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The role of amphibole in the evolution of arc magmas and crust: the case from the Jurassic Bonanza arc section, Vancouver Island, Canada

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Abstract The Jurassic Bonanza arc, on Vancouver Island, British Columbia, represents an exhumed island arc crustal section of broadly diorite composition. We studied bodies of mafic and ultramafic cumulates within deeper levels of the arc to constrain the conditions and fractionation pathways leading from high-Mg basalt to andesite and dacite. Major element trends coupled with textural information show the intercumulus crystallization of amphibole, as large oikocrysts enclosing olivine in primitive cumulates controls the compositions of liquids until the onset of plagioclase crystallization. This process is cryptic, occurring only in the plutonic section, and explains the paucity of amphibole in mafic arc volcanics and the change in the Dy/Yb ratios in many arc suites with differentiation. The correlation of octahedral Al in hornblende with pressure in liquidus experiments on high-Mg basalts is applied as an empirical barometer to hornblendes from the Bonanza arc. It shows that crystallization took place at 470–880 MPa in H_2O-saturated primitive basaltic magmas. There are no magmatic equivalents to bulk continental crust in the Bonanza arc; no amount of delamination of ultramafic cumulates will shift the bulk arc composition to the high-Mg# andesite composition of bulk continental crust. Garnet removal from wet magmas appears to be the key factor in producing continental crust, requiring high pressures and thick crust. Because oceanic island arcs are built on thinner crust, the long-term process generating the bulk continental crust is the accretion of island arcs to continental margins with attendant tectonic thickening.

Keywords Amphibole · Arc · Plutonic · Magma · Water · Crust

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Introduction

The earth is unique in our solar system in having a predominantly sialic, high-standing crust (Rudnick 1995), the origin of which is a long-standing problem in geology. One theory holds that net crustal growth has, at least since Phanerozoic time, taken place at both island and continental arcs. This idea stems from important geochemical similarities between bulk continental crust and arc magmas (Arculus 1999; Rudnick and Gao 2003; Hawkesworth and Kemp 2006; references therein), requiring that the latter must have been a key component in the generation of the continents. Field studies of modern arcs show that the majority of magmas erupted in this setting are basaltic (Arculus 1994; Rudnick 1995), but the best estimate of the composition of the *bulk* crust, however, is andesitic (Rudnick and Gao 2003) leaving a paradox (e.g. Lee et al. 2007; Behn and Kelemen 2006; Arculus 1999; Rudnick 1995).

The mineral assemblage and equilibria driving the evolution of liquid compositions in arcs from primary basalt to andesite remains a source of disagreement. Phenocryst assemblages in arc volcanics have been used as a constraint on possible fractionation assemblages (e.g., Cawthorn and O'Hara 1976; references therein), leading to widespread appeal to a gabbroic assemblage of olivine–augite–plagioclase–magnetite (Gill 1981). Nonetheless, sub-liquidus phases can be effectively fractionated by the return of interstitial liquids from crystallization zones back to the main magma body (Langmuir 1989), meaning that the absence of a phenocryst phase from arc lavas need not preclude its involvement in controlling differentiation trends. The abundance of amphibole-bearing cumulate rocks, both as plutons and as cognate xenoliths in arc lavas, suggests that amphibole plays an important role in the differentiation of many arc suites (e.g. Cawthorn et al. 1973; Arculus and Wills 1980) as shown by the Dy/Yb ratios in many arc volcanic suites (Davidson et al. 2007). The scarcity of amphibole phenocrysts in arc lavas can be attributed to its instability at low pressures (e.g., Rutherford and Devine 1988; Romick et al. 1992), leaving the possibility for amphibole fractionation at mid-crustal depths to influence the evolution of arc magmas.

Phase equilibria of H_2O-bearing basalts show the suppression of plagioclase and appearance of hornblende with increasing pressure and/or f_{H_2O} approaching the mid crust (Grove and Kinzler 1986; Anderson 1980; Grove et al. 2003; Barclay and Carmichael 2004). At still higher pressures of the lower crust, garnet appears on the liquidus in basaltic systems (Allen and Boettcher 1983; Rapp and Watson 1995). Crustal thickness could therefore exert a strong influence on fractionation pathways for arc magmas, by determining the depth at which magmas pond and undergo the first stage of crystallization (see Davidson et al. 2007; Macpherson 2008).

Exhumed arc sections provide direct field evidence for the magmatic processes at depth, leading to the bulk composition of arc crust (e.g., Burns 1985; Greene et al. 2006; Jagoutz et al. 2006). Detailed studies of arc sections at Talkeetna (south-central Alaska) and Kohistan (northwest Pakistan) show that a significant portion (25–85%) of the plutonic section is missing (DeBari and Coleman 1989; Hacker et al. 2008; Greene et al. 2006). The process by which such large portions of arc crust have been removed remains controversial, but the loss of lower crustal cumulates into the mantle provides one potential solution to the compositional quandary of producing andesitic continental crust from primary basaltic island arc magmas.

Exposed on Vancouver Island, British Columbia, the Jurassic Bonanza arc is believed to represent the southerly continuation of the Talkeetna arc crustal section (DeBari et al. 1999; Clift et al. 2005), but differs by having been emplaced into a substrate of Paleozoic island arc and a Mesozoic oceanic plateau. In this study, a combination of field mapping, petrography, and whole rock, trace element and mineral chemistry are used to constrain the *P*–*T* conditions and pathways along which the magmas that fed the Bonanza arc evolved. The exposure of cogenetic and coeval plutons and volcanics provides an opportunity to assess the geochemical relationship between magmas, which have crystallized at depth in the crust and those which have ascended to the surface. We scrutinize the difference in mineral assemblage between plutonic and volcanic rocks of similar composition, and constrain what proportion of cumulates are required to explain the observed geochemical trends in the more evolved magmas, to better understand the origin and composition of continental crust.

Geologic setting

Regional geology

The Canadian Cordillera is broadly divisible into three parts: an eastern foreland domain, a central Intermontane domain, and an Insular domain (Johnston 2008). The western portion of the Insular domain is dominated by Wrangellia, a terrane extending along the western coast of North America (Jones et al. 1977). On Vancouver Island Wrangellia consists of Devonian arc volcanics and volcaniclastics of the Sicker Group, overlain by the Permian Buttle Lake Group carbonates (Massey and Friday 1987), the 6,000 m thick succession of Triassic Karmutsen basalts, thin micritic limestone of the Quatsino Formation, and thinly bedded sediments of the late Triassic Parson Bay Formation (Massey and Friday 1987; Nixon et al. 1995). Minor arc volcanics and volcaniclastics within the Parson Bay are interpreted as the earliest phase of activity of the Bonanza island arc (Nixon and Orr 2007).

Rocks of the Bonanza arc are erupted on or intruded into the pre-Jurassic stratigraphy and have been divided into three units (Fig. 1). The Westcoast Crystalline Complex (WCC) is the deepest level and consists of variably deformed gabbro to diorite plutons and amphibolites (Isachsen 1987; deBari et al. 1999). Hornblende gabbro and variably serpentinized olivine pyroxenite have been mapped as a subunit of the WCC (Isachsen 1987; DeBari et al. 1999). The Island Plutonic Suite (IPS) represents the upper plutonic levels and varies from diorite to granite intruding the Vancouver Group, as well as the coeval Bonanza Group volcanics. The Bonanza volcanics cap the stratigraphic section and consist of interbedded basaltic to rhyolitic subaerial flows and flow breccias, with minor dacitic to rhyolitic tuff beds. Wrangellia is unconformably overlain by the Cretaceous Nanaimo Group sediments (Massey and Friday 1987).

Geochronological and geochemical data support a co-magmatic origin for the three igneous subunits of the Bonanza Group (Isachsen 1987; DeBari et al. 1999). Ages of Bonanza volcanic rocks overlap those of the plutonic rocks in both the WCC and IPS and indicate that the

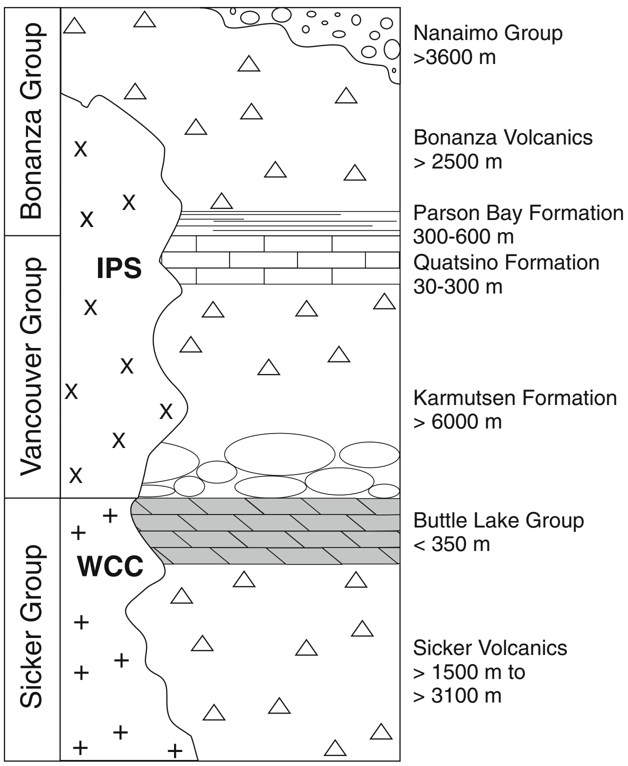

Fig. 1 Simplified stratigraphic section for southern Vancouver Island, with thickness estimates (Muller et al. 1981; Massey and Friday 1987; England and Calon 1991; Nixon and Orr 2007). *WCC* Westcoast Crystalline Complex, *IPS* Island Plutonic Suite

Bonanza arc was active from approximately 200 Ma to 167 (Palfy et al. 2000; Nixon and Orr 2007). Fossils from the Parson Bay formation suggest that arc volcanism began as early as the Norian stage (~215–203 Ma) of the late Triassic (Nixon and Orr 2007). These ages overlap with those determined from U–Pb–zircon geochronology within the Talkeetna arc (205–156 Ma) supporting the link of the Bonanza and Talkeetna arcs along strike (DeBari et al. 1999; Clift et al. 2005). DeBari et al. (1999) offer an excellent overview of the geology, geochemistry and geochronology of the Bonanza arc in central Vancouver Island. The thickness and overall composition of the arc section on Vancouver Island is examined elsewhere (Canil et al., in press). The detailed differentiation history of the arc crust is the goal of the present work.

The Port Renfrew area

On southern Vancouver Island in the region surrounding Port Renfrew (Fig. 2), we examined a crustal section of the Bonanza arc bound to the south by the San Juan Fault, and to the north by the Cowichan Uplift (Massey and Friday 1987). Exposures of all three subunits of the Bonanza Group are present along logging roads throughout the field area. The WCC is restricted to the southern parts of the area and is dominated by melanocratic to leucocratic quartz diorite and gabbro, containing varying amounts of hornblende, biotite and Fe–Ti oxides. WCC plutons are quite heterogeneous on the outcrop (meter) scale and locally display a well-developed gneissosity, generally striking southeast. Although Sicker Group country rock has been reported by DeBari et al. (1999), only contacts with the Triassic Karmutsen Group have been recognized in the present study area. Shear zones strike southeast and dipping to the southwest cut across the WCC, with a sense of shear (tops to NE) suggesting that the WCC was emplaced as a series of east-verging thrust-faulted panels, the easternmost one of which has been thrust onto the Karmutsen basalts.

Ultramafic rocks occur as discreet bodies within the WCC, ranging in size from a meter to several tens of meters. Contact relationships between the ultramafic bodies and the main gabbro–diorite phase of the WCC are variable: olivine-bearing cumulate bodies show either abrupt, undeformed contacts with their host, or are present as sheared pods and discontinuous layers; larger bodies of cumulate hornblende gabbro grade into the main gabbro–diorite phase of the WCC.

IPS plutons are large irregular bodies with no fabric up to several tens of kilometer across and range in composition from quartz diorite to alkali feldspar granite. The contact between the IPS and the WCC is not defined.

The Bonanza Group volcanics vary in composition from basalt to rhyolite. Aphanitic to plagioclase-, pyroxene-, and rare hornblende-phyric basalt to basaltic andesite is the dominant lithology. In addition to massive flows, the Jurassic volcanic rocks also occur as flow breccias. Lesser pyroclastic deposits are also present, including banded and air fall tuffs. Aphyric mafic dykes cut across the Vancouver Group and the plutonic sections of the Bonanza Group and are interpreted to represent the feeder dykes to volcanic centers.

Petrography

We examined 115 samples from the field area. Petrographic descriptions for each sample are listed in Table 1. Metamorphic alteration is on the whole very minor, with typically less than 10% secondary minerals by mode. Metamorphism is expressed through the alteration of plagioclase to sericite and epidote, and the partial replacement of biotite and hornblende by chlorite and epidote. Where present, cumulus olivine is partially serpentinized. Volcanic rocks contain quartz, chlorite, epidote, calcite and actinolite as amygdaloidal assemblages. Plagioclase and biotite are the most likely phases to be pervasively altered.

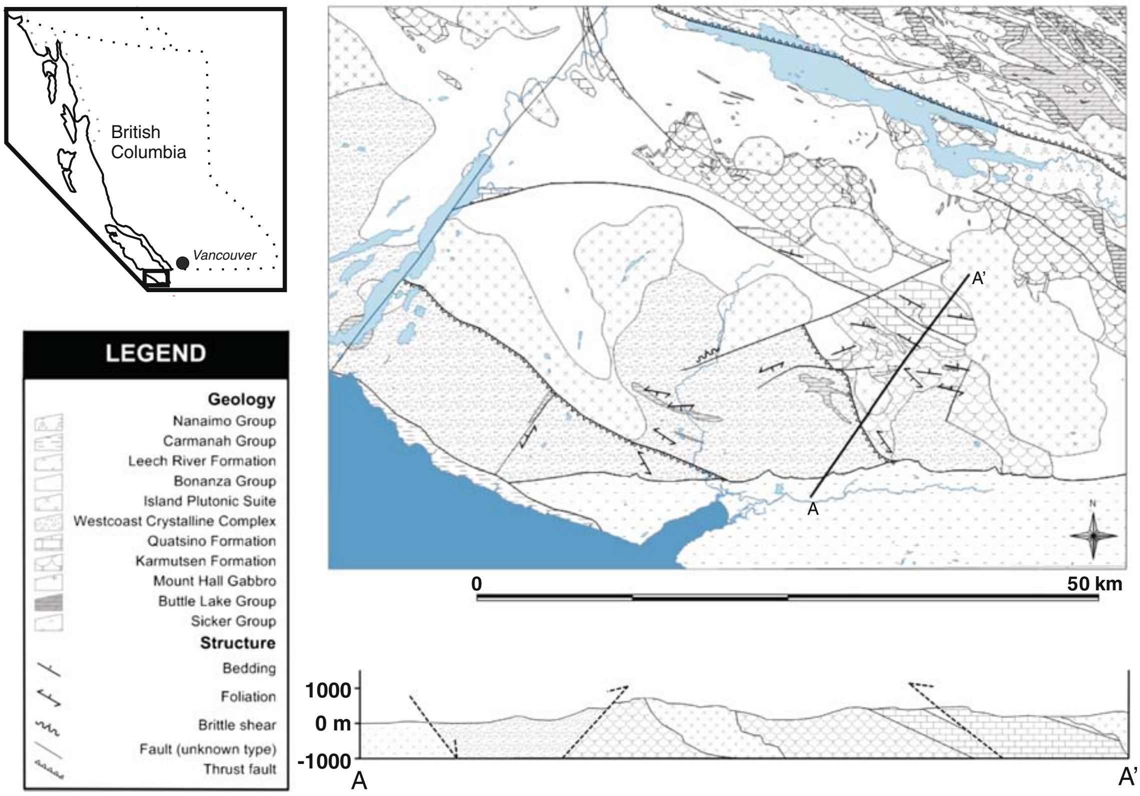

Fig. 2 Geology of the Port Renfrew field area based on 1:25,000 scale mapping. *Inset* shows the geographic location on southern Vancouver Island within British Columbia. Transect for cross section is denoted by line marked *A–A′*

Westcoast Crystalline Complex

The rocks of the WCC may be subdivided into two main groups distinguished by the presence or absence of quartz. Quartz-free rocks can be further divided into those containing (1) cumulus olivine and (2) cumulus plagioclase.

Olivine hornblendites

Olivine hornblendites display a heteradcumulate texture, with variably serpentinized olivine poikilitically enclosed either by amphibole or orthopyroxene, or rarely phlogopite (Fig. 3a). Spinel, clinopyroxene, plagioclase and magnetite are present in minor amounts in some samples. Olivine is always rounded and embayed, suggesting a reaction relationship with the surrounding phase. Clinopyroxene is rarely present, as ragged anhedral grains surrounded by amphibole, making it difficult to ascertain whether it was originally a cumulus phase. Plagioclase is present as an intercumulus phase in two samples, and is usually pervasively altered to clay, epidote, chlorite and/or sericite. In one sample (JL-031), euhedral plagioclase is a cumulus mineral. Plagioclase and olivine are never in contact and are separated by a corona of amphibole surrounding the olivine. Euhedral phlogopite is present in varying quantities in almost all samples. It may rarely form a poikilitic texture, enclosing olivine. Large amphibole oikocrysts commonly show exsolution lamellae of ilmenite and may have originally been Ti-rich (kaersutitic). Olivine may contain inclusions of spinel and, in two samples, orthopyroxene, amphibole and/or phlogopite (Fig. 3b). Euhedral orthopyroxene may contain inclusions of olivine and amphibole.

Hornblende gabbros and gabbronorites

The rocks from this group never contain any olivine. Most samples display a heteradcumulate texture where poikilitic amphibole encloses plagioclase, clinopyroxene, magnetite and/or orthopyroxene (Fig. 3c). Some samples contain euhedral cumulus amphibole and lack pyroxene. Euhedral magnetite is present in all but two samples (JL-068 and JL-105) and is found included in all other phases; it may rarely contain plagioclase inclusions. Plagioclase commonly contains inclusions of subhedral amphibole and clinopyroxene, although when orthopyroxene is present, plagioclase generally only contains magnetite inclusions. Both pyroxenes tend to be strongly anhedral, with corroded margins. Isolated, rounded pyroxene grains within

Table 1 Petrography of samples

Sample ID	Primary phases (vol.%)	Accessory
West Coast Complex		
JL06-001	Plag (55), Amph (32), Bt (3) Qtz (10)	
JL06-003	Feldspar (75), Qtz (10), Bt (9), Amph (5), Fe–Ti ox (1)	Zr, Ap
JL06-006	Amph (45), Plag (48), Qtz (5), Fe–Ti ox (2)	Tnt, Bt, Kspar
JL06-010	Amph (40), Plag (50), Bt (5), Qtz (2), Fe–Ti ox (3)	Ap
JL06-013	Amph (37), Plag (52), Qtz (7), Bt (3), Fe–Ti ox (1)	Ap, Tnt
JL06-014	Amph (35), Feld (55), Qtz (3), Fe–Ti ox (7)	Ap, relict cpx (?)
JL06-019	Amph (40), Plag (55), Qtz (2), Bt (3)	Tnt, Ap, Fe–Ti ox
JL06-020	Plag (60), Opx (20), Cpx (12), Amph (4), Fe–Ti oxides (2), Bt (2)	
JL06-025	Amph (9), Bt (6), Feld (65), Qtz (20)	Ap, Fe–Ti ox
JL06-044	Amph (54), Feld (40), Qtz (4), Fe–Ti ox (2) bt	
JL06-066	Plag (61), Amph (30), Bt (5), Qtz (3), Fe–Ti ox (1)	Relict Cpx
Bonanza volcanics (phenocrysts)		
JL06-027	Relict Ol, Cpx, Plag, Sp/Fe–Ti ox	
JL06-038	Plag, Cpx, Fe–Ti ox	
JL06-050		
JL06-053	Plag, Cpx, Fe–Ti ox, relict ol/amph	Ap
JL06-061	Plag, Cpx, Fe–Ti ox	Relict ol (?)
JL06-090	Plag, Cpx, relict amph?, Fe–Ti ox ap	
JL06-092	Plag, Amph, Cpx, Fe–Ti ox	
JL06-093	Plag, relict Ol, Fe–Ti ox	
Plagioclase cumulate		
JL06-008	Amph (40), Plag (56), Bt (3), Fe–Ti ox (1)	Relict Cpx (?), Ap
JL06-009	Plag (52), Amph (40), Cpx (5), Fe–Ti ox (3)	Bt
JL06-011	Amph (60), Opx (20), Plag (12), Cpx (3), Fe–Ti ox (5)	
JL06-015	Amph (18), Plag (80), Fe–Ti ox (2)	Ap
JL06-023	Plag (55), Amph (37), Cpx (5), Fe–Ti ox (3)	Ap
JL06-024	Plag (50), Amph (45), Cpx (3), Fe–Ti ox (2)	Ap
JL06-045	Plag (72), relict Amph? (25), Bt (2), Fe–Ti ox (1)	Qtz?
JL06-067	Plag (30), Amph (64), Cpx (3), Fe–Ti ox (1), Bt (2)	Tnt
JL06-068	Opx (10), Amph (38), Bt (2), Plag (50)	
JL06-069	Amph (65), Plag (35)	Bt, Ap, Fe–Ti ox
JL06-100	Plag (65), Amph (29–10 primary), Cpx (5), Opx (1)	Relict Bt
Olivine cumulate		
JL06-005	Ol (27), Amph (65), Opx (3), Sp (5)	
JL06-021	Ol (12), Plag (20), Amph (62), Cpx (3), Opx (3)	sp/Fe–Ti ox
JL06-030	Ol (13), Amph (73), Opx (8), Cpx (3), Bt (3)	
JL06-031	Ol (21), Amph (20), Opx (45), Plag (10), Bt (3), Sp/Fe–Ti ox (1)	
JL06-043	Ol (45), Amph (54), Sp/Fe–Ti ox (1)	Bt, Opx
IPS-granitoids		
JL06-002	Feldspar (70), Qtz (25), Bt (3), Fe–Ti ox (2) zr, ap	
JL06-040	Amph (3), Bt (5), Qtz (25), Plag (54), Kspar (12), Fe–Ti ox (1)	
JL06-041	Amph (15), Plag (63), Kspar (10), Qtz (7), Bt (5)	Tnt, Ap, Fe–Ti ox
JL06-054	Feld (80), Qtz (18), relict amph/bt (2) Fe–Ti ox,	Ap
JL06-076	Amph (10), Bt (3), Plag (50), Kspar (24), Qtz (12), Fe–Ti ox (1)	

Amph amphibole, *Plag* plagioclase, *Bt* biotite, *Qtz* quartz, *Fe–Ti ox* magnetite, ilmenite; *Opx* orthopyroxene, *Cpx* clionopyroxene, *Ol* olivine, *Kspar* K-feldspar, *Tnt* titanite, *Ap* apatite, *Zr* zircon

amphibole oikocrysts often display optical continuity. Where present, orthopyroxene contains inclusions of all other phases. Relict clinopyroxene is never in contact with plagioclase, magnetite or orthopyroxene, but is always surrounded by amphibole. Euhedral biotite is present in most samples in minor amounts.

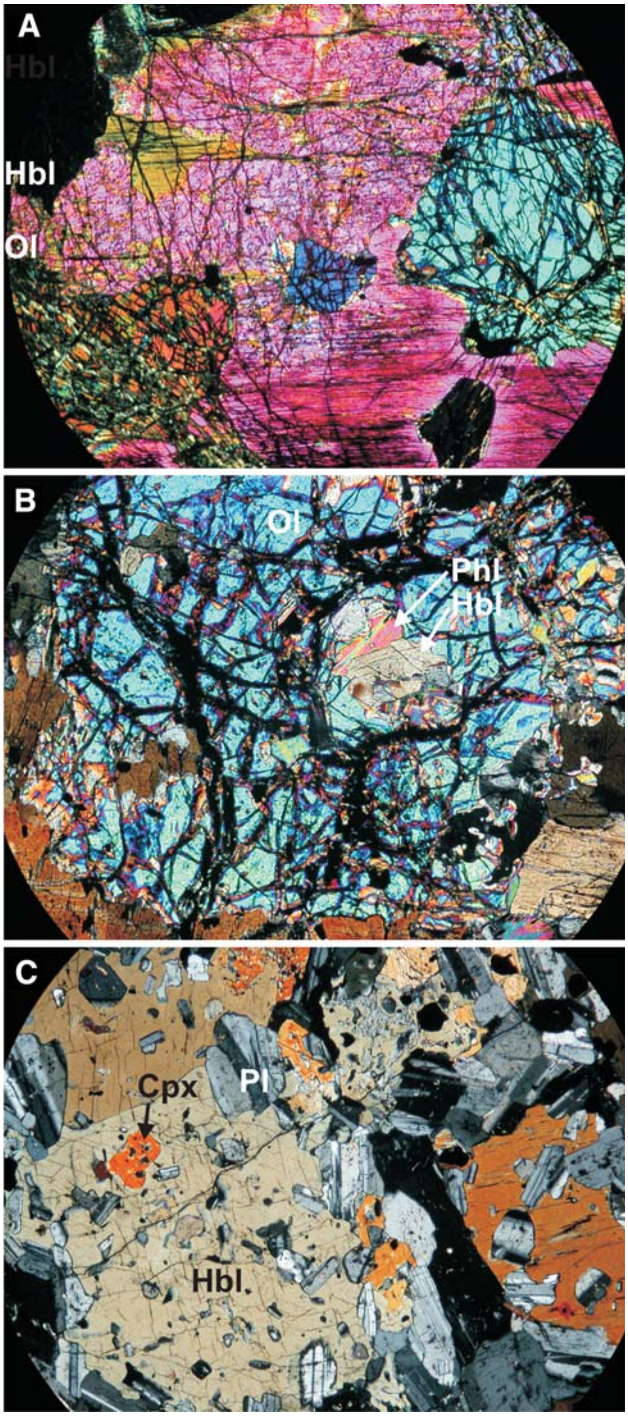

Fig. 3 Photomicrographs showing textures in cumulates. **a** Olivine hornblendite. (field of view 4 mm). **b** Hornblende and phlogopite included in olivine (field of view 2 mm). **c** Pyroxene-bearing poikilitic hornblende gabbro. *Ol* olivine, *Hbl* hornblende, *Phl* phlogopite, *Cpx* clinopyroxene, *Pl* plagioclase

Quartz-bearing samples

This group constitutes the main gabbro–diorite phase of the WCC. All samples contain abundant amphibole and plagioclase, with minor biotite and quartz. Magnetite, K-feldspar, and titanite are also present in some samples. Coarse-grained samples typically show strongly zoned subhedral plagioclase, euhedral to subhedral amphibole, euhedral biotite with variable chlorite alteration, and interstitial quartz and potassium feldspar. Finer-grained samples contain prismatic amphibole and plagioclase laths, with a finer groundmass of subhedral amphibole and feldspar clusters. Where present, magnetite occurs as a phase included in both amphibole and plagioclase.

Island Plutonic Suite

The Island Plutonic Suite samples are all quartz-bearing, having a similar mineralogy to the quartz-bearing WCC samples, but contain more quartz and potassium feldspar and less amphibole. Plagioclase shows marked zoning and tends to be euhedral–subhedral.

Bonanza Group volcanics

All volcanic samples contain plagioclase phenocrysts, with some samples also containing euhedral zoned clinopyroxene as well as Fe–Ti oxide phenocrysts. Relic olivine phenocrysts are present in two samples (JL-027, JL-093), having been replaced by talc and chlorite + calcite, respectively. Several basaltic samples preserve rounded amphibole phenocrysts or clinopyroxene pseudomorphs after amphibole (JL-092, JL-027, JL-090).

Geochemistry

Analytical methods

All major elements and Ba, Co, Cr, Cu, Ni, Sc and V were analyzed by a Philips PW2440 4 kW automated XRF spectrometer at McGill University using 32-mm diameter fused beads prepared from a 1:5 sample:lithium tetraborate mixture (e-Supplementary Table 1). Accuracy for Si is within 0.5%, while for other major elements it is within 1%. Trace element (Ni, Co, Cr) accuracy is within 5%. Overall precision is within 0.5%. Other trace elements were analyzed by solution nebulization ICPMS at the University of Victoria, using a Thermo X-series II (X7) instrument. Certified reference materials were run as unknowns along with the samples. Sample dissolution and data deconvolution procedures were based on the method of Eggins et al. (1997). Accuracy and precision for reference materials are listed in e-Supplementary Table 2.

Major elements

The question of element mobility is central to a geochemical interpretation of any igneous suite. Pearce element ratios (PER) have been used to determine the extent of element mobility in igneous suites (e.g., Beswick and Soucie 1978), but their application in our study is complicated by the amphibole-bearing phase assemblages of the Bonanza arc. Stoichiometric uncertainty due to site vacancies, as well as the fact that few elements are truly incompatible in amphibole, make PER analysis non-unique in this case. We note the normally mobile elements K and Rb show very coherent behavior throughout the range of compositions, with minor scatter in the volcanics presumably due to amygdaloid formation. This, and petrographic observations showing only minor alteration, leads us to conclude that element mobility is not a significant factor in our study.

Non-cumulate rocks within the Bonanza arc define a typical calc-alkaline trend, ranging in composition from basalt to rhyolite with the majority of samples falling in the basalt to basaltic andesite range (Fig. 4). The IPS samples define the high-SiO_2 end of the compositional spectrum, with minor overlap with the WCC at intermediate compositions. The majority of the volcanic samples are shifted toward more mafic compositions and have SiO_2 concentrations which are indistinguishable from the WCC samples (Fig. 4). Cumulate rocks comprise the low-SiO_2 end of the spectrum.

On Harker diagrams, we plot in cation units to better show the liquidus mineral stoichiometric controls on differentiation trends (Fig. 5). The WCC, IPS and Bonanza volcanic samples define an array, with the gabbroic cumulates clustering at the low-Si end of the array, and the olivine cumulates extending on a vector toward the olivine. The olivine cumulates lie on a tie line connecting olivine and hornblende, the two modally dominant phases in these rocks. Concentrations of Ti, Al and Ca are highest in the gabbroic cumulates and decrease with increasing Si.

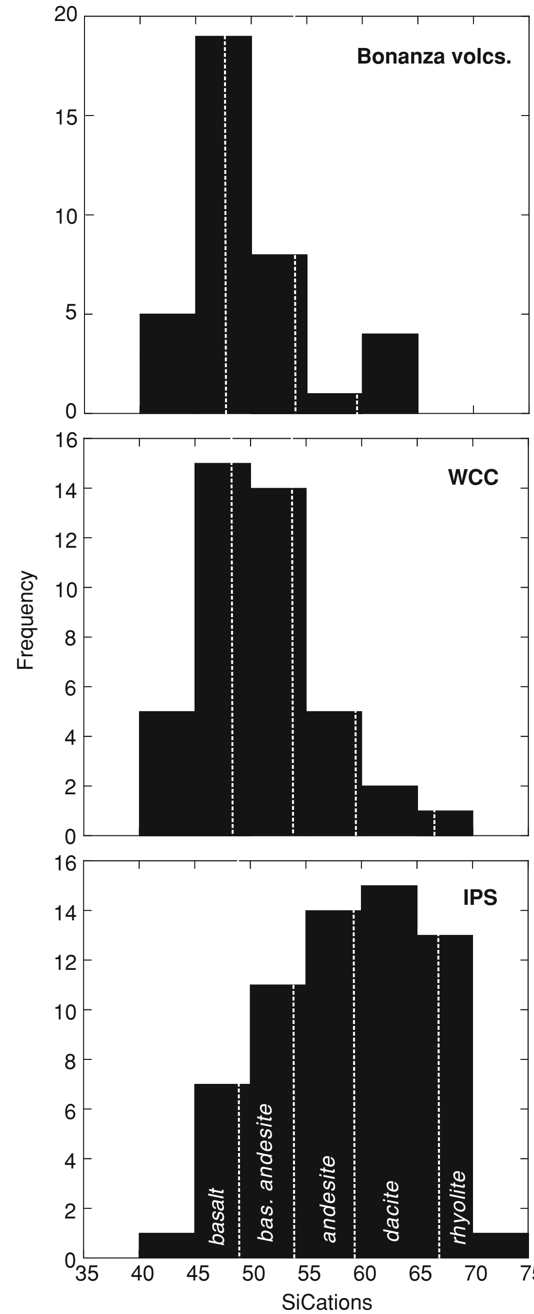

Fig. 4 Histogram of the Si concentrations (in cation units) of Bonanza arc subunits. *Dashed lines* show divisions for rock types in terms of cation units. *WCC* West Coast Complex, *IPS* Island Plutonic Suite, Bonanza volcanics. Note the overlap of the WCC plutons and Bonanza volcanics

Trace elements

All samples show chondrite-normalized negative Ta–Nb typical of an arc signature (Fig. 6). Negative Zr anomalies are absent in the IPS samples, while positive Sr anomalies are present in all but three samples (two volcanics and one olivine cumulate). Positive Ti anomalies, corresponding with the presence of Fe–Ti oxides, are present in many of the cumulate samples and mirrored by negative Ti anomalies in the volcanics and WCC rocks. Chondrite-normalized rare earth elements among all units show broadly similar, variably light rare earth enriched patterns (Fig. 7). A select few samples display LREE depleted patterns (JL-042, JL-101, JL-021). The cumulate rocks have nearly flat REE patterns, with minimal LREE enrichment, and have lower concentrations relative to chondrite than do the non-cumulate rocks. The distinct lack of Eu anomaly among the plagioclase cumulates is noteworthy. The WCC, IPS and volcanic units show essentially

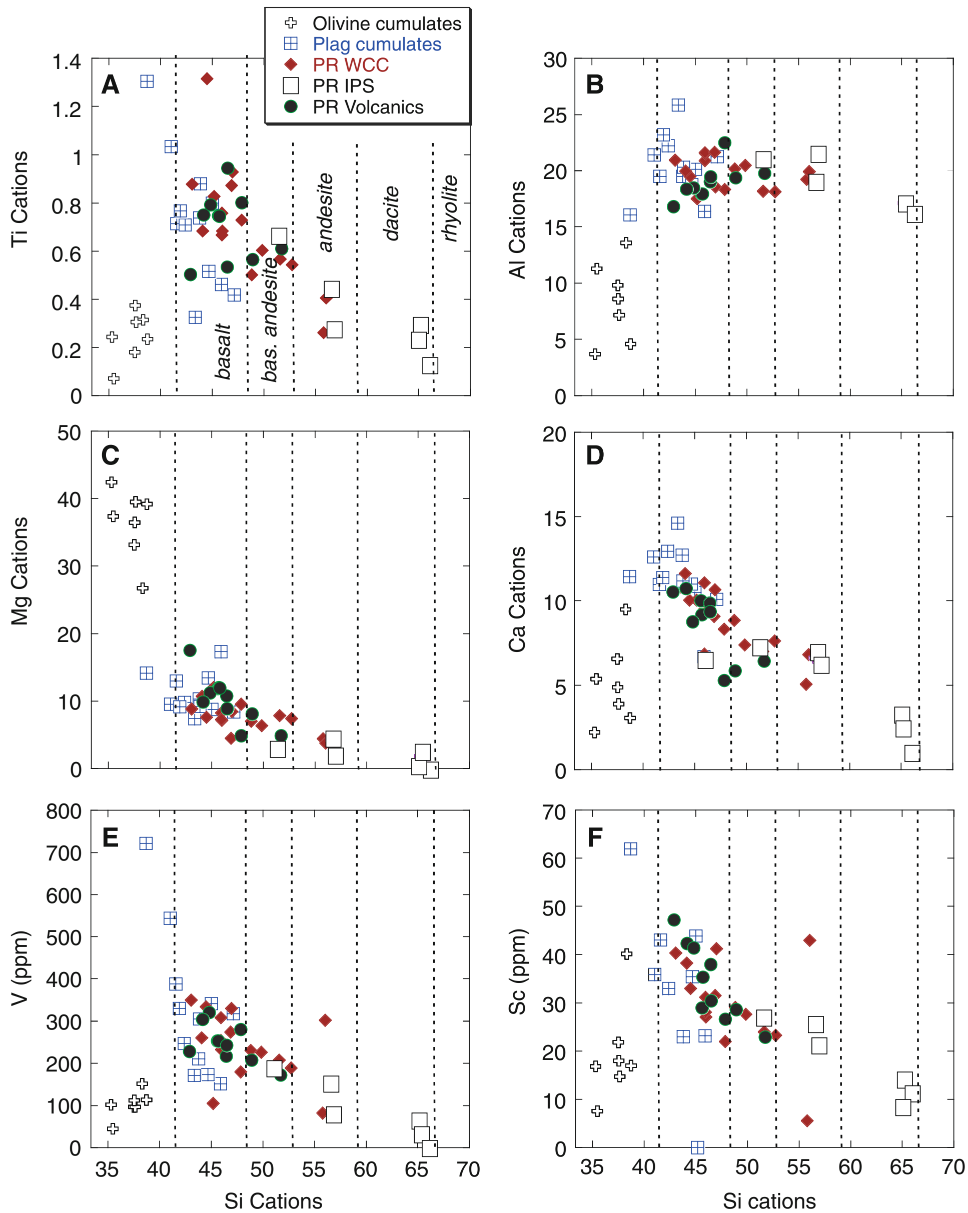

Fig. 5 Harker diagrams plotted in cation units for all Bonanza arc lithologies from the Port Renfrew (PR) area. *Dashed lines* show divisions for rock types in cation units. *WCC* West Coast Complex, *IPS* Island Plutonic Suite

identical patterns of LREE enrichment, with some samples having minor positive or negative Eu anomalies. The V and Sc concentrations are highest in the gabbroic cumulates and lowest in the most evolved IPS rocks (Fig. 4).

Mineral chemistry

Analytical methods

Samples were analyzed by a CAMECA SX50 electron microprobe at the University of British Columbia. Major and minor elements were determined at 15.03 kV acceleration voltage and a beam current of 20.1 nA for amphibole, feldspar, oxides, olivine and pyroxene, and a beam current of 10.0 nA for mica. Standards included natural olivine (Mg, Si), diopside (Ca, Si), anorthite (Ca, Si, Al), albite (Na, Si, Al), rutile (Ti) and fayalite (Fe, Si). A number of olivine cumulates and gabbroic cumulates were selected for mineral analysis, in addition to three WCC and Bonanza volcanic samples (e-Supplementary Table 2).

Olivine

Olivine shows a bimodal composition distribution, with populations of $Fo_{74–77}$ and $Fo_{81–82}$. There is an absence of zoning, and all olivine grains in a given sample have nearly

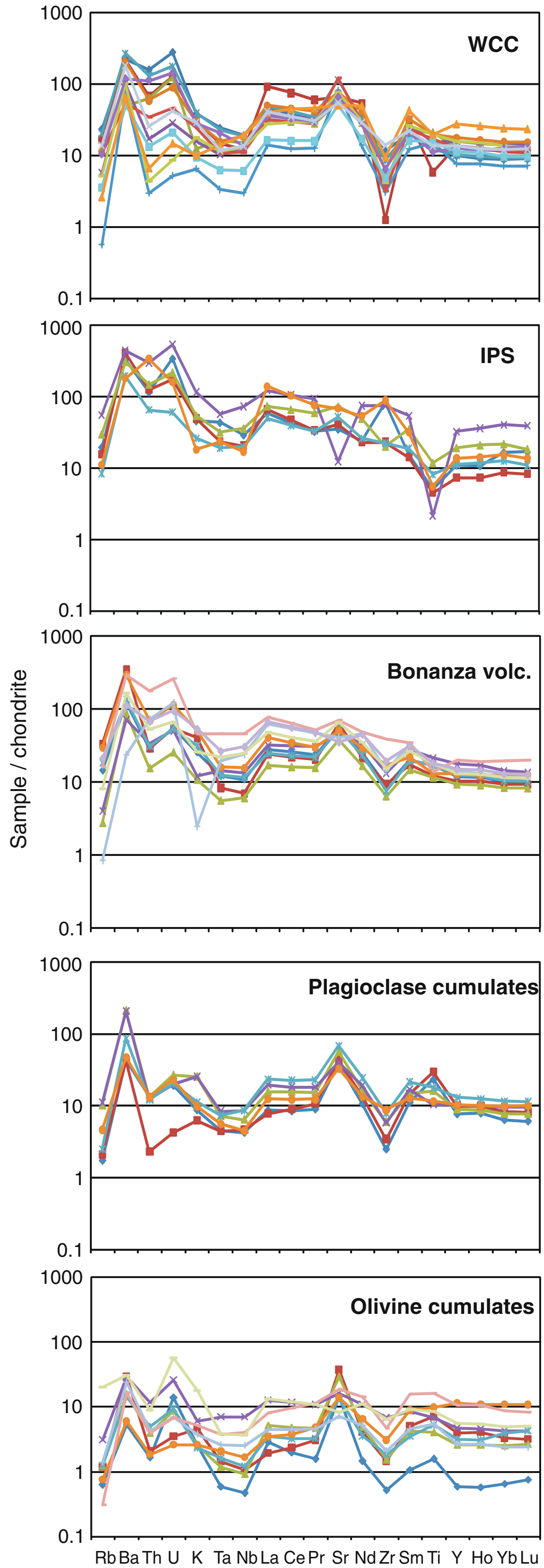

Fig. 6 Trace element concentrations of Bonanza arc lithologies from the Port Renfrew (PR) area normalized to chondrite (using values of McDonough and Sun 1995). *WCC* West Coast Complex, *IPS* Island Plutonic Suite

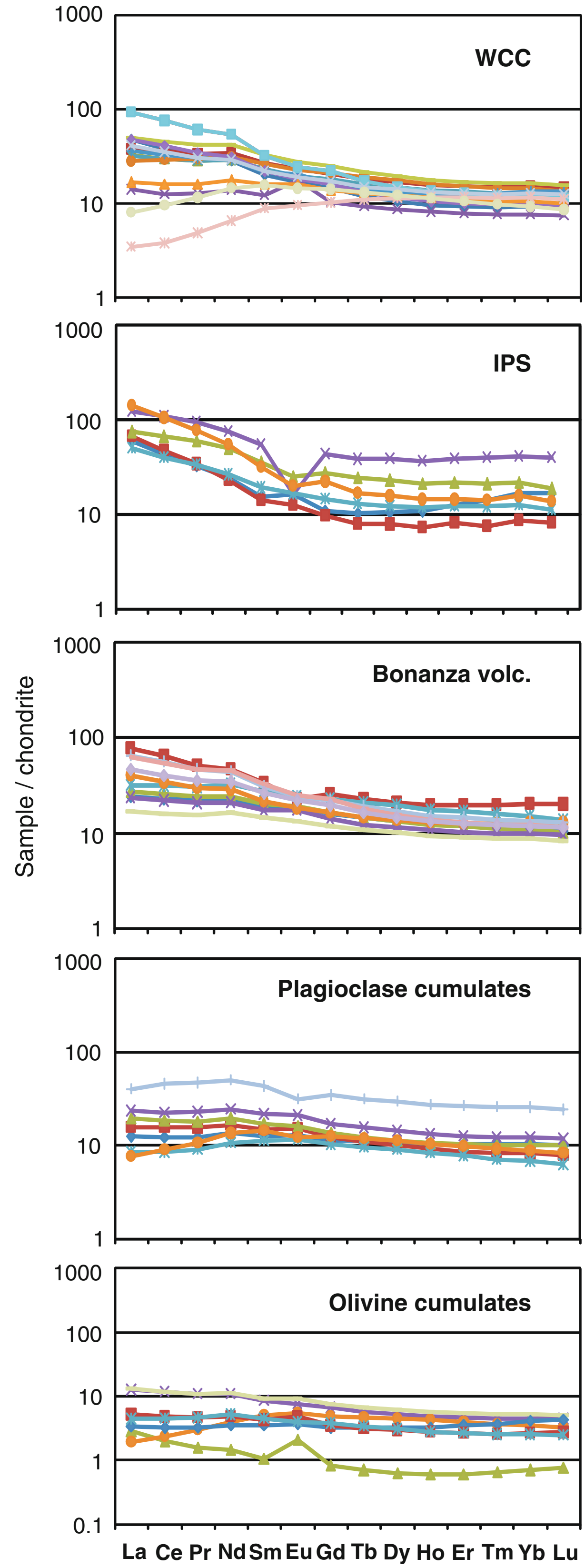

Fig. 7 Chondrite-normalized rare earth element plots for Bonanza arc lithologies from the Port Renfrew (PR) area. *WCC* West Coast Complex, *IPS* Island Plutonic Suite

identical Fo content. The Ni concentrations range from 200 to 2,400 ppm in the low Fo group, and from 1,200 ppm to over 2,600 ppm in the high Fo group.

Amphibole

Amphiboles in the olivine cumulates have the highest Mg# (77–83; identical to the olivine grains, which they enclose), decreasing to 60–77 in the gabbroic cumulates and 30–65 in the WCC and volcanic samples. The TiO_2 concentrations are highest in the gabbroic cumulates, reaching 3.5 wt%. Cr concentrations may reach almost 7,000 ppm in the olivine cumulates and are an order of magnitude lower (<500 ppm) in the gabbroic cumulates. Amphiboles included in olivine have higher octahedral Al than those which form oikocrysts in the olivine cumulates.

Clinopyroxene

Clinopyroxenes in the olivine cumulate samples contain high Mg# and Cr (80–86, >6,000 ppm), while those in the gabbroic cumulates show a greater range in Mg# (65–86) and much lower Cr (mostly <500 ppm). Zoned clinopyroxenes from a primitive dyke (JL-027) have cores, which are generally high in Cr (1,000–2,600 ppm) and have elevated Mg# (79–80) compared with their surrounding rims (70–75).

Orthopyroxene

Distinct orthopyroxene populations are defined by the olivine cumulate, plagioclase cumulate and quartz-bearing WCC samples. Mg#s are highest in the olivine cumulates (77–84, similar to coexisting olivines), lowest in the quartz-bearing WCC samples (56–60) and intermediate in the plagioclase cumulates (68–72). Ni concentrations are essentially identical among all three populations.

Plagioclase

The anorthite component of plagioclase from the gabbroic cumulates varies widely, from An_{91} to An_{48}, with a population minimum at An_{85-62}. While zoning is not prevalent in the plagioclase cumulates, rare relict Na-rich cores (An_{51-53}) are found within the most Ca-rich grains. Plagioclase grains from WCC samples range from An_{46} to An_{71}. The largest spread of compositions comes from a primitive dyke (JL-027), where plagioclase ranges from An_{31} to An_{85}.

Spinel

Spinels from the olivine cumulates fall into two populations: a magnetite–magnesioferrite–chromite solid–solution series and a spinel–hercynite–magnesioferrite–chromite series. Some samples may contain representative grains of both populations. Spinels from the gabbroic cumulates and WCC plutons are exclusively magnetite, with very little ulvospinel solid–solution (<5%), while magnetite from a mafic dyke (JL027) has 21 mol.% ulvospinel.

Discussion

Amphibole and arc magma differentiation

The timing and importance of post-cumulus amphibole crystallization in arc suites remain questionable (e.g. (Conrad and Kay 1984; Costa et al. 2002; Claeson and Meurer 2004). The origin of large, voluminous hornblende oikocrysts within the olivine-bearing cumulates is of particular importance to the current study. The rounded anhedral shapes of cumulus olivine, orthopyroxene and rare clinopyroxene encased in hornblende and/or phlogopite oikocrysts testify to the operation of an amphibole-producing reaction involving early formed minerals and hydrous melt or fluids. The degree to which hornblende can influence magmatic differentiation depends on whether large oikocrysts form by reaction between early cumulates and primitive basaltic magma, or conversely with more evolved melts. In the former situation, hornblende crystallization may exert a significant influence on magma compositions, whereas in the latter case hornblende is little more than a secondary replacement phase, having little or no influence on magmatic evolution.

Conrad and Kay (1984) report the occurrence of high-Cr amphibole oikocrysts enclosing olivine, clinopyroxene and spinel within xenolith inclusions from Adak Island, Southwestern Alaska. They note a lack of Cr zoning across amphibole oikocrysts, which appear to have been in reaction with Cr-rich phases, and the common occurrence of Cr-poor amphiboles encasing Cr-diopside and Cr-spinel. They ultimately conclude that the high-Cr character of the amphibole oikocrysts resulted from direct crystallization from primitive basalt, rather than from the breakdown of refractory Cr-rich phases. The presence of high-Cr hornblende and associated Cr-rich spinel inclusions in cumulus olivine within the Bonanza arc section clearly shows that amphibole was indeed present early on during the crystallization sequence. There is no difference in the Cr content of amphibole included in olivine and amphibole oikocrysts, and the elevated Cr content of amphibole oikocrysts is best interpreted to reflect crystallization from a primitive mafic magma, rather than an inheritance from refractory Cr-rich phases.

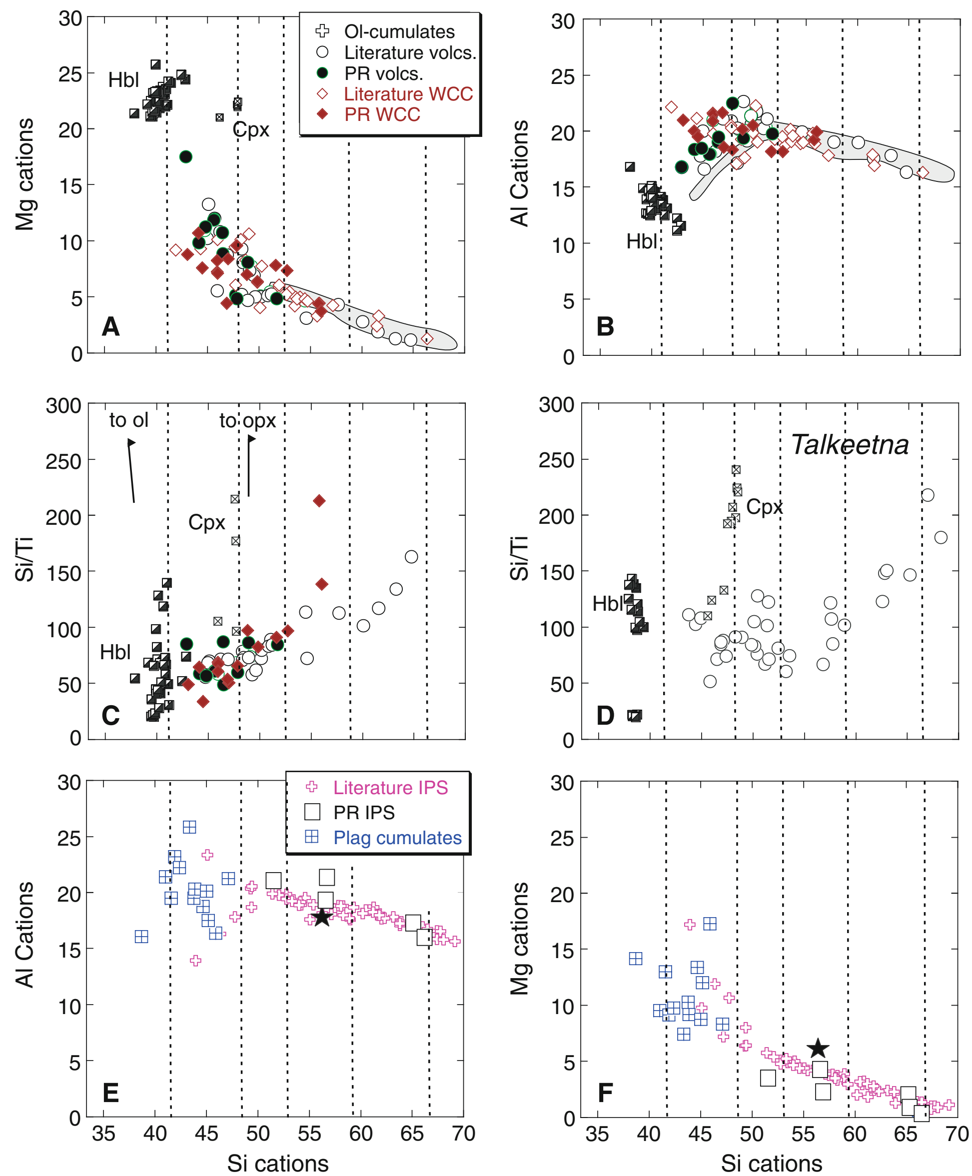

Fig. 8 **a**, **b**, **c** Harker diagrams illustrating the relationship between the WCC plutons, the Bonanza volcanics and hornblende oikocrysts in ultramafic cumulates ['PR' data from current study, 'literature' data from DeBari et al. (1999); Massey (1992–1993)]. *Gray* areas show the trend of all of IPS samples. **d** Data for Talkeetna volcanics (Greene et al. (2006)) for comparison. **e**, **f** Relationship between IPS and plagioclase cumulates. *Dashed lines* show divisions for rock types in cation units. *Filled star* is bulk continental crust estimate of Rudnick and Gao (2003). *PR* Port Renfrew area samples, *WCC* Westcoast Crystalline Complex, *IPS* Island Plutonic Suite

The influence of hornblende crystallization on magmatic differentiation is clear in major element patterns of the rocks (Fig. 8). The Bonanza volcanics and WCC plutons form well-defined trends, the projections of which intersect the locus of amphibole oikocryst compositions from the olivine hornblendites. Neither olivine nor clinopyroxene can be significant phases in driving this trend. Although both the WCC plutons and Bonanza volcanics contain abundant plagioclase, including large phenocrysts in the case of the volcanics, there is no indication of any significant plagioclase control among these rocks, as this would drastically change Al (Figs. 8, 9a). It would appear therefore that the compositions of WCC plutons and the mafic end member (Si <50 cations) of the Bonanza volcanic spectrum are controlled mainly by the removal of hornblende, the composition of which corresponds to that of the oikocrysts in the olivine cumulates.

Nonetheless, the poikilitic texture of the hornblende precludes a simple fractional crystallization mechanism. Similar post-cumulus textures are reported from the Rymmen and Eriksberg Gabbros of Sweden (Claeson and Meurer 2004) and interpreted as the result of 'imperfect fractional crystallization,' akin to the in situ crystallization model of Langmuir (1989). In this light, the mafic WCC and Bonanza volcanic rocks represent escaped interstitial liquids, which are in equilibrium with hornblende, biotite and, in some cases, plagioclase, these being the late-forming intercumulus phases within the olivine hornblendites.

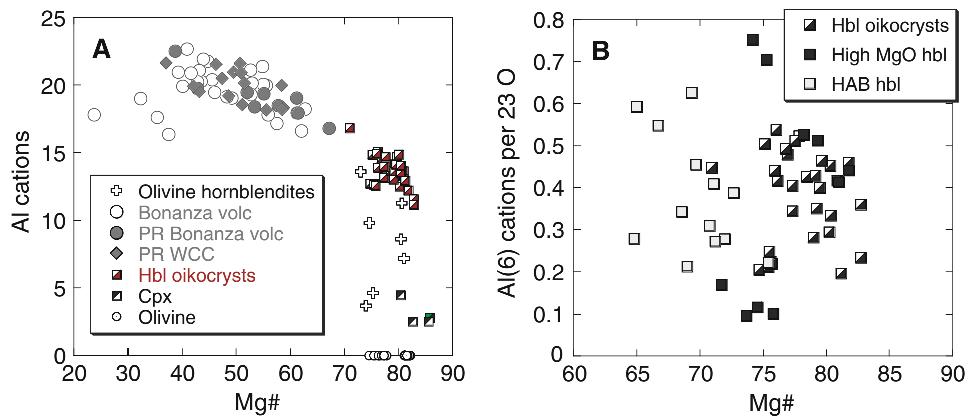

Fig. 9 **a** Mg# versus Al plots of whole rocks and hornblende compositions showing the relationship between hornblende oikocrysts and Bonanza array. **b** Comparison of hornblende oikocrysts from olivine cumulates to liquidus hornblendes from experiments on high-Al basalt (HAB) and high-Mg basalt (HMB) compositions (experimental data from Pichavant and Macdonald (2007), Barclay and Carmichael (2004), Grove et al. (2003), Muntener et al. (2001), Hilyard et al. (2000), and Sisson and Grove (1993))

The Bonanza volcanics are compositionally identical to the WCC plutonics, but, unlike the latter, are devoid of amphibole and biotite, with one exception (JL-092 contains relict amphibole). The paucity of amphibole phenocrysts in mafic arc lavas is well known (e.g. Arculus and Wills 1980; Romick et al. 1992; Costa et al. 2002), yet the variation of Dy/Yb ratios with differentiation indices points to widespread cryptic amphibole fractionation in arc volcanic suites (Davidson et al. 2007). That the mineral assemblage preserved in arc lavas need not reflect the processes occurring at depth has been pointed out by several workers. Rutherford and Devine (1988), for example, document the breakdown of amphibole with decreasing pressure in the Mount St. Helens dacite. Romick et al. (1992) suggest that magmas that contain enough H_2O to stabilize the amphibole are more likely to erupt explosively, and be emplaced at the surface as pyroclastics, rather than as lava flows. Barclay and Carmichael (2004) show that the onset of hornblende crystallization in basaltic magmas results in a greater increase in crystallinity than would occur in more felsic magmas, thereby potentially impeding the ascent and eruption of hornblende-bearing basalts. The use of volcanic phase assemblages as a window into igneous processes and differentiation pathways at depth, therefore, ought to be treated with caution.

Conditions of Bonanza arc differentiation

Constraints on the pressure–temperature conditions at which magmas crystallized in arc crust can provide an idea of how magmatic plumbing and crustal composition can change with depth. We have applied several different approaches, each having their particular shortcomings, to constrain crystallization pressures among the most primitive cumulate-textured samples.

Phase equilibria

Constraints can be placed on the P–T–fO_2 conditions of crystallization in natural rocks by comparing phase assemblages and their order of appearance with experimental data for the same bulk compositions. Textures and chemistry of the olivine cumulates point to a reaction between olivine and basaltic melt to produce amphibole. In addition, some samples preserve inclusions of amphibole within cumulus olivine grains, suggesting an early appearance for amphibole. The association of hornblende and olivine has been noted in arc volcanics ranging in composition from high-MgO basalt to andesite (e.g., Grove et al. 2003; Anderson 1980; references therein). Phase equilibrium studies of hydrous basalts under water-saturated conditions reveal that amphibole can appear with olivine on the liquidus at pressures in excess of 700 MPa (Grove et al. 2003; Pichavant and Macdonald 2007; Barclay and Carmichael 2004), and at lower pressures (200–400 MPa) in high-alumina basaltic and basaltic andesite (Sisson and Grove 1993; Moore and Carmicahel 1998). Some basaltic andesite compositions, however, do not saturate with olivine under any conditions (e.g., Mercer and Johnston 2008; Pichavant et al. 2002). These observations serve as broad constraints on the crystallization pressures of the Bonanza olivine cumulate rocks of 200–700 MPa.

Amphibole chemistry

The compositions of amphiboles from the olivine cumulates are variable, but similar to those produced in experiments on natural high-Mg basalts at 800–1,000 MPa (Fig. 10). The latter experiments show a very good correlation between octahedral Al in hornblende and pressure, which we apply as an empirical barometer for the Bonanza

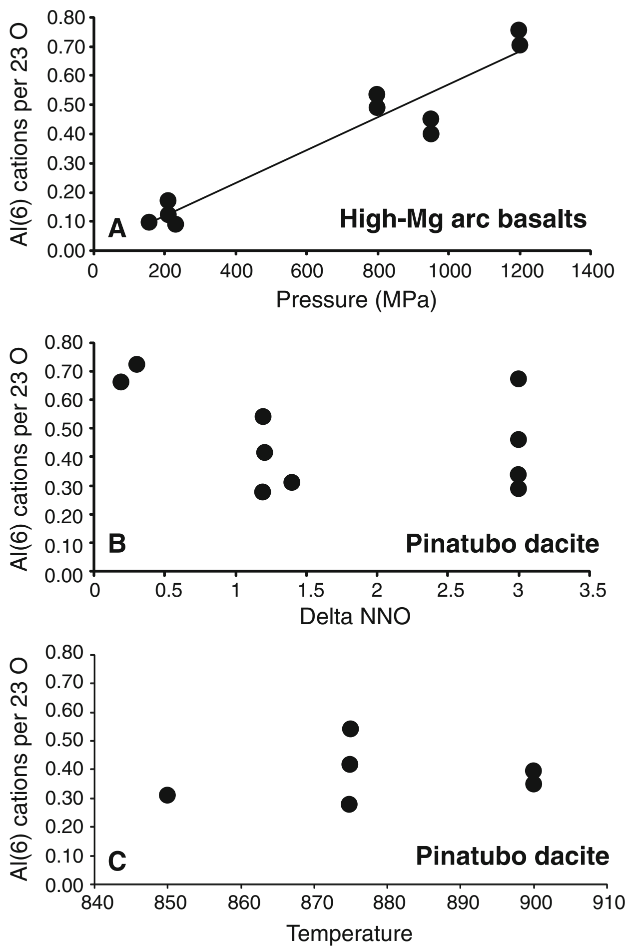

Fig. 10 **a** Correlation of Al^{VI} (on basis of 23 oxygens) with pressure for liquidus amphiboles in experiments on high-Mg basalts (data from Pichavant and Macdonald 2007; Barclay and Carmichael 2004; Grove et al. 2003; Muntener et al. 2001). The trend is fit by least squares regression: Al^{VI} cations $= 0.056*P + 0.008$ ($r^2 = 0.923$) with pressure in MPa. **b** Comparison of Al^{VI} in amphibole versus fO_2 at nearly constant pressure (200–210 MPa) and temperature (850–875°C) in experiments on Pinatubo dacite (Costa and Chakraborty (2004)). **c** Al^{VI} in amphibole versus temperature (data from Costa and Chakraborty (2004)) at near-constant pressure (200–210 MPa) and fO_2 (NNO + 1.2–NNO + 1.4) in Pinatubo dacite. All experiments were under water-saturated conditions

arc samples (Fig. 10). Application to hornblende from the olivine cumulate samples produces pressures of 470–880 MPa (see Table 2). Interestingly, amphibole inclusions in olivine give the highest pressures (880 MPa).

Both temperature and fO_2 can have potential effects on our empirical barometer, but can be evaluated using the extensive experimental data set for Pinatubo dacite (Prouteau and Scaillet 2003). No discernible correlation is observed between octahedral Al in amphibole and fO_2, at nearly constant pressure and temperature (200–210 MPa, 850–875°C) (Fig. 10b) or with temperature, at nearly constant pressure and fO_2 (200–210 MPa, NNO + 1.2–NNO + 1.4) (Fig. 10c). Assuming that amphibole behavior in dacite compositions is similar to that in basalts, we assume that temperature and fO_2 are less significant factors than pressure in the behavior of octahedral Al in amphiboles.

Cumulate rocks with strikingly similar mineralogy and textures to the Bonanza arc cumulates are reported from the Onion Valley complex of the Sierra Nevada batholiths (Sisson et al. 1996). Sisson and Grove (1993) provide experimental evidence for the origins of the Sierra Nevada hornblendites and hornblende gabbro cumulates as the products of crystallization of high-alumina basalt (HAB) at 200–400 MPa. Olivines from the Sierra Nevada cumulates have Ni concentrations, which are up to an order of magnitude lower than those from the Bonanza arc (240–420 vs. 200–2,500 ppm) at the same Fo content. Ni concentrations in olivine grains from experiments on natural HAB compositions rarely exceed 1,000 ppm (Sisson and Grove 1993). This fact, and the absence of plagioclase from the majority of Bonanza arc olivine cumulates, suggests crystallization from a parental magma more primitive than HAB, although crystallization pressure and H_2O content also may be factors. We conclude, therefore, that the most primitive olivine-bearing cumulates of the Bonanza arc crystallized from a magma more primitive than HAB and do not use amphibole compositions from HAB experiments as input into the empirical barometer we derived for application to our samples.

Table 2 Thermobarometry of samples

Sample #	Rock	Al in amphibole[a] (MPa)	Thermocalc[b] (MPa)	QUILF[c] (°C)
JL06-005	Ol hornblendite	640 ± 150		
JL06-021	Ol hornblendite	880 ± 80		
JL06-030	Ol hornblendite	650 ± 200		
JL06-031	Ol hornblendite	470 ± 180	571 ± 126	1058 ± 91
JL06-043	Ol hornblendite	710 ± 120		
JL06-106	Ol hornblendite	780 ± 100		
JL06-011	Plag cumulate		208 ± 117	898 ± 36
DC05-016	Hbl gabbro		171 ± 44	843 ± 29

All pressures in MPa, and temperatures in C, with uncertainties at 1σ

[a] Pressure by empirical Al in amphibole barometry (see Fig. 10)

[b] Holland and Powell (1990)

[c] Frost and Lindsley (1992)

Multi-equilibrium calculations

Unfortunately, only three of the Bonanza arc cumulate rocks have a sufficiently low variance to produce the independent set of reactions required by Thermocalc (Powell and Holland 1988) and QUILF (Frost and Lindsley 1992) for an accurate *P*–*T* estimate. In addition, most reactions considered by Thermocalc for these rocks involve amphibole, whose activity–composition relationships are poorly known and, thus, can introduce large uncertainties into pressure estimates. Pressure estimates vary from over 500 MPa for olivine hornblendite to 200 MPa and under for a plagioclase cumulate and a two-pyroxene WCC gabbro (Table 2).

Trace elements

The maximum Ce/Y ratio of mafic lavas has been shown to correspond closely with depth to the Moho beneath active island arcs (Mantle and Collins 2008, #2695). Filtering of the database of Bonanza volcanics (for rocks having 44–53 wt.% SiO_2, >4 wt.% MgO and <4 wt.% LOI) yields a maximum depth to the Moho of approximately 32 km. This is in accord with the constraints on crystallization pressures (Table 2), which suggest maximum average pressures of 880 MPa for the olivine cumulates, corresponding roughly to 27 km of depth.

The generation of andesite

We employ a simple graphical means to evaluate how much crystallization is required to generate the more evolved compositions of the Bonanza arc, given a parental basalt composition. Given our petrographic evidence, we assume the parental melt to the Bonanza arc suite to be in equilibrium with amphibole, and derive parental basalt composition using Fe/Mg partitioning between amphibole and basaltic melt determined by experiment. Partition coefficients ($Kd_{amp/liq}$) Fe/Mg exchange determined in experiments range from 0.30 to 0.38 (Pichavant and Macdonald 2007); references therein). Using this constraint, a range of suitable equilibrium compositions is shown in Fig. 11. The highest Mg# compositions are very similar to those used to construct Fig. 12a. Furthermore, when applied to the olivine cumulates, the partition coefficient governing Fe/Mg exchange between olivine and basalt (Roeder and Emslie 1970) yields identical equilibrium compositions to those obtained using the Fe/Mg exchange coefficient between amphibole and basalt (0.3).

Depending on our choice of parental magmas, the lever rule requires the removal of 30–45% hornblende to generate basaltic andesite compositions from parental basalt (Fig. 12b). That is, 0.43–0.82 moles of hornblende

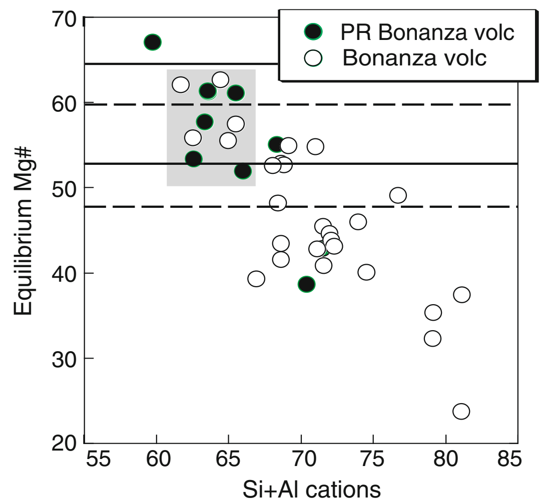

Fig. 11 Permissible parental compositions based on Fe/Mg partitioning between amphibole and basaltic liquid. *Long- and short-dashed lines* bound the Mg# of liquids in equilibrium with PR amphiboles using Kd amph/liq of 0.38 and 0.30, respectively. The *gray-shaded box* outlines probable parental basalt compositions among the Bonanza volcanics. *PR* Port Renfrew area samples

accumulate per mole of basaltic andesite produced. Hornblende fractionation is thus far more economical in producing evolved liquids than a gabbroic (ol–cpx–plag) assemblage, which requires 1.5–2 moles of cumulate per mole of basaltic andesite (Kuno 1968; Greene et al. 2006). This is so because amphibole contains less silica than do gabbroic cumulates and is, therefore, more effective in producing residual liquids with elevated SiO_2 (Davidson et al. 2007).

The basaltic andesite compositions of the Bonanza arc suite are marked by an inflection, which signals the onset of plagioclase ± magnetite saturation (Fig. 12). Major and trace element plots suggest that the intermediate to felsic compositions of the IPS and most plagioclase cumulate samples are complementary to the WCC and Bonanza volcanic rocks of basaltic andesite composition (Fig. 8). The accumulation of pyroxenes in many plagioclase cumulates explains its paucity in their complement, the IPS samples. Hornblende–plagioclase cumulates are also a suitable complement to the IPS rocks, but are less common.

Experimental studies have shown that liquids in equilibrium with a hornblende gabbro phase assemblage (calcic plagioclase + hornblende ± magnetite) are andesitic to dacitic in composition (Pichavant et al. 2002). The presence of cumulate rocks with this assemblage suggests that the generation of intermediate liquids in the Bonanza arc has been accomplished, at least in part, by crystal/liquid fractionation. The tie line connecting hornblende and plagioclase acts as an end member toward which the plagioclase cumulates trend (Fig. 12). The bulk of the plagioclase

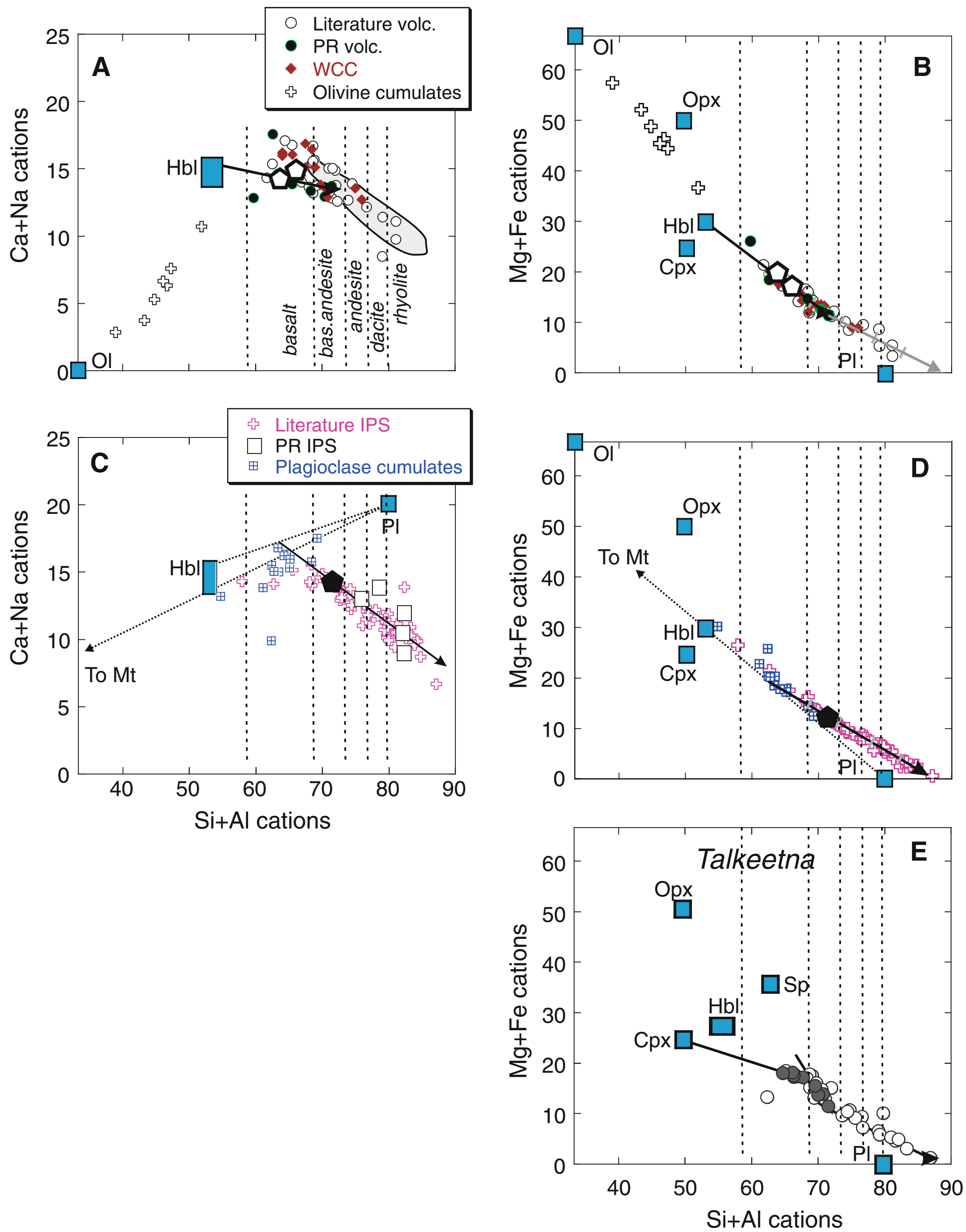

Fig. 12 Major element plots illustrating the mineralogic controls on the Bonanza arc lithologies. The *open polygons* in (**a**) and (**b**) indicate potential parental composition (see text). *Filled polygons* in (**c**, **d**) indicate starting point of hornblende gabbro fractionation (plag-in). **e** shows data for Talkeetna volcanics (*open circles*) and chilled mafic rocks (*full circles*) from Greene et al. (2006) for comparison. *Dashed lines* show divisions for rock types in cation units. *WCC* Westcoast Crystalline Complex, *IPS* Island Plutonic Suite, *PR* Port Renfrew area samples

cumulates plot very near to the intersection of the hornblende–plagioclase tie line and the extension of the trend produced by the bulk of the IPS rocks. Worth noting is the virtual co-linearity of hornblende, plagioclase and magnetite on these diagrams (Fig. 12). A few samples plot toward the magnetite end member, but magnetite is never present in plagioclase cumulates in greater proportions than 5%, and so its removal or addition has limited leverage on most major elements.

Using the point at which plagioclase appears in the fractionating assemblage as a starting composition (corresponding to the point of inflection on major element plots, Fig. 12), andesitic compositions would be produced by the removal of 13–48% hornblende gabbro. Granitic compositions corresponding to the most evolved IPS samples would be generated by the removal of yet more hornblende gabbro, up to 65%. This implies that for every mole of andesite, there would have to be 0.15–0.92 moles of hornblende gabbro cumulate, and every mole of rhyolite would require 1.5–1.9 moles of cumulate.

DeBari et al. (1999) have presented abundant field and trace element evidence to show that partial melting of preexisting amphibolite has produced some of the felsic intrusions found both in the WCC and the IPS. They suggest that the range of intermediate compositions within the Bonanza Group can be modeled as mixtures of these crustally derived melts and more primitive mantle-derived magmas. Support for this model comes from Pb isotopic studies of the IPS and Bonanza Group volcanics showing that these units require some involvement from what would most likely have been Sicker Group crust (Andrew and Godwin 1989; Andrew et al. 1991). Conclusions as to the degree of crustal assimilation required by Pb and Sr isotopic ratios to explain the Bonanza arc data, however, rest on the assumption that the mantle source from which the parental Bonanza magma was removed was in fact identical to the MORB mantle source. This is not necessarily the case, given that the mantle wedge must be fluxed with fluids driven off the subducting slab, and is therefore compositionally different from MORB mantle.

It is very difficult to quantify the relative importance of crystal fractionation versus crustal melting in the generation of the more felsic (IPS) compositions of the Bonanza arc, as there is supporting evidence for both processes. The argument against fractional crystallization as the mechanism by which granitoid plutons are generated traditionally relies on the observation that a vast volume of cumulate material is required (up to 50 units of cumulate per unit of dacite; Kuno 1968). We have seen, however, that the involvement of hornblende in the fractionating assemblage significantly reduces the volume of cumulate that is needed to produce evolved liquids. Given the existence of plagioclase–hornblende–magnetite cumulates, which provide a suitable complement to the felsic compositions of the arc, and which have been shown experimentally to coexist with liquids of andesitic to dacitic composition (Pichavant et al. 2002), it seems reasonable to conclude that liquids, which evolved as andesite, and potentially dacite, were generated by fractionation processes in the middle crust of the Bonanza arc.

Comparison with the Talkeetna arc

Aside from spatial and temporal similarities between the Talkeetna and Bonanza arcs, some important differences stand out. First and foremost is the absence of a preserved section of tectonized mantle, and of garnet-bearing cumulate rocks, in the Bonanza arc. The deeper levels of the Bonanza arc may have been displaced during the collision of the Pacific Rim terrane, but there is no geochemical support for garnet involvement in its evolution. The role for pyroxene in the Talkeetna arc (Greene et al. 2006), versus the olivine–hornblende assemblage of early cumulates from the Bonanza arc, suggests more hydrous conditions during differentiation of the Bonanza arc. As noted previously, there is a surprising lack of Eu anomaly associated with the plagioclase cumulates of the Bonanza arc, while similar lithologies from the Talkeetna arc have quite prominent europium anomalies (Greene et al. 2006). Interestingly, the olivine hornblendites and gabbroic cumulates of the Sierra Nevada batholith also have small Eu anomalies. We suggest that the conditions indicated by the olivine–hornblende association may occur at high fO_2. Under such elevated fO_2, Eu anomalies may disappear as trivalent Eu becomes the dominant species (Carmichael and Ghiorso 1990).

The difference in fractionation pathways between the Bonanza arc and the Talkeetna arc is illustrated in Fig. 12. In contrast to the mafic end of the Bonanza arc array, which trends away from hornblende, the mafic end of the Talkeetna volcanic array trends away from clinopyroxene (Fig. 12e). The petrological models of Greene et al. (2006) suggest that >25 wt.% pyroxenite (~70:30 cpx:opx) must have been removed from a primary melt to produce their most primitive volcanic compositions. Most of these primitive cumulates are thought to have delaminated, or to have crystallized below the Moho, due to the discrepancy between the modeled cumulate proportions and those observed in the field (DeBari and Sleep 1991; Greene et al. 2006).

A similar evaluation of the proportion of cumulates preserved in the Bonanza arc section is frustrated by their limited exposure or occurrence as small bodies. It is therefore difficult to assess how abundant olivine hornblendite cumulates are within the WCC. There most certainly is a missing cumulate section, as the composition of both olivine and hornblende in even the most primitive olivine hornblendites are too rich in iron to have been in equilibrium with a primary magma (Mg# ~70).

Implications for the continental crust

Figure 8f shows a clear discrepancy between andesitic compositions from the Bonanza arc and the estimated compositions of bulk continental crust: the latter has higher Mg/Si than similar magmatic compositions from the Bonanza arc. Therefore, although the removal of olivine hornblendite and hornblende gabbro cumulates would drive the bulk composition of the Bonanza arc crust toward suitable silica concentrations, such a mechanism cannot account for the elevated Mg of the bulk continental crust.

Macpherson (2008) has shown that garnet + cpx fractionation can produce andesites having much higher Mg# than those produced by amphibole + plag fractionation, and that blending of these end members over time may produce high-Mg# andesite. Furthermore, many continental arc plutons and lavas have compositions identical to estimates of bulk continental crust (Kelemen and Hanghoj 2003). These observations suggest that the generation of BCC requires high pressures and, therefore, thickened crust. Because most oceanic island arcs are built on thinner crust, compositions equivalent to BCC appear to be rare in the island arc environment. It seems instead that island arc terranes likely retain their overall basaltic bulk composition until accretion, whereupon tectonic thickening causes the formation of garnet and eventual delamination of dense garnetiferous (eclogitic) rock, leaving a remainder of andesitic bulk continental crust.

Conclusions

The removal of amphibole from the most primitive Bonanza arc non-cumulate compositions controls the compositions of the WCC plutons and Bonanza volcanics until the onset of plagioclase crystallization. Amphibole is removed by the intercumulus crystallization of large oikocrysts, in a process similar to the in situ fractionation of Langmuir (1989) and the imperfect fractional crystallization of Cleason and Meurer (2004). Intercumulus phases can exert significant influence on the differentiation of arc suites and should not be ignored during petrological modeling. Examination of only the volcanics would likely not have led to the appreciation of the role of amphibole in the Bonanza arc. This underscores the importance of the 'plutonic window' in evaluating arc processes.

Empirical amphibole barometry indicates crystallization pressures for primitive magmas of the Bonanza arc of 470–800 MPa, near water-saturated conditions in the mid-lower crust, in good agreement with phase equilibrium constraints based on the presence of amphibole and phlogopite inclusions in olivine.

Arc suites such as the Bonanza arc, which differentiate at pressures below the garnet stability field, are unable to produce the distinct Mg/Si ratio of bulk continental crust. Garnet saturation may be crucial in generating the high-Mg# andesites, which are thought to be the magmatic analog of bulk continental crust.

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