Arc composition at mid-crustal depths: Insights from the Coast Ridge Belt, Santa Lucia Mountains, California

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[1]   The Coast Ridge Belt (CRB, Santa Lucia Mts., central California) comprises mid-crustal rocks ($750-800°C$ and 0.8 GPa) of the California magmatic arc. We estimated the bulk composition of the CRB and converted our results to seismic velocities expected at the observed pressures and temperatures. The bulk composition of this arc section changes abruptly at 25 km depth from a granodiorite to a quartz-diorite or diorite. These data are in agreement with results from other Cordilleran batholiths suggesting 1.5 to 2 times thicker felsic columns than interpreted for modern continental arcs, and a relatively sharp transition from a felsic upper crustal batholith, and a mafic deep crust. This implied rheological boundary may have significant implications for intracrustal faulting or convective removal of the roots of batholiths.   INDEX TERMS: 1020 Geochemistry: Composition of the crust; 3640 Mineralogy, Petrology, and Mineral Physics: Igneous petrology; 3655 Mineralogy, Petrology, and Mineral Physics: Major element composition; 7205 Seismology: Continental crust (1242); 8159 Tectonophysics: Rheology—crust and lithosphere. Citation: Ducea, M. N., S. Kidder, and G. Zandt, Arc composition at mid-crustal depths: Insights from the Coast Ridge Belt, Santa Lucia Mountains, California, *Geophys. Res. Lett.*, *30*(13), 1703, doi:10.1029/2002GL016297, 2003.

1.   Introduction

[2]   Some of the basic unresolved questions in continental arc geology are: (1) what are the thicknesses of major felsic batholiths?, and (2) do arcs develop foundering-prone, dense roots? The overall composition and structure of continental and oceanic arcs, especially at deep crustal levels is poorly known due to the limited number of deep-crustal arc exposures [e.g., *DeBari*, 1997]. Most information on the bulk crustal compositions of arcs comes from geophysical surveys, combined with data from laboratory experiments [e.g., *Christensen and Mooney*, 1995; *Graeber and Asch*, 1999].

[3]   The Phanerozoic batholiths of western North America are found along its convergent margin with the Pacific plate [*Anderson*, 1990]. Studies of the Sierra Nevada [*Ruppert et al.*, 1998; *Ducea*, 2001, 2002] and the Peninsular Range [*Lewis et al.*, 2000] segments of these arcs suggest that the thickness of the felsic batholiths exposed at the surface exceeds $20-25$ km. Thee results are at odds with the thinner, less than $10-15$ kms felsic batholiths, as proposed in recent review papers [*Christensen and Mooney*, 1995; *Rudnick and Fountain*, 1995]. However, there is no unique solution to the geological structure of these arcs at depth based on seismic results alone. There have been few attempts to link petrographic compositions and physical properties of exposed deep-crustal arc rocks [*Rudnick and Fountain*, 1995]. More recent work in several arcs (e.g. the Sierra Nevada [*Ruppert et al.*, 1998], and the Andes [*Graeber and Asch*, 1999]) has added significant information regarding the composition of arcs at depth. Still, comparatively much more data are available for extensional and collisional environments.

[4]   In this paper, we estimate the bulk chemistry and seismic velocity of a representative transect across the Coast Ridge Belt (CRB), one of the deepest exposures of the California arc (Figure 1a). We propose that a sudden increase in v_p from ~6 km/sec to ~6.5 km/sec marks the transition from large felsic batholiths to the mafic and ultramafic roots of arcs.

2.   The Coast Ridge Belt

[5]   The Salinian block of central coastal California [*Vedder et al.*, 1982] is located west of the San Andreas Fault, east of the Sur-Nacimiento faults and north of the Big Pine fault (Figure 1a and 1b). The ages and isotopic characteristics of widespread calc-alkaline tonalites and granodiorites [*Ross*, 1978] indicate that the Salinian basement is a middle crustal exposure of a Cretaceous arc. Magmatic activity began between 100 and 110 Ma, and continued until 79 Ma [*Mattinson*, 1978; *Kidder et al.*, 2003 hereafter referred to as K03]. The average composition of the Salinian arc is one of a granodiorite [*Ross*, 1978].

[6]   The Salinian terrane has traveled northward some 330 km during the Late Cenozoic along the San Andreas fault system. While late Cretaceous uplift exposed much of the Salinian arc to shallow or mesozonal depths of up to $\sim0.3-0.6$ GPa [*Wiebe*, 1970], some $0.7-0.8$ GPa exposures [*Hansen and Stuk*, 1993; K03] surfaced along what is now the western edge of the Santa Lucia Mountains. The area where deeper rocks are exposed is the CRB (Figure 1b, *Ross*, 1978). Metamorphic grade increases gradually as the CRB is approached from the east [*Wiebe*, 1970]. The rocks exposed along the CRB represent a tilted exposure of a Cordilleran magmatic arc, with exposure depths ranging from $25-30$ km in the west to some 10 km in the east. This tilted section reveals a transition from shallow "batholithic" depths where metamorphic screens and pendants are vertical, to the exposure levels of the CRB where the foliation of the framework was horizontal (Figure 2). The transition took place at about 25 km beneath the arc [K03].

[7]   Detailed mapping and petrography of rocks from the Cone Peak area (Figure 1c) indicate that peak metamorphic conditions were 800° C and 0.8 GPa. Substantial ductile deformation of the more felsic rocks took place between
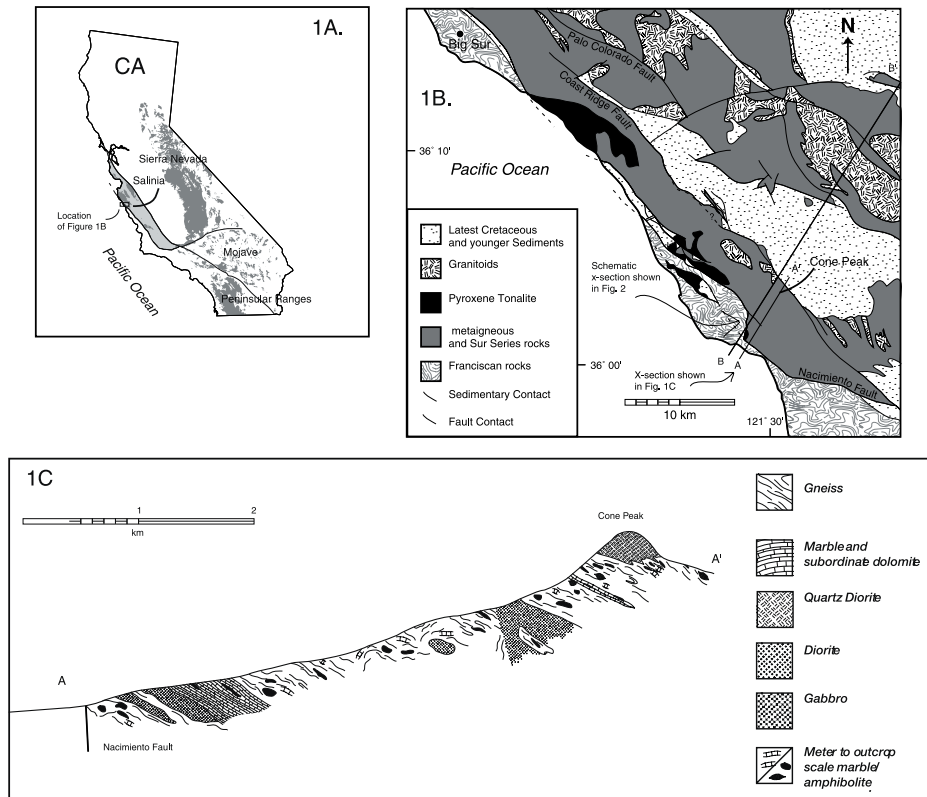
Figure 1. (A) Map showing the state of California and outcrops of Mesozoic batholithic rocks in light grey. Major strike slip faults of Cenozoic age are also shown. The segments of the California arc described in the paper, Sierra Nevada, Peninsular ranges, Salinia, and Mojave are shown. (B) Detail geologic map of Salinia in the Santa Lucia Mountains [after K03]. We interpret that a transect such as B-B' from the coast inland represents a relatively intact but tilted exposure of the Salinian arc, despite the presence of strike-slip faults in the area. (C) Geologic cross-section through the Cone Peak transect. Samples from along this cross-section and unit thicknesses were used for bulk chemistry estimates in this study.

93 and 80 Ma, concomitant with major intrusion of mafic to intermediate magmas in the section. At paleo-depths of 25–26 km of the CRB, mafic and intermediate materials are far more common than they are anywhere in the shallow exposures. Mafic sills have been emplaced at these depths but have rarely escaped into the shallower levels of the crust. This observation suggests that the current depth of exposure in the CRB represented the neutral level of buoyancy for mafic arc magmas. These interpretations were used to propose that large volume ($100-1000$ km^3) felsic plutons mapped in Cordilleran batholiths may root into mid-crustal low-strength zones spreading out horizontally as gravity currents [K03; Figure 2].

3. Results

3.1. Bulk Chemistry Estimations

[8] Our bulk composition estimate at paleo-depths of 25 km is based on the chemical analysis of 15 samples selected as the most representative of the various lithologies in the Cone Peak area (Auxiliary material can be found at ftp://ftp.agu.org/apend/gl/2002gl016297/). There are no major along-strike compositional heterogeneities. One exception is the large pyroxene tonalite body at Big Sur, ∼30 km north of the Cone Peak area [*Compton*, 1960]. This pluton is of a compositional type not represented elsewhere in the mapped area but makes up ∼14.5%

of the CRB surface area [*Ross*, 1978]. Three samples of this body were included. The weighting factors used in the bulk composition estimations are based on the field observations in the study area. Cross sections were created in order to establish the average thickness of the map-scale units (Figure 1c; K03). Marble units, which comprise about 9% by volume of the studied section, are not included in this estimate.

[9] A second estimate used the same criteria as the first, with the exception that the weighting factors were based on the distribution of the most mafic units along the strike of the CRB. For the third estimate, a bias towards the most felsic weights was used. The range covered by these estimates corresponds to SiO$_2$ contents between 52% and 57.4%. (Table 1), the approximate composition of a basaltic andesite to andesite (quartz-diorite to tonalite). The range from 52% to 57% corresponds to a gap in SiO$_2$ content separating the more mafic samples from felsic gneiss and tonalite samples, a result reflecting our observation that the CRB is a mixture of roughly equal proportions of mafic and felsic rocks.

3.2. Seismic Velocity Estimations

[10] The bulk composition estimate allows comparison between the CRB and modern *in situ* arcs. We converted our bulk composition estimates to estimates of Vp [*Sobolev and Babeyko*, 1994]. At 750–800°C and 0.75–0.80 GPa, the
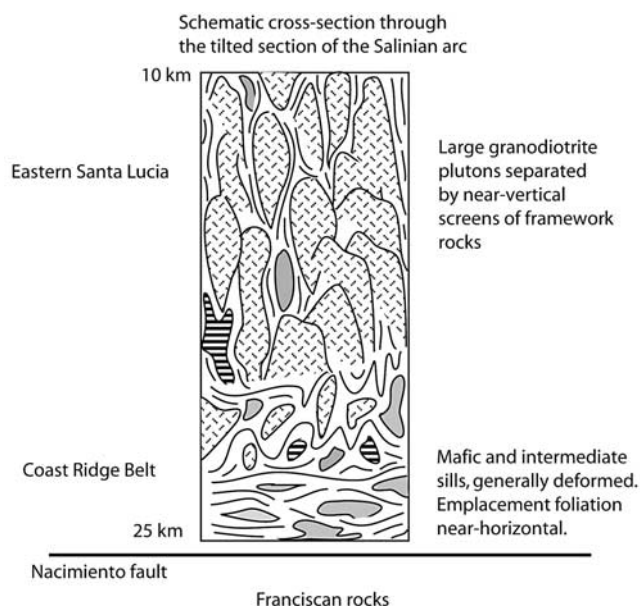
Figure 2. Schematic stratigraphic column through the tilted exposed section of the Salinian arc in the Santa Lucia Mountains. This section corresponds to the transect B-B' in Figure 1B starting in the CRB, "B" and ending in the eastern Santa Lucia Mountains, "B". The base of the column is faulted by the Nacimiento fault.

three bulk composition estimates were converted to anhydrous assemblages of plagioclase, ortho- and clinopyroxene, quartz, alkali feldspar, and magnetite. The resulting estimates of Vp range from 6.56 to 6.69 km/s. Marble, which was excluded from the bulk composition and seismic velocity calculations, has a seismic velocity of ~6.0 km/s at 750°C and 0.75 GPa [*Kern*, 1982] and would lower the above estimates by 0.06 to 0.08 km/s.

[11] At 0.75 GPa, garnet enters the 8-component system of *Sobolev and Babeyko* [1994] upon cooling to ~700°C, thereby increasing seismic velocities. The presence of garnet in the CRB with recorded temperatures of 750–800°C [*Hansen and Stuk*, 1993] is at odds with model results, and may result from the influence of fluids or other components not considered by *Sobolev and Babeyko* [1994]. The absence of water in the modeled system prevents the formation of hornblende and biotite. Replacing 10% of total rock mass of pyroxene composition with a 10% hornblende component, brings calculated mineral modes roughly in equivalence with the observed modes. This substitution decreases the calculated velocities by ~0.06 km/s. The combined effect of the hydrous minerals is therefore likely to decrease the estimated velocities by about 0.1 km/s.

4. Comparison With Regional Geological and Geophysical Data

[12] The uncertainties in the velocity estimates are within existing values of *in-situ* arc middle-lower crust averages. The estimated Vp of the CRB is between 6.39 to 6.5 km/s. *Christensen and Mooney* [1995] suggest an average of 6.69 ± 0.28 km/s at 25 km in modern arcs. This average is

slightly more mafic than ours. *Ruppert et al.* [1998] and *Fliedner et al.* [2000] interpreted results from a seismic refraction experiment across the Southern Sierra Nevada and showed that the crust beneath the batholith consists of some 25 km of felsic material (Vp = 6.0 km/sec). This material is underlined by a 5 km layer with Vp ~ 6.5 km/sec, very similar to Salinia. Some 5–7 km were removed by erosion from the top of the Sierra Nevada batholith since the Cretaceous [*Ague and Brimhall*, 1988]. Hence, the original batholith thickness was about 5 km thicker than the Salinian arc. The change in composition from felsic to mafic appears to be abrupt, a few kilometers at the most. At these crustal levels, felsic rocks should have low strength and deform ductilely, as supported by textural evidence in the field. The mafic and intermediate assemblages, in contrast, are stronger and are unlikely to flow at those depths. This abrupt change in composition could represent a favorable rheological boundary for subsequent detachment, either for intracrustal faulting or for convective removal of the deeper arc crust [*Meissner and Mooney*, 1998; *Ducea*, 2002].

[13] Another comparison that can be made is to the active Andean volcanic arc along the Western Cordillera of central South America between approximately 22° to 24°S [*Beck and Zandt*, 2002; *Graeber and Asch*, 1999; *Chmielowski et al.*, 1999]. Figure 3 shows a comparison between seismic velocity structures compiled for a global arc average [*Christiansen and Mooney*, 1995], the Andean Western Cordillera [*Graeber and Asch*, 1999], the southern Sierra [*Ruppert et al.*, 1998], and the upper portion of the Salinian arc K03. The depth scale was adjusted to the time the arc was active; consequently, erosion has been taken into account for the Mesozoic Sierran and Salinian arcs. In contrast to the global average model, all three arcs are characterized by thick granitic layers with a transition to more intermediate compositions at ~25 km. In the Andes, the presence of dipping seismic anisotropy in the crust above the magma body suggests a similar change in either rheology or stress state [*Leidig and Zandt*, 2003].

5. Implications

[14] The data above and in K03 show that there is a major compositional change from felsic intrusions separated by

Table 1. Average Major Element Composition of the CRB: Best Estimate, Mafic and Felsic End-Members

	Best estimate	Mafic end-member	Felsic end-member	Santa Lucia (20-10 km)
SiO_2	54.6	53.0	57.4	64.7
Al_2O_3	17.6	17.5	16.9	16.8
FeO	8.0	8.9	7.5	4.8
MgO	4.3	4.9	3.6	1.6
CaO	7.9	8.9	6.9	3.8
Na_2O	3.0	2.9	3.2	3.6
K_2O	0.9	0.9	0.8	1.9
TiO_2	1.5	1.6	1.2	1.2
Total	97.8	98.7	97.5	98.4
Vp (km/s)	6.45[a]	6.39[a]	6.51[a]	~6.0[b]

The average compositions of the shallower exposures east of the CRB (an un-weighted Santa Lucia mean calculated from *Ross*, 1978) are given for comparison. Best estimate, mafic, and felsic compositions are explained in text.

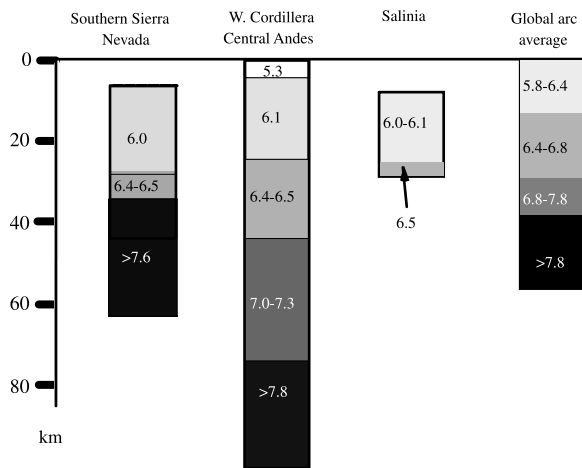[a] at 800C and 0.8 GPa.

[b] at 400C and 0.4 GPa.

Figure 3. Schematic crustal composition columns for various arcs. Numbers in each column represent compressional wave velocities (Vp) in km/sec. Values higher than 7.6 km/sec shown in dark boxes correspond to sub-Moho (sub-crustal) lithologies. The Sierra Nevada column is based on seismic refraction data from *Ruppert et al.* [1998], western central Andean Cordillera from tomographic data [*Graeber and Asch*, 1999], the global arc average from *Christensen and Mooney* [1995]. The Salinian exposure (10–25 km paleo-arc depths) is described in this paper and in K03. The lack of a mafic lower crust in the Sierra Nevada is probably a consequence of Cenozoic lower crustal delamination [*Ducea*, 2002].

near-vertical screens to near-horizontal sill-like intrusions of intermediate to mafic composition at ~25 km beneath the Salinian arc. The upper 25 km of the Salinian arc consist of rocks with the average of a granodiorite, whereas at 25 km deep the crust becomes intermediate to mafic in composition. The change is abrupt in the CRB and essentially represents the top of the root of the large felsic plutons in this arc. A similar change is evident in the central and southern Sierra Nevada batholith [*Pickett and Saleeby*, 1993; *Ducea*, 2002] and in the central Andes.

[15] We suggest that this is a widespread characteristic of the crustal architecture of other large continental magmatic arcs. The main implications of this result are:

[16] 1. The thickness of granitic batholiths may be at least 25 km, 1.5–2 times the previously suggested thickness by worldwide compilations of arc data [*Christensen and Mooney*, 1995; *Rudnick and Fountain*, 1995];

[17] 2. There may be an abrupt transition from felsic to intermediate and mafic assemblages in Cordilleran arcs. This transition could serve as a detachment surface for convective removal of the roots of arcs [*Kay and Kay*, 1991; *Jull and Kelemen*, 2001], or crustal faulting.

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