Along-Strike Variation in the Aleutian Island Arc: Genesis of High Mg# Andesite and Implications for Continental Crust

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Based on a compilation of whole rock geochemistry for approximately 1100 lava samples and 200 plutonic rock samples from the Aleutian island arc, we characterize along-strike variation, including data for the western part of the arc which has recently become available. We concentrate on the observation that western Aleutian, high Mg# andesite compositions bracket the composition of the continental crust. Isotope data show that this is not due to recycling of terrigenous sediments. Thus, the western Aleutians can provide insight into genesis of juvenile continental crust. The composition of primitive magmas (molar Mg# > 0.6) varies systematically along the strike of the arc. Concentrations of SiO_2, Na_2O and perhaps K_2O increase from east to west, while MgO, FeO, CaO decrease. Thus, primitive magmas in the central and eastern Aleutians (east of 174°W) are mainly basalts, while those in the western Aleutians are mainly andesites. Along-strike variation in Aleutian magma compositions may be related to a westward decrease in sediment input, and/or to the westward decrease in down-dip subduction velocity. $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ all decrease from east to west, whereas $^{143}Nd/^{144}Nd$ increases from east to west. These data, together with analyses of sediment from DSDP Site 183, indicate that the proportion of recycled sediment in Aleutian magmas decreases from east to west. Some proposed trace element signatures of sediment recycling in arc magmas do not vary systematically along the strike of the Aleutians, and do not correlate with radiogenic isotope variations. Thus, for example, Th/Nb and fractionation-corrected K concentration in Aleutian lavas are not related to the flux of subducting sediment. Th/La is strongly correlated with Ba/La, rendering it doubtful that Ba/La is a

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proxy for an aqueous fluid component derived from subducted basalt. Ce/Pb > 4 is common in Aleutian lavas west of 174°W, in lavas with MORB-like Pb, Sr and Nd isotope ratios, and is also found behind the main arc trend in the central Aleutians. Thus, Ce/Pb in Aleutian lavas with MORB-like isotope ratios is not always low, and may be affected by a component derived from partial melting of subducted basalt in eclogite facies. Enriched, primitive andesites, with high Sr/Y, steep REE patterns, and low Yb and Y, are an important lava type in the Aleutians west of 174°W. High Sr/Y and Dy/Yb, indicative of abundant garnet in the source of melting, are correlated with major element systematics. Lavas with a "garnet signature" have high SiO_2, Na_2O and K_2O. Enriched, primitive Aleutian andesites did not form via crystal fractionation from primitive basalt, melting of primitive basalt, mixing of primitive basalt and evolved dacite, or partial melting of metasomatized peridotite. Instead, as proposed by *Kay* [1978], they formed by partial melting of subducted eclogite, followed by reaction with the mantle during ascent into the arc crust. In the eastern Aleutians, an eclogite-melt signature is less evident, but trace element systematics have led earlier workers to the hypothesis that partial melts of subducted sediment are an important component. Thus, partial melting of subducted sediment and/or basalt is occurring beneath most of the present-day Aleutian arc. This is consistent with the most recent thermal models for arcs. Enriched primitive andesites are observed mainly in the west because the mantle is relatively cold, whereas in the east, a hotter wedge gives rise to abundant, mantle-derived basalts which obscure the subduction zone melt component. Enriched primitive andesites, partial melts of eclogite, and products of small amounts of reaction between eclogite melts and mantle peridotite under conditions of decreasing magma mass, all have middle to heavy REE slopes that are steeper than those in typical Aleutian andesite and continental crust. Thus, direct partial melts of eclogite—without magma/mantle interaction—do not form an important component in the continental crust. Extensive reaction, with gradually increasing melt mass and melt/rock ratios ~ 0.1 to ~ 0.01, is required to increase heavy REE concentrations to the levels observed in most Aleutian andesites and in continental crust.

1. INTRODUCTION

In this paper, we present results of a compilation of whole rock geochemistry for approximately 1100 lava samples and 200 plutonic rock samples from the Aleutian island arc. Aleutian lava compositions have been compiled and analyzed in several previous studies [e.g., *Kelemen,* 1995; *Kay and Kay,* 1994; *Myers,* 1988]. We combine these previous compilations, and add recent data. These data characterize along-strike variation, including data for the western part of the arc that has recently become available. We evaluate current ideas about arc magma genesis in light of the spatial-geochemical patterns in the Aleutians.

We focus on evaluating hypotheses for the origin of andesites with high Mg/(Mg+Fe), or Mg#, which are abundant at and west of Adak (~ 174°W; Figure 1). These lavas are important because they overlap and bracket the major and trace element composition of the continental crust. Such lavas are rare or absent in intraoceanic island arcs other than the Aleutians. Also, the western Aleutians show the smallest influence of a subducted sediment component of any part of the Aleutians, so that it is unlikely that enrichments in elements such as U, Th, K and light rare earths are due to recycling of subducted, continental sediments. Thus, juvenile continental crust is being produced in the western Aleutians. Understanding this process forms the main focus of our paper.

In addition, along-strike variation in isotope ratios is systematic, and clearly related to variation in sediment input. This allows us to test trace element "proxies" for sediment recycling in arc lavas. These proxies are in current use in studies of global geochemical cycling and investigations of the Central American and Marianas arcs, so our results are timely and of broad relevance.

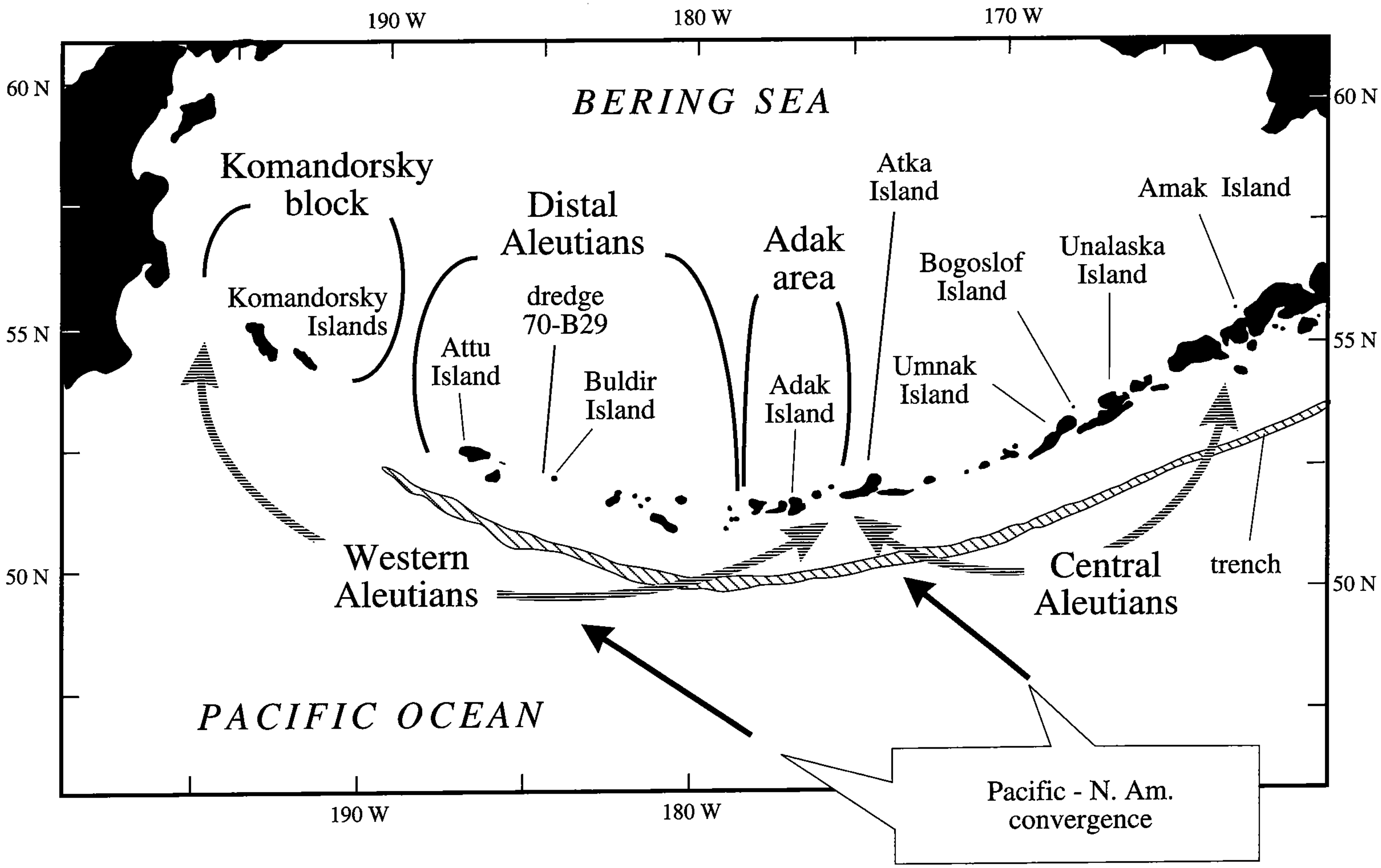


Figure 1. Overview of the Aleutian island arc, highlighting the geographic features mentioned in the text, and showing the approximate convergence vector near Adak (N42W) and Attu (N49W) from *Engebretson et al.* [1985].

1.1 Terminology

In describing lava compositions, we have used some terms that require definition. "High Mg# andesite" is defined as lava with 54 to 65 wt% SiO_2 and Mg# > 0.45. This could, in principle, include some boninites. However, classical boninites in the western Pacific generally have flat to light rare earth element (REE) depleted trace element patterns, whereas high Mg# andesites in the Aleutians are all light REE enriched. Note that MgO content plays no role in our definition of high Mg# andesite. Some Aleutian andesites with Mg# > 0.6 have MgO contents as low as 4 wt%. As a result, we have not used the familiar terms "high Mg andesite" or "magnesian andesite".

Some Aleutian high Mg# andesites—particularly some lavas on Adak Island first reported by *Kay* [1978]—also have been called "adakites" [e.g., *Defant and Drummond,* 1990]. The term adakite is used in a variety of contexts by different investigators, but generally refers to andesites and dacites with extreme light REE enrichment (e.g., La/Yb > 9), very high Sr/Y (e.g., Sr/Y > 50), and low Y and heavy REE concentrations (e.g., Y < 20 ppm, Yb < 2 ppm). In the Aleutians, all lavas with these characteristics are high Mg# andesites and dacites. However, note that the definition of "adakite" outlined above does not specify a range of Mg#. In arcs other than the Aleutians, many highly evolved lavas with low Mg# have been termed adakites. Thus, globally, not all adakites are high Mg# andesites. Similarly, most high Mg# andesites, in the Aleutians and worldwide, have La/Yb < 9 and Sr/Y < 50, so most high Mg# andesites are not adakites. Finally, we note that for some workers "adakite" has a genetic connotation as well as a compositional definition. Some investigators infer that all andesites and dacites with extreme light REE enrichment, very high Sr/Y ratios, and low Y and heavy REE concentrations formed via partial melting of subducted basalt in eclogite facies, and use the term adakite to refer to both lava composition and lava genesis interchangeably. While we believe that many "enriched andesites" may indeed include a component derived from partial melting of eclogite, we feel it is important to separate rock names, based on composition, from genetic interpretations. For this reason, we have not used the term "adakite" in this paper. Aleutian andesites and dacites with Mg# > 0.45, La/Yb > 9, and Sr/Y > 50, plus Y < 20 ppm and/or Yb<1 ppm, form an important end-member composition on most chemical variation diagrams. We refer to these as "enriched, high Mg# andesites".

More informally, we have used the terms "tholeiitic" and "calc-alkaline". For our purposes, the definitions of these terms proposed by either *Miyashiro* [1974] or *Irvine and Baragar* [1971] are approximately equivalent and equally useful. Similarly, we have informally used the term "primitive" to refer to lavas with Mg# > 0.6. This usage reflects our belief that lavas with Mg# > 0.6 have undergone relatively little crystal fractionation, and are derived from a parental liquid that was in equilibrium with mantle peridotite with an olivine Mg# > 0.88. Some investigators have suggested that some lavas and plutonic rocks with Mg# < 0.6—globally and in the Aleutians—are direct partial melts of subducted basalts [e.g., *Schiano et al.,* 1997; *Hauri,* 1996; *Myers,* 1988; *Myers et al.,* 1985; *Marsh,* 1976]. Indeed, this could be a viable hypothesis in some cases. However, it is very difficult to evaluate such hypotheses since many (most?) lavas with Mg# < 0.6 have been affected by crustal differentiation processes. In this paper, we have adopted the convention that lavas with Mg# < 0.6 are considered to be the products of differentiation from primitive magmas until proven otherwise.

Finally, for simplicity in data presentation, in this paper we have reported longitude in terms of degrees west of Greenwich so that, for example, 170°E is referred to here as 190°W.

1.2 Regional Divisions

In presenting our results, we have used regional divisions that are somewhat different from those used in previous papers (Figure 1). For our current purposes, Aleutian volcanoes from Atka eastward are all rather similar, with the exception of Rechesnoi volcano on Umnak Island. In order to avoid the complications of potential contamination from continental crust and overlying sediments, we have not compiled data for volcanic centers in the "eastern Aleutians", east of 164°W. The arc from 164 to 174°W, which we call the "central Aleutians", has been studied extensively. Most of it is a classic, oceanic arc dominated by tholeiitic basalts and their differentiation products [e.g., *Kay and Kay,* 1994; *Myers,* 1988, and references cited therein]. We call the arc west of Atka the "western Aleutians". We have subdivided the western Aleutians into three regions: (1) "the Adak area" (volcanoes on Adak, Great Sitkin, Kanaga, and Bobrof at 174 to 177°W), (2) "the distal Aleutians" from 177°W to 187°W, and (3) "the Komandorsky block" from 188°W to the Kamchatka Strait at ~ 195°W, including Komandorsky and Medny Islands and nearby, submarine volcanoes.

These subdivisions of the western Aleutians serve to remind readers of some important compositional and tectonic distinctions. The Komandorsky block lies within a transcurrent plate boundary, and may currently be moving mainly with the Pacific plate rather than with North American plate [*Avé Lallemant and Oldow,* 2000; *Geist and*

Scholl, 1994; *Geist and Scholl,* 1992]. For this reason, it is not entirely clear how the Komandorsky block is related to the modern Aleutian arc. We believe that there is a compositional continuum between the Komandorsky lavas and the main part of the active island arc further east, and this is important to our interpretations of Aleutian petrogenesis. However, it is crucial to note that this apparent continuum is dependent on very limited sampling of the distal Aleutians (Figure 2).

Adak and neighboring islands are heterogeneous, including both tholeiitic and calc-alkaline lavas [e.g., *Myers et al.,* 1985; *Kay et al.,* 1982]. Lavas in the Komandorsky block are predominantly calc-alkaline andesites, though basalts are present [*Yogodzinski et al.,* 1995; *Yogodzinski et al.,* 1994]. Distal Aleutian lavas are relatively homogeneous, compared to the Adak area, and are transitional between the dominantly tholeiitic, basaltic lavas of the eastern and central arc and primitive, calc-alkaline andesites and dacites with extreme trace element signatures that predominate in the Komandorsky block (Figure 3). As a result of this continuum in compositional variation, we presume that the Komandorsky lavas are genetically related to the rest of the western Aleutians. In fact, recent work supports this idea, and proposes that the Komandorsky block originated in the forearc region of the distal Aleutians, and later was transported ~ 700 km WNW along the transcurrent plate boundary [*Scholl et al.,* 2001; *Rostovtseva and Shapiro,* 1998].

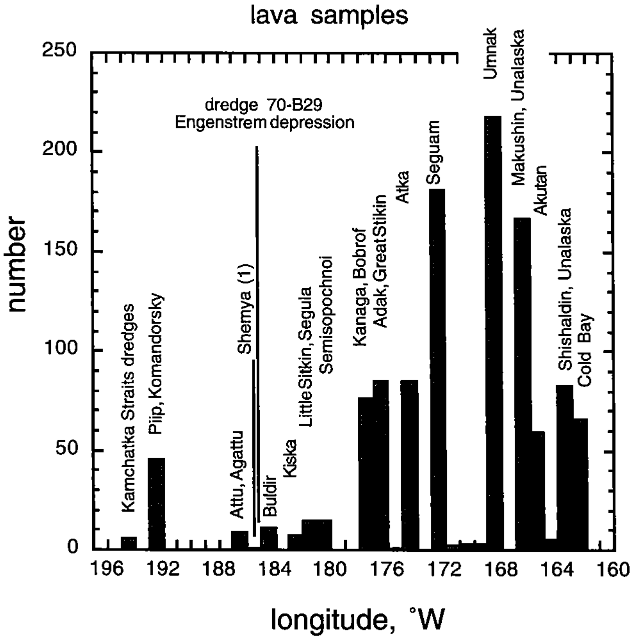


Figure 2. Histogram illustrating the number of Aleutian lava samples in our compilation as a function of longitude along the arc. Sources of data are given in the caption for Figure 3.

1.3 Andesite Paradox: Why Does Continental Crust Resemble arc Lavas?

A long-standing problem in Earth Science is to resolve the following, apparent paradox. It is well documented that the continental crust has a bulk composition very similar to high Mg# andesite lavas and plutonic rocks in subduction-related magmatic arcs, with molar Mg/(Mg+Fe), or Mg#, from 0.45 to 0.54 at 57 to 65 wt% SiO_2, 8000 to 24,000 ppm K, and La/Yb of ~ 5 to 20 (see Figures 4, 5 and 6, and [*Christensen and Mooney,* 1995; *Kelemen,* 1995; *Rudnick,* 1995; *Rudnick and Fountain,* 1995] for reviews). Lavas having these properties occur almost exclusively in arcs [*Gill,* 1981]. Thus, it is commonly inferred that continental crust formed mainly as a result of arc processes [e.g., *Kelemen,* 1995; *Rudnick,* 1995; *Kay and Kay,* 1991; *Taylor,* 1977]. However, most currently active, oceanic arcs are dominated by basalts and low Mg# andesites rather than high Mg# andesite lavas (Figure 5B).

Various hypotheses have been proposed to resolve this paradox. (1) At some times and places, the net magmatic flux through the Moho beneath arcs has been andesitic rather than basaltic [e.g., *Defant and Kepezhinskas,* 2001; *Martin,* 1999; *Kelemen et al.,* 1998; *Kelemen,* 1995; *Drummond and Defant,* 1990; *Martin,* 1986; *Ringwood,* 1974]. (2) High Mg# andesites in arcs form as a result of intracrustal crystal fractionation and magma mixing, involving mantle-derived basalts and their differentiates. Later, a dense mafic or ultramafic plutonic layer delaminates and returns to the mantle, leaving an andesitic crust [e.g., *Jull and Kelemen,* 2001; *Tatsumi,* 2000; *Kay and Kay,* 1993; *Kay and Kay,* 1991]. (3) High Mg# andesites in arcs form via fractionation of ultramafic cumulates from primary, mantle-derived basalts. The ultramafic cumulates remain, undetected, below the seismic Moho in arcs and continents [e.g., *Fliedner and Klemperer,* 1999; *Kay and Kay,* 1985b]. (4) Arcs may not have been involved at all. Processes of intracrustal differentiation and delamination have yielded a crustal composition whose resemblance to high Mg# andesites in arcs is coincidental [e.g., *Stein and Hofmann,* 1994; *Arndt and Goldstein,* 1989]. In this paper, we use data from the Aleutians to evaluate and extend hypotheses (1) through (3).

1.4 Calc-Alkaline Lavas in the Western Aleutians: Juvenile Continental Crust?

In the Aleutian island arc, particularly in the western Aleutians, high Mg# andesite lavas with compositions similar to continental crust are abundant (Figures 4, 5 and 6). Though similar lavas are also found in the Cascades, Baja

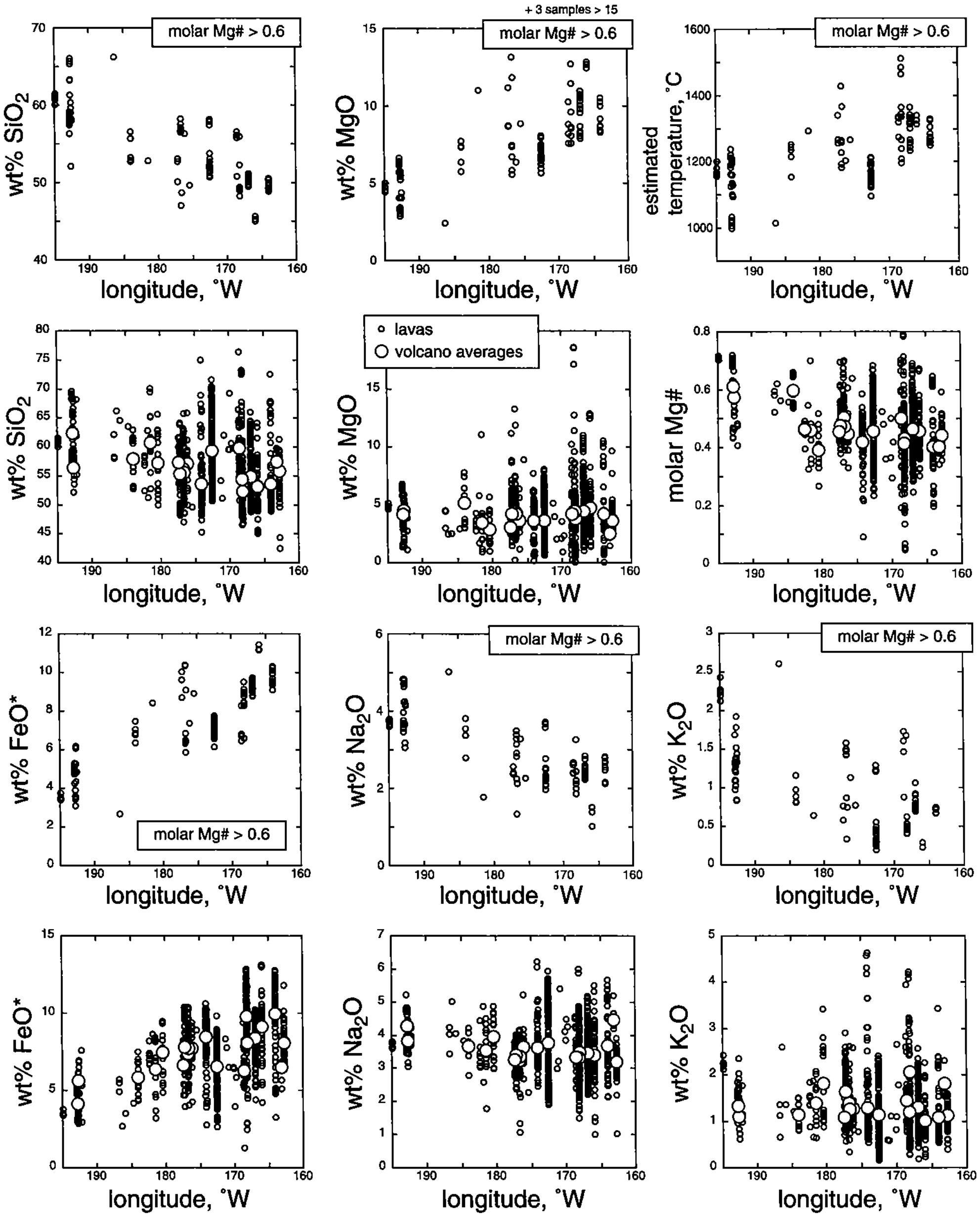


Figure 3. Major element variation and estimated magmatic temperatures (1 bar, H_2O-free) in Aleutian lavas along the strike of the arc. In this and all subsequent plots of major element oxide variation, weight percent (wt%) concentrations are normalized to 100% volatile free, with all Fe as FeO. Magmatic temperatures were calculated using the empirical olivine/liquid thermometer of [*Gaetani and Grove,* 1998], with olivine compositions estimated from liquid compositions using the olivine/liquid Fe/Mg Kd of [*Baker et al.,* 1996], assuming lava compositions are equivalent to liquids, no H_2O, pressure of 1 bar, and 80% of Fe is ferrous. Compositions of Aleutian lavas have been previously compiled by *Myers* [1988], *Kay and Kay* [1994], and *Kelemen* [1995]. More recently, compiled data have been made available by James Myers and Travis McElfrish at http://www.gg.uwyo.edu/aleutians/index.htm. The online compilation includes data from the following sources: [*Brophy,* 1986; *Myers,* 1986; *Myers,* 1985; *Morris and Hart,* 1983; *Perfit,* 1983; *Kay et al.,* 1982; *Marsh,* 1982b; *Romick,* 1982; *McCulloch and Perfit,* 1981; *Perfit et al.,* 1980a; *Kay et al.,* 1978a; *Kay,* 1977; *Perfit,* 1977; *Drewes et al.,* 1961;]. In our current compilation, these have been supplemented with additional data from: [*Class et al.,* 2000; *Yogodzinski et al.,* 1995; *Miller et al.,* 1994; *Yogodzinski et al.,* 1994; *Yogodzinski et al.,* 1993; *Tsvetkov,* 1991; *Goldstein,* 1986; *Rubenstone,* 1984; *Sun,* 1980; *Gates et al.,* 1971; *Fraser and Barrett,* 1959; *Fraser and Snyder,* 1956].

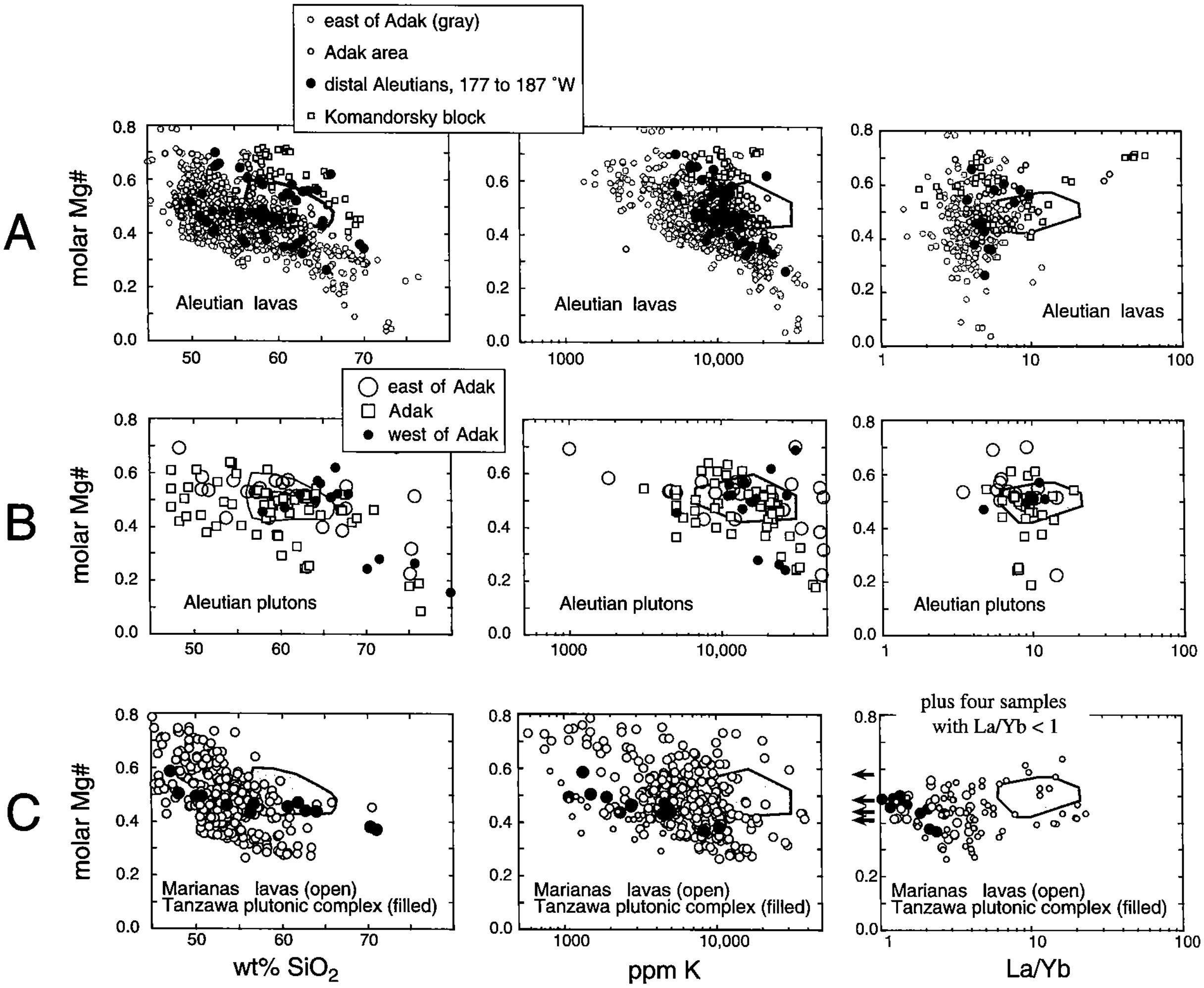


Figure 4. Compositions of Aleutian lavas (A) and plutonic rocks (B) compared to estimates of the composition of continental crust (shaded regions in each plot). Panel (C) shows compositions of lavas and plutonic rocks of the Izu-Bonin-Mariana arc system. Aleutian lavas from Adak and west of Adak, and plutonic rocks throughout the Aleutians, commonly have the SiO_2, Mg#, K, and La/Yb ratios comparable to estimates for bulk continental crust. Lavas and plutonic rocks of the Izu-Bonin-Mariana system generally do not have these characteristics. Sources of data for Aleutian lavas in caption for Figure 3. Aleutian plutonic rock data from [*Tsvetkov,* 1991; *Kay et al.,* 1990; *Romick et al.,* 1990; *Kay et al.,* 1986; *Kay et al.,* 1983; *Citron,* 1980; *Perfit et al.,* 1980b; *Gates et al.,* 1971; *Drewes et al.,* 1961; *Fraser and Barrett,* 1959; *Fraser and Snyder,* 1956], and Sue Kay, pers. comm. 2001. Estimates of continental crust composition have been recently compiled and reviewed in [*Christensen and Mooney,* 1995; *Kelemen,* 1995; *Rudnick,* 1995; *Rudnick and Fountain,* 1995]. Marianas data are from [*Elliott et al.,* 1997; *Bloomer et al.,* 1989; *Woodhead,* 1989; *Stern and Bibee,* 1984; *Wood et al.,* 1981; *Dixon and Batiza,* 1979; *Stern,* 1979]. Data on the Tanzawa plutonic complex (northern end of the Izu-Bonin Marianas arc system) are from [*Kawate and Arima,* 1998].

California, Central America, the southern Andes, the Philippines, and SW Japan [e.g., *Defant et al.,* 1991; *Defant et al.,* 1989; *Luhr et al.,* 1989; *Hughes and Taylor,* 1986; *Rogers et al.,* 1985; *Puig et al.,* 1984; *Tatsumi and Ishizaka,* 1982], these other localities are underlain by older, continental basement and/or sediment derived from continental crust. Light REE enriched, high Mg# andesite compositions are rare or absent in intraoceanic, island arcs other than the Aleutians (e.g., the Marianas, Figure 4). Also, radiogenic Pb isotope ratios in most intraoceanic arcs suggest the presence of a recycled terrigenous sediment component, whereas the western Aleutians have depleted Pb isotopes (Figure 5B). As a consequence, the western Aleutians offer the best opportunity to study the genesis of high Mg# andesites—and, by

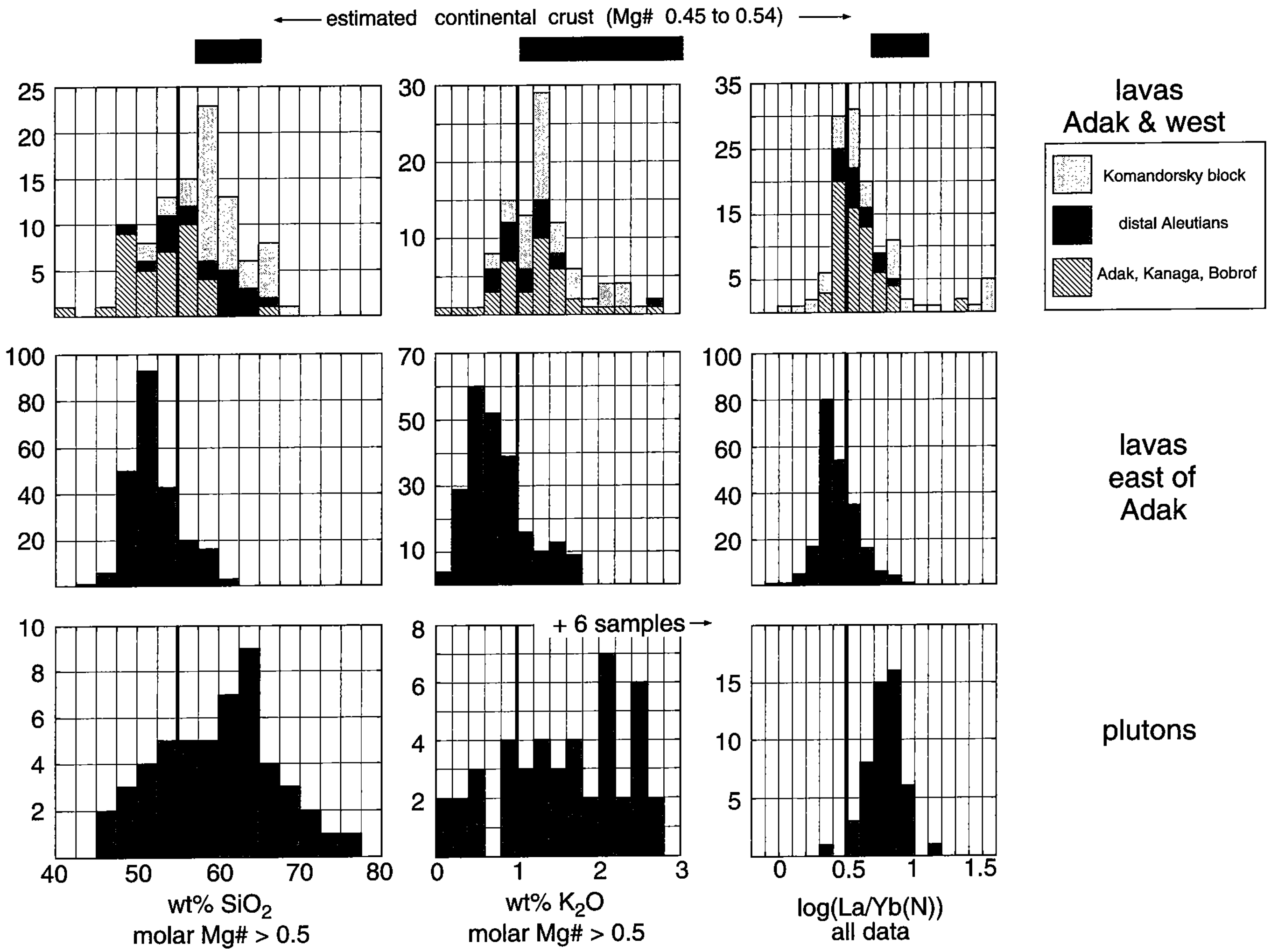
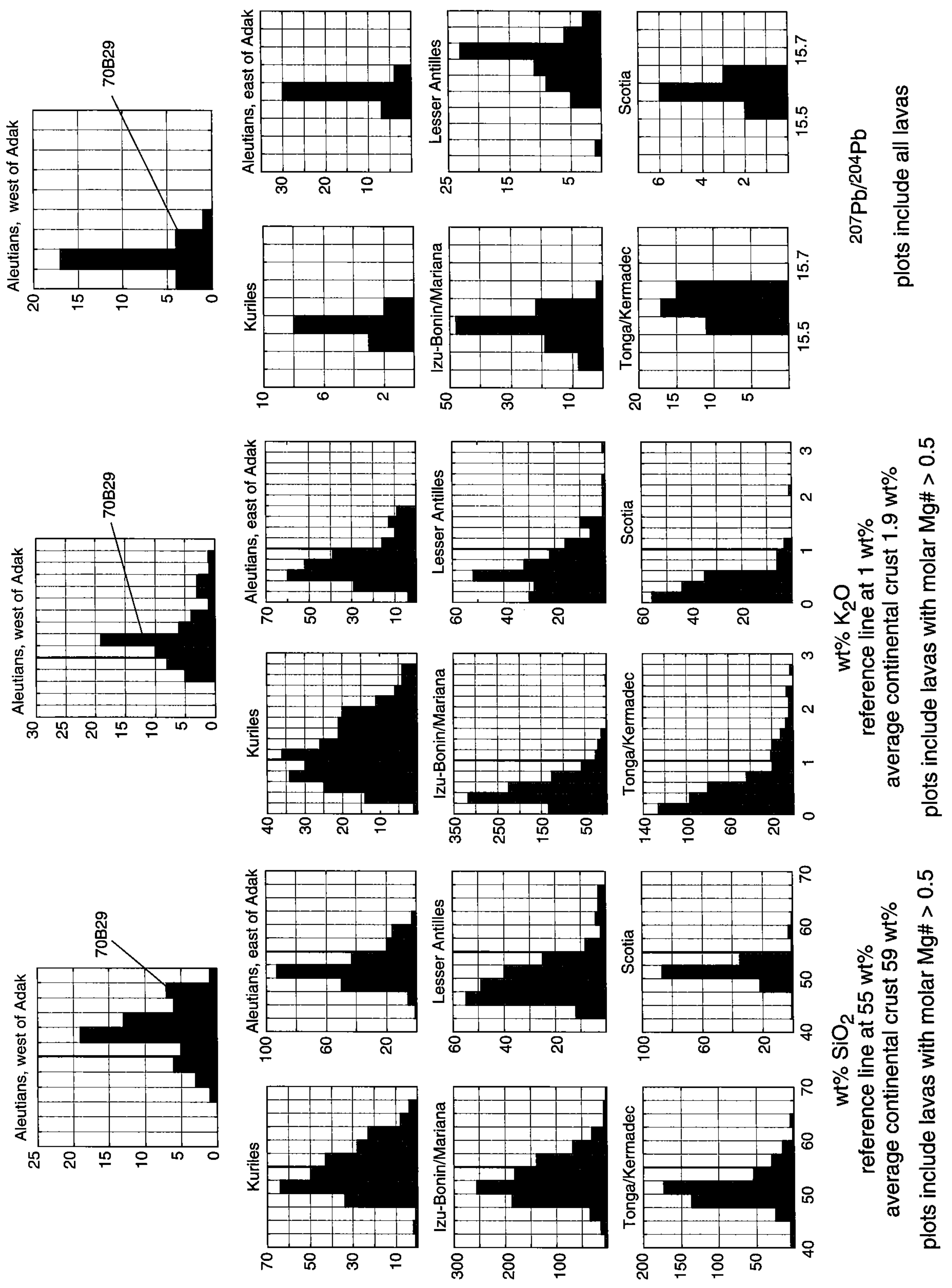


Figure 5. A. Histograms of rock compositions in the Aleutian arc. Top bars show range of estimates for the composition of continental crust. Please note that the histograms for lavas from Adak and west are cumulative, so that the maximum value for each bin refers to the sum of all samples from the Adak area + distal Aleutians + Komandorsky block. Aleutian data sources in caption for Figure 3. Range of compositions for continental crust reviewed in [*Kelemen,* 1995]. Section 1.2 and Figure 1 give definitions of regional terms. B. Histograms of wt% SiO_2, wt% K_2O, and $^{207}Pb/^{204}Pb$ in intraoceanic arc lavas. To our knowledge, the western Aleutians are unique among island arcs in having higher SiO_2 and K_2O, and lower $^{207}Pb/^{204}Pb$, in primitive magmas. Sources of Aleutian data are in caption for Figure 3. All other arc data were downloaded from the GEOROC database at Max Plank. Continental crust estimate has molar Mg# of 0.54 [*Rudnick and Fountain,* 1995]. The composition of sample 70B29, the only available dredge sample from the western Aleutians, is indicated.



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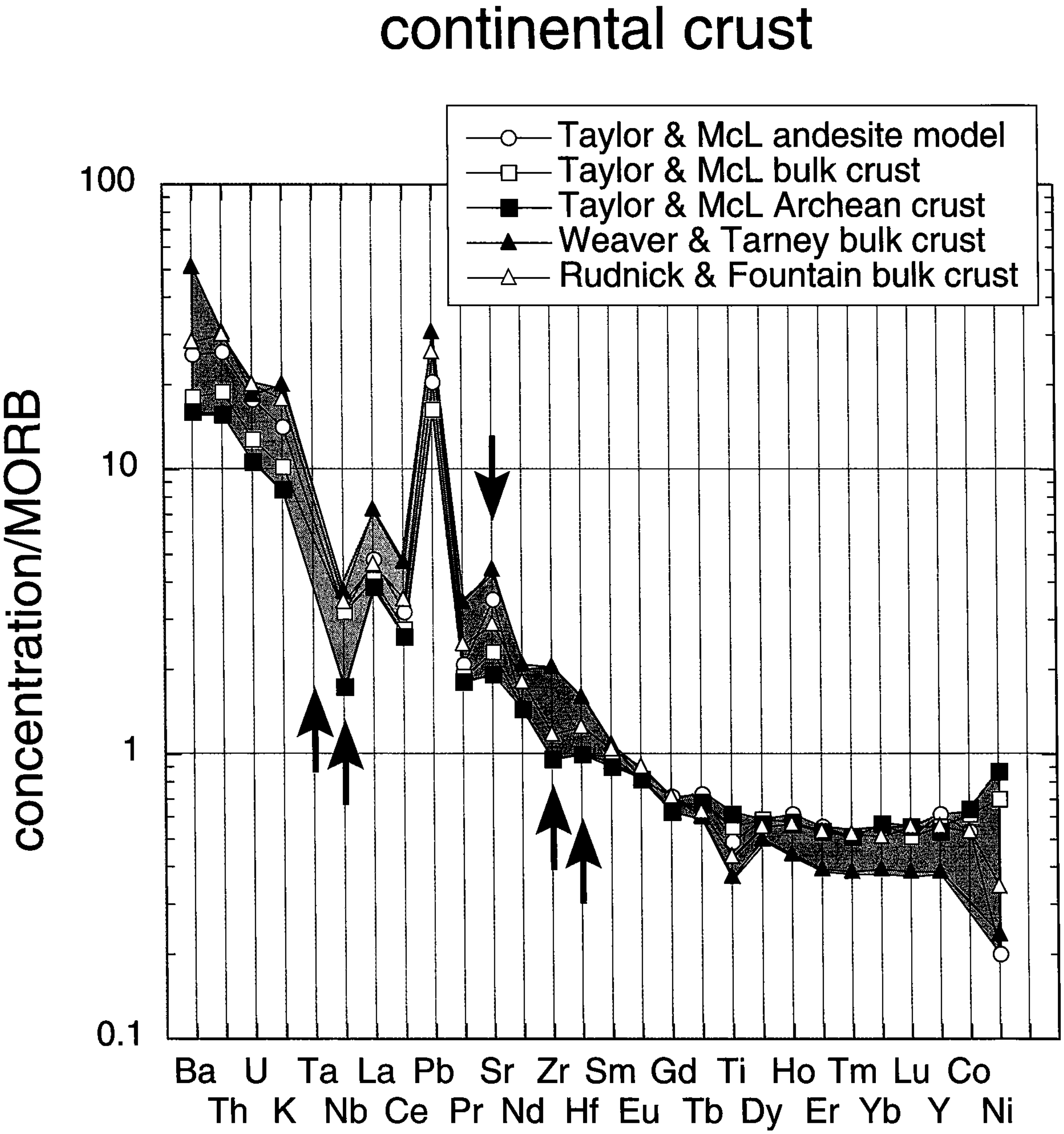
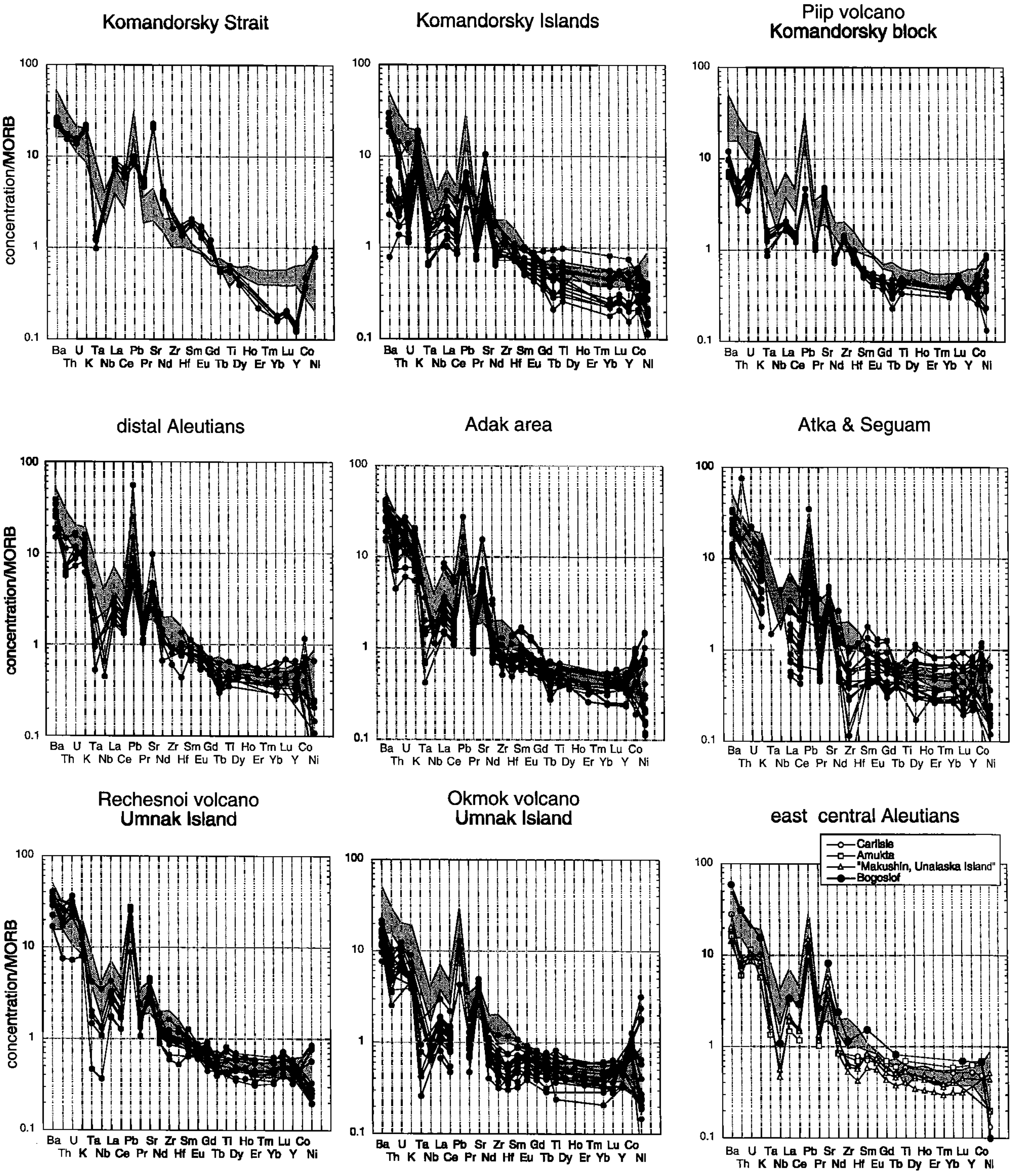


Figure 6. MORB-normalized spidergrams for estimated compositions of the continental crust (Figure 6A) and Aleutian lavas (Fig. 6b). In the Aleutian lava plots, the field of compiled estimates for the continental crust is shown in gray for reference. In plot for the Adak area, two enriched, primitive andesites with strong light REE enrichment and heavy REE depletion cross the other lava patterns. In Figure 6A, arrows emphasize elements in continental crust which may be concentrated in detrital sediments (Nb, Ta in rutile, Zr, Hf in zircon) or removed in solution during surficial weathering (Sr). In general, Aleutian magmas have higher La/Nb, La/Ta, Sm/Zr, and Sm/Hf and lower Nd/Sr than continental crust. Other than that, we feel that the similarities in trace element abundance between Aleutian lavas and continental crust is striking, and indicates that similar processes operated during formation of continental crust and Aleutian magmas. Data sources in caption for Figure 3. MORB normalization values from [*Hofmann,* 1988]. Note that *Plank and Langmuir* [1998] suggested that some estimates of Nb and Ta concentration in the continental crust [*McLennan and Taylor,* 1985; *Rudnick and Fountain,* 1995] are too high by a factor of ~ 2. However, because these estimates provide neither an upper nor a lower bound in Figure 6A, we did not modify the published values.



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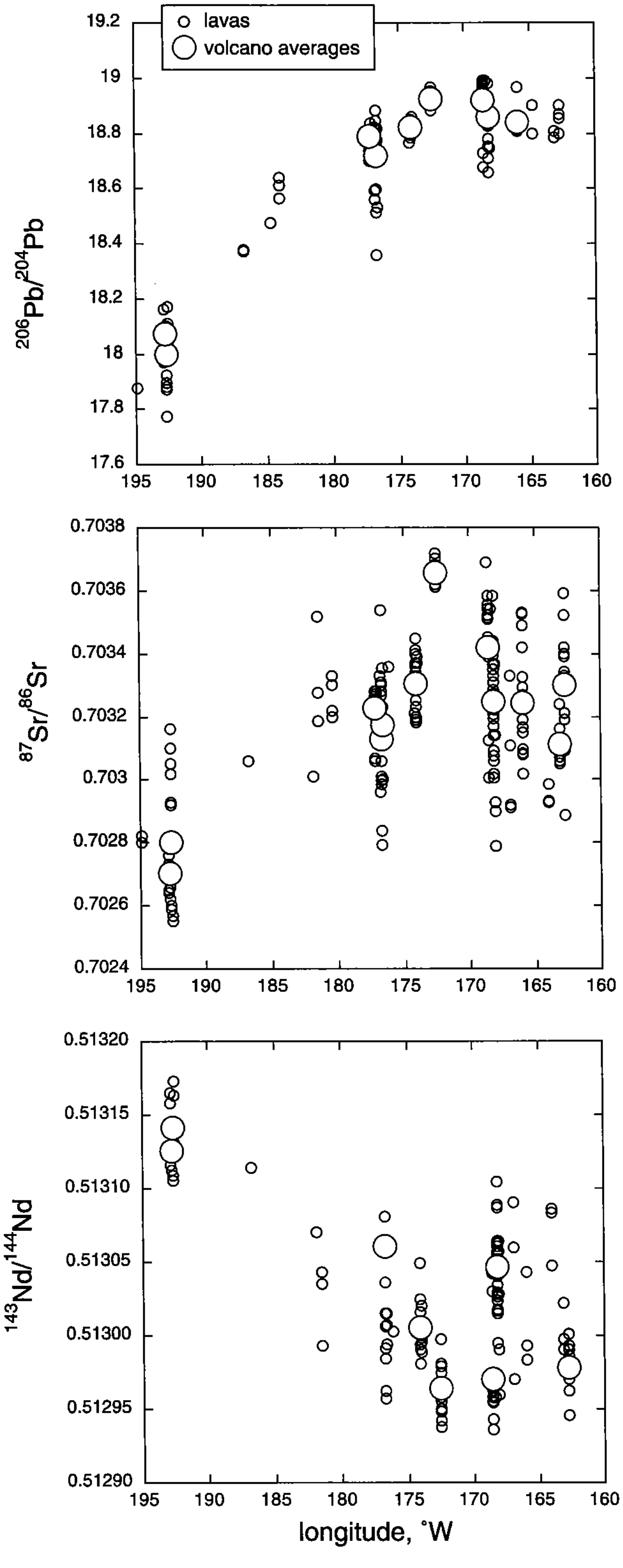

Figure 7. ^{206}Pb/^{204}Pb, ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd in Aleutian lavas versus longitude, illustrating systematic along-strike variation in these ratios. Data sources in caption for Figure 3, plus new Pb isotope data for western Aleutian lavas in Table 1.

analogy, the formation of juvenile continental crust—in a setting which is clearly free of contamination from older continental crust and sediment derived from continental crust.

Enrichment of arc lavas in some elements that are important in understanding the genesis and evolution of continental crust, such as K, U, Th, Pb and light rare earth elements (REE), is sometimes attributed to recycling of components from subducted, continentally derived sediments [e.g., *Elliott et al.,* 1997; *Hawkesworth et al.,* 1997; *Hochstaedter et al.,* 1996; *Miller et al.,* 1994; *Plank and Langmuir,* 1993]. Isotopic and geological evidence suggests that sediment input to the source of arc lavas is common in the central Aleutians, and in most arc lavas worldwide, but is absent or minimal in the west (Figures 5B and 7). Thus, if the processes that form *juvenile* continental crust in an oceanic arc can be documented anywhere on Earth, it is in the western Aleutians.

High Mg# andesites are rare in oceanic arcs worldwide. How could such lavas accumulate to form large volumes of continental crust? There are several possible answers. First, the genesis of high Mg# andesites in arcs may involve processes that were more common in the Precambrian than they are today. For example, perhaps high temperatures in subduction zones are required, and these were common in the Archean [e.g., *Martin,* 1986]. Second, formation of abundant high Mg# andesite may be related to specific events. If high subduction temperatures are required, during the Phanerozoic these may have been most common in special circumstances such as "ridge subduction" [e.g., *Rogers et al.,* 1985], in which very young, hot oceanic crust is subducted. Third, hydrous andesite magmas become much more viscous than basalts when they degas at mid-crustal pressures, and may commonly form plutonic rocks rather than erupting as lavas [*Kelemen,* 1995], as is suggested by data from the Aleutians (Figures 4B and 5A, plus [*Kay et al.,* 1990]). If so, the proportion of basaltic versus andesitic lavas is not indicative of the bulk composition of arc crust. Fourth, as suggested later in this paper, perhaps a high Mg# andesite component formed by partial melting of subducting eclogite is present in all arcs, but is difficult to detect where the flux of basaltic melts is large; in the Archean, perhaps very depleted peridotite in the mantle wedge limited formation of basaltic melts, so that the eclogite melt components comprised a larger proportion of arc magmas. These four factors, together or individually, may explain how continental crust was formed as a result of processes which are rarely evident in present-day arc lavas.

Table 1: New Pb concentrations and isotope data for Aleutian lavas.

lat (°N)	lon (°W)	location	sample	Ce ppm *	Pb ppm	^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb	^{208}Pb/^{204}Pb	data from
52.370	184.020	Buldir	BUL6B	17.2	3.02	18.565	15.486	38.028	this paper
52.370	184.020	Buldir	BUL6A	20.5	3.48	18.641	15.514	38.132	this paper
52.370	184.020	Buldir	BUL4D	22.7	2.95	18.611	15.480	38.054	this paper
52.533	184.745	dredge near Buldir	70-B29	26.6	4.31	18.477	15.484	37.941	this paper
55.455	192.832	dredge, Piip volc.	V35G5B	15.0	1.92	18.089	15.431	37.535	1
55.425	192.732	dredge, Piip volc.	V35G1A	17.2	2.32	18.098	15.430	37.520	1
55.343	192.550	Komandorsky Isl.	V35G8B	10.7	1.33	18.030	15.411	37.537	2
55.469	192.892	Komandorsky Isl.	V35G7C	14.7	2.98	18.161	15.438	37.594	2

Pb concentrations determined by isotope dilution on hand picked rock chips leached in 2.5N HCl at 80°C for 1/2 hour, dissolved and analyzed on a Finnigan MAT Element I ICPMS. Estimated precision is ± 1% relative.

Pb isotope ratios determined on powdered, hand picked rock chips leached for 1h in 6.2N HCl at 100°C analyzed on a VG 354 mass spectrometer. Estimated precision, based on standard reproducibility, is ± 0.15% relative.

All results are corrected against NBS981 (Todt et al, 1996).

*: Ce concentrations from Kay & Kay, 1994; Yogodzinski et al., 1994, 1995

1.Yogodzinski et al., 1994

2 Yogodzinski et al., 1995

1.5 Along-Strike Variation in Convergence Rate

Systematic, along-strike variation in Aleutian lava compositions may be related to along-strike variation in the rate of "down dip" convergence between the Pacific and North American plates. Because of the arcuate shape of the Aleutians, convergence is nearly orthogonal to the trench in the eastern and central arc, and strongly oblique in the west. In addition, oblique convergence leads to strain partitioning in which absolute plate motions within the western arc are intermediate between those of the North American and Pacific plates [*Avé Lallemant and Oldow,* 2000; *Geist and Scholl,* 1994; *Geist and Scholl,* 1992]. As a result, the trench orthogonal convergence velocity, which is ~ 60 to 75 mm/year beneath the arc from Adak eastward, decreases to < 40 mm/year beneath the distal Aleutians and the Komandorsky block (Figure 8). (Orthogonal convergence rates beneath the arc have been projected from values of orthogonal convergence rate versus longitude along the trench [*Fournelle et al.,* 1994] along the plate convergence vector [*Engebretson et al.,* 1985]).

In contrast to convergence rate, the age of subducting oceanic crust entering the Aleutian trench is ~ 50 to 60 Ma and does not vary systematically along-strike [*Atwater,* 1989; *Geist et al.,* 1988; *Lonsdale,* 1988; *Scholl et al.,* 1987]. According to the plate reconstructions of *Lonsdale* [1988], the dead Kula-Pacific spreading ridge (which ceased spreading at ~ 43 Ma) was subducted between 15 Myr ago at the longitude of Umnak Island (~ 168°W) and 3 Myr ago at the longitude of Attu Island (~ 187°W). During this event, the subducting crust was 28 to 40 Myr old, and at any given time it was progressively *older* to the west. For example, using Lonsdale's "simplest reconstruction" of the present down-slab position of the dead Kula-Pacific spreading ridge and a down dip convergence rate of 65-70 km/Myr, and assuming that the subducted spreading ridge had a NE-SW (not an E-W) trend when it went into the trench, we find that the minimum age of the oceanic crust consumed during subduction of the extinct ridge varied from ~ 28 Myr at 168°W to ~ 40 Myr at 187°W. Alternatively, using Lonsdale's "more plausible" reconstruction, which considers age offsets across subducted fracture zones, we find that the minimum age of the subducting crust varied from ~32 Myr at 168°W to ~ 39 Myr at 187°W.

At any particular time, the lateral gradient in average slab temperature along the ridge was not large, and in general the hottest subducting crust was in the central Aleutians. Taking the middle Miocene (~10-12 Ma), for example, when most exposed plutons were emplaced and many enriched, high Mg# andesites were erupted in the Komandorsky block, the oceanic crust entering the trench at and east of Adak (~ 177°W) was roughly 32 Myr. At the same time, west of 180°W, the thermal age of the crust entering the subduction zone was on the order of 49 Myr.

Convergence rate could affect lava composition in a variety of ways. With decreasing convergence rate, the down dip flux of subducted sediment is smaller (Figure 9). Slow convergence leads to both increased conductive cooling of the convecting mantle wedge beneath an arc and increased heating of the subducting plate [e.g., *Kincaid and Sacks,* 1997, their Figure 10]. There are many possible consequences of these thermal effects: (1) dehydration reactions in the subducting plate might occur at shallower depths

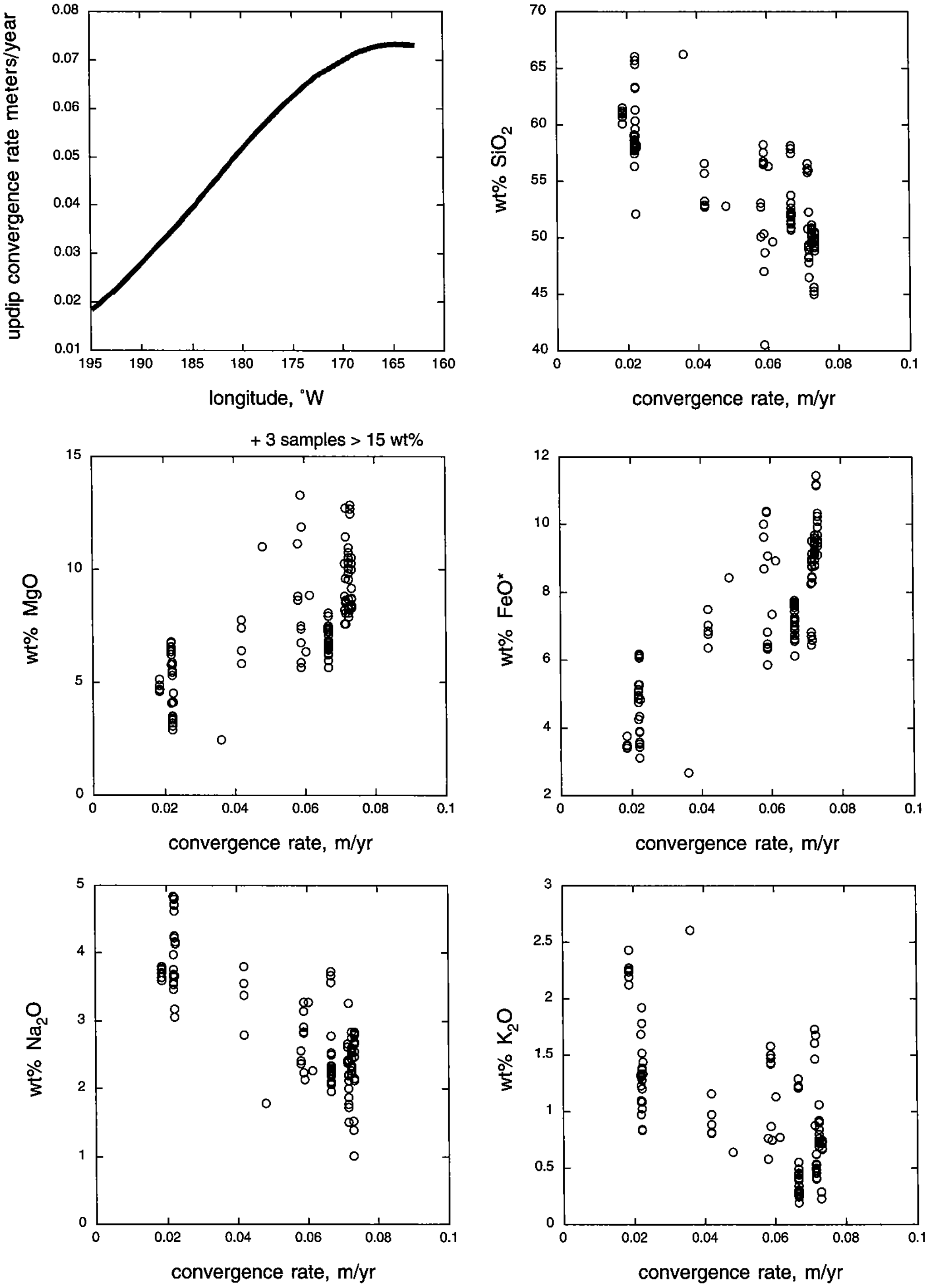

Figure 8. Some major element abundances in Aleutian lavas versus trench-orthogonal convergence rate beneath Aleutian volcanoes. Convergence rate from [*Fournelle et al.,* 1994] is plotted versus the longitude of each volcano. However, the convergence rate for each volcano is determined at a position in the trench that is updip of the volcano, projected along the plate convergence vectors shown in Figure 1 [*Engebretson et al.,* 1985]. Longitudes of positions in trench updip of each volcano were calculated using the following empirical function:

$$\text{longitude (°W)} = -393.71+5.6627*\text{volcano longitude (°W)} - 0.013863*\text{ volcano longitude (°W)}^2$$

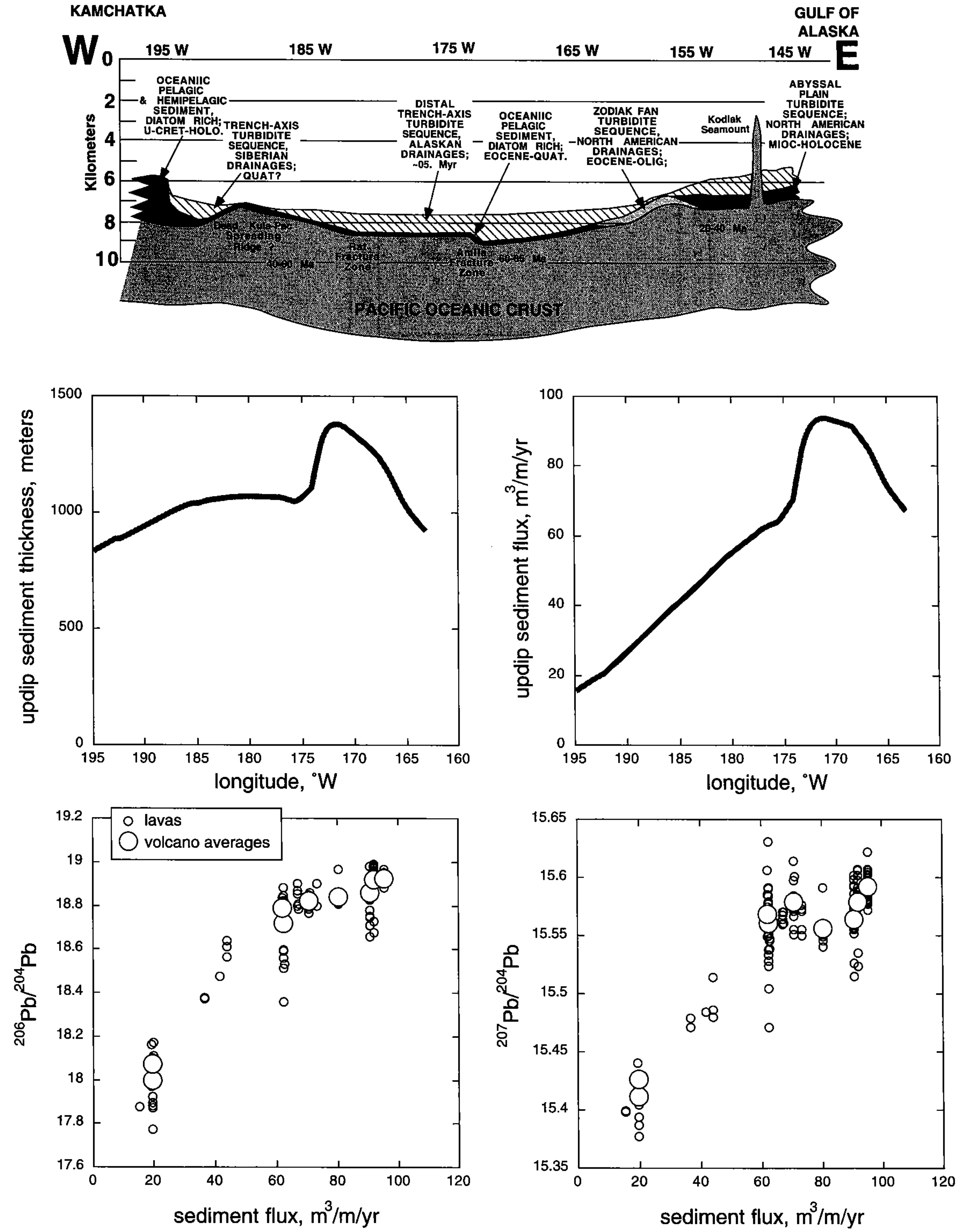

Figure 9. Geologic section along the Aleutian trench based on [*Vallier et al.,* 1994; *Ryan and Scholl,* 1989; *Scholl et al.,* 1987; *von Huene,* 1986; *McCarthy and Scholl,* 1985] and our unpublished data, sediment thickness subducted beneath Aleutian volcanoes, based on this section, sediment flux beneath Aleutian volcanoes (product of convergence rate from Figure 8 and sediment thickness), and Pb isotope ratios versus sediment flux. Sources of Pb isotope data in caption for Figure 3, and new data in Table 1.

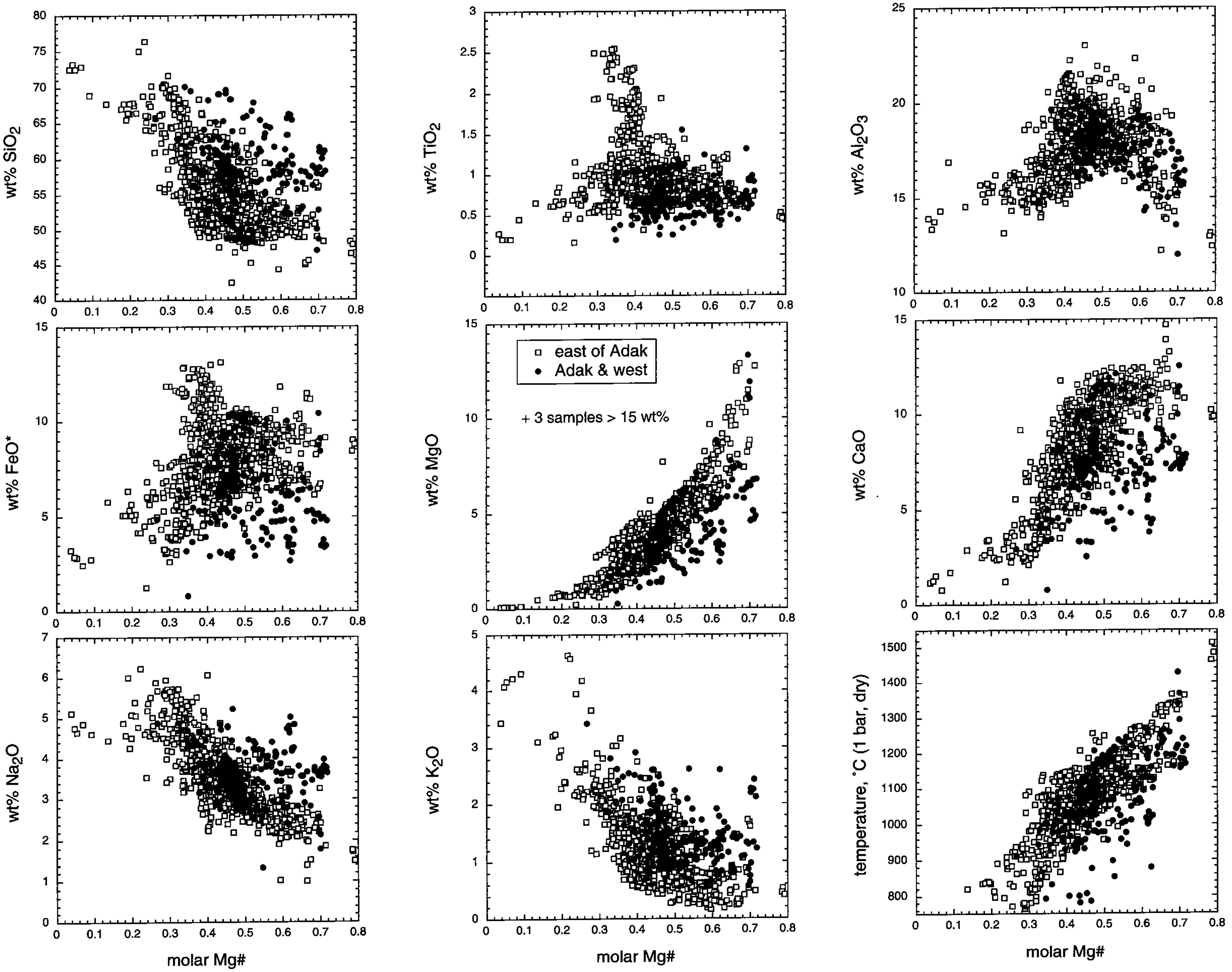

Figure 10. Variation of major element oxides versus molar Mg# in Aleutian lavas. Sources of data in caption for Figure 3.

beneath the forearc, limiting the amount of H_2O available to flux melting in the mantle wedge, (2) anatexis of subducted material might begin at shallower depths, extend to higher degrees of melting, and/or become more common or extensive, (3) there might be a lower extent of melting in the colder mantle, and (4) cooling of the shallow mantle and lower crust could lead to crystal fractionation at higher pressure, perhaps within the shallow mantle below the seismic Moho. Assuming that volcanic output is proportional to the magmatic flux through the Moho, it seems evident that some combination of (1), (3) and (4) limits the overall magma flux from the mantle to the crust in the western Aleutians. With the exception of Tanaga volcano, none of the emergent volcanoes in the western Aleutians are as large as the twenty largest volcanoes in the central Aleutians [Fournelle et al., 1994].

1.6 Along-Strike Variation in Sediment Thickness and Composition

Variation in Aleutian lava compositions might be related to the composition and volume of subducted sediment. Based on geophysical data, moderate size (20-40 km wide and as much as 6 km thick) prisms of tectonically accreted trench floor sediment form the lower part of the landward side of the Aleutian trench from 164 to 185°W. West of about 185°W, the wedge seems to rapidly dwindle in size and opposite Attu (188°W), the prism is quite small, perhaps just a few km wide and thick. Geophysical imaging, DSDP drilling, and rock dredging, imply that the mass of the modern accretionary prism began to form in latest Miocene time, i.e., 5-6 Myr ago [*Vallier et al.,* 1994; *Ryan and Scholl,* 1989; *Scholl et al.,* 1987; *von Huene,* 1986; *McCarthy and Scholl,* 1985].

Mass balance calculations imply that, during the past 5 Myr or so, no more than 20 percent of the volume of trench-floor sediment swept into the Aleutian subduction zone has contributed to the mass of the accretionary prism [*von Huene and Scholl,* 1991]. Based on more recent geophysical and drilling data, compiled during the past decade, it is now supposed that no more than 15 percent of the mass of ocean floor sediment that enters the Aleutian subduction zone is retained in an accretionary prism [*Scholl and Huene,* 1998].

Thus, it is possible to approximate the flux of sediment beneath a given part of the arc as the product of the trench-orthogonal convergence rate (Section 1.5), and the thickness of sediment in the trench. Figure 9 illustrates the thickness and inferred composition of sediments in the Aleutian trench, based on [*Vallier et al.,* 1994; *Ryan and Scholl,* 1989; *Scholl et al.,* 1987; *von Huene,* 1986; *McCarthy and Scholl,* 1985] and our unpublished data.

About half of the sediment derived from erosion of the Aleutian arc itself is shed southward toward the Aleutian Trench, with the other half accumulating in the Bering Sea. Very little of this material appears to make its way to the trench floor because the bulk of the sediment pools in the fore arc, which is underlain by a trough of arc-derived detritus, ash debris, and pelagic (mainly diatoms) sediment as thick as 3- 4 km. This fore arc basin runs along virtually the entire length of the Aleutian island arc.

In general, sediments in the trench are comprised largely of turbidites composed of sediments shed off the Alaska Range and older sediments derived from the Chugach, Wrangell, and St Elias Mountains. The trench axis slopes westward continuously to about 180°W. Sediments thicken gradually from east to west between 160 and ~172°W. West of 172°W, they thin gradually from east to west, and then more abruptly from about 1 km thick at ~182°W where the Rat Fracture Zone intersects the trench to just a few hundred meters at ~ 190°W. Even further west they thicken again as a result of turbidite sedimentation from Kamchatka. The thinning of the sedimentary section in the Aleutian trench from 182°W to 190°W is accompanied by an increasing proportion of pelagic to continentally-derived sediments.

The major variations in the thickness and relative proportions of different sediment types occur west of 182°W. Because the convergence vector is strongly oblique in the western Aleutians, any sediments beneath, e.g., Buldir volcano in the distal Aleutians (184°W) would have entered the trench at a longitude of ~ 179°W. Sediments overlying the Pacific - North America plate boundary west of ~184°W may not be subducted at all. Thus, there is little systematic, along-strike variation in the thickness or composition of sediment being subducted beneath the central and western Aleutian arc. If these estimates are correct, the main control on sediment flux beneath the Aleutian arc is the trench-orthogonal convergence rate.

2. ALONG-STRIKE VARIATION IN LAVA COMPOSITION

In this part of the paper, we emphasize systematic east-to-west trends in lava composition. Previous studies of along-strike variation in the Aleutians have not emphasized systematic trends along the entire arc. Instead, spatial variation in lava composition has been attributed to (1) varying stress regimes within a series of tectonic blocks along the arc [e.g., *Kay and Kay,* 1994; *Singer and Myers,* 1990; *Kay et al.,* 1982], or (2) the availability of volatiles and fluid associated with subduction of thick sedimentary sections deposited over ancient oceanic fracture zones [e.g., *Miller et al.,* 1992; *Singer et al.,* 1992a; *Singer et al.,* 1992b; *Singer et al.,* 1992c]. In keeping with (2), it has long been noted that some of the largest Aleutian volcanic centers overlie subducted oceanic fracture zones [*Kay et al.,* 1982; *Marsh,* 1982a].

An exception is the observation of *Fournelle et al.* [1994] that, in general, the size of Aleutian volcanoes decreases from east to west, which they ascribed to decreasing subduction rate and magma flux from east to west. Myers and co-workers noted that calc-alkaline lavas tend to be erupted from smaller volcanic centers, whereas tholeiitic lavas predominate at larger centers [*Myers,* 1988; *Myers and Marsh,* 1987; *Myers et al.,* 1986a; *Myers et al.,* 1986b; *Myers et al.,* 1985].

2.1 Along-Strike Variation in Mg# and MgO

Figure 3 illustrates along-strike variation in major element composition of lavas in the Aleutians. Prior to discussing these results, we would like to reiterate an important caveat. Lavas from the Komandorsky block form an important end-member in most of the trends apparent in Figure 3. If the Komandorsky data were omitted, the apparent correlations of major element composition with longitude would be much weaker. The Komandorsky block is tectonically anomalous, as described in Section 1.2, and it is reasonable to question whether processes there are related to magma genesis in the tectonically "normal" parts of the western and central Aleutians. We believe that a compositional continuum is evident in Figure 3, from the Komandorsky block through the distal Aleutians to the Adak area and the central Aleutians. A continuum is also evident in similar plots of isotope ratios as a function of distance along the arc, discussed later in this paper. As a result of this interpretation, we believe that the Komandorsky lavas are genetically related to the rest of the arc, and form an important compositional end-member that is present in gradually diminishing proportions to the east. This is important to our interpretation of magma genesis in the Aleutian arc. Thus, we wish to remind readers that the apparent compositional continuum is dependent on a limited number of samples from the distal Aleutians (Figure 2), which have compositions intermediate between the Komandorsky samples and lavas further to the east. Because it is relatively unknown but very important, we hope that the distal Aleutians will be an area of intensive sampling in the future.

With this caveat, we turn to Figure 3. Although the data show considerable scatter, due mainly to crystal fractionation, the average Mg# for volcanic centers apparently increases from east to west. In the western Aleutians, where samples are few, most of them are primitive. This is fortunate, because we rely heavily on the composition of primitive lavas to infer the nature of mantle-derived melts in the Aleutians. (Note that primitive lavas can be affected by magma mixing and assimilation processes, which—if ignored—could lead to erroneous conclusions concerning primary magma compositions; such effects are discussed in Section 4.2 of this paper).

MgO contents in primitive Aleutian lavas decrease from east to west. Primitive magmas in the Aleutians have a variety of MgO contents, ranging from 4 to 18 wt%, and most of this variation is not due to crystal fractionation. As a result, it is inappropriate to constrain the nature of Aleutian primary magmas by comparing concentrations of incompatible elements, such as Na, K or various trace elements, in lavas with a given MgO content. One could, instead, correct incompatible element concentrations for the effects of fractionation by extrapolating to a given Mg#. However, because the slopes of variation trends for, e.g., Na_2O and K_2O versus Mg# vary from one volcanic center to another in the Aleutians, comparisons of fractionation-corrected compositions of lavas with Mg# < 0.6 are fraught with peril. For this reason, we have chosen to concentrate on comparing uncorrected, incompatible element concentrations in primitive lavas with Mg# > 0.6.

The MgO content of mantle-derived magmas depends strongly on temperature. For example, many workers have developed geothermometers which depend on equilibrium Mg partitioning between olivine and liquid [e.g., *Gaetani and Grove,* 1998; *Roeder and Emslie,* 1970, and references cited therein]. For the most recent of these [*Gaetani and Grove,* 1998], we can use an olivine/liquid Fe/Mg Kd = 0.35 - 0.013 (mol% $Na_2O + K_2O$), based on the data of [*Baker et al.,* 1996], and the assumption that 80% of all Fe is ferrous to estimate equilibrium olivine compositions for primitive Aleutian lavas, and then derive a temperature estimate.

Based on the assumptions outlined in the previous paragraph, estimated temperatures of equilibration between olivine and primitive lavas at 1 bar vary from ~ 1500°C for three picritic lavas with 16 to 18 wt% MgO[1], or ~ 1350°C for more common basalts with ~ 10 wt% MgO, to 1000°C for lavas with 4 wt% MgO. Because Fe^3/Fe^2 and water contents for Aleutian melts prior to possible crustal degassing, crystallization and eruption are not yet known, it is not possible to quantify magmatic temperatures more accurately. Probably, the low MgO, high $Na_2O + K_2O$, andesite lavas in the western Aleutians also include abundant H_2O, whereas the primitive basalts in the eastern Aleutians have much less

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[1] *Nye and Reid* [1986] argued that these high MgO lavas do, in fact, represent liquid compositions even though they include olivine phenocrysts.

H_2O. If so, then the total variation in Aleutian primitive magma temperatures is on the order of 300°C or more. Well-studied volcanic centers in the Aleutians exhibit a ~ 200°C range of estimated temperatures for primitive lavas which is not correlated with Mg# and therefore appears to be a primary feature rather than the result of crystal fractionation. This variability makes it difficult to be sure, but in general there seems to be a systematic, along-strike variation in magmatic temperature. For example, the maximum estimated temperature varies from ~1350°C (or even 1500°C) in the central Aleutians to ~1200°C in the western Aleutians.

2.2 Along-Strike Variation in Silica and Alkali Contents

Figure 3 illustrates along-strike variation in SiO_2, FeO, CaO, Na_2O, and K_2O. SiO_2 and Na_2O show a systematic increase from east to west. There may be a similar trend for K_2O, but it is less clear. CaO, FeO and molar Ca/Al (not shown) show a systematic decrease from east to west. These trends are clearer if lava compositions are plotted versus trench-orthogonal convergence rate (Figure 8). This is because the central Aleutians show relatively little variation in both lava composition and convergence rate, and plot as a group when convergence rate rather than longitude is considered. TiO_2 and Al_2O_3 show no clear correlation with longitude or convergence rate, and we believe this is important though we have omitted both oxides from Figure 3 to save space.

Plots of major element oxides versus Mg# for Aleutian lavas (Figure 10) can be used to evaluate the amount of variation which can be produced by crystal fractionation from a parent with an Mg# of, e.g., 0.7 to produce a derivative liquid with an Mg# of 0.6. It is clear from these plots that the east-to-west variation in Aleutian lava compositions is not the result of systematically increasing degrees of crystal fractionation from east to west.

The high alkali contents of primitive lavas in the western Aleutians probably arise as a result of either (a) small degrees of partial melting of the mantle, (b) variation in mantle source composition, possibly including a component derived from subducted metabasalt and/or metasediment, (c) combined crystal fractionation and melt/rock reaction in the shallow mantle, or (d) mixing of relatively alkali-poor, primitive basalt and alkali-rich, evolved dacites or rhyolites. These possibilities will be discussed further in Section 4. However, we note here that the lack of systematic variation in TiO_2 and Al_2O_3 in primitive lavas along strike suggests that the variation of alkali element concentrations cannot be explained as the result of different degrees of melting of a common source composition, or different degrees of crystal fractionation from a common parental magma (i.e., a variety of primitive magma types are required).

High alkali and H_2O contents could explain the high SiO_2 contents in primitive lavas in the western Aleutians. Increases in Na, K and H contents increase the size of the olivine primary phase volume, thereby increasing the SiO_2 contents of magmas that can be in equilibrium with mantle olivine [*Hirschmann et al.,* 1998; *Ryerson,* 1985; *Kushiro,* 1975]. Like continental crust, Aleutian high Mg# andesites are quartz normative. After decades of debate, it remains controversial whether quartz-normative andesites can be formed by partial melting of mantle peridotites [*Hirose,* 1997; *Baker et al.,* 1996; *Falloon et al.,* 1996; *Kushiro,* 1990; *Mysen et al.,* 1974]. However, in our opinion, experimental data [*Baker et al.,* 1994; *Tatsumi and Ishizaka,* 1982] illustrate that quartz-normative, high Mg# andesites similar to those in the western Aleutians can *equilibrate* with mantle peridotite, provided they have sufficiently high H_2O contents. In Section 4, we discuss whether such liquids could have formed by small degrees of melting of mantle peridotite, or whether their high alkali contents arise via reaction of partial melts of subducted metabasalt and/or metasediment with mantle peridotite.

2.3 Along-Strike Variation in Heavy, Radiogenic Isotope Ratios

There are systematic along-strike variations in Pb, Nd and Sr isotope ratios in Aleutian lavas. $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ all decrease from east to west, whereas $^{143}Nd/^{144}Nd$ increases from east to west (Figure 7), as previously documented [e.g., *Yogodzinski et al.,* 1995]. Again, the apparent strength of the correlations between isotope ratios and longitude depends heavily on data from the Komandorsky block and the western Aleutians.

In the central Aleutians, high Pb isotope ratios have been ascribed to recycling of Pb from subducted sediments into Aleutian lavas [e.g., *Class et al.,* 2000; *Kay and Kay,* 1994; *Miller et al.,* 1994; *Singer et al.,* 1992a; *Myers and Marsh,* 1987; *Kay et al.,* 1978b, and references therein]. Indeed, very high Pb isotope ratios ($^{207}Pb/^{204}Pb$ ~ 19.2) were reported for voluminous, terrigenous sediments recovered in DSDP Site 183 at 52.57°N, 161.20°W, SE of the eastern Aleutians [*Miller et al.,* 1994]. However, pelagic and metalliferous sediments from just above the basaltic basement in Site 183 have Pb isotope ratios more similar to mid-ocean ridge basalts (MORB) [*Peucker-Ehrenbrink et al.,* 1994]. In fact, some metalliferous sediments from elsewhere in the Pacific have Pb isotope characteristics indistinguishable from MORB. Metalliferous sediments are not abundant compared to continentally derived turbidites in DSDP Site 183, but they have high Pb concentrations, and the relative abundance of pelagic sediment to terrigenous turbidites on the subducting Pacific oceanic crust may increase westward. Thus, without further evaluation, Pb isotope ratios alone cannot be used as an unambiguous tracer for a recycled sediment component in Aleutian lavas.

Pb isotope ratios in Aleutian lavas are positively correlated with $^{87}Sr/^{86}Sr$ and negatively correlated with $^{143}Nd/^{144}Nd$ (Figure 11). In contrast, pelagic and metalliferous sediments have high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$. Like Pb, Sr is likely to be mobilized in both aqueous fluids and melts derived from subducted sediment. Thus, the positive correlation of Pb and Sr isotope ratios in Aleutian lavas suggests that only the Aleutian lavas with high Pb isotope ratios include a substantial, recycled sediment component. Otherwise, we should observe high $^{87}Sr/^{86}Sr$ in lavas that include unradiogenic Pb from pelagic or metalliferous sediments. In support of this, Figure 9 shows that $^{207}Pb/^{204}Pb$ in Aleutian lavas is correlated with trench-orthogonal sediment flux (the product of sediment thickness and trench-orthogonal convergence rate).

The unusually low Pb and Sr isotope ratios in lavas from the Komandorsky block deserve special mention. A few samples of MORB from the North Pacific have similarly low values, but they are rare. It would be of great interest to obtain samples of lavas formed at the extinct Kula-Pacific spreading ridge to see if such depleted MORBs were common along that ridge, particularly near its western end.

2.4 Along-Strike Variation in Proposed Indicators of a Sediment Melt Component

As a result of the along-strike variation in trench-orthogonal sediment flux (Section 1.6 and Figure 9), and the related variation in radiogenic isotope ratios in lavas (Section 2.3 and Figure 7), the Aleutian arc represents an ideal testing ground for proposed relationships between the flux of trace elements in subducted sediment and their concentration in arc lavas. For example, *Plank and Langmuir* [1993] demonstrated that there is a worldwide correlation between the flux of subducted K and Th, and the concentration of these elements in primitive arc lavas. Similarly, *Elliott et al.* [1997] hypothesized that a vector toward high La/Sm, Th/Nb, low Ba/La in lavas from the Marianas arc represented addition of a component derived from partial melting of subducted sediment. They contrasted this with a vector toward high Ba/La in Marianas lavas, which they inferred was due to addition of an aqueous fluid derived by dehydration of subducted basalt. And, *Turner et al.* [1996] and *Hawkesworth et al.* [1997] found a correlation between Th/Ce (nearly equivalent to Th/La) and isotopic indicators of a recycled sediment component in lavas from the Lesser Antilles. Noting that Th is relatively immobile in aqueous fluid/solid equilibria, compared to silicate melt/solid equilibria, all of these groups suggested that the Th-enriched, sediment component must be a partial melt of subducted sediment, in the Marianas [*Elliott et al.,* 1997], the Lesser Antilles [*Hawkesworth et al.,* 1997; *Turner et al.,* 1996], and worldwide [*Plank and Langmuir,* 1993].

Figure 12 shows the variation in La and Th in primitive lavas, and La/Sm, Th/La, Th/Nb, and Ba/La in all lavas along the strike of the Aleutian arc. Note that variation in K along strike, in primitive lavas and all lavas, is shown in Figure 3. With the exception of Ba/La and Th/La, none of these variables show systematic variation along the arc, and in fact K may be highest in the west where the sediment component is minimal or absent. Th/La is correlated with Pb isotope ratios in Aleutian lavas (Figure 13), so it probably is a good proxy for the presence of recycled sediment, as proposed by *Hawkesworth et al.* [1997].

2.5 Evaluation of Proposed Indicators of a Fluid Component From Subducted Material

2.5.1 Barium/Lanthanum. As noted in the previous section, *Elliott et al.* [1997] and many other workers have proposed that Ba is mobile in aqueous fluids, whereas La, Nb and Ta are relatively immobile, so that Ba concentration in primitive lavas, and Ba/La, Ba/Nb and Ba/Ta in more evolved lavas, can be used to detect the presence of an aqueous fluid component derived from dehydration of subducted oceanic crust and/or sediments. Except for Ba/La (Figure 12), we see no systematic variation of these factors along the Aleutian arc (Figure 14).

Interestingly, as previously noted [*Kay and Kay,* 1994; *Yogodzinski et al.,* 1994; *Kay,* 1980], Ba/La is positively correlated with Th/La and Pb isotope ratios in Aleutian lavas (Figure 13). Aleutian lavas with high Th/La have high $^{207}Pb/^{204}Pb$ (derived from sediment) and high Ba/La. Recycling of Pb and other components in the Aleutians cannot be clearly separated into a Ba-rich fluid component and a Th-rich sediment melt, perhaps because Ba/La is very high in Aleutian sediments [Plank, pers. comm., 2001; Turner et al., pers. comm. 2001] In this way, the pattern of Ba/La variation is strikingly different from many other intraoceanic arcs worldwide [e.g., *Elliott et al., this volume*]. The relatively high solubility of Ba and Pb in aqueous fluids, compared to relatively insoluble Th, is well-documented [e.g., *Johnson and Plank,* 1999; *Ayers,* 1998; *Ayers et al.,* 1997;

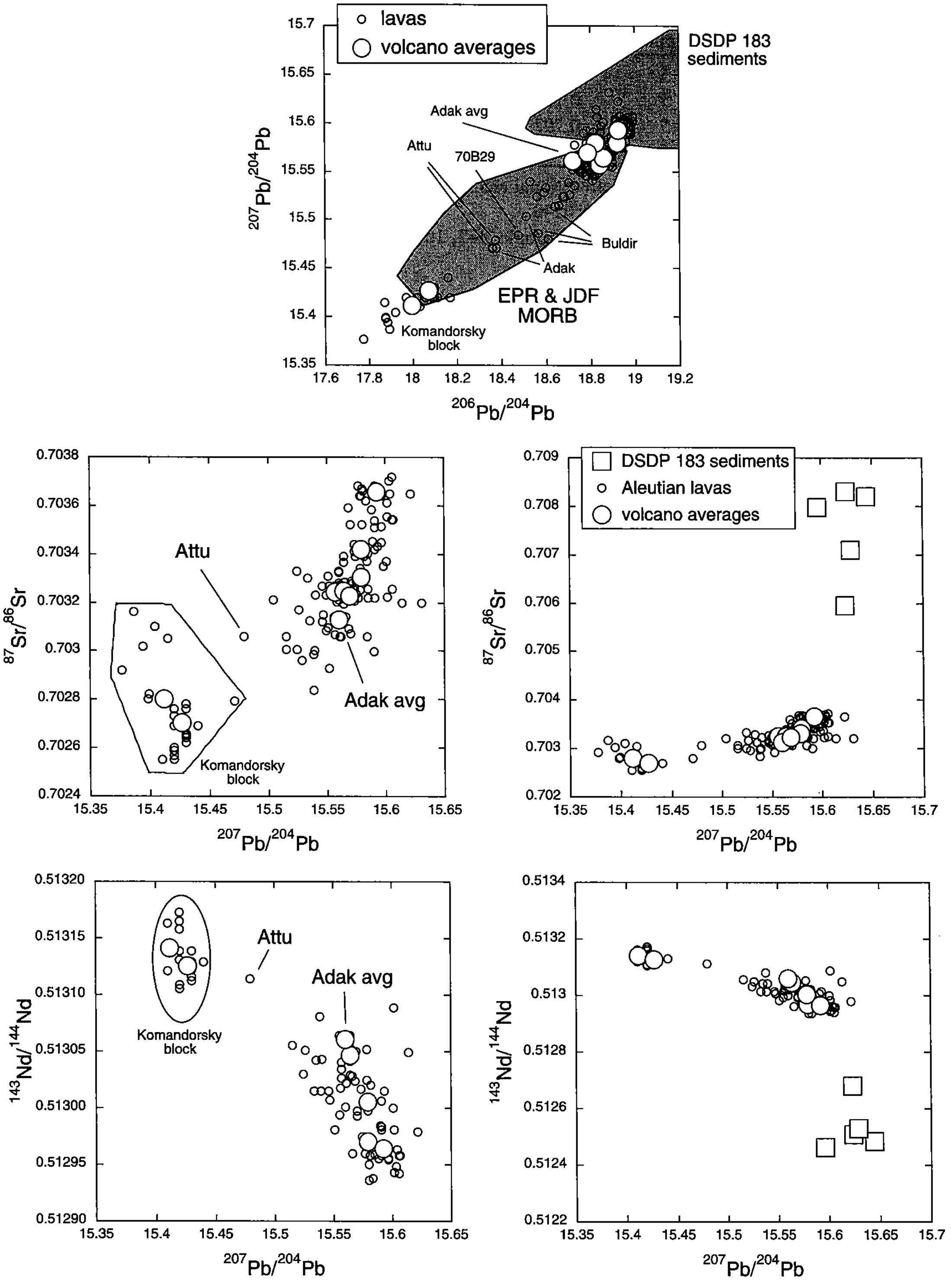

Figure 11. Isotope variation in Aleutian lavas and in sediments from DSDP Site 183 (52.57°N, 161.20°W) southeast of the Aleutian trench. Sources of data in caption for Figure 3, [*Plank and Langmuir,* 1998; *Peucker-Ehrenbrink et al.,* 1994; *von Drach et al.,* 1986], new Pb isotope data for western Aleutian lavas in Table 1, and new Sr and Nd isotope data for DSDP Site 183 sediments in Table 2.

Table 2: New Sr and Nd isotope ratios for DSDP Hole 183 sediments

sample	$^{143}Nd/^{144}Nd$	± ppm	$^{87}Sr/^{86}Sr$	± ppm	$^{206}Pb/^{204}Pb$*	$^{207}Pb/^{204}Pb$*	$^{208}Pb/^{204}Pb$*
38-3, 20-21	0.512485	5	0.708201	7	19.093	15.645	38.814
39-1, 83-84	0.512510	5	0.708309	8	18.934	15.624	38.734
39-1, 108-109	0.512462	5	0.707979	7	18.546	15.596	38.546
39-1, 108-109	0.512416	6	0.707850	7			

Sr and Nd isotopic analysis were carried out with conventional techniques (Hauri and Hart, 1993). All results are corrected against LaJolla std$^{143}Nd/^{144}Nd=0.511847$ and NBS987=$^{87}Sr/^{86}Sr=0.710240$.

*: Pb isotope data from Peucker-Ehrenbrink et al., 1994. Sample 39-1, 108-109 is a carbonate sample without Pb data

Brenan et al., 1996; *Brenan et al.,* 1995a; *Brenan et al.,* 1995b]. In contrast, Ba, Pb and Th all behave incompatibly during melting. Thus, the correlation of Ba, Pb and Th concentrations in Aleutian lavas suggests that transport of all these elements from subducted crust into the mantle wedge is mainly via a silicate melt, not an aqueous fluid.

2.5.2 Strontium/Neodymium. Virtually all primitive lavas in the Aleutians have superchondritic Sr/Nd ratios, and this ratio shows no systematic variation along-strike. Elevated Sr/Nd ratios (> 17; [*Anders and Grevesse,* 1989]), could be indicative of Sr addition to the arc magma source via an aqueous fluid, because experimental data indicate that Sr is more soluble in high P, high T aqueous fluids than the REE [*Johnson and Plank,* 1999; *Ayers,* 1998; *Stalder et al.,* 1998; *Ayers et al.,* 1997; *Kogiso et al.,* 1997; *Brenan et al.,* 1996; *Brenan et al.,* 1995a; *Brenan et al.,* 1995b; *Tatsumi et al.,* 1986]. Sr/Nd in primitive Aleutian lavas is not correlated with Ba/La, as might be expected if enrichments of Sr, Ba and Pb were all the result of aqueous fluid addition to the arc source[2]. Alternatively, superchondritic Sr/Nd could indicate the presence of a component derived from cumulate gabbro in subducted, oceanic lower crust, since plagioclase-rich cumulates are enriched in Sr relative to the REE. And finally, trace element modeling (Section 4) shows that partial melts of mid-ocean ridge basalt in eclogite facies may have super-chondritic Sr/Nd. Thus, we simply note that the explanation for elevated Sr/Nd in the Aleutians is uncertain.

2.5.3 Cerium/Lead. Miller et al. [1994] argued that unradiogenic Pb in the source of Aleutian arc magmas was transported from subducted basalts into the mantle wedge in an aqueous fluid. They suggested that Pb is relatively mobile in aqueous fluids, while Ce is relatively immobile, so that Ce/Pb can be used to distinguish between (a) Pb transported in aqueous fluids with low Ce/Pb, and (b) Pb in partial melts of the Aleutian mantle and/or subducted MORB with Ce/Pb greater than 10. This hypothesis is supported by more recent experimental data on fluid/rock partitioning [*Brenan et al.,* 1995a]. Sediments have low Ce/Pb, so Miller et al. could not use Ce/Pb to distinguish between melt and fluid transport of a sediment Pb component in Umnak lava with radiogenic Pb isotopes. However, since Ce/Pb is low (less than ~ 4) in all lavas from Umnak Island, regardless of their Pb isotope ratios, Miller et al. concluded that the unradiogenic, MORB-like Pb isotope ratios in some Umnak lavas were due to transport of Pb in aqueous fluids derived from subducted basalt. This led to the much repeated aphorism, "sediments melt, basalts dehydrate". On this basis, one could infer that Ce/Pb should be low in all Aleutian lavas, especially those with unradiogenic Pb isotope ratios.

Complicating this picture are the trace element models of possible igneous processes beneath arcs, in Section 4. They show that Ce may be fractionated from Pb during partial melting of eclogite, and during reaction of melts with mantle peridotite, producing a range of possible Ce/Pb ratios in melts even where the source Ce/Pb is constant. The resulting Ce/Pb can be greater than or substantially less than in the original source of melting.

In Aleutian data, Ce/Pb shows a weak, negative correlation with Pb isotope ratios, and shows systematic variation along-strike (Figure 15). All of the data discussed in this paragraph are for lavas whose Pb isotope ratios are known, and whose Pb concentration has been determined by isotope dilution. Ce/Pb is greater than 4 and ranges up to ~ 18 for all Aleutian lavas with $^{207}Pb/^{204}Pb$ less than 15.5, all of which are west of Adak. On Adak, 6 of 15 lavas have Ce/Pb greater than 4, ranging up to ~ 15. In the central Aleutians, ~ 50 lavas have Ce/Pb less than 4, while three have Ce/Pb greater than 4, ranging up to ~ 7. All three of the central Aleutian lavas with Ce/Pb from 4 to 7 are from volcanoes behind the volcanic front; two from Amak Island and one from Bogoslof.

To summarize, unradiogenic Pb isotope ratios, reflecting Pb derived from subducted oceanic crust and/or the sub-arc

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[2] Note that we use only primitive lavas in this discussion, in an attempt to avoid the effects of plagioclase crystallization on Sr concentration.

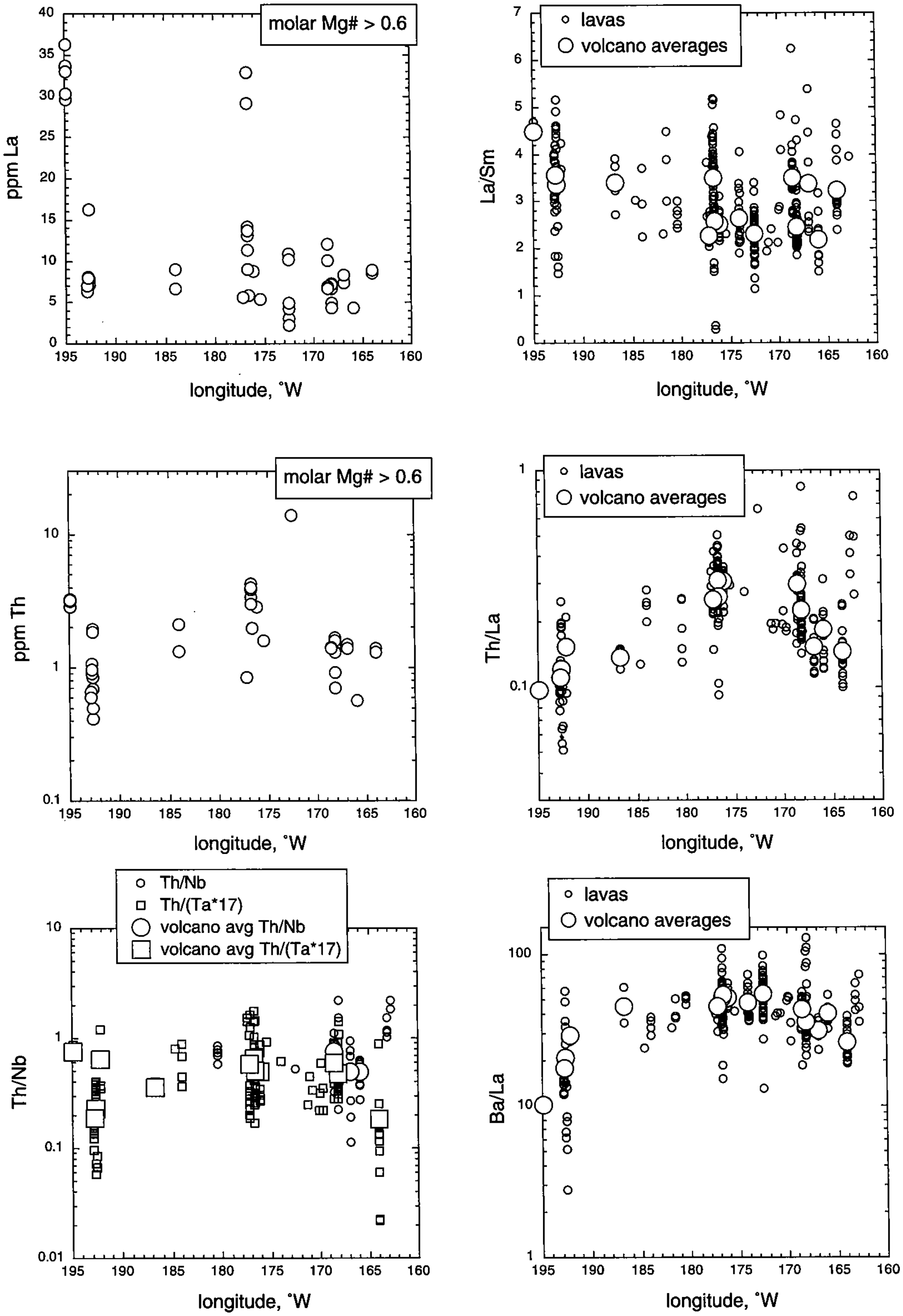


Figure 12. Proposed trace element indicators of a recycled sediment component in arc lavas, versus longitude along the Aleutian arc. Of these, only Th/La and perhaps Ba/La seem to show systematic variation along-strike. Sources of data in caption for Figure 3.

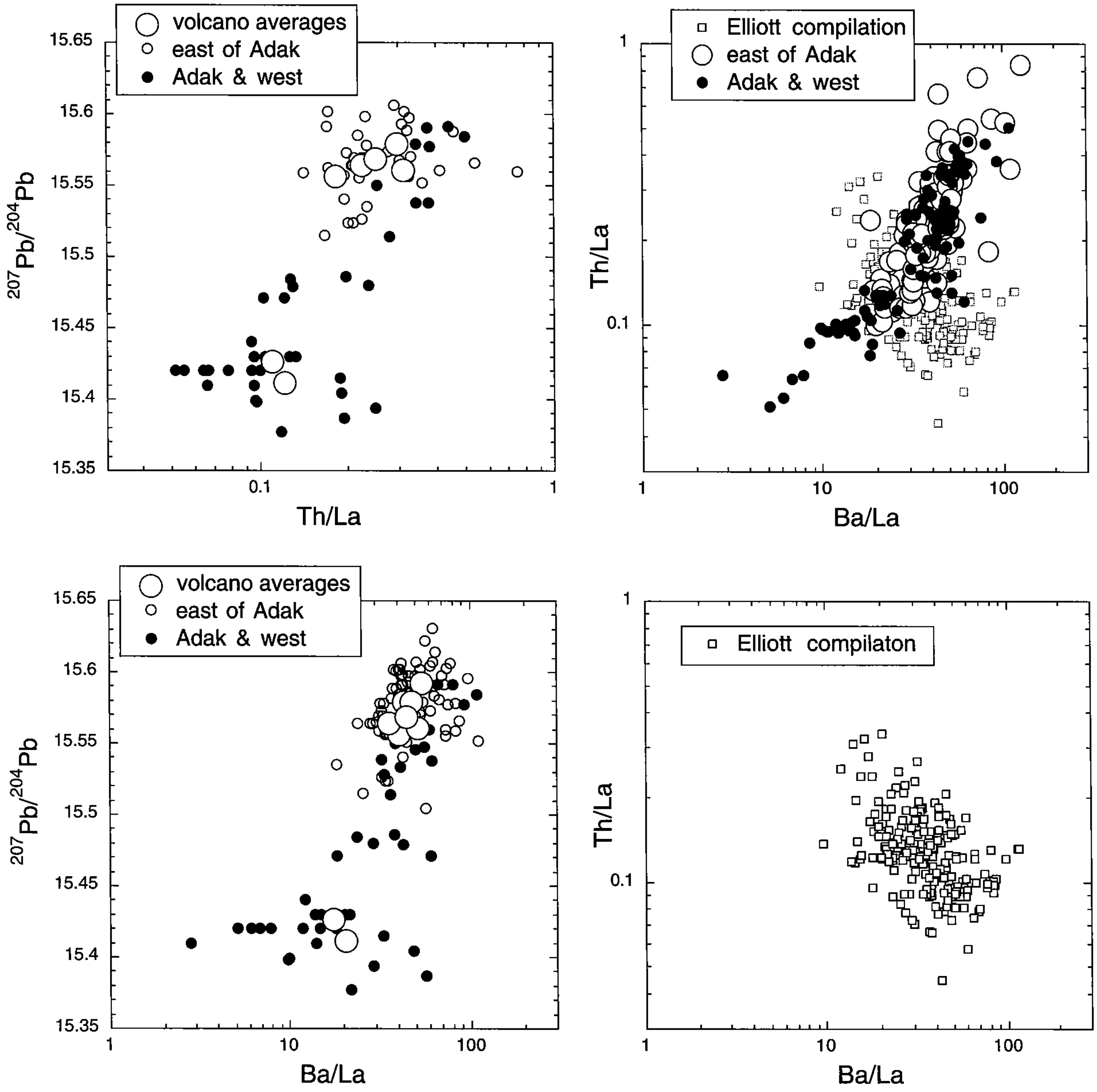


Figure 13. Variation of ^{207}Pb/^{204}Pb, Th/La and Ba/La in Aleutian lavas, and Th/La versus Ba/La for a compilation of arcs worldwide—excepting the Aleutians—from Elliott (this volume). In the Aleutians, Th/La appears to be correlated with ^{207}Pb/^{204}Pb. Th/La is definitely correlated with Ba/La, as previously noted by [*Kay,* 1980; *Kay and Kay,* 1994; *Yogodzinski et al.,* 1994]. In the "worldwide" data set, Ba/La is negatively correlated with Th/La. High Ba/La has been interpreted to reflect addition of an aqueous fluid component to the arc magma source, whereas high Th/La has been interpreted to reflect addition of a distinct, partial melt of subducted sediment. These components cannot be easily separated in the Aleutians. Sources of Aleutian data in caption for Figure 3.

mantle, are found in lavas with both low and high Ce/Pb ratios. In the western Aleutians, where Pb isotope ratios are lowest, almost all lavas have relatively high Ce/Pb, probably indicative of Pb transport in a melt rather than an aqueous fluid. In the central Aleutians, high Ce/Pb together with low ^{207}Pb/^{204}Pb are observed only in volcanoes situated behind the volcanic front. Other central Aleutian samples with low ^{207}Pb/^{204}Pb, such as some of the Umnak lavas studied by Miller et al., have low Ce/Pb. These low Ce/Pb ratios *could* reflect transport of Pb from subducted basalt in

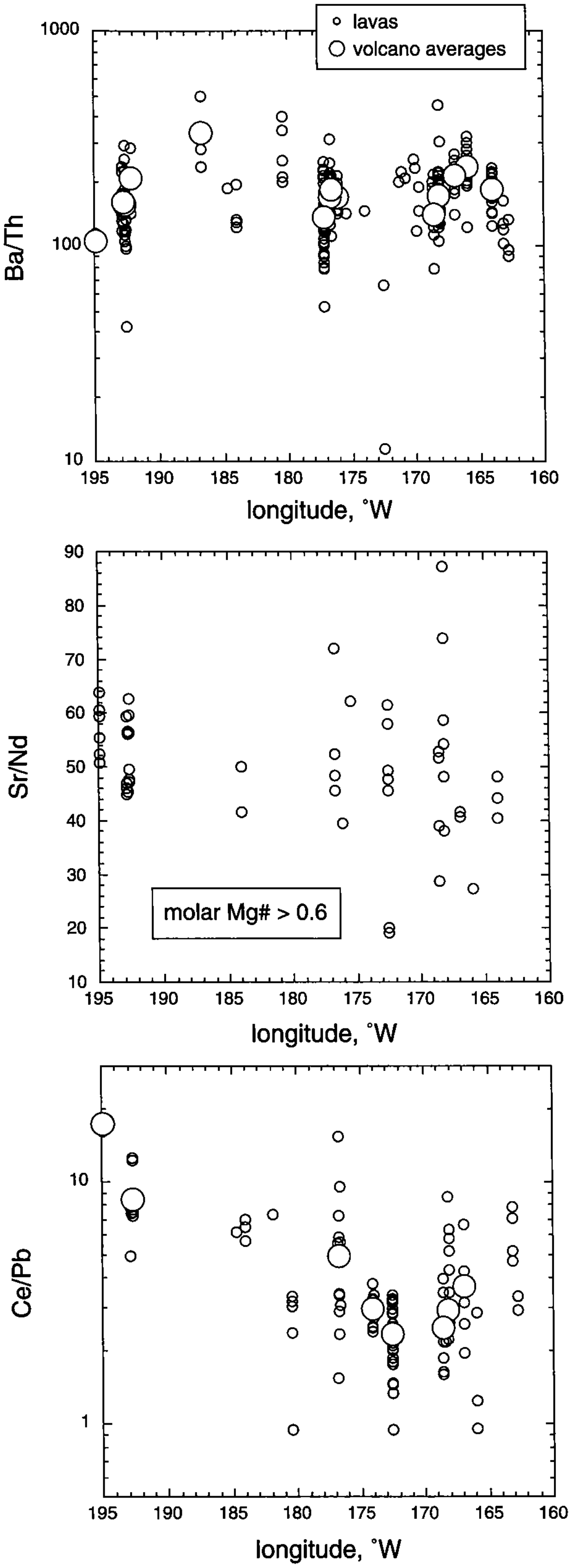


Figure 14. Proposed trace element indicators of an aqueous fluid component in arc lavas, versus longitude along the Aleutian arc. Sources of data in caption for Figure 3.

an aqueous fluid, but are *also consistent* with Pb transport in a partial melt of subducted basalt (see Section 4).

2.6 Along-Strike Variation in Proposed Indicators of an "Eclogite Melt" Component

Kay [1978] proposed that a few highly light REE enriched, heavy REE depleted, high Mg# andesites—from the base of Moffett volcano on Adak Island and two samples dredged from the Western Aleutian seafloor—were produced by partial melting of subducted basalt in eclogite facies, followed by reaction of this melt with the mantle during transport from the subduction zone to the surface. Because we feel use of the term "adakite" for these lavas is problematic (see Section 1.1), we refer to these lavas as "enriched, high Mg# andesites".

Kay noted that enriched, high Mg# andesites had such high Sr/Y, steep REE patterns, and low Yb and Y concentrations, that they seemed to require partial melting of a source with abundant garnet, in which Yb and Y were compatible and La and Sr were highly incompatible. The source must have contained little or no plagioclase, in which Sr is compatible and Yb and Y are highly incompatible. Many igneous processes can fractionate light REE from heavy REE whereas, among minerals that are abundant in metabasalt and mantle peridotite, only garnet can produce a strong fractionation of middle REE, such as Dy from heavy REE such as Yb. Thus, Dy/Yb is better than La/Yb as an indicator of abundant garnet in the source of arc magmas. Figure 16 shows that Sr/Y correlates with Dy/Yb in Aleutian lavas, reinforcing the idea that both high Sr/Y and high Dy/Yb reflect fractionation between melt and abundant, residual garnet. For further discussion of the origin of the high Sr/Y, Dy/Yb and La/Sm component in western Aleutian lavas, and particularly whether it really requires a component produced by partial melting of subducted basalt in eclogite facies, please see Sections 4.5 and 4.7.

We can look for along-strike variation in the abundance of a component with abundant, residual garnet in our data compilation using Sr/Y in primitive lavas and Dy/Yb ratios in all lavas. These should be high in magmas including a substantial component produced by small amounts of partial melting of basalt in eclogite facies followed by reaction with mantle peridotite. These ratios show little systematic variation as a function of longitude, because moderate Sr/Y and Dy/Yb ratios are found in lavas throughout the arc. However, the highest ratios are found in lavas at and west of

Adak Island. This is more easily seen in plots of Sr/Y versus La/Sm and Dy/Yb, in which it is clear that highly enriched lavas are found only in the western Aleutians (Figure 16).

Figure 16 shows that the high Sr/Y, La/Sm, Dy/Yb component in primitive Aleutian lavas is enriched in SiO_2, Na_2O, K_2O, Ce/Pb, and Th/Nb compared to the lower Sr/Y lavas in the eastern and central Aleutians. In many of these plots, lavas from Piip volcano in the Komandorsky block [*Yogodzinski et al.,* 1994] form an important, third end-member. The Piip lavas share the major element characteristics of the enriched, high Mg# andesites, and their low Ba/La ratios, but they lack high Sr/Y, La/Yb, and Dy/Yb. As pointed out by *Yogodzinski et al.* [1994], many of the characteristics of Piip lavas can be explained as the result of a small degree of partial melting of spinel peridotite.

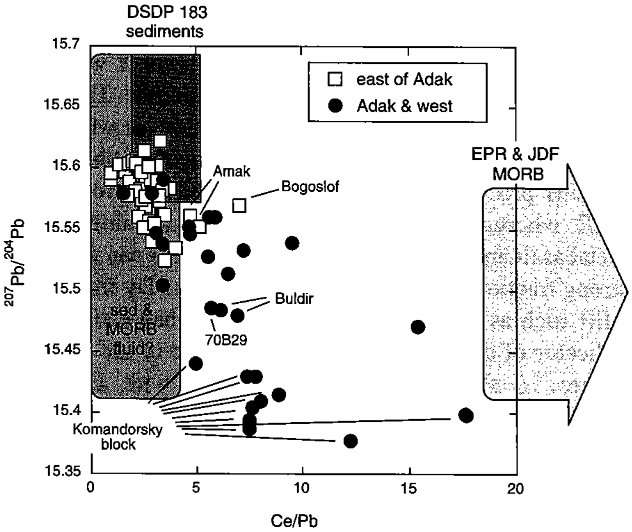


Figure 15. $^{207}Pb/^{204}Pb$ versus Ce/Pb in Aleutian lavas. All analyses by isotope dilution. Closed circles indicate data from volcanoes at and west of Adak. All closed circles that are not labeled with a location are from Adak Island. This plot is similar to Figure 4 of [*Miller et al.,* 1994], but includes data for volcanoes other than Okmok and Rechesnoi, plus updated fields for DSDP Site 183 sediments and MORB. The plot demonstrates that relatively high Ce/Pb is common in Aleutian lavas with unradiogenic Pb isotopes. Sources of Aleutian data in caption for Figure 3, plus new Pb concentrations and Pb isotope ratios for western Aleutian lavas in Table 1. Field for MORB glasses from the East Pacific Rise and Juan de Fuca Ridge based on data in the RIDGE petrological database at http://petdb.ldeo.columbia.edu/. Field for DSDP Site 183 sediments from data in [*Plank and Langmuir,* 1998; *Miller et al.,* 1994; *Peucker-Ehrenbrink et al.,* 1994; *von Drach et al.,* 1986]. Field for "aqueous fluid" is based on the reasoning of [*Brenan et al.,* 1995a; *Miller et al.,* 1994], but expanded to include fluid derived from subducted sediment as well as altered MORB.

It is noteworthy that Th/La is low in lavas with high Sr/Y, Dy/Yb and Ce/Pb, whereas Sr/Y, Dy/Yb and Ce/Pb are low in lavas with high Th/La (Figure 16). Also, recall that Ba/La is strongly correlated with Th/La (Figure 13). If high Ba/La and Th/La ratios are proxies for a component derived from partial melting of subducted sediment (Section 2.4), and high Sr/Y, Dy/Yb and Ce/Pb are caused by addition of a melt of subducted eclogite, these two components can clearly be distinguished in the Aleutians.

2.7 Proposed Indicators of Other Melt Components Derived From Subducted Basalt

Marsh, Myers, Brophy, Fournelle and their co-workers [e.g., *Brophy and Marsh,* 1986; *Myers et al.,* 1986a; *Myers et al.,* 1986b; *Myers et al.,* 1985] have proposed that more typical, low Mg#, high alumina basalt magmas in the Aleutians were also produced by partial melting of subducted basalt. Because these lavas do not have high Dy/Yb and Sr/Y, this group called upon diapiric ascent of partially molten, subducted basalt into the sub-arc mantle. Decompression within these diapirs would lead to garnet breakdown, and subsequent separation of the melt from its residue would produce high alumina basalt with the isotope signature of subducted basalt but without the trace element signature indicative of an eclogite melt. However, the hypothesis that high alumina basalts are partial melts of subducted basalts is controversial and difficult to verify, because high alumina basalts may also be produced by mantle melting [*Bartels et al.,* 1991] and by crustal crystal fractionation processes [e.g., *Sisson and Grove,* 1993; *Kelemen et al.,* 1990b; *Baker and Eggler,* 1983; *Kay et al.,* 1982].

Similarly, Drummond and Defant [e.g., *Defant and Drummond,* 1990; *Drummond and Defant,* 1990], Rapp and Watson [*Rapp and Watson,* 1995; *Rapp et al.,* 1991] and others have inferred that some low Mg# andesites and dacites might be direct partial melts of subducted eclogite that did not interact with mantle peridotite. Again, this hypothesis is difficult to verify for arcs worldwide because low Mg# andesites—even those with high Sr/Y and Dy/Yb—could be produced by crystal fractionation involving garnet, or by partial melting with residual garnet, within thick crust [e.g., *Müntener et al.,* 2001]. In the Aleutians such ambiguities do not arise, because the crust is relatively thin—at least at present—and because high Sr/Y and Dy/Yb ratios in Aleutian lavas are restricted to high Mg# andesites.

In this paper, we have adopted the assumption that low Mg# magmas are produced by differentiation of primitive magmas which were in Fe/Mg equilibrium with residual mantle olivine, unless proven otherwise.

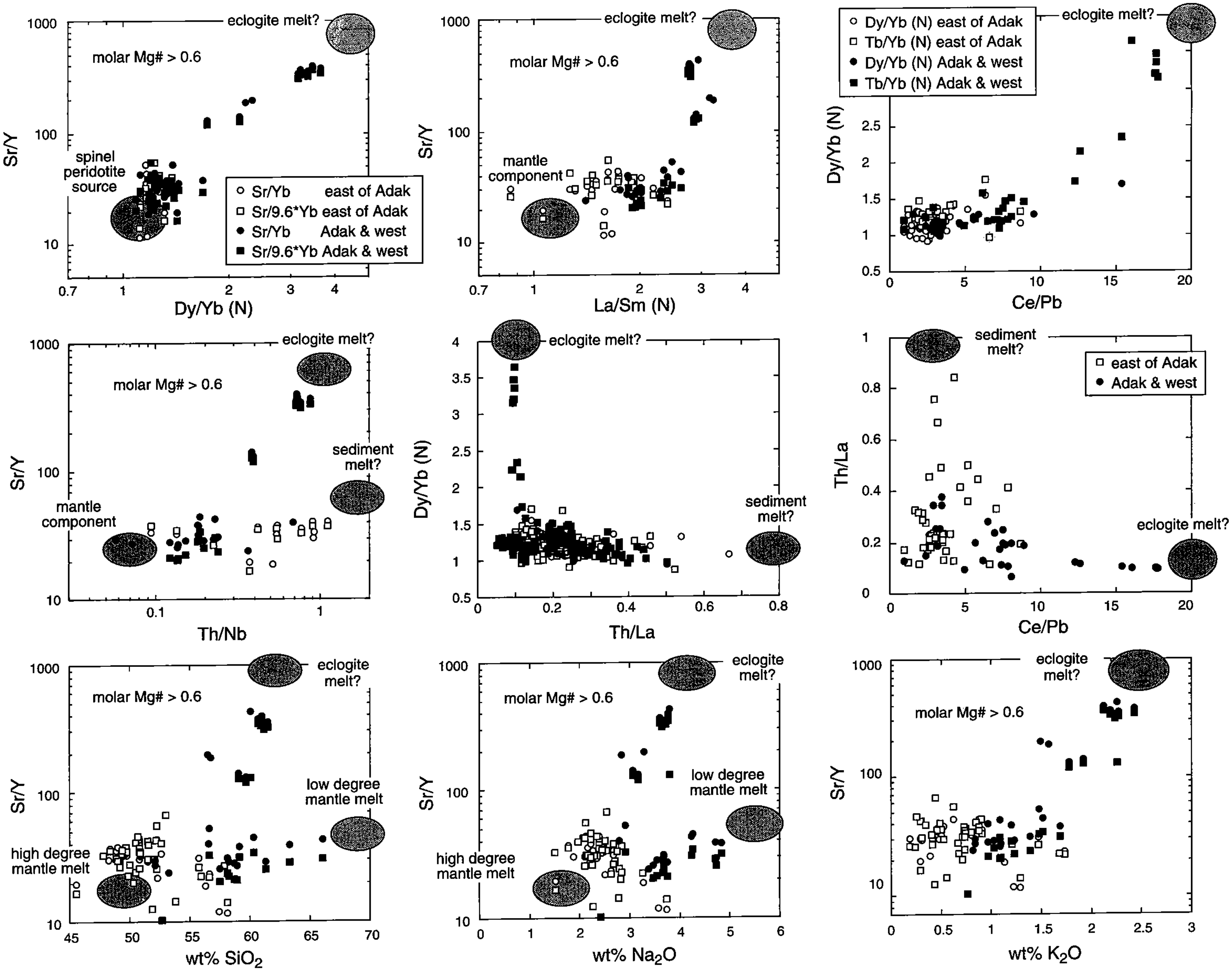


Figure 16. Sr/Y and Dy/Yb, proposed indicators of an eclogite melt component, versus other compositional data for Aleutian lavas. Sources of data in caption for Figure 3. Where Y data were not available, Sr/(9.6*Yb) was used instead, based on the chondritic Y/Yb ratio. Similarly, normalized Tb/Yb is used interchangeably with Dy/Yb, depending on what data are available. For REE, (N) indicates that concentrations are normalized to C1 chondrite values [*Anders and Grevesse,* 1989].

3. PLUTONIC ROCKS IN THE ALEUTIANS

Plutonic rocks in the Aleutians have been studied mainly on Unalaska Island in the east and in the Adak area [e.g., *Kay et al.,* 1990; *Kay et al.,* 1983; *Perfit et al.,* 1980b, and references therein]. There are also some small, hypabyssal intrusions in the western Aleutians and on the Komandorsky Islands [e.g., *Yogodzinski et al.,* 1995; *Yogodzinski et al.,* 1993; *Tsvetkov,* 1991]. Though some of the most mafic Aleutian gabbros may be "cumulate" (products of partial crystallization, from which remaining liquid was later removed), the high K contents of intermediate to felsic plutonic rocks in the Aleutians suggest that most are close to magma compositions.

Light REE enriched, K-rich, high Mg# andesite compositions similar to continental crust are more common among Aleutian plutonic rocks than they are among lavas (Figures 4 and 5). Although *Kay et al.* [1990] noted that plutonic rocks in the Adak area were somewhat more K-rich at a given Mg# than those on Unalaska Island, these variations are small compared to the along-strike variation in lava compositions.

Plutonic rocks analyzed to date—all Tertiary—may reflect an earlier phase of Aleutian magmatism. However, there is no identified change in convergence rate, age of subducting plate, or sediment source and abundance, which would explain a change in magma composition [*Atwater,* 1989; *Lonsdale,* 1988; *Engebretson et al.,* 1985]. Instead, the plutonic rocks may represent hydrous andesite magmas that were emplaced in the mid-crust after degassing of H_2O left them too viscous to erupt, as previously suggested by *Kay et al.* [1990] and *Kay and Kay* [1994]. In contrast, low viscosity, H_2O-poor, basalts may erupt readily. Thus, the proportion of high Mg# andesites among lavas may be less than their proportion within the entire crust. If true, this is very important, because it is commonly assumed that lava data can be used to estimate the proportions of the primary melts that form arc crust.

4. GENESIS OF WESTERN ALEUTIAN HIGH MG# ANDESITES

4.1 Crystal Fractionation From Primitive Basalt? No.

Kelemen [1995] reviewed experimental data on partial melting of natural basalt and peridotite compositions, with and without added H_2O, at a variety of oxygen fugacities, over a range of pressures from 1 bar to 3.5 GPa. Very few

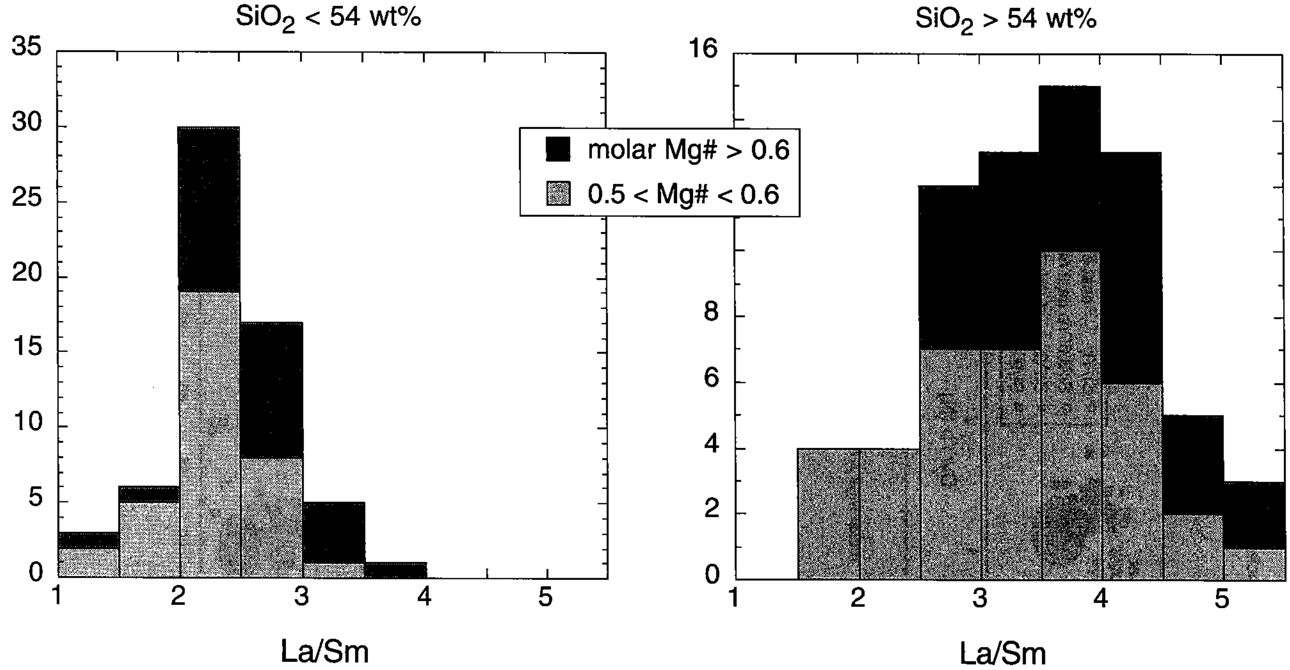


Figure 17. Histograms of La/Sm for high Mg# Aleutian lavas (molar 0.5 < Mg# < 0.6), and primitive lavas (molar Mg# > 0.6), showing a clear difference between basaltic lavas ($SiO_2 < 54$ wt%) and andesites ($SiO_2 > 54$ wt%). This difference is present in both primitive and high Mg# groups, so it suggests that primitive andesites are genetically related to more "normal" high Mg# andesites. Sources of data in caption for Figure 3.

of these experiments have produced high Mg# andesite liquid compositions, and even fewer have produced high Mg# andesites with K_2O concentrations comparable to Aleutian high Mg# andesites. *Kawamoto* [1996] melted basalts at high, unbuffered oxygen fugacity and produced a series of melt compositions that were very similar to some Aleutian high Mg# andesites. However, according to Kawamoto (pers. comm., 1997), the oxygen fugacities in those experiments were probably much higher than in most arc lavas (arc andesites record fO_2 within 2 log units of the Ni - NiO oxygen buffer [*Gill,* 1981]).

In considering the experimental data, it is also worthwhile to recall that partial melting/crystallization experiments are performed in a "closed system", in which melts continuously undergo Fe/Mg exchange with residual crystals. In fractional crystallization, which is often closely approximated in nature [e.g., *Carmichael,* 1964], residual crystals are removed so that melts evolve to lower Mg# at a given SiO_2 and K_2O content compared to closed-system crystallization. Thus, the experimental data approximate an upper bound on the SiO_2 and K_2O contents which can be achieved at a given Mg# via basalt crystallization. From this perspective, it is striking that only a few experimental melts fall into the range of Aleutian high Mg# andesite compositions, and the range of estimated continental crust compositions (two from Sisson and Grove, one in which the fO_2 buffer failed, and another at 965°C saturated in hornblende and magnetite, plus the high fO_2 experiments of Kawamoto).

Continental crust contains a significant proportion of andesitic rocks with Mg# higher than the average value, similar to primitive Aleutian andesites and dacites (summary and compilation in [*Kelemen,* 1995]). At and west of Adak, Aleutian andesites with Mg# between 0.45 and 0.6 are spatially associated with primitive andesites with Mg# > 0.6. Also, high Mg# andesites (0.5 < Mg# < 0.6) and primitive andesites (Mg# > 0.6) have similar trace element patterns, which are distinct from trace element patterns in primitive basalts (Figures 16 and 17). Therefore, it is likely that high Mg# andesites and primitive andesites are genetically related. No experimental liquids formed by partial melting of basalts approach the compositions of Aleutian primitive andesites. For these reasons, we believe that it is unlikely that western Aleutian high Mg# andesites are produced primarily via crystal fractionation from primitive basalts.

4.2 Mixing of Primitive Basalt and Evolved Dacite? Not for Enriched, Primitive Andesite

In the Aleutians, it has long been argued that both tholeiitic and calc-alkaline lava series have a common parental magma, a mantle-derived picrite with a nearly flat REE pattern [e.g., *Kay and Kay,* 1994; *Nye and Reid,* 1986; *Kay and Kay,* 1985a]. In this view, the tholeiitic series evolves mainly via crystal fractionation, perhaps at relatively low H_2O fugacity, whereas the calc-alkaline series has a more complex origin. Some light REE enriched dacite magmas are produced by crystal fractionation involving hornblende, which fractionates middle REE from light REE. Then, mixing of these evolved dacites with primitive basalt produces light REE enriched, high Mg# andesites such as those on Buldir Island in the western Aleutians.

It is well documented that Aleutian magmas, and calc-alkaline andesites in general, commonly contain oscillatory zoned clinopyroxene crystals which could be indicative of magma mixing [e.g., *Brophy,* 1987; *Kay and Kay,* 1985a; *Conrad and Kay,* 1984; *Conrad et al.,* 1983]. One possible explanation for both oscillatory zoning in clinopyroxene and high Mg# andesite lavas is mixing of primitive basalt with evolved dacite or rhyolite. Because the primitive basalt end-member has much higher Mg and Fe concentrations than the evolved end-member, mixing produces a concave downward hyperbola on plots of, e.g., Mg# versus SiO_2 or K_2O. If the evolved end-member is also light REE enriched and heavy REE depleted, perhaps as a result of crystal fractionation in the crust, then a similar trend is produced on plots of Mg# versus La/Yb (Figure 18).

Such mixing processes, or very similar processes in which primitive basalt assimilates evolved, granitic rocks, have long been proposed to explain the origin of high Mg# andesites in general, and more specifically in the Aleutians [e.g., *Brophy,* 1987; *Kay and Kay,* 1985a; *Conrad and Kay,* 1984; *Conrad et al.,* 1983, and references therein]. Mixing of low viscosity basalt and high viscosity, siliceous liquids may be physically improbable [*Campbell and Turner,* 1985]. On the other hand, there are very well documented cases of assimilation processes that produce calc-alkaline andesites [*Grove et al.,* 1988; *McBirney et al.,* 1987]. Furthermore, in considering the genesis of continental crust, tectonic juxtaposition of basaltic and evolved rocks could produce an average with the composition of high Mg# andesite without any chemical mixing.

However, it is apparent that mixing of primitive basalt and evolved dacite or rhyolite cannot explain the origin of enriched, high Mg# andesites in the Aleutians at and west of Adak. As noted in Section 2.6, among primitive Aleutian magmas, high Sr/Y, La/Sm and Dy/Yb ratios are found only in andesites and dacites, never in basalts (Figures 16 and 17). Furthermore, crystallization of plagioclase, in which Sr is compatible, lowers Sr/Y, so that all evolved Aleutian magmas, with Mg# < 0.45, have Sr/Y < 60. Thus, in the Aleutians, neither primitive basalts nor evolved magmas

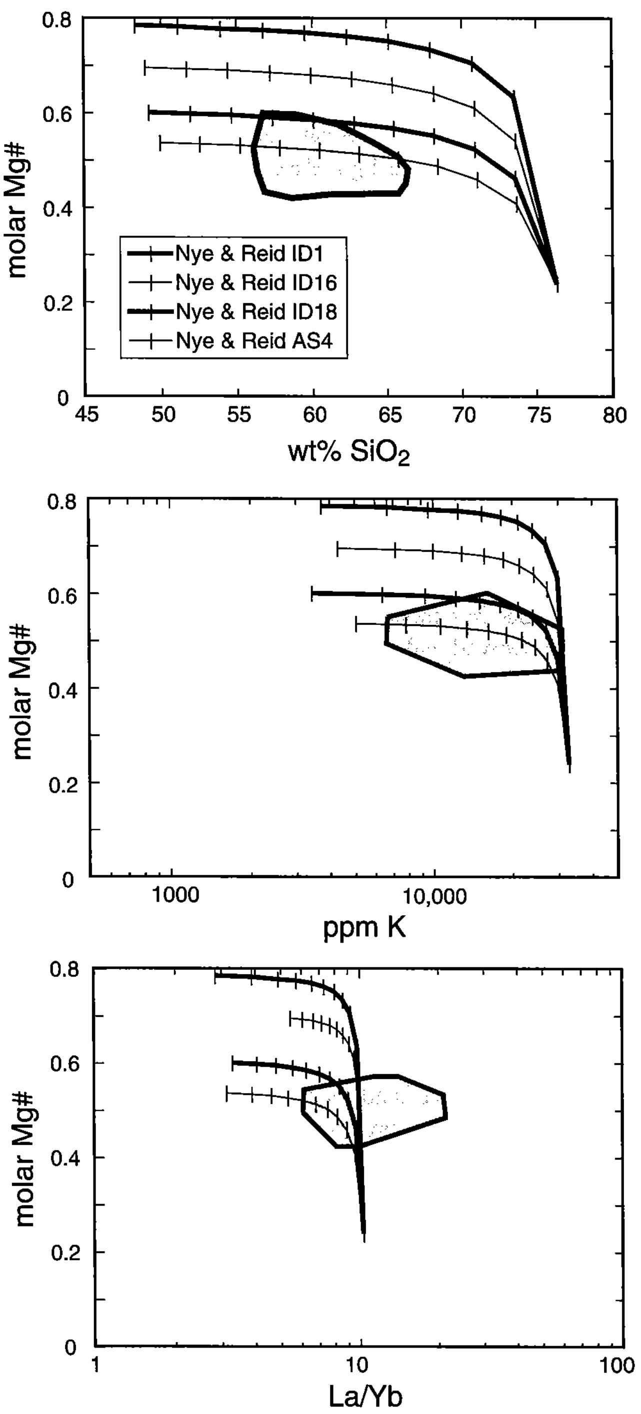


Figure 18. Calculated trends for mixing of (a) primitive basaltic lavas from Okmok volcano [*Nye and Reid,* 1986] with (b) rhyolite ia32 (also called 47ABy28) from Rechesnoi volcano [*Kay and Kay,* 1994; *Byers,* 1959]. The grey field in each panel shows estimated continental crust compositions (See Figure 4 caption for references).

have the trace element characteristics which distinguish enriched, primitive andesites.

Yogodzinski and Kelemen [1998] investigated the trace element contents of zoned clinopyroxene crystals in enriched, primitive Aleutian andesites, and compared them to trace element concentrations in clinopyroxenes from other Aleutian magma types. Primitive andesites contained clinopyroxenes with high Sr/Y, Dy/Yb and La/Yb, while primitive basalts contained clinopyroxenes with much lower ratios. Evolved lavas had relatively low Sr/Y, Dy/Yb and La/Yb, similar to the primitive basalts. In zoned clinopyroxenes in the primitive andesites, we found that the highest Sr/Y, Dy/Yb and La/Yb ratios were in the parts of crystals with the highest Mg#. Lower Mg# portions of the same crystals had lower Sr/Y, Dy/Yb and La/Yb, indicative of mixing of a primitive, highly enriched component with an evolved, less enriched component.

As Yogodzinski and Kelemen noted, trends of Aleutian lava compositions parallel those observed in the zoned clinopyroxene crystals. Primitive basalts and most evolved lavas—basaltic, andesitic, and even more silica rich—have relatively low Sr/Y, Dy/Yb and La/Yb, whereas enriched, primitive andesites have much higher Sr/Y, La/Sm and Dy/Yb (Figure 19). In fact, this bimodal distribution of trace elements may be reflected in a similar, bimodal distribution of major element contents of primitive lavas (Figures 3 and 5). Among western Aleutian lavas, a mixing trend can be seen from enriched, primitive andesites toward less enriched trace element ratios in andesites with moderate Mg#s. Thus, it is apparent that there are two primitive lava types in the western Aleutians. As previously emphasized [e.g., *Yogodzinski and Kelemen,* 1998, *Kay and Kay,* 1994; *Kay and Kay,* 1985b], magma mixing has played an important role in the genesis of many high Mg# andesites at and west of Adak. *However, the highest Mg# end-member in this mixing process was an enriched, primitive andesite, not a primitive basalt.*

It is not clear whether calc-alkaline lavas and plutonic rocks with high Mg# andesite compositions in the central Aleutians include a component derived from enriched, primitive andesites, or whether, instead, they formed via mixing of primitive basalt with enriched, evolved dacite or rhyolite. In the Adak area, hornblende-bearing, dacitic tephra include glasses with La/Yb generally between 6.5 and 7.5, and one from Kanaga has La/Yb=8.9 [*Romick et al.,* 1992]. However, there are very few dacites and rhyolites in the central and eastern Aleutians with sufficiently high La/Yb (greater than ~ 10) to explain the light REE enrichment in high Mg# Aleutian plutonic rocks (Figure 4). In our database, only 5 of ~ 900 samples from the central and eastern Aleutians have more than 60 wt% SiO_2 and La/Yb > 7. Thus, it seems plausible that magma mixing is not the general cause of light REE enrichment in Aleutian plutonic rocks. Instead, an enriched, primitive andesite component may have been an important mixing end-member throughout the arc.

Apparently, even in the Komandorsky block and on Adak, where primitive lavas include both enriched andesites and more "normal" basalts, there has been little mixing between these different, primitive magma compositions. Perhaps this is due to the different viscosities of andesitic and basaltic liquids. The mixing trend observed between enriched, primitive andesites and more evolved, but less enriched andesites may be facilitated by their similar viscosities.

4.3 An Important Role for Recycled, Continental Sediment? No.

Leaving aside the major element composition of Aleutian lavas for a moment, it might be proposed that the enrichments in Th, U, Pb, Rb, K, Sr, light REE, and so on, in western Aleutian lavas—different from other intraoceanic arcs and similar to continental crust—is simply the result of recycling of a continentally-derived sediment component. We believe that the isotopic and geologic evidence clearly indicate that this is not the case (see Sections 1.6 and 2.3). Although the concentration of some elements in primitive arc magmas worldwide may be related to the flux of these elements in subducted sediments [*Plank and Langmuir,* 1993], this is not the case in the Aleutians, at least not at and west of Adak Island.

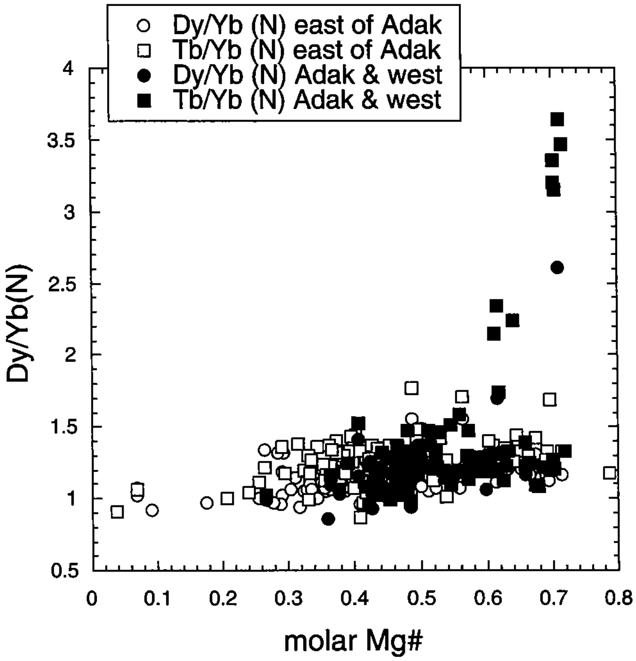


Figure 19. Dy/Yb(N) (and Tb/Yb(N)) versus molar Mg# for Aleutian lavas, illustrating that the most primitive lavas—with the highest Mg#—have the highest Dy/Yb (and Sr/Y and La/Sm, Figure 16). This is inconsistent with the mixing trajectories in Figure 18, involving primitive lavas with flat REE patterns mixing with evolved lavas with enriched REE patterns. Instead, mixing of primitive, enriched lavas with evolved lavas having flat REE patterns is consistent with the Aleutian data. Also, please see figures and discussion of this topic in [*Yogodzinski and Kelemen,* 1998]. Sources of data in caption for Figure 3.

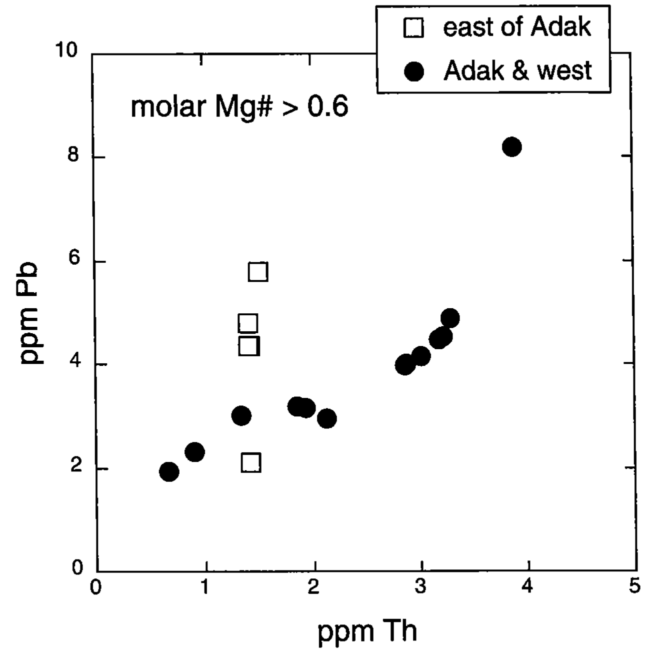


Figure 20. Concentration of Th versus Pb in primitive Aleutian lavas. Sources of data in caption for Figure 3.

4.4. Partial Melting of Spinel Peridotite Metasomatized by Aqueous Fluid? No.

As noted in Section 1.5, relatively slow convergence in the Aleutians west of Adak probably cools the mantle wedge by conduction into the subducting plate. Conversely, slow convergence produces a relatively hot subduction zone, in which most metamorphic dehydration reactions occur beneath the forearc, limiting the amount of H_2O that can flux melting beneath the arc. For these reasons, it could be that the degree of mantle melting is lower west of Adak compared to the central Aleutians. Could this explain why high Mg# andesites are abundant in the west?

High H_2O and alkali contents stabilize high SiO_2 in olivine-saturated melts [*Hirschmann et al.,* 1998; Ryerson, 1985; *Kushiro,* 1975], as demonstrated in experiments on natural systems [*Gaetani and Grove,* 1998; *Hirose,* 1997; *Baker et al.,* 1995; *Kushiro,* 1990]. Low degrees of melting of mantle peridotite could produce a melt enriched in H_2O and alkalis, and thus andesitic rather than basaltic. However, the maximum SiO_2 content is controversial [*Draper and Green,* 1999; *Baker et al.,* 1996; *Falloon et al.,* 1996].

In general, alkali-rich melts of nominally anhydrous lherzolite at ≥ 1 GPa are nepheline normative, whereas primitive andesites are quartz normative. Though H_2O tends to raise SiO_2 in mantle melts relative to NaAl and KAl, yielding quartz-normative andesite (calculated H_2O-free) at 1 to 1.5 GPa [*Gaetani and Grove,* 1998; *Hirose,* 1997; *Baker et al.,* 1995; *Kushiro,* 1990], at pressures > 1.5 or 2 GPa hydrous melts of lherzolite may be alkaline [e.g., *Kushiro,* 1969; *Kushiro,* 1968]). Partial melts of harzburgite are more SiO_2-rich [e.g., *Walter,* 1998; *Falloon et al.,* 1988; *Falloon and Green,* 1988; *Falloon and Green,* 1987]. Hydrous primitive andesites from Japan and California are in equilibrium with harzburgite at 1 to 1.5 GPa [*Baker et al.,* 1994; *Tatsumi and Ishizaka,* 1982].

In summary, primitive andesites might arise from melting of spinel peridotites. However, the trace element contents of *enriched* primitive andesites do not result from this process alone. Enrichments in Sr/Y, Dy/Yb and La/Yb must be explained via metasomatism prior to melting. If temperatures in subduction zones are too low for partial melting (see Section 4.8), transport of incompatible elements from subducted material must be in aqueous fluid. It may be that aqueous fluids carrying incompatible elements *cause* partial melting. If so, fluid composition can be estimated from H_2O in glasses combined with assumptions about the mantle source [e.g., *Grove et al.,* 2002; *Class et al.,* 2000; *Eiler et al.,* 2000; *Stolper and Newman,* 1992].

Fluid compositions inferred from this approach differ from those in experiments on aqueous fluids plus mantle peridotite or basaltic eclogite at 1 to 4 GPa [e.g., *Ayers,* 1998]. Concentrations of Th and the light REE in experimental fluids are 10 to 1000 times lower than required to explain arc enrichments [*Hawkesworth et al.,* 1993a; *Hawkesworth et al.,* 1993b]. Also, experimental data show large fractionations of soluble elements, such as Ba, Pb and Sr with fluid/rock distribution coefficients ~100, from insoluble elements such as Th and REE, with fluid/rock distribution coefficients from ~ 0.01 to 1 [*Johnson and Plank,* 1999; *Ayers,* 1998; *Stalder et al.,* 1998; *Ayers et al.,* 1997; *Kogiso et al.,* 1997; *Brenan et al.,* 1996; *Brenan et al.,* 1995a; *Brenan et al.,* 1995b; *Tatsumi et al.,* 1986]. In contrast, fluids required to metasomatize the mantle source for enriched andesites show little fractionation of Ba, Pb and Sr from light REE and Th [*Grove et al.,* 2002; *Stolper and Newman,* 1992]. Also, enriched, primitive andesites in the western Aleutians have positively correlated Pb and Th (Figure 20, and [*Kay and Kay,* 1994; *Yogodzinski et al.,* 1994; *Kay,* 1980;]). Thus, enrichment of the Aleutian mantle may be via small degree partial melts of subducted material [e.g., *Class et al.,* 2000; *Elliott et al.,* 1997; *Hawkesworth et al.,* 1997; *Plank and Langmuir,* 1993]), and not due to aqueous fluid transport.

NaCl-rich fluids in equilibrium with silicates can be "supercritical", completely miscible with H_2O-rich silicate melt at subduction zone pressures [e.g., *Keppler,* 1996]. If NaCl-rich fluids are abundant, then the distinction between aqueous fluids and melts may be artificial. However, compaction and dehydration are likely to remove much of the H_2O in subducted material beneath the fore arc. Since the solubility of NaCl in H_2O increases with temperature, aqueous fluids hotter than seawater are likely to remove most subducted NaCl at shallow depths. Thus, it seems unlikely that NaCl-rich, supercritical fluids are common beneath arcs.

In summary, while primitive andesites can be in major element equilibrium with shallow mantle peridotites, enriched, primitive andesites probably are not produced by partial melting of spinel peridotite, preceded by aqueous fluid metasomatism of the mantle source. More likely, primitive andesites form by reaction between silicate liquids—from deeper in the subduction system—and shallow mantle peridotite. During reaction at high melt/rock ratios (~1), major elements approach equilibrium with olivine + pyroxene + spinel, but incompatible trace elements are largely unchanged, and reflect processes at greater depth.

4.5 Residual Garnet? Yes.

The high Sr/Y, Dy/Yb and La/Yb ratios and low Y and Yb concentrations of enriched, primitive Aleutian andesites can be explained as the result of residual garnet in the source of melting [e.g., *Kay,* 1978; *Yogodzinski et al.,* 1995]. More specifically, high middle to heavy REE ratios must have been produced by melting or crystal fractionation involving residual garnet. In melting, if the source had chondritic Tb/Yb and Dy/Yb (Tb/Yb(N) ≈ Dy/Yb(N) ≈ 1), observed Tb/Yb(N) up to 4 and Dy/Yb(N) up to 2.5 in primitive Aleutian andesites require that the ratios of the bulk rock/liquid distribution coefficients, D(Tb/Yb) and D(Dy/Yb), must be less than 0.25 and 0.4, respectively. This is only likely where the residual assemblage includes garnet.

The main phases controlling REE abundance in melting of mantle peridotite and basaltic eclogite compositions are garnet and clinopyroxene. Over the range of melt compositions from basalt to dacite, clinopyroxene/liquid D(Tb), D(Dy) and D(Yb) are all about ~ 0.3 to 0.8, with D(Tb/Yb) and D(Dy/Yb) ≈ 1 (e.g., data compiled at http://www.earthref.org/). Measured garnet/liquid D(Tb), D(Dy) and D(Yb) are about 1 to 20, 1 to 30, and 4 to 40, respectively, with D(Tb/Yb) from 0.1 to 0.75 and D(Dy/Yb) from 0.2 to 0.7 (http://www.earthref.org/). Within this range, the highest values of D(Tb), D(Dy), D(Yb), D(Tb/Yb) and D(Dy/Yb) are for partitioning between garnet and dacite. For example, *Rapp and Shimizu* [manuscript in preparation] determined garnet/liquid D(Dy) and D(Yb) from 1 to 22 and 6 to 40, respectively, with D(Dy/Yb) ranging from 0.36 to 0.55, in the products of experimental, hydrous partial melting of basaltic eclogites [*Rapp et al.,* 1999]. Bulk rock/liquid D(Tb/Yb) and D(Dy/Yb) of ~ 0.25 and 0.4 can be attained with a garnet/clinopyroxene ratio in the source of ~ 1 or more from a variety of combinations of the garnet/melt partitioning data. Both basaltic eclogites and garnet-bearing mantle peridotites have a garnet/clinopyroxene ratio ~ 1 or more [e.g., *Rapp et al.,* 1991; *Cox et al.,* 1987; and F.R. Boyd, pers. comm. 1987].

We envision four different scenarios in which garnet plays an important role in the genesis of REE fractionation in enriched, primitive Aleutian andesites.

(1) Partial melting of unusually, hot, subducted basaltic rocks in eclogite facies gives rise to the enriched component in Aleutian primitive andesites (Figure 21B). The western Aleutian subduction zone may be unusually hot because of slow convergence rates (Section 1.5).

(2) In the unusually cold wedge in the western Aleutians, only deep-seated, garnet peridotites are hot enough to undergo fluid-fluxed partial melting (Figure 21A). The mantle wedge in the western Aleutians might be unusually cold and/or relatively H_2O-poor because slow convergence leads to increased cooling of the wedge via conduction into the subducting plate, and because a hot subducting plate may undergo most of its dehydration at shallow depths, beneath the forearc area. Low temperatures would facilitate garnet stability to depths of ~ 50 km in the wedge. For example, basaltic melt was saturated in a garnet peridotite assemblage at 1.6 GPa and temperatures less than ~ 1250°C in a system with ~ 5 wt% H_2O in the melt [*Gaetani and Grove,* 1998]. Higher H_2O contents could lead to even lower pressures for garnet stability on the mantle peridotite solidus.

(3) Subducted sediments and/or basalts melt beneath the entire arc. In the eastern and central Aleutians this component is difficult to detect because the subduction zone melt component is swamped by abundant basalts produced by mantle melting. In the west, where the mantle is colder and fluxed by a smaller amount of aqueous fluid, basalts are rare and the subduction zone melt component—with a garnet-rich, eclogite residue—is seen in its least diluted form.

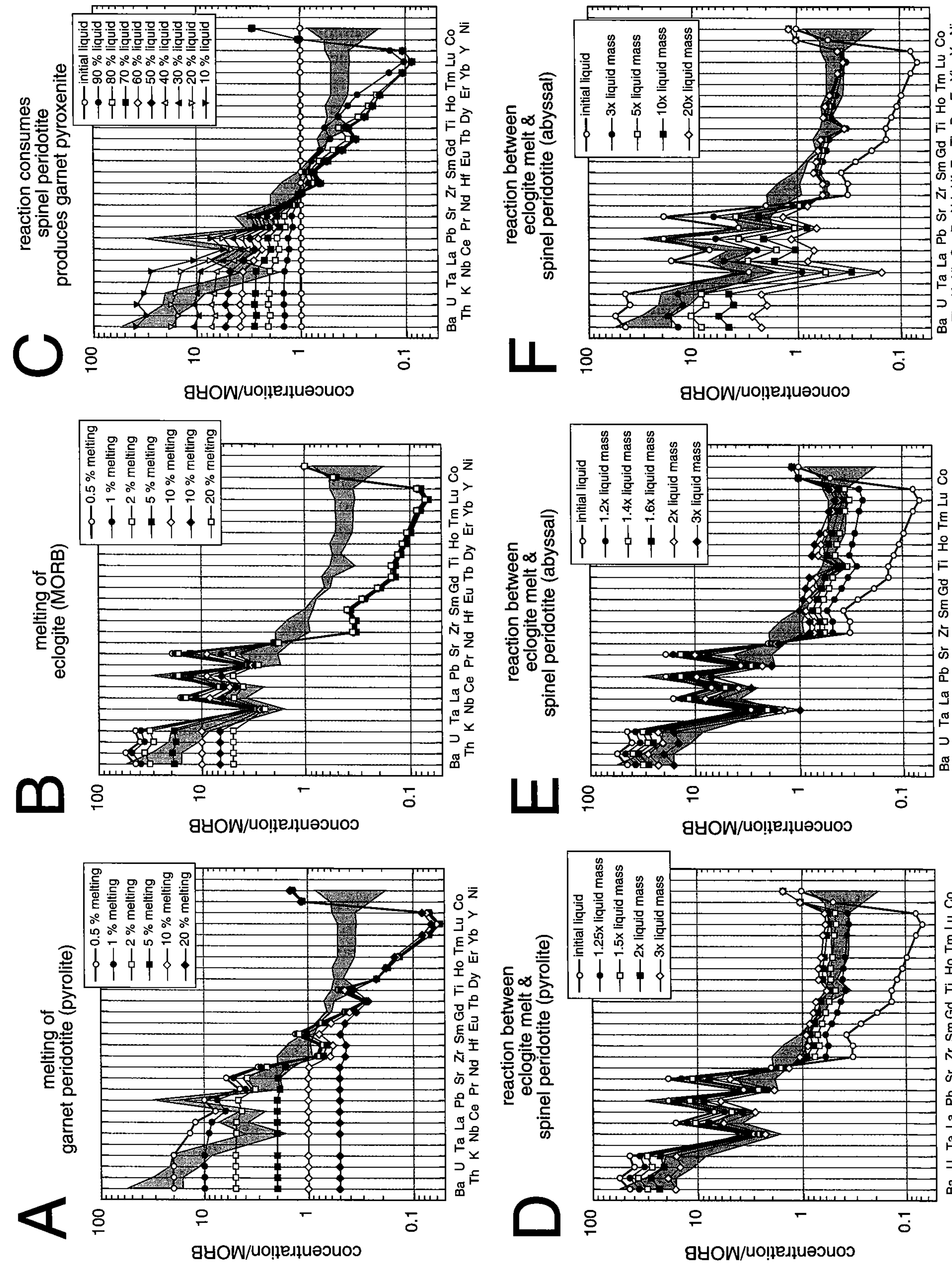
(4) Cooling melts in the uppermost mantle might begin to undergo crystal fractionation while reacting with mantle peridotite (Figure 21C). Experimental data show that hydrous high Mg# andesite melts are garnet + pyroxene saturated at 1.5 GPa [*Carroll and Wyllie,* 1989]. If reaction between such melts and surrounding mantle peridotite produced a garnet pyroxenite while maintaining a high Fe/Mg ratio in derivative liquids, it could form a high Mg# light REE enriched, heavy REE depleted liquid product.

Crystal fractionation involving garnet in the lower crust cannot explain Aleutian primitive andesite compositions for several reasons. First, all of the most light- and middle-REE enriched andesites in the Aleutians are also the most primitive lavas, with Mg#'s greater than 0.6 and in some cases greater than 0.7. This seems to rule out an important role for crystal fractionation in the crust. Second, crustal thickness in the Aleutians is ~ 30 to 35 km [*Fliedner and Klemperer,* 1999; *Holbrook et al.,* 1999; *Grow,* 1973]. Recent investigations on crystallization of a hydrous, primitive andesite composition show that such melts are not garnet saturated at 1.2 GPa [*Müntener et al.,* 2001]. Garnet was stable in andesitic and basaltic bulk compositions only after large degrees of crystallization decreased the Mg# to less than 0.5. Thus, primitive melts probably are not garnet saturated at Aleutian Moho pressures.

The role of residual garnet seems clear, but it is difficult to determine from REE systematics whether residual garnet remains in subducted eclogite or in the mantle wedge. At the end of this section, we are left with four possible scenarios: (1) Partial melting of eclogite in a relatively hot subduction zone in the west. (2) Partial melting of garnet peridotite in an unusually cold mantle wedge in the west. (3) Partial melting of eclogite in the subduction zone throughout the Aleutians, obscured by extensive partial melting of relatively hot, H2O-rich mantle peridotite in the east. (4) Combined crystallization of garnet pyroxenite and reaction with peridotite in the uppermost mantle.

4.6 Abundant High Mg# Andesites Related to Slow Subduction of Young Crust

REE systematics discussed in the preceding section require a role for residual garnet in enriched, primitive andesite genesis, but do not allow us to determine whether the residual garnet resides in subducted crust or in the mantle wedge.


A
melting of
garnet peridotite (pyrolite)
0.5 % melting
1 % melting
2 % melting
5 % melting
10 % melting
20 % melting
B
melting of
eclogite (MORB)
0.5 % melting
1 % melting
2 % melting
5 % melting
10 % melting
10 % melting
20 % melting
C
reaction consumes
spinel peridotite
produces garnet pyroxenite
initial liquid
90 % liquid
80 % liquid
70 % liquid
60 % liquid
50 % liquid
40 % liquid
30 % liquid
20 % liquid
10 % liquid
D
reaction between
eclogite melt &
spinel peridotite (pyrolite)
initial liquid
1.25x liquid mass
1.5x liquid mass
2x liquid mass
3x liquid mass
E
reaction between
eclogite melt &
spinel peridotite (abyssal)
initial liquid
1.2x liquid mass
1.4x liquid mass
1.6x liquid mass
2x liquid mass
3x liquid mass
F
reaction between
eclogite melt &
spinel peridotite (abyssal)
initial liquid
3x liquid mass
5x liquid mass
10x liquid mass
20x liquid mass
concentration/MORB
100
10
1
0.1
Ba U Ta La Pb Sr Zr Sm Gd Ti Ho Tm Lu Co
Th K Nb Ce Pr Nd Hf Eu Tb Dy Er Yb Y Ni

It might be expected that the amount of partial melting of subducted basalt would be larger in the Aleutians west of Adak, where the trench-orthogonal convergence rate is slow and therefore subducted crust has a long time to heat conductively as it descends below the arc [*Yogodzinski et al.,* 1994; 1995]. Additionally, beneath the Komandorsky block the subducting plate may have a "torn", exposed edge, and thus be heated from one side as well as from the top [*Yogodzinski et al.,* 2001]. However, the relatively hot subduction zone in the western part of the arc is probably combined with low flux of H_2O into relatively cold mantle beneath the arc. Which of these factors is most important in producing abundant, primitive andesites?

Y and Yb concentrations in andesitic-to-dacitic lavas are low where subducted crust was younger than ~ 25 Ma, and higher where subducted crust is older [*Defant and Drummond,* 1990]. This correlation might indicate that subducted basalt in eclogite facies undergoes partial melting only when hot, young crust is subducted. Defant and Drummond [1990] incorrectly inferred that subducting crust beneath the Buldir area in the Aleutians (where < 600,000 yr enriched andesite has been dredged) is 15 Ma, whereas in fact crust subducted beneath Buldir is more than 40 Ma (Section 1.5). Despite this discrepancy, if subduction of crust younger than 40 Myr old led to formation of high Sr/Y, Dy/Yb, La/Yb magmas, while subduction of older

Figure 21. Results of trace element modeling. Grey field shows estimated bulk composition of continental crust, from Figure 6A with data sources in caption. Crystal/liquid distribution coefficients, model rock compositions, and data sources for these values are given in Table 3. Figure 21A illustrates compositions of aggregated liquids formed by fractional melting [*Shaw,* 1970; *Gast,* 1968] of garnet peridotite (pyrolite). Figure 21B illustrates compositions of aggregated liquids formed by fractional melting of eclogite (MORB). Figure 21C illustrates liquid compositions resulting from reaction of MORB with spinel peridotite (pyrolite) to produce garnet pyroxenite, using the AFC equations of [*DePaolo,* 1981], with the mass of solid reactants/mass of solid products set to 0.97. The ratio of initial liquid mass/integrated mass of peridotite reactant ranges from ~0.3 at a melt fraction of 0.9 to ~0.03 at a melt fraction of 0.1.

Partial melting of eclogite produces a trace element pattern similar to some enriched, primitive andesites in the Aleutians, but with much lower heavy REE than in continental crust. Partial melting of garnet peridotite, and reaction producing garnet pyroxenite, produce steep REE patterns in resulting liquids, but without the fractionations of Nb/La, Ce/Pb and Sr/Nd seen in Aleutian lavas and continental crust.

Figure 21D shows liquids resulting from reaction of a small degree melt of eclogite with spinel peridotite (pyrolite), with no change in solid phase proportions and the mass of solid reactants/mass of solid products, Ma/Mc, of 1.05. The melt/rock ratio (initial mass of liquid/integrated mass of peridotite reactant) in these models ranges from ~0.2 where the liquid mass is 1.25 times its initial mass to ~0.02 where the liquid is 3x initial mass. Figure 21E shows results of reaction between the same eclogite melt and depleted spinel peridotite (abyssal peridotite), with no change in solid phase proportions, Ma/Mc of 1.02, and melt/rock ratio from ~0.1 to 0.01. Figure 21F shows results of reaction between the same eclogite melt and depleted peridotite, with no change in solid phase proportions, Ma/Mc of 1.04, and melt/rock ratio from ~0.02 to 0.002, extending to very large increases in liquid mass. Crystal/liquid distribution coefficients and model rock and liquid compositions are given in Table 3.

Moderate amounts of reaction between partial melts of eclogite and spinel peridotite, under conditions of increasing liquid mass, produce liquids with trace element patterns similar to continental crust. Only Zr and Hf in continental crust are not well fit by these models. Large extents of reaction between eclogite partial melts and spinel peridotite produce liquids with nearly flat REE patterns that retain enrichments in Ba, Th, U, and K and fractionations of Nb/La, Ce/Pb and Sr/Nd seen in arc lavas worldwide.

These models are presented to show *possible* outcomes of various igneous processes. We make no claim that the these are unique explanations for the trace element contents of Aleutian lavas or continental crust. Also, the models could be incorrect if we have chosen inappropriate crystal/liquid distribution coefficients (Table 3). For the most part, small variations in distribution coefficients resulting from mineral and melt composition in basaltic systems are insignificant for our purposes in modeling. However, there is a substantial difference between distribution coefficients between minerals and basaltic melt, on the one hand, and minerals and andesitic to dacitic melt on the other hand. Whereas mineral/basalt partitioning has been extensively investigated, mineral/dacite partitioning is less well studied. In compiling mineral/dacite distribution coefficients for modeling partial melting of eclogite, we have relied mainly on studies of trace element partitioning between phenocrysts and matrix in volcanic rocks. For some elements (Th, U, Nb, Pb in clinopyroxene/dacite melt) we have had to interpolate values based on the pattern of distribution coefficients for mineral/basalt, and better known values for mineral/dacite for other elements (Ba, K, Ce, Nd in clinopyroxene/dacite melt). For highly incompatible elements, such as Ba, Th, U and K, our interpolated values are not crucial to the results of modeling. However, in considering our model results which show fractionation of Ce/Pb and Sr/Nd, the choice of distribution coefficients could be crucial. Thus, readers should be cautious in evaluating these results. With this said, we note that our models are consistent with the experimental data of [*Rapp et al.,* 1999], and the trace element models of Tatsumi ([*Tatsumi,* 2001], and pers. comm., 2000).

Also, Ti is not a trace element in processes involving residual rutile. As a result, strictly speaking, it should not be modeled here. However, we adjusted the distribution coefficients for Ti in clinopyroxene, garnet and rutile to provide results that are consistent with the experimental data of [*Rapp et al.,* 1999], which show no fractionation of Ti from REE such as Dy and Tb.

Table 3. Values used in trace element modeling.

Table 3A: peridotite melting, magma/mantle interaction

element	D ol/liq	refs	D opx/liq	refs	D cpx/liq	refs	D gar/liq	refs	D sp/liq	refs
olivine	1									
opx			1							
cpx					1					
garnet							1			
spinel									1	
rutile										
Ba	1.0E-09	estim. ≈ D(K)	0.00001	estim. ≈ D(K)	0.00068	5	0.00001	estim. ≈ D(K)	0	estim. ≈ D(K)
Th	1.0E-09	estim. ≈ D(K)	0.00001	estim. ≈ D(K)	0.01 6 0.001	9	0	estim. ≈ D(K)		
U	1.0E-09	estim. ≈ D(K)	0.00001	estim. ≈ D(K)	0.003	7	0.005	9	0	estim. ≈ D(K)
K	1.0E-09	1	0.00001	1	0.0072	1,5	0.00001	1	0 1	
Nb	0.001	1	0.0029	1	0.0077	1,5	0.013	1	0.01	1
La	0.000007	1	0.001	1	0.0536	1,5	0.001	1	0.0006	1,12
Ce	0.00001	1	0.003	1	0.0858	1,5	0.008	1	0.0006	1,12
Pb	0.00001	estim. ≈ D(Ce)	0.003	estim. ≈D(Ce)	0.072	1,5	0.0005	10	0	estim. ≈ D(K)
Pr	0.00004	interpolated	0.006	interpolated	0.13	interpolated	0.033	interpolated	0.0006	1,12
Sr	0.00001	1	0.003	1	0.1283	1,5	0.007	1	0	estim. ≈ D(K)
Nd	0.00007	1	0.009	1	0.1873	1,5	0.057	11	0.0006	1,12
Zr	0.004	1	0.04	1	0.1234	1,5	0.5	1	0.07	1
Hf	0.004	estim. ≈ D(Zr)	0.04	estim. ≈ D(Zr)	0.256	1,5	0.5	1	0.07	1
Sm	0.0007	1	0.02	1	0291	1,5	0.217	11	0.0006	1,12
Eu	0.00095	1	0.03	1	0.33	1,5	0.45	11	0.0006	1,12
Gd	0.0012	interpolated	0.04	interpolated	0.37	interpolated	0.9	interpolated	0.0006	interpolated
Tb	0.0026	interpolated	0.05	interpolated	0.41	interpolated	1.5	interpolated	0.006	interpolated
Ti	0.015	1,2	0.15	1,2	0.4	1,2,5	0.6	1	0.15	1
Dy	0.004	1	0.06	1	0.442	1,5	2	11	0.0015	1,12
Ho	0.007	interpolated	0.065	interpolated	0.43	interpolated	2.8	interpolated	0.0023	interpolated
Er	0.009	1	0.09	1	0.43	8	3.5	11	0.003	1,12
Yb	0.023	1	0.1	1	0.43	1,5	7	11	0.0045	1,12
Lu	0.03	interpolated	0.12	interpolated	0.433	1,5	9	11	0.0053	1,12
Y	0.023	estim. ≈ D(Yb)	0.1	estim. ≈ D(Yb)	0.467	1,5	7	estim. ≈ D(Yb)	0.0045	estim. ≈ D(Yb)
Co	2	bulk D estim.≈ 2	2	bulk D estim. ≈ 2	2	bulk D estim. ≈ 2	1	bulk D estim. ≈ 2	2	bulk D estim. ≈ 2
Ni	10	3	3.5	4	3	4	5	4	10	4

estim. = estimated

Table 3: Values used in trace element modeling, continued.

Table 3B: eclogite melting

element	D gar/liq	refs	D cpx/liq	refs	D rutile/liq	refs
olivine						
orthopyroxene						
clinopyroxene	1					
garnet	1					
spinel						
rutile	1					
Ba	0.02	13	0.02	13,20	0	guessed
Th	0.001	estim. ≈ peridotite	0.03	21,22	0	guessed
U	0.005	estim. ≈ peridotite	0.04	21,22	0	guessed
K	0.02	13	0.02	13	0	guessed
Nb	0.05	14	0.02	21	30	25, 30
La	0.08	15	0.04	23	0	guessed
Ce	0.2	13,15	0.08	23	0	guessed
Pb	0.005	estim. ≈ 10x perid	0.1	21	0	guessed
Pr	0.4	interpolated	0.14	interpolated	0	guessed
Sr	0.03	13,16,17	0.07	13,22,24	0	guessed
Nd	0.8	13,15	0.2	23	0	guessed
Zr	5	16	0.3	21,23	40	estim. > D(Nb)
Hf	5	15	0.3	20,23	40	estim. ≈ D(Zr)
Sm	5	13,15,16,18	0.4	23	0	guessed
Eu	7	13,15	0.45	13,21,22,23	0	guessed
Gd	10	13,15	0.6	23	0	guessed
Tb	14	13,15	0.65	interpolated	0	guessed
Ti	12	19	0.6	19	100	19, 30
Dy	16	13,18	0.7	13,23	0	guessed
Ho	18	15,18	0.7	interpolated	0	guessed
Er	20	13	0.7	23	0	guessed
Yb	25	13,15,18	0.7	13,21,22,23	0	guessed
Lu	30	13,15	0.7	13,21,22,23	0	guessed
Y	25	16	0.8	21	0	guessed
Co	2	15	1	22	0	guessed
Ni	1	bulk D estim. ≈ 1	1	bulk D estim. ≈ 1	0	guessed

crust did not, and this was *independent of subduction rate,* then we could infer that subduction zone temperature was crucial in enriched, high Mg# andesite genesis, and thus that eclogite melting is essential.

There are many localities with enriched, primitive andesites similar to those in the Aleutians: e.g., SW Japan, the Cascades, Baja California, Mexico, and the Astral Volcanic Zone in southern Chile [*Defant et al.,* 1991; *Defant et al.,* 1989; *Hughes and Taylor,* 1986; *Rogers et al.,* 1985; *Puig et al.,* 1984; *Tatsumi and Ishizaka,* 1982]. Unfortunately, in all of these areas the subducting oceanic crust is younger than 25 Ma and trench-orthogonal convergence rates are less than 40 mm/yr. Thus, it is difficult to separate the effect of subducting young crust from the effect of slow convergence. Young crust is subducting at high convergence rates along the Andean subduction zone north of the Austral Andes. With the exception of the Puna Plateau area [*Kay and Kay,* 1994], primitive andesites are not found north of the Austral volcanic zone[3]. Perhaps, subduction of young oceanic crust alone is not sufficient to ensure the presence of abundant, enriched primitive andesite lavas.

The Lesser Antilles and the South Sandwich arcs have among the slowest arc convergence rates [*DeMets et al.,* 1994; *Argus and Gordon,* 1991; *DeMets et al.,* 1990]. High Mg# andesites are found in neither arc. Oceanic crust older than 60 Ma is being subducted beneath the Lesser Antilles and the northern half of the South Sandwich arc. Crust subducting beneath the southern half of the South Sandwich arc

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[3] The primitive andesites of the Puna Plateau have been interpreted as the result of delamination and partial melting of exceptionally thick lower crust [*Kay and Kay,* 1993].

Table 3: Values used in trace element modeling, continued.

Table 3C: bulk distribution coefficients

element	eclogite source & melt mode (MORB)	garnet peridotite source mode (pyrolite)	garnet peridotite melt mode (pyrolite)	spinel peridotite source mode (pyrolite)	spinel peridotite source mode (abyssal peridotite)
reference	26	27	27	27	28
olivine	54	10	46	75	
orthopyroxene	17	18	28	20	
clinopyroxene	0.495	9	30	18	
garnet	0.495	20	42		
spinel	8	5			
rutile	0.01				
Ba	0.020	6.5E-05	2.1E-04	1.3E-04	2.0E-06
Th	0.015	1.1E-03	3.4E-03	1.8E-03	2.0E-06
U	0.022	1.3E-03	3.0E-03	5.4E-04	2.0E-06
K	0.020	6.5E-04	2.2E-03	1.3E-03	2.0E-06
Nb	0.335	4.3E-03	8.4E-03	3.3E-03	1.8E-03
La	0.059	5.2E-03	0.017	0.010	2.4E-04
Ce	0.139	0.010	0.030	0.016	6.4E-04
Pb	0.052	7.1E-03	0.022	0.014	6.1E-04
Pr	0.267	0.019	0.054	0.025	1.3E-03
Sr	0.050	0.013	0.042	0.024	6.1E-04
Nd	0.495	0.030	0.082	0.036	1.9E-03
Zr	3.024	0.120	0.255	0.039	0.015
Hf	3.024	0.132	0.294	0.063	0.015
Sm	2.673	0.073	0.182	0.058	0.005
Eu	3.688	0.125	0.293	0.068	0.007
Gd	5.247	0.221	0.496	0.078	0.009
Tb	7.252	0.347	0.762	0.089	0.012
Ti	7.237	0.190	0.401	0.130	0.049
Dy	8.267	0.452	0.984	0.098	0.015
Ho	9.257	0.614	1.317	0.099	0.018
Er	10.247	0.759	1.616	0.107	0.025
Yb	12.722	1.468	3.089	0.116	0.037
Lu	15.197	1.876	3.935	0.126	0.047
Y	12.771	1.471	3.100	0.123	0.037
Co	1.485	1.800	1.580	1.960	2.000
Ni	0.990	7.265	4.630	6.720	8.700

Table 3D: bulk compositions/MORB

element	MORB	"pyrolite" (approx MORB source)	abyssal peridotite
reference		Ringwood, 1966	29
Ba	1	0.1	0.001
Th	1	0.1	0.001
U	1	0.1	0.001
K	1	0.1	0.001
Nb	1	0.1	0.001
La	1	0.1	0.001
Ce	1	0.1	0.015
Pb	1	0.1	0.01
Pr	1	0.1	0.02
Sr	1	0.1	0.02
Nd	1	0.1	0.03
Zr	1	0.1	0.03
Hf	1	0.1	0.03
Sm	1	0.1	0.03
Eu	1	0.1	0.03
Gd	1	0.1	0.03
Tb	1	0.1	0.03
Ti	1	0.1	0.03
Dy	1	0.1	0.03
Ho	1	0.1	0.03
Er	1	0.1	0.03
Yb	1	0.1	0.03
Lu	1	0.1	0.03
Y	1	0.1	0.03
Co	1	2	2
Ni	1	10	10

Table 3: Values used in trace element modeling, continued. Notes

1. Kelemen et al., 1993, references cited therein, and our unpublished ion probe data
2. Kelemen et al., 1990b
3. Arndt, 1977; Hart & Davis, 1978; Kinzler et al., 1990
4. Olivine/liquid from refs. in 3, plus mineral/olivine from Bodinier et al., 1987; Kelemen et al., 1998
5. Hart & Dunn, 1993
6. Value based on Hauri et al., 1994 and LaTourrette & Burnett 1992; for our purposes, these are sufficiently close to other values suggested by Beattie, 1993; Lundstrom et al., 1994; Salters & Longhi, 1999; Wood et al., 1999
7. Value based on Beattie, 1993; for our purposes, these are sufficiently close to other values suggested by Hauri et al., 1994; LaTourrette & Burnett 1992; Lundstrom et al., 1994; Salters & Longhi, 1999; Turner et al., 2000
8. Adjusted from value in Hart & Dunn (1993) to give smooth REE pattern for garnet peridotite and eclogite melting.
9. Values based on LaTourrette & Burnett, 1992; Beattie, 1993; and Hauri et al., 1994; for our purposes these are sufficiently close to other values suggested by Salters & Longhi, 1999
10. Hauri et al., 1994; Beattie, 1993; Salters et al., 2001
11. Shimizu & Kushiro, 1975
12. Stosch, 1982
13. Philpotts & Schnetzler 1970a,b; Schnetzler & Philpotts, 1970
14. Interpolated based on garnet D pattern in ref. 1 and K, La values
15. Irving & Frey, 1978
16. Green et al., 1989
17. Jenner et al., 1993
18. Nicholls & Harris, 1980
19. Ti is a major element during partial melting with residual rutile, and its concentration is controlled by phase equilibrium rather than partitioning. However, for modeling, Ti value is interpolated based on garnet and cpx D patterns in refs. 1, 5, plus and Tb, Dy values in this Table, then adjusted to fit observation by Rapp et al., 1999, that Ti is not fractionated from REE during rutile saturated partial melting of eclogite.
20. Luhr & Carmichael, 1984
21. Larsen, 1979
22. Dostal et al., 1983
23. Fujimaki et al., 1984
24. Hart & Brooks, 1974
25. Green & Pearson, 1987
26. Rapp papers
27. Kelemen et al., 1992
28. Dick, 1989
29. Based on ~5% cpx (exsolved from high temperature opx) and cpx data from Johnson et al., 1990; Johnson & Dick, 1992
30. Foley et al., 2000

formed at the super-slow spreading American-Antarctic Ridge. Super slow spreading crust is anomalously cold, at a given age, compared to oceanic crust created at full spreading rates greater than ~ 0.01 m/yr [e.g., *Henstock et al.,* 1993; *Phipps Morgan and Chen,* 1993; *Reid and Jackson,* 1981; *Sleep,* 1975], and is sometimes composed mainly of serpentinized mantle peridotite [*Dick,* 1989; *Snow,* 1995]. However, the examples of the Lesser Antilles and the South Sandwich arc illustrate that slow convergence alone is insufficient to ensure the presence of abundant, enriched primitive andesites.

In summary, both slow convergence and young subducting crust may be necessary in order to produce abundant primitive andesite lavas.

4.7 Residual Rutile? Yes, in Partial Melting of Eclogite

Kay [1978] presented a simple model of a small degree of melting of MORB in eclogite facies, which accounted for the REE and Sr contents of the enriched, high Mg# andesites on Adak. Noting that the Mg# and Ni contents of these lavas were much higher than in a small degree melt of MORB, Kay suggested that eclogite melts reacted with the mantle during ascent. More recently, this model has been extended to include additional incompatible elements. In particular, rutile is residual during small to moderate degrees of melting of MORB-like compositions in eclogite facies [*Rapp and Watson,* 1995; *Rapp et al.,* 1991]. Elements such as Ta and Nb are compatible in rutile, and thus the depletion of Ta and Nb relative to La in enriched, high Mg# andesites—and other arc lavas—can result from eclogite melting [*Yogodzinski et al.,* 1995; *Kelemen et al.,* 1993; *Ryerson and Watson,* 1987].

Rutile might also be stable in some peridotite/melt systems [e.g., *Bodinier et al.,* 1996], perhaps under conditions where melts are hydrous, silica-rich, TiO_2-rich, and low temperature [*Schiano et al.,* 1995; *Schiano and Clocchiatti,* 1994; *Schiano et al.,* 1994]. To evaluate this, we calculated TiO2 required for rutile saturation ([*Ryerson and Watson,* 1987], using temperatures from Section 2.1) and compared it to observed TiO_2 in Aleutian primitive andesites. At 1 to 3 GPa, with 0 to 10 wt% H_2O, assuming an uncertainty of 0.5 wt%, more than 75% of 50 primitive Aleutian andesites have too little TiO_2 for rutile saturation.

Thus, residual rutile *in the mantle* does not cause Ta and Nb depletions in primitive andesites. Instead, we infer that a component in *all* primitive Aleutian andesites—regardless of the degree of light REE enrichment—is a rutile-saturated eclogite melt. Ta and Nb in primitive Aleutian lavas are weakly correlated with La concentration. Therefore, Ta and Nb depletion probably form in the same manner as light REE enrichment, due to residual rutile and garnet in an eclogite source.

4.8 Thermal Models and Partial Melting in the Aleutian Subduction Zone

Up to this point, we have reviewed a variety of possible explanations for genesis of enriched, primitive Aleutian andesites. At the end of Section 4.5, we were left with four possibilities in explaining the genesis of primitive Aleutian andesites, two of which involved partial melting of subducted eclogite. In Section 4.7, we concluded that eclogite melting is required to explain depletions of Nb and Ta relative to REE in these lavas. Therefore, we can narrow the list to two possibilities: (1) Eclogite melting in a hot subduction zone in the west, or (2) eclogite melting throughout the arc, obscured in the east by extensive melting of hot, H_2O-rich mantle.

If a sediment melt component is clearly required in the central Aleutians (Section 2.4), and a basaltic eclogite melt component is required in the western Aleutians (Sections 2.6 and 4.7), then we should choose option (2); partial melting of subducted material is ubiquitous throughout the arc. Indeed, as already mentioned in Section 2.4, Plank, Langmuir, Miller, Class and colleagues have proposed that a sediment melt component is important in the central Aleutians, based on correlation between subducted Th in sediments and Th concentration in arc lavas, correlation between Th concentration and Nd isotope ratios, and data on Th partitioning between sediments, aqueous fluids, and melts [*Class et al.,* 2000; *Plank and Langmuir,* 1998; *Miller et al.,* 1994; *Plank and Langmuir,* 1993; *Miller et al.,* 1992]. However, because this relies mainly on ideas about Th partitioning, this hypothesis may be open to question due to lingering uncertainty about aqueous fluid/rock partitioning.

To further evaluate these two options, we consider the thermal state of subduction zones and the overlying mantle wedge, both for the Aleutians and on a worldwide basis. We turn first to Aleutian data. With one exception, the 18 Aleutian high Mg# andesites with the strongest light REE enrichment (La/Yb > 9) are Miocene [*Kay et al.,* 1998; *Yogodzinski et al.,* 1995]. These samples, found on Adak Island and in the Komandorsky block, have Sr/Y > 50 and other distinctive characteristics. They have been interpreted as partial melts of subducted basalt in eclogite facies, which underwent reaction with the mantle during transport to the surface [*Yogodzinski and Kelemen,* 1998; *Yogodzinski et al.,* 1995; *Defant and Drummond,* 1990; *Kay,* 1978]. One might infer that partial melting of subducted basalt occurred during the Miocene but has since ceased.

However, the exception is a single dredged lava from a submarine cone near Buldir Island in the western Aleutians (sample 70B29, 184.7°W) has 63 wt% SiO_2, an Mg# of 0.56, 9960 ppm K, La/Yb of 9.8, and Sr/Y of 73 (or Sr/(9.6*Yb) of 104). This sample was too young to date by conventional K/Ar methods [*Scholl et al.,* 1976] and so is estimated to be less than 600,000 years old. The down-dip subduction velocity beneath this site is estimated to be ~ 0.04 m/yr and the age of the plate beneath this site is estimated to be ~ 45 to 50 Ma.

Additional evidence for a young, enriched high Mg# andesite component in the western Aleutians comes from plutonic xenoliths in Holocene lavas from Adak. These xenoliths include clinopyroxene crystals with fine-scale oscillatory zoning, and interstitial glass that was quenched against the host lava [*Conrad and Kay,* 1984; *Conrad et al.,* 1983]. The preservation of fine scale zoning (zones with distinct Fe and Mg contents as small as 25 microns) and quenched interstitial glass both indicate that the xenoliths are not much older than their host lavas. Even assuming that the interstitial glasses were hydrous and therefore relatively low temperature, one can use a lower limit diffusivity of ~ 10^{-22} m^2/s for Fe/Mg interdiffusion in clinopyroxene (e.g., summary in [*Van Orman et al.,* 2001]) to calculate that the 25 micron zones are less than ~ 200,000 years old.

Our recent ion probe analyses of clinopyroxene in these xenoliths [*Yogodzinski and Kelemen,* 2000] show that some zones have Sr/Y as high and higher than the clinopyroxene phenocrysts in previously analyzed, enriched primitive andesites [*Yogodzinski and Kelemen,* 1998], suggesting that the xenoliths crystallized, in part, from Holocene, enriched primitive andesites. The down-dip subduction velocity beneath Adak is ~ 0.06 m/yr and the age of the subducting plate beneath this site is ~ 45 to 50 Ma. Tectonically, Adak overlies a normal Benioff zone [e.g., *Boyd et al.,* 1995; *Boyd and Creager,* 1991], not a "torn slab".

Thermal models for arcs are reviewed in two separate papers in this volume [*Kelemen et al.,* this volume; *Peacock,* this volume], to which the reader is referred for references, models, and discussion. Here we give a short summary. Published thermal models up to 2002 suggest that partial melting of subducted oceanic crust more than 20 Myr old, and sediments overlying such crust, is unlikely. This is the chief objection to the geochemically-based hypothesis that there is a sediment melt component in the central Aleutians. However, this modeling result is inconsistent with evidence for an eclogite melt component in the enriched, high Mg# andesites at Adak Island. Also, these thermal models are inconsistent with petrological PT estimates for melt-mantle equilibration and metamorphic conditions in arc shallow mantle and lower crust, and do not account well for seismic data which indicate a region of anomalously low velocities (probably, a few percent melt) at 35 to 50 km depth in the shallow mantle beneath the NE Japan and Tonga arcs. Very recent work shows that incorporation of temperature-dependent viscosity and non-Newtonian mantle rheology yields thermal models consistent with fluid saturated melting of subducted sediment and/or basalt beneath the central Aleutians [*Kelemen et al.,* this volume; *van Keken et al.,* 2002; *Conder et al.,* 2002]. Some of these models are also consistent with petrological PT constraints from arc shallow mantle and lower crust [*Kelemen et al.,* this volume].

These new models do not "prove" that subducted sediment and/or basalt beneath the central Aleutians must undergo partial melting. However, they do show that well-constrained thermal models using widely accepted formulations for temperature- and stress-dependent mantle rheology, can be consistent with petrological PT constraints. Thus, the most recent results of thermal modeling show that melting of subducted material beneath the entire Aleutian arc may be likely, rather than impossible.

4.9 Melting of Subducted Material Throughout the arc, or Only in the West? Throughout.

The results of very recent thermal modeling show that subducted sediment and basalt could melt beneath both the central and western Aleutians. We find the incompatible trace element evidence for a partial melt component derived from subducted material in the central Aleutians persuasive [*Class et al.,* 2000]. Similarly, in Sections 4.5 and 4.7, we have argued that there is strong trace element evidence for partial melting of subducted eclogite in the western Aleutians, even beneath Adak where subducting crust is 45 to 50 Ma and the subduction zone geometry is "normal". Therefore, we hypothesize that partial melting of subducted material is ubiquitous throughout the arc.

If partial melting of subducted material is ubiquitous beneath the Aleutian arc, then why are the highly enriched trace element signatures indicative of an eclogite melt component most clearly observed in lavas at and west of Adak? One possible explanation is that the colder mantle wedge in the western Aleutians, convecting more slowly and fluxed by a smaller proportion of aqueous fluid, undergoes relatively little partial melting. As a result, in the western Aleutians partial melts of eclogite rise through and react with the surrounding mantle (Section 4.10), but generally do not mix with basaltic magmas derived from melting of peridotite. Further east, the hotter mantle wedge undergoes extensive melting, due to rapid convective upwelling and abundant hydrous fluids derived from the colder subducting plate. In this region, the mantle-derived basalts are far more voluminous than the component derived from partial melting of subducted material. As a result, the subduction zone melt component is difficult to detect unambiguously, except via enrichments of highly incompatible and insoluble elements such as Th.

This conclusion is somewhat at odds with the conclusions of *Miller et al.* [1992] who argued that the geochemical component derived from subducted basalt at Umnak Island in the central Aleutians was transported entirely in aqueous fluids. Miller et al. used the relationship of Ce/Pb and ^{207}Pb/^{204}Pb in lavas from Umnak Island in the central Aleutians to argue that Pb derived from subducted basalts is transported into the mantle wedge in a low Ce/Pb fluid rather than a high Ce/Pb melt phase. This, combined with evidence for sediment melting described in the previous paragraph (and in Section 2.4) gave rise to the aphorism, "sediments melt, basalts dehydrate". However, as we have shown in Section 2.5 and Figure 15, MORB-like Pb isotopes are observed in both high and low Ce/Pb Aleutian lavas. Because Ce/Pb is correlated with Dy/Yb and Sr/Y, thought to be indicative of an eclogite melt component in the Aleutians, we infer that the MORB-like Pb isotope signature in high Ce/Pb Aleutian lavas is derived from a partial melt of subducted basalt, not from the mantle wedge. While high Ce/Pb lavas are mainly found at and west of Adak, they are also present at Bogoslof and Amak Islands, behind the main arc trend in the central Aleutians.

Where sediments are present, their high Ba, Pb, Sr and REE contents and extreme isotope ratios (compared to MORB and the mantle) will dominate most trace element and isotopic characteristics of a partial melt derived from both sediment and basalt. Under these circumstances, it is difficult or impossible to detect a basalt melt component. Only where sediments are rare or absent is it easy to clearly detect a component derived from partial melting of basaltic eclogite.

At a given pressure, the fluid-saturated solidus should be at very similar temperatures in both basaltic and sedimentary bulk compositions, since both pelitic sediments and basalts in eclogite facies are composed of mixtures of garnet, omphacite, kyanite, coesite and phengite, plus various minor phases (Max Schmidt, pers. comm. 2000). This is borne out by experimental data [*Johnson and Plank,* 1999; *Schmidt and Poli,* 1998; *Nichols et al.,* 1994; *Carroll and Wyllie,* 1989; *Stern and Wyllie,* 1973; *Lambert and Wyllie,* 1972], in which some sediments apparently melt at higher temperatures than basalt, while others apparently melt at lower temperatures. Thus, it is difficult to envision a realistic scenario in which subducted sediments consistently undergo partial melting while subducted basalts never do. Instead, it seems likely that, for any given subduction zone geotherm, both undergo partial melting, or both do not.

4.10 Reaction Between Partial Melts of Subducted Eclogite and Overlying Mantle Peridotite

4.10.1 Phase equilibria. Small degree partial melts of eclogite are not in equilibrium with mantle olivine. Since the primitive andesite magmas which carry the trace element signature of eclogite melting show signs of having equilibrated with mantle peridotite—at least in terms of Fe/Mg and Ni exchange—we infer that they did not ascend in cracks all the way from the subduction zone to the crust. However, it is possible to envision scenarios in which melt is initially transported in cracks that terminate within the mantle, and then react with surrounding peridotite. Alternatively, eclogite melts may begin to react with the mantle wedge immediately above the subduction zone.

At constant temperature and pressure, siliceous melts of eclogite react with olivine to produce pyroxene (± garnet) and modified, lower SiO_2 melt. In simple chemical systems, and probably in some natural systems, such reactions consume more liquid than they produce, ultimately leading to complete solidification, or "thermal death" [*Rapp et al.,* 1999; *Yaxley and Green,* 1997]. This is particularly likely where reaction takes place below the solidus temperature for the peridotite, but also could occur at conditions above the peridotite solidus in systems that have a "thermal divide" between eclogite and peridotite melts [*Yaxley and Green,* 1997]. It is possible that some eclogite melts do undergo thermal death, and then hybridized, pyroxene-rich mantle peridotite circulates to some other part of the mantle wedge, later melting to give rise to an enriched magma [e.g., *Yogodzinski et al.,* 1994; *Ringwood,* 1974].

However, the observation of ^{230}Th excess in enriched, primitive andesites from Mt. Shasta in the Cascades [*Newman et al.,* 1986] and in the Austral Volcanic Zone in southernmost Chile [*Sigmarsson et al.,* 1998] provides an important constraint on the transport time of eclogite melt from source to surface. Radiogenic ^{230}Th excess is produced by small degrees of partial melting under conditions in which daughter ^{230}Th is less compatible in residual solids than parent ^{238}U. Present knowledge indicates that U is more compatible than Th in garnet [*Salters and Longhi,* 1999; *Hauri et al.,* 1994; *Beattie,* 1993; *LaTourrette and Burnett,* 1992] and—perhaps—high pressure, Na-rich clinopyroxene [*Wood et al.,* 1999]. Thus, the ^{230}Th excess in enriched, primitive andesites is consistent with derivation of the Th enriched component in such magmas by partial melting of subducted eclogite. The half-life of ^{230}Th is ~ 75,000 yrs. After a few half lives, excess ^{230}Th will decay, and ^{230}Th /^{238}U ratios will return to steady state, "secular equilibrium". Therefore, one can infer that the eclogite melt component in primitive andesites from Mt. Shasta and the Austral Volcanic Zone was transported from the subduction zone to the surface in less than ~ 300,000 years. This is plausible for magma transport via porous flow, hydrofracture, or, perhaps, in partially molten diapirs, but implausible for transport via solidification, solid state convection to a hotter part of the mantle wedge, and remelting.

For this reason, we prefer a model in which the eclogite melt component interacts with mantle peridotite in the wedge, and is modified but never completely solidified. As emphasized by Kelemen and co-workers [*Kelemen,* 1995; *Kelemen,* 1993; *Kelemen,* 1990c; *Kelemen et al.,* 1986], a key to considering reaction between eclogite melt and overlying peridotite is that above subduction zones, melts must heat up as they rise and decompress [*Kelemen and Hirth,* 1998]. *Grove et al.* [2002] recently made a similar point for partial melts of mantle peridotite deep within the mantle wedge. The combined effect of increasing temperature and decreasing pressure will move melt in a closed system away from its liquidus. In a reacting system in which decompressing melt is heated, these effects might counterbalance constant temperature and pressure reactions that lead to "thermal death". Thus, at temperatures below the peridotite solidus, melt mass might be nearly constant. And, if H_2O-rich melt is present at temperatures greater than the fluid-saturated peridotite solidus, melt mass will increase due to the combined effects of heating and decompression.

We also must consider the effect of alkalis and H_2O on melt/peridotite equilibria, via freezing point depression and shifting of melt composition. If reactions between subduction zone melts and peridotite consume melt, alkali and H_2O contents will rise in the remaining liquid. The aqueous fluid-saturated solidus for mantle lherzolite at 2.4 GPa is at less than 920°C [*Grove,* 2001], at least 500°C lower than the nominally anhydrous solidus [e.g., *Hirschmann,* 2000]. This is very close to experimentally constrained fluid-saturated solidii for sediment and basalt at the same pressure, ~ 650 to 750°C [*Schmidt and Poli,* 1998; *Nichols et al.,* 1994; *Lambert and Wyllie,* 1972][4]. Furthermore, because high alkali and H_2O contents stabilize olivine relative to pyroxenes [*Hirschmann et al.,* 1998; *Ryerson,* 1985; *Kushiro,* 1975], stable peridotite melt compositions at the fluid-saturated solidus will be more "felsic" than basalt; i.e., they will have relatively low normative olivine and high normative quartz or nepheline. In an open system, addition of alkalis from a subduction zone melt will heighten this effect. Thus, fluid-saturated partial melts of subducted material need not change much in temperature or composition to be stable in fluid-saturated mantle peridotite. This process is poorly constrained, but it seems likely that subduction zone melts interact with mantle peridotite in the wedge, and are modified but never completely solidified, to become an important component in Aleutian arc lavas.

4.10.2 Trace element modeling. As noted by *Gill* [1981], most arc magmas, including light REE enriched, calc-alkaline andesites, do not have REE slopes as steep as those in partial melts of eclogite, or even garnet peridotite. This can be seen by comparing trace element results for partial melting of garnet lherzolite (Figure 21A) and eclogite (Figure 21B) with trace element data for Aleutian lavas in Figure 6. Gill inferred from this that partial melting of lherzolite or eclogite with residual garnet did not play an important role in arc petrogenesis. However, *Kelemen et al.* [1993] reasoned that reaction between ascending eclogite melts and spinel peridotite in the mantle wedge might modify REE patterns, particularly if the reaction involved increasing magma mass, as discussed in Section 4.10.1. Middle to heavy REE concentrations can be modified by such reactions to values for melt in equilibrium with spinel peridotite (Figure 21D, E and F).

As a result of mass balance, light REE concentrations are modified much more slowly, and remain high. A rule of thumb is that trace element concentrations are modified by this type of reaction when the integrated melt/rock ratio (the mass of liquid to solid reactants) approaches the bulk crystal/liquid distribution coefficient for a particular element. Thus, in models in which the integrated melt/rock ratio is less than 1 but greater than 0.01, the light REE enriched, heavy REE depleted pattern characteristic of eclogite melts is transformed to produce a light REE enriched melt with a flat middle to heavy REE pattern, similar to common, light REE enriched arc magmas, and to the estimated composition of continental crust. Such a pattern is typical for lavas throughout the Aleutians, and we infer that it is possible—though by no means certain—that the light REE enrichment in Aleutian magmas may be due to the presence of a cryptic eclogite melt component, modified by extensive reaction with spinel peridotite in the mantle wedge.

A more subtle result of this type of modeling is that intermediate concentrations of elements modified by reaction are rare. Thus, for the models in Figure 21D for example, liquids with integrated melt/rock ratios greater than ~ 0.5 preserve the heavy REE depleted characteristics of an eclogite melt, though Ni and Cr (and Mg, Fe, Si) are modified to values in equilibrium for mantle peridotite. In the same models, liquids with integrated melt/rock ratios less than ~ 0.2 have heavy REE close to equilibrium with mantle peridotite. There is a very narrow range of integrated melt/rock ratios (not shown in the Figures) that yield intermediate heavy REE slopes. This is why there are no intermediate heavy REE slopes in Figures 21D, E and F. This may also explain why, in the western Aleutians, we see lavas whose heavy REE preserve a clear eclogite melting signature, and lavas with nearly flat heavy REE slopes, but very few with intermediate heavy REE slopes.

Subduction zone melts may react with mantle peridotite in ways that modify their trace element characteristics substantially. It is even possible that arc tholeiites with unexceptional trace element patterns started out as partial melts of subducted basalt and sediment in eclogite facies. In this view, reaction between subduction zone melts and overlying peridotite may lead to large increases in magma mass, modifying and diluting the original melt composition (Figure 21F). Thus, an arc tholeiite might derive more than 90% of its K_2O and light REE from a partial melt of subducted basalt, but 90% of its heavy REE and MgO from overlying, mantle peridotite.

We do not mean to imply that no aqueous fluid is derived from subducting material and incorporated into arc magmas. In the hypothetical arc tholeiite discussed in the previous paragraph, perhaps 90% of the B is derived from a fluid. In this paper, we have not concentrated on characterizing an aqueous fluid component, except to note that some proposed fluid component indicators (e.g., high Ba/La) do not appear to be separable from proposed sediment melt component indicators (e.g., high Th/La) in the Aleutians (Section 2.5). This does not mean that there are

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[4] However, see [*Johnson and Plank,* 1999] for a hotter sediment solidus.

no fluids in the Aleutian arc source, but it does make it much more difficult to discern their nature and mode of transport.

For simplicity, we have used the same type of model in Figure 21F as we used for 21D and E. However, liquid mass increases by a factor of up to 20 in 21F. For such conditions, it might be more appropriate to use a fluxed melting model [e.g., *Grove et al.,* 2002; *Eiler et al.,* 2000; *Stolper and Newman,* 1992], or to approximate this effect by mixing a small degree eclogite melt with a larger degree melt of spinel peridotite, rather than using the AFC model we applied. However, it is easy to show that the trace element results of these alternative modeling approaches would be very similar to those in 21F.

5. IMPLICATIONS FOR CONTINENTAL GENESIS

5.1 Reaction Between Eclogite Melt and Mantle Peridotite

Figures 21C and D illustrate results of trace element models of reaction between a small degree partial melt of subducted eclogite and spinel peridotite under conditions of increasing melt mass. As previously proposed by *Kelemen et al.* [1993], the trace element contents of calculated liquids are strikingly similar to the estimated composition of the continental crust. Similarly, major element contents of liquids produced by experimental reaction of silicic melt with mantle peridotite closely approach those of high Mg# andesites and continental crust [*Carroll and Wyllie,* 1989], and of primitive andesites [*Rapp et al.,* 1999]. Thus, we believe that reaction of melts of subducted eclogite with the mantle wedge is a viable model for continental genesis.

In a parallel line of reasoning, many investigators have suggested that unusually orthopyroxene-rich mantle xenoliths derived from Archean cratons underwent SiO_2 enrichment as a result of reaction between highly depleted mantle residues and rising partial melts of subducted eclogite [*Rudnick et al.,* 1994; *Kelemen et al.,* 1992; *Kesson and Ringwood,* 1989]. Recently, *Kelemen et al.* [1998] showed that this hypothesis was compatible with the observed correlation of Ni in olivine with modal orthopyroxene in cratonic mantle xenoliths worldwide, and emphasized that orthopyroxene-rich mantle xenoliths cannot be simple residues of high pressure partial melting of primitive mantle peridotite. Thus, both continental crust and cratonic mantle peridotites may be related by a process of reaction between subduction zone melts and sub-arc mantle peridotites.

A point of clarification is required here. Enriched primitive andesites [e.g., *Kay,* 1978], partial melts of eclogite ([e.g., *Gill,* 1981] and our Figure 21B), and products of small amounts of reaction between eclogite melts and mantle peridotite under conditions of decreasing magma mass [*Rapp et al.,* 1999], all have middle to heavy REE slopes that are much steeper than those in typical Aleutian, calc-alkaline andesite (Figure 6), and much steeper than those estimated for continental crust (Figure 6A). Thus, in detail, we disagree with numerous authors who have proposed that direct partial melts of eclogite—without magma/mantle interaction—form an important component in the continental crust [e.g., *Defant and Kepezhinskas,* 2001; *Martin,* 1999; *Rapp and Watson,* 1995; *Rapp et al.,* 1991; *Drummond and Defant,* 1990; *Martin,* 1986]. We believe that enriched, primitive andesites have undergone relatively little reaction with surrounding mantle. More extensive reaction, with gradually increasing melt mass and melt/rock ratios ~ 0.1 to ~0.01, is required to increase heavy REE concentrations to the levels observed in most calc-alkaline andesites and in continental crust (e.g., Figures 21C and D).

At small melt/rock ratios, such as are required to explain REE systematics, compatible element concentrations and ratios (e.g., Mg#, Ni) would be completely modified to values in equilibrium with mantle peridotite, and thus the liquids parental to high Mg# andesites and continental crust are inferred to be primitive andesites with Mg# > 0.6. Thus, in addition to the reaction of eclogite melt with mantle peridotite, an additional process is required to explain the relatively low Mg# of continental crust (0.45 to 0.55) compared to primitive andesite. We believe the most likely explanation is that primitive andesites fractionate ultramafic cumulates in the uppermost mantle or at the base of the crust [*Müntener et al.,* 2001; *Miller and Christensen,* 1994; *DeBari and Coleman,* 1989], followed by "delamination" and return of these cumulates to the convecting mantle [*Jull and Kelemen,* 2001; *Kay and Kay,* 1993; *Kay and Kay,* 1991; *Arndt and Goldstein,* 1989].

5.2 Archean Versus Present-day Thermal Regime Beneath Arcs

It has often been proposed that Archean continental crust was formed by a process similar to that which forms "adakite" magmas today. *Martin* [1986] suggested that strong light REE enrichment and heavy REE depletion in Archean granitoids was the result of ubiquitous partial melting of eclogite in hotter, Archean subduction zones. Archean subduction zones may have been hotter than today's because of higher mantle potential temperatures and faster rates of mantle convection (and plate tectonics) in the past. In support of Martin's hypothesis, *Defant and Drummond* [1990] noted that modern "adakites" and arc granitoids, both with trace element contents similar to Archean granitoids, are found mainly in arcs where young oceanic crust (< 25 Ma) is being subducted. They inferred that this is due to partial melting of eclogite in unusually hot, modern subduction zones.

In this paper, we have developed the idea that partial melting of subducted sediment and/or basalt may be common in modern subduction zones. This is supported by a variety of trace element evidence from arcs worldwide. We argue that what is uncommon at present is a relative lack of basaltic magmas generated by partial melting of mantle peridotites in arcs such as the western Aleutians, the Cascades, parts of Central America, the Austral volcanic zone in Chile, and SW Japan. We suggest that the lack of basaltic melts in a few unusual localities, due to cooling of the mantle wedge and extensive shallow dehydration of the subducting plate at slow convergence rates, makes it possible to detect end-member magmas with a trace element signature reflecting a large input from partially molten eclogite.

If primitive andesites in modern arcs are the result of partial melting of subducted eclogite and a *cold* mantle wedge, why should this form magmas that are compositionally similar to those which played a large role in *hot*, Archean crustal genesis? Following *Martin* [1986] and many subsequent workers, we believe that Archean subduction zones were hotter than today, on average, due to higher mantle potential temperatures and more rapid rates of plate formation and subduction. Thus, most dehydration reactions in subducting volcanic rocks and sediments would have occurred at shallower depths than today, reducing the amount of H_2O available to flux partial melting in the mantle wedge. In addition, we believe that the Archean shallow mantle was much more depleted in basaltic components than at present. For example, there is good evidence that Archean decompression melting, beneath ridges and/or hot spots, extended to 40% melting at shallow depths, and produced residues with Mg#'s of 0.93 or more [e.g., *Bernstein et al.,* 1998]. Such refractory residues can undergo very little additional melting, even under hydrous conditions. For these reasons, there may have been very little melting in an Archean mantle wedge even though mantle potential temperatures in the Earth's interior may have been much higher than at present. Thus, partial melts of subducted volcanic rocks, reacting with overlying mantle peridotite, might have constituted a large proportion of the total magma flux in Archean arcs.

6. CONCLUSIONS

High Mg# andesites are abundant at and west of Adak at ~ 174°W. In this region, there is a systematic along-strike increase in SiO_2 from east to west. Aleutian high Mg# andesite lavas are important because they are similar in major and trace element composition to the continental crust. Such lavas are rare or absent in intraoceanic island arcs other than the Aleutians. Also, the western Aleutians show the smallest influence of a subducted sediment component of any part of the Aleutians, so that it is unlikely that enrichments in elements such as U, Th, K and light rare earths are due to recycling of subducted, continental sediments. Thus, it appears that juvenile continental crust is being produced in the western Aleutians.

As proposed by *Kay* [1978], enriched, primitive andesites in the western Aleutians are produced by partial melting of subducted oceanic crust in eclogite facies, followed by reaction of these melts with peridotite in the overlying mantle wedge. Such melts probably form beneath the central Aleutians as well as the western Aleutians. In the central Aleutians, they are obscured by coeval partial melts of subducted sediment, with higher incompatible element contents and distinctive isotope ratios, and by mixing with abundant tholeiitic basalts produced by partial melting of the mantle wedge. Enriched, primitive andesites are commonly observed in the western Aleutians because partial melts of subducted sediment and mantle peridotite are much less abundant there. Sediment flux is greatly reduced in the western Aleutians compared to the central arc. Slow convergence rates in the western part of the arc lead to heating of subducting crust and cooling of the mantle wedge. High subduction zone temperatures cause extensive dehydration of sediments and oceanic crust at shallow depths, beneath the forearc region, leaving little H_2O to flux mantle melting.

Partial melts of subducted eclogite are transported through the coldest, deepest portion of the mantle wedge in cracks or partially molten, pyroxenite diapirs. At shallower depths, they interact with mantle peridotite via reactions which increase melt mass, increase molar Mg#, Ni contents, and MgO contents of derivative liquids, and decrease SiO_2 contents of derivative liquids. The andesitic—rather than basaltic—nature of the derivative liquids in the western Aleutians probably reflects the effect of alkalis and H_2O, increasing the silica content of olivine-saturated liquids. Where the mantle wedge is hotter and/or more hydrous, similar reactions may increase magma mass still further, producing a less enriched, basaltic liquid product. In this context, partial melts of eclogite could be a ubiquitous "flux" component in many arcs, even where enriched, primitive andesites are not observed.

End-member, enriched primitive andesites in the western Aleutians provide important insights into the nature of eclogite melt components which may be present in other arcs. They have high Th concentrations, similar to proposed partial melts of sediment in the Marianas, Lesser Antilles and central Aleutian arcs. Thus, high Th, and high Th/Nb, are not good discriminants between eclogite and sediment melt components. However, Th/La correlates well with Pb isotope ratios in Aleutian lavas, so Th/La may be used to distinguish between eclogite and sediment melt components. Interestingly, Th/La also correlates with Ba/La, suggesting that Ba in Aleutian lavas may be transported in partial melts of subducted material rather than, or in addition to, aqueous fluids. Enriched, primitive andesites also have very high Na contents at a given Mg#, compared to other Aleutian lavas. It has been proposed that Na can be used as an indicator of the degree of partial melting in the mantle source of arc magmas, with high Na indicative of low degrees of melting and vice versa [*Plank and Langmuir,* 1992]. However, this can only be true where the "subduction component", added to the mantle source, contains a small and/or constant proportion of Na. In the data we have compiled, Na concentration in primitive lavas correlates with trace element ratios such as Sr/Y and Dy/Yb which are indicative of an eclogite melt component in Aleutian magmas. This suggests that a large proportion of the total Na in primitive magmas is transported in partial melts of subducted eclogite, and thus that Na contents of primitive magmas cannot be used as an indicator of the degree of melting of the mantle wedge, at least in the western Aleutians.

Moderate amounts of reaction of enriched primitive andesites with upper mantle peridotite, followed by crystal fractionation and mixing with evolved lavas, have produced high Mg# andesite lavas and plutonic rocks with compositions very similar to continental crust. We consider it likely that the processes which form high Mg# andesites in the western Aleutians are similar to those which formed continental crust. In the Archean, the mantle wedge above subduction zones was composed of highly depleted, shallow residues of ~ 40% decompression melting beneath spreading ridges or hot spots. Enriched, primitive andesite magmas were transported through the mantle wedge without extensive dilution with mantle-derived melts because of the highly refractory nature of these residual peridotites.

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