Day 6: Overview of arc processes and tempos


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INTRODUCTION

Our goals today are several-fold. We have now spent five days examining different parts of the Mesozoic Sierran arc, and hopefully discussions are already under way attempting to integrate both the shared and distinct characteristics of these individual magma plumbing systems and synchronous tectonics. We will briefly continue these discussions below. Our main focus will be to consider the arc as a whole and introduce a number of new regional data sets related to the tectonic and magmatic components of this arc. By the end of the day, we hope that our discussions have evolved to a consideration of the overall petrologic evolution of the arc, the tectonic and magmatic arc tempos, and their potential links. Without an airplane, or satellite, or “Hollywood earth coring machine,” it is difficult to take you to field locations where we can observe large sections of the arc. Instead, as we travel west back across the arc, we have selected a number of scenic overview stops, where we will introduce and discuss these new data sets while looking at gorgeous views of the arc.

COMPARISONS OF PLUTONIC-VOLCANIC SYSTEMS

All of the individual magmatic systems seen in Days 1–5 grew incrementally, although with different pulse size and number, different growth durations, different volume addition rates (VARs) and resulting magma chamber sizes, and thus with different magnitudes of internal processes (e.g., mixing versus
fractionation). We can now continue our comparisons of these systems: for example, Figure 6-1 compares the absolute values and spreads of εNd-Sr isotopic values from these systems. The canonical Sr-Nd array has long been used to depict the broad mixing of depleted mantle and crustal end members in the Sierra (DePaolo, 1981), with intrusive suites in the eastern Sierra lying lower along the array as a result of greater proportions of aged crust and lithospheric mantle in their sources. The Sr-Nd array shows intriguing variations in the coherence or steepness of trends in individual intrusive complexes suggesting second-order controls influenced these isotopes, such as the extent of isotopic mixing or number of sources. Two domains of samples in the Fine Gold Intrusive Complex are separated and show change of slope between one another because of increased crustal input in the source of the younger eastern domain rocks (lower down on the array). Collectively, these data suggest a wealth of information remains to be learned from combined isotope approaches, including integrating new Hf data.

Another exciting direction to pursue, in cases where high-precision geochronology is available, is to more carefully examine the temporal changes in all aspects of these systems. For example one can now much more carefully evaluate the history of magmatic fabric formation or of temporal evolution of isotopic values in a single system. Figure 6-2 is one example of the latter showing εNd versus Sr isotopes from the Tuolumne Intrusive Complex, color coded by age. There is a clear temporal change in these isotopes—a pattern that we also see in several other plutons in other parts of the Mesozoic Cordilleran arc. In a later section, we can compare these temporal patterns to those seen at the arc scale. At Stop 4-4, we examined the temporal change of a variety of magmatic structures, and in a later section we will describe a third example of exciting information obtained from looking at temporal changes in magmatic fabric orientations. Also needed are detailed studies of temporal changes in host-rock displacement during incremental growth of magma chambers, which must include studies of how earlier parts of the plutonic systems are displaced during emplacement of younger pulses.

A further intriguing aspect of our comparison of individual intrusive suites seen on this trip is the highly variable degree to which outcrop-scale magmatic structures (e.g., Table 4-1 in Memeti et al., this volume) are formed. The Tuolumne Intrusive Complex is riddled with them, whereas the Guadalupe Intrusive Complex has very few. Why? Furthermore, although studies of many of these structures are in their infancy, they show great promise as tools to aid in gaining both a greater understanding of the petrologic evolution of plutons, the mechanical history of physical processes in evolving chambers, and temporal changes in the accompanying regional tectonics.

![Sr-Nd isotope array for the Sierra Nevada with fields showing locations of different intrusive complexes visited during the Field Forum and reference sets from other intrusive suites. Granitoid data from the North American volcanic and intrusive rock database (NAVDAT; www.navdat.org), unpublished data of the conveners, and from xenolith studies by Ducea (2001, 2002) and Mukhopadhyay and Manton (1994).](image-url)
A third fruitful direction of study is the expansion of single-mineral studies and a reevaluation of the previously established geochemical patterns based on whole-rock analyses. We have examined a number of new data sets (Hf in zircon, O in several minerals, major- and trace-element patterns in single minerals in the Tuolumne Intrusive Complex, and single-zircon age populations), which are compatible with complex incremental growth histories, but also draw attention to extensive mixing and internal recycling of minerals. These initial studies are the “tip of the iceberg,” and we suggest it is particularly important to better understand where and how this mineral mixing occurred and how widespread it is.

**BASEMENT UNITS**

One natural point of departure in moving away from single systems toward our arc-scale discussion is to revisit what are the likely basement terranes, including both the mantle and crustal components that this arc was built through. Potential mantle and deeper crustal components are best considered later with a discussion of geochemistry. Here, we begin by summarizing our study of presently exposed host-rock units. In collaboration with a number of others, we have recently collected >7000 laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) U-Pb detrital-zircon ages from ~80 new samples of metasedimentary and some volcaniclastic Sierran units (Paterson et al., 2009, 2012). These ages, combined with our mapping, have helped to further refine the “terrane map” (Fig. 6-3) constructed by Chapman et al. (2012). From east to west these host-rock sequences include: (1) only slightly displaced shallow- to deep-water passive margin units, presumably overlying Proterozoic crust, some of which extend into eastern Sierran pendants (Stevens and Greene, 1999); (2) Roberts Mountain and Golconda assemblages (northern part of central Sierra) and El Paso assemblages (southern Sierra), all displaced deep-water assemblages and sometimes associated Paleozoic volcanics, which now occur in scattered fragments along the eastern crest of the Sierra (Schweickert and Lahren, 1987; Dunne and Suczek, 1991; Chapman

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**Figure 6-2.** $\epsilon$Nd versus Sr isotopic data from the Tuolumne Intrusive Complex, color coded for age. Isotopic values are a function of age (more primitive are older) and also show a slightly increasing heterogeneity with time.
et al., 2012); (3) a fault-bounded shallow-water, passive margin assemblage (Snow Lake block) along the central axis of the Sierra (Lahren et al., 1990; Memeti et al., 2010b), which may overlie Proterozoic basement and have its eastern margin marked by the Bench Canyon shear zone (e.g., Kistler, 1993; Paterson et al., 2012); (4) the Shoo Fly Complex, another passive margin terrane that may or may not be exotic to North America; and (5) outboard oceanic terranes to the west (on this trip, the Calaveras Complex and Foothills Terrane; see also Saleeby, 2011). Our detrital-zircon studies also confirm that a westward younging, Jurassic marine sedimentary sequence occurs unconformably on all of these terranes and in the Jurassic arc sequences, indicating that the Triassic and Cretaceous arcs were emergent, but during the Jurassic, arc volcanoes poked their heads through a marine embayment.

Based solely on the distribution of these terranes, we might predict that the largest isotopic jumps in magmatic sys-

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**Figure 6-3.** Exposed host-rock terrane map for the central and southern Sierra Nevada redrafted from Chapman et al. (2012). Terrane designations are in part based on statistical comparisons of detrital-zircon age distributions. Note that oceanic units are widespread in the west, the miogeoclinal “Snow Lake block” is located in the central Sierra Nevada, and a complex juxtaposition of shallow and deeper water miogeoclinal units occurs to the east.
tems should occur between basement units #1 and #2 (unnamed bounding fault), #2 and #3 (Bench Canyon shear zone?), and #4 and #5 (the Foothills suture?), if the magmatic systems were significantly interacting with these terranes. Clearly, there are complications to this prediction as we saw on Day 2, and we will discuss the degree to which magmatism in this arc significantly interacted with these middle crustal terranes (see also Lackey et al., 2008). While doing so, we are excited that we can now compare these proposed basement terrane boundaries to actual shear zones in the field and to isotopic breaks inferred from other data sets. Figure 6-4 is one attempt to do so.

**TECTONISM**

To better understand the cause of arc tempos and the styles of magma ascent and emplacement in arcs, we need to fully understand the changing styles of synchronous tectonism. Obviously this is not always easy, particularly for older periods of tectonic activity in arcs, which are potentially masked by younger magmatism and tectonism. There has been a long history of evaluating the regional tectonics in the Sierran arc, which is beyond our abilities to summarize here. Our syntheses of published papers indicate a general pattern of regional tectonics in the arc that shifts from Permian sinistral motion, to Triassic orthogonal shortening (Barth et al., 2012), to possibly local near-surface extension in the early Jurassic (Busby-Spera, 1988), to orthogonal contraction in the Late Jurassic–Early Cretaceous, and/or deeper in the arc (Tobisch et al., 1995, 2000; Dunne and Walker, 2004), and to dextral transpression in the Late Cretaceous (Tikoff and Teyssier, 1992). Excellent recent papers by Ducea and Barton (2007), DeCelles et al. (2009), and Barth et al. (2012) emphasize the connections of this intra-arc tectonism to synchronous deformation within forearc and reararc domains. Clearly plutonic and volcanic flare-ups and lulls in arcs can and do occur during different styles of tectonism, and there is no suggestion that contractional shortening of arcs in any way inhibits plutonism or volcanism. Below, we will show that the periods of plutonic and volcanic flare-ups in the Sierran arc are typically associated with shortening and vertical thickening of the arc. Our compilation of Al-in-hornblende barometry from Triassic,

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**Figure 6-4.** Generalized central Sierra map comparing the terranes from Figure 6-3, known and inferred Mesozoic regional faults, and isotopically defined boundaries. Colors: pink—Mesozoic plutonic rocks; gray—oceanic terranes; light blue—Snow Lake block; dark blue—North American miogeocline units; green—Mesozoic (dark—Triassic + Jurassic; light—Cretaceous) volcanic sections. Black dashed lines—strike-slip faults; blue lines—isotopically defined boundaries. Pendant names as follows: BL—Benson Lake; CL—Cinko Lake; EC—Eagle Creek; MG—Mount Goddard; ML—May Lake; MM—Mount Morrison; OK—Oakhurst; RR—Ritter Range; SL—Saddlebag; QM—Quartz Mountain; WMB—Western Metamorphic belt. IBB2—intrabatholithic belt #2.
Jurassic, and Cretaceous plutons also indicates a weak correlation between age and depth with younger plutons emplaced at slightly shallower depths, indicating that slow midcrustal exhumation occurred throughout the Mesozoic (Memeti et al., 2010b; Paterson et al., 2012).

It is also important to examine the styles and magnitude of Mesozoic intra-arc deformation in the central Sierra and determine if this deformation has direct links to plutonism and volcanism (e.g., Tobisch et al., 2000). We have made some progress in evaluating potential links by combining (1) the relative timing of volcanism, plutonism, and deformation established from field mapping and structural studies; (2) the new geochronological results from plutons, volcanic units, and detrital zircons from sedimentary units presented below; (3) an examination of magmatic and subsolidus fabrics in dated plutons, particularly in regards to their continuity with host-rock structures; and (4) strain analyses in dated host-rock units. At the moderate crustal depths now exposed in the central Sierran arc, deformation clearly involves a complex interplay between rigid rotation of stratigraphic units, internal ductile strain of both of these units and the plutons intruded into them, local folding, and ductile-brittle faulting, with the timing of each not always coincident (e.g., Schweickert and Lahren, 1993a, 1993b; Sharp et al., 2000; Tobisch et al., 2000). Our results indicate that the Triassic volcanic and older Paleozoic units were already rotated to steep dips prior to intrusion of Triassic (210–232 Ma) plutons, a pattern that is repeated for both Jurassic and Cretaceous stratigraphic units and plutons. Our data also indicate that earlier, typically bedding-parallel faults with reverse motion associated with regional rotations (e.g., Tobisch et al., 2000) are often overprinted by Jurassic, mid-crustal, contractional deformation (Tobisch et al., 1995; this study) followed by middle Cretaceous dextral, oblique, transpressional shearing (Fig. 6-4), culminating in Late Cretaceous, dextral, brittle faulting.

One new exciting data set now available is our compilation of >650 measurements of finite strain across the central Sierra Nevada (Fig. 6-5). Finite-strain values are a function of rock type, primary fabrics, geographic location, and tectonic setting (e.g., shear zones and folds). Surprisingly, we see little evidence that finite-strain intensities are a function of distance to pluton margins or of age. We have also examined the degree to which volume losses might have occurred during strain at the arc scale and conclude that no more than 10%–15% volume loss are com-

![Figure 6-5. Shortening (parallel to Z axis) versus extension (X axis) values from >650 finite strain measurements in a broad corridor across the central Sierra Nevada. Lines—possible % extension values along Y. Dots—strain measurements mostly determined from shapes of clastic objects (see Paterson et al., 1989, for measurement and calculation techniques). Strain determined using March method on slates marked in shaded area. Data generally rule out >10%–15% volume loss or arc parallel extension during straining of the arc. Data also show the large heterogeneity of arc strains, but averaging of data suggests that ductile deformation resulted in ~50% horizontal shortening and ~100% vertical extension of the arc during the Mesozoic.](image)
patible with the strain measurements. In most cases, finite strains are closely linked to regional, ductile structures with directions of greatest extension being parallel to steeply plunging mineral lineations, and directions of greatest shortening perpendicular to regional, NW-striking and steeply dipping cleavages. Strain intensities are very heterogeneous but indicate an overall bulk NE-SW shortening of the arc of ~50% and overall bulk vertical extension of ~100% (Fig. 6-5). These shortening and/or extension values are minimums since they do not record shortening and/or extension caused by other deformation mechanisms active in the arc. We will further discuss implications of these results in a later section.

To date, we have not studied internal structures in any Triassic plutons in the central Sierra. But for the examined Jurassic and Cretaceous plutons, internal magmatic and subparallel solid-state foliations and lineations are statistically parallel to and continuous with nearby host structures in all mapped areas (Fig. 6-6), indicating that significant ductile NE-SW shortening and vertical ductile extension occurred throughout the Mesozoic during and after pluton emplacement. Whether shortening and extension rates are continuous or episodic remains difficult to determine, although significant shortening must have occurred during the crystallization of both Jurassic and Cretaceous plutons. We are particularly impressed with the amount of middle to early Late Cretaceous deformation in the arc (see also Sharp et al., 2000). Even volcanic units as young as ca. 96 to ca. 113 Ma are now

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**A Summary of Structural Measurements**

<table>
<thead>
<tr>
<th>Area</th>
<th>Magmatic foliation</th>
<th>Host rock foliation</th>
<th>Angular difference</th>
<th>Magmatic lineation</th>
<th>Host rock lineation</th>
<th>Angular difference</th>
</tr>
</thead>
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<tr>
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<td>306/78</td>
<td>4</td>
<td>78/090</td>
<td>71/089</td>
<td>7</td>
</tr>
<tr>
<td>Saddlebag</td>
<td>303/86</td>
<td>336/79</td>
<td>33*</td>
<td>80/132</td>
<td>80/086</td>
<td>8</td>
</tr>
<tr>
<td>Waugh Lake</td>
<td>310/82**</td>
<td>322/81</td>
<td>12</td>
<td>88/269</td>
<td>79/269</td>
<td>9</td>
</tr>
<tr>
<td>Jackass Lakes</td>
<td>336/89</td>
<td>332/84</td>
<td>6</td>
<td>89/341</td>
<td>85/046</td>
<td>5</td>
</tr>
<tr>
<td>Cinko Lake</td>
<td>330/90</td>
<td>325/80</td>
<td>11</td>
<td>82/314</td>
<td>82/358</td>
<td>7</td>
</tr>
<tr>
<td>Kuna Lobe</td>
<td>293/90</td>
<td>See Waugh Lake</td>
<td>30</td>
<td>88/272</td>
<td>See Waugh Lake</td>
<td>9</td>
</tr>
<tr>
<td>Cathedral Lobe</td>
<td>285/85</td>
<td>See Virginia Canyon</td>
<td>22</td>
<td>87/001</td>
<td>See Virginia Canyon</td>
<td>19</td>
</tr>
<tr>
<td>N HD Lobe</td>
<td>295/82</td>
<td>See Cinko Lake</td>
<td>30</td>
<td>89/319</td>
<td>See Cinko Lake</td>
<td>7</td>
</tr>
<tr>
<td>S HD Lobe</td>
<td>304/88</td>
<td>See Jackass Lakes</td>
<td>28</td>
<td>89/022</td>
<td>See Jackass Lakes</td>
<td>4</td>
</tr>
</tbody>
</table>

*Magmatic = central Cathedral Peak
**Satellite plutons; Average of magmatic+solid-state in plutons = 322/83

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Figure 6-6. (A) Summary of >>5000 structural measurements in the central Sierra measured in both plutons and in adjacent host rocks: comparisons of statistical averages show the close coupling of foliations and lineations in metamorphic rocks with pluton-wide magmatic foliations and lineations (usually type 3). (B) Stereonet plot shows poles to average measured magmatic and metamorphic foliations (blocks) and mineral lineations (circles), the latter of which are all steeply plunging. An important exception to this close coupling occurs in the Tuolumne Intrusive Complex, where WNW magmatic foliations are at higher angles to nearby metamorphic foliations.
moderately to steeply tilted and internally strained. Ductile strain estimates vary from −20% to locally −50% shortening in these Late Cretaceous metavolcanic units.

This close coupling of regional host-rock fabrics and magmatic fabrics suggests that the latter fabrics may be important records of paleostrain and inferred paleostress directions in ancient arcs. We suggest that "regional" magmatic fabrics in plutons are frozen late in their crystallization histories and record incremental shortening and extension directions (Fig. 6-7; see also Cao et al., 2012). In cases where multiple plutons of different ages are available, one can track the temporally changing incremental shortening and extension directions in the arc. Figure 6-7 shows one example of this based on our work in the central Sierra Nevada area.

This change in strain orientations through time is well displayed in a number of plutons examined during this trip, such as the Tuolumne Intrusive Complex. We can discuss several alternative hypotheses to explain these changing directions of strain including shifting plate motions (Fig. 6-7), a large Cretaceous oroclinal bending in the central Sierra Nevada (Schweickert and Lahren, 2006) that has been recorded both by magmatic fabrics and locally by host-rock fabrics (Cao et al., 2012), late arc-parallel shortening (Paterson, 1989), or internally inherent processes resulting from the final crystallization of plutons.

THE MESOZOIC ARC

Only small scraps remain of the former volcanic carapace of the Mesozoic Sierran arc, and only a few relict volcanic centers have been recognized (Fig. 6-8). Even so, a comparison of these volcanic fragments indicates that a number of regional patterns may exist. In the large sections along much of the eastern Sierra crest (e.g., Ritter and Saddlebag pendants) the volcanic sections are all steeply dipping, young to the west, and units are laterally quite continuous. The western edge of these pendants grade into a laterally extensive belt of Middle to Late Cretaceous volcanics located along the central axis of the Sierra Nevada, and includes the Minarets and Merced Peak caldera complexes (Fig. 6-9). Many of the recently obtained ages coming out of

Figure 6-7. Changing orientations of planar structures versus age in the central Sierra Nevada. (A) The crystallization ages and average pluton-wide fabric orientations in Jurassic and Cretaceous plutons in the Virginia Canyon area (north of Day 5 stops). Shaded area—orientation of arc. Gray text—plate motion of Farallon versus North American plate and inferred rotation of changing plate motions through time. Change from pure shear dominated shortening to strike-slip dominated transpression occurred around 95 Ma. (B) Changing orientations (strike/dip) of average foliations and bedding through time relative to a constant steep lineation. Boldface letters—strain ellipsoid long (X), intermediate (Y), and short (Z) axes. VCSZ—Virginia Canyon shear zone; GLP—Green Lakes pluton; CPP—Cathedral Peak pluton; SLP—Soldier Lake pluton. Maximum extension directions remain vertical, whereas maximum shortening directions, recorded by mineral foliations, rotate with time to more northwesterly directions. Diagram drafted by Wenrong Cao.
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Figure 6-8. Map of pendants in the Sierra Nevada preserving Mesozoic volcanic rocks with volcanics color coded by approximate age. Inset shows details of pendants in the eastern Sierra visited during Days 4–6. Dashed circles—possible calderas. Figure drafted by Jeff Thompson.
Figure 6-9. Contoured and color-coded age distributions of Mesozoic plutons based on a compilation of 665 U-Pb zircon ages (in Ma) completed by Chapman et al. (2012). Figure modified from their diagram. Note that if taken at face value, there is a focusing and/or younging of Cretaceous magmatism, which in the central Sierra is centered on the Tuolumne Intrusive Complex.
this belt fall between ca. 106 and 96 Ma and thus overlap with the largest magmatic surge in this arc (Fig. 6-10). The belt of Cretaceous volcanics continues well southward along the central axis of the Sierra Nevada (Fig. 6-9) and includes Cretaceous metavolcanic rocks previously recognized in the Goddard pendant (Tobisch et al., 1986, 2000), Oak Creek and Boyden Cave pendants (Saleeby et al., 1990), and in pendants in the southern Sierra (Saleeby and Busby-Spera, 1986; Saleeby et al., 1990, Nadin and Saleeby, 2008; Saleeby et al., 2008; Starnes et al., 2010). A gap in preserved volcanic sections occurs west of this belt until tectonically mixed Triassic and Jurassic volcanic belts are encountered in the Western Metamorphic belt (Day 1).

Plutonic patterns across the central-eastern Sierra are more complex compared to the largely westward younging seen in the preserved volcanic section (Fig. 6-9; Chapman et al., 2012). In general, Triassic plutons are only preserved along the eastern edge of the Sierra and in the adjacent White-Inyo Mountains (Barth et al., 2011). Jurassic plutons are preserved in the same areas as the Triassic plutons and to the west, particularly in the Western Metamorphic belt and equivalent regions to the south. Cretaceous plutons swamp these Triassic and Jurassic belts, dominating the central Sierra arc and are now known to be widespread beneath the eastern Great Valley sediments (Evernden and Kistler, 1970; Stern et al., 1981; Bateman, 1992; Saleeby, 1990; Saleeby, 2007; Lackey et al., 2008; Barth et al., 2011; Chapman et al., 2012). Besides these broad patterns, there is evidence of smaller-scale patterns such as the loci of magmatism migrating during the Cretaceous. For example Tobisch et al. (1995) summarize data supporting a ~2.7 mm/yr eastward migration of Cretaceous magmatism (see also Stern et al., 1981; Lackey et al., 2008; Chapman et al., 2012).

REGIONAL GEOCHRONOLOGY

There are several arc-scale geochronologic data sets worth examining. These include the >7000 LA-ICP-MS U-Pb ages from detrital zircons mentioned earlier (Fig. 6-10), the 665 published U-Pb zircon ages from plutons (Fig. 6-11) compiled by Chapman et al. (2012), published single- and multi-grain thermal ionization mass spectrometry (TIMS) ages, and our

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Figure 6-10. Unpublished laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) U-Pb zircon ages (>6000) collected by Paterson and colleagues from the central Sierra Nevada. Most ages are from detrital zircons in Sierran sedimentary rocks. A few are from volcaniclastic or volcanic rocks. Note the three prominent Mesozoic peaks separated by lulls, the first peak of which begins at ca. 250 Ma. We argue that these ages record the initiation of the Mesozoic arc at 250 Ma and the three well-known magmatic surges separated by magmatic quiet periods.
unpublished LA-ICP-MS U-Pb ages from plutonic and volcanic rocks from the central Sierra (Fig. 6-11). When ages of all new LA-ICP-MS zircons from Sierran units are combined, a histogram plot shows large age peaks centered at ca. 104 Ma, ca. 176 Ma, and ca. 216 Ma, with smaller Paleozoic peaks at ca. 400 Ma and ca. 500 Ma (Fig. 6-10). Precambrian peaks (not shown on Fig. 6-10) also occur and match well with expected North American cratonal sources. The three Mesozoic peaks match the well-known pattern of magmatic surges in the Sierra Nevada (Stern et al., 1981; Ducea and Barton, 2007; Ducea, 2011). Of particular interest is that the Triassic peak begins at ca. 250–260 Ma, suggesting that this is the age of Mesozoic arc initiation, a conclusion that agrees well with the continuous spread of zircons from ca. 235 Ma to ca. 260 Ma seen in the samples from the Cooney Lake quartzites near the base of the arc in the Saddlebag Lake area (Day 5).

All three of the above regional data sets are compared in Figure 6-11. These data sets show that both plutonic and volcanic units have a large Cretaceous age peak centered at ca. 90–105 Ma, a smaller Jurassic peak centered at ca. 165 Ma, and a Triassic peak centered at ca. 210–220 Ma (Fig. 6-11). We have also estimated the ages of 17 intra-arc, metasedimentary sequences in the central Sierra Mesozoic arc (Fig. 6-11) using a combination of fossil ages, minimum age peaks of detrital zircons, and stratigraphic bracketing with nearby dated volcanic sequences. These sedimentary packages have ages defining a larger peak centered at ca. 165–175 Ma and two smaller peaks between ca. 210 and 230 Ma.

These data document that equivalent timing and relative magnitudes of magmatic surges and lulls are recorded in both the volcanic and plutonic records, although there is a suggestion that a greater percentage of volcanism occurred early in surges relative to plutonism. These age comparisons also support our field studies, which indicate that a widespread Jurassic marine incursion occurred in the Mesozoic arc (see also Saleeby and Busby-Spera, 1986; Busby-Spera, 1988; Sorensen et al., 1998),
a pattern also seen in other parts of the Cordilleran (e.g., Busby-Spera, 1988; LaMaskin et al., 2011; Alsleben et al., 2012). During this incursion, marine sequences in the arc continued to receive zircons from both Precambrian North American sources and from ca. 400 Ma and ca. 500 Ma Paleozoic sources of possible Golconda—Roberts Mountain, northern Sierra and eastern Klamath origins and/or sources, or displaced fragments of Baltic (Gehrels et al., 2000; Harding et al., 2000; Spurlin et al., 2000; Wallin et al., 2000; Miller, 2011).

**Summary Geochemistry and Isotopes**

The numerous prior geochemical and isotopic studies in the Sierra (Lindgren, 1915; Moore, 1959; Wollenberg and Smith, 1968; Ague and Brimhall, 1988; Glazner, 1991; Bateman, 1992; Kistler, 1993; Ducea, 2001; Gray et al., 2008; Memeti et al., 2010b; Barth et al., 2011) concentrated on defining magma sources, petrologic processes in the evolving magma systems, and basement terranes. In the arc-systems synthesis we present here, published and new geochemical and isotope data are reviewed with three questions in mind: (1) To what degree are the volcanic and plutonic systems chemically linked in this arc? (2) What are the major processes controlling the compositional diversity in these magmatic systems? And (3) do the temporal age patterns and isotopic variations give clues about what ultimately controls the tempo of magma productivity?

In order to compare Mesozoic coeval plutonic and volcanic rocks and examine spatial and temporal patterns, we summarized whole-rock geochemistry from the central Sierra Nevada batholith region. Geochemical analyses come from a variety of published sources and include data from NA VDAT (North American volcanic and intrusive rock database; www .navdat.org), unpublished theses, and our new data. Together, our geochemical data set includes over 700 samples with major-element analyses, 322 samples with rare-earth element (REE) analyses, and 319 samples with other trace-element analyses. We have a wide number of plots available on which these data are separated into plutonic and volcanic components and into Triassic, Jurassic, and Cretaceous ages (Figs. 6-12 and 6-13 are simply two examples). There are certainly sampling biases in all data sets, including those in this field guide, such as the paucity of isotopic data from volcanic relative to plutonic rocks and of geochemistry in general from Triassic plutons. Even so, the close overlap of spatial and temporal geochemical patterns in both the plutonic and volcanic records (Figs. 6-12, 6-13, 6-14, 6-15, and 6-16, panels #1 and #2) suggests a close temporal and chemical link between the volcanic and plutonic systems in this arc.

Whereas Triassic plutons of the central Sierras are metaluminous to peraluminous and calc-alkaline in composition, volcanic rocks of the same age have a broader compositional range, and some are tholeiitic, particularly the more mafic members. This is a feature shared with plutons of Jurassic age. In contrast, Cretaceous plutons and most Cretaceous volcanic rocks are strictly calc-alkaline. Although many of these Mesozoic units are metaluminous, peraluminous compositions are more prevalent in the felsic portions of Cretaceous plutons. However, we note that there are many A/CK values for Triassic and some Jurassic volcanic rocks that are either too low or too high for pristine igneous rocks. Much of this is due to variation in alkali abundances, particularly Na, indicating that these rocks have been altered (e.g., Hanson et al., 1993; Sorensen et al., 1998).

In this section of the arc, Triassic and Cretaceous plutonic and volcanic units are fairly similar in their geochemistry, although the Jurassic units tend to have slightly higher K2O and Na2O, and some Jurassic rocks are marginally alkaline. Otherwise, we see no other significant differences in elemental composition as a function of age. Rare-earth element patterns through time are also similar with light rare-earth element (normalized) (LREE) average near 100 and heavy rare-earth element (normalized) (HREE) averaging near 10.

Mesozoic plutons and volcanic units of the central Sierra have fewer chemical variations through time than those of more inboard units located farther south in the Mojave desert regions of southern California (Barth et al., 1990; Anderson et al., 1992; Miller et al., 1992). For the latter, the Triassic units are distinctively less silicic, often alkalic or tholeiitic, with adakitic Sr (concentrations often trending above 1000 ppm) and high ratios of Sr/Y and La/Lu compared to younger Mesozoic plutons (Fig. 6-13). In the same region, Jurassic plutons are also high K, but in contrast, Cretaceous plutons are almost entirely calc-alkaline, more silicic, and some peraluminous (Lackey et al., 2008).

We have presented widespread field and mineral-scale evidence (both isotopic and age heterogeneity) that implies quite extensive reworking of earlier inputs by new injections, whether by mixing of magma with mush, or with relatively crystal-poor magma, processes compatible with much of our geochemical syntheses, particularly in the larger, longer lived, more “mature” systems. However, there is also geochemical evidence for mineral fractionation in all suites, regardless of age, including compatible element behavior for Ca, Mg, Ti, and Fe, reflective of fractionation of mafic minerals and plagioclase. Na2O and K2O are generally seen as incompatible, more so for K2O. Na2O initially increases for mafic and intermediate rocks but levels off or decreases after ~60–65 wt% SiO2 for all units, which is consistent with plagioclase as a fractionating phase becoming more sodic. In this regard, Al2O3 increases with increasing SiO2 for mafic rocks but decreases after ~53–57 wt% SiO2, consistent with the onset of plagioclase fractionation. Similarly, P2O5 also peaks at ~55 wt% SiO2 for all units signifying whereapatite becomes a fractionating phase. Likewise, Y and most REEs, particularly heavy rare-earth elements (HREEs), decrease with increasing SiO2 indicating further accessory phase control during mineral fractionation and presumably by minerals that concentrate these elements such as zircon, sphene (titaneite), allanite, and apatite. Other elements exhibiting compatible element behavior consistent with arc-wide fractional crystallization include Sr.
(plagioclase) and both Sc and V (magnetite). Biotite may play a relatively minor role, given that on most Harker plots Rb is elevated only at high SiO₂. Also, whole-rock Zr/Hf ratios stay around the crustal average until high SiO₂ compositions, again indicating that the effects of zircon fractionation occur relatively late (cf. Claiborne et al., 2006). At the final emplacement levels, perhaps the most clear-cut evidence of fractionation shows up as relatively small to modest volumes of more evolved rocks (e.g., Sentinel felsic sheets, equigranular Half Dome aplites, Cathedral Peak granites, and southern Half Dome lobe), and felsic layers associated with schlieren.

Mid-ocean ridge basalt (MORB)–normalized spider diagrams show large-ion lithophile element (LILE) enrichment and also certain negative anomalies typical of most arc magmas, such as for the high field strength elements Ti, Ta, and Nb. The latter is consistent with the presence of accessory rutile in source residue of these magmas. An additional negative anomaly is that of P, which is indicative of residual apatite.

For the central Sierra, however, we are aware of only two plutons with Sr levels above 1000 ppm (Fig. 6-13). Both plutons are of Jurassic age—one is located in the Reno area of Nevada and another in the eastern Sierra. High Sr and high ratios of Sr/Y

Figure 6-12. Harker diagrams comparing data from plutonic and volcanic systems in the central Sierra. Color coded by broad age groups. Volcanic data shown with dots, plutonic data are in colored fields.
and La/Lu (Fig. 6-13), along with other elemental attributes, are indicative of production of melts in equilibrium with an eclogitic residue, such as magmas derived from an eclogite-bearing slab or eclogitic lower crust (Martin et al., 2005; Castillo, 2006). High Sr and high Sr/Y ratios are particularly indicative of low % melts in equilibrium with an eclogitic residue, and the REE trends should be steep with La/Lu ratios at ~100. With the two exceptions noted above, most of the central Sierran rocks have Sr between 600 and 800 ppm, which lessens in more felsic members. As indicated above, REE trends are similar with consistent LREE enrichment over HREE with minimal to no Eu anomaly, and La/Lu ratios average close to ~10 for all units, regardless of

Figure 6-13. Sr (ppm) versus SiO₂ for central Sierra Nevada plutonic (A) and volcanic (B) rocks and Sr/Y versus La/Lu plots for central Sierra plutonic (C) and volcanic (D) units. Color coding of data in all plots shows change from Triassic (blue), Jurassic (green), to Cretaceous (red).
The lack of an Eu anomaly requires the absence or near absence of plagioclase in the residue. Melting of a source with chondritic (La/Lu \sim 1) distribution of REE will yield LREE-enriched melts because residual mafic minerals such as pyroxene and hornblende have HREE distribution coefficients versus melt that are \sim 10 times greater than those for LREE. For garnet, this value is close to 200, so where garnet is a significant residue phase, values for Sr and Sr/Y are high, and the REE trends steepen when the amount of melting is rather low (15%-20%). However, these relationships change with greater percentages of melting. At more than 30% melting, Sr and Sr/Y lessen as do the relative abundances of LREE to HREE. Melt models have many unknowns, leading to fairly unconstrained assumptions about residue mineral proportions, relative rates of mineral melting,
Figure 6-16. Summary plot of the temporal characteristics of central Sierran magmatism versus tectonism: a close examination of this plot has led us to evaluate what intra-arc processes may play a role in arc-wide cycles and their tempos. See text for full discussion.
and source composition. That aside, the more primitive portions of these central Sierran rocks have compositions consistent with fairly high percentage melting and a residue that was mafic and likely eclogitic.

**Isotope Summary**

Despite the many isotopic studies in the Sierra Nevada, some of which we have discussed here, the Sierran arc exhibits tremendous crustal- to crystal-scale isotopic variability that we are only beginning to understand. Broadly, this zoning records the multi-dimensional reprocessing of preexisting crustal and mantle reservoirs in a laterally and vertically zoned, and continually changing (4-D) arc system. Thus, the time-integrated isotopic signals that we measure are merely the integrated records of sources, their melts, and the ascent, and repeated mingling and mixing of those melts and crystals formed therein. Thus, every rock is a mixture of numerous possible source inputs in the 4D framework of an arc system. Nonetheless, a review of the isotopic data among the different field trip days does suggest some important characteristics of the Sierran arc that serve as points for further discussion.

Paterson (lead author) and Lackey (Pomona College) have established a database of published and new data focusing on a comparison of four different isotopic values (εNd, Sr, δ18O, and Pb); the database now has >700 measurements from Sierra plutonic and volcanic units. Lackey and J. Miller have also begun analyses of Hf isotopes, some of which were presented earlier in this Forum. Our preliminary evaluations of these data sets also indicate a close link between volcanic and plutonic components of this arc since isotopic values show significant overlap and vary spatially and temporally in similar ways (Fig. 6-14). Our syntheses indicate that the lithospheric column, including melt sources, clearly exhibits first-order control on the variation of isotope ratios in the Sierra both horizontally (Kistler and Peterman, 1973, 1978; DePaolo, 1981; Masi et al., 1981; Kistler, 1990; Lackey et al., 2008), and vertically (Lee et al., 2000; Ducea, 2001, 2002; Lee et al., 2007). This control results in the distinct positioning of individual intrusive complexes on isotopic arrays (e.g., Sr versus Nd; Fig. 6-1). Our field and geochemical studies provide strong evidence that source region compositions (particularly seen in isotopic data), and both fractionation and mixing of magmas and limited host-rock contamination, all had an important role in developing the final compositional diversity of both plutonic and volcanic units in this arc. Our spatial and temporal comparison of four different isotopic systems (Sr, εNd, δ18O, and Pb) broadly supports earlier studies indicating that melt sources in the western portion of the arc are of depleted mantle with minor input from heterogeneous, but largely oceanic crustal sources during the Jurassic and Cretaceous (no Triassic data are available). The more primitive units in the central Sierran rocks have compositions consistent with fairly high percentage melting and a residue that was mafic, verging on ultramafic compositions, and likely eclogitic. Central Sierran melt sources are also explained by a mix of depleted mantle and minor Proterozoic crustal input with the latter possibly representing Proterozoic basement (e.g., Lackey et al., 2012), perhaps beneath the passive margin metasediments of the Snow Lake block. Eastern sources are more equivocal. One possible explanation is that the base-ment in this part of the arc varies tremendously over short distances as exemplified by Sr, εNd, δ18O, and 206Pb/204Pb isotopic ratio discontinuities (Kistler, 1990; Lackey et al., 2008). These basement types include Precambrian continental crust of different age overlain by a passive margin sedimentary sequence, possible oceanic basement overlain by marine sediments such as the El Paso terrane or Golconda terrane farther north, and the Snow Lake passive margin fragment and its uncertain basement. Thus it is likely that at the scale of our comparisons, we are including units that have been generated from and passed through different lithospheric columns (see also Miller et al., 1995). At present our best working hypothesis for the eastern Sierra is that magmas represent a mix of mantle and both young (Triassic and Jurassic) or more homogenized (by Cretaceous) continental crust. As contraction of the arc host rocks continued throughout the Mesozoic, these units would have been dramatically shortened horizontally, extended vertically, and increasingly juxtaposed. Thus during the voluminous Cretaceous magmatism, these arc magmas were generated from mantle magmas that interacted with and ascended through this partially homogenized crust, and/or rising magmas rose through previous Triassic and Jurassic plutonic bodies, which may have played an important role in reducing isotopic heterogeneity in the Cretaceous.

Besides the above first-order controls, additional complexities are indicated by isotopic patterns at the single magmatic system scale to even single crystals, and some of these may relate to the size or maturity of these systems. For example, the large texturally homogeneous sections of the Fine Gold Intrusive Complex (Lackey et al., Day 2) and Tuolumne Intrusive Complex (Memeti et al., Day 3) show considerable isotopic variability, whereas isotopic variations in the Guadalupe Intrusive Complex (Putirka et al., Day 1) and lobes of the Tuolumne Intrusive Complex (Memeti et al., Day 4) show less isotopic variation over large ranges of silica and bulk composition. Thus one hypothesis we can explore is that smaller, mafic systems are inherently less isotopically diverse, although Hf and O isotope variations in zircon crystal populations are highly variable in mafic magmas (Miller and Lackey, 2012, personal obs.). In contrast, the larger intrusive domains, such as the Bass Lake Tonalite and Cathedral Peak Granodiorite, seem to retain isotopic diversity despite their texturally homogeneous look, a result of these large domains possibly being built as a result of protracted magma mingling and mixing, either in complexly evolving conduits or dynamically emplaced batches of magma that are incrementally assembled.

Another approach we are exploring is to examine the temporal changes and patterns of isotopes in addition to the spatial changes noted above. For example we previously mentioned the temporal change of εNd-Sr in the Tuolumne Intrusive Complex (Fig. 6-2), and Figure 6-15 shows the temporal (and spatial) changes in O isotopes across the Sierra. The spatial and tem-
poral evolutions of arc-wide δ18O values show distinct features: (1) magmas throughout the Triassic (only eastern Sierra) show a relatively narrow and elevated range of δ18O, ~8‰ to 10‰; (2) most Jurassic samples from the eastern Sierra are likewise elevated, with a narrow range of lower values (6‰ to 7.2‰) in coeval plutons in the northern and western Sierra; (3) in the Cretaceous, the western Sierra shows the greatest range of δ18O at any time (6‰ to 10‰, average = 8.77 ± 1.25‰), but becomes less variable and progressively lower from the mid (average = 8.65 ± 0.83‰) to late (average = 7.79 ± 0.6‰) Cretaceous in the central and eastern Sierra. Thus, the Cretaceous arc reveals a focusing of δ18O values over time. One group of small-volume, high-δ18O plutons from the mid-to lower-crustal exposures in the southern Sierra Nevada (Ross, 1983; Saleeby et al., 1987; Lackey et al., 2005) has values that are distinct from the main body of data in the Late Cretaceous, but these samples likely represent near-pristine crustal melts.

The sheer volume of granitic magmas in the Cretaceous arc flare-up (Fig. 6-16) implies considerably more crustal reworking than in early arc episodes. However, the narrowing and lowering of δ18O in the Cretaceous magmatic units require further consideration. We propose that the lowering and narrowing δ18O values from the western to eastern Sierra reflect scales of melting that were unprecedented in the Triassic or Jurassic, with these voluminous melts derived from highly heterogeneous lithologies, including previously unmelted rocks from the accretionary domain of the western Sierra (Lackey et al., 2012). Over time, magma mixing and establishment of interconnected sources led to increased efficiency of the arc magma system to average the δ18O from mantle and crustal melts. The slight lowering of δ18O is consistent with increased input of lithospheric mantle; however, radiogenic isotopes indicate a persistent and significant crustal component in eastern Sierra magmas.

**ARC TEMPOS**

One of our field trip goals is to attempt to examine potential links between volcanism and plutonism and between tectonism and magmatism in general in the central Sierran arc to better understand controls on arc tempos. Figure 6-16 is our attempt to summarize and compare our central Sierra data sets with the above goals in mind (Paterson, 2012). Below, we briefly discuss each component of this plot followed by comparisons of data sets and a discussion of the implications.

Ducea (2001) argued that there was no apparent correlation between magma production rates in the Sierran arc with either subduction convergence rates or subduction obliquity, indicating that the driving forces that controlled tempos of arc magmatism and/or connections between magmatism and tectonism must be sought within the arc itself. To further explore this, panel #5 in Figure 6-16 reproduces the normal and tangential velocity of subduction versus age along the North American margin at the latitude of the central Sierra region and the inferred age of the subducting plate after Engebretson et al. (1985). Values of relative plate motion prior to 170 Ma were not available. We will compare these plate motion and age curves to other data sets below.

Panel #1 in Figure 6-16 is a comparison of addition rates of plutonic, volcanic, and sedimentary materials to the arc through time. Paterson et al. (2011) discuss a number of serious challenges in attempting to construct such plots, and you are encouraged to interpret these curves cautiously. Plotted values should not be viewed as fluxes (km³/km²/time) but as relative magnitudes (thus no scale on vertical axis) of volume addition rates (km³/time) through time for the central Sierra region. Figures 6-17 and 6-18, taken from Paterson et al. (2011), present definitions useful for discussions on incremental growth of magmatic systems and the relationships between pulse size and recurrence intervals, volume addition rates (VARs), and true fluxes. Curves were constructed using the known age distributions of all three rock types and estimated volumes of each rock type. For plutonic material this requires significant assumptions about the 3D shape of plutons plus emplacement scenarios (see Paterson et al. [2011] for full discussion). For stratigraphic units, we used the known age distributions, preserved stratigraphic thicknesses corrected for strain intensities, and assumptions about their pre-till and pre-erosion lateral extent. Sampling and unit preservation biases certainly affect this plot: for example, Barth et al. (2011) note that Triassic plutons are best exposed in the easternmost portion of the Sierras and in the White-Inyo Mountains; however,

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Units</th>
<th>Sometimes referred to as</th>
</tr>
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<tbody>
<tr>
<td>Total added volume</td>
<td>km³</td>
<td>magma addition</td>
</tr>
<tr>
<td>Volume addition rate</td>
<td>km³/my</td>
<td>magma flux; magma addition rate</td>
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<tr>
<td>Volumetric flux</td>
<td>km³/km²/my</td>
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<td>Areal addition rate</td>
<td>km²/my</td>
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<tr>
<td>Volume addition rate per arc-length</td>
<td>km³/my/(arc-km)</td>
<td>apparent intrusive flux; Armstrong unit; magma addition rate</td>
</tr>
</tbody>
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Figure 6-17. Definitions used to discuss incremental growth of magmatic systems. After Paterson et al. (2011).
the latter area is not considered in this study. And as noted above, only small portions of the volcanic and sedimentological records are preserved in the Sierras. We thus suspect that the positions of the age peaks on this plot are fairly robust, but that the relative magnitudes of the peaks, and more importantly, the integrated areas under the curves, will change as data from additional studies are used to refine the plot.

If taken at face value, several things are immediately apparent from this plot. Our data suggest that the Sierra Nevada arc started at ca. 250 Ma and shut down in the central area at ca. 80 Ma. Volume addition rates of plutonic, volcanic, and sedimentary rocks dramatically changed through time. There is also a fairly close link between so-called flare-ups and lulls of both plutonic and volcanic materials, although there is an intriguing suggestion that the peak volcanic activity occurred slightly before the peak plutonic activity in at least the Jurassic and Cretaceous flare-up events. A comparison between plate motions (panel #5) and these curves also shows no obvious correlations. These curves also support conclusions by others that 50%–70% of all magmatic material added to the middle and upper crustal sections of arcs is preserved as plutonic versus volcanic units. Since the plutonic curve ignores the growth of large, complementary mafic to ultramafic roots of residues beneath arcs (e.g., Ducea, 2001), this percentage must be significantly greater if the entire crustal column is considered. The sediment curve largely consists of marine sedimentation indicating that the Triassic and certainly the Jurassic arcs were not particularly emergent in contrast to the Cretaceous arc.

Panel #2 presents a simplified attempt to look at the variations in whole-rock Sr, εNd, δ18O, and 206Pb/204Pb isotopic ratios through time. Isotopic patterns are well constrained during flare-up events, but obviously only limited data are available during lulls. Although general east-west patterns of isotopic ratios remain the same throughout the Mesozoic, suggesting the overall basement types remain roughly the same, the details show significant variations through space and time. During flare-ups, the general pattern is that Sr, εNd, δ18O, and 206Pb/204Pb isotopic ratios tend to become more scattered (displayed by greater spread of double arrows on Fig. 6-16) and often toward more evolved values. This scatter tends to decrease with time as the flare-ups progress. Values of εNd increase slightly during the Triassic flare-up but decrease dramatically during the Jurassic and Cretaceous flare-ups. We interpret these isotopic shifts to indicate an increased involvement of new, compositionally varied, typically more evolved rock types into melt generation sites, and/or to a much lesser degree, assimilated by magmas during their ascent.

Figure 6-18. Graphical representation of relationships between pulse size, rate of pulse emplacement, size of feeder channels, volume addition rates, and fluxes during magmatic surges and lulls. After Paterson et al. (2011).
The focusing of isotopic values as flare-ups progress may reflect a combination of the swamping and homogenization of values as melting continued in cases where mantle lithospheric magmas dominated the system. The assumption is that such magmas would be less contaminated during ascent since they rose along preexisting magma pathways with less ability to interact with non-plutonic host rock.

Panel #3 on Figure 6-16 displays data sets that constrain the exhumation of the central Sierran arc. This plot is adapted from Cecil et al. (2006), onto which we have added our new pressure-temperature (PT) data (red region). This combined exhumation curve suggests that fairly slow exhumation occurred through the Jurassic and Cretaceous, and then increased exhumation rates began at ca. 85 Ma. This increased exhumation agrees well with widespread 80–85 Ma biotite cooling ages in the central Sierra and the lack of widespread gneisschist-facies retrograde metamorphism noted earlier. Both the shutting off of magmatism and increased exhumation rates led to an increase in cooling rates. This plot also shows that only ~10 km of crust has been removed from the central Sierra region and that >4 km of this removal happened after ca. 80 Ma, which is well after magmatism ceased in the central Sierra region. A comparison of the exhumation curve to panel #1 indicates that the only possible correlation between magma addition and exhumation rates is that increased exhumation may increase as flare-ups shut down (e.g., increased exhumation rates after Cretaceous and Tertiary events), although data are not yet sufficient to determine if this is true for the Triassic and Jurassic events.

Panel #4 and the rows below this panel summarize host-rock displacements and regional tectonism in the arc. Here again we are heavily reliant on age constraints from plutons, thus our timing of tectonic events tends to be better during magmatic flare-ups than during lulls. Our studies indicate that during each of the magmatic flare-ups volcanic and sedimentary units were tilted, displaced downwards to deeper crustal levels, and often internally strained. We are uncertain if the downward displacement of host rocks continued during magmatic lulls. Ductile strains in the arc are quite variable, but if we exclude the effects of rock type and presence of shear zones on strain, then there is a general regional pattern of higher strains in older units. It is hard to establish a cumulative strain path given the limited data available during magmatic lulls, but our tentative conclusion is that strain rates increased during flare-up events, which is why we show a non-steady-state increase in total strain through time (Fig. 6-16, panel #4). Intriguingly, we do not typically see high-strain aureoles around individual plutons. Thus, these aureoles have either been removed, or this pattern of increasing strain during flare-ups is related to regional processes, such as increased shortening aided by regional heating and weakening of the host rocks.

The rows below panel #4 on Figure 6-16 show a summary of the structural patterns and types of regional tectonism in the central Sierra that we summarized earlier. A comparison of all panels in Figure 6-16 suggests the following in regards to magmatic flare-ups: (1) there is a change in isotopic values consistent with introduction of new, typically more evolved units into melt source regions; (2) strain rates potentially increase and downward displacement of host rocks occur; and (3) rates and styles of plate motions, exhumation, and styles of tectonism don’t seem to play a direct role in causing flare-ups. However, more complex links are possible. For example, the possible increases in strain rates and downward flow are potentially linked to increased rates of tectonism, causing greater crustal thickening and lateral shortening, which in turn likely play a role in the introduction of new materials to zones of magma generation or contamination. Subtle changes in plate motions may also change tectonic styles in the arc resulting in the shifting of basement terranes, which then could play a role in introducing new materials to magma generation and/or contamination sites. Comparisons of different panels also indicate that magmatic activity was not strongly controlled by styles of tectonic regimes and thus refute models in which the magmatic system switches from volcanic- to plutonic-dominated activity during a tectonic switch from oblique to orthogonal convergence such as that presented by Glazner (1991) and/or models where flare-ups occurred during a certain tectonic regime (see discussion in Tobisch et al., 1995).

The above hypotheses must be viewed with the caveat that conditions during magmatic lulls remain much less well constrained simply due to the limited data on ages of deformation during lulls, lack of volcanic units to act as markers during these episodes, and paucity of temporally constrained geochemical data from lulls. It would thus be important for future studies to focus on these time periods, that is 200–180 Ma and 140–120 Ma. We also suspect that there is a much finer scale of temporal and spatial changes in tectonic styles within the arc that we cannot presently resolve and show on Figure 6-16.

ARC-SCALE MASS BALANCE ISSUES

A number of mass balance issues in arcs remain contentious such as (1) how space is made for the rising magmas; (2) the role of tectonism in shortening, thickening, and extending arc crust; (3) the magnitudes of tectonically and petrologically formed crustal roots; and (4) related issues of how the above link to mountain building and the support of high topography (Ducaea and Saleeby, 1998; Ducea, 2002; Frassetto et al., 2011; Putirka and Busby, 2011). Our central Sierran synthesis allows us to further evaluate these issues and to particularly address some huge mass balance challenges in magmatically active and deforming arcs. Our results indicate the following constraints on any attempts to address these issues: (1) basement terranes were largely in place prior to initiation of the arc at ca. 250 Ma; (2) at least 50% arc-perpendicular shortening (and likely significantly more) and at least ~100% vertical arc thickening occurred during the Mesozoic with shortening and thickening synchronous with ascent, magma chamber growth, and eruption of magmas; (3) between 250 and 85 Ma, a maximum of 5–6 km of crust was removed from the upper surface of the arc; (4) during ascent and emplacement of magmas, the boundaries of basement terranes,
regional faults, strikes of stratigraphic units, and contacts of older plutonic units were not significantly laterally displaced at the arc scale nor at the scale of individual batholiths; and (5) fractionation of mixed mantle and crustal melts is an important process during the rise and eruption of Sierra arc magmas.

If we consider an arbitrary 100-km-wide (a minimum width of deformed arc rocks) and 30-km-thick (a possible thickness to Moho prior to arc magmatism) section through the arc (Fig. 6-19), the tectonic constraints noted above indicate that this section would be laterally shortened to 50 km and vertically thickened to 60 km by the time the arc shut down. If we remove ~5 km from the top of this section as indicated by the exhumation curve (Fig. 6-16), then the Moho would be at ~55 km (Fig. 6-19). However, at the same time as shortening and thickening were occurring, magmas were ascending into this crust and now make up ~70% of the preserved exposures at both central Sierra crustal levels (7–11 km) and at the deeper crustal levels (20–30 km) exposed in the southern Sierra (Saleeby, 1990; Ducea and Saleeby, 1998; Saleeby et al., 2008; Paterson et al., 2011). The geochemistry of many of these magmas excludes

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Figure 6-19. Cartoon showing area balanced NE-SW–striking, vertical cross sections through the Mesozoic Sierra Nevada arc to emphasize the approximate magnitude of and links between both magmatic and host-rock mass balance processes in this arc. Note that these considerations strongly suggest that large volumes of crustal host rocks were driven downwards into the melting regions in zones typically considered to be mantle lithosphere. See text for full discussion.
significant assimilation of upper crustal materials indicating that ~60%–70% of the previous crustal host rock must have been displaced out of this portion of the arc. Since lateral shortening continued throughout arc magmatism and pre-arc, regional-scale markers are not laterally displaced, it is difficult to argue for lateral displacement of large volumes of host rock. Exhumation constraints preclude removal of significant materials off the top of the arc by erosion or tectonism. Some strike-slip faulting occurred during arc magmatism (Tobisch et al., 1995; Tikoff and Greene, 1997) but was largely parallel to the strike of the arc, not of large displacement relative to the arc, and thus may shift units in the arc, but will not remove any more host-rock volume from the arc than it brings in. Thus, a huge amount of host-rock downward transport is required, which would further lower the Moho and require that host rocks move downwards to at least 100 km (Fig. 6-19).

A temporally and spatially linked process also occurred in the growing column of magmatic bodies. Since the upper 30 km of this magmatic column is dominated by tonalite to granite overlain by erupted materials dominated by andesite to fairly com-}

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from the arc than it brings in. Thus, a huge amount of host-rock from the arc than it brings in. Thus, a huge amount of host-rock downward transport is required, which would further lower the Moho and require that host rocks move downwards to at least 100 km (Fig. 6-19).

A temporally and spatially linked process also occurred in the growing column of magmatic bodies. Since the upper 30 km of this magmatic column is dominated by tonalite to granite overlain by erupted materials dominated by andesite to fairly common rhyolite, a large lower section of mafic cumulates must have formed (Ducea and Saleeby, 1998; Lee et al., 2007). This is supported by both plutonic and volcanic units having chemistries indicating fractionation and is also well demonstrated by major-element mass balance calculations for xenolith and crustal compositions (Lee et al., 2006, 2007). Ducea and Saleeby (1998) concluded that an ~2:1 ratio must exist between lower crustal cumulates and the upper crustal fractionates and that the resulting magmatic column would extend down to >100 km.

Thus, a combination of tectonic shortening and thickening of the arc, emplacement of magmas into the deforming crust, and crustal-scale fractionation processes within magmatic bodies all played a role in the formation of a large crustal root beneath the arc that extended well down into mantle lithospheric regions (Fig. 6-19). Presumably, additional tectonic and magma processes also affected this mantle lithosphere, including volatile fluxing and melt generation, thus potentially leading to dynamic interactions between and recycling of crustal and mantle components beneath active arcs. For example, Ducea and Saleeby (1998), Ducea (2002), and Lee et al. (2006, 2007) discuss evidence from xenolith studies that require transport of crustal materials into the mantle beneath arcs, including loss of some of the crustal mass that is incorporated into arc roots that eventually founder. We suspect that some of the temporal evolution of isotopic values discussed above reflects the temporal evolution of rock types and environmental conditions during arc root–mantle interactions. Moreover, this mass exchange of dominantly upward movement of increasingly mixed and fractionated magmas and downward transport of displaced host rocks solves, without violating a number of structural constraints within the arc, the “space problem” required by largely replacing pre-arc host rocks by syn-arc plutonic bodies.

One intriguing theme in several of the discussions above is that of the downward movement of host-rock materials in the arc during the rise of magmas. We have seen direct evidence of this since volcanic rocks formed at the Earth’s surface now reside at 10–30 km depths and are intruded by plutons that sometimes have ages that lie within 1 m.y. of the age of the volcanic rocks. In an attempt to better understand both the rise of magmas and the return flow of host-rock materials, we are presently pursuing a finite-element modeling study of magmatic arcs. Figure 6-20 displays examples of two numerical simulations (produced by Wenrong Cao and Boris Kaus, 2012) of the incremental growth and rise of magma bodies into a crust that eventually founders. If time allows, we will discuss some of the issues with and implications of these simulations.

CONCLUSIONS

Through a synthesis of our new mapping, structural analyses, geochronology, and geochemistry with previous data sets, we reach the following conclusions for the central Sierra Mesozoic arc: (1) Both the plutonic and volcanic components of this ca. 250–85 Ma arc are spatially, temporally, and geochemically linked and thus part of the same vertically connected magmatic system. (2) Magmas in this arc are derived from mixing of mantle and crustal melts and show evidence of fractionation and remixing during ascent, the relative intensities of which may scale to the size and maturity of individual magmatic systems. (3) Fluctuations in arc magmatism (i.e., lulls and flare-ups and changing chemistries) are not directly related to plate motions or overall tectonic style but may be loosely linked to the rates and magnitudes of the tectonic deformation that resulted in the >100% vertical thickening and >50% horizontal shortening of the arc. (4) Both these tectonic and magmatic processes require the growth of large crustal roots beneath the arc consisting of downward-displaced host rocks and large cumulate piles, which in turn led to the modification of the underlying mantle lithosphere.

What about other segments of this arc and/or other arcs around the world? We are beginning to collect and evaluate similar coupled tectonic, geochronologic, and geochemical data sets from other Cordilleran arc segments (Paterson wishes to acknowledge an ongoing collaboration with Ben Clausen in a number of these projects), and we are beginning a comparison of these data sets. For example, Figure 6-21 is a preliminary comparison of isotopic data (included here to generate discussion) from a number of Mesozoic Cordilleran arc segments.

ROAD LOG

All UTM’s are in Nad83 Conus and zone 11S.

<table>
<thead>
<tr>
<th>Mileage</th>
<th>Directions</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 mi</td>
<td>Mammoth Inn. (0320123, 4169185)</td>
</tr>
<tr>
<td>4.0</td>
<td>Turn left (east) onto Main Street.</td>
</tr>
<tr>
<td>7.8</td>
<td>Go under Highway bridge, turn left, and head north on Hwy 395.</td>
</tr>
</tbody>
</table>
Figure 6-20. Two finite-element numerical simulations on ascent and emplacement of felsic plutons in a continental crust. Algorithms of multiple pulses and pseudo-diking are included. Wet quartzite flow law (Ranalli, 1995) is used for both crust and magma. Temperature field is shown below the material phases. In a warmer crust (top model, A to F), magma reservoirs are assembled incrementally by several diapiric bodies. The rising of diapiric magma is accommodated by downward transport of host-rock materials. In a colder crust (bottom model, a to f), the initial ascent of magma is aided by rise of magma in dikes. Later pulses of magma take advantage of the pre-heated weak zones defined by multiple dikes to reach shallower levels. In detail, intrusive units typically truncate the crust layers. The simulations are run on MILAMIN_VEP, a visco-elasto-plastic finite-element and marker-in-cell code by Wenrong Cao and Boris Kaus (2012, personal commun.). PRB—Peninsular Ranges batholith.
STOP 1: June Lakes Overview—Sierran Basement Terranes

While staring at the beautiful eastern escarpment of the Sierra Nevada, which exposes sections of Paleozoic metasedimentary units, and both volcanic and plutonic components of the Mesozoic arc, we will begin our discussion of arc-scale characteristics and processes by introducing to you two of our new regional data compilations: (1) >6000 Sierran detrital-zircon ages (mostly unpublished) and (2) >500 Sierran isotopic measurements (mostly published by others). We will use these to discuss the types and distributions of both mid-crustal host-rock terranes and potential mantle sources beneath these terranes.

STOP 2: Lee Vining Canyon Overview—The Mesozoic Arc

Here we are looking at Triassic, Jurassic, and Cretaceous plutons intruding Paleozoic metasediments and Mesozoic volcanics. We will examine regional maps of both the volcanic and plutonic components of this arc, look at regional geochronologic data sets, and discuss potential regional and temporal patterns in the arc.

STOP 3: Saddlebag Lake—Links between Regional Tectonics and Magmatism

From this viewpoint, we can look north across Saddlebag Lake and west toward Sawmill Canyon and see both pre-arc Paleozoic metasediments, the Triassic through Cretaceous volcanic section, and both Triassic and Cretaceous plutons all deformed by regional tilting, intense ductile strain, and large shear zones. What better place to discuss the potential connections between

Figure 6-21. Comparison of εNd-Sr isotopic pairs for different Mesozoic arc segments from southern Canada to Peru. Published and our new unpublished data compiled by Paterson and Ben Clausen.
regional tectonics, potential isotopic breaks, strain, and magmatic fabrics. We will introduce another new regional data compilation: >650 strain measurements across the Sierra Nevada arc.

STOP 4: Olmsted Point—Temporal and Spatial Evolution of Geochemistry (Internal Magma Processes?)

This stop was so fantastic the first time (Day 4, Stop 2), we decided to return. Here, we largely see a sea of plutonic material in every direction. So of course it is time to think about the temporal and spatial patterns of geochemical and isotopic data and grapple with the long-standing issue of what we can learn about potential sources of the magma and the magmatic processes occurring within the crustal columns. We will also discuss whether magmatic and volcanic components of the system are geochemically linked. Time for the geochemists to step up to the plate and take some swings!

STOP 5: Wawona Overlook of Yosemite Valley—Structure, Strain, Mass Balance, and Downward Flow

This is one of the most famous overlooks into Yosemite Valley. After enjoying the view and getting reacquainted with the intrusive complexes seen on Day 3, we will address the issue of tectonic and magmatic controls on arc tempos. Figures 6-22 and 6-23 display hypothetical and estimated tempos of magmatism at both the scales of arcs and individual magmatic systems. We can also think about some petrologic and tectonic mass balance processes in arcs and will present some in-progress, finite-element modeling of these processes.

We have now spent six days looking at a continental margin arc (1) at spatial scales ranging from single minerals to the entire arc and single plutonic/volcanic systems to the present-day result of many, sometimes interacting, magma plumbing systems; (2) at different geographic positions from the western (more oceanic affinity) to eastern (more continental basement) parts of the arc;
(3) by examining and comparing both magmatic and tectonic histories; and (4) by examining all of the above through time. Particularly the latter has allowed us to examine the “tempo” or “cyclicity” of processes in this arc and thus how it “lives and breathes.” There remains much to sort out about what drives arc tempos, about many of the standard petrologic issues of how we alter mantle and crustal magmas to get the final petrologically diverse arc present today, and about the tectonic shuffling of mantle sources, overlying tectonic basement terranes, and the role that active tectonism played in the evolving arc.

We hope the spectacular examples we saw of portions of this arc plus the tentative conclusions shared throughout the guide will inspire all of you to join our studies of this and other arcs to help solve the remaining mysteries.

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