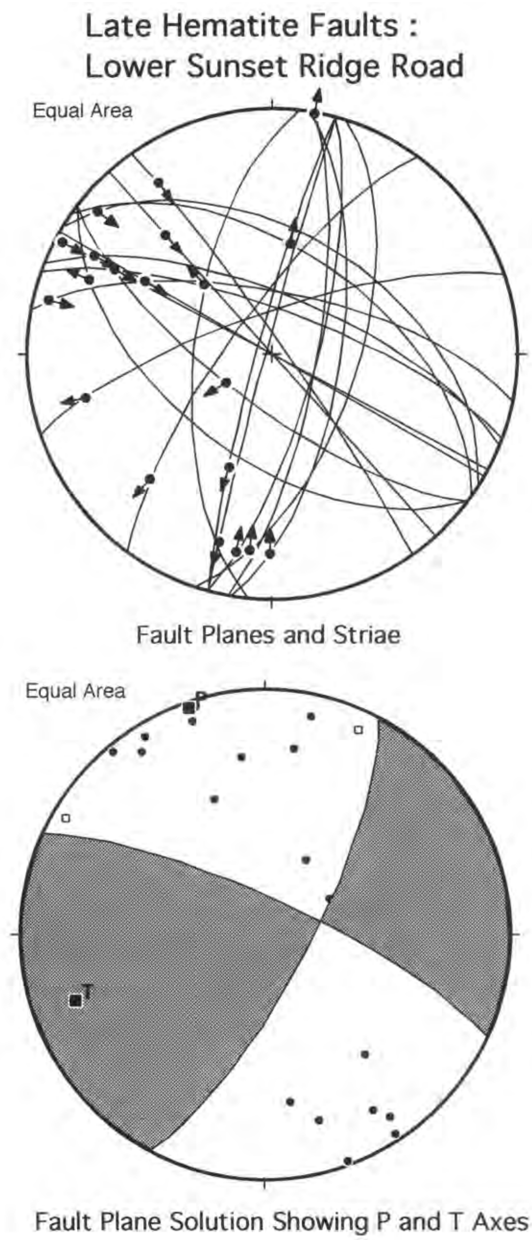

Figure 14. Equal area stereonet plots showing conjugate strike-slip fault planes and the fault-plane solution of faults that displace Middle(?) Miocene dikes on Lower Sunset Ridge Road

Three dark-gray, northwest-striking basaltic andesite or andesite dikes intrude sharply across the rhyodacite and quartz diorite. Two of these dikes appear to have intruded into the pre-existing normal faults on projection with those described above. This interpretation is supported by offset marker units on either side of the dikes, and lack of shearing along the dike margins.

Farther down the road close to the dangerous curve, a third generation of northwest-striking faults is developed along the margins of two mafic dikes. These faults (Fig. 14) have the appropriate orientation and style to be associated with major dextral displacement on the north branch of the Late Miocene San Gabriel fault, whose main trace is located about 1 km to the north. The San Gabriel fault is known to affect dikes of similar composition and texture in several places near the East and West Forks of the San Gabriel River.

Highlights enroute to Lunch Site

Continue northeast up the Mt. Baldy Road, immediately crossing Hogback saddle. Roadcuts in Hogback saddle display landslide blocks of San Gabriel gneiss derived from a bedrock source located structurally above quartz diorite, approximately 1000 ft higher up on the east-face of Sunset Peak. Note the spoon-shaped scar in the steep slope to the west. Recently obtained ^{36}Cl surface exposure dates (Herber, 1998) indicate that Hogback landslide was deposited catastrophically at about10Ka.

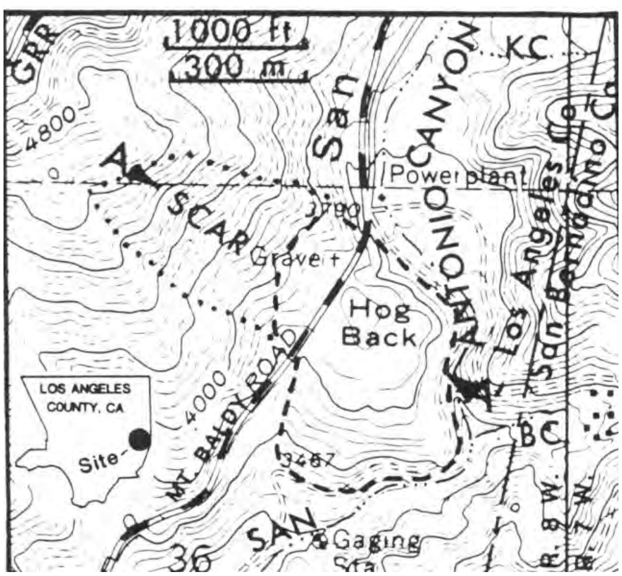

Figure 15. Topographic map of area near Hogback Landslide, reproduced from Herber (1987). Note location of cross section A-A' shown in Figure 16.

Hogback pass transects the top of the landslide mass; stratigraphically deeper deposits composed entirely of angular quartz diorite boulders occur to the east. Detailed mapping in the area (Herber, 1987; see also Figures 15-16) reveals that the toe of Hogback landslide is exposed on the west side of Hogback gorge, where it overlies old alluvial terrace deposits. Access to this exposure is attained by walking the old Mt. Baldy Road southeast from its junction with Barrett-Stoddard Road. The Barrett Road branches east from Mt. Baldy Road about 300 m north of Hogback saddle. Although we do not have time to do this hike today, it is worth returning to for the purposes of viewing dramatic effects of recent erosion. Casual inspection will reveal that significant portions the Old Mt Baldy Road have been washed out, in this case during the flood of 1969.

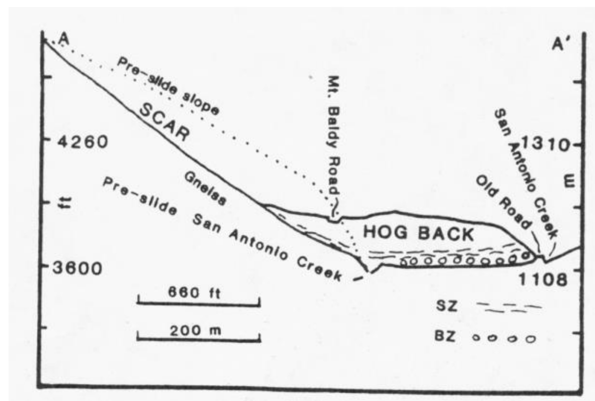

Figure 16. Geologic cross section through Hogback landslide, reproduced from Herber (1987).

Proceed northeast one Mt. Baldy Road, passing Mt. Baldy School on the right, then the turnoff to Glendora Ridge Road on the left as you enter Mt. Baldy Village. About 1/4 mile farther, look for a left turn into Mt. Baldy Visitor Center, just beyond the Mt. Baldy Lodge.

Lunch Break: Mt. Baldy Visitor Center

Mt. Baldy Visitor Center is a combination rest stop, picnic area, nature display, and educational outreach center operated by the U. S. Forest Service. We will break for lunch here amongst the evergreens and cedars. Feel free to wander the facilities and view the displays. Of particular interest is the old one-room Mt. Baldy Schoolhouse that currently serves as a museum.

Highlights enroute to Stop 6:

Continue up Mt. Baldy Road and cross a bridge over San Antonio Creek. To the right are Ontario Ridge and Sugarloaf Peak, both underlain by Cretaceous tonalite and granite intruded into metasedimentary rocks (May and Walker, 1989). To the left (along the west side of the creek) are pristine exposures of Late Oligocene rhyodacite dikes and Middle(?) Miocene mafic-intermediate dikes intruded into layered metamorphic rocks that form steep cliffs. Refer to the 1998 field-trip guidebook (enclosed) to learn more about the geology of this site. Higher up to the northwest, the shoulder of Mount San Antonio is underlain by mylonites and gneisses composing the upper plate of the Vincent thrust (Nourse, 1991, 2002).

Cross Icehouse Creek just above its confluence with San Antonio Creek. Pass the intersection with Icehouse Canyon Drive and continue left. Alternatively, one may park in Icehouse Canyon Parking lot and view the features described below:

Optional Lunch Stop: Icehouse Canyon

Icehouse Creek flows westward down a prominent fault-controlled canyon. Comparison of talus boulders derived from opposite sides of Icehouse Canyon will convince most geologists that the bedrock exposed on the south slopes is quite different from that on the north. Icehouse Canyon marks the position of the north branch San Gabriel fault, a major right-lateral strike slip fault that recorded at least 19 of displacement during Late Miocene time (Nourse, 2002; Dibblee, 2003). Younger sinistral displacement on the north-easterly San Antonio fault has offset the axis of Icehouse Canyon (and the eastern segment of the San Gabriel fault) about 3 km from an earlier alignment with Cow Canyon and the East Fork San Gabriel Canyon. One can view outcrops of the San Gabriel fault zone (here named the Icehouse Canyon fault) along the first kilometer of the Icehouse trail. Close examination of small-scale structures within the crush zone of the Icehouse Canyon fault reveals an early history of right-lateral movement along subvertical east-southeast planes, and younger reverse displacements along moderately north-dipping planes. Late left-lateral faults with northeast strikes locally disturb the Icehouse fault zone.

Bedrock on the south walls of Icehouse Canyon is composed of Late Cretaceous biotite-hornblende granodiorite and leucocratic biotite granite (May and Walker, 1989) intruded into complexly deformed metasedimentary gneiss country rocks. The granodiorite and granite are easily recognized by the presence of pink K-feldspar. Boulders of biotite gneiss, marble, and calcsilicate gneiss with spectacular folds are present about 2 km farther up the trail just after entering Cucamonga Wilderness. In contrast, bedrock underlying the north side of Icehouse Canyon is very similar to that exposed adjacent to the Buckhorn Restaurant (See Stop #5 of Nourse et al., 1998; enclosed). Predominant lithologies are mylonitized quartz diorite, diorite, and granodiorite of the Vincent thrust. These mylonites are intruded by 26±1 Ma porphyritic biotite granodiorite (May and Walker, 1989) on the south summit of Telegraph Peak. Boulders of Telegraph Peak granodiorite may be identified on the basis of unfoliated character and preponder-ance of white K-feldspar. Rhyodacite porphyry dikes similar to the one observed earlier at Stop #5 share a strong geochemical affinity with the Telegraph Peak pluton (Nourse et al., 1998). Mafic and intermediate mid Miocene(?) dikes similar to those of Stop #5 are also present on the north side of Icehouse Canyon.

The steep canyon walls on the south side of Icehouse Creek prevent direct sunlight from entering the canyon during at least two months between Thanksgiving and late January. An obvious side effect is cold conditions ideal for preserving ice and snow. This feature was exploited during the 1850s by hardy pioneers who sold block ice from an icehouse located in the lower canyon (hence the name Icehouse Canyon). In terms of hydrology, one reason for year-around flow in Icehouse Creek is the persistence of snow on the north-facing slopes that typically melts between April and July to supply springs during the dry season. While hiking the lower 2 km of the trail, one may observe several springs feeding into Icehouse Creek. In most cases these springs mark places where groundwater in a porous and permeable talus aquifer is forced to the surface by a non-porous bedrock barrier.

Continued Highlights enroute to Stop 6:

The road climbs steeply (with many switchbacks) through a landslide derived from the east bowl of Mt. San Antonio (see also Trent and Nourse, 2001). Distinctive clasts include Late Triassic Mt. Lowe quartz monzodiorite and Late Cretaceous(?) quartz diorite.

The switchbacks end at a minor pass, then the road crosses Manker Creek. Snowcrest Lodge is to the left. The road divides above here, with Manker Campground occupying the island between. Continue uphill. Beyond Manker Campground, a left fork leads to San Antonio Falls Road (locked gate). A hike up this dirt fire road leads to sights described in **Alternative Stop #6B**. Continue on Mt.Baldy Road through additional switchbacks. Park in the Mt. Baldy Ski Resort lot. Walk up paved road to hut where sightseeing chair lift tickets may be purchased for $10 ($5 per person for large groups).

Stop #6A: Chair Lift to Mt. Baldy Notch; Overview of San Antonio Canyon

The lowermost chair lift of Mt. Baldy Ski Resort is the most efficient way to access Mt. Baldy Notch (elevation 7802 ft), where spectacular views and refreshments await us. Alternatively, one can hike 4 mi up the San Antonio Falls Road (1600-ft elevation gain). Geologic features crossed by this alternative route are described in the next section.

The chair lift climbs up the axis of Sugarpine Canyon, which follows the trace of the left-lateral San Antonio Canyon fault. Outcrops of Pelona schist representing the lower plate of the Vincent thrust (Ehlig, 1981) occur to the left, whereas greenschist-facies mylonite derived from upper plate quartz diorite, tonalite, granodiorite, and granite crop out intermittently on the right. One of the best views of the San Antonio Canyon fault is obtained about 2/3 of the way to the top. Watch for a prominent northwest-dipping dark gray gouge zone cutting outcrops to your left, directly below the point where the San Antonio Falls Road makes a switchback adjacent to the chair lift. Above this location, the fault follows the axis of the valley. Typically its trace is obscured by talus, but runoff from snow-melt occasionally creates exposures that can be studied in detail.

Carefully dismount the chair lift and regroup on the patio outside the Mt. Baldy Notch restaurant. The view southwest provides a dramatic backdrop for discussion of the San Antonio Canyon fault. On a clear day, one can see the Pacific Ocean and Catalina Island. San Antonio Canyon owes its existence to preferential erosion of pervasively fractured rocks resulting from two phases of movement on the San Antonio fault. A similarly oriented left-lateral fault (the Sunset Ridge fault of Nourse, 2002) may be traced to the southwest through a series of saddles located west of San Antonio Canyon. Also visible is the lower portion of Icehouse Canyon that contains an offset segment of the San Gabriel fault (described earlier).

To the west is Mt. Harwood (elevation 9552 ft), capped by a thin zone of mylonite marking the Vincent thrust (Ehlig, 1981; Dibblee, 2003). This mylonite zone (Figure 17) dips gently southwest away from us, forming cliff exposures above San Antonio Falls (see also Stop #6B). Outcrops of mylonite exposed along uppermost San Antonio Creek and in Miners Bowl (southeast of the Notch) were targets of gold mining between 1882 and 1900 (Trent, 2001; see also Figure 17). Between Mt. Baldy notch and the summit of Mt. Harwood are good exposures of Pelona schist. Representative outcrops of greenschist (metabasalt) and grayschist (metagraywacke) can be viewed directly west of the Notch restaurant. Notice the complex folding of metamorphic foliation.

A modest hike 200 m to the northeast offers another spectacular view into Cajon Pass and the Mojave Desert. With the aid of maps contained in the companion article (Dibblee, 2003), it is easy to pick out Blue Ridge, an elongate body of Pelona schist isolated between the San Andreas and Punchbowl-San Jacinto fault zones. Those with extra time (and energy!) can walk the fire road from this viewpoint to the top of Thunder Mountain (Elevation 8600 ft)

Return to the chair lift, and ride back down to the parking lot.

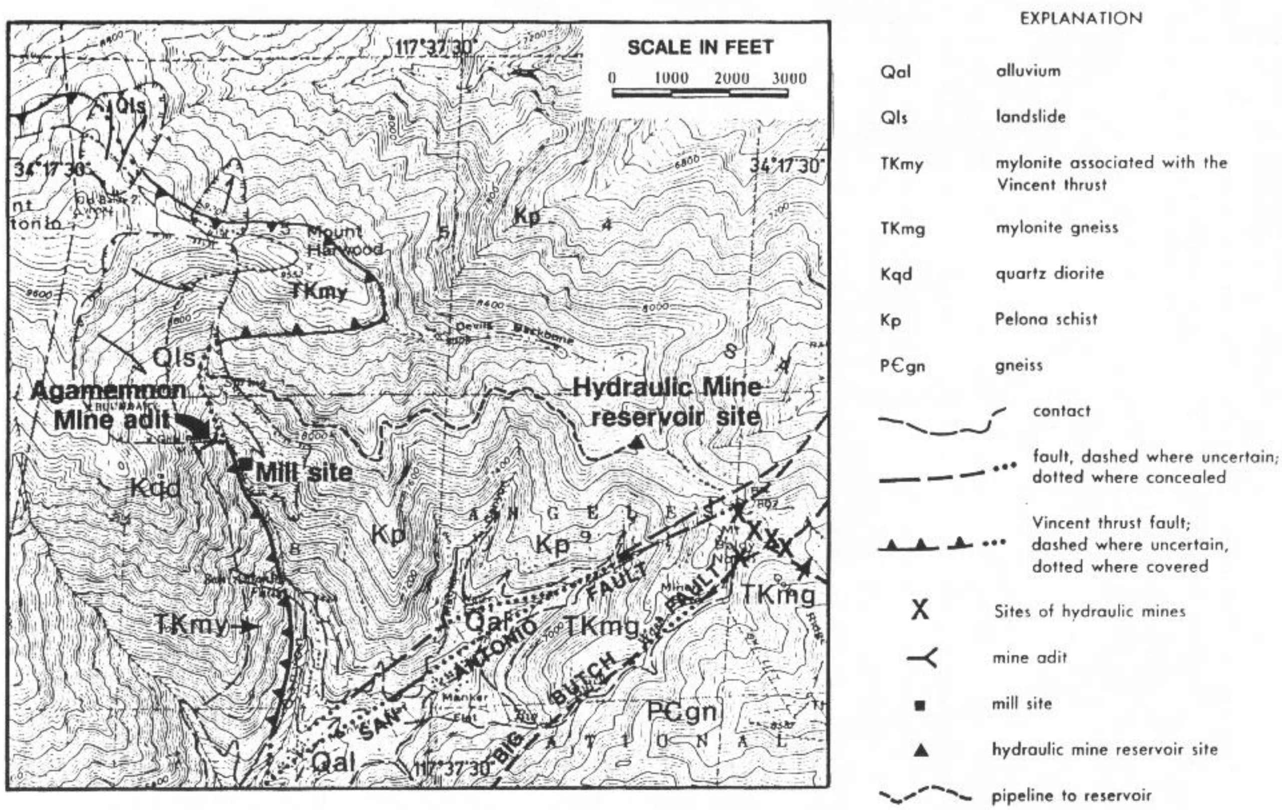

Figure 17. Geologic map of the Mount Harwood-Baldy Notch area, showing extent of gold mining operations during the late 1800s. Geology by Dee Trent. Reproduced from Figure 4-2 in Trent (2001).

Alternative Stop #6B: Pelona Schist and Transpressional Faults Along the San Antonio Falls Road

Walk up road through a west-dipping section of Pelona schist that composes the footwall of the Vincent thrust. These rocks were first mapped in detail by Perry Ehlig (1958) as part of his doctoral dissertation. Greenschist, grayschist, and quartzite derived from mafic igneous rocks, graywacke/mudstone, and chert, respectively, is strongly sheared and transposed. These oceanic rocks were overthrust by San Gabriel continental basement during late Mesozoic-Early Cenozoic time (Ehlig, 1981; Nourse, 2002; Dibblee, 2003). Notice the complex mesoscopic folds, especially well-preserved in metachert layers. Along this stretch of the road, the metamorphic fabrics are intruded by several rhyolite porphyry dikes and one mafic dike.

From the first switchback (0.6 mi above the gate) is a spectacular view of San Antonio Falls (Figure 18). These waterfalls in upper San Antonio watershed provide a beautiful illustration of local hydrology and geology. The primary water source for San Antonio Creek is a line of springs located upstream at 8200ft elevation, just above Sierra Hut. At Sierra Springs, water contained in a porous talus boulder slope (Baldy Bowl) is forced to the surface along a lower boundary with impermeable rock (Pelona schist). Water passing over San Antonio Falls (elevation 6400 ft) is joined downstream by flow from Manker springs and Icehouse Creek. Farther downstream San Antonio Creek supplies water to residents of Mt. Baldy village and Upland. Hydroelectric power is also generated as the creek drops 1660ft elevation between the Mt. Baldy village and San Antonio Dam.

The cliffs before you reveal rock layers that have been carved and exposed by the erosive action of San Antonio Creek. In detail, these rocks compose two contrasting packages separated by the Vincent thrust (a fault named for its exposure near Vincent Gap). The Vincent

Figure 18. San Antonio Falls, with the Vincent thrust and Baldy Bowl in the background.

thrust marks a major tectonic collision zone between an ancient continent and an adjacent ocean basin. Perry Ehlig (1927-1999) was first to map this fault in detail during the 1950s as part of his PhD dissertation. Perry walked virtually every inch of the Vincent thrust, a significant accomplishment in this rugged country.

The gray rocks exposed in the lower part of the falls are metamorphosed sands, silts, and muds, originally deposited in a deep ocean basin about 80 Ma. The green layers represent metamorphosed basaltic lavas that erupted within this ocean basin. The Vincent thrust is exposed just above the prominent tree-covered ledge to the upper left of San Antonio Falls. The steep cliffs above the Vincent thrust contain rocks of continental origin ranging in age from about 1700 to 80 Ma. Samples of these rocks may be viewed in the talus slope to the left of the falls. Especially noticeable is a distinct white rock with large black crystals informally named "dalmationite" by Ehlig. This igneous rock crops out along with a finer grained black and white quartz diorite near the summit of Mt. San Antonio.

Close inspection of the waterfall outcrop reveals uniformly dipping Pelona schist intruded by two prominent rhyodacite porphyry sills, in turn cut by thinner mafic-intermediate dikes. Several northeast-striking faults disrupt the continuity of the rhyodacite sills. Apparent left-lateral and/or reverse displacements are compatible with more accessible exposures observed farther up San Antonio Falls Road. Follow a narrow trail to the base of the falls. A somewhat treacherous scramble up the talus slope south of the falls will afford up-close examination of the intrusive relationships.

The road climbs another 3 mi to Mt. Baldy Notch, during which it crosses the San Antonio Canyon Fault four times as it bends from a N30E to N80E strike. Brittle strain near this fault appears to be partitioned into reverse and sinistral components to accommodate local transpression. For example, near Manker Creek crossing (1.4 to 1.7 mi above the gate), about 300 m northwest of the San Antonio fault), rhyolite porphyry sills in Pelona schist are offset by a family of reverse faults. Differential movements between reverse faults (see also Figure 2-8 of Trent and Nourse, 2001) have rotated schist foliations to steep southwest dips and resulted in moderate northeast dips for two mafic-intermediate dikes. One mafic dike exposed 120 m up Manker Creek displays significant sinistral offsets. Farther up the road (2.8 mi past the gate) the main trace of the San Antonio fault is exposed beneath the ski lift. Kinematic features here indicate pure left-lateral displacement.

Highlights enroute to Stop #7

Drive down the switchbacks to Mt. Baldy village. About 1/4 mi past Mt. Baldy Visitor Center. Turn right onto Glendora Ridge Road. Proceed uphill about 3/4 mi. Roadcuts on the right display chaotically arranged angular boulder deposits of the Cow Canyon landslide. Distinctive clast types include garnet-biotite quartz-feldspar gneiss, quartzite, marble, calcsilicate gneiss, and graphitic phyllite. These boulders are not locally derived. Instead, they originated from bedrock sources about 3/4 of the way up Ontario Peak (elevation 8892 ft), located on the east side of San Antonio Canyon. The landslide appears to have traveled down Kirchoff Canyon, leaving behind huge mounds of debris visible on the east side of San Antonio Canyon. It continued across westward into the headwaters of Cow Canyon. Park on the right in a large lot at Cow Canyon Saddle (elevation 4523 ft).

Optional Stop #7--Late PM

The valley to the west is controlled by at least three strands composing the north branch of the San Gabriel fault zone. This fault recorded 22km of dextral slip, probably between 12Ma and 5 Ma (these age constraints are from the northwest end of the San Gabriel fault near Ridge Basin; see Crowell, 1975). To the east, the San Gabriel fault is truncated by the San Antonio Canyon fault, and displaced sinistrally 3 km to Icehouse Canyon (Nourse et al., 1994; Nourse, 2002). The intersection of the two faults is buried by Cow Canyon landslide, which forms this geomorphically peculiar saddle. However, pristine exposures of minor structures probably associated with the San Gabriel and San Antonio faults can be viewed along the lowermost segment of Sunset Ridge fire road, directly to the south.

Conclusion

The eastern San Gabriel Mountains provide a dramatic natural laboratory in which to study the effects of igneous intrusion and strike-slip faulting, revealed as a consequence of late Cenozoic uplift accompanied by erosion and catastrophic flooding. The places we have visited today represent a few accessible examples of processes we have discussed. Many additional sites remain for those able to expend more time and energy. Please ask your leaders for ideas. We hope you have the opportunity to revisit this area someday.

Acknowledgments

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1969 Southern California Flood

(by Ray Minnich)

Editor's Note: Ray Minnich is a long-term cabin owner from the Snowcrest Heights area of the eastern San Gabriel Mountains. His family has owned a cabin at the mouth of Big Butch wash near Manker Campground since the mid-1900s. The personal account below describes Ray's experiences during a series of 1969 storms that included heavy February snowfall in addition to the January rains. Thank you, Ray, for your contribution to this guidebook!

The floods of January and February, 1969, are now history. Comparisons are being made with previous "Big Ones" such as 1938. The conclusion is that this series of storms exceeded all previous storms of the past hundred years. Despite this, we still have a cabin. There have been some anxious times but Ray has been confident all along that the cabin is now protected.

These "Big Ones" are supposed to hit on the average, every twenty-five to forty years. The 1938 flood severely damaged our cabin, but in succeeding years we repaired it to quite a livable condition. Then starting in November 5, 1965, we had a series of three gully washers in rapid succession. The third one piled rocks on the roof, put mud on the floors but did not do important structural damage. We removed 650 half-ton mining-car loads plus 400 wheelbarrow loads, adding considerable acreage to the front yard. We next hired a bulldozer to build three successive diversionary dikes in the fall of 1965.

Starting January 19, 1969, a series of warm tropical storms deluged Southern California with the greatest precipitation of the past 100 years. Rainfall in the Los Angeles basin for the thirty days of that period has been 25 inches, or more than double the annual average. Rainfall at the cabin in January-February was between 80 and 90 inches, compared to the 1938 flood of 40 inches.

Although about a hundred lives were lost in this area, there was no damage or loss of life in our part of Long Beach. During the first two parts of the storm, there was severe damage to roads, utilities, and buildings in the mountain areas but no loss of life in our canyon. Then on February 23, another fairly heavy rainfall caused a landslide at Mt. Baldy Village killing four out of a family of nine and destroying their large two story home.

These were very exciting times. Richard is our family climatologist and can see the "Big Ones" coming. He phoned before the heavy January rains and wanted to go up the canyon. The access roads have been closed to the public most of the time. We did phone a neighbor who lives across the highway from the cabin but he couldn't tell us anything because it was raining too hard to see any distance (over 2 inches per hour during this period). He did say that boulders were rolling down the highway and trees were falling. He and his wife were marooned for two weeks with no lights, phone, or water (in the pipes!) A bucket on the porch filled in short order. Richard attempted to get up the canyon, could not drive beyond Mt. Baldy Village. He hiked about a mile farther to a bridge washout and got several remarkable pictures and wet to the skin.

The last weekend in January we talked our way through the police roadblock and drove to the village. Here, fifteen cabins had been completely destroyed and about twenty thoroughly damaged. Although the road from here up the canyon was in sad shape, we managed to drive all the way to the cabin. We found the four-lane highway reduced to two lanes. Nine trees down in the area where our private road used to be, and about one-fourth of the neighbor's front yard washed away. There was no structural damage to the 120 cabins in our Association. About six inches of new snow were doing a rather poor job of hiding the damage. Our cabin was absolutely untouched except for two watermarks across the Kitchen floor. The highest of the three diversionary dikes was completely washed away, but the second one held. The third dike was not even tested. The water system that supplies our Association was severely damaged.

On successive weekends we have helped repair the main line. On February 15 we got around to locating and repairing our own branch waterline (in a snow storm) with the help of a 70-year-old Indian. By February 22, snow depths had reached five feet and we decided to shovel off the roof which was very heavily loaded with snow and ice. Another two feet of snow fell the next week.

Many avalanches came down the mountainside. One particularly large one came down by San Antonio Falls and continued down to Snow Crest, (about ½ of a mile). The Minnich cameras were quite busy recording these unusual events. This has been a most exciting and profitable time for Richard as he has been making long-term studies of these phenomena for geography papers. Recent correlation of rainfall data shows that a sudden 24-inch rain into the heavy snow on February 25 brought down the avalanches as heavy, relatively slow moving masses. The slide at the San Antonio Falls left tremendous vertical ice walls on both sides of its path.

On our visit March 22, all kitchen windows were covered with snow and the views out other windows were decidedly arctic. Two small boys playing in the snow got “lost” on our cabin roof.

This is all a little hard to believe when one drives in one hour to an 80-degree climate with swimming in the ocean. The wife of our nephew, Bob Minnich, visited Mt. Baldy with us recently and remarked that compared to the Alps, this mountain is “wild and untamed.”