Aleutian lead isotopic data: Additional evidence for the evolution of lithospheric plumbing systems

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Abstract—Lead isotopic ratios and concentrations have been measured in lavas from the Aleutian volcanic centers of Adak (12) and Atka (12). Whereas lavas from Atka have very small Pb-isotopic ranges ($^{206}\text{Pb}/^{204}\text{Pb} = 18.78\text{--}18.86$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.55\text{--}15.62$; $^{208}\text{Pb}/^{204}\text{Pb} = 38.31\text{--}38.52$) those from Adak have ranges nearly twice as large ($^{206}\text{Pb}/^{204}\text{Pb} = 18.34\text{--}18.86$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.47\text{--}15.63$; $^{208}\text{Pb}/^{204}\text{Pb} = 37.81\text{--}38.56$). On lead-lead isotopic diagrams, Atka data form tight clusters whereas those from Adak define a well-developed linear trend extending from the Atka field toward less radiogenic values. At a given $^{206}\text{Pb}/^{204}\text{Pb}$, the lavas from both islands plot in the MORB trend for $^{208}\text{Pb}/^{204}\text{Pb}$ but Atka lavas plot above the MORB $^{207}\text{Pb}/^{204}\text{Pb}$ trend and those from Adak fall both within and above the trend.

Lead contents in lavas from Atka increase four-fold (5–21 ppm) over the compositional range of the volcanic suite (49–68% SiO_2). In contrast, Adak lavas (49–65%) have concentration levels of 0.6–13 ppm and display no simple correlation with SiO_2 . The lead isotopic data alone can be explained by three different processes. Model 1 assigns lead isotopic differences to original magma source heterogeneity. According to Model 2, the isotopic ratios of a primary, non-radiogenic component from the mantle are elevated by the addition of an isotopically enriched slab-derived component. In contrast, Model 3 assumes a primary radiogenic magma produced by melting of the slab is contaminated by a non-radiogenic lithospheric component during conduit formation. Because these models all adequately explain the lead isotopic data, supplementary geologic, petrographic, geochemical and isotopic data must be used to select the most likely model. Careful consideration of the evidence suggests Model 3 best explains our extensive lead isotopic data as well as other characteristics of Aleutian lavas. Our study suggests detailed isotopic studies of individual volcanic centers (arc or otherwise) can be extremely useful in understanding the complex processes of magma generation, extraction, ascent and evolution.

INTRODUCTION

BECAUSE THE LEAD concentrations and isotopic compositions of subducted sediment are so different from those of peridotite or MORB (TATSUMOTO, 1978), lead studies have been useful in evaluating the role of sediment in arc magma genesis (TATSUMOTO, 1969; ARMSTRONG and COOPER, 1971; CHURCH and TILTON, 1973; CHURCH, 1976; KAY *et al.*, 1978; BARREIRO, 1983; MORRIS and HART, 1983). Most of these investigations have, however, been regional in nature. That is, they have analyzed a large number of samples from a given arc or arcs, but only a limited number from any one volcanic center. Although such studies have been useful in understanding the general aspects of arc magma genesis, they lack sufficient detail to document differences within and between individual volcanic centers. An extensive strontium isotopic investigation of lavas from two Aleutian volcanic centers has recently shown that significant isotopic differences do indeed exist on the smaller scale (MYERS *et al.*, 1985). Accordingly, we have performed a detailed lead isotopic investigation of two volcanic centers in the central Aleutians (Fig. 1). The two centers (Adak and Atka) were selected for study because: 1) they occur in an oceanic environment far removed from the possible effects of continental crust contamination; 2) pre-

viously published lead data exist for Adak (KAY *et al.*, 1978); and 3) extensive petrographic, compositional and initial $^{87}\text{Sr}/^{86}\text{Sr}$ data exist for both centers (COATS, 1952; MARSH, 1976; KAY *et al.*, 1978; KAY *et al.*, 1982; MYERS *et al.*, 1985, 1986a). Using the new data, we wished to: a) determine if lead isotopic differences exist between the two volcanic centers; b) delimit the role of subducted sediment in parental magma genesis; and c) test the proposed petrologic models of KAY *et al.* (1982), MORRIS and HART (1983) and MYERS *et al.* (1985).

GENERAL GEOLOGY AND PETROGRAPHY

Adak is located in the central Aleutians (Fig. 1). Recent volcanic activity at this center, confined to the northern 100 km² of the island (COATS, 1952, 1956), has been centered on three main volcanic vents (oldest to youngest): Andrew Bay Volcano, Mt. Moffett and Mt. Adagdak. A K-Ar date on a basal flow from Andrew Bay volcano (~500,000 years; MARSH, 1976) suggests this volcanism has covered only the last million years or so. Recent volcanic products total an estimated 40 km³ (MARSH, 1982) and consist of tuff-breccias, breccias and lavas. The volcanic center of Atka is located 150 km east of Adak (Fig. 1). Although recent volcanism is also confined to the northern part of the island (MARSH, 1980), this volcanic center is much larger than Adak. At least fourteen major volcanic vents, each consisting of a thick basaltic shield topped by a composite cone, have been identified. The north-

FIG. 1. Map showing the locations of the Aleutian volcanic centers of Atka and Adak and other volcanic centers mentioned in the text (after MYERS *et al.*, 1985).

ernmost of these volcanoes, Korovin, is presently active. The total volume of erupted material on Atka ($\sim 200 \text{ km}^3$) is nearly five times that of Adak (MARSH, 1982). Like Adak, the most recent phase of volcanism appears to have spanned only about the last million years (MARSH, 1980).

The Atka and Adak volcanic rocks are highly porphyritic with phenocryst abundances between 22 and 50 vol%. Plagioclase is the dominant phase and constitutes well over three-fourths of the phenocryst assemblage. Principal mafic phases, which rarely exceed 6%, include olivine, clinopyroxene, orthopyroxene and magnetite. In lavas with less than 53% SiO_2 , olivine is the characteristic mafic phase but is replaced by orthopyroxene in more siliceous volcanics. Small amounts of magnetite ($\leq 4\%$) are common in both suites. Rare amphibole is found in the late-stage, siliceous domes of Adak (MARSH, 1976). Although no hydrous phases occur in the mafic and intermediate lavas of Atka, minor amounts ($\leq 3\%$) occur in a late-stage dacitic dome (MARSH, 1980). Three important characteristics distinguish the lavas of these two volcanic centers. First, lavas from Atka contain lower total phenocryst contents than those from Adak. Second, xenolithic material is found in at least two Adak units (CONRAD *et al.*, 1983; CONRAD and KAY, 1984; DEBARI *et al.*, 1985) but has not been found in the Atka volcanics. Finally, Atka is dominated by basalts whereas Adak has a more even distribution of rock types.

BULK ROCK COMPOSITIONS

Major elements. With increasing silica (48–67 wt%), Al_2O_3 , FeO^1 , MgO and CaO decrease significantly. TiO_2 decreases slightly and Na_2O and K_2O increase in both volcanic suites (MYERS *et al.*, 1985). For Adak, these trends are marked by significant variability. In contrast, the Atka lavas define smooth compositional trends. Mafic lavas from Atka are typical high-alumina

(20–21%) basalts with low TiO_2 ($< 1\%$) and MgO ($< 6\%$; MYERS *et al.*, 1985, 1986a). The two volcanic suites are also distinguished by differences in: 1) K_2O - SiO_2 variations; 2) absolute oxide abundances for given silica content; and 3) the distribution of lavas within the observed SiO_2 ranges. Despite these differences, mafic lavas from both suites have distinctive major element characteristics (*i.e.* low MgO and TiO_2 , large $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios, high Al_2O_3 , CaO and K_2O) that readily distinguish them from typical MORB (MYERS *et al.*, 1985, 1986a).

Trace elements. Adak Rb, Sr and Ba abundances do not show any systematic variation with silica; rather, they define wide horizontal bands when plotted against silica (MYERS *et al.*, 1985). In contrast, the Atka volcanics display fairly systematic trace element- SiO_2 trends. With increasing silica, Sr decreases (660 to 158 ppm) whereas Ba (300 to 950 ppm) and Rb (10 to 120 ppm) increase significantly. Relative to the Atka mafic lavas, incompatible elements are enriched and more variable in the Adak basalts. In addition, the ranges in trace element abundances for the entire compositional suite are significantly greater in the Atka lavas. The high-alumina basalts of Atka are slightly LREE-enriched, lack significant Eu anomalies and have overall REE abundances that are lower than those typical of other Aleutian basalts (MYERS *et al.*, 1986a).

$^{87}\text{Sr}/^{86}\text{Sr}$. Initial strontium isotopic ratios of Adak volcanics range from 0.70284 to 0.70354 (KAY, 1977; KAY *et al.*, 1978; MYERS *et al.*, 1985) and those of Atka from 0.70320 to 0.70345 (MYERS *et al.*, 1985, 1986a). Relative to Adak, the Atka volcanics are slightly

more radiogenic with a narrower isotopic range. In all except one instance, the Adak lavas are displaced toward lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios relative to Atka.

ANALYTICAL METHODS

Samples chosen for study span the petrographic and compositional range of the two volcanic centers and were previously analyzed for major elements, selected trace elements (Rb, Sr and Ba) and strontium isotopic compositions (MYERS *et al.*, 1985, 1986a). Sample locations are given in MYERS *et al.* (1985). Powders were acid washed in cold, quartz distilled 0.5 N HCl and dissolved in a HF-HNO₃ mixture. One gram of sample was used for isotopic measurements and 400–500 mg for concentration determinations. The lead fraction was separated using one ml quartz columns and the HBr separation procedure. Total lead blanks ranged from 1 to 2 ng. Because of the high lead contents measured (≥ 3 ppm), blank corrections were not necessary. Isotopic ratios were acquired using a 35 cm radius, 90° sector mass spectrometer and the silica gel-phosphate method (CAMERON *et al.*, 1969). Collection of between 50 and 60 ratios yielded an internal precision of 0.05% or better for $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$. Replicate analyses ($n = 17$) of CIT isotopic standard gave the following means: $^{206}\text{Pb}/^{204}\text{Pb} = 16.582 \pm 5$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.412 \pm 6$; $^{208}\text{Pb}/^{204}\text{Pb} = 36.11 \pm 2$. Normalization of our data to absolute values of CIT (CATANZARO, 1967) yielded a per mass fractionation factor of 0.125%. Duplicate analyses gave per cent variations of 0.05, 0.03 and 0.14 for $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$, respectively. Duplicate analyses of U.S.G.S. standard BCR-1 yielded similar variations (Table 1). Lead concentrations and isotopic compositions for Adak and Atka lavas are presented in Table 1. Also reported are corresponding SiO₂ contents (COATS, 1952; MARSH, 1976; MYERS *et al.*, 1985, 1986a).

ANALYTICAL RESULTS

The two volcanic centers have distinctly different lead isotopic characteristics. Lavas from Atka have limited isotopic ranges ($^{206}\text{Pb}/^{204}\text{Pb} = 18.782\text{--}18.860$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.551\text{--}15.617$; $^{208}\text{Pb}/^{204}\text{Pb} = 38.31\text{--}38.52$). In contrast, the Adak

samples are characterized by considerable variability. Including the data of KAY *et al.* (1978), which are similar to ours, the isotopic ranges for Adak are nearly three times those of Atka ($^{206}\text{Pb}/^{204}\text{Pb}$: 18.359–18.883; $^{207}\text{Pb}/^{204}\text{Pb}$: 15.471–15.631 and $^{208}\text{Pb}/^{204}\text{Pb}$: 37.81–38.56, respectively). Although generally less radiogenic, the most enriched Adak lavas have Pb isotopic ratios similar to the Atka volcanics. These differences in lead isotopic character almost exactly mimic those for initial strontium isotopic ratios (MYERS *et al.*, 1985). On Pb-Pb isotopic diagrams, Adak data define a linear trend but Atka isotopic ratios cluster in a group at the radiogenic end of this linear array (Fig. 2). Lead isotopic ratios from both volcanic centers fall within the MORB trend for $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$. For a given $^{206}\text{Pb}/^{204}\text{Pb}$, Atka lavas are, however, enriched in ^{207}Pb relative to MORB. Adak volcanics with high $^{206}\text{Pb}/^{204}\text{Pb}$ (≥ 18.7) are enriched in ^{207}Pb relative to MORB but those with lower values have MORB-like $^{207}\text{Pb}/^{204}\text{Pb}$ (Fig. 2).

Lead isotopic data exist for only five Aleutian volcanic centers other than Adak and Atka (Fig. 3). Since these centers are from the eastern and central Aleutians, the geographic coverage of the Aleutian arc with respect to lead isotopic data is strongly skewed. Lavas from four of the complexes have lead isotopic characteristics similar to those of Atka. The number of lavas analyzed per center is, however, only a third of that for Atka. Consequently, these measured ranges may not accurately reflect the isotopic variability of these centers. In contrast, fifteen lavas from Okmok volcano on Umnak have been analyzed for lead isotopic composition (NYE and REID, 1986). These data define isotopic ranges that are larger than those of Atka but smaller than Adak's (Fig. 3). On Pb-Pb isotopic diagrams, the combined Aleutian data define fields that are displaced to higher $^{206}\text{Pb}/^{204}\text{Pb}$ relative to Adak and Atka (Fig. 2). For a given $^{206}\text{Pb}/^{204}\text{Pb}$, these data also plot at slightly lower values for the other lead isotopic ratios. Relative to MORB, the entire Aleutian data mimic the relations observed for the lavas from Atka and Adak. For a given $^{206}\text{Pb}/^{204}\text{Pb}$, the Aleutian $^{208}\text{Pb}/^{204}\text{Pb}$ ratios plot below those of lavas from the South Sandwich (COHEN and O'NIONS, 1982a; BARREIRO, 1983) and Kermadec (OVERSBY and EWART, 1972) arcs but within the fields of Tonga (OVERSBY and EWART, 1972; SUN, 1980) and the Mariana (MEIJER, 1976, 1982; MEIJER and REAGAN, 1981). On the $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagram, lavas from Tonga, South Sandwich and Kermadec plot at $^{207}\text{Pb}/^{204}\text{Pb}$ ratios above or at the upper limit of those from the Aleutians (Fig. 2). In contrast, Mariana samples fall at the lower boundary of the Aleutian field. Clearly, there is a continuum in arc lava lead isotopic compositions from nearly MORB-like (Mariana, Aleutians) to much more enriched values (South Sandwich).

Lead concentrations range from 3 to 21 ppm (Table 1). Atka lead abundances increase from 4–5 ppm in the basalts to 21 ppm in the most siliceous lavas analyzed. This increase in lead content is, however, not linear; a large compositional range characterizes lavas with silica between 60–65 wt%. In contrast, the maximum lead contents of Adak lavas (13 ppm) do not occur in the most siliceous lavas. With increasing SiO₂, lead abundances increase from 2–3 ppm in the basalts to ~5 ppm in the basaltic andesites and then to a maximum (9–13 ppm) at 60% SiO₂. At higher silica contents, lead content decreases. In general, Adak lavas are also characterized by considerable variability. The lead concentrations in the basaltic lavas from these two islands differ in a manner opposite that of other incompatible elements. Measured Pb abundances of Atka basalts (~5 ppm) are slightly greater than those of Adak lavas (2–3 ppm; Table 1). In contrast to lead, the Atka lavas are significantly depleted in Rb and Ba relative to Adak basalts (MYERS *et al.*, 1985, 1986a).

LEAD ISOTOPIC SYSTEMATICS

Our detailed study of these two volcanic centers has revealed: 1) significant lead isotopic variability in Adak

TABLE 1: Pb concentrations and isotopic compositions for Adak and Atka lavas.

Sample Number	SiO ₂	Pb (ppm)	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
AD-36	48.39 ²	3.6	18.718	15.560	38.289
AD-61	52.14 ³	2.5	18.598	15.533	38.148
AD-109	54.16 ¹	5.2	18.776	15.546	38.299
AD-49	56.34 ³	6.1	18.721	15.552	38.279
AD-114	58.01 ¹	9.4	18.883	15.631	38.561
AD-9	58.86 ³	4.9	18.591	15.528	38.068
AD-99	58.88 ¹	13.4	18.823	15.579	38.400
AD-90	60.46 ¹	7.3	18.812	15.591	38.430
AD-92	60.94 ¹	8.6	18.511	15.504	37.988
AD-58	62.92 ¹	7.2	18.816	15.547	38.139
AD-104	65.02 ¹	3.2	18.530	15.539	38.118
AD-97	90.83 ¹	0.6	18.560	15.523	38.078
			18.557	15.525	38.068
AT-66	50.13 ⁴	5.2	18.828	15.575	38.400
AT-67	49.10 ⁴	4.4	18.782	15.573	38.400
AT-68	50.87 ⁴	5.0	18.829	15.571	38.190
AT-73	49.08 ⁴	4.8	18.825	15.578	38.410
AT-76	50.42 ⁴	5.1	18.815	15.617	38.390
			18.838	15.612	38.520
AT-90	53.1 ¹	8.0	18.837	15.582	38.400
AT-21	55.70 ¹	8.3	18.839	15.584	38.430
AT-34	56.34 ¹	7.5	18.791	15.555	38.309
AT-22	61.37 ¹	18.1	18.847	15.597	38.470
AT-117	62.49 ¹	11.6	18.860	15.601	38.480
AT-150	63.60 ¹	7.9	18.765	15.563	38.119
			18.768	15.570	38.139
AT-121	66.77 ¹	21.4	18.819	15.551	38.150
BCR1	13.0		18.829	15.648	38.752
	12.2		18.829	15.645	38.752

¹Myers *et al.*, 1985

²Coats, 1952

³Marsh, 1976

⁴Myers *et al.*, 1986

FIG. 2. $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagrams for Aleutian (left) and other oceanic arc (right) lavas. Left: On both diagrams, the Atka lavas plot as tight clusters at the radiogenic ends of linear arrays defined by the Adak lavas. Lavas from both volcanic centers lie within the MORB array for $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ but Atka volcanics lie above the array for $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ and Adak data plots at an angle to it. Lead isotopic data from other Aleutian volcanic centers cover more restricted ranges that are displaced to higher $^{206}\text{Pb}/^{204}\text{Pb}$ and lower $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$. Although the combined Aleutian lead isotopic data define pronounced linear trends, they are due mostly to the Adak lavas. Right: Compared to other oceanic arcs, Aleutian lavas have lead isotopic compositions similar to lavas from Tonga and Mariana. In contrast, for a given $^{206}\text{Pb}/^{204}\text{Pb}$, Aleutian lavas plot below the South Sandwich and Kermadec arcs. Data sources: Aleutians as in Fig. 3; MORB sources: HAMELIN *et al.* (1984); VIDAL and CLAUER (1981); COHEN *et al.* (1980); DUPRÉ and ALLÈGRE (1980); DUPRÉ *et al.* (1981); WHITE and SCHILLING (1978); TATSUMOTO (1978); SUN *et al.* (1975); COHEN and O'NIONS (1982b); CHURCH and TATSUMOTO (1975); arcs: MEIJER (1976, 1982), MEIJER and REAGAN (1981); COHEN and O'NIONS (1982a); BARREIRO (1983); OVERSBY and EWART (1972); SUN (1980).

lavas but limited ranges for those from Atka; 2) generally less radiogenic lead isotopic ratios for Adak than Atka lavas; 3) pronounced linear trends for the Adak data but clustering of Atka samples on Pb-Pb isotopic diagrams; 4) elevated Atka $^{207}\text{Pb}/^{204}\text{Pb}$ ratios for given $^{206}\text{Pb}/^{204}\text{Pb}$ relative to MORB but variable behavior for Adak; and 5) MORB-like characteristics for both suites on $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagrams. The observed lead isotopic differences between these two volcanic suites are similar to those reported for initial $^{87}\text{Sr}/^{86}\text{Sr}$ (MYERS *et al.*, 1985). In light of these data, any model of Aleutian arc magma genesis and evolution must account for: a) lead (and Sr) isotopic compositional differences between volcanic centers; and b) different degrees of intracenter isotopic variability. Considering for the moment only the lead isotopic data, the observed relations could be produced by, at least, three different mechanisms.

Model 1. The Pb isotopic characteristics of the Aleutian volcanics could simply reflect original heterogeneities in the source regions of each volcanic center. A center with small isotopic ranges must tap a source region with relatively homogeneous character whereas a heterogeneous source is required when the lavas of a volcanic center have a large degree of isotopic variability. Given the spacing of Aleutian volcanic centers, the scale of source region heterogeneity must be of the order of 70–100 km, *i.e.* the spacing of volcanic centers.

Model 2. Model 2 assumes the lead isotopic characteristics are generated by mixing a primary, non-radiogenic component with MORB- or mantle-like lead isotopic characteristics and a contaminant with elevated $^{207}\text{Pb}/^{204}\text{Pb}$ but MORB-like $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ (Fig. 4). Centers whose lavas have limited isotopic ranges reflect relatively constant non-radio-

FIG. 3. Aleutian lead isotopic data plotted by volcanic center. Analyses exist for lavas from only a few centers and are concentrated in the central and eastern portions of the arc. Although four centers (Cold Bay, Amak, Unimak, Bogoslof) have isotopic ranges similar in magnitude and value to Atka, the number of lavas (<5) analyzed per center is significantly less than for Atka. Fifteen lavas have been analyzed from Umnak and define isotopic ranges greater than Atka but slightly less than Adak. See text for additional discussion. Data sources: ARCULUS *et al.* (1977); KAY (1977); KAY *et al.* (1978); MORRIS and HART (1983); NYE and REID (1986); this paper.

FIG. 4. Schematic illustration of two of the isotopic models that could explain the observed lead isotopic characteristics of Adak and Atka lavas. Model 2 assumes combination of a primary, non-radiogenic parent with a more enriched component. This mixing process produces an isotopic shift toward higher isotopic values. According to Model 3, the parental magma has relatively high lead isotopic ratios and is contaminated by a non-radiogenic end member. The resultant isotopic shift, *i.e.* from high to low isotopic ratios, is opposite that characteristic of Model 2. Because they lie in the MORB trend for $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$, both end members must have MORB-like characteristics for these two ratios (top). In contrast, the elevated $^{207}\text{Pb}/^{204}\text{Pb}$ of Atka and some Adak lavas requires an end member that is enriched in $^{207}\text{Pb}/^{204}\text{Pb}$ relative to MORB (bottom). See text for additional details.

genic/enriched component ratios. In contrast, significant variations in the proportions of these two components are required when the observed isotopic ranges are large.

Model 3. The lead isotopic characteristics of the Aleutian volcanics can also be generated by an isotopic shift opposite that just discussed, *i.e.* from high to low values (Fig. 4). Although the end members have isotopic characteristics like those just described, their petrologic significances are entirely different. In this alternative model, the enriched component is primary and the addition of a non-radiogenic contaminant produces decreases in the Pb isotopic ratios. As before, isotopic composition and variability reflect variations in the ratio of non-radiogenic to enriched component.

As presented, these models represent static processes, *i.e.* they produce lead isotopic characteristics that do not vary with time. MYERS *et al.* (1985) have suggested, however, that the process of Aleutian magma generation and evolution generates lavas that differ signifi-

cantly in petrographic, compositional and isotopic characteristics with time. Thus, the possible lead isotopic models must be evaluated in both a dynamic as well as a static framework. The three lead models must also be examined with respect to previously proposed arc magma genesis models. Because all three models can adequately explain the lead isotopic characteristics of Adak and Atka lavas, it is impossible to select between these models based solely on such data. Other lines of evidence, including geologic, geochemical and other isotopic data, must be considered.

DISCUSSION

Attempts to identify the source of Aleutian magmas have employed three different lines of reasoning. One approach assigns primary status to the rare primitive basalts found in the arc and a crystal fractionation origin to the more voluminous high-alumina basalts (PERFIT *et al.*, 1980; KAY *et al.*, 1982; GUST and PERFIT, 1986). Given such a primary magma, the major magma source must be the peridotitic mantle wedge (KAY *et al.*, 1978; PERFIT *et al.*, 1980; MCCULLOCH and PERFIT, 1981; KAY *et al.*, 1982; GUST and PERFIT, 1986). The distinctive geochemical and isotopic character of primitive arc basalts are generated by incorporation of a component from the subducted slab (*i.e.* oceanic crust and/or sediment). A second class of petrologic studies assigns primary status to the more abundant high-alumina basalts. Generation of a primary magma of this composition requires partial melting of subducted oceanic crust and sediment (MARSH, 1976, 1982; BROPHY, 1986; BROPHY and MARSH, 1986; MYERS, 1986a,b; MYERS *et al.*, 1986a,b). Within this framework, the rare primitive basalts are produced by contamination of high-alumina basaltic magma during magmatic conduit formation (MYERS *et al.*, 1985). The other petrologic procedure used to identify magma source has considered only isotopic and incompatible element ratio data. Assuming these geochemical parameters record primary magma characteristics, MORRIS and HART (1983) have suggested a plum-pudding mantle as the source of Aleutian magmas. These petrologic models correspond to the three possible lead models. In particular, lead model 1 and a plum-pudding mantle source are similar, a mantle source with incorporated slab component approximates lead model 2 and lead model 3 and the slab source/conduit model describe a similar process. Accordingly, each lead model can be examined in a more general context.

According to the lead 1/plum-pudding mantle model, intercenter isotopic variability is produced by mantle variability along the arc and the differences in intracenter isotopic ranges simply reflect differences in original source heterogeneity. Although such variability could produce static isotopic differences between centers, there are several difficulties with such a model. Since small volume centers draw magma from smaller source regions with less opportunity to incorporate

FIG. 5. Schematic model illustrating details of the petrologic process assumed responsible for the lead isotopic characteristics of Adak and Atka lavas. (a) The elevated $^{207}\text{Pb}/^{204}\text{Pb}$ ratios of high-alumina basalts are produced by partial melting of oceanic crust and subducted sediment. If these magmas ascend through well-traveled magmatic conduits, their isotopic characteristics are changed very little. Lavas erupted from conduits in this stage of development are characterized by limited isotopic ranges. Atka is an example of a volcanic center in a mature stage of development. (b) Parental magmas ascending through conduits that are not well-established interact significantly with the lithosphere wedge. This interaction produces a decrease in isotopic ratios and an increase in variability. Lavas erupted from immature conduits will display a considerable range in isotopic ratios. The characteristics of the lavas from Adak are clearly suggestive of an immature stage of conduit development. See text for additional details.

isotopically distinct components, the lavas of such centers should display smaller degrees of isotopic variability than those of large centers. The observed isotopic characteristics are, however, opposite these predicted relations. Since the recent ^{10}Be data clearly require a sediment component in Aleutian magma genesis, a plum-pudding mantle source appears highly unlikely (BROWN *et al.*, 1982; TERA *et al.*, 1986). When viewed in a dynamic framework, the means by which the isotopic character of a center's lavas is varied with time is unclear. For these reasons, the differences in lead isotopic characteristics between Adak and Atka lavas are unlikely to result from original magma source heterogeneity.

With the lead 2/mantle-dominated source model, intercenter isotopic differences are produced by lateral variations in the amount of enriched component incorporated in mantle melts. Since the lack of systematic isotopic variation along the arc precludes any regular change in the fraction of enriched component (KAY *et al.*, 1978; MCCULLOCH and PERFIT, 1981; VON DRACH *et al.*, 1986), intercenter isotopic differences must be produced by unknown spatial and/or physical mechanisms. Using such a model, the high lead and strontium isotopic ratios common to all centers (Fig. 3) are difficult to explain. If the primary and dominant magmas are mantle melts, the isotopic compositions common throughout the arc should be mantle-like and the high isotopic ratios (*i.e.* the products of contamination) more variable in character. Although the absence of a common non-radiogenic isotopic limit may be attributed to sampling bias, a mechanism to produce the common high isotopic ratios and different degrees of intercenter variability is still lacking. In addition to failing to explain the isotopic data, this model is inconsistent with many of the characteristics of Aleutian basalts (MYERS, 1986a,b). In particular, primitive liquid-lines-of-descent that do not match observed major and trace element trends, similar primitive and high-alumina basalt REE abundances, incompatible-incompatible trace element fractionation paths that are not internally consistent and REE data that plot at an oblique angle to possible fractionation paths are all inconsistent with a crystal fractionation relation between primitive and high-alumina Aleutian basalts. When viewed in a dynamic framework, this model also lacks a physical mechanism to produce isotopic variations during the lifetime of a volcanic center. For these reasons, we feel that a predominantly mantle source cannot explain either our extensive lead isotopic data or the generation of primary Aleutian high-alumina basalts.

The lead 3/slab source-conduit model predicts that the common high intercenter Sr and Pb isotopic ratios of Aleutian arc lavas result from partial melting of the subducted slab and sediment. Differences in intercenter isotopic compositions and intracenter isotopic variability are produced by contamination of these primary melts during magmatic conduit formation (MYERS *et al.*, 1985, 1986b). This model has several advantages

over the other models. Because parental magmas presumably have similar characteristics throughout the arc, the common high intercenter strontium and lead isotopic ratios represent magmas that have experienced a minimum of contamination. The limited Sr and Pb isotopic variability of centers such as Atka result from fully-established, chemically more inert conduits that prevent later magmas from being contaminated and the availability of only homogeneous, late-stage lavas for sampling. Since these lavas have undergone a minimum of contamination, the data from such centers plot near the upper limits of the Sr and Pb isotopic ranges. Large isotopic ranges and non-radiogenic ratios, *e.g.* Adak, suggest magmatic conduits that are not completely established. Because the degree of isotopic variability measured is controlled by variations in the amount of lithospheric material assimilated and the portion of a center's evolutionary history that is available for sampling, the lower limits of Pb and Sr isotopic ratios measured at individual centers varies. When viewed in a dynamic framework, this model has a distinct advantage over the other models. Since magmatic conduits evolve chemically and thermally with the passage of successive magma bodies, the temporal evolution of erupted lavas is a direct consequence of this process. Of the three general classes of Aleutian magma genesis, only this one specifically predicts temporal variations in the petrographic, geochemical and isotopic characteristics of a given center's lavas.

Limited initial strontium isotopic data from Amak and Cold Bay (MORRIS and HART, 1983) are also compatible with the lead 3/slab-conduit model. Amak, a small island behind the main volcanic front (MARSH and LEITZ, 1979), emerged relatively recently and represents an immature stage of development. In contrast, Cold Bay is a much larger center located on the main arc in front of Amak. The consistently lower initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of Amak lavas relative to Cold Bay samples presumably reflects the greater role of mantle component in the former. At the same time, the $^{87}\text{Sr}/^{86}\text{Sr}$ increase with time at Cold Bay (MORRIS and HART, 1983) probably records the flushing out of the conduit system.

Further support for this model comes from a systematic and simultaneous examination of major elements and Pb, Sr and Nd isotopic systems that suggests primary high-alumina basaltic magmas are quantitatively consistent with derivation from a slab-sediment source (MYERS *et al.*, 1986b). This study suggests primary magmas are a three component mixture of eclogite partial melt (44–70%), carbonate (8–13%) and pelagic sediment (21–44%) or some chemically equivalent material. The large sediment fraction predicted by this study reflects, in part, more realistic lead contents for eclogite partial melts. Since Pb is an incompatible element and enriched in any melt extracted at less than complete melting, lead abundances appropriate for eclogite partial melts range from 1 to 2 ppm. Given these higher elemental abundances, greater amounts of sediment are required to produce the ob-

served isotopic ratios. Despite their unusual values, these mixing proportions are qualitatively consistent with preliminary results from other isotopic systems. A carbonate component has been previously suggested to explain ^{230}Th - ^{238}U measurements (NEWMAN *et al.*, 1984) and a pelagic sediment fraction confirmed by recent ^{10}Be data (BROWN *et al.*, 1982; TERA *et al.*, 1986). Although the ^{10}Be data have been interpreted as limiting sediment contribution to 10% or less, such a conclusion is strongly model dependent and does not account for older sediment that may be incorporated in primary magmas. Thus, the ^{10}Be data accurately indicate the presence of young sediment but cannot easily quantitatively limit the total sediment fraction. Since the samples analyzed for ^{10}Be are predominantly from Atka and have undergone little lithospheric contamination, the pronounced sediment signature is not unexpected. Due to the effects of lithospheric contamination, lavas from immature centers such as Adak may not show similar strong evidence of sediment involvement. (The limited number of analyses from Adak prevents examining this possibility with the current data.)

Lithospheric contamination involves assimilating mafic material (*i.e.* peridotitic wallrock) by much less mafic magma (high-alumina basalt), a process suggested in several other geologic settings (ARCULUS *et al.*, 1983; KUDO, 1983; KELEMEN and SONNENFELD, 1983; EVANS, 1985; KELEMEN and GHIORSO, 1986). As pointed out by BOWEN (1922), assimilation of this type does not occur by melting but by interaction with solid wallrock phases and alters the magma composition so that it is in equilibrium with its surroundings. For a magma traversing the mantle, equilibrium is achieved when the magma becomes saturated with olivine of the same composition as that in the mantle. Lithospheric assimilation by magmas saturated with plagioclase involves several steps and may incorporate large amounts of lithospheric component (KELEMEN, 1986). Because the isotopic character of possible assimilants spans a large range, quantitatively modeling this process with Pb and Sr isotopic data is strongly model dependent. Using major and trace element compositions of primitive and high-alumina basalts, MYERS (1986a,b) was able to show, however, that hybrid primitive magmas contain between 27–50% assimilated. Given probable lithospheric isotopic compositions, such proportions are capable of producing the Pb and Sr isotopic shifts observed between Adak and Atka lavas.

CONCLUSIONS

The lead isotopic data from Atka and Adak provide strong corroborative evidence for the petrogenetic model proposed by MYERS *et al.* (1985). This model suggests a volcanic center's magmatic conduits, and hence erupted lavas, evolve with time. Early during a center's evolution ascending magmas interact strongly

with the lithosphere. A significant but volumetrically small, lithosphere-derived component alters key geochemical and isotopic characteristics of the parental magmas. Due to this interaction, lavas of immature centers are characterized by considerable petrographic, compositional and isotopic variability. As a center matures, magmatic conduits are more fully established and the imprint of the lithosphere decreases. Late-stage mafic lavas are, therefore, more uniform in character and indicative of their source region.

According to this model, the lead (as well as Sr and Nd) isotopic character of Aleutian arc lavas is determined at two different evolutionary stages. Parental magmas inherit their geochemical and isotopic signatures during partial fusion of the subducted slab (*i.e.* unaltered and altered oceanic crust plus subducted sediment). Lavas from the mature center of Atka suggest Aleutian parental magmas have the following lead characteristics: $^{206}\text{Pb}/^{204}\text{Pb} = 18.82$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.58$; $^{208}\text{Pb}/^{204}\text{Pb} = 38.42$; Pb = 4–5 ppm. The lead data provide little constraint on mixing proportions but are quantitatively consistent with the proposed physical model. Because this stage of magma evolution is relatively 'static', the characteristics of parental magmas should be quite uniform and constant.

During the initial stages of conduit formation, these characteristics are altered by interaction between the ascending magmas and the lithosphere. This contamination process is extremely dynamic and complex. Since the energy needed to produce contamination is supplied by the ascending magma and the thermal structure of the lithosphere is continually evolving, magma bodies ascending at different times in a center's evolutionary history probably undergo different degrees of contamination and crystal fractionation. Our results suggest this contamination event produces hybrid liquids with lead isotopic ratios lower than those of the parent, a shift opposite to that typical of crustal contamination.

Although our model has been derived solely for the Aleutians, it may be of more general applicability. Compositional differences between various oceanic arcs may result not from fundamentally different petrologic processes but from differences in end member characteristics and abundances. Presently, the data necessary to test this possibility are not available. For example, much of what is known about the Tonga-Kermadec, Scotia, Kuriles and other oceanic arcs is regional in nature. Without extensive field, petrographic, geochemical and isotopic data from individual volcanic centers, the petrologic model derived for the Aleutians can not be tested at other oceanic arcs. Although such data exist for some continental arc centers, shallow-level processes such as crustal contamination (HALLIDAY *et al.*, 1983; MYERS *et al.*, 1984; CHURCH *et al.*, 1986) and density-filtering (CARR, 1984) tend to overprint the subtle geochemical and isotopic characteristics indicative of lithospheric contamination. Clearly, understanding the process of lithospheric con-

tamination requires extensive data on individual volcanic centers located in arcs with relatively simple geologic settings.

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