Plutonism across the Tujunga–North American terrane boundary: A middle to upper crustal view of two juxtaposed magmatic arcs

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ABSTRACT

Opportunities to study middle crust magmatic arc construction are uncommon. Petrologic studies in southern California have revealed middle to upper crustal portions of two juxtaposed Mesozoic magmatic arcs, one being a native terrane of the Cordilleran orogen and the other the "suspect" Tujunga (or San Gabriel) terrane. Crystallization thermobarometry of successively intruded and dated plutons provide "crustal nails" that track the variable depth history of orogenic crust in both terranes. Deep crust is now exposed at the surface by virtue of two contrasting tectonic settings — lower plates of extensional detachment faults in Tertiary metamorphic core complexes and upper plates of Mesozoic basement-involved thrust faults.

The goal of this research has been to document the nature of Mesozoic arc development as a function of crustal depth (from >25 km to subvolcanic) across the inferred terrane boundary and to utilize this information to constrain the accretionary history of this region. Timing of the terrane boundary has been enigmatic and existing interpretations vary from the pre-Middle Jurassic Mojave-Sonoran megashear to thrust faults of pre-Middle Jurassic to Late Cretaceous age. The Tujunga terrane is everywhere in fault contact with adjacent units. Plutonism, thrust and detachment faults, and Neogene disruption by the San Andreas fault have obscured the nature of the boundary and the origin of the Tujunga terrane.

Our data indicate that the Tujunga terrane has Cordilleran roots regardless of the magnitude of displacement by bounding faults. A unique feature of the Tujunga terrane is its Middle Proterozoic history, including the emplacement of a 1.2 Ga anorthosite-charnockite complex into 1.4 Ga granulites. Much of this apparent "suspect" nature of the Tujunga terrane stems from its partial derivation from the middle crust. Early Proterozoic, Triassic, Jurassic, and Cretaceous plutonism of the Tujunga terrane are all separately distinct, yet each has close compositional affinity to, and most are indistinguishable from, that in the adjacent Mojave Desert region of the Cordillera. Mesozoic and Cenozoic tectonic disruption are thus viewed as intra-arc events and not the result of original suturing of a long-displaced terrane.

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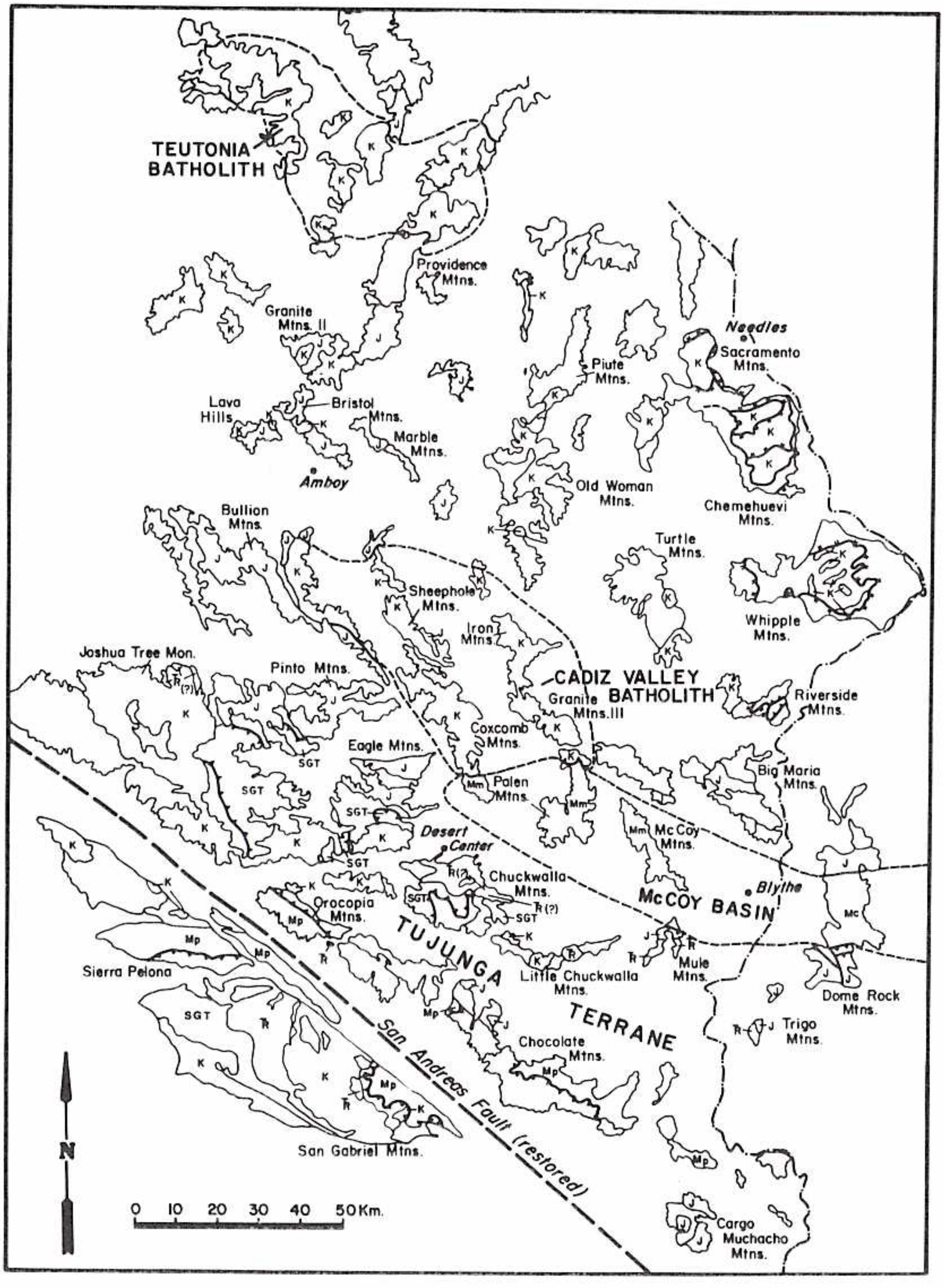
TEUTONIA BATHOLITH
Providence Mtns.
Granite Mtns. II
Needles
Sacramento Mtns.
Piute Mtns.
Lava Hills
Bristol Mtns.
Marble Mtns.
Amboy
Old Woman Mtns.
Chemehuevi Mtns.
Bullion Mtns.
Turtle Mtns.
Sheephole Mtns.
Iron Mtns.
Whipple Mtns.
Joshua Tree Mon.
Pinto Mtns.
CADIZ VALLEY BATHOLITH
Granite Mtns. III
Riverside Mtns.
Coxcomb Mtns.
Eagle Mtns.
Palen Mtns.
Big Maria Mtns.
Desert Center
McCoy Mtns.
Chuckwalla Mtns.
Blythe
McCOY BASIN
Orocopia Mtns.
TUJUNGA TERRANE
Sierra Pelona
Little Chuckwalla Mtns.
Mule Mtns.
Dome Rock Mtns.
Trigo Mtns.
Chocolate Mtns.
San Andreas Fault (restored)
San Gabriel Mtns.
N
0 10 20 30 40 50 Km.
Cargo Muchacho Mtns.

Details of these results are more fully developed below. An exciting aspect of the work is the documentation of deep crustal exposures in both the Tujunga terrane and native portions of the Cordillera. Geologic sampling of deep crust is derived from two tectonic environments: the lower plate of extensional detachment faults of metamorphic core complexes, and the upper plate of basement-cored thrust faults. Exceptions to these generalizations include the lower plate in the Sacramento Mountains core complex and the crustal assemblages above the Late Cretaceous Mule Mountains thrust fault, which are both of upper crustal origin (<10 km) (Anderson and others, 1988a; Barth and others, 1988). The question of "how deep" appears to be a function of longevity and style of upward transport along these zones of crustal shear, whether developed during regional extension (core complexes) or compression (thrust faults).

The above conclusion is derived through thermobarometry of pluton emplacement which, when there are successive stages of intrusion, allows tracking of ascent and/or descent of crust during orogenic tectonism. The impetus for this type of application stemmed from work in metamorphic terranes where pressure-temperature-time (P–T–t) paths were obtained from compositional zoning profiles and prograde inclusions in porphyroblasts (*e.g.*, Spear and Selverstone, 1983). We are one of a few research groups who have extended this method in igneous suites (see also Zen, 1985; Hollister and others, 1987). The success of the approach is striking, despite the uncertainties of some of the thermobarometers applicable to plutonic rocks.

There is much interest today in the physical construction of the middle crust, including attempts to seismically image and drill into deep crust. Our field-based research has shown that such crust is locally exposed at the Earth's surface, the study of which provides a base of ground truth and should accelerate the benefits derived from these other projects.

PREBATHOLITHIC UNITS

Proterozoic Basement: Tujunga Terrane and Mojave Desert

The Early Proterozoic crystalline assemblages of the Tujunga/San Gabriel terrane exhibit marked similarities with respect to rocks of similar age exposed throughout the Mojave-Sonoran Desert regions of the southern Cordillera. We recently completed a number of investigations dealing with Proterozoic crustal history of the Mojave region (Anderson, 1983; Anderson, 1987; Thomas and others, 1988; Orrell and others, 1987; Bender and others, 1988; Anderson and Bender, 1989; Young and others, 1989). The oldest rocks in both the Tujunga terrane (Ehlig, 1981) and the Mojave (Anderson and others, 1990) include layered gneisses of probable metasedimentary and metavolcanic origin that were regionally metamorphosed at high grade and intruded by synkinematic to late kinematic foliated granitoids and augen gneisses at ≈1.7 Ga. The chemistry of these ≈1.7 Ga plutons is indistinguishable (see below). In the Mojave Desert region, these metamorphic rocks record a high amphibolite to granulite metamorphic event at low pressure (≈ 3.5 kb) and subsequently were intruded by high potassium (rapakivi) granites at 1.4 Ga and swarms of younger diabase dikes as part of a transcontinental "anorogenic" magmatic event (Anderson, 1983, 1987; Anderson and Bender, 1989).

A key feature of the Tujunga terrane is its unique Middle Proterozoic history with no 1.4 Ga granites or Proterozoic diabase swarms. A granulite metamorphic event was defined by Silver and others (1963) at 1.4 Ga based on U-Pb dating of zircon from a pegmatite. Granulites of 1.4 Ga age have not been recognised elsewhere in North America; however, such rocks should be abundant at depth as a lithologic record of magma generation of the widespread 1.4 Ga granites. Subsequent intrusions include anorogenic massif-type anorthosite and charnockite at 1.22 Ga (Carter and Silver, 1972), the only such occurrence of that age in the western United States. The anorthosite-charnockite rocks are distinctive and served as key lithologic elements in constraining the magnitude of offset by the San Andreas fault (Crowell, 1962, 1981).

We are not yet able to estimate the depth of emplacement of the anorthosite complex — notably, the anorthosite occurs only in sections that were at middle crustal levels during all or part of the Mesozoic (San Gabriel and Chuckwalla Mountains), implying that the anorthositic portion of the complex is deep seated. In contrast, the associated charnockitic intrusives (jotunite and syenite) are more widespread and occur in areas that were at both deep (San Gabriel, Chuckwalla, and Little Chuckwalla Mountains) and shallow (Eagle and Orocopia Mountains) crustal levels by Mesozoic time.

Paleozoic Supracrustal Rocks

Paleozoic rocks, transitional from cratonic to miogeoclinal facies, locally overlie Proterozoic rocks of the Mojave Desert region. The sequence, occurring in Mesozoic fold and thrust nappes in the Big Maria and Old Woman Mountains and in thrust slices in the Little Harquahala and Granite Wash Mountains, is commonly attenuated and/or disrupted by late Mesozoic tectonic events (Stone and others, 1983). In a few areas, the section is unmetamorphosed, such as in the Marble and Providence Mountains. Elsewhere, metamorphic facies range from middle greenschist to upper amphibolite (Hoisch, 1985a,b; Hoisch, 1987; Hoisch and others, 1988) at pressures ranging from 3 kb (Big Maria Mountains) to >5 kb (Old Woman Mountains). The section is absent throughout much of the region owing to removal by pre-Miocene erosion. In several ranges, strata are preserved that are structurally overlain by Proterozoic rocks (Spencer and others, 1987).

Although pelitic and carbonate metasedimentary rocks occur in the southeastern San Gabriel Mountains (Dibblee, 1982; Barth and May, 1987), their correlation with native Paleozoic sections is uncertain. Possible Paleozoic rocks have not been identified elsewhere in the Tujunga terrane.

Mesozoic Supracrustal Rocks

Most stratified rocks of Mesozoic age occur in the southern portion of the area depicted in **Figure 1** and can be divided into four lithostratigraphic units, as described most recently by Tosdal and others, (1987). Three of these units occur primarily in or near the structural McCoy Basin and are only weakly metamorphosed, including, in ascending order: *(1)* a Triassic to lower Jurassic clastic section, *(2)* the dominately volcanic Dome Rock sequence of Jurassic age, and *(3)* the Jurassic(?) to Cretaceous McCoy Mountains Formation of Harding and Coney (1985).

The fourth supracrustal unit is predominantly an oceanic metasedimentary section now exposed in an intracontinental position. The unit has been termed, depending on locality, the Rand, Pelona, or Orocopia schist and collectively has been referred to as the Baldy terrane by Coney and others (1980) and Blake and others (1982), based on exposures that underlie Mount Baldy of the San Gabriel Mountains. Its Neogene dispersal due to strike-slip faulting in southern California is similar to that of the structurally overlying Tujunga terrane. The principal lithology is metagreywacke schist derived from continental detritus, with only a minor component of magmatic arc material (Haxel and others, 1987). Subordinate metamorphosed lithologies include tholeiitic (MORB) basalt, chert, marble, and serpentinite. The metamorphism, coeval with development of overlying thrust (presumably subduction-related) faults, was of greenschist to rare blueschist to lower amphibolite facies at pressures >8 kb (Graham and England, 1976; Graham and Powell, 1984). Thus, like the Tujunga terrane, the Pelona/Orocopia schist resided at deep crustal levels during the Late Cretaceous and underwent subsequent rapid upward transport during the early Tertiary. Protolith age for the schist is constrained to be Mesozoic (Haxel and Tosdal, 1986; Haxel and others, 1987). Tosdal and others (1987) suggested that the original sedimentary basin of the schist protolith may have originated within the Mojave-Sonoran megashear, similar to the proposed model for deposition of the McCoy formation by Harding and Coney (1985).

METHODOLOGY

Why Study Granites?

This effort is directed at the plutonic history of the craton and adjacent Tujunga terrane. Additional goals are to evaluate the origin of magmatism leading to crustal development and to constrain the depth history (P–T–t) of crust during the orogenic process. A provocative variation of crustal depth is exposed on both sides of the terrane boundary, allowing the exciting opportunity to evaluate mid- to upper-crustal arc construction of two juxtaposed sections of crust.

Granitoid magmas can undergo major modification during ascent and emplacement. Determination of original magma composition requires "seeing through" these changes. The problem is often workable and important, as the derived data provide the only evidence available on the age and composition of the source region that, due to tectonic separation, may no longer underlie the magmatic arc.

Depths of emplacement are obtainable through use of several new thermobarometers (see below) applicable to granitic rocks. Contact metamorphic rocks are also useful in this regard, but in multiply

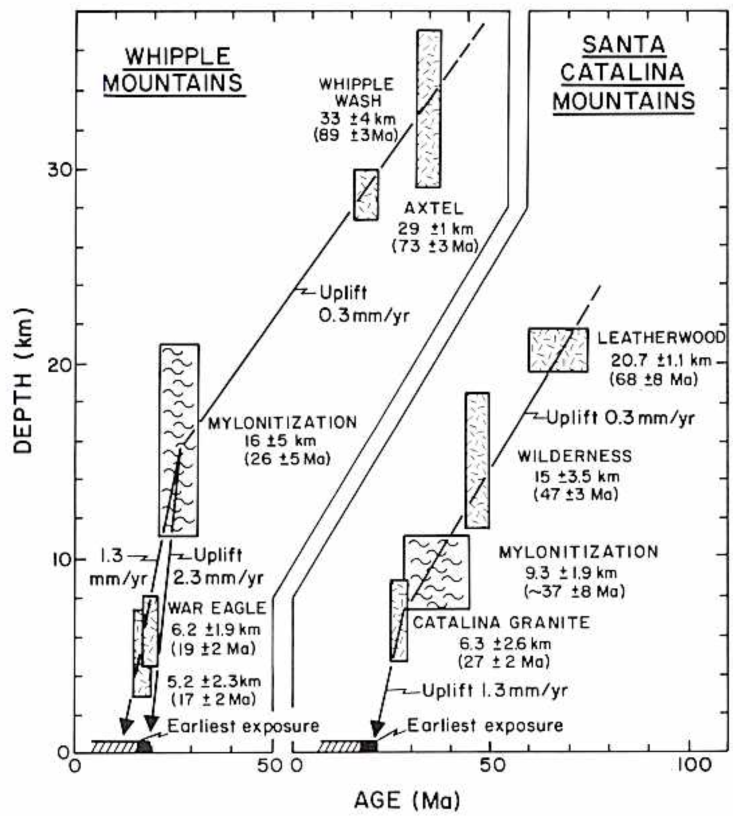

Figure 2. Upward transport of the Whipple and Santa Catalina core complexes as a function of age. Depth calculated from an assumed geobarometic gradient of 3.7 km/kb (for average crustal densities) derived from barometry of plutonic emplacement and deformational events. From Anderson and others (1988b).

intruded terranes, such as those in this study, such applications are difficult owing to extensive overprinting. In contrast, high-temperature mineral phases of igneous rocks often retain primary compositions, despite the occurrence of subsequent plutonism or deformation. Thermochronological data are also often used to constrain depth history but are hampered by large uncertainties in assumed thermal gradients. Our approach is more direct and utilizes dated plutons as crustal nails to constrain the variable ascent and/or descent of the crustal section during its tectonic history. An example of this application is shown in **Figure 2**, which depicts the depth-time path for lower plate assemblages of two metamorphic core complexes — those of the Whipple and Santa Catalina Mountains (Anderson and others, 1988b). Barometry for four (Santa Catalina) or five (Whipple) pluton emplacement and deformation events, plus ages of earliest unroofing, track the upward transport of crustal sections since the Late Cretaceous, with a notable acceleration of decompression coincident with onset of mid-Tertiary mylonitization and extension. The depth-time history of the Whipple complex is well constrained. Older plutons were emplaced at 73-89 Ma when the crustal section resided at 29-33 km. Tracking the upward ascent of the complex, subsequent regional mylonitization at 26 Ma occurred at 16±5 km, followed by Miocene (17-19 Ma) plutonism with emplacement depths of 5-7 km. Unroofing occurred after 16 Ma as a consequence of Miocene decompression rates that exceeded 2 mm/yr.

We are using three analytical approaches to constrain evolution of granitic magmas within the area (**Figure 1**): *(1)* major and trace element analyses of whole rock samples; *(2)* Rb-Sr, U-Pb, and common Pb isotopic analyses of selected samples; and *(3)* detailed examination of mineral chemistry through characterization of critical substitutions, evaluation and judicious use of thermobarometry, and theoretical treatment of mineral-liquid equilibria.

Isotopic Analyses

U-Pb ages of zircon separates and Pb-Pb and Rb-Sr data presented here are being acquired through a collaborative investigation with Joe Wooden and Dick Tosdal (U.S. Geological Survey, Menlo Park, California). The Pb and Sr isotopic data are critical to model source characteristics and crustal interaction during ascent. Determination of isotopic abundances is not only necessary to constrain crystallization ages but also to provide information required to understand magma evolution.

Existing Sr isotopic data are limited. Miller (1985) and Miller and others (1990) showed that Cretaceous plutons in the Old Woman and Piute Mountains have elevated initial $^{87}Sr/^{86}Sr$ ratios, or $Sr_i > 0.708$, and are crustally derived based on isotopic Sr, Pb, and O data. Anderson and Cullers (1990) described less radiogenic (average $Sr_i = 0.7077 \pm 0.0013$) Cretaceous plutons of the Whipple Mountains core complex and concluded derivation from a crust-enriched, oceanic reservoir. Likewise, several of the Jurassic plutons have an elevated Sr_i (averaging 0.7065), thus requiring a crustal component in their derivation (Young and Wooden, 1989). The only initial Sr data available for the San Gabriel terrane comes from the Triassic Lowe intrusion (Joseph and others, 1982). At 0.70456 ± 0.00006, the value is sufficiently low to preclude an older, feldspathic crustal component in its evolution (Barth and Ehlig, 1988).

Wooden and others (1986) and Wooden and Stacy (1987) provided an extensive set of feldspar common Pb data for Jurassic and Cretaceous plutons of the Mojave Desert region showing that Mesozoic plutons have a distinctive isotopic trend, defining a $^{207}Pb/^{206}Pb$ pseudo-isochron with an age similar to that of the Proterozoic basement. Working with Wooden, we have added new data that are in concert with the above findings (**Figure 3**). Ratios of $^{208}Pb/^{206}Pb$ for Mesozoic plutons also fall within the field defined by Proterozoic plutons. Taken together, the data require an extensive crustal component in the origin of these Mesozoic plutons. In contrast, common lead for the Lowe intrusion (Davis and Barth, 1985) does not have a crustal signature (**Figure 3**), which is consistent with the inferred subcrustal origin of this large batholith.

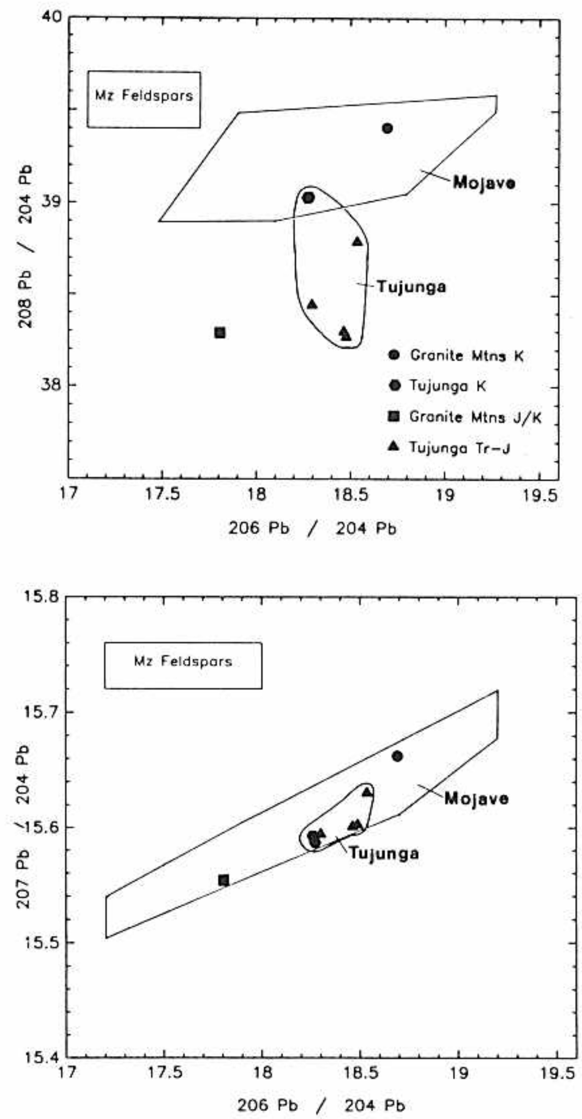

Figure 3. Comparision of common Pb isotopic composition of Mesozoic plutons of the Mojave Desert region (North America) and the Tujunga terrane. The Mojave field is drawn from data (not shown) of Wooden and Stacey (1987) and the data points originate from this study in collaboration with Wooden. Cretaceous plutons in both terranes are similar in thorogenic Pb. Early Mesozoic plutons in the Tujunga terrane are lower in thorogenic Pb relative to Mojave. A single pluton in the Granite II Mountains also shows low $^{208}Pb/^{204}Pb$ and is anomalous relative to other Mesozoic plutons of the Mojave Desert.

Apart from common Pb, there has been no dedicated study to amass the isotopic composition of Mesozoic plutons in this region of southern California. The Pb data are indicative of a major crustal role, but it is unclear why the same Pb trend exists for both Cretaceous and Jurassic igneous suites of the Mojave, given their compositional differences (see below).

Mineral Chemistry

Compositions of granitoid mineral phases are sensitive to P, T, fluid composition, and interaction with coexisting liquid and other solid phases. Chemical variation in biotite, calcic amphibole, white mica, and garnet are particularly useful in elucidating changes in these parameters because they exhibit multi-site exchanges. Dominant substitutions that are bulk composition-independent can be attributed to changes in intensive parameters and equilibria with coexisting phases.

Several differences in the chemistry of the above mineral phases occur, due in large part to temperature and depth of crystallization. Because magmas can crystallize over a range of pressure during their crustal ascent, pressure-sensitive exchanges will be modified as a mineral grows from core to rim. Other variations can be correlated with changes in phase assemblage along the crystallization path. With these factors in mind, the following sections review the approach taken in this study to extract crystallization history as recorded in the composition of the magmatic mineral phases.

Thermobarometry

The extensive mineral compositional data accumulated during the course of this research afford the opportunity to not only apply but also to test and refine numerous thermometers and barometers in granitoids. Several thermobarometers we use have been thoroughly tested only in metamorphic rocks but, thermodynamically, are rigorously applicable to liquid-bearing systems. To accurately estimate emplacement depth, the phase compositions must represent near solidus conditions, as the solid phases in a magmatic system could have been acquired at any stage during ascent, if not from the restitic source. Complete characterization of compositional variations in the phase assemblage is a fundamental prerequisite to any of the barometric applications described below.

Many igneous rocks lack pressure-sensitive phase assemblages, yet a prominent example in peraluminous granites is the assemblage garnet, muscovite, plagioclase, and biotite (Ghent and Stout, 1981; Hodges and Royden, 1984). The equilibria are fluid independent and involve an increase in the grossular component in garnet at the expense of the anorthite component in plagioclase with increasing pressure. Although originally intended for pelitic schists, the barometer appears to work well for granitic rocks (Anderson, 1985; Anderson, 1988; Anderson and others, 1988b) and can be used in concert with the garnet-biotite thermometer of Ferry and Spear (1978) or, for more manganiferous garnets, with a suggested modified formulation by Ganguly and Saxena (1984). For the same rocks, we obtain similar, though less precise, pressure estimates with the phengite barometer (based on the silica content of muscovite in equilibrium with biotite and K-feldspar) of Massonne and Schreyer (1987). A previous calibration of this barometer by Powell and Evans (1983), however, appears to yield estimates 1-3 kb too high. We are uncertain of the cause, but the Massonne and Schreyer formulation also gives high results when the ferrimuscovite component in muscovite exceeds a weight fraction of 0.1.

The presence of magmatic epidote is suggestive of minimum crystallization pressures of 4-6 kb, the lower limit variation being a function of oxygen fugacity (Zen and Hammarstrom, 1984; Zen, 1985). The significance of this mineral as an indicator of pressure must be evaluated as both supersolidus and subsolidus growth stages can occur. Chemographic relations (**Figure 4**) demonstrate pressure dependence and paragenetic growth of magmatic epidote. With decreasing temperature, epidote should have a reactive relationship with hornblende, leading to its stable coexistence with biotite (as shown by Naney, 1983). Many of the high pressure plutons encountered in this study have magmatic, or probable magmatic, epidote, including the Lowe, Waterman, and Josephine intrusions of the San Gabriel Mountains (Barth, 1990), the Old Woman granodiorite of the Old Woman Mountains (Young, this report), the Corn Springs granodiorite of the Chuckwalla Mountains (Davis and Farber, 1989; Farber and Davis, 1989), and the Whipple Wash and Axtel intrusions of the Whipple Mountains (Anderson, 1988).

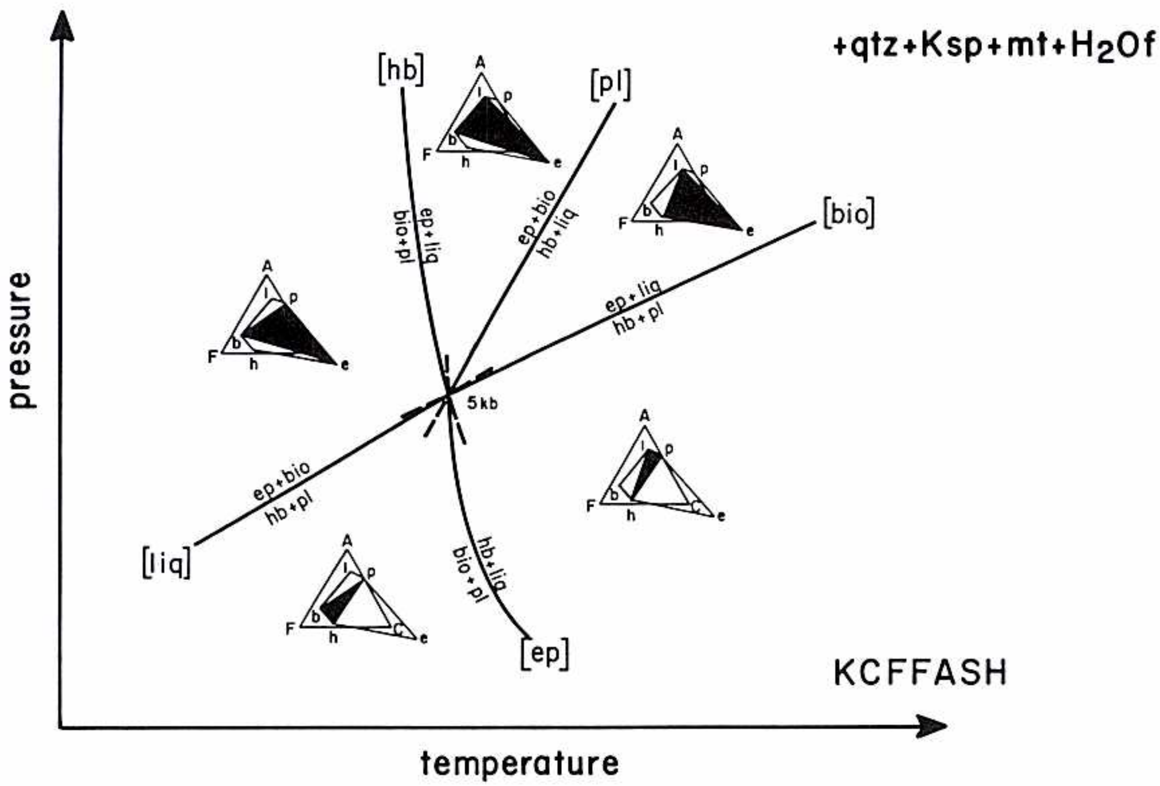

Figure 4. Chemographic analysis of the KCFFASH system projected from quarz, feldspar, magnetite, and H_2O, elucidating possible equilibria amongst analyzed epidote (e), hornblende (h), biotite (b), plagioclase (p), and granitic liquid (l). darkened field encloses the compositon of a metaluminous granodiorite from the Old Woman Mountains. A= Al_2O_3–K_2O–CaO; F = FeO–Fe_2O_3; and C = CaO.

For metaluminous granites, barometric estimates are possible based on the solubility of total aluminum in hornblende (Hammarstrom and Zen, 1986; Hollister, and others, 1987; Rutter and Wyllie, 1988). We observe that total Al and Fe/(Fe + Mg) are positively correlated and that iron-rich hornblendes yield erroneously high pressures. We are working on an empirical modification of the barometer that will compensate for the apparent Fe/Mg_1 influence, but meanwhile we are restricting its usage to hornblendes of intermediate composition (Fe/(Fe+Mg) = 0.42 to 0.58). The revision by Hollister and others (1987) lessened the uncertainty to ±1 kb over a pressure range of 2-8 kb. Subsequently, Rutter and Wyllie (1988) confirmed that calibration at 10 kbar for hornblende coexisting with quartz and K-feldspar. As a test case, we completed a comparison with pressures derived from contemporaneous low-variance metamorphic mineral assemblages. In the southwestern San Gabriel Mountains, amphibolite to granulite-facies gneisses are intruded by synkinematic hornblende tonalites. Metamorphic pressures were estimated at 4±1kb based on GAR-CORD, GAR-BIO, and GAR-PLAG-SIL-QZ equilibria (Barth and May, 1987). Hornblende barometry yielded 4.2±0.3 kb. We have established similar, within 1 kb, correspondence of hornblende crystallization and contact metamorphic barometry for two other plutons, one in the eastern San Gabriel Mountains and the other in the Coxcomb Mountains.

To estimate crystallization temperatures, we have had some success with integrated two-feldspar thermometry (Whitney and Stormer, 1977; Hazelton and others, 1982; Fuhrman and Lindsley, 1988) and with the Aliv hornblende thermometer of Nabelek and Lindsley (1985). Where we obtained good integrated compositions of K-feldspar, the two thermometers have yielded similar results with the Aliv thermometer averaging ≈40°C higher.

Mineral-Liquid Equilibria

Early crystallizing phases that exhibit growth zoning (*e.g.*, garnet, hornblende, and plagioclase) potentially record changing intensive parameters during large parts of the ascent and crystallization history of magmas. Past approaches to recovering this information utilized mineral-melt exchange reactions (*e.g.*, Helz, 1979) and are not generally applicable to plutonic rocks where equilibrium melt compositions (*cf.* Criscenti and Ghiorso, 1985) and melt activity models are difficult to obtain.

The utility of simultaneous consideration of heterogeneous equilibria (Gibbs method) has been demonstrated in metamorphic rocks (Rumble, 1976; Grew, 1981; Spear and Selverstone, 1983). The strength of this technique lies in its relative insensitivity to uncertainties in thermodynamic data and compositional variability of the melt phase.

An example of application to a two-mica + garnet granodiorite from the Whipple Mountains is summarized in **Figure 5**. The calculated $(\partial P/\partial T)_x$ for isopleths of grossular component in garnet (Xgr) and albite component in plagioclase (Xab) are parallel with lines of constant K_D defined by the empirically derived thermobarometer of Ghent and Stout (1981). The method (not shown) demonstrated that zoning in hornblende from foliated quartz diorites of the Granite II Mountains is consistent with formation prior to crystallization of quartz (Young, in prep.). Such comparisons also aid in identifying mineral compositions of magmatic origin, where deformation and/or thermal overprinting occurred, and in the identification of probable disequilibrium assemblages.

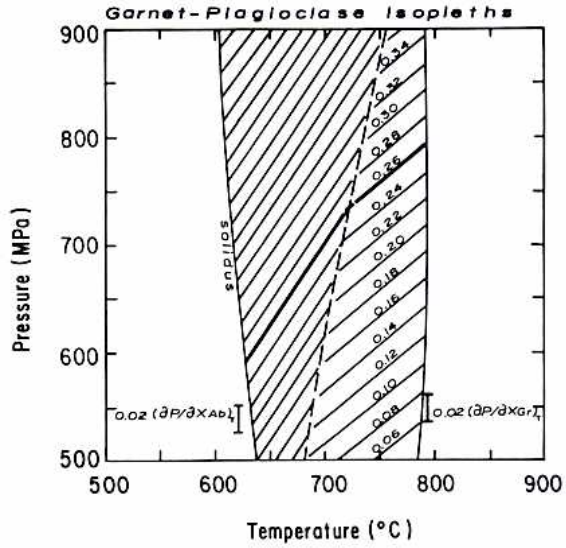

Figure 5. Gibbs method calculations for garnet-plagioclase composition isopeths in peraluminous granitic magma. The sytem is composed of melt + GAR + BIO + PLAG + MUSC + KSP + QTZ, and the isopleths are for mole fraction grossular component (XGr). The heavy isopleth (XGr = 0.26) is an average value for garnet in a Cretaceous pluton from the Whipple Mountains core complex. Similar isopleths can be drawn for the albite component in plagioclase (XAb), the spacing of which is designated. The dashed curve is the approximate high-temperature limit of KSP + QZ (Naney, 1983), the high-temperature curve is the terminal stability of MUSC + QTZ, and the low-temperature curve is the water-saturated granodiorite solidus.

MAGMATIC CONTRASTS ACROSS THE TERRANE BOUNDARY

Early Proterozoic Plutonism

On a global basis, the late Early Proterozoic (1.7-1.9 Ga) was a time of major orogenic continental growth characterized by regional metamorphism of variable grade, construction of mafic to felsic metavolcanic belts, and synorogenic intrusion — predominately mantle-derived calcalkaline plutons. The Proterozoic portion of the North American craton records this same event; age provinces ranging from 1.8-1.9 Ga occur in Canada and the Lake Superior region and young southwestward to 1.7-1.8 and 1.6-1.7 Ga. The Mojave crustal province of Wooden and Miller (1989) and Anderson and others (1992) encompasses southeastern California and adjacent portions of western Arizona and southern Nevada and is strikingly atypical relative to the remainder of the continent. There are no mafic metavolcanic suites and orogenic plutonism (U-Pb dated at 1.66-1.74 Ga) is void of any calc-alkaline members. Variably deformed to foliated granitic and augen gneisses, the plutons are all high or ultra-high K. Bender (1989) recently completed a comparitive study of Early Proterozoic plutons in the southwestern United States and found that those of the Joshua Tree and Tujunga/San Gabriel terrane are indistinquishable from those of the regionally unique Mojave province. **Figure 6** compares the SiO_2-K_2O and Rb-(Y+Nb) compositional fields of Mojave, Joshua Tree, and San Gabriel plutons to those of central Arizona, the latter being akin to the remainder of the craton. The correspondence between the Mojave, Joshua Tree, and San Gabriel plutons is further tied by other data (not shown), demonstrating that all are A-type granitoids (as defined by Whalen and others, 1987), including high Ti and other high field-strength elements, Ba, rare earth, and other large ion lithophile elements, and high Fe/Mg ratios at any silica level.

Triassic Plutonism

Plutons of Triassic age are not abundant in the Cordillera. U-Pb dated plutons in the Sierra Nevada have ages of 200 to 215 Ma (Bateman, 1983; Saleeby, 1981; Stern and others, 1981; Chen and Moore, 1982). Triassic plutons in the Mojave Desert region include a K-Ar dated, 194 Ma pluton in the San Bernardino Mountains, a U-Pb dated, 230 Ma pluton in the adjacent Granite I Mountains (Miller, 1977, 1978), and an ≈220 Ma dated pluton (U-Pb model age based on an assumed upper intercept, J. Wooden, pers. comm., 1987) in the Joshua Tree National Monument (Brand and Anderson, 1982; Brand, 1985). [***Note:*** *there are four Granite Mountains in the Mojave Desert: the Granite I Mountains occur just to the west of the area depicted in* ***Figure 1****. The areal extent of two others is shown in* ***Figure 1****; these have been termed Granite II and Granite III Mountains.*] The Mojave-occurrence rocks are strikingly distinctive relative to the far more abundant, typically calcalkaline, Cretaceous plutons by which they are often intruded. Metaluminous, high K, and low silica, the plutons are principally monzonite, with lesser amounts of monzodiorite and diorite. Megacrystic K-feldspar is common. The principal mafic minerals are clinopyroxene, hornblende, and biotite; a quartz monzonite in the Granite I Mountains contains calcic (andraditic) garnet + hornblende. Compositionally, most plutons are alkalic, with a shoshonitic affinity (**Figure 7**). High abundances of Ba, Sr (>1000 ppm), and LREE are characteristic. For plutons in the San Bernardino and adjacent Granite I Mountains, Miller (1978) convincingly argued that the magmas were derived from a LILE-enriched, quartz eclogite

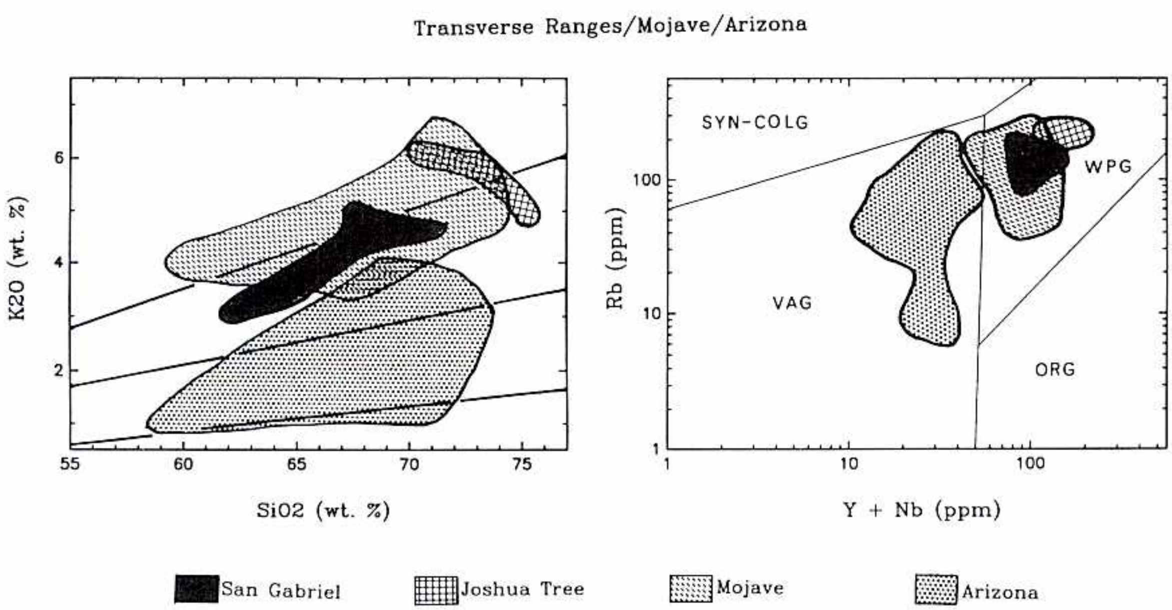

Figure 6. Comparision of K_2O versus SiO_2 and Rb versus Y+Nb for Early Proterozoic plutons of Tujunga/San Gabriel and Joshua Tree terranes (southeastern California), Mojave Desert region (California, western Arizona, and southern Nevada), and central Arizona. Data from Bender (1989). Solid lines on K_2O–SiO_2 diagram separate low-K, medium-K, high-K, and ultra high-K fields of Gill (1981). Compositional field labels on the Rb+Y+Nb diagram from Pearce and others (1984): SYN-COLG = syncollisional granites; VAG = volcanic arc granites; WPG = within-plate granites; ORG = ocean-ridge granites.

source. Hornblende barometry (calibration of Hollister and others, 1987) for the Triassic(?) pluton in the Joshua Tree Monument indicates emplacement at 3.9±0.9 kb.

If the Tujunga terrane is far traveled with respect to North America, then it is a remarkable coincidence that the terrane contains Triassic plutonism with affinity to those described above. The Mount Lowe intrusion is an immense, batholith-sized (>300 km^2), zoned plutonic complex that occurs in the San Gabriel Mountains (Ehlig, 1975). Dated at 220±10 Ma (Silver, 1971), the magmatic evolution and emplacement history of the complex served as the basis of an ongoing dissertation study (Barth, 1987; Barth and Ehlig, 1988; Barth, 1990). In addition, Barth and others (1988) demonstrated petrologic correlation to other exposures east of the San Andreas (Chocolate, Little Chuckwalla, Mule, and Trigo Mountains), as originally suggested by Dillon (1976) and Crowell (1981). The zoned marginal facies of the complex is composed of hornblende quartz monzodiorite and quartz monzonite, grading inward into garnet-biotite quartz monzodiorite and granodiorite. A younger, central

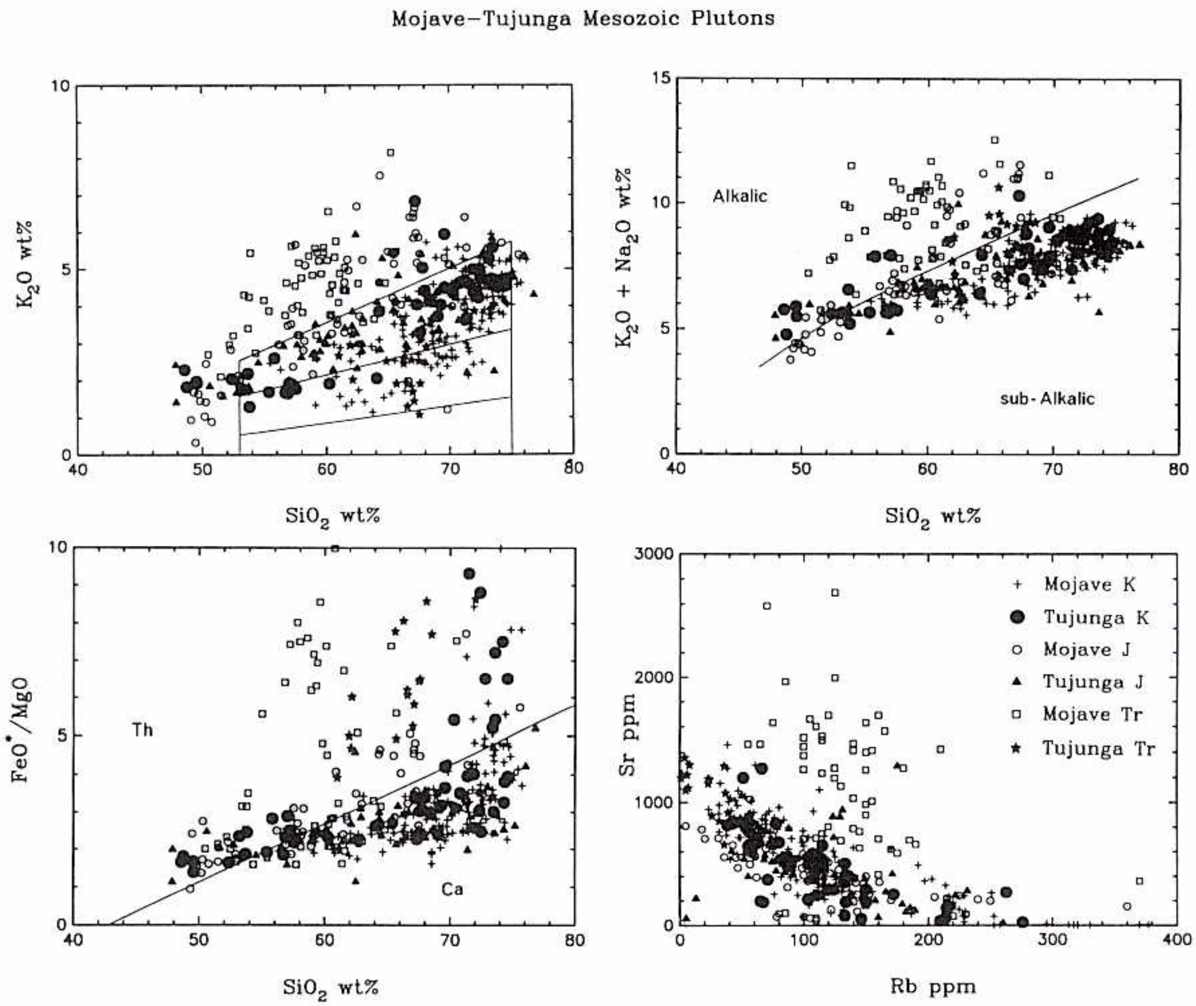

Figure 7. Compositional comparison of Triassic, Jurassic, and Cretaceous plutons of the Tujunga terrane and the Mojave Desert region. Sources of data include this study and others given in the text. Grid on SiO_2–K_2O plot is from Gill (1981); alkalic/subalkalic boundary on the SiO_2–(K_2O+Na_2O) plot is from Irvine and Baragar (1971); and calcalkaline/tholeiitic boundary on the SiO_2–(FeO/MgO) plot is from Miyashiro (1974).

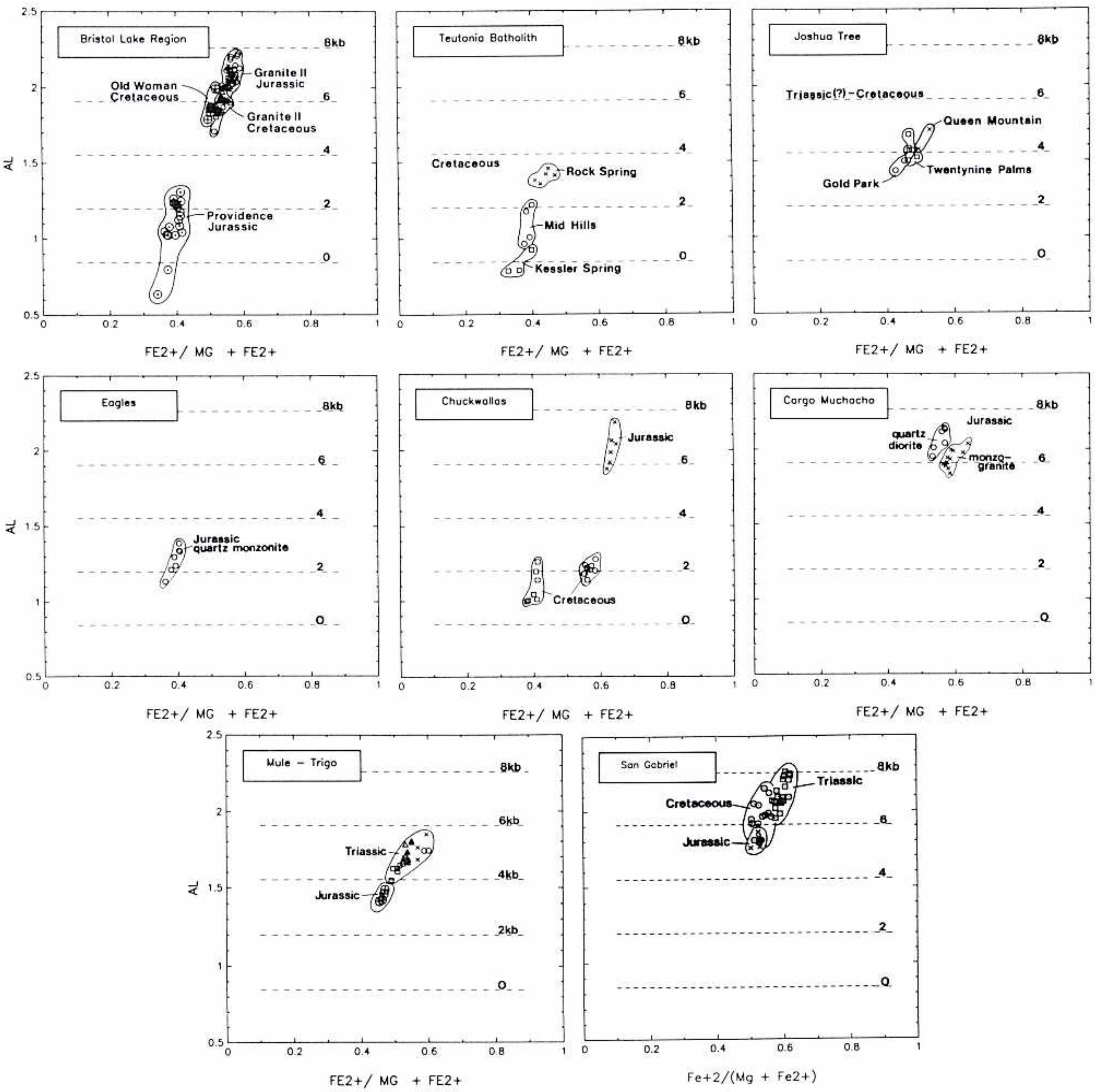

Figure 8. Composite of hornblende rim chemisty and barometry for eight areas of the Mojave Desert and the Tujunga terrane. Sources of data include Anderson and others (1988a), Young and Wooden (1988), Barth and others (1988), Farber and Davis (1989), and Hayes (1989). Al = total aluminum atoms per 23 oxygens and isobars from the calibration of Hollister and others (1987).

intrusion is composed of leucocratic biotite and diorite and monzodiorite. Like the similar-aged plutons of the craton, the Mount Lowe is metaluminous, low in silica, and enriched in alkalis, Ba, and Sr (>1000 ppm in the more primitive members). The main differences from those described above include lower K (**Figure 7**) and higher Na (to >7 wt %); some of the more evolved rock types could be trondhjemitic except for their low SiO_2. Once again, there is the unusual (with respect to this portion of the Cordillera) occurrence of calcic garnet (≤45 mole % grossular + andradite) + hornblende. Barth and Ehlig (1988) have independently, but for the same general reasons given in Miller (1978), suggested an eclogite-melting model for the origin of the magmatic suite.

One of the most striking findings of Barth's ongoing study has been documentation that the Lowe and all younger phases of Mesozoic plutonism in the San Gabriel Mountains were emplaced in the middle crust. Calculated pressures range from 5.5 to 6.6 kb (**Figure 8**), consistent with several attributes of deep-seated crystallization, including markedly aluminous hornblende (to >11% Al_2O_3), calcic grarnet, magmatic epidote, and siliceous primary muscovite (in Cretaceous granites). In contrast, the offset exposures of the Lowe east of the San Andreas fault record shallower levels of emplacement at ≈5-6 kb in the Little Chuckwalla Mountains (Farber and Davis, 1989) and 4-5 kb in the Mule Mountains (Barth and others, 1988). In this region, the Lowe complex resides above the Red Cloud and Mule Mountains thrusts, implying that prior to San Andreas disruption, these faults detached the upper portions of an intrusion that once vertically occupied some 6-10 km of crust.

Jurassic Plutonism

By Middle Jurassic time, magmatic arc construction in the southern Cordillera and in the Tujunga terrane became a major feature of the orogen. **Figure 1** depicts the regional extent of the event broadly dated at 180-155 Ma, plus a minor pulse at 145 Ma (John, 1981; Powell, 1981; D. M. Miller and others, 1982; Allen and others, 1983; Tosdal and others, 1989; Young and Wooden, 1988). Magmatism here is part of a well-defined arc trending southeast from the Klamath Mountains and northern Sierras into the White-Inyo Mountains and extending south across the Mojave Desert region into southern Arizona and Sonora. The Jurassic plutons throughout the area shown in **Figure 1** comprise a compositionally expanded suite with silica contents that vary continuously (48-76 wt %). Rocks from all areas are predominantly metaluminous and range from hornblende-clinopyroxene gabbro and diorite to biotite-hornblende quartz monzodiorite, quartz monzonite, and biotite sphene monzogranite or syenogranite. The granitic rocks are commonly coarse grained and seriate to porphyritic with large, lavender-colored alkali feldspar phenocrysts. Like the Triassic suite, the Jurassic plutons have high Ba and alkalis, modest levels of SiO_2, and intermediate Fe/Mg ratios (data largely straddle the calcalkaline/tholeiitic boundary of Miyashiro, 1974). A major difference is lower Sr, usually <700 ppm.

Although the data show considerable overlap, some distinction can be made between plutons of the Tujunga relative to those of the adjacent Mojave Desert. A few Tujunga plutons, such as those of the Cargo Muchacho Mountains (Hayes, 1989), have lower K, total alkalis, and Fe/Mg ratios, but others in the Chocolate, Chuckwalla, and Eagle Mountains (Tosdal and others, 1987; Farber and Davis, 1989; Johnson, in prep.) are as potassic and iron-rich as those of the Mojave Desert region (**Figure 7**). In terms of age, the Jurassic magmatic suite is compositionally distinct and, despite differences noted, we see minimal contrast between plutons of the Tujunga terrane and those of the Mojave Desert region.

A key feature of the Jurassic magmatic event is emplacement of the Independence dike swarm (Moore and Hopson, 1961). Dated at 148 Ma in the Sierras (Chen and Moore, 1979), this north-trending swarm varies from diabase through dacite and rhyolite and can be traced semi-continuously into the western Mojave and the eastern Tranverse Ranges, including the San Gabriel, Eagle, and Chuckwalla Mountains portion of the Tujunga terrane (Powell, 1981; Karish and others, 1987; James, 1989; Barth, 1990). The swarm post-dates all of the Jurassic plutons described above but is intruded by younger Cretaceous plutons. As noted by James (1989), and important to the goals of this study, is the observation that correlative Independence dikes can be followed along strike across the inferred Tujunga-North American terrane boundary.

Thermobarometric estimates of emplacement conditions (all from hornblende barometry using the calibration of Hollister and others, 1987) show a surprising variation (**Figure 8**) because we expected most of the intrusive centers to be shallow. That prejudgment came from the fact that several plutons intrude Jurassic volcanic or unmetamorphosed Paleozoic sections, including complexes in the Providence, Marble, Bristol, and Eagle Mountains. These specific plutons, in fact, yield shallow (2-3 kb) emplacement barometric determinations consistent with their geologic setting. Other shallow intrusions occur in the Chuckwalla (2-3 kb for plutons with U-Pb ages <169 Ma) and the Mule and Trigo Mountains (3-4 kb). Yet, three deep-seated Jurassic complexes are identified — specifically the Granite II (south of the Teutonia batholith, **Figure 1**), the Chuckwalla Mountains (the oldest Jurassic pluton in that range, with a U-Pb age of ≈169 Ma), and the Cargo Muchacho Mountains — all yielding crystallization pressures of 6-7 kb. These results have recently been described by Anderson and others (1988a), Barth and others (1988), Young and Wooden (1988), Farber and Davis (1989), Davis and Farber (1989), and Hayes (1989).

Cretaceous Plutonism

After an extended magmatic lull, extensive igneous activity resumed during the Late Cretaceous in both the Tujunga terrane and the Mojave region, beginning at ≈95 Ma and reaching a peak at 72-80 Ma (Carter and Silver, 1972; Miller and others, 1982; Beckerman and others, 1982; Wright and others, 1986; Wright and others, 1987). The composition and geologic setting of several Cretaceous intrusive complexes in the Mojave Desert have been well documented: *(1)* the Joshua Tree National Monument (Brand and Anderson, 1982; Brand, 1985; Anderson and others, 1988a); *(2)* the Cadiz Valley batholith (John, 1981; D. Miller and others, 1981, 1982; Howard and others, 1982; Calzia, 1982; Howard and John, 1984; D. Miller and Howard, 1985; Anderson, 1988); *(3)* the Old Woman-Piute Range (Miller and others, 1982; Young and Miller, 1983; Foster and others, 1989; Young and Miller, 1989); *(4)* the Teutonia batholith (Beckerman and others, 1982; Anderson and others, 1988a); *(5)* the Chemehuevi Mountains core complex (John, 1982, 1987; John and Wooden, 1989; Howard and others, 1987); and *(6)* the Whipple Mountains core complex (Davis and others, 1980; Anderson and Rowley, 1981; Anderson, 1985; Anderson and others, 1988a, b; Anderson, 1988; Anderson and Cullers, 1990).

Compositionally and by rock type, the Mojave Cretaceous suites are unlike those of the early and middle Mesozoic. None are alkalic, the K_2O abundance is lower, and most plutons are relatively silicic (>66 wt. % S_iO_2) and calcalkaline (**Figure 7**). Being within the inner peraluminous belt of Miller and Bradfish (1984), two-mica granites are common, as are metaluminous hornblende-biotite-sphene granodiorites. Geochemically and isotopically, most appear to have been derived from melting of older crust (Miller, 1985; Wooden and Stacey, 1987; Miller and others, 1990),. Exception are the plutons of the Whipple core complex (Anderson and Cullers, 1990).

Cretaceous plutons in the Tujunga terrane are also widespread. Powell (1981) defined a belt of Cretaceous granitic plutons in the Hexie, Eagle, Chuckwalla, and Little Chuckwalla Mountains. Correlative plutons also occur in the Orocopia Mountains (Anderson, unpublished data). In the San Gabriel Mountains, Carter and Silver (1972) reported an 80±10 Ma age for the Mt. Josephine intrusion, and petrographically similar plutons include the Mt. Wilson, Mt. Waterman, and Vetter Mountain of the same range (Barth and others, 1989). These intrusive complexes show strong compositional similarity to the Cretaceous plutons of the Mojave (**Figure 7**). If the Tujunga terrane is far traveled, ≈1000 km, and was sutured to North America in the early Tertiary (Vedder and others, 1983), then some difference in composition of the Mesozoic suites would be expected. However, no differences are evident amongst the Cretaceous plutons.

Depths of emplacement of Cretaceous plutons were derived from a variety of thermobarometers. Unlike those of Jurassic age, many of these Cretaceous complexes are deep seated (**Figure 8**). Mid-crustal intrusions (depths of emplacement >20 km) reside in the San Gabriel, Old Woman, Granite II, Chemehuevi, and Whipple Mountains. Upper crustal intrusions are identified in the Teutonia and Cadiz Valley batholiths, the Chuckwalla Mountains, and the Sacramento Mountains core complex (Anderson and others, 1988a; Young and Wooden, 1988; John and Wooden, 1989).

A major compositional difference among Cretaceous plutons is seemingly related to depth of emplacement. Shallow-emplaced (<12 km) complexes tend to be fundamentally granitic and often leucocratic, whereas deeper Mesozoic plutons in both areas (Tujunga and craton) tend to be more mafic, including metaluminous diorite to quartz diorite and marginally metaluminous to calcic peraluminous tonalite and granodiorite. Exceptions occur (*e.g.*, Old Woman Mountains), but this generalization may extend to older elements of the orogen as well. For example, deeper portions of the Tujunga terrane also contain the more mafic components of the Triassic Lowe intrusion and Proterozoic anorthosite and leucogabbro. The implication is that a fundamental contrast existed between the upper (<15 km) and middle (15-27 km) portions of the crust in this region of the Cordillera. Although most of the upper crust intrusives appear to have been derived from crustal sources, plutonism in the deeper complexes is more varied in origin, including crust-derived two-mica granitoids of the Old Woman Mountains, mixed oceanic/continental crust-derived plutons of the Whipple Mountains, and mantle-derived Lowe intrusion of the Tujunga terrane.

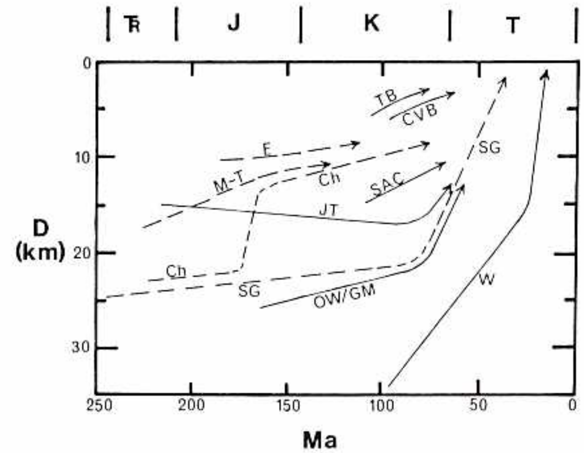

Figure 9. Crustal depth history of southern California based on barometry of plutonic emplacement and deformational events. Tujunga terrane complexes (dashed paths) include those exposed in the San Gabriel (SG), Chuckwall (Ch), Mule and Trigo (M-T), and Eagle (E) Mountins. North American complexes (solid paths) include Whipple (W), Old Woman and Granite II (OW/GM), and Sacramento (SAC) Mountains, Joshua Tree National Monument (JT), and the Cadiz Valley (CVB) and Teutonia (TB) batholiths. The sharp bend in the Chuckwalla path represents change in determined crustal level relative to pre- and post-late Red Cloud thrusting. From Anderson and others (1988a), Young and Wooden (1988), Barth and others (1988), and Farber and Davis (1989).

CONCLUSIONS

The primary results of this study are *(1)* assessment of fundamental differences in magmatic arc construction of Early Proterozoic age through Mesozoic arc magmatism at upper and mid-crustal levels, and *(2)* constraints on the timing and nature of the accretionary history of the southern Cordillera.

Crustal Depth History

The above sections have delineated the relative barometric evidence we have collected from a number of ranges. **Figure 9** is a composite of all data; depth was calculated from derived pressures with an assumed geobarometric gradient (from average crustal density) of 3.7 km/kb. For some ranges (Eagle, Sacramento, Joshua Tree), we used a "best guess" crystallization age; all others are from U-Pb (zircon) geochronology and those paths are fairly well constrained. Evident is a broad range of exposed crustal depth for both Tujunga and native complexes. Although preliminary, two levels of crust were sampled in this study. Shallow intrusive centers (< 12 km) include the Teutonia and Cadiz Valley batholiths, the Sacramento core complex, plutons of the Eagle, Mule, and Trigo Mountains, and younger members of the Chuckwalla plutonic complex. The granites of the Joshua Tree Monument appear to have been emplaced at moderate depths (≈12-16 km). Deep-seated, middle crust appears to have developed in two contrasting tectonic regimes — the lower plate of core complexes (the Whipple Mountains), and basement-cored thrust complexes (Old Woman, Granite II, San Gabriel, Cargo Muchacho, and Chuckwalla Mountains). The abrupt change for the Chuckwalla path is constrained by deep emplacement barometry of a syn-Red Cloud thrust (≈159 Ma) pluton and shallow barometry for post-thrust, Jurassic (<159 Ma) and Cretaceous plutons, implying that the thrusting event involved upward ascent of 8-10 km of crust.

Some of these deeper crustal sections may have originated in the middle crust, including the Tujunga terrane. Proterozoic (1.2 Ga) anorthosite and charnockite and Triassic to Late Cretaceous granitic intrusives characterize the "allochthonous" complex which, in part, resided at depths >25 km during all of the Mesozoic (if not since the Proterozoic). Uplift commenced after early Tertiary underthrusting of oceanic lithosphere and/or accretion to North

America. In contrast, the Old Woman path must be part of a protracted depth-time loop. Originating at surface conditions during the Paleozoic, the Old Woman crustal and supracrustal sections were tectonically buried to depths >20 km by 74 Ma, as recorded by conditions of intrusion of granitic plutons coeval with high-grade regional metamorphism (Miller and others, 1982; Young and Wooden, 1988). Rapid uplift occurred during the latest Cretaceous (Miller and others, 1990; Foster and others, 1989). We have yet to understand the tectonic mechanism leading to the uplift.

Allochthoneity of the Tujunga Terrane: A Native Terrane Model

A central objective of this study has been to evaluate the degree of allochthoneity of the Tujunga/San Gabriel terrane. If the terrane was far traveled, then marked differences in crustal history with respect to native portions of the craton are anticipated up to the time of accretion. Yet, instead of differences, we observe a striking similarity. The Cretaceous plutons are equivalent in being calcalkaline and containing both metaluminous and peraluminous members. The Independence dike swarm has been traced >500 km into the Tujunga terrane (James, 1989). The Jurassic suite exhibits minor differences but has compositional affinity in being largely metaluminous, high to ultra high K, with modest silica and Sr abundances. We are also impressed by the similarity of pre-Jurassic history. The Triassic Lowe intrusion exposed in the San Gabriel, Mule, and Trigo Mountains is markedly sodic but otherwise maintains the low silica, high alkali and Sr (>1000 ppm), and mineralogic character of similar-aged intrusions in the Granite I and San Bernardino Mountains of autochthonous North America (Barth and Ehlig, 1988; Barth, 1990; Miller, 1977). Both have been explained as the result of melting of an LILE-enriched eclogitic source. Finally, Bender (1989) demonstrated *(1)* that the Early Proterozoic, ≈1.7 Ga, plutons of the Mojave region are unusal (with respect to the remainder of the craton) in lacking calcalkaline members and being solely comprised of A-type granitoids, and *(2)* that the same type of plutons also occur in abundance in the Tujunga terrane.

The principal difference between Tujunga and the craton resides in their Middle Proterozoic history. The data of Silver and others (1963) for a 1.4 Ga granulite event in the Tujunga terrane has never been published. It remains unclear whether the age represents a granulite-grade orogenic episode or magma-crust interaction event, such as one related to derivation of the anorogenic 1.4 Ga plutons common to the craton. The occurrence of the 1.2 Ga anorthosite-charnockite in the Tujunga terrane is certainly unique. Yet, the single largest exposure of the complex occurs in the San Gabriel Mountains, which resided in the middle crust throughout the Mesozoic if not since the Proterozoic.

In conclusion, we suggest that the "suspect" nature of the Tujunga terrane is due to derivation from deep crust and see no reason for the terrane to be far traveled relative to native portions of the southwestern United States. Because the Cordillera, like most orogenic belts, has along-strike continuity of major lithotectonic units, strike-slip faulting could lead to intra-arc displacement and juxtaposition of lithologically similar terranes. Thus, we cannot rule out that Tujunga originated elsewhere in the Cordilleran orogen and may have travelled hundreds of kilometers. Yet, great transport on the scale of thousands of kilometers (Vedder and others, 1983) and an extra-Cordilleran origin for Tujunga appear improbable.

Figure 10 proposes a native terrane model for Tujunga at 60 Ma. Three subterranes are defined:

- a southern subterrane (San Gabriel Mountains) of mid-crustal origin at 20-25 km;
- a middle subterrane (Chuckwalla to Mule/Trigo Mountains region) that also originated at mid-crustal depths but, by the latest Cretaceous, was at 5-15 km; and
- a northern subterrane, representing the mid-crustal Old Woman/Piute Mountains, containing Late Cretaceous, west-directed thrust faults structurally overlain by supracrustal sections of the Providence and Marble Mountains.

The variable crustal levels now exposed within Tujunga are shown in the model to have been successively juxtaposed by early Red Cloud (ERCT), late Red Cloud (LRCT), Mule Mountains (MMT), and Vincent-Chocolate Mountains (VCMT) thrust faults.

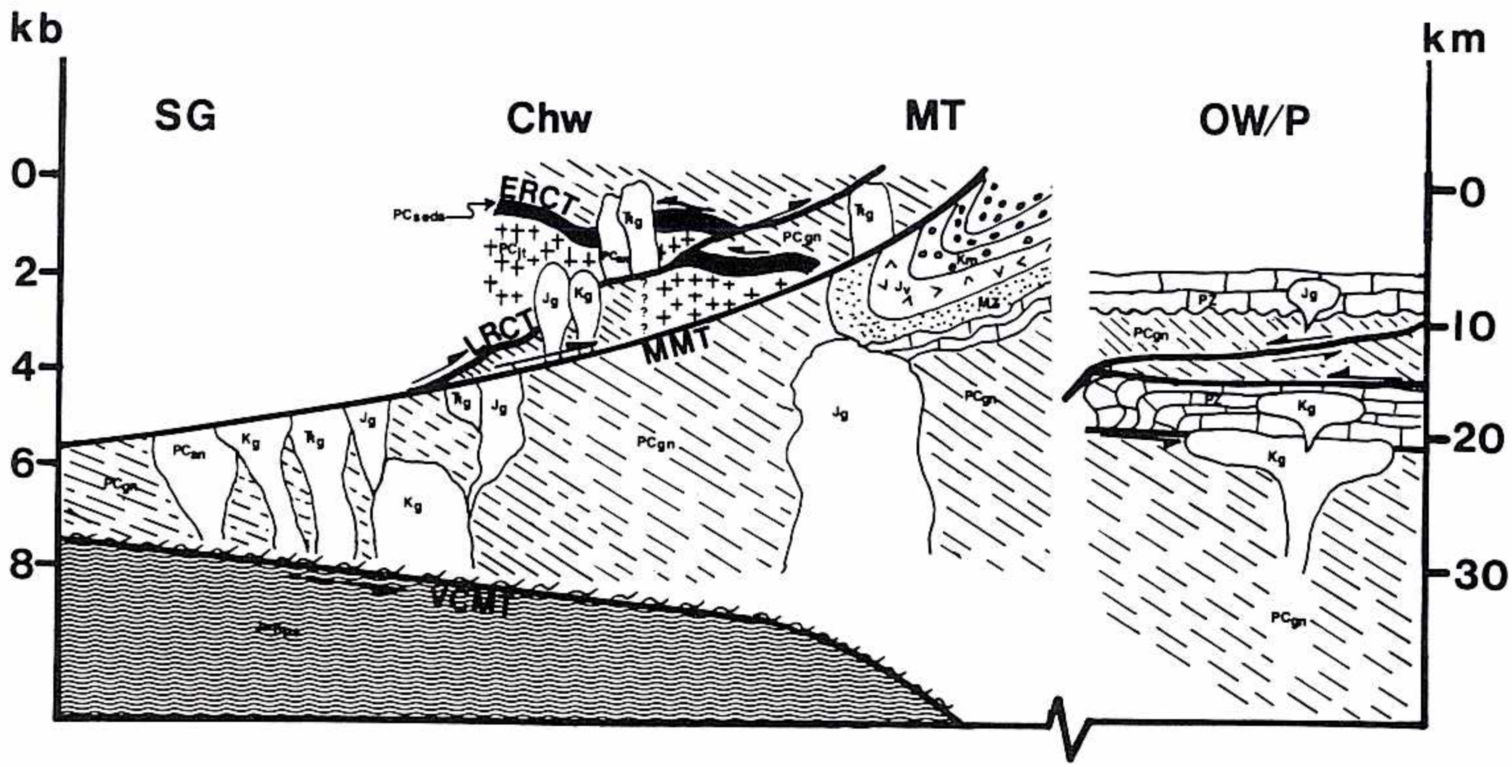

Figure 10. Model cross section at 60 Ma, showing the relative crustal levels exposed in the San Gabriel (SG), Chuckwalla (Chw), Mule-Trigo (MT), and Old Woman/Piute (OW/P) Mountains due to disruption of crust by the Vincent/Chocolate Mountains (VCMT), Mule Mountains (MMT), late Red Cloud (LRCT), and early Red Cloud (ERCT) thrust faults. The composite section is shown to be in partial structural contact with the underlying Pelona/Orocopia schist (JKps) across the Vincent/Chocolate Mountains thrust fault. Unit symbols: PCgn, Proterozoic gneiss; PCan, Proterozoic anorthosite and syenite; PCjt, Proterozoic Joshua Tree terrane gneisses; PCseds, Proterozoic strata; Pz, Paleozoic strata; TRg, Triassic Lowe intusion; JRg, Jurassic granites; Mz, older Mesozoic strata; Jv, Jurassic volcanics; Km, McCoy Formation; Kg, Cretaceous granites.

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