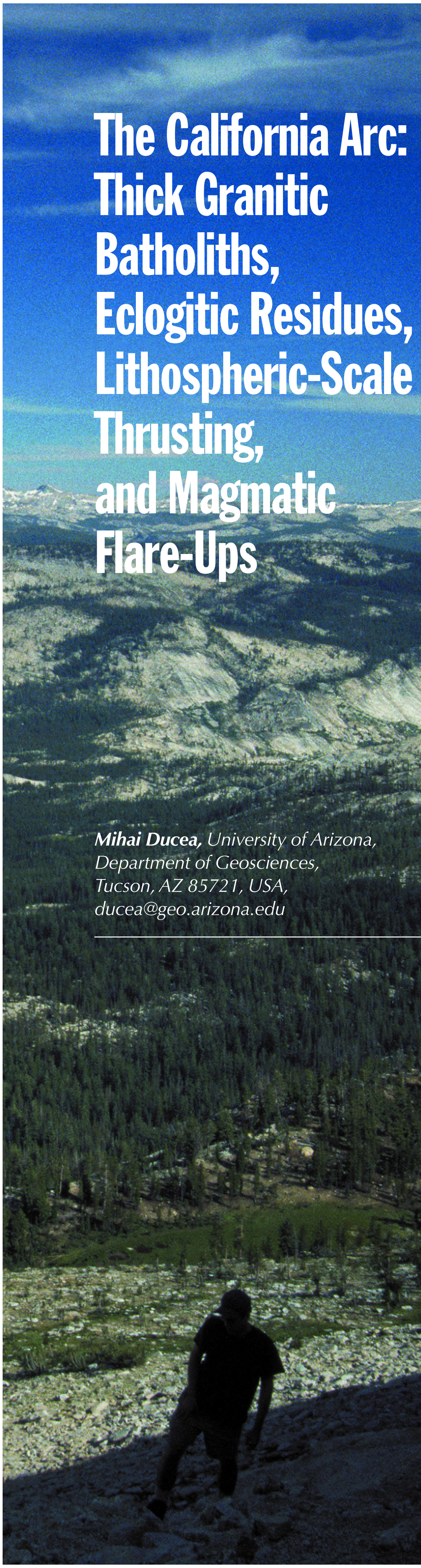

The California Arc: Thick Granitic Batholiths, Eclogitic Residues, Lithospheric-Scale Thrusting, and Magmatic Flare-Ups

Mihai Ducea, *University of Arizona, Department of Geosciences, Tucson, AZ 85721, USA, ducea@geo.arizona.edu*

ABSTRACT

Recent geological and geophysical data show that a significant fraction of the crust (~33 km) in the central Sierra Nevada batholith is granitic, requiring that the batholith be underlain by a significant residual mass prior to Cenozoic extension. Although batholith residua are commonly thought to be granulites, xenolith data indicate that eclogite facies residues were an important part of the California arc at depth. The arc was continuously active for >140 m.y., yet most surface and/or shallow crustal magmatism took place via two short-lived episodes: one in the Late Jurassic (160–150 Ma), and a second, more voluminous one in the Late Cretaceous (100–85 Ma). These magmatic flare-ups cannot be explained solely by increases in convergence rates and magmatic additions from the mantle. Isotopic data on xenoliths and midcrustal exposures suggest that North American lower crustal and lithospheric mantle was underthrusted beneath accreted rocks in the arc area. The Late Cretaceous flare-up is proposed to be the result of this major west dipping–lithospheric scale thrusting, an event that preceded flare-up by ~15–25 m.y. I suggest that the central part of the arc shut off at ~80 Ma because the source became melt-drained and not because of refrigeration from a shallowly subducting slab.

INTRODUCTION

Cordilleran batholiths are extensive belts of intermediate calc-alkalic plutons that formed above subduction zones. Understanding the petrology and tectonic framework of these granitic batholiths has stirred great geologic controversies and continues to pose several major problems in modern geology, such as quantifying the rates and processes of crustal growth versus recycling in arc environments (e.g., Hamilton, 1988). One of our major limitations in deciphering large-scale arc magmatic features is the limited knowledge of their vertical dimension. How deep do they extend, what is their composition at depth, and how thick is the crust beneath arcs? How much of the crustal thickening is tectonic versus magmatic? Are batholiths riding on major thrust faults or emplaced along major strike-slip faults? Is magmatism in major arcs steady state, and how do magmatic rates correlate with plate convergence rates?

Mesozoic arc rocks of the western North American Cordillera (Anderson, 1990) are exposed throughout California (Fig. 1) and once formed a continuous belt that has since been dismembered by Cenozoic tectonism. This paper presents an updated view on the composition, structure, and tectonic evolution of the magmatic arc of California.

SETTING

The California arc formed as a product of the prolonged subduction of ocean floor beneath the southwestern edge of the North America plate (Dickinson, 1981). The arc was active between 220

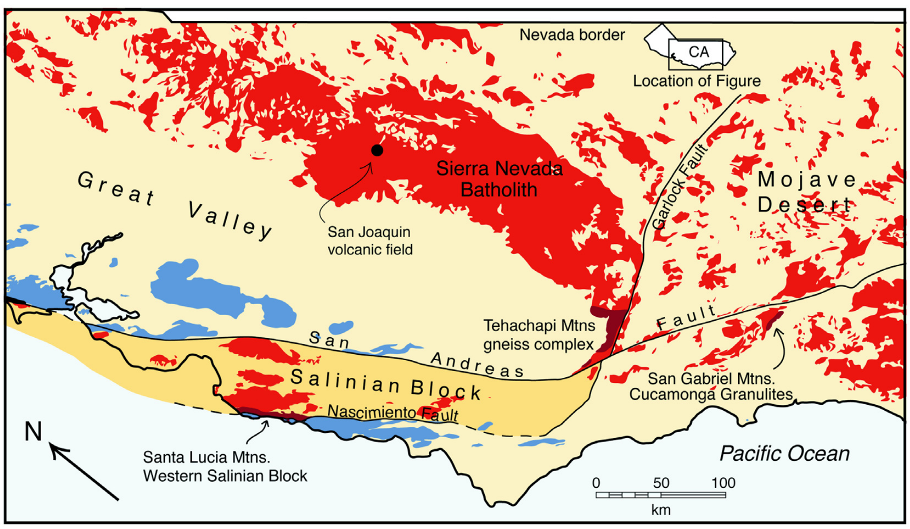

Figure 1. Map of central and southern California (after Jennings, 1977) showing geologic features discussed in text. Mesozoic granitic and related metamorphic rocks are in red. In blue are mainly Jurassic Franciscan formation rocks. Darker red areas show location of Mesozoic arc-related amphibolite-granulite terrains.

and 80 Ma. The igneous crystallization depths of the presently exposed rocks vary from 0 to ~30 km (Ague and Brimhall, 1988; Saleeby, 1990). Together, the segments of the California arc generated ~0.7 million km^3 of granitic material. Figure 1 shows three key features that, together, provide information on the nature of the crust beneath the arc.

1. The granitoid plutons are mostly upper crustal exposures of tonalites and granodiorites, with only minor (<3% of exposed rocks) mafic intrusions. The central and southern Sierra Nevada batholith represents the main and most studied part of the arc and consists of >90% magmatic products.
2. Three deeper crustal exposures of the arc—the western Salinian block (Compton, 1960), the Tehachapi complex, southernmost Sierra Nevada (Ross, 1985), and the Cucamonga complex in the San Gabriel Mountains (Barth and May, 1992)—expose midcrustal plutons and upper amphibolite to granulite facies framework rocks that equilibrated at as much as ~30 km beneath the arc.
3. Miocene volcanic rocks from the central Sierra Nevada in the San Joaquin volcanic field (Fig. 1; Dodge et al., 1986) host xenoliths representing samples of the deepest crust and upper mantle beneath the batholith.

A VERY THICK (30–35 km) GRANITIC BATHOLITH

In two classic papers, Bateman and Wahrhaftig (1966) argued for and Hamilton and Myers (1967) argued against thick granitoids underlying the currently exposed Sierra Nevada batholith. Various geophysical data such as gravity, heat flow, and various seismic results have not been able to resolve this controversy convincingly.

We now have two lines of evidence that argue strongly for a significant (35 km) thickness of granitoids (rocks that have >60% SiO_2) in the California arc. First, a recent seismic refraction study carried out across the Sierra Nevada shows that crustal rocks have V_p of 6–6.3 km/s throughout the ~33 km of seismologically defined crust, and are underlain by mantle peridotite (Fliedner and Ruppert, 1996). On this evidence, Fliedner et al. (2000) concluded that tonalites and granodiorites extend to the deep crust in the southern Sierra Nevada. Second, the three exposed sections of the midcrustal arc rocks have intermediate compositions and are dominated by Mesozoic igneous and meta-igneous rocks. The southern Sierra Nevada is particularly important because it represents a tilted exposure through the batholith showing that arc-related granitoids dominate the shallow to ~30-km-deep section of the crust. The bulk chemistry of these deeper exposures corresponds to a low-silica tonalite (Saleeby, 1990).

This evidence suggests that ~25–30 km of the present-day Sierra Nevada crust comprises rocks that are mainly granitoids. Adding the average erosion depth of ~6 km in the Sierra Nevada (Ague and Brimhall, 1988) to the estimates from seismic data, one can conclude that the batholith must have been ~30–35 km thick. The calculated batholith thickness has important implications for the composition of the deeper arc crust. Calc-alkaline intermediate rocks cannot be directly extracted by mantle melting (Wyllie, 1984), thus requiring a second stage of fractionation or partial melting of mantle-derived rocks and significant crustal residues. If melting of the downgoing oceanic crust (Drummond and Defant, 1990) was responsible for arc magmas in California, the residue could have been "disposed of" via subduction. However, the negative ε_{Nd} values of most California arc magmas (published values range between +5 and −12 with an average of ~–6) are incompatible with such a model because the oceanic lithosphere has a fairly constant ε_{Nd} of ~+10. Therefore, most of the second-stage melting and/or fractionation and generation of a residue must have taken place in the lower lithosphere beneath the arc in a complex transition from lower crust to upper mantle located on thickened continental crust (Hildreth and Moorbath, 1988). The residual mass could be (1) a restite (i.e., the solid left after partial melting and extraction of melt from the deep crust), (2) a cumulate (i.e., resulting from crystal fractionation in deep-seated magma chambers), or (3) both. In this paper, the nongenetic term residue is used to include restite and cumulate.

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Simple mass balance calculations using major elements indicate that the ratio of residue to melt in an arc column is ~1 to 2 if the bulk material is basaltic or andesitic (Ducea, 1998). Thus, accepting a granitoid thickness of 30–35 km and assuming a 40 km depth for the transition from granulitic to eclogitic residues (Wolf and Wyllie, 1993), there may have been 30–50 km of eclogite facies residues beneath the batholith, depending on the bulk chemistry of the system.

RESIDUE BENEATH THE BATHOLITH

Exposed Deeper Crust

The three midcrustal arc exposures in California consist of deformed sequences of metamorphosed intrusions interspersed with a commonly migmatized metasedimentary framework, all of which are intruded by younger, weakly deformed, or undeformed plutons. Cretaceous U-Pb zircon ages (e.g., Mattinson and James, 1986; Sams and Saleeby, 1988) indicate that the metamorphism and magmatism in these exposures is Cordilleran arc–related. The metamorphosed framework consists of mostly upper amphibolite and subordinate granulite facies rocks that record peak pressures of 7–9 kbar (Pickett and Saleeby, 1993; Barth and May, 1992; Compton, 1960). The rocks are heavily foliated, lineated, and partly migmatized. The intimate spatial association of amphibolite and granulite facies rocks is thought to reflect dehydration melting reactions of amphibolite protoliths (e.g., Hansen and Stuk, 1993). Several intrusions of large (>100 km^2), undeformed bodies of pyroxene tonalites and granodiorites crosscut the foliated framework. The mineral assemblages of the undeformed plutons indicate that they were emplaced at pressures similar to those recorded by the metamorphic assemblage. Significantly, although there is widespread evidence for migmatization, it appears

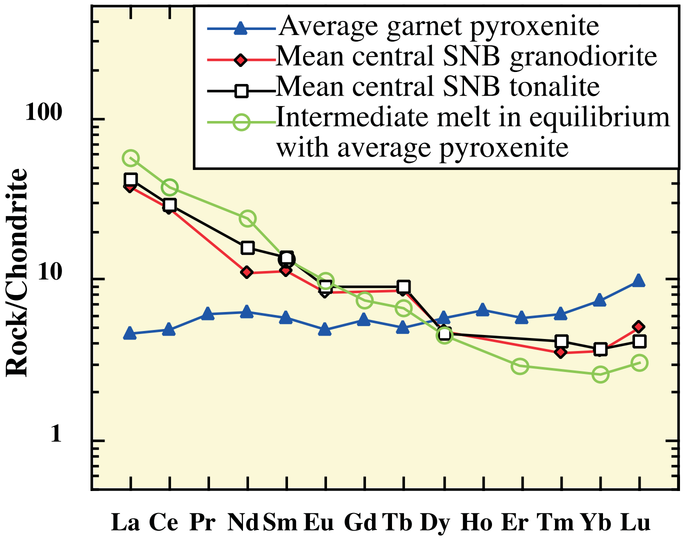

Figure 2. Chondrite-normalized rare earth element (REE) concentrations of intermediate melts in equilibrium with residue averaging garnet pyroxenite compositions. Average Sierran pyroxenite assumed to contain 50% clinopyroxene, 40% garnet, and 10% amphibole. Average REE compositions of surface granodiorites and tonalites in area (Dodge et al., 1982) shown for comparison. SNB—Sierra Nevada Batholith.

that these large plutons were generated at a deeper level, in the presence of a feldspar-poor residue, and that migmatite leucosome extraction was minimal.

U-Pb zircon geochronology indicates that dehydration melting in the section and the local formation of granulite facies rocks is coeval with the larger intrusions (90–100 Ma), and younger than the age of peak metamorphism (~115 Ma) (Mattinson and James, 1986; Pickett and Saleeby, 1994). Kinematic data indicate that deformation associated with the ~115 Ma amphibolite facies metamorphism is a result of ductile thrusting in the mid-crust (Compton, 1966).

Deepest Crust and the Upper Mantle: Xenoliths

San Joaquin volcanic field xenoliths comprise the following petrographic groups: (1) granulites, high-Al pyroxene- and feldspar-bearing rocks that equilibrated at depths between 30 and 35–45 km and are identical to the rocks exposed in the midcrustal exposures; (2) pyroxenites, garnet-bearing and feldspar-free rocks, which equilibrated at >35 km depth; (3) metasedimentary rocks (mostly quartzites and metapelites) with barometric record demonstrating residence in the deep crust (>40 km); and (4) peridotites, samples from the mantle lithosphere. The first three groups are lower crustal rocks and have mineral Sm-Nd ages of 80–120 Ma and initial Sr and Nd ratios consistent with an arc origin (Dodge et al., 1986; Ducea and Saleeby, 1998).

Garnet pyroxenites represent an eclogite facies suite that equilibrated at 10–30 kbar (Ducea and Saleeby, 1996). These rocks are never seen in Cordilleran crustal exposures and are oddities in any arc root terranes (they are found in the Jijal sequence of the Kohistan arc; Ringuette et al., 1999), but they are predicted by experiments to represent deep crustal (>10–15 kbar) residues of dehydration melting resulting in tonalitic melts (Rapp and Watson; 1995, Wolf and Wyllie, 1993). These rocks are interpreted here to be an important part of the lower crustal residue beneath the arc. This is based on the large range of equilibration pressures for the Sierran garnet pyroxenites, the great thickness of batholithic crust, and mass balance constraints calling for a thick residue and hence a significantly thickened crust during arc formation. Trace element patterns are consistent with the garnet pyroxenite xenoliths being batholith residues. The observed rare earth element compositions of Sierran garnet pyroxenites would have been in equilibrium with the average trace element concentrations observed in arc granitoids (tonalites and granodiorites) from the San Joaquin area (Fig. 2). This result suggests that arc granitoids formed via partial melting or fractional crystallization at deep-crustal and/or upper-mantle depths and differentiated primarily from a garnet-rich, plagioclase-poor "eclogitic" residue. These observations do not preclude some melt extraction from having taken place within the realm of a shallower, granulite facies residue.

THICKER ARC CRUST AND LITHOSPHERE IN THE MESOZOIC

The present crust beneath the Sierra Nevada is thin (33 km thick; Wernicke et al., 1996) and is probably an effect of Late Cenozoic extension and delamination in the area. Two xenolith observations suggest that the Mesozoic crust was at least ~70 km thick and the mantle lithosphere was at least 120 km thick.

1. Metasedimentary xenoliths found in the San Joaquin volcanic field are relatively fresh eclogite facies quartzites (i.e., the minor mafic phases present are mostly garnet and clinopyroxenes) that equilibrated at pressures in excess of 15 kbar. The deepest measured eclogite facies quartzite (P ≈ 25 kbar; Ducea and Saleeby, 1998) indicates that the Mesozoic subarc crust was at least 70 km thick. This rock has North American isotopic signatures and has a mineral Sm-Nd age of 85 Ma. However, it is possible that the deepest crust represents a complex transition from lower crustal (mostly mafic with minor metasedimentary lithologies) to mantle assemblages.

2. Garnet peridotite xenoliths with North American lithospheric isotopic signatures equilibrated as deep as ~120 km (Mukhopadhyay and Manton, 1994; Ducea and Saleeby, 1998). This indicates that the mantle lithosphere beneath the arc was significantly thicker in the Mesozoic than at present and that even after a decrease of the angle of subduction during the Laramide orogeny, the top of the oceanic slab was never shallower than ~120 km in the central Sierra Nevada.

These observations strengthen the argument that the Cretaceous arc must have had a thick crustal root consisting mostly of residues and/or cumulates of the granitoids that make up the California batholith. Figure 3 is a schematic column through the arc lithosphere summarizing the data presented above.

MULTIPLE DEEP SOURCES OF ARC MAGMAS

The San Joaquin xenoliths, together with the well-known granitoids exposed at the surface in the area (Dodge et al., 1982), are ideal to check for isotopic heterogeneities in a vertical dimension through the arc. The xenolith "column" is located on

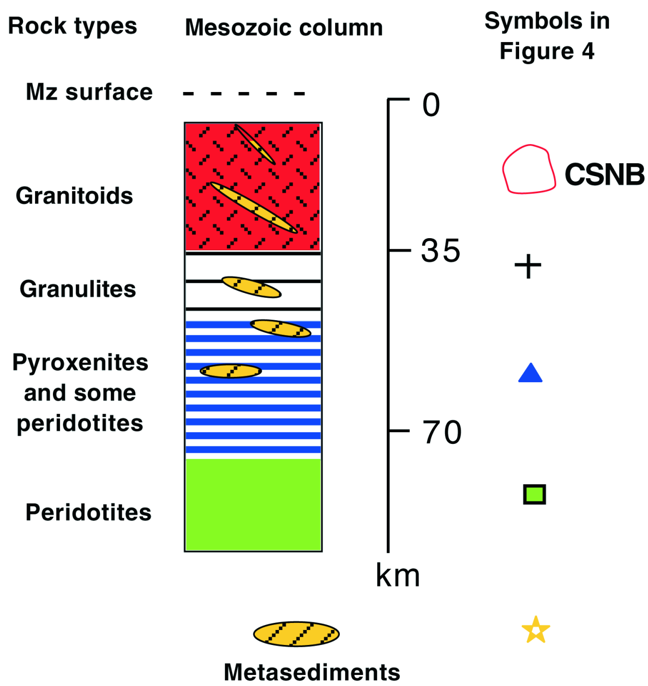

Figure 3. Simplified compositional column through California arc lithosphere, as constrained by surface exposures and xenolith data. Lower parts of lithospheric column may have changed significantly since the Miocene due to foundering of eclogite facies keel into mantle (Ducea and Saleeby, 1996). Symbols used in Figure 4 for samples with various compositions in lithospheric column also shown. CSNB—Cretaceous Sierra Nevada Batholith.

the axis of the composite Sierra Nevada batholith.

Two diagrams summarizing whole-rock Sr, Nd, and O isotopic measurements on these rocks indicate that vertical isotopic heterogeneities of the Sierra Nevada lithosphere are larger than the ones observed across the surface exposures of the entire batholith (Fig. 4). These data do not uniquely constrain the proportions of mantle versus crustal components in the arc (Miller et al., 1988), but help identify qualitatively three important end members that contribute to the isotopic heterogeneity of the batholith. These end members (S is sedimentary, C is old lower crustal, and M is young mantle [Fig. 4]) are treated as broad fields rather than points, given the likelihood of internal isotopic variability. End member S is characterized by high $\delta^{18}O$, $^{87}Sr/^{86}Sr_{100}$ (100 denotes that the radiogenic isotopes are age-corrected for 100 Ma) and relatively elevated $\varepsilon_{Nd\text{-}100}$. The $\delta^{18}O$ data indicate that end member S is represented by rocks that must have resided at or near the surface of Earth prior to their transport to lower crustal depths, and thus is most likely sedimentary or volcanic in origin. The xenoliths richer in this component are either high-Al basalts or silica-rich metasediments. End member C comprises mafic and ultramafic rocks, has $^{87}Sr/^{86}Sr_{100}$, $\varepsilon_{Nd\text{-}100}$, and $\delta^{18}O$ compatible with a Precambrian lower crustal and/or lithospheric mantle material (Taylor, 1988). The bulk chemistry of the garnet pyroxenites suggests that they are residual assemblages of the arc (Ducea and Saleeby, 1998). End member M is relatively elevated in $\varepsilon_{Nd\text{-}100}$ and has a low $\delta^{18}O$ (~6), typical for mantle-derived materials. The relatively elevated $\varepsilon_{Nd\text{-}100}$ suggests that this component may be derived from young mantle beneath the arc.

The isotopic signatures of the xenoliths refine Kistler's (1990) proposal that two distinct types of lithosphere exist beneath the Sierra Nevada: accreted oceanic lithosphere (Panthalassan) beneath the western batholith, and an eastern continental lithosphere (North American). Specifically, the end members S (and possibly M) and C dominate the signatures of the accreted and autochthonous North American lithospheres, respectively. The data indicate that the central Sierra Nevada granitoids are chemically complementary and isotopically similar to the garnet pyroxenites and are dominated by the end member C component (Ducea and Saleeby, 1998).

LITHOSPHERIC-SCALE THRUSTING OF NORTH AMERICA BENEATH THE ARC

The data shown in Figure 4 indicate that granulites are dominated by the end member S component, and the garnet pyroxenites are dominated by the end member C component, suggesting that Precambrian basement units of western North

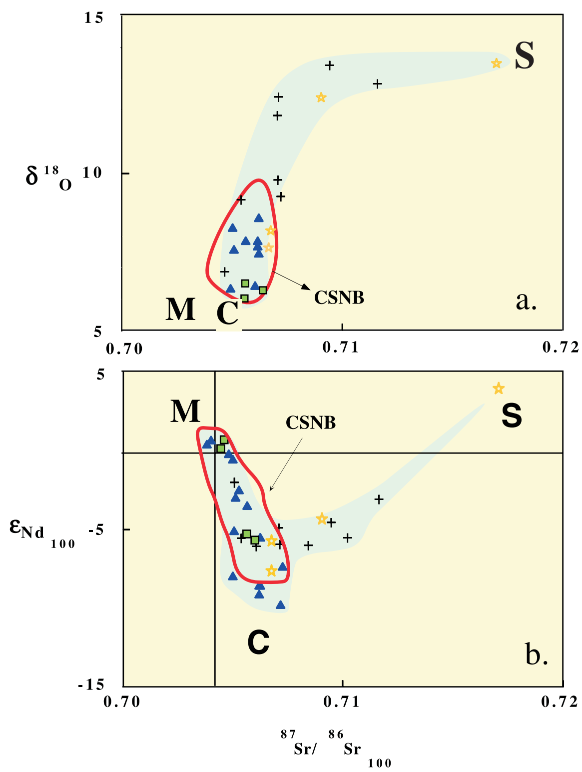

Figure 4. A: $^{87}Sr/^{86}Sr_{100}$ vs. $\delta^{18}O$ measured in lower crustal and upper mantle xenoliths from San Joaquin volcanic field. Trend defined by xenolith data shown as light blue field. Green squares—garnet peridotites; blue triangles—pyroxenites; crosses—granulites; brown stars—metasediments. End member C—old lower crustal; end member M—young mantle; end member S—sedimentary. **B:** $^{87}Sr/^{86}Sr_{100}$ vs. $\varepsilon_{Nd\text{-}100}$ in San Joaquin xenoliths. Symbols as in Figure 4A. Data taken from Masi et al. (1981); DePaolo (1981); Domenick et al. (1983); Dodge et al. (1986); Mukhopadhyay (1989); Mukhopadhyay and Manton (1994); Ducea (1998); Ducea and Saleeby (1998); and Clemens-Knott (1996). CSNB—Cretaceous Sierra Nevada Batholith.

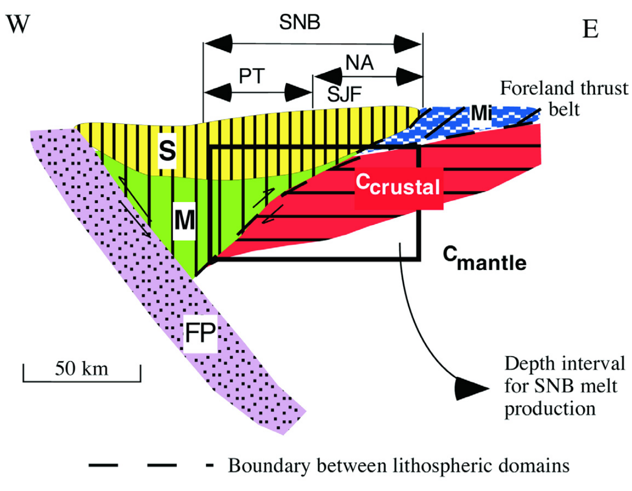

Figure 5. Schematic west-east interpretative cross section (vertical ~ horizontal scale) through Sierra Nevada lithosphere prior to generation of Cretaceous batholith. Approximate location of source region of Cretaceous Sierra Nevada batholith (SNB) is indicated, as well as Panthalassan (PT) and North American (NA) segments of batholith (Kistler, 1990). SJF marks the approximate location of San Joaquin xenolith probe in Sierra Nevada. Dark box delineates area that experienced partial melting during magmatic flare-up. Lithospheric domains: $C_{crustal}$—Precambrian lower crust; C_{mantle}—Precambrian enriched-mantle lithosphere; S—accreted crustal rocks; M—accreted mantle; Mi—miogeocline rocks; FP—the subducting Farallon plate.

America were underthrust beneath Mesozoic arc rocks with oceanic or continental margin affinity. The ~30-km-deep amphibolite and granulite facies basement from the Santa Lucia, Tehachapi, and San Gabriel areas is isotopically rich in end member S (e.g., Mattinson, 1978; Pickett and Saleeby, 1994; Barth et al., 1992), consistent with that interpretation. This process led to the significant crustal and lithospheric thickening of the Mesozoic arc. Figure 5 is a schematic cross section of the proposed prebatholithic domains involved in Mesozoic magmatism in the California arc region. The scenario envisioned is that arc magmas tap different proportions of the two lithospheres depending on their location. The western Sierra Nevada plutons represent mixtures between young accreted mantle (end member M) and corresponding supracrustal rocks (end member S), whereas the central and eastern Sierra Nevada isotopic signature is dominated by the Precambrian lower crust-lithospheric mantle (end member C), and overthrusted supracrustal rocks. The presence of the mantle slice of end member M shown in Figure 5 is constrained by the presence of a few spinel-bearing peridotites with the isotopic characteristics of this reservoir in the San Joaquin xenolith suites.

No sharp transition from one lithospheric type to the other is preserved in the isotopic record of the surface granitoids, questioning the commonly inferred near-vertical boundary between Panthalassa and North America along the $^{87}Sr/^{86}Sr = 0.706$ isopleth. The lithospheric-scale thrusting hypothesis can explain the smooth isotopic gradients measured in the surface granitoids across the arc. Thrusting was likely synchronous with the ductile deformation in the amphibolite to granulite facies frame-

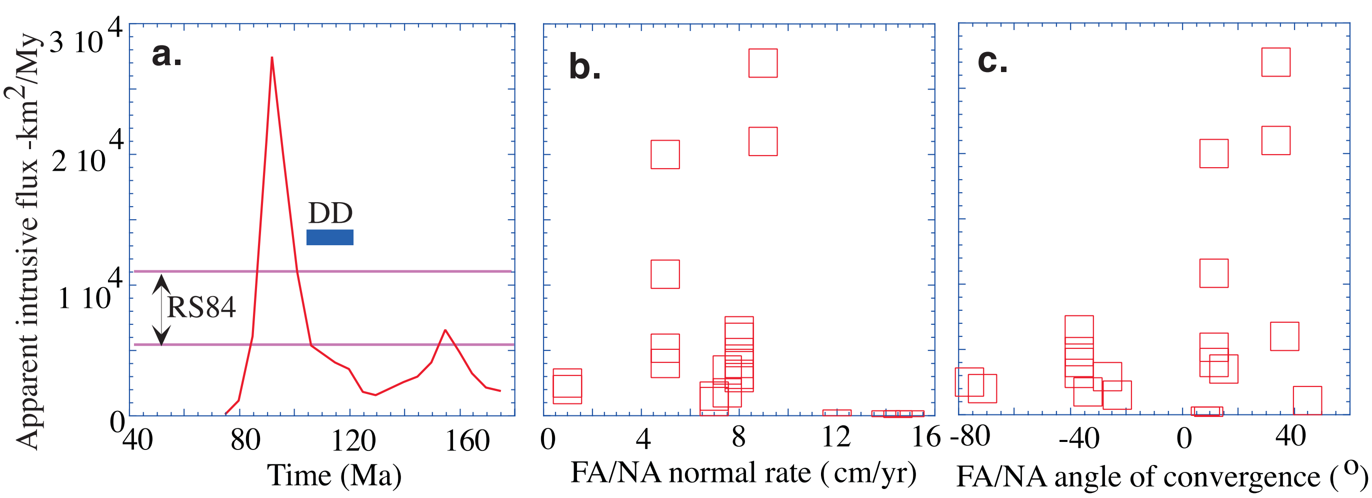

Figure 6. A: Plot of total California arc apparent intrusive flux (area of presently exposed plutonic rocks produced per units of time; in km^2/m.y.) vs. time of magmatism, using an updated version of CONTACT88 (Barton et al., 1988). About 600 plutons representing almost 65% of arc-exposed area have been included in database. Line labeled DD indicates period of ductile deformation in exposed mid-crust of arc and in granulite xenoliths. RS84 corresponds to magmatic addition rates in range of 20–40 km^3/km • m.y., typical of island arcs (Reymer and Schubert, 1984). Magmatic addition rate is defined as total volume of magma produced in an arc per unit of time scaled over length of arc, assuming an average granitoid thickness of 30 km for California arc. **B:** Plot of apparent intrusive flux vs. normal convergence rate between Farallon and North American plates in California (Page and Engebretson, 1985) for 5 m.y. intervals between 170 and 60 Ma. **C:** Plot of apparent intrusive flux vs. angle of convergence in degrees. Zero corresponds to normal convergence, positive angles reflect right-lateral motion, and negative angles represent left-lateral motion.

work in the middle crust. Ages of intrusive rocks that are concordant with the penetrative foliation as well as metamorphic peak ages known from the three exposed terranes all indicate that this ductile deformation lasted from ~125–103 Ma (Fig. 6A).

TWO SHORT (10–15 M.Y.) EPISODES OF VOLUMINOUS ARC MAGMATISM IN THE 140 M.Y. LIFE OF THE ARC

A database compiling ages, petrography, surface area, and exposure depths of dated plutons representing >60% of the surface area of the arc reveals that the arc was continuously but variably active between ~220 and 80 Ma. There are no correlations between depth of emplacement and ages or between latitude and ages, suggesting that plutons were more or less randomly emplaced in the exposed crustal section and that there was no along-strike migration of the arc with time. Figure 6A shows that the baseline apparent intrusive flux corresponds to a magmatic addition rate of ~10 $km^3/km \cdot m.y.$, and that arc magmatism was punctuated by two episodes of higher magmatic volume and emplacement rates (magmatic flare-ups), one in the Jurassic (160–150 Ma) and the second, more dramatic one in the Late Cretaceous (100–85 Ma). The Late Cretaceous (100–85 Ma) magmatic episode is particularly important: ~78% of the California arc magmatic volume was emplaced within only 15 m.y. with a magmatic addition rate as high as 85 $km^3/km \cdot m.y.$ All of the large (>1000 km^2) plutons found along the eastern Sierra Nevada crest are 100–85 m.y. old (Coleman and Glazner, 1998). Magmatic flare-ups similar to the Late Cretaceous one in the California arc are known from other regions in the Cordillera (e.g., Pitcher, 1993), indicating that non–steady state magmatism may be a general feature of large-scale granitic magmatism in continental arc areas.

The arcs are intimately associated with subduction, and thus it is reasonable to suspect that higher convergence rates may imply faster turnaround times in the corner-shaped mantle wedge, faster devolatilization of the downgoing slab, and hence higher melt production in the mantle wedge. Figure 6B shows, however, that there is no apparent correlation between the known convergence rates (Page and Engebretson, 1985) and the California arc's magmatic flux. In particular, the Late Cretaceous flare-up cannot be explained by the somewhat higher convergence rates at that time as compared to the 120–100 Ma period. Magmatism in the California arc also cannot be directly correlated to the angle of convergence of subduction (Fig. 6C). Without minimizing the role of subduction and subduction-related basaltic magmatism in the evolution of this long-lived continental arc, an additional conceptual model that can explain both the flare-up and subsequent demise of granitic magmatism is needed.

ARC FLARE-UP CAUSED BY THRUSTING

I propose that the major Cretaceous flare-up of magmatism in the California arc was a consequence of lithospheric-scale underthrusting of North America beneath the arc. The xenolith data provide firsthand evidence for large-scale imbrications beneath the arc. The exposed terranes document a datable metamorphic foliation that is indicative of shortening and that predates the Late Cretaceous magmatic flare-up by ~15–25 Ma. The delay between the peak of thrusting and the peak of lower lithosphere en masse magmatism might be a consequence of the relaxation time needed for the geotherms to rebound (and then continue to increase) after initial thrusting (Glazner and Bartley, 1985). Typical thermal relaxation times for a 35-km-thick thrust sheet with the characteristics of the California arc are 10–25 m.y. The details of how and why the deeper crust and the mantle lithosphere of the North American craton melted so profoundly at 100–85 Ma are not known, but clearly the cratonic lithosphere must have been very melt fertile, possibly because of an abundance in volatiles. The link between magmatism and deformation in arcs has been questioned for decades (e.g., Bateman and Wahrhaftig, 1966). However, studies of other segments of Cordilleran arcs where magmatism is thought to be intimately linked to shortening (e.g., Hollister and Crawford, 1986) typically, although not always, postulate that magmatism predates and triggers or enhances deformation in the middle to deep crust, in contrast to the hypothesis presented here.

This model does not negate the continuous additions of new water and melt from the mantle into the lower crust, but stresses the importance of intracrustal processes responsible for a major magmatic flare-up.

ARC SHUTDOWN DUE TO A MELT-DRAINED SOURCE REGION

Previous interpretations that call upon shallowing the subduction angle and inward migration of magmatism (Dickinson and Snyder, 1978) are undoubtedly correct at the scale of the western North American Cordillera. However, the data presented here refute the hypotheses that the top of the slab was subducted at depths as shallow as 35–60 km beneath the Sierra Nevada in early Cenozoic times (Dumitru, 1990), thus refrigerating the area and shutting the arc off. A mantle wedge continued to exist beneath the arc after its cessation at 80 Ma. The southern Sierra Nevada, in contrast, had been underthrusted by a shallow forearc sequence and probably a true shallowly subducting slab during the Late Cretaceous (Malin et al., 1995). With convergence rates accelerating toward the Laramide, the magmatic shutoff in the central Sierra Nevada can be better explained by the hypothesis that continental mantle lithosphere and lower crust were melt-drained and became infertile after the Late Cretaceous flare-up, rather than by refrigeration. Thermodynamic calculations using the algorithm MELTS (Ghiorso and Sack, 1995) suggest that garnet-rich pyroxenites with the compositions of the San Joaquin xenoliths can only produce nephelinitic and other exotic magmas in the presence of water and are virtually infertile as dry assemblages at crustal temperatures. Thus, once granitoids were extracted during the Late Cretaceous flare-up, such residual assemblages were fundamentally unable to generate more granitic melts, even after subsequent hydration.

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