

Constraints on the bulk composition and root foundering rates of continental arcs: A California arc perspective

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[1] Garnet pyroxenites are the most common deep lithospheric xenolith assemblages found in Miocene volcanic rocks that erupted through the central part of the Sierra Nevada batholith. Elemental concentrations and isotope ratios are used to argue that the Sierra Nevada granitoids and the pyroxenite xenoliths are the melts and the residues/cumulates, respectively, resulting from partial melting/fractional crystallization at depths exceeding 35–40 km. The estimated major element chemistry of the protolith resembles a basaltic andesite. Effectively, at more than about 40 km depth, batholith residua are eclogite facies rocks. Radiogenic and oxygen isotope ratios measured on pyroxenites document unambiguously the involvement of Precambrian lithosphere and at least 20–30% (mass) of crustal components. The mass of the residual assemblage was significant, one to two times the mass of the granitic batholith. Dense garnet pyroxenites are prone to foundering in the underlying mantle. An average removal rate of 25–40 km³/km Myr is estimated for this Cordilleran-type arc, although root loss could have taken place at least in part after the cessation of arc magmatism. This rate is matched by the average subcrustal magmatic addition of the arc (~23–30 km³/km Myr), suggesting that the net crustal growth in this continental arc was close to zero. It is also suggested that in order to develop a convectively removable root, an arc must have a granitoid melt thickness of at least 20–25 km. Residues of thinner arcs should be mostly in the granulite facies; they are not gravitationally unstable with respect to the underlying mantle. *INDEX TERMS*: 1020 Geochemistry: Composition of the crust; 1040 Geochemistry: Isotopic composition/chemistry; 3640 Mineralogy and Petrology: Igneous petrology; *KEYWORDS*: arc, bulk composition, root foundering, Sierra Nevada

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1. Introduction

[2] Models that incorporate melting of the mantle wedge above a subduction zone have been proposed for the origin of both oceanic and continental arcs. The limitation of simple mantle melting models is that typical olivine-rich upper mantle compositions (peridotites) can not produce granitoids by partial melting [e.g., *Wyllie*, 1984]. Either mafic melts generated in the mantle have later incorporated a substantial amount of preexisting continental crust [*DePaolo*, 1981], large scale fractional crystallization led to the distillation of uppermost crustal granitoids while leaving behind large volumes of mafic restites and cumulates [*Coleman et al.*, 1992], or both.

[3] The late Mesozoic–early Cenozoic batholiths of western North America (known as Cordilleran batholiths) are found along its convergent margin with the Pacific oceanic plate [*Anderson*, 1990]. Geologic and geophysical data indicate the granitoid thickness (hereafter also referred to as the “melt column” thickness) of some of the North American arc segments is about 20–30 km [*Ruppert et al.*,

1998; *Fliedner et al.*, 2000; *Lewis et al.*, 2000]. The trace element and isotope record of Cordilleran-type batholiths [*Hildreth and Moorbath*, 1988; *Barton*, 1996] suggests that continental basement is a significant component; hence, modification of mantle wedge melts must have taken place in the middle to deeper crust beneath the arcs. The proposed deep crustal domain of primary melt modification is known as the MASH zone, the zone of melt mixing, assimilation, storage, and homogenization [*Hildreth and Moorbath*, 1988]. The MASH zones must fundamentally represent the *residual* low-silica mass required to complement the silicic batholiths and volcanic rocks found in arcs. They could form either via fractional crystallization (as cumulates) and/or partial melting in the lower crust (as restites). Geochemically it is difficult to distinguish between these two processes. In this paper the nongenetic term “residue” is used to refer to restite and cumulate. The composition and distribution of the residues in these giant magmatic systems is generally known only speculatively, based on information on batholith rocks [e.g., *Gromet and Silver*, 1987] and experimental data simulating melting/fractionation of mafic to intermediate sources at deep crustal pressures [e.g., *Rapp and Watson*, 1995]. This is a major limitation in deciphering the bulk composition of arcs, the relative balance of

reservoirs involved (lithospheric mantle, lower cratonic crust, upper crust, etc.), and ultimate relevance of Cordilleran arcs to crustal growth.

[4] The Sierra Nevada batholith of California is a typical Mesozoic Cordilleran batholith, composed primarily of tonalitic and granodioritic plutons, 87% of which were emplaced between 100 and 85 Ma [Saleeby, 1990; Ducea, 2001]. Granitoid rocks are known from present-day surface exposures to extend to a depth of at least 30 km in the Cretaceous crustal column [Pickett and Saleeby, 1993]. Samples of more deeply seated rocks are entrained as xenoliths in extension-related Miocene volcanic rocks from the central Sierra Nevada [Ducea and Saleeby, 1996, and references therein]. These provide a rare opportunity to constrain the composition of a Cordilleran batholith in the vertical dimension to levels that have not been exposed at the surface by tectonic processes (~100 km deep). In this paper, new major and trace element, as well as Sr, Nd, Pb, and O isotope data are reported on xenoliths from the deep lithosphere collected from the Miocene San Joaquin field [Dodge *et al.*, 1986, 1988; Ducea and Saleeby, 1996], central Sierra Nevada. These data are used to (1) investigate the petrologic relationship between the batholith and the deeper lithosphere beneath the Sierra, (2) estimate the bulk chemistry of the Sierra Nevada arc, and (3) place constraints on the rate of return to the mantle of large arc roots.

2. Sierra Nevada Garnet Pyroxenites

[5] Four lithologic types of xenoliths were described in central Sierra Nevada Miocene volcanic rocks: (1) *granulites*, which are high-Al feldspathic rocks with lower crustal mineralogy (e.g., rich in pyroxenes and garnets), equilibrated at depths between 20–30 and 35–45 km; (2) *garnet pyroxenites*, all of which are feldspar-free rocks, including some rocks transitional to eclogites (i.e., Na-rich pyroxenites), and generally equilibrated at >35 km depth; (3) *metasediments* with barometric record demonstrating residence in the deep crust (deeper than 20 km); and (4) peridotites (bearing spinel and/or garnet), which equilibrated at >45 km deep, and are the deepest samples from the Sierran lithosphere (see a summary of petrography in the works of Wilshire *et al.* [1988] and Ducea and Saleeby [1996]). The most common petrographic types observed in these central Sierra Nevada xenoliths and the subject of this paper are cumulate-textured pyroxenites, commonly garnet-bearing, amphibole-bearing, and occasionally transitional to eclogites, i.e., rocks with high-Na clinopyroxene [Dodge *et al.*, 1988; Ducea and Saleeby, 1996]. These assemblages are broadly classified as eclogite facies rocks. Barometric determinations [Mukhopadhyay and Manton, 1994; Ducea and Saleeby, 1996] indicate that garnet-bearing Sierra Nevada pyroxenites equilibrated over a large range of depths between ~35–40 and as much as 100 km, whereas granulites equilibrated at less than 40 km. The depth interval between 40 and 100 km probably represents a complex petrologic subarc transition from a lower crust (eclogitic) to an upper mantle (peridotitic) environment, even though most of this material would be identified seismologically as “mantle” based on the high P wave velocities of both eclogite facies and peridotitic rocks.

Peridotites are rare in these xenolith populations; they contain either spinel, spinel + garnet or garnet and appear to have equilibrated at depths between 45 km [Lee *et al.*, 2000] and 125 km [Ducea and Saleeby, 1998b]. The abundance of garnet pyroxenites, including some composite samples displaying transitions to feldspathic lithologies, and mass balance arguments presented below, suggest that olivine-free garnet + pyroxene (\pm amphibole) assemblages had to have been important at depths between ~35 and at least 70 km and possibly as much as 100 km beneath the Sierra Nevada batholith.

[6] Eight pyroxenites (Table 1) were selected from a larger set of 60 samples by picking those with the least amounts of alteration products as noted in thin section. The selected samples all display negligible (0–2%) interactions with the host volcanic rocks [Ducea and Saleeby, 1998b].

3. Analytical Techniques

[7] Major elements were determined on an automated, wavelength dispersive X-ray fluorescence spectrometer at the University of Southern California. Trace element determinations were performed on an Ar source quadrupole ICP-MS at Caltech. USGS and NBS standards were used for calibrating the XRF and ICP-MS instruments [Ducea, 1998]. Sr and Nd isotopes were measured using the techniques described by Ducea [1998] and Ducea and Saleeby [1998b]. The common isotopes of lead were analyzed on whole rock samples, previously dissolved for Sr and rare earth element (REE) separations. Separate batches of dissolved samples were saved for lead chemistry. Lead was extracted using an anion exchange procedure modified after Chen and Wasserburg [1981]. Isotopic analyses were performed on a VG Sector TIMS instrument. All isotopes were measured in Faraday cups, with the exception of samples with low signal, whose ^{204}Pb was measured using a Daly photomultiplier.

[8] Olivine, pyroxene, garnet, amphibole, plagioclase, and/or quartz clean mineral separates (1–2 mg) were analyzed for oxygen isotopic ratios. The oxygen was extracted using a laser fluorination line, followed by analysis of isotopic ratios of major minerals [Holt and Taylor, 1998], expressed as $\delta^{18}\text{O}$ in per mil relative to SMOW. The whole rock $\delta^{18}\text{O}$ values were calculated by material balance using the modal proportions of major minerals in each sample. The extracted oxygen was converted to CO_2 using a heated carbon rod. This CO_2 was analyzed with a Finnigan MAT252 mass spectrometer. Precision is better than 0.2 per mil (1σ) for mineral separates analyzed in this study. The departures of individual mineral analyses from the whole rock averages were always within the analytical uncertainties of the method, a minuscule fractionation predicted for the silicates present in these rocks when equilibrated at lower crustal/upper mantle temperatures.

4. Geochemical Results

[9] The pyroxenites form trends that are oblique to the trends defined by the granitic batholith on major element diagrams (Figure 1). These weak correlations among the various major oxides in the pyroxenites can be explained in

Table 1. Major and Trace Element Concentrations of Central Sierra Nevada Xenoliths

Sample	Bc221	Bc216	Bc218	B75	F34	Bc207	G39	G36	ASP ^a
^b	o/c/g/h	c/g/h	g/c	g/c/p	c/o/g	g/c/h	g/c	c/g/h	
SiO ₂	43.15	45.75	41.67	43.14	47.77	45.5	45.2	46.08	44.78
TiO ₂	1.09	0.27	0.34	2.87	1.17	0.53	3.46	0.58	1.29
Al ₂ O ₃	12.95	17.6	20.56	13.64	7.15	12.58	9.41	12.68	13.21
FeO ^c	19.1	9.08	14.52	16.4	8.87	9.12	12.69	12.1	12.73
MnO	0.32	0.14	0.27	0.27	0.12	0.88	0.14	0.19	0.29
MgO	18.53	9.85	11.37	8.72	16.76	5.71	11.52	11.82	11.78
CaO	2.81	10.08	9.4	12.06	16.6	23.58	14.37	14.58	12.93
Na ₂ O	0.13	1.33	0.26	1.2	0.83	3.38	1.49	1.27	1.24
K ₂ O	0.25	0.37	0.30	0.21	0.13	0.35	0.29	0.23	0.27
P ₂ O ₅	0.01	0.01	0.34	0.13	0.01	0.01	0.01	0.01	0.07
Rb	11.39	11.25	23.33	6.54	2.45	1.64	8.45	8.29	9.17
Sr	43.34	197.5	60.77	131.1	129.9	40.69	71.38	93.95	96.08
Y	37.64	4.59	17.63	57.29	10.47	22.69	14.49	66.16	28.87
Zr	31.24	9.35	16.48	69.49	20.42	16.17	130.4	14.44	38.49
Nb	3.22	0.40	0.53	7.52	0.57	1.17	29.06	0.23	5.34
Ba	163.3	152.8	335.2	181.1	54.11	55.72	66.68	205.7	151.83
La	1.43	1.16	0.37	8.38	2.40	2.95	8.07	1.05	3.23
Ce	2.68	2.85	0.67	20.29	6.86	4.48	26.26	1.28	8.17
Pr	0.49	0.57	0.151	3.74	1.55	0.69	5.73	0.68	1.7
Nd	2.12	2.78	1.177	17.31	7.55	2.36	24.91	4.78	7.87
Sm	0.81	0.64	1.036	5.22	2.25	0.61	5.17	2.78	2.31
Eu	0.44	0.29	0.497	1.58	0.59	0.19	1.17	1.12	0.73
Gd	2.25	0.67	2.521	7.35	2.28	1.06	4.31	5.31	3.21
Tb	0.45	0.10	0.437	1.11	0.28	0.18	0.45	0.89	0.49
Dy	4.35	0.62	3.753	8.61	1.63	1.86	2.42	8.02	3.91
Ho	1.13	0.10	0.876	1.97	0.29	0.51	0.43	1.64	0.87
Er	2.51	0.28	2.155	4.75	0.70	1.43	1.01	3.60	2.05
Tm	0.47	0.04	0.322	0.74	0.09	0.24	0.12	0.65	0.33
Yb	5.08	0.27	3.344	8.31	1.11	2.96	1.33	7.05	3.68
Lu	1.11	0.11	0.735	1.73	0.19	0.67	0.29	1.69	0.81
Hf	0.72	0.24	1.013	2.97	0.97	0.74	4.56	0.61	1.48
Ta	0.07	1.55	0.048	1.41	0.01	0.04	0.27	0.01	0.43
Th	0.21	0.20	0.004	0.19	0.02	0.19	0.11	0.07	0.12
U	0.11	0.12	0.051	0.18	0.03	0.12	0.22	0.10	0.12

Major element concentrations are in oxide wt.%, trace element concentrations in ppm.

^aASP = average Sierran pyroxenite.

^bMajor constituent minerals. Abbreviations: c = clinopyroxene, o = orthopyroxene, h = amphibole, g = garnet, p = plagioclase, and wr = whole rock.

^cTotal FeO + Fe₂O₃.

terms of the modal variations of the dominant minerals (pyroxenes, garnet and amphibole); this is interpreted to represent an artifact of the small sample sizes (2–5 cm radius), combined with the rather large grain sizes (~0.25–0.5 cm radius) of the analyzed xenoliths. Using the data presented in Table 1, the average major and trace element concentrations of the Sierra Nevada pyroxenites were calculated. The major element concentrations of the pyroxenites are within 5% of the average pyroxenite major element concentrations calculated using the average mineral chemistry of pyroxenes and garnets determined on 22 samples [Ducea and Saleeby, 1996], together with the average modal proportions of pyroxenes and garnets (pyroxene/garnet = 3/2) estimated from a total of 60 thin sections. Thus, there is an excellent correspondence between the entire pyroxenite population and the subset of 8 xenoliths analyzed in detail in this study. For example, the average SiO₂ concentrations measured in the 8 xenoliths is 44.71 wt.%, whereas the average SiO₂ calculated from modes and mineral chemistry on the larger data set is 45.01 wt.%.

[10] The trace element concentrations vary by a factor of as much as 30 in the Sierran pyroxenites (Figure 2). However, the abundances are correlated with the modal abundances of garnet, pyroxene, and amphibole in the

samples. For example, the garnet-rich samples (which are also the lowest in silica) have the lowest La/Yb ratios. The REE pattern of the pyroxenite average is flat with abundances of about 10 times those of chondrites.

[11] The range of calculated whole rock oxygen isotope compositions ($\delta^{18}\text{O} \sim +6.5\%$ to $+8.5\%$) (Tables 1 and 2) from the analyzed Sierran pyroxenites is practically identical to the range of values measured in the central Sierra Nevada granitoids [Masi *et al.*, 1981]. The Sierran pyroxenites show consistently higher $\delta^{18}\text{O}$ values compared to the $\delta^{18}\text{O} < 6.4\%$ measured in spinel + garnet and garnet peridotites from the same locations [Ducea, 1998]. These garnet-bearing pyroxenites have Sm-Nd mineral ages [Ducea and Saleeby, 1998b] identical to the range of ages calculated for the surface plutons in the central parts of the batholith [Chen and Moore, 1982, Coleman *et al.*, 1992]. The intercepts on Nd isochrons [Ducea and Saleeby, 1998b], and the age-corrected isotopic ratios of Sr and Pb measured on these samples (Table 1) also fall within the range of ratios measured on the surface granitoids of the central Sierra Nevada [Kistler and Peterman, 1973, 1978; DePaolo, 1981; Chen and Tilton, 1991; Coleman *et al.*, 1992; Coleman and Glazner, 1998] (Figure 3). The geochronologic and whole rock isotopic data indicate that the garnet pyroxenites are in some manner cogenetic with the

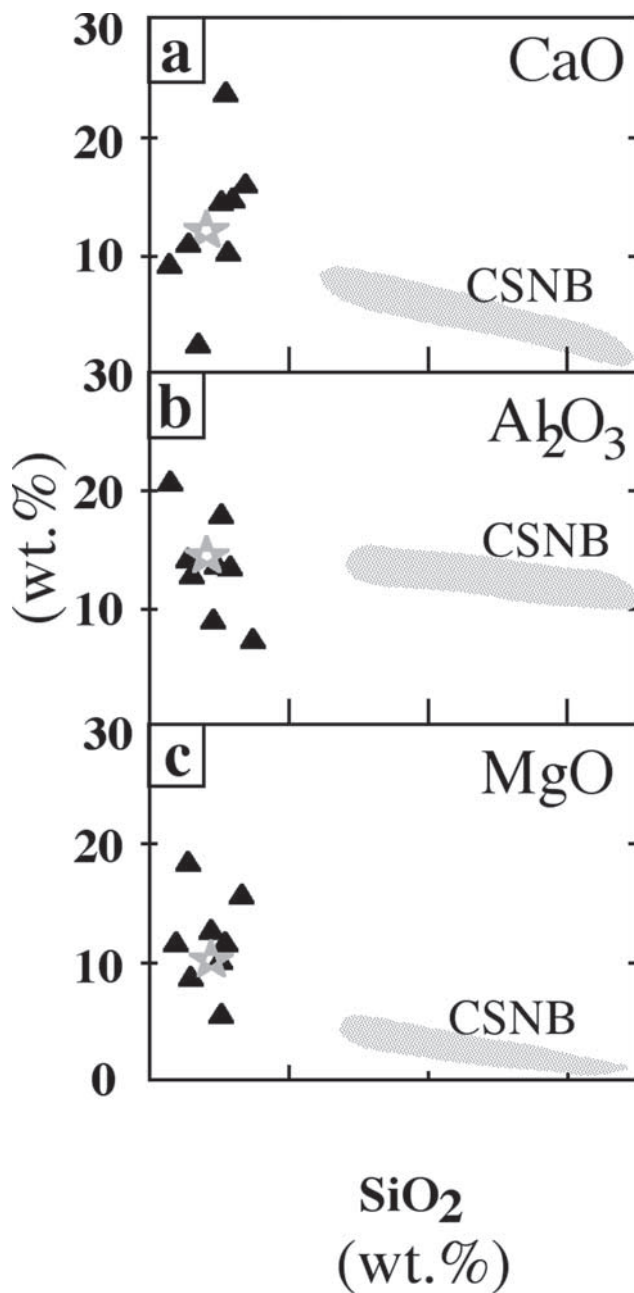


Figure 1. Silica variation diagrams for (a) CaO, (b) Al₂O₃, and (c) MgO (all oxides in wt.%) for Sierran pyroxenite xenoliths (black triangles) and granitoid rocks from the surface outcrops of the central Sierra Nevada batholith (CSNB) in the vicinity of the xenolith-bearing volcanic rocks (data shown with dotted fields from the work of *Bateman and Dodge* [1970]). The average Sierran pyroxenite, calculated as explained in text, is represented by a star symbol.

overlying batholith, presumably as melts, cumulates, or restites after melt extraction.

5. Origin of Sierran Pyroxenites

[12] Pyroxenites major element concentrations (e.g., SiO₂ as low as 41.7 wt.%) indicate that these rocks cannot be

simply the high pressure equivalents of basaltic melts (e.g., modern MORB or eclogites from subduction complexes); instead, taken together with their textures and mineralogical features, the major element data are most consistent with a residual origin for these xenoliths.

[13] The REE compositions of silicate melts (C_l) that would have been in equilibrium with the average pyroxenite (C_s) were modeled. The results of this calculation depend only on the modal proportions of solids in the residue and the partition coefficients (D) for any given element (i), and not on the percent of partial melt (C_s = D_iC_l). Partition coefficients appropriate for equilibrium between an intermediate melt (quartz-normative, 60 wt.% SiO₂) and crystalline solids (pyroxene/garnet/amphibole, data summarized by *Rollinson* [1993]), were used. A close match between the model melts and the trace element concentrations observed in the Sierra Nevada granitoids (Figure 2b) was obtained. This result suggests that the central Sierra Nevada granitoids differentiated by partial melting or fractional crystallization at deep crustal/upper mantle depths from a predominantly garnet-rich and plagioclase-poor residue similar to the xenolithic pyroxenites.

[14] This interpretation is further supported by the Nd mineral ages of the pyroxenites studied here [*Ducea and Saleeby*, 1998b]. These ages are coeval with the late Cretaceous magmatic pulse in the Sierra Nevada (120–80 Ma) [*Ducea*, 2001]. The similarity between the ⁸⁷Sr/⁸⁶Sr, ¹⁴³Nd/¹⁴⁴Nd, ²⁰⁶Pb/²⁰⁴Pb, ²⁰⁷Pb/²⁰⁴Pb, ²⁰⁸Pb/²⁰⁴Pb, and δ¹⁸O isotopic ratios of the Sierran pyroxenites and the surface batholith is also indicative of a genetic relationship. Figure 3 shows the distribution of isotopic ratios measured on deep crustal xenoliths from the San Joaquin field compared to the average isotopic ratios measured on surface batholith rocks within a 20 km radius of the San Joaquin field and the range of ratios measured throughout the central Sierra Nevada granitoids. The pyroxenite data match the surface batholith ratios for every isotopic system investigated. The xenoliths as well as the bulk of the batholith are dominated by a component represented by old lower crustal lithospheric mantle material (component “C” of *Ducea* [2001]). The shallower, granulite facies residual xenoliths studied by *Dodge et al.* [1986] and *Clemens-Knott* [1996] from the San Joaquin field are typically more enriched in a supra-crustal component (“S” of *Ducea* [2001]) and could not match, alone, the ratios measured in the surface batholith.

[15] It is here proposed here that these xenoliths represent samples of a residual MASH zone underlying the Sierra Nevada batholith. While xenoliths of both granulitic and pyroxenitic compositions are residual to the surface batholith, trace element and isotopic ratios suggest that the garnet pyroxenites constitute the main residual mass.

6. Garnet Pyroxenites and Arcs

[16] These results and interpretations suggest that a giant Cordilleran granitic batholith like the Sierra Nevada to a first order were extracted from a lower crustal “eclogitic” residue, in contradiction to most models on generation of large-scale granitoids that postulate a “granulitic” residue [e.g., *Clemens and Vielzeuf*, 1987]. Shallower melt generation in the granulite field cannot be ruled out but appears to have been less important here.

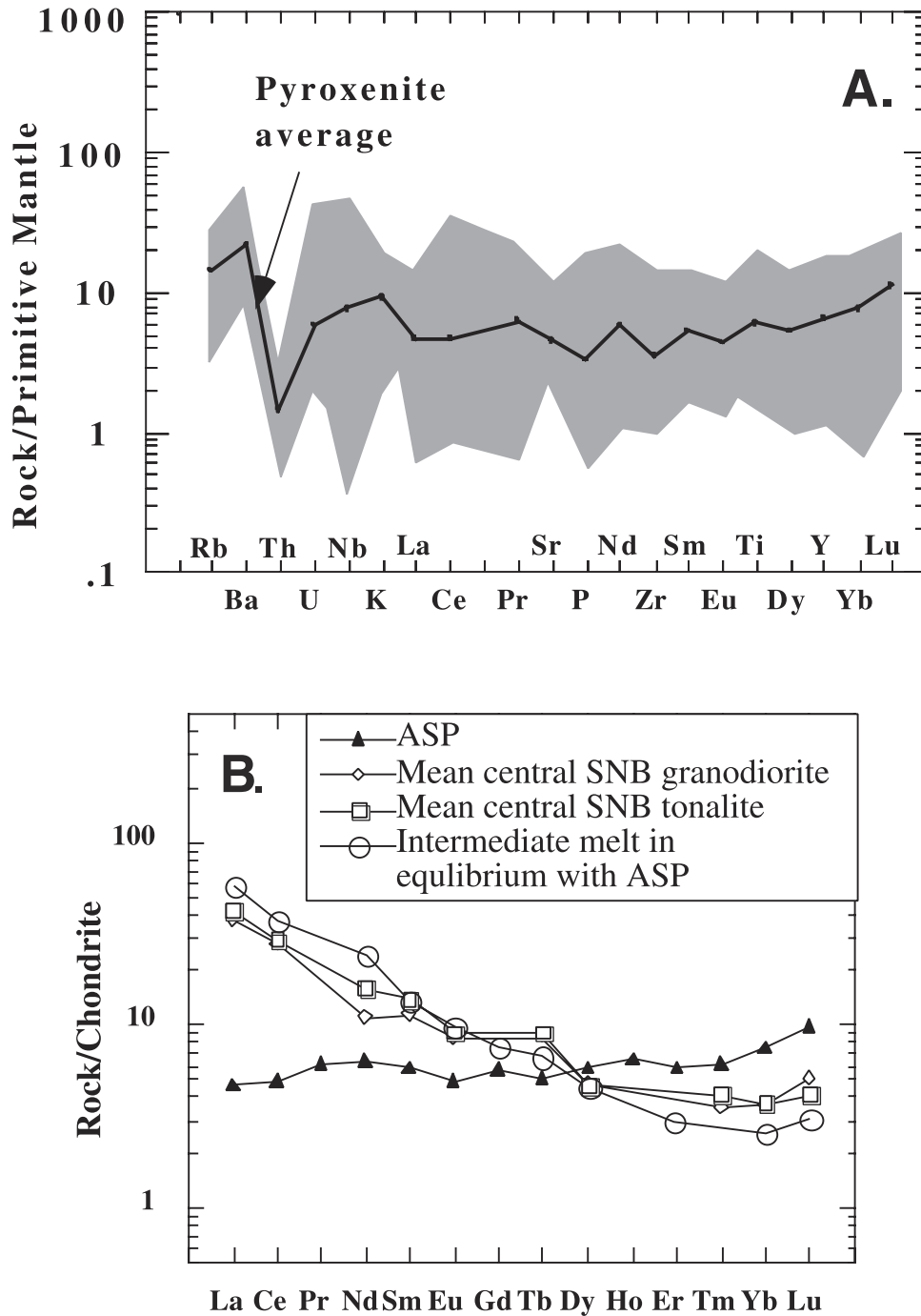


Figure 2. (A) Chondrite-normalized trace element patterns of the Sierra Nevada pyroxenites. The compositional range of analyzed samples is shown as a shaded field. (B) Chondrite-normalized REE concentrations of intermediate melts (circles) in equilibrium with a residue with the pyroxenite average composition (filled triangles). The average Sierran pyroxenite (ASP) is assumed to contain 50% clinopyroxene, 40% garnet, and 10% amphibole in this model. The average REE compositions [Dodge *et al.*, 1982] of surface rocks of the central Sierra Nevada batholith (CSNB), i.e., granodiorites (open diamonds) and tonalites (open squares), are shown for comparison.

[17] The presence of garnet-rich, feldspar-poor residues beneath large batholiths has been suggested based on the highly fractionated REE patterns observed in certain surface granitoids for the Sierra Nevada [e.g., Dodge *et al.*, 1982] and elsewhere [Gromet and Silver, 1987; Kay and Kay, 1991; Kay and Mpodozis, 2001]. To my knowledge, the

Sierra Nevada garnet pyroxenites provide the first physical evidence for the elusive eclogite facies Cordilleran residual assemblages postulated in these earlier studies. Extraction of granitoids from eclogitic residues has been proposed by Rollinson [1997] for west African Archean rocks. In the Archean case however, the eclogitic assemblages were

Table 2. Isotope Ratios of Central Sierra Nevada Xenoliths

Sample	Bc221	Bc216	Bc218	B75	F34	Bc207	G39	G36	ASP ^a	CSNB ^b
^c	o/c/g/h	c/g/h	g/c	g/c/p	c/o/g	g/c/h	g/c	c/g/h		
δ ¹⁸ O c	7.3	7.7	7.2	6.5	6.4	7.9	8.4	7.8		
δ ¹⁸ O g	7.6	7.9	7.6	6.5	6.5	8.6	8.6	7.7		
δ ¹⁸ O h	7.8	8.0				8.3		8.0		
δ ¹⁸ O o	7.7				6.4					
δ ¹⁸ O p				6.6						
δ ¹⁸ O wr ^d	7.62	7.80	7.51	6.50	6.42	8.24	8.55	7.85	7.56	6–9.5
⁸⁷ Sr/ ⁸⁶ Sr (100)	0.70522	0.70567	0.70618	0.70501	0.70595	0.70506	0.70623	0.70618	0.70569	0.7040–0.7075
ε _{Nd} (100)	-2.27	-3.51	-9.16	-7.82	-6.23	-5.15	-5.53	-8.63	-6.04	-8.6 to +1.5
²⁰⁶ Pb/ ²⁰⁴ Pb (100)	19.16	18.92	18.89	18.69	18.95	18.42	18.69	19.45	18.9	18.5–19.4
²⁰⁷ Pb/ ²⁰⁴ Pb (100)	15.77	15.69	15.33	15.58	15.64	15.60	15.62	15.74	15.62	15.55–15.75
²⁰⁸ Pb/ ²⁰⁴ Pb (100)	38.95	38.76	38.10	38.39	38.85	38.52	38.68	39.33	38.72	38.2–39.2

Nd isotopic ratios are presented as ε values relative to the Chondritic Uniform Reservoir, and the oxygen isotopic ratios are expressed as δ¹⁸O in per mil relative to SMOW.

^aASP = average Sierran pyroxenite.

^bCSNB = Central Sierra Nevada Batholith range of isotope ratios; data sources cited in text.

^cMajor constituent minerals. Abbreviations: c = clinopyroxene, o = orthopyroxene, h = amphibole, g = garnet, p = plagioclase, and wr = whole rock.

^dWhole rock values are calculated based on modes and mineral δ¹⁸O.

interpreted to represent fragments of a former subducting oceanic slab, fragments of which were incorporated into the continental lithospheric mantle. In the Sierra Nevada case, the Nd isotope ratios rule out an oceanic crustal origin for the garnet pyroxenites.

[18] Are the sub-Sierran xenoliths representative of the roots of major continental arcs? Dehydration (vapor-absent) melting of a mafic or intermediate protolith is the most likely mechanism to generate the compositions observed in the large Cordilleran batholiths [Johannes and Holtz, 1996] and thus represents our best conceptual framework for understanding partial melting in a deep crustal subarc zone. All available high-pressure dehydration melting experiments using basaltic to intermediate starting materials indicate that at pressures exceeding 1 GPa silicic melt should equilibrate with granulitic or eclogitic residues [Rapp and Watson, 1995, and references therein]. Olivine typically is not a residual phase in these assemblages. Melting experiments indicate that feldspar-rich (“granulitic”) assemblages are replaced by feldspar-free garnet and clinopyroxene-dominated (“eclogite facies”) assemblages with increasing depth (see, e.g., the work of Wyllie and Wolf [1993] for a review). This result is consistent with thermobarometric observations on Sierra Nevada xenoliths [Ducea and Saleeby, 1996]. Both granulitic and eclogitic residues are permissible beneath this arc, but given the great vertical extent of the granitic batholith, the sub-Sierra Nevada batholith residue should be primarily eclogitic. Figure 4 summarizes the experimentally predicted transition from granulitic to eclogitic residues [Wolf and Wyllie, 1993] and the observations from the Sierra Nevada [Ducea and Saleeby, 1996]. Figure 5 shows the predicted mineral assemblages in equilibrium with granitic melts during dehydration melting of a material with Sierran arc average composition (Table 3) containing 1% H₂O. The model was generated using the MELTS algorithm [Ghiorso and Sack, 1995] for pressures of 1 and 1.5 GPa. A subarc transition from garnet-rich feldspathic to feldspar-free assemblages possibly similar to the case presented here is exposed in the Jijal sequence of the Kohistan arc, Pakistan [Ringuette et al., 1999], although the relationships between the Jijal and other sequences within the Kohistan arc are complex and remain

to be established. Similarly, MASH zones [Hildreth and Moorbath, 1988] underlying other large Andean batholiths may also consist primarily of eclogite facies rocks such as those analyzed in this study, as proposed by Kay and Kay [1991]. Clearly, this result should hold only for major arcs with granitoid thicknesses in excess of 20 km, or else much of the crustal residue could be contained within a depth domain that would generate granulite facies rocks.

7. The Bulk Chemistry of the Sierran Arc

[19] The bulk composition of protoliths can be estimated if the compositions and proportions of the melts and residues are known [e.g., DeBari, 1997]. Such estimates are critically important to understanding crustal evolution in arcs. However, at present there are no good estimates of bulk continental arc chemistry, largely because of the paucity of deep crustal exposures from arc settings.

[20] The major element chemistry of the upper 30 km of the Sierra Nevada lithosphere was averaged using data on surface exposures of the Sierra Nevada batholith and framework rocks [Bateman and Dodge, 1970; Saleeby, 1990]. This estimate is possible because the current exposure of the southern part of the batholith is tilted such that it exposes volcanic and shallow intrusive levels in its central part, and progressively deeper levels toward the south, culminating with the 30 km deep exposure of the Tehachapi Mountains [Ague and Brimhall, 1988; Saleeby, 1990]. The average composition of the upper 30 km of the Sierra Nevada arc is given in Table 3 and corresponds to a tonalite. A similar estimate was obtained for the upper ~15 km of the Peninsular Ranges batholith [Silver and Chappell, 1988]. Some of the rocks taken into account in the Sierra Nevada estimate are not former melts, but are either metasedimentary shallow level framework rocks, or amphibolite to granulite facies residues from the Tehachapi Mountains. These rocks are however quantitatively subordinate to the calc-alkaline tonalitic and granodioritic intrusive rocks [Saleeby, 1990].

[21] The average tonalitic to granodioritic composition of the upper Sierra Nevada arc places limiting constraints on the bulk chemistry of the starting materials. A starting composition more silicic than 55–60% SiO₂ would gener-

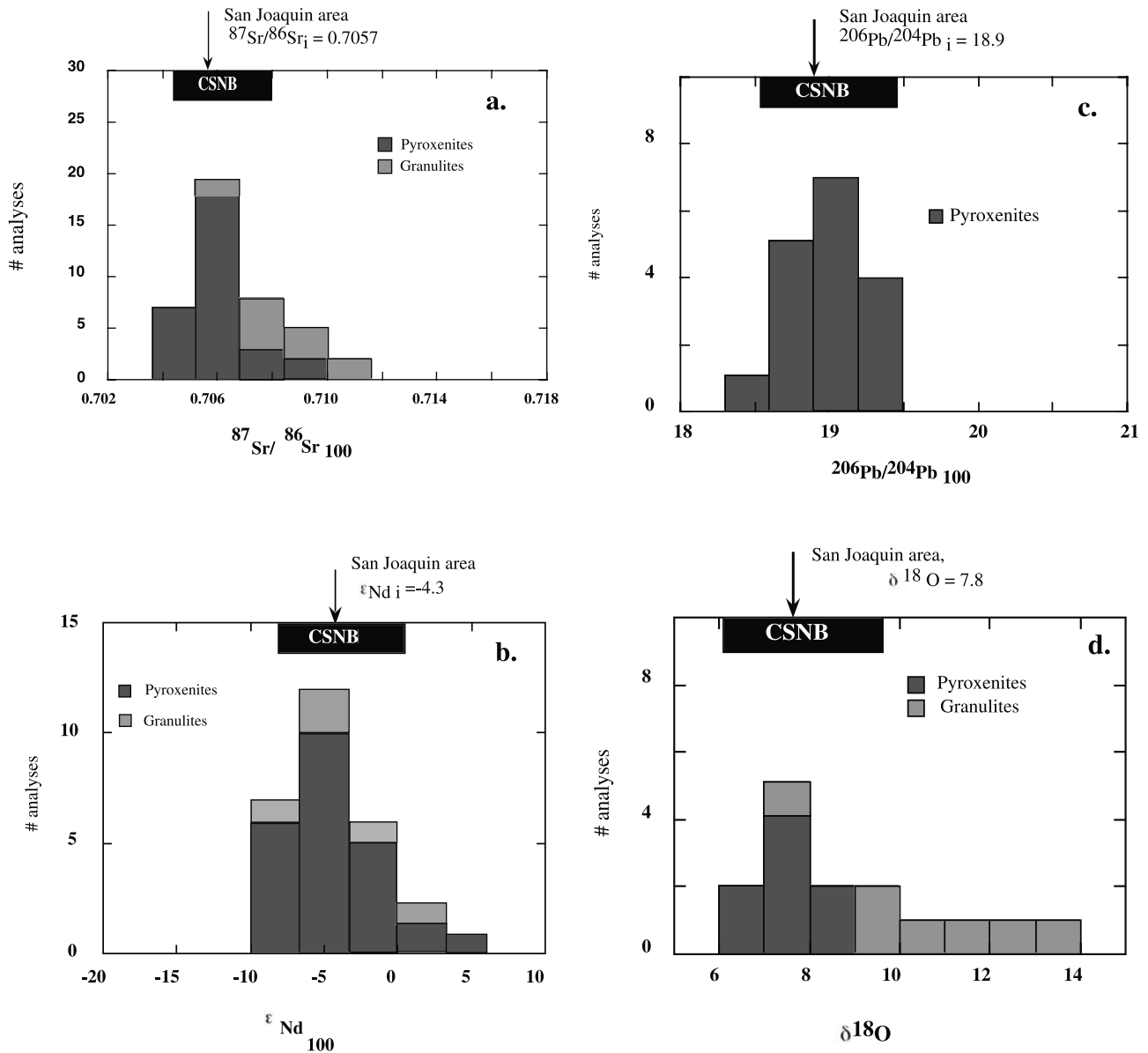


Figure 3. Histograms of (a) $^{87}\text{Sr}/^{86}\text{Sr}_{100}$, (b) $\epsilon(\text{Nd})_{100}$, (c) $^{206}\text{Pb}/^{204}\text{Pb}_{100}$, and (d) $\delta^{18}\text{O}$ measured on garnet pyroxenite and granulite xenoliths from the San Joaquin volcanic field (data reported in this study and previously published analyses on similar rocks by *Mukhopadhyay and Manton* [1994], *Domenick et al.* [1983], and *Dodge et al.* [1986]). Subscript “100” denotes the age-corrected isotope ratios at 100 Ma, the average age of the Sierra Nevada arc. The ranges in isotopic compositions measured across the central Sierra Nevada batholith (CSNB) are shown for comparison. The local (i.e., San Joaquin area) surface batholith isotopic ratios are marked with vertical arrows. Batholith data are from the work of *Kistler and Peterman* [1973, 1978] for Sr isotopes, *DePaolo* [1981] for Nd isotopes, *Masi et al.* [1981] for O isotopes, and *Chen and Tilton* [1991] for Pb isotopes.

ate true granitic melts, and not tonalites and granodiorites [Wyllie, 1984; Johannes and Holtz, 1996], while a bulk starting material less silicic than a typical MORB basalt is improbable given the Phanerozoic thermal state of the Earth’s shallow mantle [e.g., BVSP, 1981]. A basaltic bulk chemistry requires a ratio of melt to residue of $\sim 1/3:1/4$, and an andesitic bulk chemistry could generate the average melt composition of the arc with a maximum melt/residue ratio of 1:1. Thus, deep crustal remelting or fractionation of average arc basalt to andesite will generate a certain mass of

granitoids, and by mass balance requires a residue that is one to four times the mass of the granitoids.

[22] In the Sierra Nevada the average batholith exposure depth is 6 km [Ague and Brimhall, 1988]. The current vertical extent of the granitic batholith constrained by geophysical methods is ~ 30 km [Fliedner et al., 2000], thus indicating a total granitoid thickness of 35 km, much thicker than previously hypothesized [e.g., Hamilton and Myers, 1967]. It is assumed that the Tehachapi deep exposure [Pickett and Saleeby, 1993] and the granulite and pyroxenite xenoliths

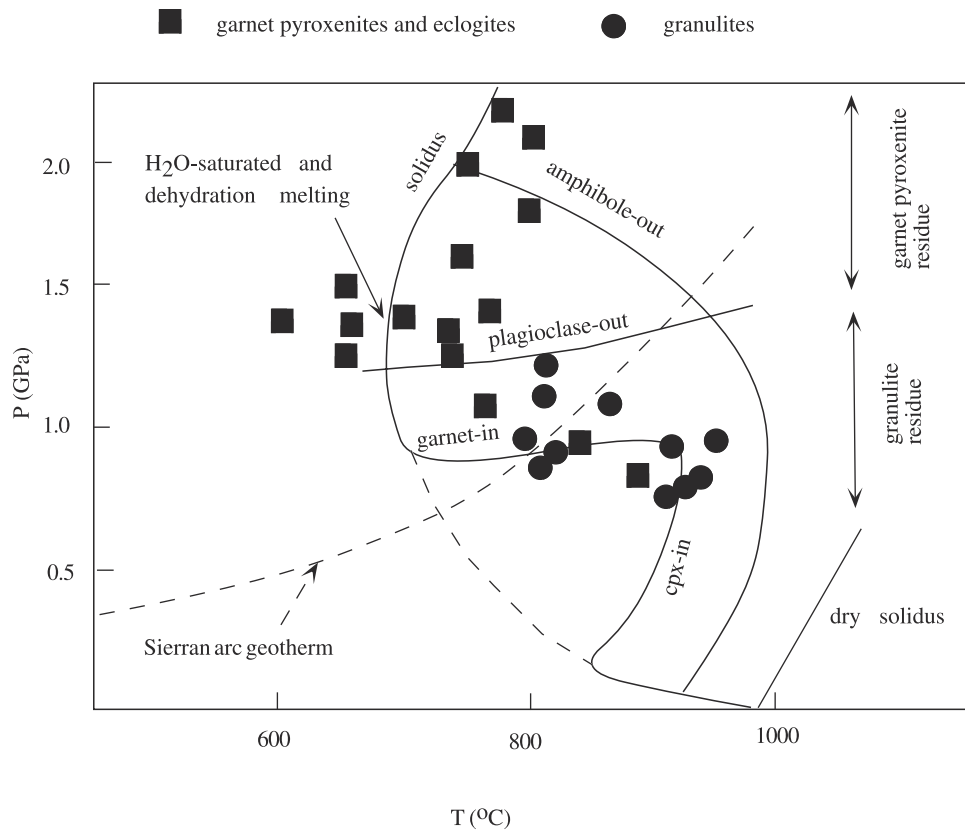


Figure 4. Pressure–temperature diagram showing the solidus curve for dehydration melting of amphibolites, the amphibole-out, clinopyroxene-in, and garnet-in curves [Johannes and Holtz, 1996, based primarily on data from Wyllie and Wolf, 1993]. The plagioclase-out curve was determined for a composition resembling the average Sierran arc (Table 3) using the thermodynamic data set of Berman [1988]. Equilibration pressures and temperatures for Sierran xenoliths (granulites and garnet pyroxenites) also are shown [Ducea and Saleeby, 1996]. The Sierran arc geotherm is based on thermobarometry on Sierran framework rocks [e.g., Pickett and Saleeby, 1993].

approximate the deeper composition of this arc. This assumption is based on the range of equilibration pressures measured on the granulites and pyroxenites, their isotopic characteristics, and is strengthened by experimental petrology data that predict that the granitoid residues should be similar to the observed xenolith compositions. This implies that residue at the very least ~ 35 km in thickness should exist beneath the batholith. Allowing 40 km depth to be a generic transition from granulitic to eclogitic residues [Wolf and Wyllie, 1993], at least about 30 km of eclogite facies residues are required beneath the batholith, depending on the bulk chemistry of the entire system (less silicic requires more residue).

[23] Sierran pyroxenite geobarometry data [Ducea and Saleeby, 1996] are consistent with the above calculations. The ratio of residue to silicic melt in the arc column is probably between 1 and 2, based on the xenolith range of equilibration pressures. The xenolith data cannot distinguish whether pyroxenites dominate the lithospheric column below 35 km to depths of ~ 70 km (pyroxenite/granitoid melts ~ 1 in a vertical column) or ~ 100 km (pyroxenite/granitoids = 2). In both cases, the calculated major element chemistries of the protolith (Table 3) are characterized by concentrations high in MgO and low in Al_2O_3 , similar to bulk compositions of some island arc crustal sections

[DeBari, 1997]. The silica concentration of the protolith corresponds to a basaltic andesite, whose composition depends on the exact ratio of garnet pyroxenite and subordinate granulite facies residues to silicic melt. A basaltic composition of the bulk arc with a corresponding ratio of melts/residue of less than 1/2 is not supported by the distribution of xenolith assemblages; the deepest pyroxenite equilibrated at ~ 3.3 GPa, or about 100 km. The presence of at least 20–30% preexisting crustal materials within the arc (see below) is also consistent with a more “intermediate” (basaltic andesite) bulk chemistry of the arc.

[24] These calculations show that a nonperidotitic residue of thickness similar to or larger than the melt column is possible beneath Cordilleran arcs. The residual, low silica material can be either in granulite or eclogite facies. In the case of a major arc with granitoid thickness in excess of 30 km, like the Sierra Nevada, most of the residue is predicted to be garnet pyroxenite with a subordinate granulite residue.

8. Old and Crustal Signature of Pyroxenites

[25] The radiogenic and oxygen isotope ratios of the batholith [Kistler, 1990] and xenoliths [Domenick et al.,

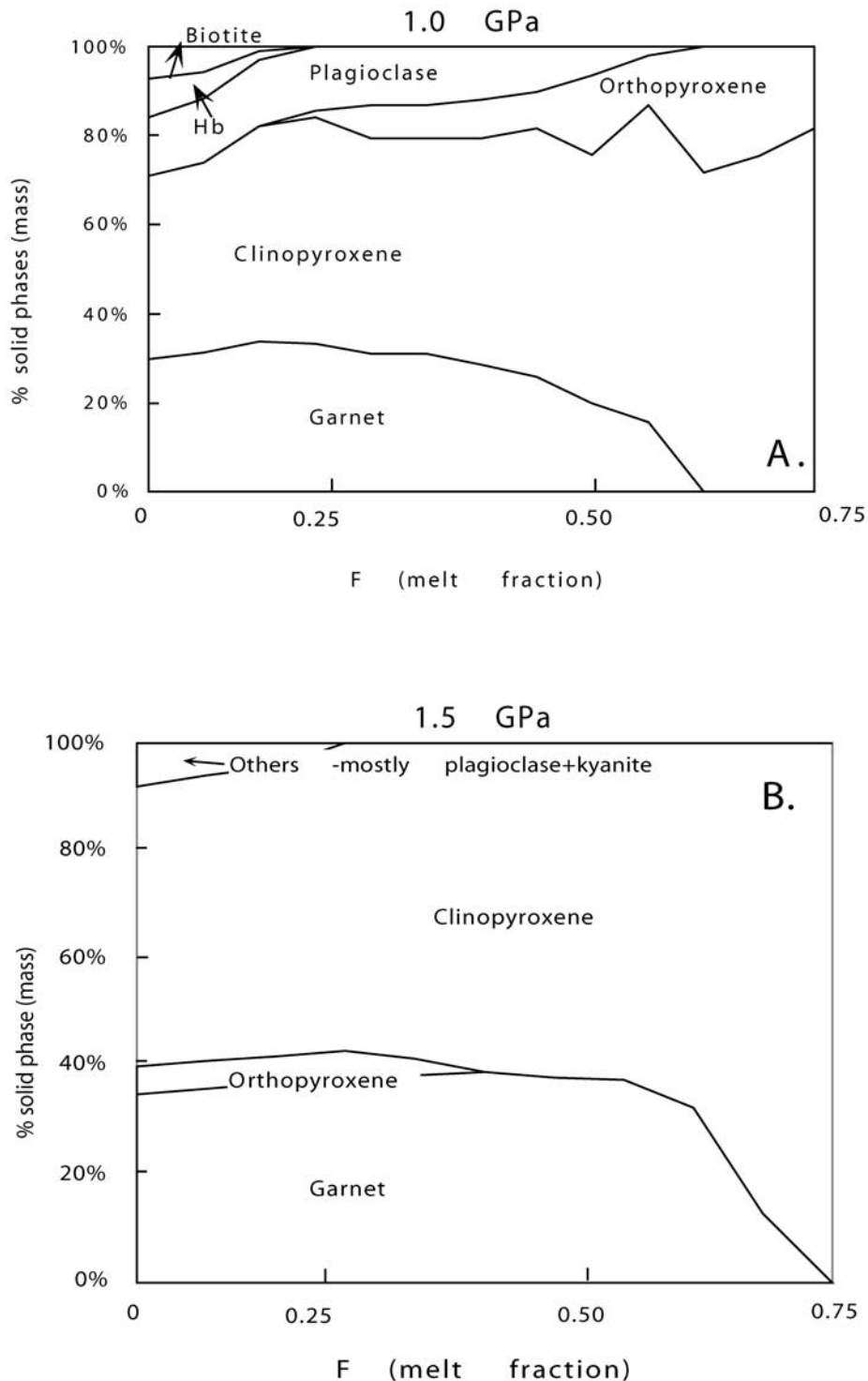


Figure 5. Diagrams showing the residual assemblage during dehydration partial melting of material with the composition shown in Table 3, column 5, to which 1% H₂O was added. The modal proportion of residues were calculated using the thermodynamic algorithm MELTS at two pressures: 1 and 1.5 GPa. The results are shown as a function of fraction of melt. These runs yielded compositions suitable for the Sierra Nevada batholith at melt fractions between 10% and 55%. These diagrams illustrate that the experimentally and theoretically predicted assemblages are granulitic at 1.0 GPa (with garnet present) and feldspar-poor, eclogitic, at 1.5 GPa.

Table 3. Estimated Bulk Composition of the Sierra Nevada Arc Source Material

	ASP ^a	SNB upper 30 km ^b	Bulk arc (ASP/SNB = 1) ^c	Bulk arc (ASP/SNB = 2) ^c	Bulk arc (ASP/SNB = 3) ^c	Bulk arc (ASP/SNB = 4) ^c
SiO ₂	44.78	64.90	54.86	51.50	49.81	48.80
TiO ₂	1.29	0.56	0.93	1.05	1.107	1.14
Al ₂ O ₃	13.21	16.61	14.91	14.34	14.06	13.89
FeO ^d	12.73	4.70	8.71	10.05	10.72	11.12
MgO	11.78	2.25	7.01	8.60	9.39	9.87
CaO	12.93	4.34	8.63	10.07	10.78	11.2
Na ₂ O	1.24	3.34	2.29	1.94	1.76	1.66
K ₂ O	0.27	2.25	1.26	0.93	0.76	0.66

^a ASP = average Sierran pyroxenite (Table 1).

^b SNB = Sierra Nevada batholith; data compiled by *Bateman and Dodge* [1970], *Pickett* [1991], and *Saleeby* [1990].

^c Assuming that the thickness of residues with the composition of ASP was 1–4 the thickness of SNB, etc.

^d All Fe as FeO.

1983; *Ducea*, 2001, this study] clearly indicate that the protolith has multiple sources. At least three major end-members are involved: the subarc mantle, crust with accreted (oceanic) affinities and lower craton-like crust [*Kistler*, 1990; *Ducea*, 2001]. The isotopic results presented in Table 1 indicate that vertical isotopic heterogeneities of the Sierra Nevada lithosphere are as large as the horizontal ones observed across the surface exposures of the Sierra Nevada batholith. The significant isotopic heterogeneities measured in lower crustal residual pyroxenites confirm that the variance of isotopic ratios measured in the Sierra Nevada batholith is primarily inherited from the source rocks at depth [*Kistler and Peterman*, 1973]. The study of radiogenic and oxygen isotope ratios can not resolve the proportions of various end-members postulated to have been involved in the formation of the batholith. However, two isotopic systems, ¹⁴³Nd/¹⁴⁴Nd and $\delta^{18}\text{O}$ put some important limiting constraints on the formation of batholiths.

[26] The elevated $\delta^{18}\text{O}$ of the pyroxenites suggests that they contain a significant crustal component. The oxygen isotope data indicate that the pyroxenites are partially comprised of materials that prior to arc-related melting in the deep crust were at or near the surface of the Earth. Thus, this end-member is most likely sedimentary or volcanic in origin. This high $\delta^{18}\text{O}$ end-member is similar to one identified by *Taylor* [1988, and references therein] for the source of the Peninsular Ranges batholith based on extensive studies of granitoids exposed at the surface. Assigning a rather high value for the surficial component ($\delta^{18}\text{O} = 13\text{‰}$), and a mantle value of $\delta^{18}\text{O} = 6\text{‰}$, at least 20–30% by mass of the pyroxenites are supracrustal rocks. This rules out the possibility that the batholith has been built entirely on juvenile basaltic materials.

[27] Neodymium isotopes show that the pyroxenites are dominated by an ancient component that has to be to some extent crustal (see above) but could also be represented by crustal additions from an old lithospheric mantle [*Coleman et al.*, 1992]. Xenolith model Nd ages commonly fall between 1 and 2 Ga, whereas some samples yield unrealistic model ages. These values may not be reliable measures of the actual crustal age of the xenoliths, given their possibly complicated geologic history. The ϵ_{Nd} ratios at 100 Ma are quite low (between -9.2 and -2), strongly suggesting that the pyroxenites represent Precambrian basement rocks (or at least contain an end-member component of that nature). The presence of Precambrian basement beneath the central

Sierra Nevada batholith is supported by geochronologic studies of zircon in surface Sierra Nevada granitoids, which detected inherited zircon of Precambrian age (~ 1.8 Ga) [*Chen and Moore*, 1982]. The available data do not rule out arc-related additions of “young” asthenospheric basaltic magmas to the Sierra Nevada MASH zone, which are in fact required in order to explain the heat budget of any large continental arcs.

9. Foundering of the Arc Root

[28] Several geologic and geophysical lines of evidence suggest that the sub-Sierran batholithic keel (lower crustal and mantle lithosphere) may have been convectively removed from the base of a silicic remnant crust and foundered in the mantle [*Wernicke et al.*, 1996; *Ducea and Saleeby*, 1998a; *Manley et al.*, 2000; *Lee et al.*, 2000], either during and/or after the demise of arc magmatism. The present-day Moho beneath the southern Sierra Nevada is a tectonic boundary located at approximately 33 km deep and separates a felsic (batholithic) crust from a peridotitic mantle [*Ruppert et al.*, 1998; *Wernicke et al.*, 1996; *Fliedner et al.*, 2000]. The structure, petrology and geochemistry of the exposed batholithic rocks of the entire Sierra Nevada region are similar to the batholithic rocks of the central Sierra [*Saleeby*, 1990], so it is reasonable to assume that the entire batholith possesses a three dimensional root structure grossly similar to that of the central Sierra Nevada.

[29] Residual pyroxenites are extremely dense rocks, due to their garnet-rich (50% by volume compared to about 15% in typical subduction-related basaltic eclogites) [*Carswell*, 1990] and Fe-rich nature. Figure 6 shows the calculated densities of the eight rocks studied here as a function of depth at their equilibration pressures and temperatures [*Ducea and Saleeby*, 1996, 1998b]. The densities were calculated using the mineral database of *Niu and Batiza* [1991] and the pyroxenite mineral modes. Rocks that equilibrated at pressures in excess of ~ 1.5 GPa have densities of 3450–3550 kg/m³, significantly higher than that of typical mantle peridotites (~ 3300 kg/m³) and in agreement with model calculations by *Jull and Kelemen* [2001]. The curve shown in Figure 6 represents the MELTS-calculated density profile for a residual assemblage resulting from partially fusing the average bulk composition of the Sierra Nevada arc (Table 3, column 5) plus 1% H₂O at pressures between 0.7 and 3.0 GPa. For any given

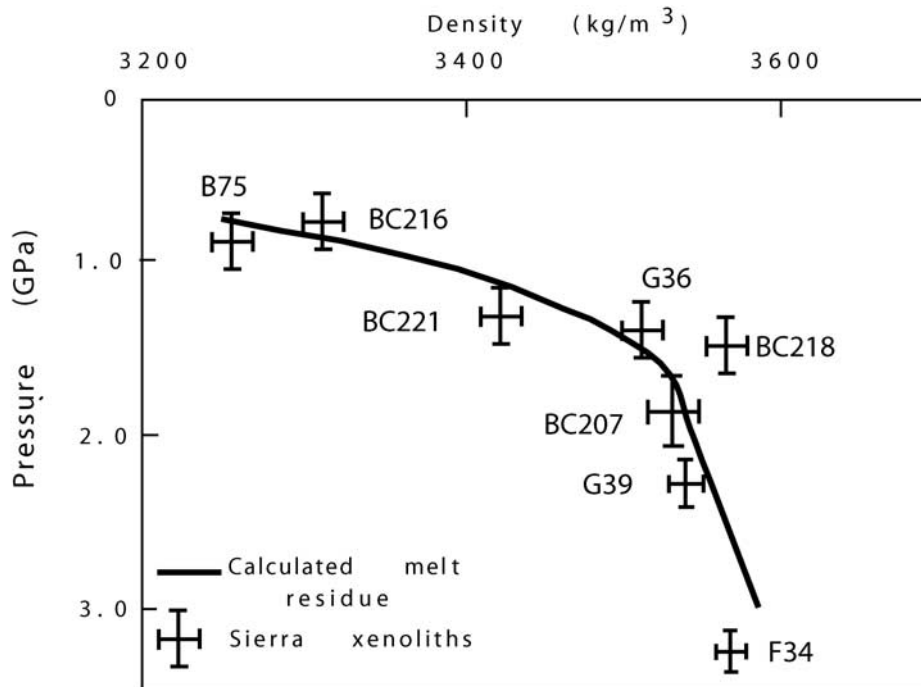


Figure 6. Diagram showing the calculated densities of the eight pyroxenites studied here, against their equilibration pressures [Ducea and Saleeby, 1998b]. The densities were calculated at the pressures and temperatures of equilibration of the xenoliths using the mineral database of Niu and Batiza [1991] and the modal proportions of various phases. The uncertainties in pressure determinations are given at 1σ level; the uncertainties assigned to the densities are due to errors in pressure and temperature determinations. The solid line represents the MELTS-calculated density profile for a residual assemblage resulting from partially fusing the average bulk composition of the Sierra Nevada arc (Table 3, column 5) plus 1% H_2O at pressures between 0.7 and 3.0 GPa (under the assumption of batch melting). For any given pressure, the residual composition was calculated at a temperature typical of an arc geothermal gradient of $25^\circ C/km$ [Barton and Hanson, 1990]. For every calculation performed, the composition of liquids was also checked to be within the range of major element chemistry of the surface batholith [Bateman and Dodge, 1970].

pressure, the residual composition was calculated at a temperature typical of an arc geothermal gradient of $25^\circ C/km$ [Barton and Hanson, 1990]. For every calculation performed, the compositions of liquids were also checked to be within the range of major element chemistry of the surface batholith [Bateman and Dodge, 1970].

[30] The xenolith data and model calculations indicate that the residue underlying the arc should become significantly denser at ~ 1.5 GPa corresponding to a transition from a granulite facies (plagioclase bearing) to an eclogite facies (plagioclase free) assemblage. If foundering is an important mechanism for recycling mafic-ultramafic residues back into the mantle in continental arc environments [Kay and Kay, 1991], it is predicted that only arcs with granitoid, or “melt” thickness in excess of 25 km would undergo such a process. Thinner arcs would simply not develop a gravitationally unstable root.

10. Rate of Root Foundering

[31] Two major mechanisms for recycling continental crust have been proposed: subduction of sediments and lower crustal foundering [Rudnick, 1995]. K-Ar constraints [Coltice et al., 2000] indicate that no more than 30% of the

modern mass of K-rich upper continental crust has been subducted back into the mantle during the Earth’s history. These results are consistent with a modern sediment recycling rate of 1.3×10^{12} kg/yr [Plank and Langmuir, 1998]. The continental crust is highly heterogeneous with respect to K however [Taylor and McLennan, 1985], and recycling of materials low in K is not considered in these calculations. There are currently no estimates of the flux of lower crust recycling by foundering in arc or other tectonic environments [http://www.EarthRef.org/GERM/]. The viability of lower crustal foundering in arc environments is particularly relevant to continental evolution [Kay and Kay, 1991], because these are the main tectonic settings where silicic upper crust is being refined via arc magmatism.

[32] It appears that at least in the southern Sierra Nevada, the dense residual mass has been recycled into the mantle. If all residues have been recycled via foundering, the averaged rate of foundering over the active life of the Sierran arc (~ 120 Myr) is $25\text{--}40$ km³/km Myr, assuming that the average width of the arc is 90 km and a 35–50 km thick lower crust foundered during and/or after arc formation. This calculation may be somewhat misleading since convective removal of the batholithic root most likely took place in short catastrophic events that may [Lee et al., 2000]

or may not [Ducea and Saleeby, 1998a] have been contemporaneous with arc magmatism. In either case, the calculation puts an upper bound on how much mass can be recycled via convective removal in arc settings.

[33] This rate of foundering is similar to modern crustal addition rates at island arcs (20–40 km³/km Myr) [Reymer and Schubert, 1984]. Is that estimate valid for the Sierra Nevada and continental arcs in general? The apparent intrusive flux of the Sierra Nevada arc was calculated by Ducea [2001] as a function of time; the magmatic flux of this arc was extremely nonsteady state, with most of the arc volume emplaced during two flareup episodes, one in the late Jurassic, and the other in the late Cretaceous. These flareups were separated by periods of low intrusive fluxes. When integrated over the life span of the arc the average magmatic addition rate for the Sierra Nevada is about 45 km³/km Myr. If about 50% [DePaolo, 1981] to a maximum of 70% (this study) of the arc mass is subcrustal, then the magmatic addition rate in the Sierra Nevada was about 23–30 km³/km Myr. If foundering is an effective mechanism of returning arc lower crust to the mantle, then the net crustal growth at this continental arc was close to zero. In the process, a significant amount of preexisting continental crust, as clearly indicated by the oxygen isotopic results has been involved in arc magmatism. However, the bulk arc chemistry must have been less silicic than the remnant Sierra Nevada batholith. Continental arcs may by this process be the settings where silicic upper crust is efficiently differentiated, thus being ultimately responsible for the refinement of the bulk continents into high-silica materials, even if the net crustal growth (i.e., new material added from the mantle) may be close to zero.

[34] The Sierra Nevada example illustrates that in order for an arc to develop a sizable foundering-prone eclogite facies root, its melt thickness must be in excess of 20–25 km. For a bulk composition identical to that estimated here for the Sierra Nevada, a thinner arc would develop a granulitic residue that is not denser than peridotite and thus would likely escape foundering.

11. Conclusions

[35] Data presented here and by Ducea and Saleeby [1998b] indicate that the Sierra Nevada batholith was extracted by large-scale melting of a multilithologic source with a bulk composition of a high-Mg basaltic andesite. This process generated at depth a large volume of mafic–ultramafic “residual” material composed of solid restites and/or cumulates. Granitoid melts were extracted from depths exceeding 35–40 km; consequently, the residue was mostly garnet-rich and pyroxene-rich (“eclogitic”) and subordinately granulitic. Low ¹⁴³Nd/¹⁴⁴Nd ratios throughout the Sierra Nevada column of residues and melts support a previous suggestion that old continental components (crustal and/or mantle lithospheric) dominate the arc mass. Elevated δ¹⁸O isotope ratios measured throughout the column document unambiguously the involvement of Precambrian lithosphere and at least 20–30% (mass) of supra-crustal components. Deep crustal residues of similar Cordilleran batholiths should consist primarily of garnet pyroxenites if the arc melt thickness was at least 20–25 km, and should range in mass from 1 to 2 times that of the

granitic batholith. Thus, a large reservoir denser by up to 250 kg/m³ than the underlying mantle should exist beneath arcs. Such a dense keel is prone to foundering [Kay and Kay, 1991]. Several lines of evidence suggest that the Sierra Nevada lower lithosphere did founder in the mantle, possibly in several steps during and after the cessation of arc magmatism [e.g., Ducea and Saleeby, 1998a]. The return rate is estimated to be about 25–40 km³/km Myr, similar to the magmatic addition rate in the arc; therefore the net crustal growth in this continental arc was close to zero.

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