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Petrology and tectonics of Phanerozoic continent formation: From island arcs to accretion and continental arc magmatism

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Abstract

Mesozoic continental arcs in the North American Cordillera were examined here to establish a baseline model for Phanerozoic continent formation. We combine new trace-element data on lower crustal xenoliths from the Mesozoic Sierra Nevada Batholith with an extensive grid-based geochemical map of the Peninsular Ranges Batholith, the southern equivalent of the Sierras. Collectively, these observations give a three-dimensional view of the crust, which permits the petrogenesis and tectonics of Phanerozoic crust formation to be linked in space and time. Subduction of the Farallon plate beneath North America during the Triassic to early Cretaceous was characterized by trench retreat and slab rollback because old and cold oceanic lithosphere was being subducted. This generated an extensional subduction zone, which created fringing island arcs just off the Paleozoic continental margin. However, as the age of the Farallon plate at the time of subduction decreased, the extensional environment waned, allowing the fringing island arc to accrete onto the continental margin. With continued subduction, a continental arc was born and a progressively more compressional environment developed as the age of subducting slab continued to young. Refinement into a felsic crust occurred after accretion, that is, during the continental arc stage, wherein a thickened crustal and lithospheric column permitted a longer differentiation column. New basaltic arc magmas underplate and intrude the accreted terrane, suture, and former continental margin. Interaction of these basaltic magmas with pre-existing crust and lithospheric mantle created garnet pyroxenitic mafic cumulates by fractional crystallization at depth as well as gabbroic and garnet pyroxenitic restites at shallower levels by melting of pre-existing lower crust. The complementary felsic plutons formed by these deep-seated differentiation processes rose into the upper crust, stitching together the accreted terrane, suture and former continental margin. The mafic cumulates and restites, owing to their high densities, eventually foundered into the mantle, leaving behind a more felsic crust. Our grid-based sampling allows us to estimate an unbiased average upper crustal composition for the Peninsular Ranges Batholith. Major and trace-element compositions are very similar to global continental crust averaged over space and time, but in detail, the Peninsular Ranges are slightly lower in compatible to mildly incompatible elements, MgO, Mg#, V, Sc, Co, and Cr. The compositional similarities suggest a strong arc component in global continental crust, but the slight discrepancies suggest that additional crust formation processes are also important in continent formation as a whole. Finally, the delaminated Sierran garnet pyroxenites have

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some of the lowest U/Pb ratios ever measured for silicate rocks. Such material, if recycled and stored in the deep mantle, would generate a reservoir with very unradiogenic Pb, providing one solution to the global Pb isotope paradox.

Keywords: continental crust; subduction; Peninsular Ranges; Sierra Nevada; garnet pyroxenite; granodiorite

1. Introduction

The continental crust represents only 0.6% of the Earth's mantle, but it accounts for 30–50% of the Earth's budget of highly incompatible trace elements (Hofmann, 1988). These same elements are depleted in the Earth's upper mantle (Hofmann, 1988), suggesting that the cumulative formation of continental crust efficiently extracted these elements from the mantle into the crust. However, from a major-element perspective, mantle-derived melts are basaltic and hence mafic (low Si and high Mg), yet the continental crust on average is thought to be andesitic and hence felsic (higher Si and lower Mg) (Kelemen, 1995, Rudnick, 1995, Hawkesworth and Kemp, 2006). This global paradox is further exemplified by the fact that although a significant fraction of Phanerozoic continental crust appears to be formed by island arc accretion (Sengör et al., 1993, Rudnick, 1995, Hawkesworth and Kemp, 2006), integrated vertical sections of island arcs, before they have accreted to form continents, are still basaltic (Kelemen et al., 2003). These island arc basalts must therefore have differentiated into felsic and mafic complements, the latter being recycled into the mantle or hidden beneath the seismic Moho to drive the remaining crust to felsic compositions (Rudnick, 1995, Kelemen et al., 2003).

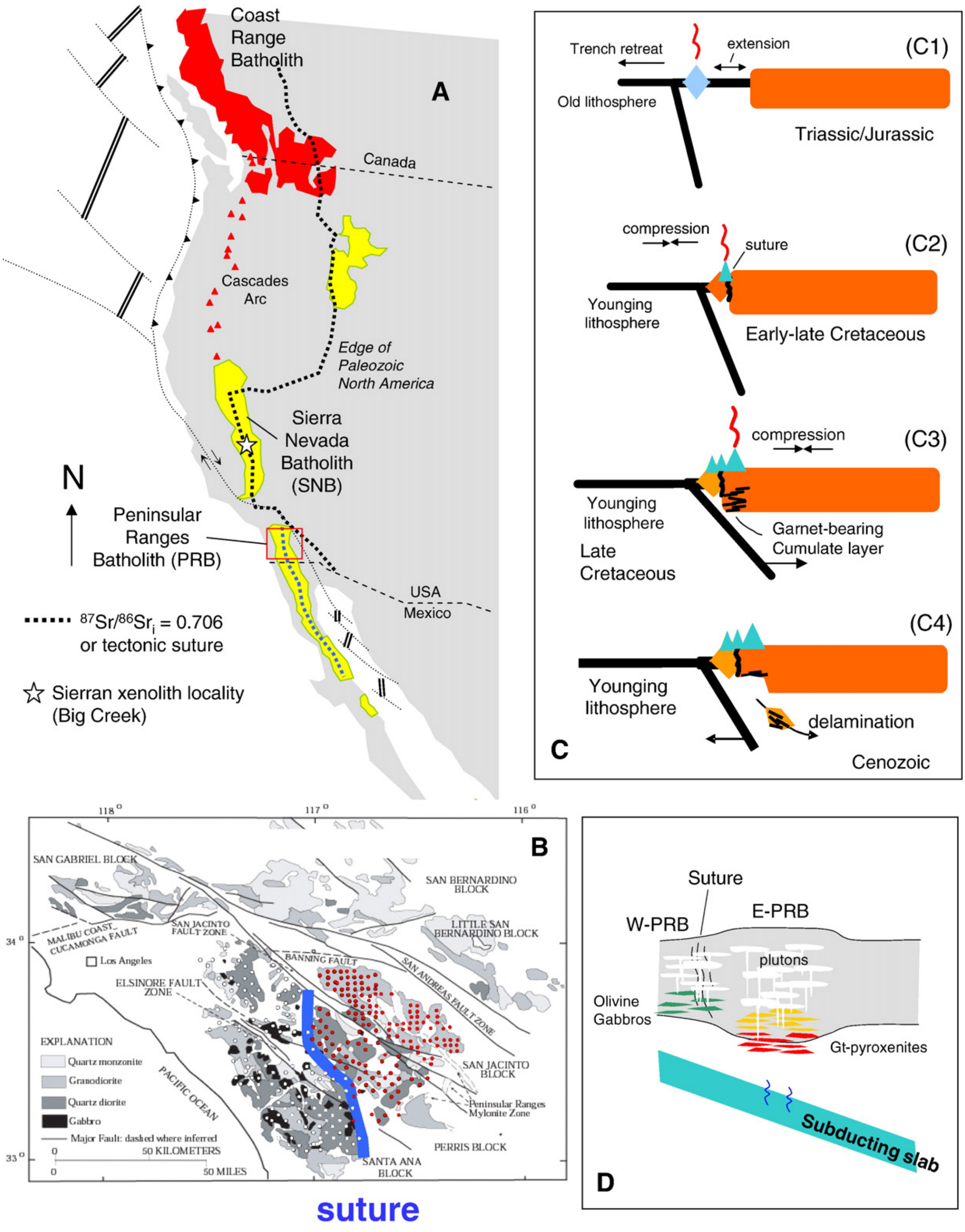
This is what is known (Hawkesworth and Kemp, 2006), but what is still not fully understood is exactly how and when island arcs differentiate, how arcs assemble into continents, when the mafic components are removed, and how all of these processes are intertwined. This paper focuses on the global crustal paradox from the perspective of Phanerozoic continent formation. Why have we chosen this perspective when continent formation has been going on since 4 Gyr ago and that crust-forming processes in the deep past might have been very different, perhaps not even involving arcs? Certainly, a complete view of crust formation on Earth requires a window into these processes throughout Earth's history in its entirety, but the farther back in time we go, the more incomplete the record. For this reason, we turn here to the Phanerozoic as the exposures and completeness of these younger crustal sections are superior to those of the Archean. A systematic study of the petrology and tectonics of a Phanerozoic crustal section would help establish a baseline to which crust types, young and old, can be compared.

Towards these ends, we embarked on a case study of Mesozoic continental growth along the western North American margin (e.g., the Cordillera) (Fig. 1A). We investigated 287 plutonic samples collected by Baird in 1979 (Baird et al., 1979) on a uniform grid in the Cretaceous northern Peninsular Ranges Batholith (PRB) in southern California (Fig. 1B). One of Baird's goals was to extract representative compositions of each pluton. To avoid heterogeneities on the hand-specimen lengthscale, he collected samples from each of the four corners of a 400 × 400 foot square centered on a given grid point. Two samples from each corner were collected, making a total of 8 samples per locality, all of which were mixed together to generate a homogeneous mixture believed to be representative on the 400 × 400 foot lengthscale. We present new major and trace-element data along with previously published Sr isotopic data (Kistler et al., 2003) on these homogenized samples. To the best of our knowledge, such data represent the most systematic and representative geochemical sampling of a batholith to date. To this lateral sampling, we add a vertical dimension by turning to garnet pyroxenite xenoliths found in late Miocene diatremes in the Cretaceous Sierra Nevada Batholith (SNB), the northern equivalent of the PRB. These pyroxenites originate from the deepest parts of the SNB. Such rocks represent cumulates and/or restites associated with the formation of the SNB as well as the PRB.

By combining these geochemical observations with regional geology and tectonics, we are able to link the petrogenetic and tectonic processes involved in making continental crust.

2. The Peninsular Ranges (PRB) and Sierra Nevada Batholiths (SNB)

This study focuses on the Peninsular Ranges (PRB) and Sierra Nevada Batholiths (SNB), which are the eroded remnants of Mesozoic continental arcs formed on the edge of the Precambrian North American craton by subduction of the Farallon oceanic plate beneath North America. The PRB (northern part) and the SNB were emplaced between 125–85 Ma and 120–89 Ma, respectively and within these time intervals, plutonism migrated from west to east, e.g., away from the trench (Silver and Chappell, 1988, Kistler, 1990, Coleman and Glazner, 1997, Kistler et al., 2003). The batholiths are characterized by an E–W dichotomy in terms of isotopic compositions and the nature of prebatholithic lithologies (Gastil, 1975, Silver and Chappell, 1988, Todd et al., 1988, Kistler, 1990, Kistler,



1993, Coleman and Glazner, 1997, Kistler et al., 2003, Tulloch and Kimbrough, 2003, Busby, 2004). In both batholiths, eastern plutons have radiogenic Sr and unradiogenic Nd isotopes (Figs. 1A and 2A; (Kistler et al., 2003)), higher oxygen isotopic compositions (Kistler et al., 2003), and contain roof pendants or screens of metamorphosed continental shelf-type Paleozoic sediments, such as quartzites and carbonates (Todd et al., 1988). Western plutons, in contrast, have more mantle-like oxygen, less radiogenic Sr and more radiogenic Nd isotopic compositions (Fig. 2A), and have been intruded through Triassic/Jurassic volcanic bedrock intercalated and overlain by continental and volcaniclastic sediments (Todd et al., 1988).

These differences indicate that plutons in the east intruded through and assimilated older and possibly more evolved basement and sediments. The general interpretation is that plutons in the east were built through the pre-existing (Paleozoic) North American continental margin, whereas the western plutons intruded through Mesozoic (Triassic/Jurassic) island arcs accreted to North America during the late Jurassic–early Cretaceous (Kistler, 1990, Busby, 2004). The transition from the western to eastern “provinces” is generally interpreted to be the tectonic suture between the accreted island arc terrane (the Alisitos and Santiago Peak formations in the PRB) and the North American continent. In the case of the PRB (Fig. 1B), the suture is manifested by ultramafic outcrops, the presence of back-arc basin sediments (with North American continent and the Triassic/Jurassic island arc affinities), and a change from passively emplaced magmatic structures in the west to compression-related magmatic foliation in and near the suture (Morton, 2003). These features are less obvious in the SNB due to the more extensive exhumation and erosion experienced in the western SNB compared to the PRB (Ague and Brimhall, 1988). Nevertheless, the existence of a tectonic suture in the Sierras is still inferred from the marked E–W changes in isotopic compositions of the plutons (Kistler, 1990).

3. Compositional and isotopic trends across the Peninsular Ranges Batholith (PRB)

3.1. Western PRB

The E–W dichotomies described above are also accompanied by major and trace-element differences (Baird et al., 1979, Gromet and Silver, 1987, Silver and Chappell, 1988), well elucidated by our PRB dataset (Figs. 2 and 3 with sample localities in Fig. 1A and Supplementary Information). Data for individual samples are given in the Supplemental information while averages are given in Table 1. Gabbroic, dioritic, tonalitic and monzogranitic plutons are common in the western PRB. Tonalites to monzogranites occur in the eastern PRB, but more primitive compositions, such as gabbros and diorites, are very rare in the east. Western plutons show a continuous differentiation trend extending from a gabbroic (50 wt.% SiO_2) endmember having 7 wt.% MgO and Mg#s ~ 0.55–0.75 (Mg# = atomic Mg/(Mg + Fe)) to a monzogranitic endmember having SiO_2 contents up to 75 wt.%. The high end of the gabbro Mg#s approaches values that would be in equilibrium with mantle peridotite (denoted by a star in Figs. 2B–D and 3). In terms of trace elements, the western PRB is characterized by uniformly low Gd/Yb ratios (Fig. 2E) and distinct negative Eu anomalies. The latter indicates the involvement of plagioclase fractionation. The former indicates a lack of heavy rare-earth depletion, which suggests that garnet was never involved in the differentiation of the western PRB (see also Gromet and Silver (1987)). The low and uniform initial $^{87}Sr/^{86}Sr$ compositions of the western PRB plutons superficially

Fig. 1. A. Locations of Mesozoic batholiths formed by subduction of the Farallon plate beneath North America are shown. Dotted line represents inferred edge of Paleozoic North America and corresponds to the initial $^{87}Sr/^{86}Sr$ value of 0.706 (Kistler and Peterman, 1973). Blue-dashed line in the Peninsular Ranges Batholith (PRB) represents the suture between Triassic/Jurassic island arc terranes and Paleozoic North America (this corresponds to an initial Sr of roughly 0.705; Fig. 2A). Red triangles represent active volcanoes in the Cascades arc. Star represents xenolith locality for Sierran garnet pyroxenites. B. Sample locations from the grid-based study in the PRB. Red circles represent samples of plutons east of the tectonic suture (eastern PRB). White circles represent western plutons (western PRB). Blue line represents tectonic suture. C. Conceptual model for lateral growth of the North American continent by island arc accretion and subsequent continental arc magmatism in the Mesozoic. (C1) “Fringing” arc is formed just off the edge of the North American in an extensional environment due to trench associated with subduction of old oceanic lithosphere (Triassic/Jurassic). (C2) As the age of the subducting slab youngs, trench retreat subsides and the back-arc closes, resulting in the accretion of the fringing arc to the Paleozoic continental margin and the formation of a tectonic suture (Jurassic). (C3) Further younging of the subducting slab results in trench advance, generating arc magmatism through the newly accreted terrane. Younging of the subducting slab eventually manifests itself in the form of a shallowing subduction zone, causing arc magmatism to migrate eastwards through the suture zone and into Paleozoic North America. D. Basaltic magmas stall at depths as they ascend through the lithosphere — magmas ascending through thick North American lithosphere are forced to crystallize dense garnet pyroxenite cumulates at depth; magmas ascending through the thinner accreted lithosphere do not crystallize dense garnet-bearing cumulates. Delamination of the garnet-bearing cumulates (C4) leaves behind a continental crust biased towards felsic compositions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

suggest that the entire differentiation trend resulted from closed-system fractionation. However, a more likely scenario is an open system wherein juvenile magmas assimilated pre-existing crust (e.g., the accreted Alisotos island arc terrane), the latter of which was not much older than the western PRB plutons themselves so that the elapsed time between formation of the island arc, accretion, and subsequent continental arc magmatism was too short to permit significant isotopic evolution.

3.2. Eastern PRB

The eastern PRB differentiation trend shows a subtle but significant offset from the western differentiation trend: for a given SiO_2 content, the eastern PRB has lower MgO and Mg#, higher Al_2O_3, higher Gd/Yb and Sr/Y ratios, lower Y contents, and less pronounced negative Eu anomaly than the western PRB (Figs. 2–4). Although the eastern PRB differentiation trends also point towards a gabbroic endmember ($SiO_2 \sim 50$ wt.%), the projected gabbroic endmembers have lower MgO and Mg# and possibly higher Al_2O_3 for a given SiO_2 content than the gabbroic endmembers for the western plutons. The high Gd/Yb and Sr/Y ratios require garnet involvement sometime in the genesis of the eastern PRB plutons, implying that differentiation started at deeper depths in the east than in the west (Gromet and Silver, 1987, Tulloch and Kimbrough, 2003). Small negative Eu anomalies, however, indicate that plagioclase was also involved during differentiation and this suggests that fractionation, although initiating deep, continued to shallow levels. Finally, the more radiogenic and variable initial $^{87}Sr/^{86}Sr$ isotopic compositions require a component of assimilation and re-melting of ancient pre-existing crust in the genesis of the eastern PRB. Thus, the eastern PRB was emplaced through the ancient margin of the North American continent (Kistler, 1990, Kistler et al., 2003).

3.3. Contrasting early petrogenetic histories

Different petrogenetic histories are clearly required to explain these differentiation trends. To shed more light on these differences, we compare the PRB data to magmas from the active Cascades arc (shown as fields in Fig. 2B–D), which extends from northern California to Washington. The Cascades represent a modern continental arc emplaced through recently accreted terranes onto the margin of North America. Like the western PRB, the Cascades do not have a significant garnet trace-element signature (Leeman et al., 2005), which indicates a relatively thin differentiating column. The Cascades may hence be an analog for the extrusive equivalents of the western PRB. Indeed, the major-element differentiation trends defined by the western PRB overlap closely with those of the Cascades, but the eastern PRB do not. The mafic endmembers of the Cascade volcanics and the western PRB appear to derive from mantle-derived magmas, and their initial differentiation trends involve a decrease in MgO and increase in SiO_2, suggesting olivine crystallization during the earliest stages of differentiation (Leeman et al., 2005). An example of an olivine fractionation trend (see Supplementary Information for model details) is shown in Fig. 3. The role of olivine suggests that early magmatic differentiation in the Cascades and western PRB occurred at relatively low pressures (<1 GPa). Consistent with this conclusion is that olivine–plagioclase–augite cumulates are commonly found in oceanic type arcs, which intrude through thin lithosphere (Snoke et al., 1981). Olivine–plagioclase cumulates also occur locally in the western PRB (Morton, 2003) and western part of the Sierra Nevada Batholith (Snoke et al., 1981).

Olivine fractionation, however, probably did not apply to the eastern PRB differentiation history (Fig. 2B–D). The mafic parents of the eastern PRB require the removal of a component with less MgO and/or higher SiO_2 than olivine in order to explain the anomalously low MgO at a given SiO_2 content compared to the Cascades and western PRB. One possibility is a pyroxene-dominated lithology as pyroxenes have high MgO content but similar SiO_2 contents to basalt. Pyroxene crystallization may be favored over olivine under both hydrous conditions and higher pressures, e.g., >1 GPa (Müntener et al., 2001). Indeed, the eastern PRB has high Gd/Yb and Sr/Y ratios, low Yb and Y contents, all of which suggest the involvement of garnet (Fig. 2E–F) and hence higher pressures of differentiation in the east than in the west (Gromet and Silver, 1987). Thus, unlike the western PRB where olivine gabbros controlled early differentiation, garnet-bearing pyroxenite lithologies were the early differentiates in the eastern PRB.

4. Garnet-bearing pyroxenites

As stated above, the olivine gabbro cumulates predicted to exist are confirmed by outcrops in the western Sierras and PRB. However, outcrops of garnet pyroxenite do not exist anywhere, begging the question of whether the predicted garnet-bearing pyroxenite compositions exist. Although there are no known xenolith localities in the Peninsular Ranges, such xenoliths occur in the late Miocene alkali basalts

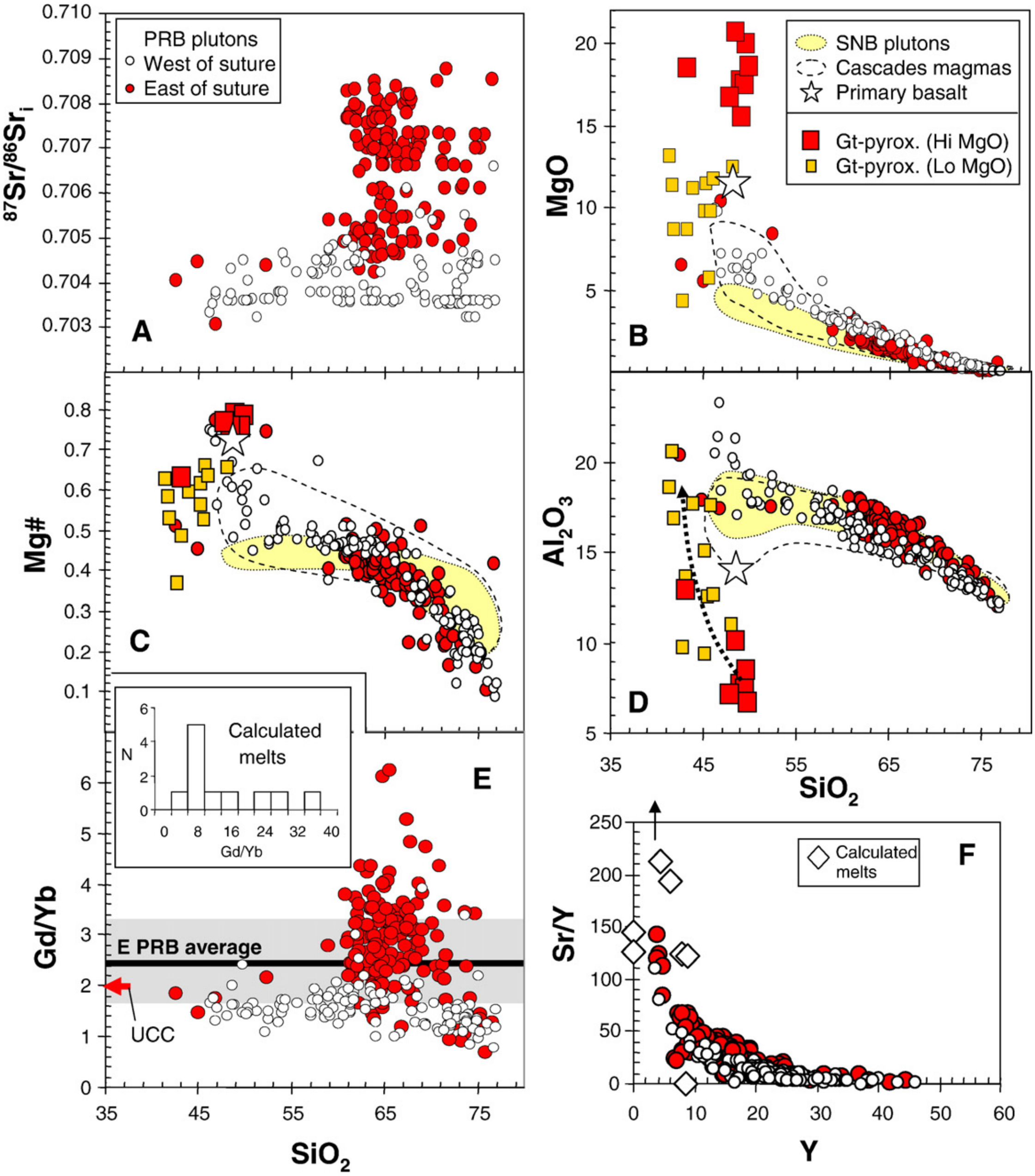


Fig. 2. New geochemical data on plutonic rocks from the Peninsular Ranges Batholith (PRB) are shown here. Western PRB plutons are denoted by white circles and eastern PRB plutons are denoted by red circles. Dashed white envelope represents field of Cascades volcanics (GEOROC database) and yellow shaded envelope represents field of plutons from the Sierra Nevada Batholith (SNB). Sierran garnet pyroxenites are denoted as squares: large red squares represent high MgO pyroxenites and small orange squares represent low MgO pyroxenites (data from (Lee et al., 2006)). Open star in B–D represents approximate primary basaltic magma composition. A. Initial Sr isotopic compositions are plotted versus whole-rock SiO_2 (wt.%) content. B. MgO (wt.%) versus SiO_2 (wt.%). C. Mg# (atomic Mg/(Mg+Fe)) versus SiO_2. D. Al_2O_3 (wt.%) versus SiO_2. E. Gd/Yb ratio versus SiO_2. Inset shows a histogram of the Gd/Yb ratios of magmas calculated to be in equilibrium with Sierran garnet pyroxenites, whose compositions were reconstructed from mineral compositions determined by laser ablation inductively-coupled plasma mass spectrometry. Average (with 1 SD) of eastern PRB denoted along with that of globally averaged upper continental crust (UCC; (Rudnick and Gao, 2003)). F. Sr/Y versus Y (ppm). Large open diamonds represent magma compositions calculated to be in equilibrium with Sierran garnet pyroxenites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

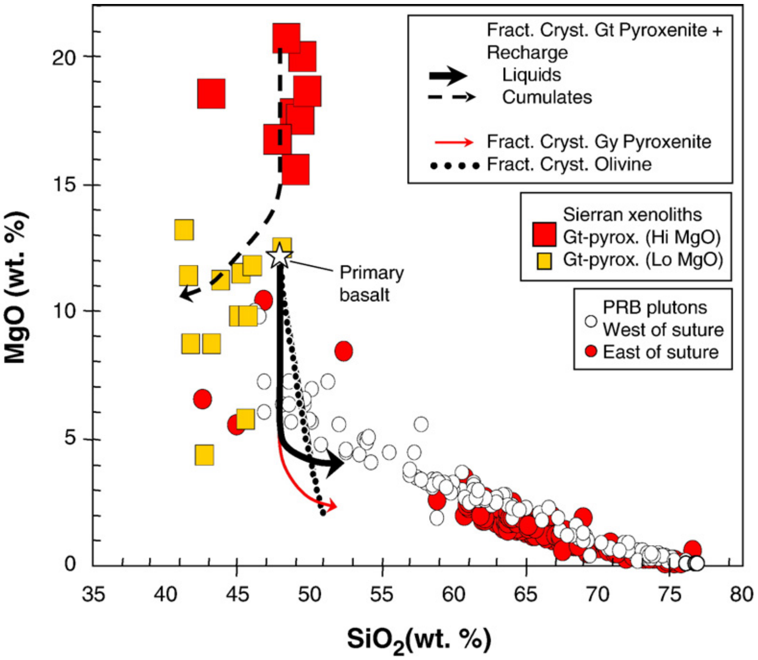


Fig. 3. Simplified version of Fig. 2B, but model fractionation curves are shown. Line composed of black circles represents the liquid line of descent caused by fractional crystallization of olivine from a primary basalt (star). Red arrowed line shows fractional crystallization of Sierran garnet pyroxenites. Thick black arrowed line shows fractional crystallization of Sierran garnet pyroxenites plus magmatic recharge of a primitive arc basalt (total mass of magma chamber is assumed to be at steady state). Complementary crystal line of descent during recharge-crystallization process is shown as dashed arrowed line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

erupted through the Sierra Nevada Batholith (the northern extension of the PRB) just east of the tectonic suture between accreted terranes to the west and North American lithosphere to the east (Dodge et al., 1988, Ducea and Saleeby, 1996). The Sierran garnet pyroxenites have similar Nd isotopic signatures as the overlying SNB plutons, supporting a petrogenetic link between the garnet pyroxenites and the SNB (Domenick et al., 1983, Ducea and Saleeby, 1998a,b, Saleeby et al., 2003, Lee et al., 2006).

Average low and high MgO garnet pyroxenites from the Sierran xenolith suites are shown in Table 1 based on data from Lee et al. (2006). Average trace-element compositions are also shown in Table 1, but unlike the whole-rock measurements of Ducea (2002) and Lee et al. (2006), what is presented here are reconstructed whole-rock compositions using in situ laser ablation ICP-MS data on garnets and pyroxenes (Supplementary Information), a method which allows one to see through contamination of xenoliths from the host lava. Reconstructed whole-rock compositions are generally in good agreement with measured whole-rock rock compositions for Fe, Cr, Mn, Co, Hf and the heavy rare-earth elements (REEs). However, reconstructed Nb, Ti, Th, U Li, Pb and the light REEs under-estimate measured whole rock because primary accessory phases (such as rutile, which incorporate Nb and Ti) and secondary enrichments on grain boundaries by recent contamination from the host magma not accounted for in our reconstructions. Our reconstructed compositions for U, Li, Pb and the light REEs are thus likely to be more representative of the pre-contaminated host (Stosch and Seck, 1980, Zindler and Jagoutz, 1988, Eggins et al., 1998, Condie et al., 2004, Lee et al., 2007).

The Sierran garnet pyroxenites can be classified into high and low MgO groups as shown in Figs. 2 and 3 (Lee et al., 2006, Horodyskyj et al., 2007). The high MgO group has high Ni, Cr, and Mg#, low Al_2O_3, and higher pyroxene than garnet modes, the latter manifested by high SiO_2 contents (~50 wt.%) similar to that of basaltic magmas (Fig. 5A). The more evolved low MgO group has low Ni, Cr and Mg#, higher Al_2O_3, lower SiO_2 (~45 wt.%) contents, and higher garnet than pyroxene modes (Fig. 2B–D). The low SiO_2 content of the low MgO group is simply due to the higher proportion of garnet than pyroxene (Lee et al., 2006). The general lack of significant positive Eu anomalies and the presence of heavy REE enrichments in the reconstructed bulk rocks indicate that most of the Sierran

Table 1

	Average garnet pyroxenite				Average PRB plutonic rocks				Average crustal compositions			
	Sierran high MgO	1 SD $n=6$	Sierran Low MgO	1 SD $n=7$	Western PRB	1 SD $n=129$	Eastern PRB	1 SD $n=158$	Upper continental crust	Middle continental crust	Lower continental crust	Global continental crust
wt.%												
SiO_2	49.19	0.49	43.83	2.5	64.10	8.72	65.62	4.73	66.60	63.50	53.40	60.60
TiO_2	0.54	0.13	0.73	0.65	0.57	0.30	0.67	0.33	0.64	0.69	0.82	0.72
Al_2O_3	8.03	1.2	15.58	3.8	15.61	2.28	15.94	1.18	15.40	15.00	16.90	15.90
$Fe_2O_3^T$	10.88	1.4	14.69	0.91	5.36	2.60	4.32	1.55	5.60	6.69	9.52	7.46
MnO	0.19	0.03	0.33	0.11	0.15	0.07	0.11	0.03	0.10	0.10	0.10	0.10
MgO	18.38	1.8	10.18	3.0	2.48	2.16	1.57	1.22	2.48	3.29	7.24	4.66
CaO	11.52	3.5	14.30	5.4	5.19	3.40	4.30	1.80	3.59	5.25	9.59	6.41
Na_2O	0.82	0.27	0.91	0.44	3.35	0.76	3.45	0.47	3.27	3.39	2.65	3.07
K_2O	0.18	0.13	0.22	0.16	1.92	1.15	2.46	0.91	2.80	2.30	0.61	1.81
P_2O_5	0.014	0	0.26	0.30	0.13	0.05	0.18	0.06	0.15	0.15	0.10	0.13
Total	99.72		101.04		98.87		98.61		100.63	100.36	100.93	100.86
ppm		1 SD $n=6$		1 SD $n=7$		1 SD $n=129$		2 SD $n=158$				
Li	5.9	4.0	7.6	12.0					24	12	13	16
Sc*	52.9	6.4	42.8	24	17	10	8.9	6.9	14	19	31	21.9
V*	276	42	332	178	105	82	66	80	97	107	196	138
Cr	1752	440	82.2	27	57	87	26	66	92	76	215	135
Co	44.3	14	37.4	13	15	12	9.1	6.7	17.3	22	38	26.6
Cu*	71.3	16	95.9	77	13	9	15	11	28	26	26	27
Zn*	72.8	16	104	45	50	20	68	18	67	70	78	72
Rb					62	42	85	32	82	65	11	49
Sr	62.2	37	35.1	22	236	98	420	138	320	282	348	320
Y	11.9	3.6	20.8	7.1	23	8	16	8	21	20	16	19
Nb*	0.5	0.6	2.5	3.8	4.9	2.1	9.5	3.9	12	10	5	8
Zr*	22.0	12	32.5	18	146	199	162	56	193	149	68	132
Cs					2.4	1.6	2.8	1.6	5	2	0	2
Ba					574	295	955	349	628	532	259	456
La	1.36	1.2	0.13	0.2	15	7	28	12	31	24	8	20
Ce	6.12	5.0	0.91	1.1	33	15	59	25	63	53	20	43
Nd	6.08	3.5	2.32	1.6	18	7	27	9	27	25	11	20
Sm	2.48	0.6	1.66	0.33	4.6	1.9	5.7	1.7	4.7	4.6	2.8	3.9
Eu	0.71	0.3	0.87	0.30	1.1	0.5	1.4	0.4	1.0	1.4	1.1	1.1
Gd	2.57	1.1	3.05	0.59	4.4	1.7	4.3	1.3	4.0	4.0	3.1	3.7
Tb	0.39	0.13	0.54	0.13	0.8	0.5	0.7	0.3	0.7	0.7	0.5	0.6
Yb	1.65	0.57	4.1	2.2	3.0	1.4	1.8	1.4	2.0	2.2	1.5	1.9
Ta	0.043	0.04	0.13	0.15	0.5	0.4	0.9	0.5	0.9	0.6	0.6	0.7
Hf	0.77	0.37	0.77	0.52	4.5	5.5	4.6	1.4	5.3	4.4	1.9	3.7
Th	0.019	0.02	0.007	0.01	8.0	5.9	12.0	7.9	10.5	6.5	1.2	5.6
U	0.005	0.01	0.027	0.06	1.9	1.3	2.3	1.3	2.7	1.3	0.2	1.3
Pb	0.20	0.13	0.18	0.12								
$Mg/(Mg+Fe^T)$	0.77		0.58		0.48	0.14	0.42	0.08	0.47	0.49	0.60	0.55
Gd/Yb	1.56		0.74		1.5	0.4	2.4	0.9	2.0	1.8	2.1	1.9
Nb/Ta	12.5		19.6		9.1	4.5	10.3	3.7	13	17	8	11

Trace-element concentrations for PRB plutonic rocks are based on whole-rock solution ICP-MS; garnet pyroxenite trace-element data based on reconstructions of laser ablation ICP-MS except for those elements denoted with (*), which represent whole-rock dissolutions; Fe is expressed as total Fe; blank entries indicate that the element was not measured or, in the case of xenoliths, thought to have contamination from the host lava.

garnet pyroxenites were not metamorphosed from plagioclase-bearing cumulates but instead equilibrated with a magma in the presence of garnet. However, even if the garnet pyroxenites had a plagioclase-bearing protolith, they must have been later melted in the "eclogite" stability field so that any hints of Eu anomalies were erased and replaced by garnet trace-element signatures.

The high MgO group has the necessary composition to drive a primary mantle-derived magma towards decreasing MgO without significant increase in SiO_2,

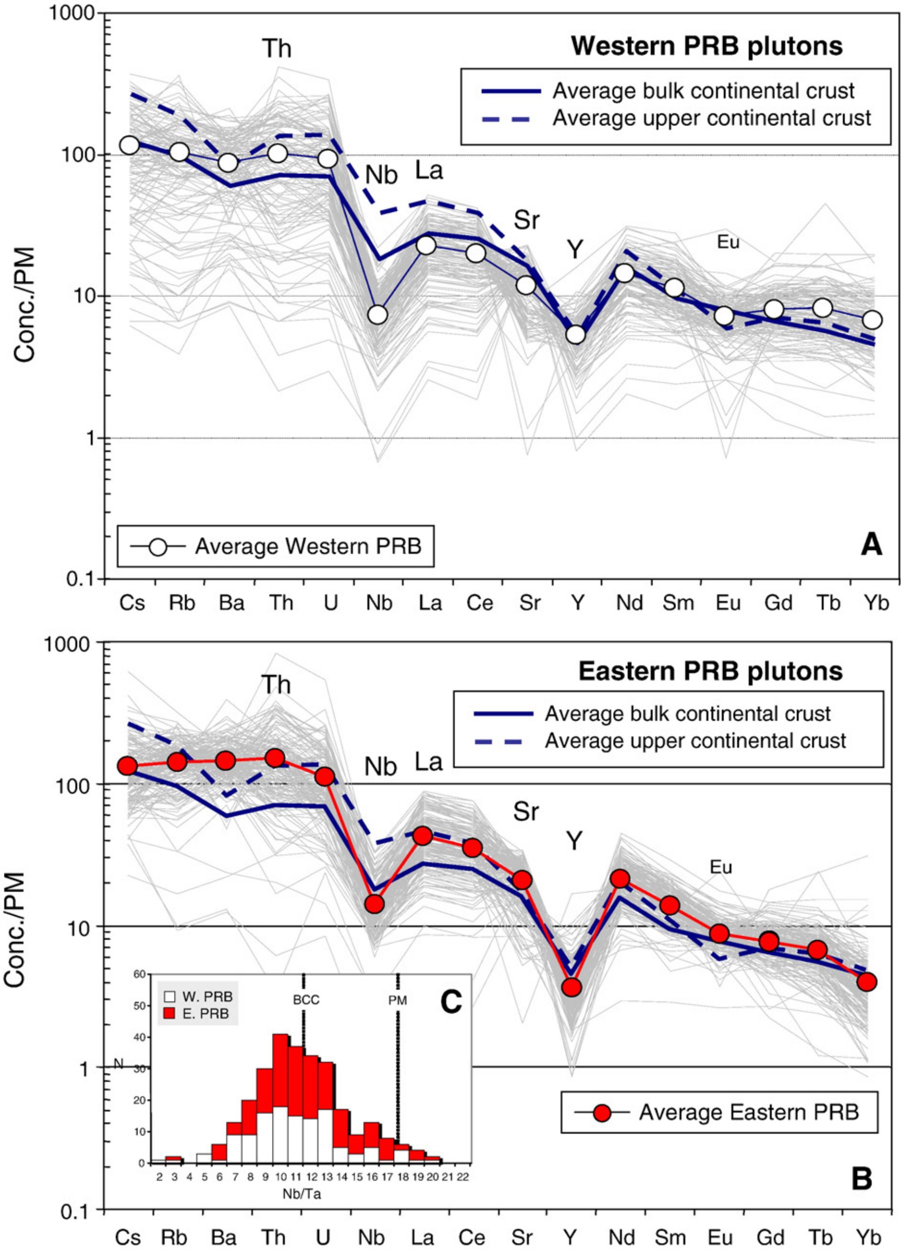


Fig. 4. Trace-element compositions of western (A) and eastern (B) Peninsular Ranges plutons normalized to primitive mantle. Bold and bold-dashed lines represent average bulk and upper continental crust, respectively (Rudnick and Fountain, 1995). Linear averages of eastern and western PRB plutons are shown as red and white circles. C. Histogram shows Nb/Ta ratios of PRB plutons (red = eastern; white = western). Note PRB plutons and average continental crust have Nb/Ta ratios lower than primitive mantle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

thus explaining the low MgO contents of the eastern PRB plutons for a given SiO_2 (Figs. 2B and 3). The subsequent increase in SiO_2 with progressive differentiation appears to have been driven by removal of the low MgO garnet pyroxenites, which have low SiO_2. Fig. 3 shows an example of how fractional removal of high MgO garnet pyroxenites followed by fractionation of low MgO garnet pyroxenites can cause an initial decrease in MgO in the magma followed by an increase in SiO_2 (details given in Supplementary Information). The modeled fractional removal process is applicable to either fractional crystallization or fractional melting of previously underplated basalt and mafic lower crust: The high MgO garnet pyroxenites are likely to be

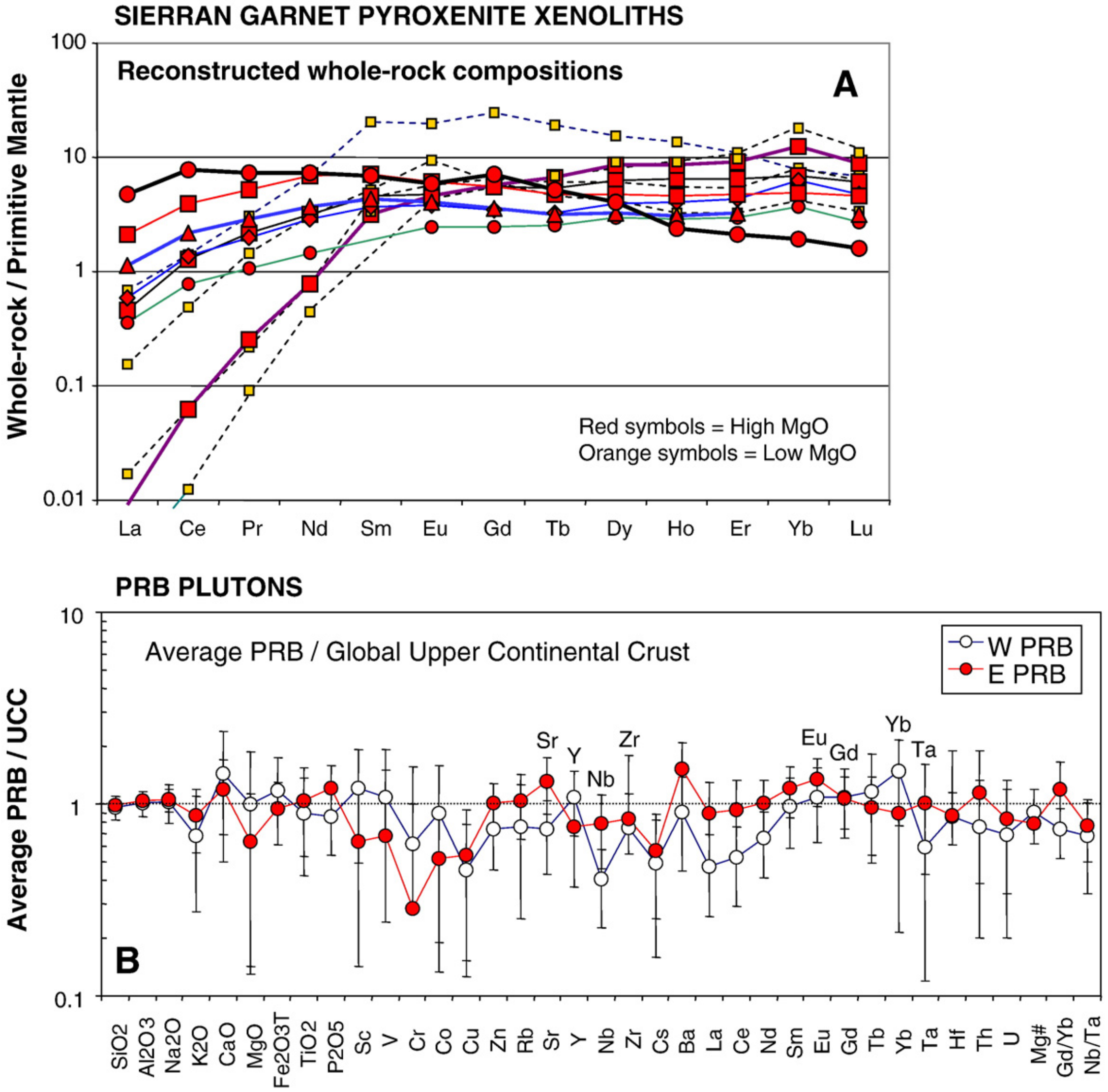


Fig. 5. A. Reconstructed rare-earth element compositions of garnet pyroxenite xenoliths from the Sierra Nevada based on laser ablation ICP-MS analyses of garnets and clinopyroxenes. B. Average compositions of the western and eastern PRBs divided by global upper continental crust (nominal values from (Rudnick and Gao, 2003)). Mg# refers to molar Mg/(Mg+Fe), where Fe represents total Fe.

cumulates, whereas the low MgO pyroxenites could be cumulates or restites (Saleeby et al., 2003, Lee et al., 2006). A problem with the fractional removal model is that the predicted rate at which MgO decreases is more rapid than that seen in the actual data (Fig. 3), but this drop in MgO can be compensated for by recharge of mafic magmas during the crystallization process (Lee et al., 2006) (Fig. 3). Finally, the trace-element compositions of magmas in equilibrium with these garnet pyroxenites were calculated (using appropriate partition coefficients (Pertermann et al., 2004)) and found to yield high Gd/Yb and Sr/Y values (Fig. 2E and F; see Supplementary Information for details), consistent with the high values seen in the eastern PRB plutonic rocks. Collectively, these observations support the above suggestion that early differentiation in the eastern PRB and SNB was controlled by garnet pyroxenite fractionation (Fig. 2B–D).

5. A general model for crust formation by arc magmatism: the role of island and continental arcs

5.1. From island arc to accretion to continental arc

These E–W petrogenetic dichotomies can be placed into a tectonic context (Busby, 2004). During Triassic–

Jurassic times, an island arc formed off the coast of North America after the initiation of the subduction of the Farallon plate (C1 in Fig. 1C). Back-arc basin sediments with North American affinities suggest the arc was not far off the coast and hence was manifested as a "fringing" island arc (Busby, 2004). The reason that the trench was outboard of the continental margin was most likely due to the fact that the Farallon plate at this time was old and cold at the trench and therefore the subduction zone was in retreat and the island arc was emplaced in an extensional setting (Busby, 2004). However, with time, the age of the slab at the trench became younger so that the rate of trench retreat decreased. In late Jurassic to early Cretaceous times, the back-arc basin closed and this fringing arc accreted onto the edge of the North American continent (C2 in Fig. 1C). With further younging of the Farallon plate, continued eastward subduction into the early Cretaceous gave forth to new mantle-derived arc magmas, which were emplaced through the accreted island arc, initiating the continental arc stage of Farallon–North America subduction (Todd et al., 1988, Busby, 2004). The remarkable homogeneity of Sr and Nd isotopic compositions (Kistler et al., 2003) in the western PRB (Fig. 2A) indicates that formation of the fringing island arc, its accretion and subsequent emplacement of the late Cretaceous continental arc plutons were closely spaced in time. Shallowing of the subduction angle in the mid- to late Cretaceous eventually drove the locus of continental arc magmatism to the east and transformed the arc setting into a fully compressional environment (C3, Fig. 1C). This eastward progression of arc magmatism and the evolution of the arc from an extensional to compressional environment, resulted in the stitching of late Cretaceous plutons through the suture and the pre-existing North American lithosphere (Silver and Chappell, 1988, Todd et al., 1988, Tulloch and Kimbrough, 2003).

5.2. *Refinement of crust compositions occurs after island arc accretion*

It is during and after accretion that the composition of continental crust was refined. Hydrous basaltic magmas derived from the hydrated mantle wedge rise up through the overlying lithosphere and crust, crystallizing along the way (Fig. 1D) (Grove et al., 2003). These magmas provide the heat source for melting pre-existing lower continental crust or previously underplated hydrous basalts. The magmas that eventually go on to make the bulk of the continental crust are evolved magmas that represent mixtures of deep-fractionated mantle-derived magmas with granitic melts derived from melting of pre-existing crust at shallower levels (Hildreth and Moorbath, 1988, Sisson et al., 1996, Ratajeski et al., 2001, Jackson et al., 2003, Ratajeski et al., 2005). Magmas that rise through thicker lithosphere (eastern PRB and eastern SNB) leave behind a long column of mafic garnet pyroxenite lithologies, while those that rise through the thinner accreted terranes (western PRB) do not develop such long differentiation columns. Instead of generating a garnet pyroxenite root, these magmas go on to underplate the arc and fractionate olivine-bearing lithologies.

There is extensive circumstantial evidence that the Sierran garnet pyroxenites foundered back into the mantle in the Pliocene: lack of garnet pyroxenites in Pliocene, lack of a seismically defined crustal root, and low sub-Moho seismic velocities (Ducea and Saleeby, 1996, Wernicke et al., 1996, Saleeby et al., 2003, Zandt et al., 2004). The PRB has received less attention, but a shallow Moho and uncompensated high elevations in the eastern PRB also suggest that the deep root of the PRB may have also suffered the same fate as the Sierra Nevada (Lewis et al., 2000). Thus, the final step (C4 in Fig. 1C) in refining the major-element composition of the continental crust is the foundering of garnet pyroxenites. We recognize that many investigators have discussed the possibility of delamination long before us (Herzberg et al., 1983, Arndt and Goldstein, 1989, DeBari and Sleep, 1991, Kay and Kay, 1993, Rudnick, 1995, Ducea and Saleeby, 1996, Jull and Kelemen, 2001, Foley et al., 2003, Kelemen et al., 2003, Plank, 2005, Bedard, 2006), but our integrated and comprehensive study enables us to better quantify the composition of the delaminated material and how it relates to the overlying plutonic rocks in space and time.

5.3. *When does delamination occur?*

One outstanding question that our model can shed light on is when delamination actually occurs. It has been suggested that delamination of garnet pyroxenites occurs in island arcs (DeBari and Sleep, 1991, Jull and Kelemen, 2001, Behn et al., 2007). However, here we showed that, at least in the case of the Cordilleran perspective, garnet pyroxenites were never involved in the genesis of the island arcs. Instead, olivine–plagioclase cumulates (gabbros) were involved in the early differentiation of island arc basaltic magmas. Because of the low densities of plagioclase, the negative buoyancy of these gabbros is much less than that of garnet pyroxenites, thus begging the question of whether delamination of mafic components is indeed a pervasive feature of island arcs. What appears to have happened in the Cordillera is that dense, garnet pyroxenite lithologies only formed during the continental arc stage of crust formation, wherein tectonic thickening associated with accretion, metamorphoses gabbroic cumulates into garnet pyroxenites or generates a thicker differentiation column so that garnet pyroxenites are formed as cumulates (or restites) from the outset. But even for those garnet pyroxenites that have gabbroic protoliths, they must have re-melted in the "eclogite" stability field because "ghost" Eu anomalies are absent in the garnet pyroxenites. Thus, the high densities needed to provide enough negative buoyancy to the lower crust are likely to be only achieved during or after the accretionary stage of continent formation wherein secondary refinement of the crust occurs. Because of this complicated multi-stage process, the Sierran and PRB crusts are expected to have both Eu anomalies and HREE depletions, the latter imposed by fractionation at great depth, and the former superimposed by fractionations at shallower depths.

5.4. Global generalizations

One criticism that we have faced is that any study of the SNB and PRB is simply a regional study and is not representative of continental crust formation. However, it is important to recognize that the SNB and PRB environment applies across the entire Cordilleran margin, from Alaska south to Chile. If we define continental crust as crust that has managed to escape being subducted and recycled into the mantle, then the North and South American Cordillera clearly dominate present day crust formation. Clearly, the Cordilleran case studies have a lot to tell us about continent formation.

To summarize, an accretion cycle begins with subduction initiation on an old passive continental margin, leading to the generation of juvenile arc magmas in the form of a fringing island arc. Due to retrograde migration of the trench (Schellart et al., 2007), the slab age youngs with time, causing the fringing island arc to eventually collapse onto the old passive margin (Busby, 2004). Continued subduction and younging of oceanic lithosphere leads to continental arc magmatism, where juvenile arc magmas intrude and mix with pre-existing crust. It is at this stage that the differentiation column is thick enough to generate and separate felsic magmas to the upper crust and garnet-bearing mafic residues and cumulates to the lower crust. The latter are eventually delaminated. Thus, through coupled tectonic and petrologic processes, island arcs are transformed into continents. We speculate that the Japanese arc represents a modern example of a fringing island arc that eventually will accrete onto the Eurasian continent. Indeed, arc accretion appears to be an important mechanism of crustal growth in the Phanerozoic (Sengör et al., 1993). Below, we discuss our model in the context of globally averaged continental crust.

6. Implications for the composition of continental crust

Regularly grid-spaced sampling eliminates observer sampling bias and hence permits us to calculate meaningful average compositions of the PRB upper crust (Table 1 and Figs. 4 and 5B). Figs. 4 and 5B and Table 1 compare average western and eastern PRB compositions to compositional models of the global upper continental crust, UCC (Rudnick and Gao, 2003). But before continuing our discussion, we remind ourselves that "global continental crust" is model-dependent. It represents a weighted average of idealized endmember compositions over space and time, but there is uncertainty in the weighting factors. Thus, it is naïve to think that the globally averaged composition of continental crust ever matches the composition of any given section of continental crust.

With these caveats in mind, our purpose in comparing PRB compositions to global continental crust is simply to look for first order similarities and not dwell on small discrepancies. Both the western and eastern PRBs are overall very similar to UCC in terms of relative enrichments of fluid-mobile elements (large ion lithophile elements) over fluid-immobile elements (high field strength elements). For example, the PRB and UCC both have low Nb/La and high Cs, Sr, Rb, Ba, and U concentrations (Fig. 4). These signatures are well-known characteristics of arc magmas and result from the preferential enrichment of fluid-mobile elements over fluid-immobile elements, such as the high field strength elements, when fluids from subducting slabs are liberated into the mantle wedge (Rudnick and Fountain, 1995, Plank, 2005). For the most part, these fractionations are not imposed by intracrustal differentiation (e.g., fractional crystallization or re-melting of pre-existing crust) but derive instead from the mantle wedge. The ratios of Nb to Ta, both fluid-immobile elements, in the western and eastern PRBs are indistinguishable from each other, both being lower than estimates of bulk silicate Earth (Fig. 4C). Because the western and eastern PRBs have undergone substantially different intracrustal differentiation histories, the low Nb/Ta ratios in the PRB plutons must *pre-date* intracrustal differentiation, hence Nb and Ta fractionation occurs in the mantle wedge or subducting slab.

Extending our discussion to other elements, we find that the western PRB is slightly less silicic ($SiO_2 = 64.1 \pm 8.7$; 1 SD) and less potassic ($K_2O = 1.92 \pm 1.1$) than UCC ($SiO_2 = 66.6$; $K_2O = 2.8$). It also has lower LREE contents and lower LREE to HREE ratios than UCC. The low LREE/HREE ratio is manifested by low Gd/Yb (1.5 ± 0.4) ratios, which reflect the lack of garnet retention during differentiation (Fig. 2E). We note that both the western PRB and UCC both exhibit negative Eu anomalies although many of the western PRB samples have more pronounced negative Eu anomalies than UCC. As for the eastern PRB, most of the major and minor elements as well as the REE contents are identical to UCC to within error. For example, the Gd/Yb ratio of the eastern PRB is 2.4 ± 0.9 as compared to 2.0 for the UCC, and the K_2O content is 2.46 ± 0.9 as compared to 2.8 (Table 1, Fig. 2E). However, the eastern PRB shows less pronounced negative Eu anomalies than UCC.

The overall trace-element similarities between eastern PRB and UCC make it reasonable to speculate that a significant fraction of continents could be built by processes analogous to Cordilleran arcs. If so, this would imply that even some Archean continental crust might have an arc origin. Indeed, many high MgO garnet pyroxenite xenoliths (eclogites and websterites) from Archean cratons are similar in composition to the Sierran high MgO garnet pyroxenites, and have thus been interpreted to represent arc cumulates (Horodyskyj et al., 2007). One potentially important process of continent formation throughout Earth's history might indeed be island arc accretion followed by further refinement during continental arc magmatism. In the latter step, deep-seated fractionation may occur, yielding crusts with slightly high Gd/Yb and Sr/Y ratios as a result of garnet retention in cumulates or residues. Although it is not often stated that the UCC shows a garnet signature, the UCC's Gd/Yb and Sr/Y ratios, like those of the eastern PRB, are higher than the western PRB. Given that garnet was not involved in the genesis of the western PRB but was involved in the eastern PRB, there may, after all, be a hint of a garnet signature in global continental crust. We note that the negative Eu anomaly seen in UCC is not inconsistent with a simultaneous garnet signature, e.g., a depletion in heavy REEs. As can be seen from the eastern PRB plutons, a HREE depletion is imposed by deep fractionation, but a Eu anomaly is subsequently imposed by shallow level fractionation later on in the differentiation sequence. In any case, we note that high Sr/Y ratios, commonly attributed to direct melting of eclogitized oceanic crust undergoing subduction (Drummond et al., 1996), could also be generated by intracrustal differentiation.

There are, however, limitations to generalizing the Cordilleran case study in space and time. First, the MgO content and Mg# (molar Mg/(Mg+Fe), where Fe is taken as total Fe) of the western and eastern PRBs are lower than that of global UCC (Table 1, Fig. 4B). Sc, V, Cr, and Co are also lower in the eastern PRB compared to UCC. What these elements have in common is that they are either compatible or moderately incompatible elements. It has long been recognized that global continental crust has unusually high MgO, Mg#, Cr and Ni contents and a number of explanations have been suggested (Kelemen, 1995, Rudnick, 1995). It is not our goal to discuss these scenarios in detail, but one possibility is that Archean continental crust is made up of slab melts, which passed through and reacted with peridotitic mantle wedge and attained high Mg#s (Drummond et al., 1996, Rapp et al., 1999). Another possibility is that there is an intraplate basalt component in continents (Rudnick, 1995).

In summary, Phanerozoic continent formation, in the form of Cordilleran batholiths, generates many of the geochemical features of global UCC. This implies a possible link between Cordilleran type processes and continent formation. However, some outstanding discrepancies between the PRB and UCC indicate that additional components or modifications of the arc scenario are needed to fully explain the composition of continental crust throughout Earth's history. Nevertheless, our Phanerozoic case study provides a baseline to which other crust formation processes can be compared.

7. Additional implications

7.1. Lower crustal recycling rates and the origin of mantle heterogeneities

Assuming a typical basaltic parent and that the Sierran garnet pyroxenites are complementary to an intermediate Sierran or Peninsular Ranges magma composition, we can crudely estimate the amount of complementary Sierran garnet pyroxenite. Because there are two types of garnet pyroxenites, two steps are required. The first differentiation step involves the high MgO garnet pyroxenites. Assuming that the parental basalt has 10–12 wt.% MgO, high MgO garnet pyroxenite has ~18 wt.%, and the evolved basalt has <7 wt.%, we estimate that 27–45% of the parental basalt forms high MgO garnet pyroxenites. Next, the derivative melt/crust from the first step separates into low MgO garnet pyroxenites and the continental crust. We assume that the second stage parental melt has ~7 wt.% MgO, the low MgO garnet pyroxenites ~10 wt.% and the average continental crust ~3 wt.% (note that this is higher than the average PRB upper crust because we are interested in the total crust composition). This calculation indicates that ~57% of the second stage melt goes on to make low MgO garnet pyroxenites. Combining steps 1 and 2 shows that 60–75% of the original juvenile basalt is disposed of in the form of garnet pyroxenites to generate the Sierran and Peninsular Ranges Batholiths. While this seems like a lot, it is consistent with xenolith observations from Miocene diatremes that the Sierras were underlain by at least 70 km of mafic lithologies (Ducea and Saleeby, 1996, Ducea and Saleeby, 1998a,b, Ducea, 2002, Lee et al., 2006). For comparison, Plank (2005) estimated from Th/La mass balance that 25–60% of the parental basalt would be manifested as delaminated mafic lithologies.

Although these mafic lithologies were still present in the Miocene, they are no longer present beneath most of the PRB and SNB as evidenced from the lack of garnet-bearing xenoliths in Pliocene and younger volcanics, the thin Moho, and the low seismic velocity anomalies in the underlying mantle (Ducea and Saleeby, 1996, Wernicke et al., 1996, Ruppert et al., 1998, Lewis et al., 2000, Lee et al., 2001, Zandt et al., 2004). If all the hypothetical garnet pyroxenite was recently delaminated (Ducea and Saleeby, 1996) and if the Cordilleran process can be generalized, we are naturally led to ask how significant in a global sense is lower crustal recycling? To approximate lower crustal recycling rates, we take 3–9 km^3/yr as the average *total* production rate of magmas in arcs (Peacock, 1990). If 60 to 70% of this material is mafic garnet pyroxenite, 1.8 to 6 km^3/yr of mafic lower crust is recycled. To place this in context, the recycling rate of oceanic crust is ~20 km^3/yr (basaltic+gabbroic sections (Peacock, 1990)), which means that lower crustal recycling rates could be 10–30% that of subduction recycling of oceanic crust. Plank's analysis based on Th/La gives a value of 10%, which agrees with the lower end of our range (2005). Regardless of the uncertainties in these mass balance calculations, it is clear that lower crustal recycling in the form of delamination is significant.

What then is the fate of recycled arc-related garnet pyroxenites (e.g., "arc-eclogites")? Some of these garnet pyroxenites might partially melt shortly after they founder (Ducea and Saleeby, 1998a,b, Gao et al., 2004). Others could reside in the upper mantle, forming fertile heterogeneities that could eventually generate intraplate magmas (Anderson, 2007), and if so, exploring the compositions of arc-eclogite melts would be particularly useful in understanding the compositions of hotspot magmas (Sobolev et al., 2005). Finally, some of these "arc-eclogites" could sink into the lower mantle and reside there indefinitely.

7.2. Implications for the lead (Pb) paradox

If recycled garnet pyroxenites represent a significant reservoir in the upper or lower mantle, what type of geochemical or isotopic signature would be imparted on the bulk silicate Earth? An outstanding paradox is that of lead isotopes (Allegre, 1969, Hofmann, 1997). In brief, the continental crust and upper mantle (as sampled by mid-ocean ridge basalts and ocean island basalts) have ^{207}Pb/^{204}Pb and ^{206}Pb/^{204}Pb isotopic compositions that plot on or to the right of the geochron (Fig. 6A), that is, the crust and the upper mantle are both more radiogenic than the bulk Earth (the geochron represents the locus of points in ^{207}Pb/^{204}Pb–^{206}Pb/^{204}Pb space upon which the bulk Earth should roughly lie). This can be seen in Fig. 6A, where ocean island and mid-ocean ridge basalts define a locus of points (the "mantle array") that plot to the right of the geochron. Since the continental crust and upper mantle are believed to roughly complement each other in terms of chemical enrichments or depletions, there is a global imbalance in terms of Pb isotopes. A hidden reservoir characterized by low U/Pb ratios and hence low time-integrated ^{207}Pb/^{204}Pb–^{206}Pb/^{204}Pb ratios is needed to resolve this balance. One possibility is that Pb (but not U) is being continually sequestered to the Earth's core (Hart and Gaetani, 2006). Another possibility is that the lower crust might represent the missing reservoir because of its low U/Pb ratios due to preferential removal of U during high grade metamorphism, but this hypothesis fell out favor because it was shown that, despite these low U/Pb ratios, the Pb isotopic composition of the lower crust is often overprinted by metamorphic or metasomatic processes during orogenic episodes (Rudnick and Goldstein, 1990). The implication was that the present lower crust is not the missing Pb reservoir.

But what about delaminated lower crust in the form of garnet pyroxenites? Such material, if allowed to sink to the lower mantle, might never be modified by metasomatism. In the inset of Fig. 6B, we show that the U/Pb ratios of the Sierran garnet pyroxenites are even lower than present lower continental crust. Thus, if Sierran type garnet pyroxenites were formed early in Earth's history, it would now be characterized by very unradiogenic Pb isotopes. To illustrate, we have estimated the Pb isotopic composition of a garnet pyroxenite formed ~1.7 Gyr ago (Fig. 6A), an age we take as a very crude estimate of the average age of global continental crust (and roughly corresponds to the

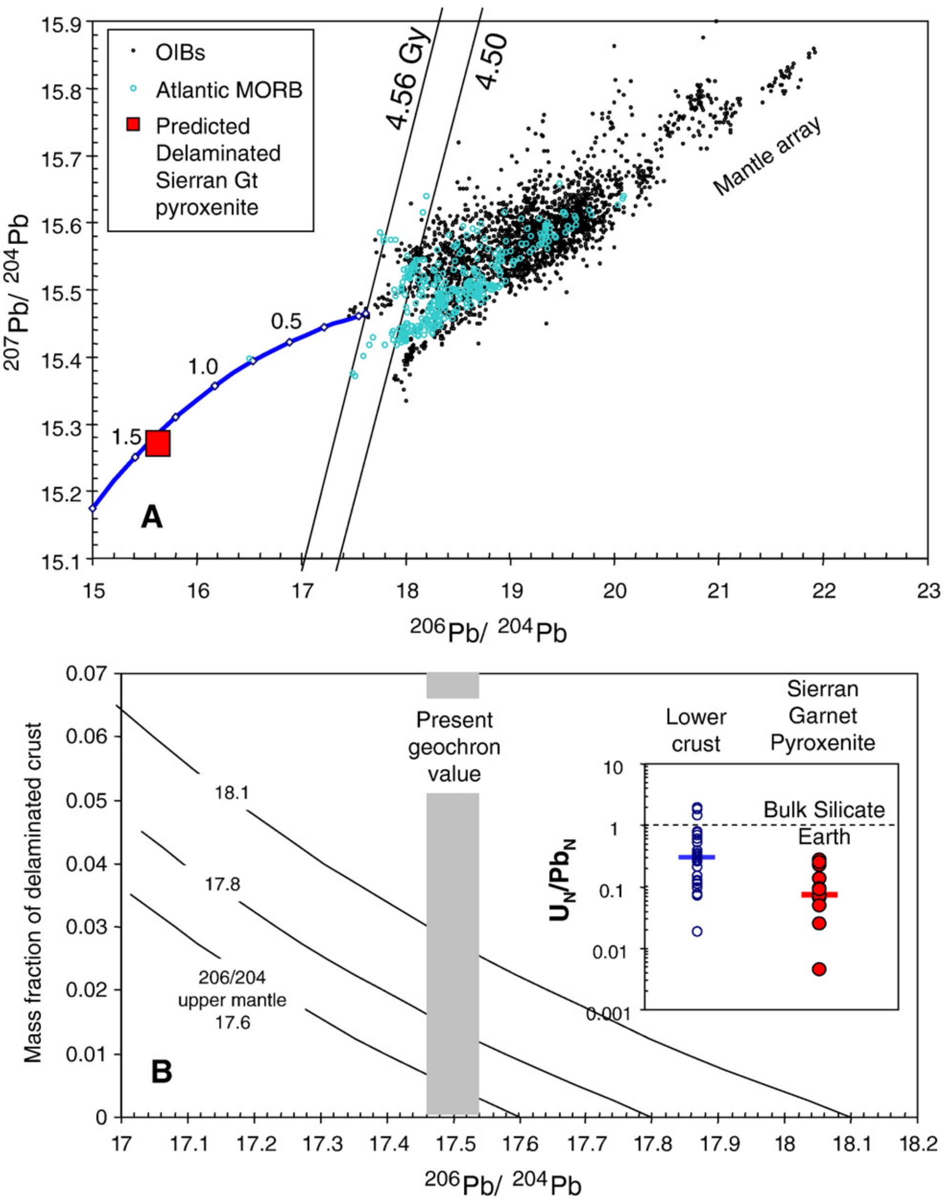


Fig. 6. A. Pb isotopic diagram showing a compilation of ocean island and mid-ocean ridge basalt data ("mantle array"). Geochrons for 4.56 and 4.5 Gyr are shown. A Pb isotope growth curve for a mantle having $^{238}U/^{204}Pb = 8$ is shown. Tick marks on this curve are at 0.25 Gyr. B. Mass fraction (relative to entire mantle) of delaminated lower crust (with Sierran garnet pyroxenite compositions) needed to counterbalance the radiogenic Pb isotopic composition of the upper mantle with respect to the geochron. Curves represent different assumed present day mantle isotopic compositions. Vertical gray bar represents estimate of original bulk silicate Earth composition. Inset shows the U/Pb concentration ratio of present lower crust (Rudnick and Goldstein, 1990) compared to that of Sierran garnet pyroxenites, all normalized to bulk silicate Earth estimates of U/Pb (McDonough and Sun, 1995). Horizontal bar represents geometric mean of each dataset. Note, Sierran garnet pyroxenite values represent reconstructed values from in situ measurements of mineral grains. Red square near the 1.5 Gyr tick mark on the Pb growth curve shows the hypothetical Pb isotopic composition of ancient (1.7 Gyr) delaminated lower crustal rocks having U/Pb compositions similar to that of the Sierran garnet pyroxenites.

effective Pb–Pb age of the mantle array seen in Fig. 6A). It can be seen that the predicted Pb isotopic compositions are sufficiently unradiogenic to plot well to the left of the geochron.

The question of course is whether a reasonable mass balance can be obtained. Fig. 6B shows different estimates of the required amount of stored mafic crust to balance the radiogenic Pb isotopic composition of the mantle. For the model, we assumed that the delaminated mafic crust has a $^{206}Pb/^{204}Pb$ of 15.4 and a Pb concentration of 0.2 ppm. The bulk silicate Earth *prior* to Pb segregation is assumed to lay on the geochron, hence an isotopic composition denoted by the intersection of the mantle array with various model geochrons was taken ($^{206}Pb/^{204}Pb \sim 17.4$). For the present day upper mantle, we assumed a Pb concentration of 0.02 ppm (Workman and Hart, 2005), but varied its Pb isotopic composition from 17.6 to 18.1. Although the Pb isotopic composition of these components and reservoirs are highly uncertain, it is the relative effects that are important in this calculation. As expected, the amount of missing delaminated crust (expressed in terms of mass proportion of entire mantle) is very sensitive to what we assume as the Pb isotopic composition of the mantle. The more radiogenic the value, the greater the amount of delaminated crust needed. We show that although U/Pb ratios of the Sierran garnet pyroxenites are low, U and Pb concentrations are much lower than continental crust estimates. Thus, the fraction of delaminated lower crust in the mantle would have to range from <1 to 3% in order to resolve the Pb paradox. The present day continental crust makes up only 0.6% of the mantle. If the amount of delaminated crust is roughly equal to that of continental crust, our estimated proportions are too large. On the other hand, a larger amount of delaminated lower crust could exist if significant amounts of continental crust have been recycled into the mantle. In any case, our calculations show that it may be worth revisiting delaminated lower crust as a possible low U/Pb reservoir.

7.3. Some words on chemical weathering

Finally, we remark that although fractionation of mafic garnet pyroxenites drives derivative magmas towards more felsic conditions, this process is not likely to yield the granitic compositions defining the most silicic endmembers seen in PRB or SNB granitoids. Thus, a glaring gap in this manuscript is how the granitic endmembers are formed, but any detailed discussion on this topic is beyond the present scope. Melting or incorporation of sediments probably plays an important role in making granites (Kemp et al., 2007). This, in turn, would imply that chemical weathering associated with making sediments also plays a role in modulating the composition of the continental crust. We are thus aware that the view presented here for making continental crust is incomplete as the differentiation effects of weathering have not been dealt with. We will deal with this issue in an upcoming manuscript.

8. Conclusions

Although it is generally believed that arc magmatism plays an important role in the formation of continents, exactly how arcs assemble into continents and evolve into felsic crust is not clear. We show from a North American Cordilleran perspective that continental crust here was formed, assembled and refined through a multi-step process, beginning with island arc formation, followed by arc accretion, and ending with continental arc magmatism. Differentiation into felsic crust and mafic, garnet pyroxenitic lower crust occurs only after accretion, that is, in the continental arc stage. Delamination of the mafic component thus occurs during and after the continental arc stage, not during the life of the island arc. Mature continental arcs and globally averaged continental crust have many compositional similarities, suggesting that Cordilleran crust-forming processes may operate commonly over space and time. Small discrepancies in some elements imply that other crust-forming processes, such as intraplate magmatism, are still necessary to explain continent formation in their entirety. Nevertheless, our Cordilleran case study provides a baseline for future comparisons.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2007.09.025.

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