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EVOLUTION OF MAGMAS IN CONTINENTAL AND OCEANIC ARCS: THE ROLE OF THE LOWER CRUST

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ABSTRACT

A comparative study of two exposed sections of lower crust in a magmatic arc setting has shown an impressive similarity between the primitive magmas that feed continental and oceanic arcs, and has highlighted the critical role that intracrustal evolution plays in producing some of the characteristic chemical signatures of arc magmas erupted at the surface. This study has focused on the Tonsina–Nelchina assemblage, a cross-sectional exposure from upper mantle–lower crust to volcanic carapace of the Jurassic Talkeetna island arc, located in south-central Alaska, and the Fiambalá gabbro, a pluton that was intruded into the lower crust of the South American active continental margin in the Ordovician. The two intrusive suites crystallized in the lower crust from high-Mg parental magmas [100Mg/(Mg + Fe) = 68.1 and 74.5, respectively], and have a trace-element chemistry that is generally depleted relative to mid-ocean-ridge basalts (MORB), but they are enriched in the large-ion lithophile elements Sr, Rb, K, U, and Ba. The two suites crystallized a similar mineral assemblage (olivine + pyroxenes, followed by pyroxenes + plagioclase ± amphibole ± oxide), with proportions dependent upon the H_2O content of the parental magma. Higher contents of H_2O in the oceanic arc enhanced the stability of olivine and suppressed plagioclase, producing Al-poor fractionates that resulted in Al enrichment in the evolved magmas, *i.e.*, evolution toward high-Al basaltic compositions. Differentiation in the continental arc was controlled by mineral phases that did not provide for SiO_2 enrichment (pyroxenes + plagioclase), and was characterized by coupled fractional crystallization and assimilation. Accelerated enrichment in incompatible elements (*REE* and *HFSE*) relative to the oceanic example is attributable to crustal assimilation. Plots of elemental abundances in the parental magmas on spider diagrams for both suites display trends parallel to MORB, but with lower absolute abundances, and also characteristic spikes from a subducted-slab component rich in Sr, Rb, K, and Ba. In both arcs, *in situ* evolution of high-Mg, low-Al basaltic compositions to high-Al, low-Mg compositions precludes a subducted-slab source for the magmas. Ta and Nb troughs in normalization diagrams appear to be an artifact of ordering of the elements; these elements do not appear to be more depleted than other elements relative to MORB.

Keywords: island-arc magmatism, lower crust, gabbro, continental environment, oceanic environment, Argentina, Alaska.

SOMMAIRE

Une étude comparative de deux séquences de la croûte inférieure d'arcs magmatiques montre qu'il y a une ressemblance frappante entre les magmas primitifs qui nourissent les systèmes continentaux et océaniques; de plus, les résultats soulignent le rôle important que joue les roches crustales dans le développement de certaines signatures géochimiques de laves qui sont considérées typiques des roches d'arcs. Ce travail a surtout porté sur l'assemblage de Tonsina–Nelchina, affleurant le long d'une coupe à partir de l'interface manteau supérieur – croûte inférieure jusqu'à la carapace volcanique dans la séquence d'arc insulaire Talkeetna, d'âge jurassique, situé en Alaska sud-central, et le massif gabbroïque de Fiambalá, pluton mis en place dans la croûte inférieure de la marge continentale en Amérique du Sud, à l'époque ordovicienne. Les deux suites intrusives dans la croûte inférieure ont cristallisé à partir de magmas parentaux magnésiens [Mg/(Mg + Fe) égal à 68.1 et 74.5, respectivement], et ont une composition en termes d'éléments traces qui est relativement appauvrie par rapport à des basaltes de rides médio-océaniques (MORB), mais par contre enrichie en éléments lithophiles à large rayon, comme Sr, Rb, K, U, et Ba. Les deux suites contiennent un assemblage semblable de minéraux primaires (ol + pyx, suivi de pyx + pl ± amph ± oxydes), leurs proportions variant selon la teneur en H_2O du magma parental. Les teneurs plus élevées dans le cas de l'arc océanique ont élargi le champ de stabilité de l'olivine et éliminé le plagioclase, ce qui a mené à des compositions de cumulats à faibles teneurs en Al, et par conséquent des augmentations importantes des teneurs en Al des magmas plus évolués, c'est-à-dire, les magmas basaltiques enrichis en Al. La différenciation dans le contexte d'arc continental a été régi par des phases minérales qui n'ont pas pu causer un enrichissement en SiO_2 (pyr + plag); les processus importants sont la cristallisation fractionnée de concert avec l'assimilation. Un enrichissement accéléré en éléments incompatibles, comme les terres rares et les éléments à rapport élevé de charge à rayon ionique, comparé à l'exemple océanique, est atribuable à l'assimilation de la croûte continentale. Les abondances normalisées des éléments dans les magmas parentaux des deux arcs montrent un parallèlisme aux compositions des magmas MORB, mais décalé vers des teneurs plus faibles; par contre, ces tracés montrent les anomalies caractéristiques d'une plaque enfouie par subduction, enrichie en Sr, Rb, K, et Ba. Dans les deux cas, l'évolution *in situ* d'une composition basaltique magnésienne à faible teneur en Al vers une composition basaltique alumineuse à faible teneur en Mg élimine de considération une source de ces magmas dans la plaque en

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subduction. Les déficits en Ta et Nb dans les diagrammes d'abondances normalisées pourraient être le résultat de la séquence utilisée pour dresser la liste des éléments. Ces deux éléments ne semblent pas plus appauvris que les autres par rapport à leurs concentrations dans les basaltes MORB.

(Traduit par la Rédaction)

Mots-clés: magmatisme d'arc insulaire, croûte inférieure, gabbro, milieu continental, milieu océanique, Argentine, Alaska.

INTRODUCTION

The role of the lower crust in generating the characteristic differences among magmas erupted in various arc settings worldwide is not well understood. Petrologists envision the lower crust either as a region where magmas stall and evolve, obtaining their characteristic chemical signatures, or as a relatively unimportant passageway through which magmas pass unmodified to the surface. This debate concerns both oceanic and continental arc magmatism. For example, in the oceanic realm, voluminous outpourings of high-Al basalt are argued on the one hand to be products of differentiation after fractionation of hydrous high-Mg tholeiitic magma at high pressure in the deep crust of the arc (*e.g.*, Conrad & Kay 1984, Crawford *et al.* 1987, DeBari & Sleep 1991, Kay 1985, Kay & Kay 1985) and, on the other, as primary magma derived from eclogite melting in the subducted slab (*e.g.*, Brophy & Marsh 1986, Myers 1988, Myers *et al.* 1986). In the continental realm, debate centers on the ultimate origin of enriched trace-element and isotopic signatures that are so characteristic of continental arc lavas: is this signature due to assimilation of crust during stagnation in the lower crust (*e.g.*, Hildreth & Moorbath 1988), or is it indicative of magma generation from an enriched subcontinental lithosphere (*e.g.*, Hawkesworth & Volmer 1979, Hickey *et al.* 1986, Pearce 1983, Rogers & Hawkesworth 1989)? My intent in this study is to clarify the role of magmatic evolution within the lower crust in the development of characteristic features of arc magmas. I analyze two exposed magma-chambers exhumed from the lower crust and compare a simple case, a purely oceanic island arc, with a more complicated case, a continental margin arc with its associated continental crust. The first is from the Tonsina–Nelchina assemblage in south-central Alaska, which is a cross section from upper mantle to upper crust of the Jurassic Talkeetna island arc (DeBari & Coleman 1989, DeBari & Sleep 1991), and the second is the Fiambalá gabbroic intrusive complex of northwestern Argentina, an uplifted section of lower crust from a continental margin into

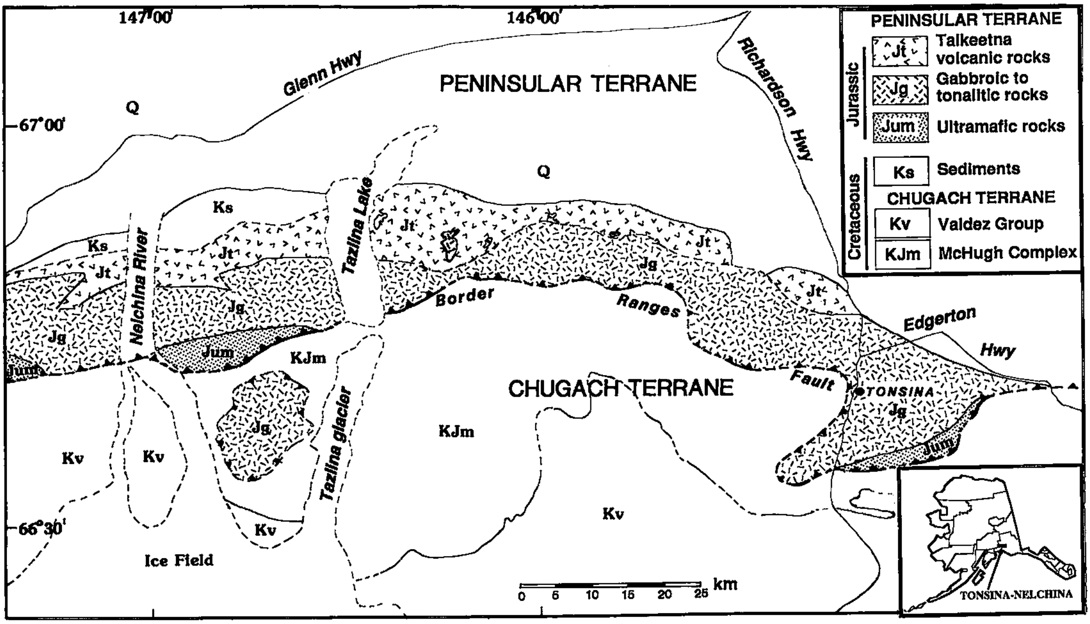

FIG. 1. Map of the Tonsina–Nelchina assemblage, a cross section of the Jurassic Talkeetna island arc. The arc is located within the Peninsular terrane and has been thrust to the south over the Chugach terrane along the Border Ranges Fault. Structures dip steeply to the north, so that a cross section of the arc is exposed from ultramafic cumulates at the base to calc-alkaline volcanic rocks at the top. Figure from DeBari & Sleep (1991).

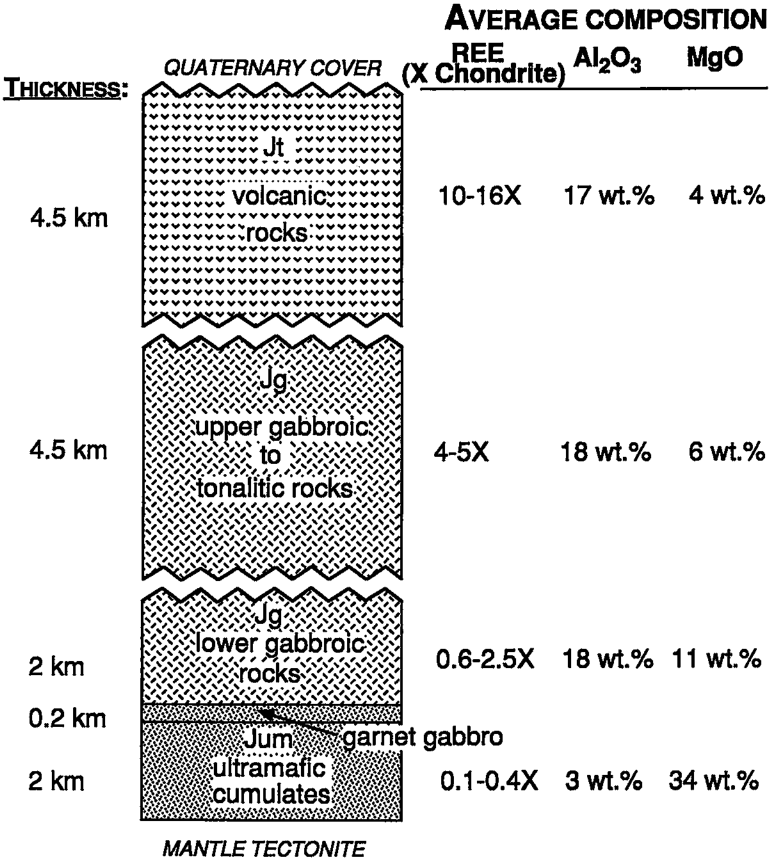

FIG. 2. Schematic stratigraphic column of the Alaskan Talkeetna island arc in the Tonsina–Nelchina area. Units correspond to those in Figure 1; however, the gabbroic rocks are divided into a lower gabbroic and an upper gabbroic to tonalitic unit. Modified from Pearcy *et al.* (1990) and DeBari & Sleep (1991).

which subduction-related magma was intruded (DeBari 1994, Grissom *et al.* 1992).

GEOLOGICAL SETTING AND PETROLOGY OF THE TONSINA–NELCHINA ASSEMBLAGE

The Tonsina–Nelchina assemblage, a section of the Jurassic Talkeetna island arc, is located at the southern end of the Peninsular terrane in south-central Alaska (Fig. 1). The arc was thrust to the south over the Chugach terrane along the Border Ranges Fault System (BRFS), and was subsequently tilted on end to form a cross-sectional exposure from upper mantle to upper crust. The deep levels of the Talkeetna island arc are now exposed all along the BRFS, which forms an arcuate belt from southwestern Kodiak Island to southeastern Alaska (Burns 1985). In the Tonsina–Nelchina area, the base of the arc consists of mantle tectonite and ultramafic cumulate rocks. The lower to middle crust of the arc is made up of gabbroic to dioritic plutonic rocks, and the upper crust consists mainly of calc-alkaline volcanic rocks (Fig. 1; DeBari 1990). All units dip steeply to the north, hence progressively shallower units are exposed from south to north. The arc was built entirely on oceanic crust; the wallrock to the plutons consists only of minor metamorphosed basalt and gabbro (pre-existing MORB basement?), minor highly metamorphosed carbonate layers (in the Nelchina River area only), or, most commonly, coeval plutonic rocks. A schematic "stratigraphic column" of the arc is shown in Figure 2.

The rocks of the Tonsina–Nelchina assemblage have been described in detail elsewhere (Burns 1985, DeBari 1990, DeBari & Coleman 1989). These descriptions are briefly reviewed here. As seen in Figure 1, ultramafic rocks crop out immediately to the north of the Border Ranges Fault. They consist of tectonized harzburgite and dunite, interpreted to be residual mantle plus a 2-km-thick section of variably deformed, ultramafic cumulate rocks that include dunite, wehrlite, and pyroxenite. The cumulate rocks display layering that dips steeply to the north. The modal proportion of clinopyroxene and orthopyroxene increases dramatically in a traverse from Cr–Al-spinel-bearing dunite in the south (the base) to wehrlite, olivine-bearing pyroxenite, and olivine-free websterite or clinopyroxenite to the north (upward). The pyroxenitic layers are overlain by a 0.5-km-thick garnet-bearing transition zone consisting of varying proportions of pyroxene, plagioclase, amphibole, and poikilitic garnet (garnet formed by isobaric cooling at ~10 kbar; see DeBari & Coleman 1989). The composition of the pyroxenes becomes progressively more aluminous upward in this section; for example, the clinopyroxene from wehrlite contains 2 wt.% Al_2O_3, and that of websterite and garnet pyroxenite contains 8 wt.% Al_2O_3 (DeBari & Coleman 1989). The garnet-bearing transition zone passes upward into spinel-bearing gabbroic rocks that contain varying proportions of clinopyroxene, orthopyroxene, plagioclase, amphibole, and pure Mg–Al spinel (Jg unit of Fig. 1). Again, the clinopyroxene is very aluminous (8 to 9 wt.% Al_2O_3). No olivine is found anywhere in coexistence with plagioclase. The gabbroic rocks are layered, and range from strongly recrystallized to cumulate-textured. Rare pargasitite composed of 100% pargasitic amphibole is locally found in a cross-cutting relationship with gabbroic rocks. The entire sequence of rocks just described represents the deepest exposed levels within the arc.

Further north, at higher levels in the arc, more differentiated intrusive rocks are found. They consist of two-pyroxene hornblende gabbro (± olivine), hornblende gabbro, hornblende diorite, hornblende quartz diorite, and lesser tonalite (Jg unit of Fig. 1; Burns 1985, DeBari 1990). All rock types are rich in Fe–Ti oxides. In the Tonsina area, these rocks represent a sharp break from the lower gabbroic rocks, both chemically and texturally. This break is interpreted to be due to the structural juxtaposition of deep and shallow levels of the arc (DeBari & Coleman 1989). In the Nelchina River area, however, the gabbroic rocks chemically and texturally seem to represent the intermediate levels missing at Tonsina. Thus for simplicity in Figure 1, all the rocks from both the lower and upper gabbroic unit have been shown as one unit (Jg).

The uppermost unit in the arc is a sequence of volcanic rocks (the Talkeetna Formation) consisting of basaltic to andesitic flows and felsic ignimbrites, as well as lithic graywackes (Barker & Grantz 1982). In the Tonsina area, these volcanic rocks are intruded by quartz diorite and tonalite of the unit described above, but in most places the contact is a fault.

The above descriptions and the stratigraphic column in Figure 2 show that each of the units within the arc has distinctive characteristics; hence the arc is fairly well stratified. Because of this stratification, the arc is chemically stratified as well, with most of the Mg concentrated in the lower crust, and most of the Al concentrated in the upper crust (Fig. 2). This same stratification can be seen in concentrations of the compatible elements Ni and Cr (Fig. 3), and the rare-earth elements (*REE*; Fig. 4; DeBari & Sleep 1991). The bulk of the compatible elements is found in the basal cumulates

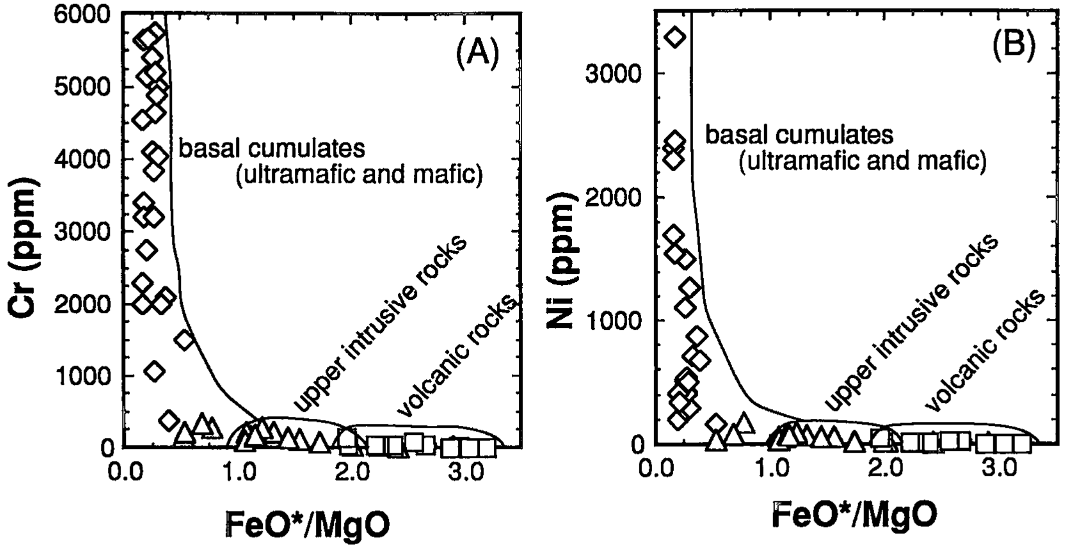

FIG. 3. Concentrations of (A) Cr and (B) Ni *versus* FeO/MgO (molar basis) for the various units from the Tonsina–Nelchina section of the Talkeetna arc. Note that the bulk of the compatible elements is concentrated in the deepest levels in the crust.

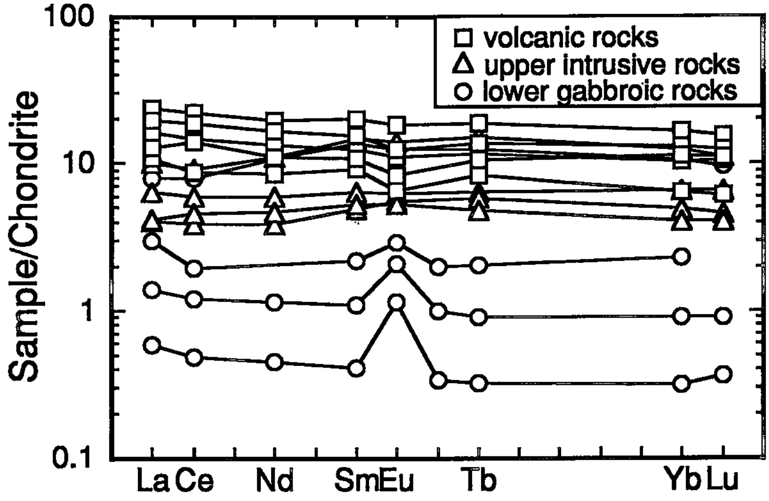

FIG. 4. Concentrations of the rare-earth elements (*REE*) for the different lithological units from the Tonsina–Nelchina section of the Talkeetna arc. Note that the highest abundances of the *REE* are concentrated in the upper levels of the crust. Modified after DeBari & Sleep (1991).

in the lower crust, whereas the intrusive and volcanic rocks of the middle and upper crust are relatively poor in these elements. In contrast, the lowest *REE* abundances are found in the rocks of the deep crust, the high-level mafic to intermediate intrusive rocks of the mid-crust contain intermediate abundances, and the volcanic rocks of the upper crust, dominantly differentiates issued from the underlying intrusive bodies, contain the highest abundances of the *REE*.

GEOLOGICAL SETTING AND PETROLOGY OF THE FIAMBALÁ GABBROIC COMPLEX

The Fiambalá gabbroic intrusive complex, Ordovician in age (DeBari & Wright, unpubl. manuscript), is located in the Sierra de Fiambalá, within the Sierras Pampeanas of northwestern Argentina (Fig. 5). The Sierras Pampeanas are a series of basement-block uplifts located to the east of the active volcanic arc, in the region of shallow-slab subduction (28°S latitude, 67°W longitude). The gabbroic complex consists of a syntectonic pluton and associated dikes and sills. They were intruded into metasedimentary rocks in the deep crust of an arc that was located along the western continental margin of South America during the Ordovician (DeBari 1994). These rocks and their tectonic setting are well described by Grissom *et al.* (1992) and DeBari (1990, 1994). The main gabbroic body, with 30 km^2 of surface exposure, was emplaced at ~21–24 km depth during pervasive regional amphibolite-facies metamorphism of the surrounding crust (Grissom *et al.* 1992). However, synchronous with intrusion, the metamorphic grade of the country rock (metagreywacke and calc-silicate rocks) was locally upgraded to granulite facies in a km-wide aureole around the pluton (Grissom 1991, Grissom *et al.* 1989). The plutonic rocks are extremely fresh, and preserve striking igneous textures. During uplift to present levels of erosion, rocks of the Sierra de Fiambalá have been rotated through 90°, so that the map effectively illustrates a complete cross-section of the intrusive complex from base to top (Fig. 5).

The main gabbroic pluton is 12.2 km long, with a maximum thickness of 2.8 km at its center, but because it is exposed as a vertical section, its width is uncertain. It is located on a major lithological boundary between greywacke (denoted Mg in Fig. 5) to the east and calc-silicate rocks (denoted Mcs) to the west. The western margin, or base, is in sharp contact with the calc-silicate rocks, and along this margin, plagioclase-free ultramafic cumulates (dunite and pyroxenite) and pyroxene-rich gabbroic cumulates form the lowest stratigraphic units. In contrast, the contact with metagreywacke rocks along the eastern, or upper, margin is very diffuse. Along this margin, zones from 100 to 500 m thick display gabbroic rocks and migmatitic metagreywackes that are interlayered on the scale of a few meters to tens of meters. These gabbroic zones become gradually less abundant away from the main pluton, but they can still be found as far as 5 km away.

On the eastern (bottom) side of the pluton, olivine-free websterite or clinopyroxenite invariably occurs in a layer 2–30 m thick between dunitic cumulate rocks and gabbroic rocks. As with the Tonsina–Nelchina rocks, olivine and plagioclase never coexist, and the first appearance of plagioclase is abrupt. Two-pyroxene gabbro becomes dominant within 1 m of the first

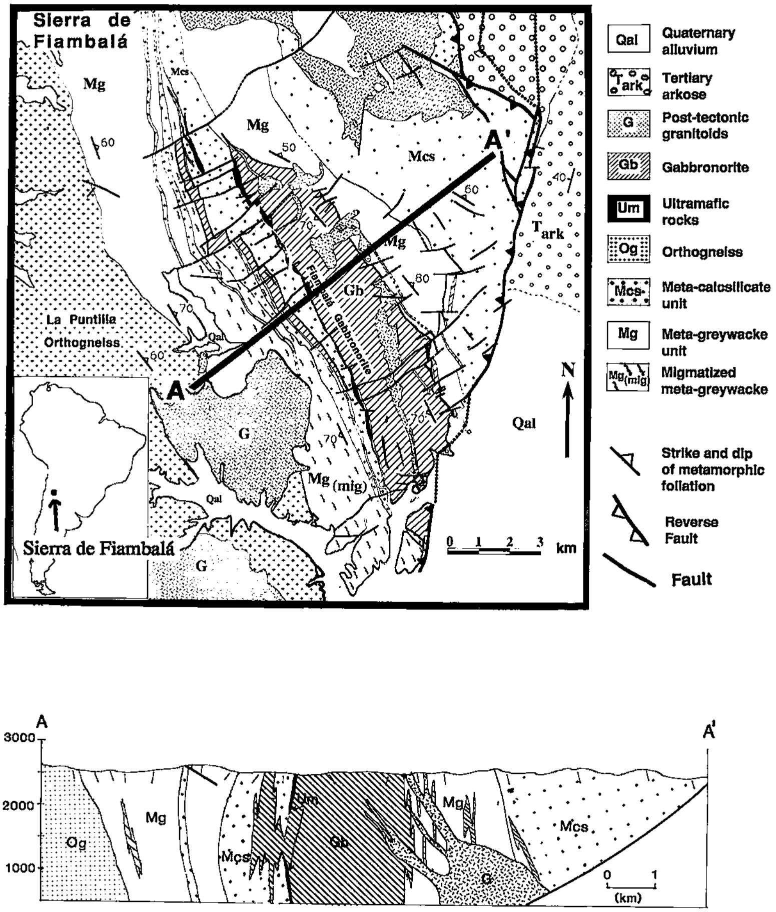

FIG. 5. Map of the southern Sierra de Fiambalá. After Grissom *et al.* (1992).

appearance of plagioclase in the pyroxenites. Centimeter- to meter-thick layers of pyroxenite (websterite and clinopyroxenite) are found within the gabbro for several tens of meters eastward of the pyroxenite–gabbro contact. The gabbro interlayered with pyroxenite is a cumulate of plagioclase, clinopyroxene, and orthopyroxene. Amphibole and spinel first appear in gabbro after the disappearance of pyroxenite interlayers. There is a gradual increase of amphibole at the expense of pyroxene from west to east across the pluton, and there is also a change from dominantly layered units in the west to dominantly massive units in the central and eastern (upper) parts. The mineralogy of the massive gabbro is the same as that in the gabbroic rocks at Tonsina–Nelchina; however, the oxide phase is ilmenite rather than Mg–Al spinel. Compositions of mineral phases become significantly more evolved across the pluton, even though there is no evolution in whole-rock composition to diorite or tonalite at this level of exposure.

Metasedimentary xenoliths (both greywacke and calc-silicate) are common within the pluton. They range from a few centimeters to tens of meters on a side. They typically have been metamorphosed to the granulite facies and partially melted, and many have been stretched into schlieren.

COMPARISON OF THE LEVELS OF EXPOSURE

The difference in the level of exposure of these two magmatic suites is an important factor in the following discussion. The Alaskan oceanic example is a cross-sectional exposure from mantle to upper crust, whereas the continental example from Argentina is a section of lower crust only. The Fiambalá gabbroic rocks are analogous to the lower cumulates and massive gabbroic rocks in the deepest portion of crust exposed in the Tonsina–Nelchina section of the Alaskan arc. However, pressures of crystallization for the lower cumulates in the Alaskan arc were estimated to be approximately

TABLE 1. COMPARISON OF MINERAL COMPOSITIONS FROM OTHER MAFIC INTRUSIVE SUITES

	MAGMATIC ARCS						RIFT MAGMAS	
	Fiambalá[1]	Tonsina[2]	Lesser Antilles xenoliths[3]	Aleutian lower crustal xenoliths[4]	Bear Mtn calc-alkaline suite[5]	Peninsular Ranges batholith[6]	Kiglapait layered intrusion[7]	Skaergaard intrusion[8]
Mg# (Ol)	91-90	89-84	90-59	86-83	83-69	79-70	72-04	40-02
Mg# (Di)	94-53	92-75	90-56	92-75	87-79	84-65	73-15	66-02
Mg# (Opx)	91-54	87-62	77-43	–	83-74	80-50	–	62-50
Mg# (Hbl)	89-55	92-62	86-38	84-70	82-53	80-65	–	–
An (Pl)	89-48	94-62	100-36	95-88	94-74	98-55	62-28	66-30

[1]DeBari (1994); [2]DeBari & Coleman (1989); [3]Arculus & Wills (1980); [4]DeBari *et al.* (1987); [5]Snoke *et al.* (1981); [6]Smith *et al.* (1983); [7]Morse (1979); [8]Wager & Brown (1968). Analyses of minerals in the Fiambalá and Tonsina columns were performed with the Stanford JEOL 733 electron microprobe equipped with a Kevex software system and ZAF matrix correction. Analytical uncertainties for major elements in these minerals are within ±0.20 wt.%.

8 to 10 kbar on the basis of pyroxene barometry and phase relations (DeBari & Coleman 1989), whereas crystallization pressure for the Fiambalá intrusive complex was slightly lower, 7 to 8 kbar (21 to 24 km), on the basis of geobarometric studies of the host metasedimentary rocks (Grissom 1991, Grissom *et al.* 1989). As discussed in the next section, this difference in pressure plays an important role in the relative proportions of crystallizing mineral phases and hence in the evolutionary paths of the magmas.

The ultramafic cumulates and deep gabbroic plutonic rocks in Alaska clearly represent a deeper section in the crust. They are underlain by mantle tectonites, and a "petrological Moho" is preserved. In Argentina, the crustal level is less clear. There is no indication of proximity to the Moho during intrusion of the Fiambalá

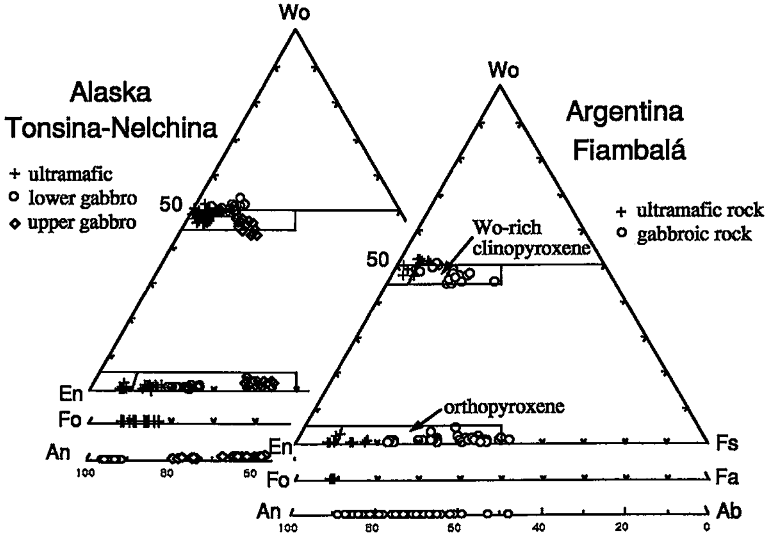

FIG. 6. Representative compositions of pyroxenes in terms of (Wo), (En), and (Fs) components. Below the triangle, compositions of olivine are plotted in terms of forsterite (Fo) – fayalite (Fa), and those of plagioclase, in terms of anorthite (An) – albite (Ab). Clinopyroxene maintains a high Wo content with differentiation in both arc sections. Plagioclase in the most primitive rocks from both sections is minimally zoned and highly calcic. Olivine in both suites is present only in ultramafic rocks and is Fo-rich.

gabbro. However, several lines of evidence suggest that the depth of intrusion estimates of 21 to 24 km may well be representative of the Ordovician lower crust. These include: (1) the margin on which the Ordovician arc developed had undergone rifting during the Late Precambrian and Early Cambrian, suggesting that the arc was built on relatively thin continental crust (Breitkreuz *et al.* 1989), and (2) coeval arc-related volcanic and sedimentary rocks of the Faja Eruptiva de la Puna (north of the Sierra de Fiambalá) were all deposited in shallow-water environments (Allmendinger *et al.* 1983, Coira *et al.* 1982), suggesting eruption from a non-thickened continental margin. Hence, my interpretation has been that 20–30 km is a reasonable thickness of crust for a thinned, recently rifted continental margin (Grissom *et al.* 1992).

EVOLUTION OF THE ARGENTINE AND ALASKAN GABBROIC ROCKS

Comparative mineralogy and mineral chemistry

Both the Alaskan and the Argentine lower crustal suites have a base consisting of plagioclase-absent ultramafic cumulates that grade into gabbroic rock-types consisting of clinopyroxene, orthopyroxene, plagioclase, amphibole, and an oxide phase. In both suites, olivine never coexists with plagioclase; layers of pyroxenite are always present between olivine- and plagioclase-bearing lithologies. The crystallization sequence for both suites was olivine plus Al-rich chromite, followed by almost simultaneous crystallization of orthopyroxene and clinopyroxene, after which olivine crystallization ceased, and plagioclase crystallization began. Chromite ceased to crystallize after the onset of plagioclase crystallization and was replaced by Mg–Al spinel in the Tonsina–Nelchina gabbroic rocks, and ilmenite in the Fiambalá gabbroic rocks. Simultaneous crystallization of clinopyroxene, orthopyroxene, and plagioclase yielded the gabbroic rocks. Amphibole in both sequences is a late igneous phase, and occurs in a reaction relationship with pyroxene.

Olivine from both Fiambalá and Tonsina–Nelchina is Mg-rich and unzoned. Cumulate olivine from the Tonsina–Nelchina ultramafic suite is Fo_{89-84}, whereas cumulate olivine from the Fiambalá ultramafic rocks is Fo_{91-90} (Table 1, Fig. 6). The occurrence of olivine at Fiambalá is very restricted; it was not present on the liquidus long enough to develop much compositional variation. In contrast, olivine from the Tonsina–Nelchina suite cocrystallized with pyroxene for a longer interval and shows a broader compositional range (Table 1, Fig. 6).

Pyroxenes from both the Tonsina–Nelchina and Fiambalá ultramafic suites are also Mg-rich, reflecting the fact that in both suites clinopyroxene and orthopyroxene followed olivine very closely on the liquidus, before the magma was depleted in Mg (Table 1, Fig. 6). This early crystallization of the pyroxenes reflects moderate to high pressures of crystallization (6–10 kbar), a factor that decreased the stability field of olivine relative to pyroxene (Presnall *et al.* 1979, Walker *et al.* 1979). In the Fiambalá dunite and pyroxenite, the Mg-number [$100Mg/(Mg + Fe^{2+})$] of the clinopyroxene ranges from 94 to 89, and that of orthopyroxene, from 91 to 82. In the Tonsina–Nelchina ultramafic suite, the Mg-number of the clinopyroxene ranges from 94 to 87, and that of the orthopyroxene, from 92 to 83. As shown in Table 1, a high Mg-number in pyroxene seems to be a characteristic feature of cumulate rocks from the root of island arcs relative to rift-related layered intrusions, and probably reflects the deeper level of crystallization in arcs in general. In the Tonsina–Nelchina and Fiambalá suites, the clinopyroxene is highly calcic and displays a trend to more Fe-rich compositions (Fig. 6). This highly calcic trend has been attributed to high contents of H_2O during crystallization (Conrad & Kay 1984, Gaetani *et al.* 1993, Helz 1976, Murray 1972, Sisson & Grove 1993); it is found in clinopyroxene from lower-crust island-arc xenoliths as well as Alaskan-type zoned ultramafic complexes (*e.g.*, Conrad & Kay 1984, DeBari *et al.* 1987, Murray 1972). This trend is quite distinct and may be an important discriminant for pyroxene crystallized in magmatic arcs.

As shown by Mg-numbers of the coexisting pyroxenes, plagioclase began crystallizing earlier in the Fiambalá suite than at Tonsina–Nelchina. The earliest-formed plagioclase at Fiambalá coexists with clinopyroxene having a Mg-number of 87.7, whereas that at Tonsina–Nelchina coexists with clinopyroxene having a Mg-number of 82.5. Thus, clinopyroxene had evolved to lower Mg-numbers at Tonsina–Nelchina before plagioclase joined the crystallization sequence. As discussed later, this effect is probably related to higher H_2O pressure in the Tonsina–Nelchina parent magma than in the Fiambalá magma; H_2O suppresses the crystallization of plagioclase (*e.g.*, Helz 1973, 1976, Holloway & Burnham 1972). Plagioclase is highly calcic in the most mafic samples of both suites, and evolves to more sodic compositions with differentiation (Fig. 6). The range is An_{89-48} at Fiambalá, and An_{94-62} at Tonsina–Nelchina. Extensive oscillatory zoning in plagioclase in both suites is restricted to the most evolved samples. The most calcic plagioclase (An_{90-80}) shows zoning only on the order of 2 to 4%. Highly calcic plagioclase such as this is ubiquitous in gabbroic rocks from island arcs (Table 1), and has been attributed to the presence of H_2O in the melt during crystallization (*e.g.*, Helz 1973). The preponderance of highly calcic plagioclase in arcs has been used as a tool in determining the tectonic setting of gabbroic plutons (Beard 1986).

Pargasitic amphibole was the final major phase to crystallize in both suites, as a result of a reaction relationship between pyroxene and melt. This reaction is widely documented in melting experiments on hydrous basaltic compositions (*e.g.*, Helz 1973, 1976, Holloway

& Burnham 1972). In the 5-kbar experiments of Holloway & Burnham (1972) on the 1921 Kilauea olivine tholeiite, the stoichiometry of the melting reaction of hornblende between 999 and 1051°C was given as:

$$100 \text{ Hbl} \rightarrow 23 \text{ Cpx} + 77 \text{ Liq.}$$

Amphibole is much more abundant at Tonsina–Nelchina than at Fiambalá; igneous pargasitite and pargasite–plagioclase assemblages make up a significant proportion of the deeper levels of the oceanic arc. In contrast, most of the Fiambalá gabbroic rocks have volumetrically less amphibole, and the grains of amphibole typically contain relict clinopyroxene in their core (*i.e.*, the clinopyroxene–melt reaction did not go to completion).

The greater abundance of amphibole at Tonsina–Nelchina agrees with other indicators of higher H_2O contents during crystallization, such as limited crystallization of olivine, more calcic clinopyroxene, greater suppression of plagioclase crystallization, and more highly calcic plagioclase. Increasing pressure decreases the stability field of olivine, whereas high H_2O pressure enhances it (Nicholls & Ringwood 1973, Presnall *et al.* 1979, Walker *et al.* 1979). Thus, although the Tonsina–Nelchina ultramafic cumulates crystallized at slightly higher pressure than at Fiambalá (8 to 10 kbar as compared to 7 to 8 kbar), the higher proportion of H_2O in the parent magma was responsible for the extended stability of olivine in the Tonsina–Nelchina suite relative to Fiambalá. In addition, plagioclase crystallization is suppressed relative to pyroxene at both high confining pressure and high $P(H_2O)$ (Helz 1976, Johannes 1978, Sisson & Grove 1993, Yoder & Tilley 1962). Thus, a combination of high P_{total} and $P(H_2O)$ will cause an extended period of fractionation of Al-poor minerals, namely olivine and pyroxene, yielding plagioclase-free ultramafic cumulates. The higher H_2O pressure and slightly higher total pressure in the lower crust of the Tonsina–Nelchina section thus had important effects on the relative proportions and temperature ranges of the phases in the crystallizing assemblage. As discussed in the next section, these differences were responsible for different evolutionary paths of the respective magmas.

Comparative major-element chemistry of the two suites: parental magmas

Perfit *et al.* (1980a) pointed out that primitive island-arc basalts are similar in major-element chemistry to primitive mid-ocean-ridge basalts (MORB), and hence their sources may be similar. They also suggested that some of the chemical differences between island-arc basalts and MORB could result from fractional crystallization of arc basalts at relatively high pressures (*i.e.*, deeper in the crust), where the main crystallizing phases are olivine and pyroxene, as opposed to low-pressure fractionation of olivine and plagioclase in the case of MORB. The higher-pressure crystallization of Al-poor phases in arc settings, as discussed further below, is one of the factors responsible for the generation of high-Al basalt.

Compositions of the parental melt for both magma suites have been determined and are given in Table 2. They both correspond to high-Mg, low-Al primitive tholeiite, with similar major-element chemistry to other suggested primary magmas in arc settings (Table 2). The Alaskan parental composition was calculated by determining the bulk composition of the entire arc using mass-balance calculations (DeBari & Sleep 1991). Because the Tonsina–Nelchina section of the Alaskan Talkeetna arc is so well stratified (Figs. 2–4), the bulk composition of the crust can be calculated. Assuming that arcs are derived totally from the mantle, the bulk composition of the arc is considered equivalent to the composition of the parental magma. The arc was divided into its constituent segments (from Fig. 2: ultramafic cumulates, lower gabbroic rocks, upper gabbroic to tonalitic rocks, and volcanic rocks). An average composition was calculated for each of those segments, and then weighted averages (dependent upon segment thickness) were used to calculate a bulk composition. The values used for these calculations are shown in Table 3. As can be seen from Figure 2, the

TABLE 2. PRIMITIVE MAGMAS IN MAGMATIC ARCS

	Alaskan parental magma	SF-39 Argentine parental magma	SF-39 +4% ol	Ladakh parental magma[1]	New Georgia picrite[2]	Aleutian picrite[3]	Aleutian parental magma[4]	Aleutian high-Mg basalt[5]	South Sandwich Islands[6]
SiO_2 wt.%	51.1	49.7	49.3	49.15	48.90	48.94	48.55	51.20	–
Al_2O_3	15.0	15.5	14.9	13.07	11.40	16.01	16.88	15.69	–
FeO	9.51	8.12	8.14	8.35	9.97	8.90	7.67		–
MgO	11.29	11.70	13.23	11.65	14.70	11.42	10.51	9.64	–
CaO	9.21	12.47	11.97	8.70	10.30	10.89	12.52	10.12	–
Na_2O	2.51	1.45	1.39	1.82	1.84	2.21	2.22	2.77	2.11
K_2O	0.48	0.37	0.36	0.83	1.18	0.52	0.68	0.92	0.34
TiO_2	0.65	0.39	0.38	0.61	0.50	0.70	0.67	0.75	1.10
P_2O_5	0.11	0.05	0.05	0.14	0.23	0.12	0.13	0.21	0.07
MnO	0.18	0.21	0.19	0.16	0.18	0.17	0.17	0.16	–
H_2O	–	–	–	4.84	–	–	–	–	–
CO_2	–	–	–	0.85	–	–	–	–	–
Mg#	67.9	72.0	74.3	71.4	74.9	71.9	71.0	67.4	–
Rb ppm	<20	18	–	–	–	6	–	–	9.46
Sr	254	291	–	–	–	501	–	–	123
Zr	39	33	–	–	–	60	–	–	–
Y	<20	22	–	–	–	16	–	–	–
V	–	126	–	–	–	–	–	–	–
Cr	723	590	–	–	–	662	300	337	54
Ni	247	163	233	–	–	266	100	91	29
Cs	0.41	2.39	–	–	–	0.52	0.32	–	–
Ba	2543	121	–	–	–	231	164	–	–
U	0.29	0.06	–	–	–	–	0.43	–	–
Th	0.34	0.14	–	–	–	1.0	0.92	–	–
Hf	0.91	0.68	–	–	–	1.5	1.04	–	–
Ta	0.09	0.09	–	–	–	–	0.08	–	–
La	2.84	5.33	–	–	–	7.1	4.29	–	2.21
Ce	6.59	13.58	–	–	–	15.9	11.03	–	7.13
Nd	5.06	8.77	–	–	–	9.9	6.40	–	6.13
Sm	1.72	2.53	–	–	–	2.2	2.00	–	2.07
Eu	0.60	1.02	–	–	–	0.83	0.70	–	0.78
Tb	0.42	0.55	–	–	–	0.49	0.37	–	–
Yb	1.54	2.06	–	–	–	1.3	1.29	–	–
Lu	0.23	0.30	–	–	–	–	0.20	–	2.28

[1] Dietrich *et al.* (1983); magmatic composition.
[2] Ramsay *et al.* (1984); estimated composition.
[3] Nye & Reid (1986); melt composition.
[4] Kay *et al.* (1982), and Kay & Kay (1988); estimated composition.
[5] Gust & Perfit (1987).
[6] Hawkesworth *et al.* (1977).

TABLE 3. TONSINA-NELCHINA: MASS BALANCE RESULTS

	Ultramafic unit[1]	Lower Gabbroic unit[2]	Upper Intrusive unit[3]	Volcanic unit[4]	Bulk arc[5]	Error range[6]
SiO_2 wt.%	45.25	43.78	51.81	57.29	51.08	50.55 - 51.54
Al_2O_3	3.08	18.69	18.02	16.79	14.98	14.70 - 15.22
FeO*	8.95	10.17	9.69	9.31	9.51	9.48 - 9.54
MgO	33.98	10.63	6.28	3.85	11.29	10.74 - 11.93
CaO	8.19	13.97	10.57	5.98	9.21	8.97 - 9.49
Na_2O	0.25	1.74	2.30	4.42	2.51	2.34 - 2.65
K_2O	0.01	0.11	0.39	1.03	0.48	0.43 - 0.52
TiO_2	0.12	0.66	0.63	0.96	0.65	0.62 - 0.67
P_2O_5	0.01	0.08	0.12	0.18	0.11	0.11 - 0.12
MnO	0.15	0.17	0.19	0.18	0.18	0.18 - 0.18
Total	100.00	100.00	100.00	100.00	100.00	
FeO*/MgO	0.26	0.96	1.55	2.54	0.84	–
Nb ppm	<10	<10	<10	<5	<10	–
Rb	<10	<10	<10	20	<20	–
Sr	52	239	327	302	254	255 - 264
Zr	<10	22	<10	69	39	–
Y	<10	<20	<10	22	<20	–
Ni	1172	66	46	17	247	231 - 267
Cr	3436	239	112	45	723	675 - 781
Cs	b.l.d.	b.l.d.	0.73	0.50	0.41	0.38 - 0.43
Ba	b.l.d.	22	203	535	243	218 - 264
U	b.l.d.	b.l.d.	0.21	0.70	0.29	0.26 - 0.32
Th	b.l.d.	b.l.d.	0.27	0.78	0.34	0.30 - 0.37
Hf	b.l.d.	0.25	0.71	1.99	0.91	0.82 - 0.99
Ta	b.l.d.	0.13	0.08	0.12	0.09	0.08 - 0.09
La	0.05	1.21	1.94	6.22	2.84	2.55 - 3.09
Ce	b.l.d.	2.83	4.39	14.63	6.59	5.90 - 7.18
Nd	0.27	2.67	3.87	10.30	5.06	4.61 - 5.45
Sm	0.15	0.99	1.46	3.28	1.72	1.59 - 1.84
Eu	0.14	0.40	0.55	1.01	0.60	0.56 - 0.63
Tb	0.05	0.23	0.39	0.74	0.42	0.39 - 0.44
Yb	0.19	0.88	1.54	2.66	1.54	1.45 - 1.63
Lu	0.03	0.13	0.24	0.40	0.23	0.22 - 0.24

[1] Ultramafic and garnet gabbro unit. A weighted average of dunite (45.5%), wehrlite (13.6%), clinopyroxenite (8.0%), websterite (23.8%), and garnet gabbro (9.1%). Includes data for 27 rocks (major- and trace-element data) of which 7 have been analyzed for REE (data in part from Plafker et al., 1989).

[2] Low level gabbroic unit. Average of 8 rocks, 7 of which have REE data.

[3] High level gabbroic and dioritic unit. Average of 10 rocks, 7 of which have REE data (data in part from Plafker et al., 1989).

[4] Volcanic unit (Talkeetna Formation). Average of 13 rocks, all of which have REE data (data in part from Barker et al., 1994).

[5] Bulk arc, a mass-weighted average of columns 1 (18%), column 2 (16%), column 3 (34%), and column 4 (32%).

[6] Error range, assuming 25% change in any upper unit (fraction of ultramafic unit stays fixed).

TABLE 4. FEO*/MGO AND NI CONCENTRATIONS OF PARENTAL MAGMAS CALCULATED FROM EARLY CRYSTALLIZING OLIVINES

	ALASKA		ARGENTINA			
	ak-9	alu-60	AR-7	SF-17	SF-170	SF-163
Olivine compositions						
SiO2	39.51	39.88	41.27	40.73	41.07	40.64
MgO	47.22	48.05	50.38	49.62	49.62	49.87
FeO	13.1	11.01	8.28	8.50	8.83	8.71
CaO	0.0	0.0	0.13	0.04	0.07	0.01
MnO	0.21	0.1	0.07	0.09	0.11	0.08
NiO	0.23	0.25	0.37	0.41	0.30	0.36
Sum	100.27	99.29	100.5	99.39	100.04	99.70
FO	86.53	88.61	91.6	91.2	90.9	91.1
FA	13.47	11.39	8.4	8.8	9.1	8.9
FeO/MgO (mol%)	0.16	0.13	0.09	0.10	0.10	0.10
Ni (ppm)	1807	1965	2907	3222	2357	2829
Olivine-liquid equilibria						
Using $D_{FeO/MgO}$(ol-liq) = 0.30 (Roeder & Emslie, 1970):						
liquid FeO*/MgO (mol%)	0.52	0.43	0.31	0.32	0.33	0.33
liquid Mg# (=100Mg/(Mg+Fe))	66	70	76	76	75	75
Assuming parent with 10 wt% MgO						
D_{MgO}(ol/liq) = 4.49, D_{Ni}* = 13.91						
liquid Ni(ppm)	130	141	209	232	169	203
Assuming parent with 11 wt.% MgO						
D_{MgO}(ol/liq) = 4.45, D_{Ni}* = 12.14						
liquid Ni (ppm)	149	162	239	265	194	233
Assuming parent with 13.5 wt.% MgO						
D_{MgO}(ol/liq) = 3.67, D_{Ni}* = 9.09						
liquid Ni(ppm)	225	245	362	401	294	352

*D_{Ni}(ol/liq) = [3.92 x (D_{MgO}) - 5.30] (after Jones, 1984)

total exposed thickness of the Tonsina–Nelchina section is 13.2 km, but the entire arc at the time of formation was probably 27–30 km thick. How valid is the result of a calculation of bulk composition with only ~50% of the section exposed? DeBari & Sleep (1991) addressed this question by discussing several important checks on the validity of the calculations, especially with regard to the relative thicknesses of the units. First, the composition of the mass-balance-inferred parent is consistent with a composition calculated by mineral–melt partition coefficients from the earliest-formed ultramafic cumulates. The FeO*/MgO value (molar basis) and Ni concentrations in the earliest-crystallized olivine yield an inferred FeO*/MgO = 0.43 (K_d = 0.30) and Ni in the range 225–245 ppm [C_S/C_L = 11.8; from Jones (1984); $K_d = X(\mathrm{FeO})^{Ol}/X(\mathrm{FeO})^{Liq} \times X(\mathrm{MgO})^{Liq}/X(\mathrm{MgO})^{Ol}$ (Roeder & Emslie 1976)] for the coexisting magma, which matches closely with the FeO*/MgO value and Ni content from the mass-balance-inferred parental magma (0.47 and 247 ppm, respectively; see Table 4 for calculations). Second, since most of the Mg and Ni in the arc is found in the ultramafic cumulate unit (Fig. 2), the fact that mineral–melt partition coefficients from the earliest cumulate crystals yield compositions that agree with the mass-balance-inferred parent suggest that the *relative* fraction (thickness) of the ultramafic unit in the total must be correct. Whether the crustal section is 15 or 30 km thick, the ultramafic cumulates *must* equal about 18% of the section. Third, since very little of the Al in the arc is contained in the "fixed" proportion of ultramafic cumulates, the concentration of Al in the mass-balance-inferred parent is dependent only on change in the thicknesses of the upper units relative to each other. The average Al content, however, does not vary much in the upper units (16.8 to 18.7 wt.% Al_2O_3; Table 1), and so changing their relative fractions will not change the Al content of the mass-balance-inferred parent by very much. The same logic can be applied for Mg; it is concentrated in the ultramafic unit and is relatively scarce in the upper units. Hence, changing the relative proportions of the upper units will not seriously affect either the Mg or the Al of the mass-balance-inferred parent. This is shown in Table 3, where I calculate a range of errors assuming an arbitrary 25% change in thickness of any one unit (column 5). Hence, even with as much as half of the section missing, I am confident that the bulk composition calculated approximates the arc as a whole. The parental magma corresponds to a high-Mg,

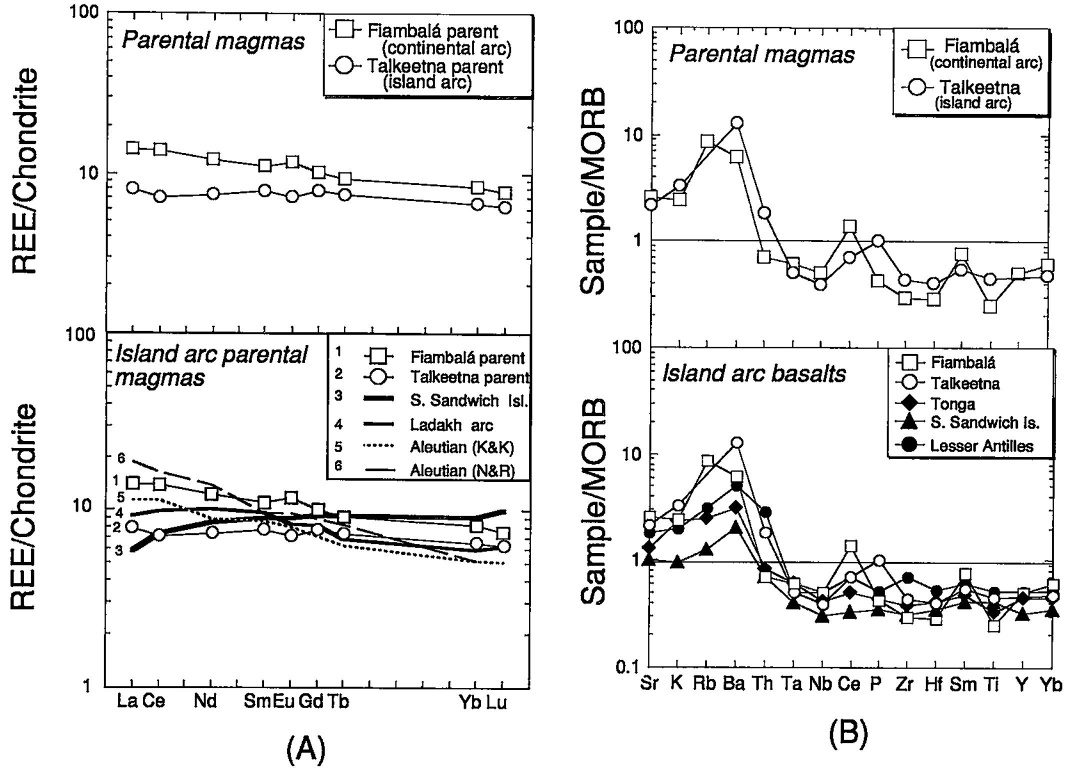

FIG. 7. A. Comparison of *REE* patterns of Talkeetna and Fiambalá parental magmas with others from a variety of island arcs worldwide. B. Comparison of other trace elements for the two arcs on a MORB-normalized plot. Data for the South Sandwich Islands are taken from Hawkesworth *et al.* (1977), for the Ladakh arc, from Dietrich *et al.* (1983), and for the Aleutian primary magmas, from Kay & Kay (1988) and Nye & Reid (1986).

low-Al olivine tholeiite with a relatively flat *REE* pattern (Fig. 7).

The composition of the parental magma for the Fiambalá gabbroic intrusion in Argentina can be estimated by: (1) application of mineral–melt partition coefficients to the most primitive cumulate minerals, (2) comparison of the crystallization sequence and mineral compositions with those from experimental studies, and (3) consideration of the composition of the most primitive, non-cumulate gabbroic rocks. Application of these three constraints restricted the parental magma to correspond to a silica-saturated, high-Mg basalt (DeBari 1994). A likely composition is sample SF–39 (DeBari 1994), collected near the western margin of the intrusive complex (within the vicinity of a postulated feeder dike). This composition fits all the requirements to have produced the gabbroic suite at Fiambalá. However, the composition of SF–39 is less Mg-rich than what would be in equilibrium with the most magnesian olivine in the sequence of ultramafic cumulates, which suggests that SF–39 has undergone some prior fractionation of olivine (DeBari 1994). If 4 wt.% olivine is added back to SF–39, the result is a composition acceptable for that required by olivine–liquid equilibria; *i.e.*, its Mg-number is 74.3, and it contains 13.2 wt.% MgO (Table 2). The *REE* pattern of SF–39 is slightly light-rare-earth-enriched (Fig. 7).

Comparative major-element chemistry of the two suites: genesis of high-Al basalt

Both the Fiambalá and Tonsina–Nelchina suites have high-Al derivative compositions formed from low-Al (high-Mg) parental magmas (Table 5). For the Tonsina–Nelchina suite, extended fractionation of plagioclase-free, Al-poor ultramafic cumulates (olivine and pyroxene) at the base of the crust of the oceanic arc produced highly Al-enriched magmas. By the time plagioclase began crystallizing, the magma was so enriched in Al that the resulting gabbroic rocks had compositions equivalent to high-Al basalts [Fig. 8, Table 5; see fractionation model in DeBari & Sleep (1991)]. A reliable monitor of this Al-enrichment is provided by the changing Al content of the pyroxenes with differentiation. A plot of Al_2O_3 in clinopyroxene and orthopyroxene (Fig. 9) *versus* their Mg-number

TABLE 5. CHEMICAL COMPOSITION OF ARGENTINE AND ALASKAN PARENTAL AND DERIVATIVE MAGMAS, AND GREYWACKE ASSIMILANT

	Parental magmas		Derivative magmas: High alumina basalts		Assimilant
	Alaska Bulk arc	Argentina SF39 +4% ol	Alaska RGC20	Argentina SF-93	Sierra de Fiambalá greywacke
SiO_2 wt.%	51.1	49.3	51.3	50.5	72.0
Al_2O_3	15.0	14.9	17.7	17.9	13.16
FeO*	9.51	8.14	7.21	7.11	3.87
MgO	11.29	13.23	7.39	6.86	1.36
CaO	9.21	11.97	11.13	11.16	1.75
Na_2O	2.51	1.39	2.13	2.27	2.17
K_2O	0.48	0.36	0.66	0.68	4.64
TiO_2	0.65	0.38	0.45	0.93	0.74
P_2O_5	0.11	0.05	0.14	0.13	0.21
MnO	0.18	0.22	0.16	0.15	0.05
FeO*/MgO (mol%)	0.47	0.35	0.55	0.58	
Mg# (=100Mg/(Mg+Fe))	67.9	74.3	64.6	63.2	42.8
Ni (ppm)	247	233	80	33	21

shows a steady trend of sharply increasing Al from the ultramafic cumulate rocks (2 wt.% Al_2O_3) to the gabbroic rocks (7 to 9 wt.% Al_2O_3). This increase represents increasing Al-content in the crystallizing magma (DeBari & Coleman 1989). The same extensive fractionation of ultramafic cumulates did not occur in the Fiambalá suite in the continental arc, although the end product after differentiation was still a high-Al basalt composition (Fig. 8). At Fiambalá, plagioclase came on the liquidus much sooner than at Tonsina–Nelchina; there was no chance for significant Al-enrichment of the crystallizing magma during the formation of the ultramafic cumulates. However, the concentration of Al does increase, from 13.5 wt.% in primitive gabbros to 19 wt.% Al_2O_3 in more evolved gabbros (Fig. 8, Table 5), suggesting that Al behaved incompatibly, and that plagioclase was less important than pyroxene as a fractionating phase (DeBari 1994). Hence, Al-enrichment is interpreted to have occurred in both suites, during fractionation of ultramafic cumulates at Tonsina–Nelchina and during crystallization of gabbroic rocks at Fiambalá. Thus I conclude that crystallization in the deep crust, regardless of minor variations in crystallizing phases, is a viable mechanism for production of high-Al basalt from low-Al, high-Mg parental magmas. At least in these two arcs, the presence of high-Mg parental magmas precludes a subducted-slab source for magmatism.

The mineral assemblage crystallizing in the continental arc as observed at Fiambalá had roughly the

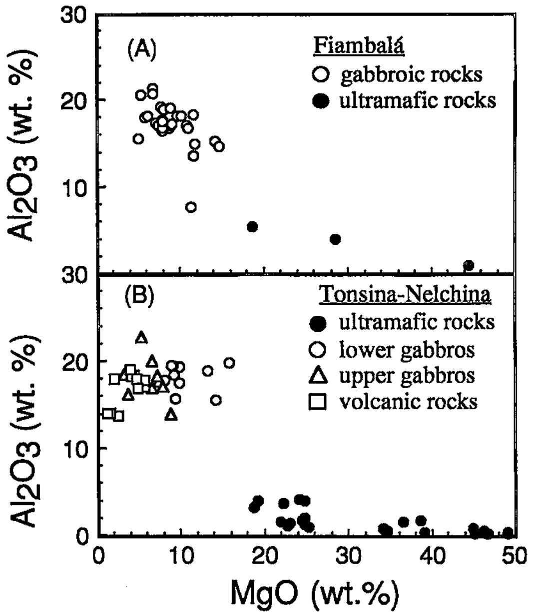

FIG. 8. Plot of wt.% Al_2O_3 *versus* wt.% MgO in (A) the Fiambalá gabbroic rocks (Argentina), and (B) the Tonsina–Nelchina suite (Alaska). A steadily increasing proportion of Al throughout the ultramafic to gabbroientiation at Fiambalá, whsharp jump in the proportion of Al occurs between the ultramafic and gabbroic rocks in the Tonsina–Nelchina suite.

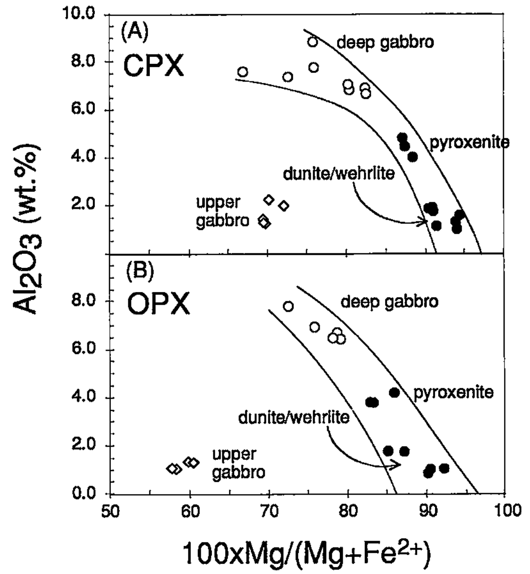

FIG. 9. Plot of wt.% Al_2O_3 *versus* 100*Mg/(Mg + Fe^{2+}) in (A) clinopyroxene and (B) orthopyroxene from the Tonsina–Nelchina assemblage of the Talkeetna oceanic island arc. Note the progressively higher contents of Al in the pyroxenes with differentiation from ultramafic to mafic rocks in the deep crustal rocks. The shallower plutonic rocks contain pyroxenes poorer in Al. Modified after DeBari & Coleman (1989).

same SiO_2 content as its parental magma [~52–55 wt.% SiO_2 in clinopyroxene, 53–56 wt.% in orthopyroxene, and 48–55 wt.% in plagioclase; DeBari (1994)]. Hence, although much differentiation occurred with respect to other elements, the SiO_2 content of the crystallizing magma remained at ~50–51 wt.%. It is clear that differentiation in the lower crust can produce rocks that are still basaltic in composition, but that have depleted Mg contents, increased Al contents, and, as seen below, strongly differentiated trace-element concentrations.

Comparative trace-element chemistry of the two suites

Both the Fiambalá gabbroic intrusion in the Argentina continental arc and the Tonsina–Nelchina assemblage in the Alaskan oceanic arc are characterized by enrichment in large-ion lithophile elements (Sr, Rb, K, Ba) and depletion in high-field-strength elements (Ta, Nb, P, Zr, Hf, Ti, Y) relative to MORB; such a pattern characterizes subduction-related magmas worldwide. These enrichments and depletions are best displayed in a plot of concentrations normalized relative to MORB (Fig. 10; Pearce 1983). The compositions of the most primitive rocks from both gabbroic suites display very similar patterns. Both the Alaskan and the Argentine suites contain some cumulate rocks; those samples have extremely depleted patterns relative to MORB, yet are still enriched in the large-ion lithophile elements. The estimated parental magmas for the two suites also are shown in Figure 10; they are quite similar to each other in their relative abundances and the shape of their patterns (see also Fig. 7). However, the most differentiated gabbroic rocks (7.4 and 6.9 wt.% MgO, respectively; Table 5) display very different patterns (Figs. 10a, b). The differentiated gabbroic rocks from Argentina are enriched in *all* incompatible elements relative to MORB, including the high-field-strength elements Ta, Nb, and Zr. The most differentiated oceanic (Alaskan) gabbroic rocks are not as enriched, and retain patterns that are parallel to the parental magma. Even comparing the most differentiated volcanic rocks from Alaska, those that contain 65 wt.% SiO_2 and 2.2 wt.% MgO (Fig. 10c), there still is not a trend toward such highly enriched compositions relative to MORB as in Fiambalá. Thus this enrichment cannot be related solely to the degree of differentiation. The enriched pattern of the evolved Fiambalá gabbroic rocks relative to MORB is typical of volcanic rocks erupted in continental arcs, and has been interpreted to be a characteristic of their source. Pearce (1983) suggested that the enrichment is characteristic of an enriched subcontinental mantle. In Fiambalá, however, this enrichment can be shown to be due to open-system crystallization of a primitive parental magma like that expected in an island arc, with concomitant assimilation of metagreywacke country-rocks and periodic replenishment by fresh batches of magma (DeBari 1994). There is abundant evidence in the field for this assimilation-and-replenishment process (DeBari 1994).

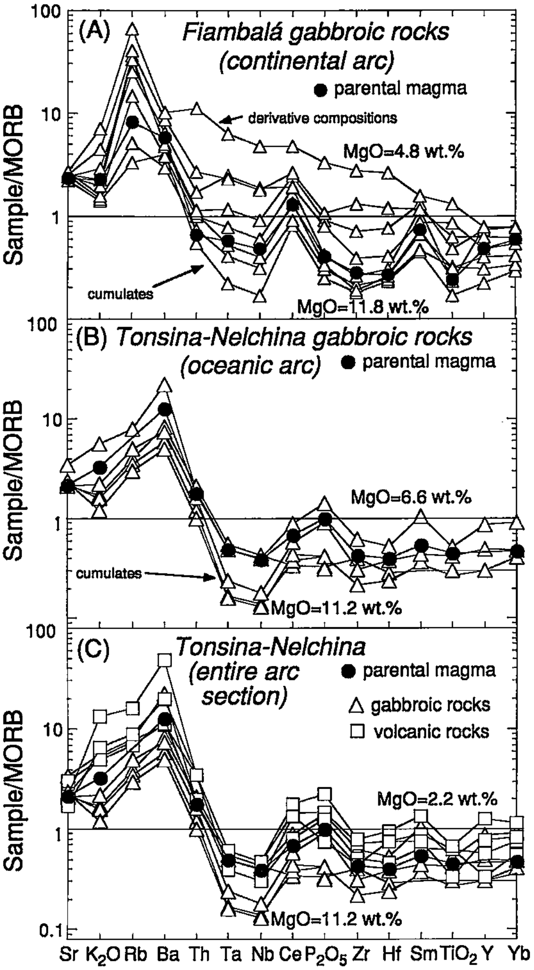

FIG. 10. MORB-normalized incompatible element diagram (Pearce 1983) of elemental abundances relative to MORB for (A) the Fiambalá gabbroic rocks (Argentina), (B) the Tonsina–Nelchina gabbroic rocks (Alaska), and (C) the entire Alaskan arc from lower to upper crust. Note that although primitive compositions from both suites have similar patterns relative to MORB, more differentiated compositions with lower MgO contents display very different patterns. Major-element compositions of the more differentiated gabbros from each suite are given in Table 2.

Figure 11 shows results of calculations intended to model assimilation and fractional crystallization (AFC), in which the parent magma (SF–39) assimilates metagreywacke country-rock (SF–66). A hybrid composition that closely matches derivative composition

SF–93 can be produced by these calculations using an *r* value (ratio of rate of assimilation to rate of crystallization) of 0.4, with 86% melt fraction still remaining (DeBari 1994). This combination requires only 3% assimilation, and is validated by isotopic data to be presented elsewhere (DeBari & Wright, unpubl. manuscript). Note that the enriched, differentiated Fiambalá gabbroic rocks are still basaltic in composition, with 6 to 7 wt.% MgO, 30 ppm Ni, and 60 ppm Cr (DeBari 1994). Thus, parental magmas in continental arcs can evolve into characteristic "enriched" hybrid compositions while still retaining a basaltic bulk-composition.

Accelerated enrichment is also interpreted to occur for the rare-earth elements during differentiation of the Fiambalá magma in the continental example. There is a threefold increase in *REE* abundances, from the parental magma at ~51 wt.% SiO_2 and ~12 wt.% MgO to a differentiated gabbroic rock at ~51 wt.% SiO_2 and 6 wt.% MgO. In contrast, the Alaskan gabbroic rocks exhibit much less than a twofold increase for the same

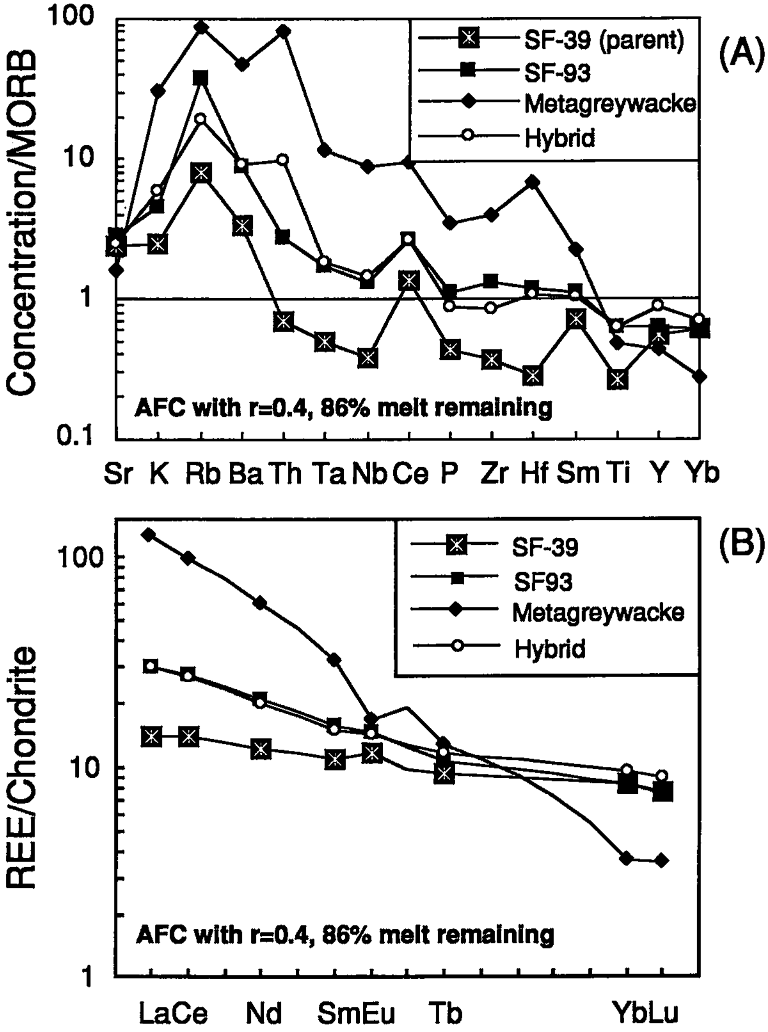

FIG. 11. A. MORB-normalized incompatible element diagram showing results of chemical modeling. Open-system AFC using the metagreywacke as the assimilant (r = 4) will produce SF–93 (a derivative) from SF–39 (the parent) with 86% melt still remaining. B. Results for the *REE* using the same modeling parameters as in A. From DeBari (1994).

change in wt.% MgO. A threefold increase in *REE* abundances in the Alaskan suite occurs only after differentiation to andesitic volcanic rocks, with 4.7 wt.% MgO. The most likely explanation for this accelerated increase in *REE* abundances, and perhaps for the preponderance of basalts with elevated *REE* abundances in continental arcs in general, is the effect of crustal assimilation.

The parental magmas for both suites fall well into the field defined by other primary magmas from island arcs (Fig. 7). This agreement suggests that the parental magmas of both the island arc in Alaska and the continental arc in Argentina were derived from sources that are typical of island arcs worldwide. There is, at least in this case, no need to call on an enriched subcontinental mantle to produce the characteristic trace-element signature of a continental arc magma erupted at the surface. The signatures can be produced during residence time in the lower continental crust.

MANTLE SOURCES FOR ARC MAGMAS

Petrogenetic models are hampered by the complexities of magma genesis in arcs and the knowledge that more than one source is involved (*e.g.*, Davidson 1987, Kay 1980, Perfit *et al.* 1980b). The favored models include a mantle-wedge source essentially like that which produced MORB magmas, and that has been enriched either by incorporation of sediment (*e.g.*, Kay 1980) or by infiltration of hydrous fluids that have equilibrated with altered seafloor basalt and sediments (*e.g.* Davidson 1987, Dupuy *et al.* 1982, Hawkesworth *et al.* 1987, Hole *et al.* 1984, Kay 1980). Pb, Nd, and Sr isotopic constraints limit the proportion of bulk sediment mixed into the mantle wedge to be less than 2%, an amount that does not adequately account for patterns of trace-element enrichment, especially elevated Ba/La values (Davidson 1987, White & Dupré 1986). Elevated Ba/La values in arc magmas can, however, be obtained in the mantle by incorporation of fluids that have equilibrated with weathered subducted basaltic seafloor (*e.g.*, Davidson 1987). Models for magma genesis in arcs are even further complicated by crustal contamination of "primary magmas" during ascent through the crust, and, in the case of continental arcs, the possible existence of an old, enriched lithospheric source in the mantle. In addition to the above uncertainties, the origin of the characteristic depletions in high-field-strength elements (*e.g.*, Ta and Nb) in arc magmas is still uncertain. The prominent depletion of Ta and Nb is especially noticeable if the composition of arc magmas is plotted relative to chondrite abundances. The low abundance of these elements has been proposed to be due to (1) stability of Ti-rich residual phases (*e.g.*, rutile, titanite, and perovskite) during partial melting in the mantle source (*e.g.*, Saunders *et al.* 1980), (2) interaction of

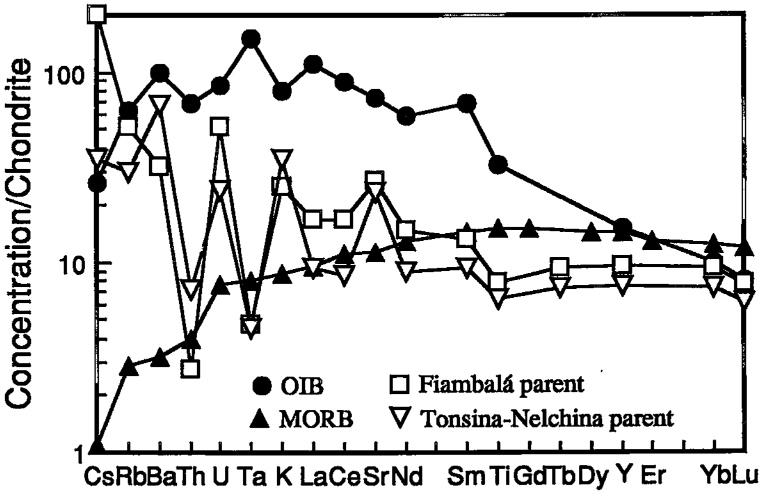

FIG. 12. Plot of elemental abundances normalized to primordial values in the Tonsina–Nelchina and Fiambalá parental magmas, as well as examples of typical MORB and OIB magmas. Normalizing values, MORB composition, and OIB composition are from Sun (1980). Note that trace element abundances in the two parental magmas are generally parallel to, but depleted, relative to MORB, except for enrichments in slab-derived components such as the light *REE*, Rb, Ba, U, K, and Sr. As suggested by Davidson & Wolff (1989), the position of Ta in the downturned limb of the MORB pattern and the contrast to its enriched neighbors U and K produce a "Ta anomaly" which may only be an artifact of the order of elements chosen.

slab- or mantle-derived magmas with a harzburgitic mantle (Kelemen *et al.* 1990, 1993), (3) prior Ti-depletion of the mantle in the source region (Green & Pearson 1986, McCulloch & Gamble 1991), and (4) high degrees of partial melting of the mantle source concurrent with enrichment with large-ion lithophile elements derived from the subducted slab (*e.g.*, Davidson 1987). The first argument, retention by a residual phase in the mantle, is becoming increasingly less acceptable as experimental studies and trace-element modeling limit the possibilities for what the residual phase could be (*e.g.*, Ryerson & Watson 1987). Davidson & Wolff (1989) proposed that these depletions may actually be an artifact of element ordering on the plots, that Ta/Yb values in primitive island-arc basalts are similar to those of N–MORB, and that their sources are similar. They inferred that enrichments in the light rare-earth elements and large-ion lithophile elements are superimposed on this source to yield the typical spiked pattern in "spidergrams".

Figure 12 compares the abundances of incompatible elements, normalized to abundances in the primordial mantle (Sun 1980) for the parental magmas to the Alaskan oceanic arc, the Argentine continental margin arc, and typical MORB magmas. The pattern for the two parental magmas displays the typical "spikes" that are characteristic of magmatic arcs. These spikes occur at Sr, K, Rb, U, and Ba, with distinct troughs at Nb and Th. Except for the spikes, the pattern is parallel to but depleted relative to MORB, and suggests that the explanation offered by Davidson & Wolff (1989) may be valid in this case. The marked trough at Nb does not reflect any more of a depletion than do the other trace elements relative to MORB; the apparent sharpness of the trough is due to enrichments of adjacent large-ion lithophile elements. The Alaskan and Argentine examples represent close examples of "primary" melts, and suggest that, as also pointed out by McCulloch & Gamble (1991), care should be taken when evaluating diagrams showing trace-element normalizations and the relative depletions of Nb and Ta.

CONCLUSIONS

A study of lower-crust mafic intrusive suites from the Tonsina–Nelchina segment of the Talkeetna island arc and the Fiambalá section of the Argentine continental margin arc has provided a direct way to interpret the evolution of arc magmas from their "primary" stage to their more characteristic differentiated compositions. Most importantly, the composition of parental magmas in both oceanic island arcs and continental magmatic arcs can be similar. At least in these two examples, the parental magmas are high-Mg, low-Al basaltic melts that resemble primitive MORB in major-element characteristics. Trace elements, however, are more depleted than in MORB, except for the subduction-derived enrichments of Sr, Rb, Ba, K, U, and the light rare-earth elements. Although different in detail, magmatic-arc mantle sources may indeed be similar worldwide, regardless of their existence beneath continental or oceanic crust.

Crystallization of these parental magmas in the deep crust produces a characteristic assemblage of minerals whose proportions and temperature intervals will vary depending upon the depth of crystallization and the H_2O content. This characteristic assemblage allows for significant differentiation to take place without concomitant increase in SiO_2, and provides a mechanism for the generation of high-Al basalt. In addition, crystallization in the deep crust of a continental arc may allow for significant assimilation of country rock, to produce accelerated enrichments in incompatible trace-elements, including the high field-strength elements. Therefore, trace-element enrichments in basalts erupted from magmatic arcs at continental margins need not be a characteristic of an enriched subcontinental mantle. Enrichment can occur during residence in the lower crust, to produce a hybrid magma very different from evolved magmas in oceanic island-arcs, but very similar to most basalts erupted in continental arcs.

Finally, as suggested by Davidson & Wolff (1989), the existence of Ta and Nb "anomalies" in arc magmas may be called into question. Depletions in these elements are no more pronounced relative to MORB than for any other trace elements that have not been enriched by a slab-derived fluid. In many cases, the apparent "anomalies" in normalized distributions can be attributed to sharp enrichments in adjacent elements, and the positioning of Nb and Ta in the downturned limb of a typical MORB pattern.

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APPENDIX I. ANALYTICAL TECHNIQUES

Whole-rock chemical data presented in this paper and used in mass-balance calculations were collected using an X-ray-fluorescence (XRF) spectrometer and by instrumental neutron-activation analysis (INAA). The concentration of the major elements in the rocks was obtained by XRF at Stanford University using a Rigaku fully automated spectrometer and flux-fusion disks. These disks were prepared from a mixture of 80% lithium tetraborate and 20% lithium nitrate flux, combined with rock powder in the weight ratio 7.5:1. The mixtures were melted in a platinum crucible in a furnace at 1050°C for 30 minutes, and then were poured into a platinum mold. The data were reduced by the method of fundamental parameters; analytical uncertainties are less than 5%. Concentrations of the trace elements (Ni, Cr, V, Rb, Sr, Zr, Nb and Sr) were established by XRF with pressed-pellet disks. The pellets were prepared using 5.5 g of sample backed with powdered boric acid. Uncertainties for the trace elements also are within ±5%.

The concentrations of the *REE*, Cs, Ba, U, Th, Hf, Ta and Na were established by INAA at Cornell University and the U.S. Geological Survey at Menlo Park. Errors are <1% for La, Sm and Na, within 5% for Ce, Eu, Yb, Lu and Ta, within 10% for Hf, Ba and Cs, and within 20% for Th and U. Errors in excess of 10% are due to extremely low concentrations of those elements in individual samples. Values of Ta were corrected for contamination by the tungsten carbide shatterbox by comparing the W/Ta value of the shatterbox with the measured W peak in the sample. The correction assumes that no W was originally present in the samples. This correction was successfully tested by comparing results of three replicate analyses of samples ground in an alumina shatterbox with the corrected results of analyses of the same three samples as ground in the tungsten carbide shatterbox.