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Strontium isotopic and selected trace element variations between two Aleutian volcanic centers (Adak and Atka): implications for the development of arc volcanic plumbing systems

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Abstract. Major and trace element concentrations and initial $^{87}Sr/^{86}Sr$ ratios of lavas from the Aleutian volcanic centers of Adak and Atka have been used to study the evolution of their respective lithospheric plumbing systems. The centers are within 150 km of one another and show similar overall silica ranges (47–67%), but Adak ($\sim$40 km^3) is smaller than Atka ($\sim$200 km^3). Adak's lavas are chemically and isotopically heterogeneous ($^{87}Sr/^{86}Sr$:0.70285–0.70330) and two units contain lithospheric xenoliths. The lavas of the much larger Atka, on the other hand, have much less variability in major and trace elements as well as $^{87}Sr/^{86}Sr$ (0.70320–0.70345). We suggest that these characteristics are a measure of the relative maturity and "cleanliness" of the lithospheric plumbing systems that supply magma to these centers. Because Aleutian volcanic centers often remain fixed for relatively long periods of time ($\sim$5 m.y.), once established, magmatic passageways are repeatedly used. Young plumbing systems are relatively cool and contain large amounts of wallrock contaminant, and ascending magmas undergo contamination as well as concurrent crystallization and fractionation. With time, however, heat and mass transfer between ascending magmas and wallrock produce thermal and chemical boundary layers that insulate subsequent magmas. In effect, the plumbing system matures. The chemical heterogeneity displayed by young, "dirty" systems (like Adak) reflects not only the magma source but also the wallrock encountered during ascent and possibly the effects of extensive crystal fractionation. Thus, it is the petrologic data of mature, clean systems, like Atka, that yield the most direct and unambiguous information on the ultimate origin of the lavas and their near surface evolution.

Introduction

Since island arc volcanic centers remain relatively fixed for substantial periods of time ($\sim$5 m.y.) while eruptive cycles are much shorter, magma repeatedly traverses a common region of the lithosphere underlying the volcanic center. Assuming the magma and wallrock are compositionally distinct, interaction between ascending magmas and lithosphere may alter the character of the magmas. Because of the mechanical difficulties associated with the initial opening of a passageway through the lithosphere, magma first appearing on the surface should show the strongest evidence of chemical and physical interaction with lithospheric wallrock. Thus, early lavas may be characterized by a geochemically noisy signature. As the volume of magma flushed through the lithosphere increases, a chemical aureole develops, insulating successive bodies from further chemical interaction with primitive lithospheric wallrock. Regular, low-variance geochemical trends of large volcanic systems probably reflect this limited degree of magma-wallrock interaction. An elucidation of the chemical differences between large and small volcanic centers is, therefore, of paramount importance in shedding light on the mechanics of magma ascent (Marsh 1982a) and separating chemical characteristics of the source region from those of the wallrock along the magma's ascent path. Failure to recognize these effects in petrogenetic studies may result in attributing geochemical characteristics of the lithospheric passageway to the source region, thereby obscuring a clear recognition of the magma's source.

Although chemical differences between some Aleutian centers have been previously recognized by Marsh (1982b) and Kay et al. (1982), they were not discussed in terms of center maturity or lithospheric plumbing systems. To test these general ideas, we have, therefore, carried out a detailed investigation of two adjacent Aleutian volcanic centers. These centers, Adak ($\sim$40 km^3) and Atka ($\sim$200 km^3), are both in the central Aleutians, of similar age and within 150 km of one another. The close proximity of these two centers minimizes potential effects of regional differences in lithospheric and crustal structure and composition. In addition, of the Aleutian centers studied, Adak and Atka best exemplify the previously mentioned characteristics that may typify small and large centers. We begin by reviewing the geological histories of these centers then consider their chemical characteristics. This is followed by a discussion of the implications of these data.

General geology

Adak and Atka are located in the central Aleutians (Fig. 1). Since the recent volcanism on Adak has been described by a number of authors (Coats 1952, 1956; Marsh 1976), we give only a brief summary here. In contrast, little has been published about Atka, however, it is the subject of an extensive, on-going petrologic investigation by Marsh and will be discussed in considerable detail in future reports.

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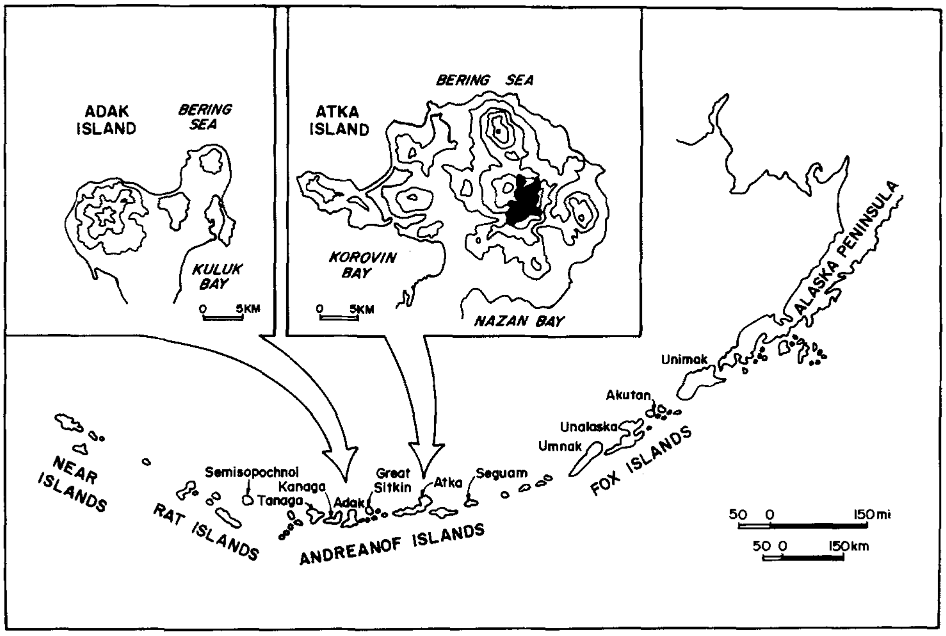

Fig. 1. Map of the Aleutian Islands showing the locations of Adak and Atka as well as other volcanic centers discussed. The maps of the two centers are drawn to the same scale and illustrate the greater surface area covered by the Atka volcanics

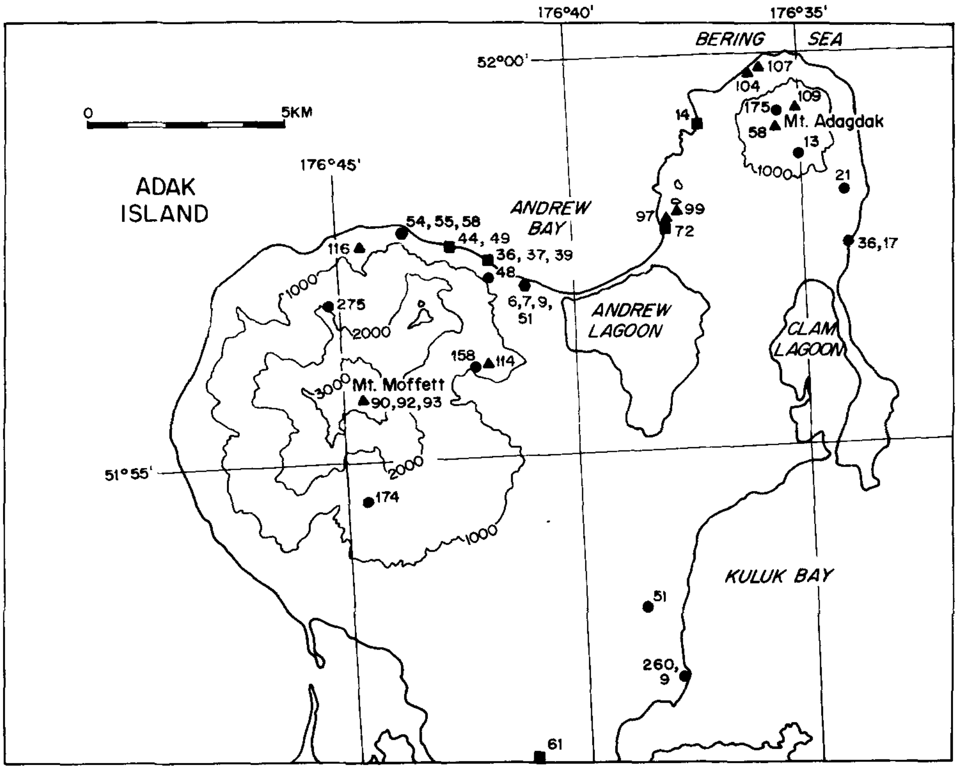

Fig. 2. Volcanic portion of the island of Adak and the location of samples analyzed in this study. Also shown are the locations of other samples described in the literature. Modified from Coats (1956). *solid circles* – Coats 1952; *solid hexagons* – Kay et al. 1978; Kay 1978; *solid squares* – Marsh 1976; *solid triangles* – this paper

Adak

The island of Adak covers 778 km^2, but recent volcanic activity has been confined to an area of about 100 km^2 on the northern portion of the island (Coats 1952, 1956) with a total volume of 40 km^3 (Marsh 1982b). Three major volcanic centers have been identified (Fig. 2). From oldest to youngest, these vents are: Andrew Bay Volcano, Mt. Moffett and Mt. Adagdak. Andrew Bay Volcano, which was located in the present Andrew Bay, has been almost completely removed by erosion (Coats 1956). A K–Ar date on a basal flow from this volcano has given an age of ~500,000 years (Marsh 1976), suggesting that the recent volcanism on Adak has covered only the last million years or so. Mt. Moffett, the largest volcano on Adak (1181 m), consists of a main composite cone, a large (990 m) parasitic cone on the NE flank and several extrusive basaltic domes located on both cones (Coats 1956). The main cone consists of tuff-breccias, breccias and lava flows. In contrast, the parasitic cone is composed of a series of thin (~2–4 m) basaltic lavas interbedded with lapilli-tuffs (Coats 1956). The younger Mt. Adagdak is a small basaltic composite cone of lava flows interbedded with various sedimentary units. The older part of the composite cone consists of lapilli-tuff beds and lesser amounts of lava flows and plugs of hornblende andesite. After an explosive episode and an erosional interval, a younger volcano

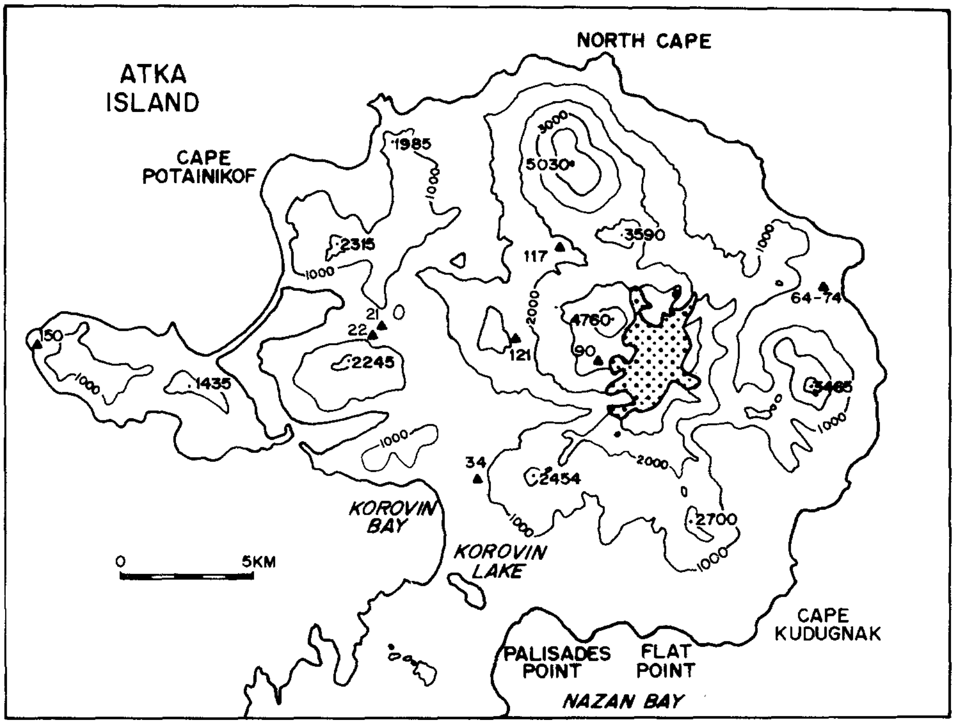

Fig. 3. Map of the northern portion of Atka showing the major geographical features as well as the locations of samples described in this study. The shaded region represents that part of the island covered by ice

Table 1. Petrographic modes of some of the analyzed samples

sam. #	plag	ol	opx	cpx	mag	hbl
AT-64	24.3	0.8	–	–	0.1	–
AT-76	34.6	0.9	–	–	tr	–
AT-74	36.6	1.7	–	–	0.4	–
AT-73	34.1	2.8	–	–	0.2	–
AT-90	13.9	1.6	–	3.0	0.4	–
AT-21	24.6	–	0.3	0.7	0.5	–
AT-34	29.4	0.05	0.5	6.8	1.4	–
AT-22	5.5	–	0.1	0.4	tr	–
AT-150	41.1	–	–	0.3	1.0	3.0

formed on the western flank of the older cone. Presently, two hornblende andesite domes occupy the crater of the younger cone and basaltic domes occur on the flanks of the older volcano.

Atka

The island of Atka is located 150 km east of Adak (Fig. 1). Like Adak, recent volcanism has been confined to the northern part of the island (Fig. 3; Marsh 1980). This volcanic center is, however, very much larger, covering an area of about 360 km^2 (Fig. 1). Marsh (1980) has identified at least fourteen vents associated with central and satellite cones and has estimated the total erupted volume at about 200 km^3. Each cone consists of a thick, basaltic shield topped by a composite cone. Cessation of activity at central cones is signaled by the eruption of a small amount of dacitic material (Marsh 1980) and a simultaneous shutdown of the satellite vents which remained basaltic throughout their activity. The northernmost volcano, Korovin, is presently active. Although activity shifts between different volcanic edifices, overall it has been confined to a relatively small area (10–20 km in diameter) for at least several million years. The most recent phase of volcanism at both Adak and Atka appears to have spanned principally the last million or so years (Marsh 1980, 1982b).

Petrography

Like Aleutian lavas from other volcanic centers (Marsh 1976; Kay et al. 1982), Atka and Adak volcanics are highly porphyritic (Table 1). Total phenocryst abundances vary from 22 to 50% (vol) in Adak volcanics but are slightly lower (6–50%) in the Atka lavas. Throughout the entire compositional range, plagioclase is the dominant phenocryst phase. In nearly all lavas, it comprises well over three-quarters of the phenocryst assemblage. The principal mafic phases include olivine, clinopyroxene, orthopyroxene and magnetite. Olivine is characteristic of the more mafic lavas ($<53\%$ SiO_2) but is replaced by orthopyroxene at higher silica contents. The abundance of these two phases rarely exceeds 3 vol% in the Atka lavas but is slightly greater in those from Adak ($\leq 6\%$). Clinopyroxene is also more abundant in the Adak lavas. Small amounts of magnetite ($\leq 4\%$) are ubiquitous in both volcanic 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 (Marsh 1980), minor amounts (≤ 3 vol%) occur in a late-stage dacitic body (Table 1).

Compositionally, plagioclase phenocrysts from Adak vary, on average, from An_{85-90} in the basalts to approximately An_{70-80} in the andesites and the degree of zoning increases from basalt to andesite (Marsh 1976). Phenocrysts averaging An_{78-85} in Atka basaltic lavas (46–50% SiO_2), are commonly rimmed by thin sodic zones which are 20 mole% more anorthitic than coexisting microlites. Olivine is generally fairly iron-rich, averaging about Fo_{70} (Marsh 1976, unpublished data).

Although their major phenocryst phases are similar in type and composition, two important petrographic differences distinguish lavas of Adak from those of Atka. First, the Atka lavas contain lower total phenocryst contents than do those from Adak. Second, xenolithic material is found in at least two Adak units. One is a thick andesitic lava cropping out on the north cape of Mt. Moffett (Marsh 1976; Conrad et al. 1983; Conrad and Kay 1984) while the other is a lahar on the western flank of Mt. Adagdak (Debari et al. 1984). From the Mt. Moffett lava, Conrad and Kay (1984) describe both mafic and ultramafic xenoliths with olivines more Mg-rich ($>Fo_{85}$) than those typical of most Aleutian basalts (Marsh 1976). Also included among this xenolithic suite are coarse-grained nodules composed predominantly of clinopy-

Table 2. Adak whole rock analyses

	AD-109	AD-107	AD-116	AD-114	AD-99	AD-93	AD-90	AD-92	AD-58	AD-104	AD-97
SiO_2	54.16	56.18	57.90	58.01	58.88	59.45	60.46	60.94	62.92	65.02	90.80
TiO_2	0.73	0.80	0.50	0.57	0.61	0.60	0.56	0.53	0.63	0.25	0.19
Al_2O_3	18.43	16.35	14.90	17.48	15.41	16.67	17.05	17.47	17.03	16.08	2.41
Fe_2O_3	3.96	3.00	2.86	4.83	4.46	6.23	5.06	3.04	3.39	2.03	0.59
FeO	5.74	4.21	3.79	1.98	2.24	0.48	1.66	2.36	2.35	2.17	0.27
MnO	0.19	0.15	0.16	0.16	0.15	0.16	0.14	0.16	0.16	0.08	0.01
MgO	3.59	4.50	6.73	3.08	5.20	2.59	2.68	2.40	2.35	2.25	0.24
CaO	8.95	7.29	8.18	8.08	8.50	7.00	7.00	6.23	6.74	4.78	0.77
Na_2O	3.28	3.94	3.13	3.57	3.06	3.62	3.52	3.24	3.69	4.09	0.55
K_2O	1.22	2.59	1.41	1.28	1.22	1.82	1.84	1.67	1.39	2.22	0.30
P_2O_5	0.27	0.31	0.17	0.17	0.13	0.18	0.17	0.19	0.14	0.16	0.12
LOI	0.10	0.54	0.08	0.67	0.00	0.21	1.21	2.40	0.69	0.07	2.84
Total	100.62	99.87	99.81	99.90	99.86	99.01	101.36	100.63	101.47	99.22	99.07
Rb(ppm)	25	51	30	31	29	47(48)	49	90	35	36	9(9)
Sr(ppm)	480	515	584	503	491	480(479)	451	447	403	620	99(103)
Ba(ppm)	502	595	572	545	546	850(814)	749	750	555	422	58
$^{87}Sr/^{86}Sr$	0.70312 ±7	–	0.70301 ±16	0.70320 ±5	–	–	–	0.70321 ±6	0.70315 ±6	0.70299 ±10 0.70301 ±8	0.70336 ±8 0.70330 ±7

Major element analyses performed by AA in Rock and Water Geochemistry Lab, University of Wyoming, Steve Boese – analyst; trace elements by XRF at VPI – J.D. Myers, analyst

roxene with minor amounts of orthopyroxene and olivine (Marsh 1985, unpublished data). The xenoliths from Mt. Adagdak include dunites, wehrlites, clinopyroxenites and hornblendites (Debari et al. 1984). Because Aleutian lavas are generally characterized by a paucity of xenolithic material (Marsh 1982b), the occurrence of these xenolithic suites is unusual. Indeed, the only other reported occurrence of abundant xenoliths (dunites, clinopyroxenites) are from a single unit on Kanaga (DeLong et al. 1975; Pope et al. 1981). The host rock of this xenolithic suite is, however, an alkalic basalt of Tertiary age and is not of typical calc-alkaline composition (Fraser and Barnett 1959). Like Adak, Kanaga is a relatively small center (~25 km^3) and the xenoliths have a restricted distribution within the volcanic pile.

An additional major difference is the abundance of rock types. Atka is dominated by basalts (~50% SiO_2) while Adak has a more even distribution of rock types. This distribution may reflect the higher crystallinity at Adak which could indicate, on average, a more evolved volcanic suite.

Analytical procedures

Samples chosen for analysis were selected to span the compositional range of each volcanic center as well as to represent all the major eruptive vents within a center. Although the location of their vent is uncertain, samples (AD-61, AD-9) from the oldest phase of the recent volcanism on Adak were also analyzed. The inclusion of these samples assured complete coverage of that center's most recent volcanic phase. All samples chosen for analysis were unaltered and any weathered surfaces removed before sample preparation.

Samples from Atka were analyzed for major elements by XRF and wet chemistry while those from Adak were analyzed by wet chemistry using standard atomic absorption techniques (Shapiro and Brannock 1962). Rubidium, strontium and barium concentrations were measured on pressed pellets using the method of Norrish and Chappell (1977). Duplicate XRF analyses for this study and an earlier investigation (Myers et al. 1984) agree within 2% for Rb and Sr and 5% for Ba. Rubidium concentrations of some Atka samples were also determined by isotope dilution (ID). For all concentration levels, XRF and ID results agree within 10% and improve substantially at higher concentrations. For Rb values less than 10 ppm, ID values have been used in subsequent plots. Strontium isotopic analytical procedures are described by Myers et al. (1984). Isotopic ratios are reported to 2σ error and have been normalized to $^{86}Sr/^{88}Sr$ of 0.1194 and an E&A value of 0.70800. Analytical results are presented in Tables 2, 3, 4 and 5; sample locations are shown in Figs. 2 and 3.

Results

Major elements

With increasing silica (48 to 67 wt%), the Adak lavas exhibit marked decreases in Al_2O_3, FeO^T, MgO and CaO, a slight decrease in TiO_2 and small increases in Na_2O and K_2O (Fig. 4). For all of the Adak volcanic vents, these trends are characterized, however, by considerable variability. Although characteristic to varying degrees of all oxides, MgO and Al_2O_3 display the greatest deviations from systematic, coherent trends. MgO contents between 4 and 7 wt% occur in the mafic lavas (<53% SiO_2). In the intermediate volcanics (53–59 wt% SiO_2), MgO content displays an even greater compositional range (2–7 wt%). Basaltic lavas also have Al_2O_3 contents between 16 and 21 wt% while values ranging from 14 to 17 wt% occur in the intermediate volcanics. Despite their overall similarities, two subtle compositional differences distinguish the lavas from the Andrew Bay and Adagdak volcanoes. The two relatively siliceous (57–59%) Andrew Bay lavas are characterized by unusally high MgO ($\geq$7 wt%) and low Al_2O_3 ($\leq$16%). On the other hand, the compositional variability of the Adagdak volcanics, presumably the youngest vent, is slightly smaller than those for the other volcanics (Fig. 4). Analyzed mafic (AD-116N) and ultramafic (AD-117N)

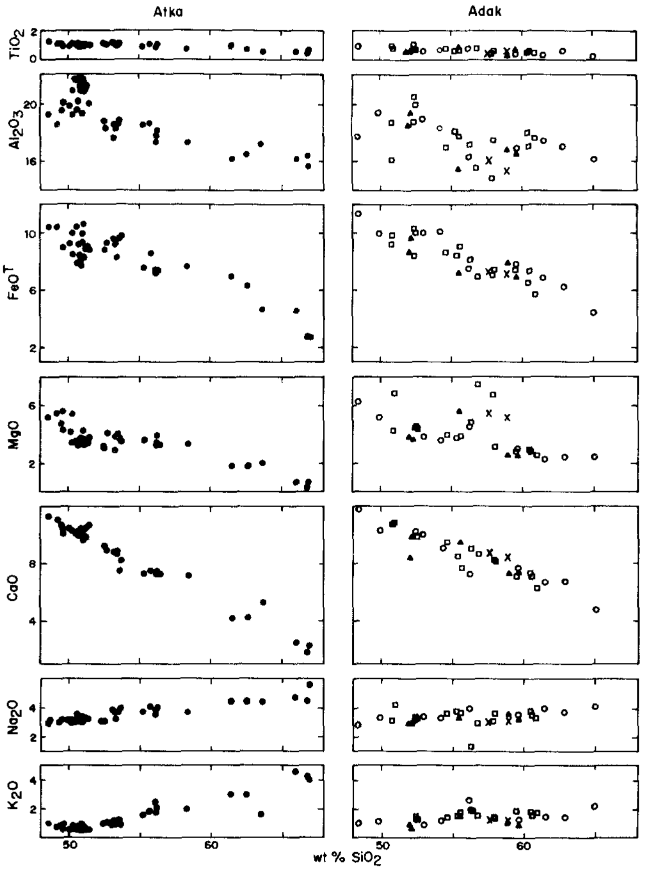

Fig. 4. Major elements plotted against SiO_2. The two volcanic suites are distinguished in major element compositions by different degrees of compositional variability, variation in K_2O-SiO_2 trends, differing absolute oxide abundances at given SiO_2 contents as well as different volumetric distribuions within the observed silica ranges. See text for discussion. Atka – solid dots; Adak symbols: open squares – Mt. Moffett; open circles – Mt Adagdak; crosses – Andrew Bay volcano; solid triangles – older lavas. Data sources: Adak: Coats 1952; Marsh 1976; Kay 1977, 1978; Kay et al. 1982, this paper; Atka: this paper; Marsh, unpublished data

Table 3. Additonal Adak trace element and isotopic analyses

Sample #	SiO_2	Rb (ppm)	Sr (ppm)	Ba (ppm)	$^{87}Sr/^{86}Sr$
AD-36	48.39[a]	24	437	484	0.70323±6
AD-14	49.93[b]	22	453	427	0.70319±5
AD-36M	50.87[b]	19	640	372	0.70328±7
AD-61	52.14[b]	12	657	293	0.70330±5
AD-49	56.34[b]	32	850	577	0.70327±7
AD-72	57.63[b]	29	495	555	0.70317±6
AD-9	58.86[b]	20(20)	668(676)	461	0.70299±8 0.70293±7

[a] Coats 1952

[b] Marsh 1976

Table 4. Major element analyses of Adak nodules

	AD-116N	AD-117N
SiO_2	49.55	39.99
TiO_2	0.31	0.09
Al_2O_3	7.01	1.96
FeO^T	10.20	15.47
MnO	0.21	0.23
MgO	24.80	36.40
CaO	4.93	4.53
Na_2O	1.04	0.06
K_2O	0.33	0.01
P_2O_5	0.01	0.00
LOI	0.00	0.59
Total	98.46	99.33

Analyses by Steve Boese in the Rock and Water Geochemistry Lab, University of Wyoming

nodules from Mt. Moffett (Table 4) have major element compositions distinctly different from typical Aleutian andesitic basalts. Relative to the lavas, these nodules are strongly enriched in FeO^T and MgO and markedly depleted in all remaining oxides. A range in silica contents (40–50 wt%) is also evident in these samples. In addition, a large disk-like (0.1 × 1 m), crystal-free bomb found within the Andrew Bay sequence has the unusual silica content of 90.8% but nevertheless is isotopically similar to the mean of the suite (see below).

When considered as a whole, lavas from Atka (48–67 wt% SiO_2) define smooth compositional trends marked by little variability. With increasing silica, Al_2O_3, FeO^T, MgO and CaO decrease while K_2O defines two different trends. A well-developed trend yields very high potassium values (>4 wt%) at high silica contents. Lower maximum values (<3%) are characteristic of a less well-developed trend (Fig. 4). The mafic lavas of Atka, the dominant lava-type of this volcanic center, are typical high alumina andesitic basalts with low TiO_2 (<1%) and MgO (<6%) and high Al_2O_3 (20–21%).

Although they span nearly identical silica ranges and exhibit similar gross major element trends (e.g. increasing Na_2O and K_2O with increasing silica), the two volcanic suites differ in: 1) degree of compositional variability; 2) K_2O-SiO_2 variations; 3) absolute oxide abundances for given silica contents; and 4) the distribution of lavas within the observed silica ranges. The differences in compositional variability is best illustrated by MgO and Al_2O_3. Relative to the systematic, coherent trends of Atka, Adak MgO values are consistently displaced to higher values while Al_2O_3 tends to lower abundances. The MgO variation in the intermediate Adak lavas alone equals that displayed by the entire Atka volcanic suite. In terms of K_2O variations, Adak defines a single trend of nearly constant K_2O while Atka displays the two trends described previously. Kay et al. (1982) recognized this variation in K_2O behavior for other centers within the arc and have used it as one criteria to distinguish calc-alkaline and tholeiitic centers. At a given silica content, Adak and Atka lavas are also characterized by distinct differences in oxide abundances (Fig. 4). For example, Adak volcanics are enriched in FeO^T, MgO and CaO and depleted in TiO_2 and Na_2O relative to those from Atka. Because of the marked difference in K_2O-SiO_2 trend slopes, the K_2O concentrations of the two volcanic centers show a more complex relationship. At low SiO_2 (<53%), the Adak lavas are more potassic whereas at greater silica contents the Atka volcanics have higher potassium concentrations. Lastly, the two volcanic suites are distinguished by differences in the silica content of the most voluminous lavas. On Atka, as men-

Table 5. Atka whole rock analyses

	AT-64[a]	AT-76[a]	AT-74[c]	AT-73[a]	AT-90[a]	AT-21[b]	AT-34[b]	AT-22[b]	AT-117[b]	AT-150[a]	AT-121[b]
SiO_2	50.2	50.6	50.98	51.0	53.1	55.70	58.34	61.37	62.49	63.60	66.77
TiO_2	0.96	0.92	0.89	0.94	1.08	0.98	0.69	0.84	0.62	0.52	0.44
Al_2O_3	20.9	20.9	21.63	20.8	17.6	18.58	17.33	16.09	16.37	17.20	16.41
Fe_2O_3	–	–	–	–	–	4.21	3.91	4.03	1.99	–	2.01
FeO	8.39	9.09	8.22	10.5	9.45	3.81	3.25	2.39	3.95	4.62	0.87
MnO	0.20	0.17	0.21	0.22	0.20	0.18	0.16	0.13	0.15	0.18	0.04
MgO	3.27	3.08	3.45	3.17	3.81	1.87	3.24	1.70	1.69	1.93	0.15
CaO	10.2	9.88	10.34	9.92	8.71	7.41	7.10	4.10	4.23	5.21	1.64
Na_2O	3.11	3.56	3.16	3.49	3.89	4.12	3.74	4.50	4.53	4.42	4.46
K_2O	0.83	0.76	0.79	0.76	1.12	1.82	2.00	2.97	3.00	1.77	4.18
P_2O_5	0.18	0.17	0.11	0.18	0.27	0.30	0.19	0.37	0.19	0.24	0.12
LOI	–	–	0.18	–	–	1.05	0.44	1.46	0.21	–	2.14
Total	98.24	99.13	99.96	100.98	99.19	100.03	100.29	99.95	99.42	99.69	99.23
Rb(ppm)[c]	8.7 (7.9)	8.5 (10.2), 10.2)	9.7 (9.7)	9.2 (10.5)	22.7	40.3 (40.1)	41.3	77.8 (78.8)	36.0 (33.0)	36.6, 36.4	115.3, 115.5
Sr(ppm)[c]	660	653	643	643	478	469	489	336	427	–	158(157)
Ba(ppm)[c]	310	322	305	295	404	508	720	747	480	–	936(946)
$^{87}Sr/^{86}Sr$[d]	0.70337 ±6	0.70319 ±7 0.70320 ±7	0.70331 ±10 0.70335 ±7	0.70331 ±6 0.70337 ±7	0.70339 ±8	0.70337 ±6 0.70337 ±6	0.70326 ±6 0.70324 ±8 0.70324 ±6	0.70345 ±6 0.70346 ±6	0.70339 ±8 0.70334 ±8	0.70321 ±8	0.70331 ±10

[a] XRF analysis by Donnelly (SUNY, Binghamton, NY)
[b] Wet chemical analysis by von Knorring (Leeds University, England)
[c] XRF analysis performed by J.D. Myers at VPI
[d] Analyst – J.D. Myers

Rb values in parentheses are by isotope dilution

tioned earlier, andesitic basalts (≤53 wt% SiO_2) comprise over 90% of the erupted volcanics (Fig. 4, Marsh 1980), while Adak is characterized by more siliceous lavas.

The major element differences between these two volcanic suites are subtle. In general, the lavas from both centers display similar gross geochemical characteristics (i.e., low TiO_2 and MgO, high Al_2O_3, CaO and K_2O, large Fe_2O_3/FeO ratios). Despite statements to the contrary (Perfit et al. 1980a), the dominant mafic Aleutian lavas are compositionally distinct from ocean ridge basalts (MORB). As pointed out by Marsh (1976, 1982b), MORB and Aleutian andesitic basalts are readily distinguished by significant differences in TiO_2, Al_2O_3, MgO and K_2O. The new data from Atka reported here are entirely consistent with these observations. Within the arc, rare basaltic lavas with major element characteristics similar to MORB (e.g. some of the lavas from Adak) can be found among the more typical andesitic basalts (Perfit et al. 1980a). However, assigning these compositionally and volumetrically rare lavas prominent roles in the evolution of arc magmas is probably unwarranted (see later discussion and Myers et al. 1985).

Trace elements

Adak Rb, Sr and Ba contents do not show any systematic trace element-silica variations (Fig. 5). Rb contents in the Mt. Moffett and Adagdak lavas (10 to 100 ppm for the entire suite) are characterized by considerable heterogeneity. This variability is particularly pronounced between 55 and 62 wt% SiO_2. In this silica range, Rb varies from 20 to 50 ppm for Moffett and 20 to 60 ppm for Adagdak (Fig. 5). Although represented by only three analyses, the older volcanics have slightly lower Rb concentrations (10–20 ppm). Measured strontium contents range from 350 to 850 ppm (Tables 2 and 3). Previously published analyses (Kay 1978) extend this compositional range to 1783 ppm but most analyses fall within the smaller interval (Fig. 5). While lavas from Mt. Moffett vary from 350 to 850 ppm, those from Adagdak display a considerably smaller range (400–500 ppm). Neither compositional range is systematic with respect to silica content. When plotted against silica, the Ba contents of the Adak volcanics are high (400–500 ppm) in the mafic lavas, decrease slightly, increase again to a maximum (~800 ppm) in the intermediate silica range and finally decrease at high silica contents (>62 wt%). This trend is, however, a composite of several distinctly different patterns characteristic of individual volcanic vents. Lavas from Mt. Moffett increase in Ba content with increasing silica. In contrast, Adagdak volcanics display a fairly narrow compositional range (400–600 ppm) independent of silica (Fig. 5). The limited data for the older lavas suggest low Ba contents (<500 ppm) that are only weakly correlated with SiO_2.

The Atka volcanics generally display fairly systematic trace element-silica variations (Fig. 5). As SiO_2 increases, Rb content increases along a very well-developed trend

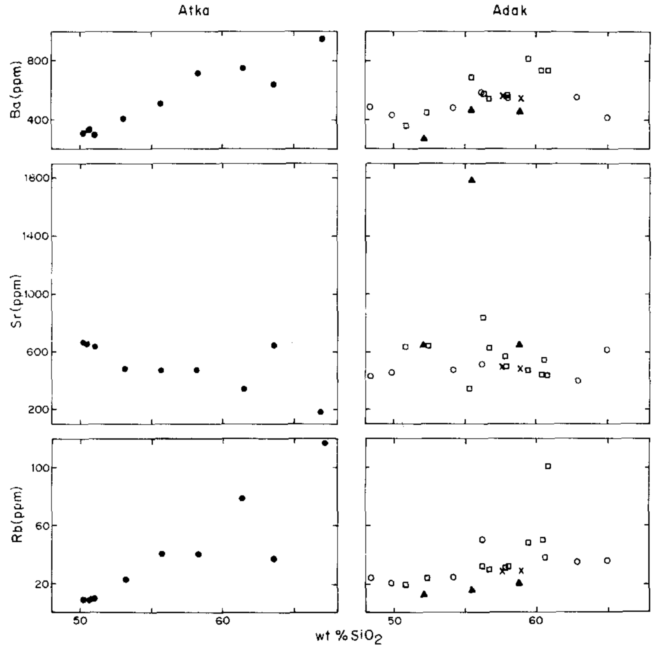

Fig. 5. Rb, Sr and Ba plotted against SiO_2. Compared to Atka, Adak is characterized by considerable heterogeneity and distinctly different trace element – SiO_2 trends. See text for discussion. Symbols as in Fig. 4

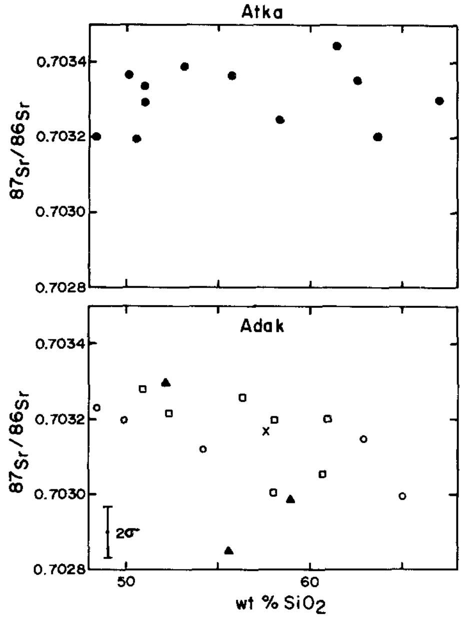

Fig. 6. Initial $^{87}Sr/^{86}Sr$ versus SiO_2. Atka forms a narrow band at slightly elevated isotopic ratios whereas a greater scatter in $^{87}Sr/^{86}Sr$ characterizes Adak. Symbols as in Fig. 4. Data sources: Adak: Kay et al. 1978; Kay 1978; von Drach et al. 1985; this paper; Atka – von Drach et al. 1985; this paper

from ~10 ppm in the andesitic basalts to slightly less than 120 ppm in the dacites. A trend toward lower Rb contents (~40 ppm) at silica contents of 58–59 wt% is also evident but not as strongly developed. These two trends mirror those previously described for K_2O. Unlike Rb, strontium abundances decrease with increasing SiO_2. From a maximum of ~650 ppm in the basaltic lavas, Sr systematically declines to a low of 158 ppm in the most siliceous lavas. Over the same compositional range, Ba increases in a regular fashion from a low of 300 ppm in the mafic lavas to a maximum of 950 ppm at 67% SiO_2 (Fig. 5).

Three differences distinguish the trace element abundances of the Adak and Atka volcanics. Compared to Atka, the lack of systematic trace element-silica variations in the Adak volcanics is striking (Fig. 5). In addition, the range in trace element concentrations is significantly greater in the Atka lavas. In contrast, the Adak volcanics have relatively constant trace element abundances that are independent of silica content. Lastly, there is a distinct difference in Rb, Sr and Ba concentrations in the basic lavas (≤ 53 wt% SiO_2) of the two volcanic centers. Rb averages 20 ppm at Adak compared to only 9 ppm for Atka; Adak values (12–24 ppm) also display a greater variability than those of Atka (8.3–9.8 ppm). At Adak, Ba has a mean of 362 ppm and varies from 293 to 502 ppm, but maximum and minimum values for Atka differ by only 47 ppm and average 303 ppm. In contrast to Rb and Ba, strontium contents are higher in the basic lavas of Atka. Atka basalts average 646 ppm and span only 40 ppm whereas Adak has a mean of 531 ppm Sr and a range of 209 ppm. Relative to the Atka lavas, incompatible elements are enriched in the Adak basalts while for the suite as a whole all three trace element concentrations are much more variable.

Measured Rb, Sr and Ba abundances of the Atka and Adak volcanics are similar to those found at other Aleutian volcanic centers (Arculus et al. 1977; Kay 1977; Kay et al. 1978; Morris and Hart 1983; White and Patchett 1984). Unfortunately, most studies previously reporting trace element contents have been regional in nature and the number of analyses per volcanic center is, accordingly, very small. Detailed comparison of Atka and Adak lavas with those of other Aleutian volcanic centers is, therefore, not presently warranted and must await more detailed studies of other Aleutian centers.

Strontium isotopic ratios

We have measured twenty-five $^{87}Sr/^{86}Sr$ initial isotopic ratios for Adak (14) and Atka (11). Combined with previous data (Kay 1978; Kay et al. 1978), the measured isotopic range for Adak extends from 0.70284 to 0.70354. While the variability of the lavas from Mt. Moffett is of this magnitude, the ranges defined for the other Adak vents are somewhat smaller. However, the variations within the Andrew Bay and older lavas are defined by a smaller number of analyses while the Adagdak lavas analyzed do not cover the total major element compositional range characteristic of that vent. Lavas from Atka vary in $^{87}Sr/^{86}Sr$ from 0.70320 to 0.70345 (Table 3). Relative to Adak, the Atka volcanics are slightly more radiogenic with a narrower isotopic range. When plotted against silica, these differences as well as the lack of correlation with silica are readily apparent (Fig. 6). (Because corresponding silica values have not been published for all Adak samples analyzed for $^{87}Sr/^{86}Sr$ (Kay et al. 1978), the entire isotopic range of this volcanic center is not represented on Fig. 6). In all except one instance, the Adak lavas are displaced toward lower $^{87}Sr/^{86}Sr$ ratios relative to Atka. While the isotopic variability

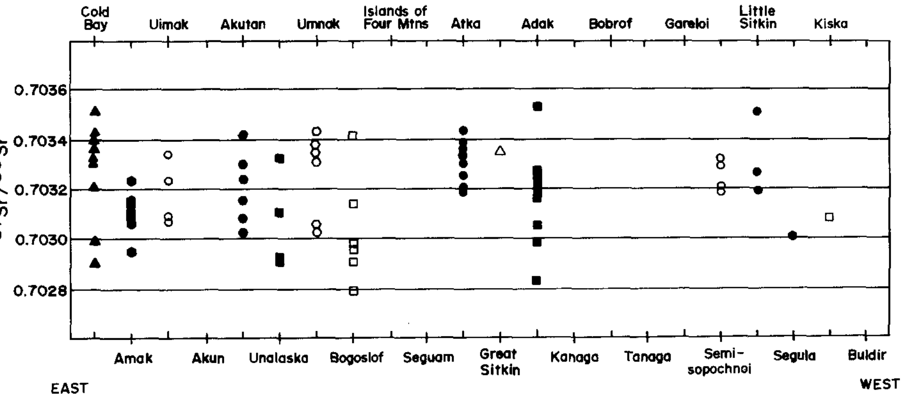

Fig. 7. Strontium isotopic data plotted by volcanic center. Left to right on the diagram corresponds to east to west along the Aleutian arc. Of the centers, seven (Akun, Islands of Four Mountains, Seguam, Kanaga, Bobrof, Tanaga, Gareoli) have no data and a single analysis each exists for Mt. Simeon, Unimak; Vsevidof and Recheshnoi, Umnak; Great Sitkin, Segula, Kiska. Data Sources: Arculus et al. 1977; Kay et al. 1978; Perfit et al. 1980b; McCulloch and Perfit 1981; Morris and Hart 1983; White and Patchett 1984; DeLong et al. 1985; von Drach et al. 1985; this paper

of the Atka basalts equals that defined by the entire suite, the range of the Adak volcanic suite exceeds the basaltic variability. No $^{87}Sr/^{86}Sr$ ratios have been reported for the Adak xenoliths. Although Debari et al. (1984) imply that some ratios have been measured for the Adagdak xenoliths, no data is reported nor are the types of xenoliths analyzed described. Future analytical work coupled with petrologic study will provide isotopic and petrologic data from a variety of different types of xenoliths.

Because of an unequal distribution of analyses within the arc (Arculus et al. 1977; Kay et al. 1978; Perfit et al. 1980b; McCulloch and Perfit 1981; Reid and Nye 1981; Morris and Hart 1983; White and Patchett 1984; von Drach et al. 1985; DeLong et al. 1985), comparison of the strontium isotopic results from Adak and Atka to data from other Aleutian centers is difficult. Whereas eighty-eight $^{87}Sr/^{86}Sr$ analyses exist for the Aleutians, thirty-seven percent are from Atka and Adak with the remainder distributed between fifteen different volcanic centers. Consequently, the number of analyses per volcanic center is generally less than six. Indeed, six centers have a single analysis each and the small, secondary centers of Amak (9 analyses) and Bogolsof (7) have the largest data bases. Given these limitations, any comparisons with the current data must be considered preliminary and considerably more detailed isotopic work on individual Aleutian arc centers is clearly necessary.

The measured strontium isotopic ratios of Adak and Atka fall in the range characteristic of other Aleutian volcanics (Fig. 7). Three volcanic centers, Akutan (0.70302–0.70342), Okmok (0.70302–0.70355) and Bogolsof (0.70279–0.70343), have isotopic ranges similar to that of Adak. Of these three centers, Bogolsof (<5 km^3) is very small, Akutan intermediate in volume (80 km^3) and Okmok (210–310 km^3) very large (Marsh 1982b). Isotopic ranges of the remaining centers are similar to that of Atka (Fig. 7), however, they are defined by a smaller number of analyses generally covering a limited range in major element composition. Typically, smaller centers are characterized by slightly lower $^{87}Sr/^{86}Sr$ ratios. The data from Adak and Atka clearly show that definition of a center's isotopic variability requires a large number of analyses from samples spanning the entire major element compositional range. Compared to the other Aleutian centers, the $^{87}Sr/^{86}Sr$ ranges of Adak and Atka are somewhat unique. Despite one of the largest data bases covering a large compositional range (48–67% SiO_2), the Atka lavas have an extremely small isotopic range. Conversely, the maximum and minimum $^{87}Sr/^{86}Sr$ isotopic ratios measured from the Adak volcanics span almost the entire range defined by all other Aleutian samples combined.

Lithospheric contamination

This detailed examination of Adak and Atka clearly shows significant differences in petrography, chemical composition and strontium isotopic signatures. Any study attempting to isolate the ultimate source of these lavas must first understand the origin of this variability in these nearby volcanic centers. In particular, the following observations must be explained: (1) the greater crystal contents in the Adak lavas; (2) the predominance of mafic lavas at Atka; (3) the systematic major and trace element-silica variations of Atka and the erratic, nonsystematic trends of Adak; (4) the unusual presence of xenoliths in the Adak lavas; and (5) relative to Atka, the more variable and on average less radiogenic $^{87}Sr/^{86}Sr$ ratios characteristic of the Adak lavas. We feel that these differences are best explained by the relative degree of maturity of the plumbing systems feeding these volcanic centers.

Petrologic model

Regardless of the ultimate source of these magmas and their means of ascent, for a magma to arrive at the surface a pathway must be forced through the lithosphere. Because Aleutian volcanic centers have remained relatively fixed over the past ~5 m.y., once established, these pathways are repeatedly used by ascending magma. (We do not necessarily mean the same *exact* pathway is used, but magmas always transverse a specific localized region of the lithosphere.) During the initial establishment of the pathway, any chemical and thermal contrasts between lithospheric wallrock and ascending magmas are greatest. Thus, the magmas may be markedly altered during initial development of a magmatic passageway. Since newly established volcanic centers are fed by such immature plumbing systems, their magmas have had the maximum possibility of

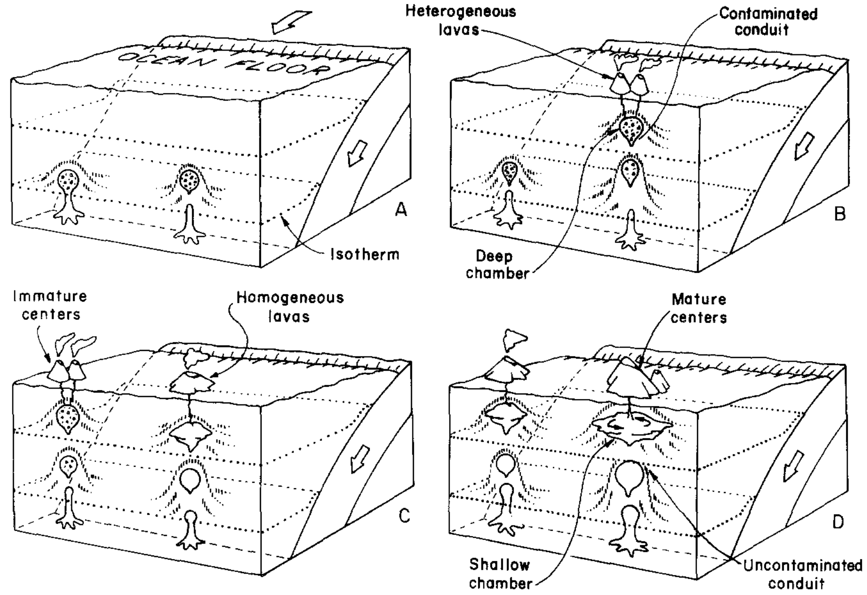

Fig. 8A–D. Schematic representation of the evolution of an Aleutian volcanic center (volcano on the right is described).
A Early stages of magma ascent with significant thermal and chemical interaction between magma and wallrock.
B Eruption of the first highly contaminated lavas from deep-seated magma bodies.
C Magma bodies are closer to the surface and erupted lavas are less contaminated.
D Fully developed plumbing system. Eruptions are from well-established shallow magma chambers. Material in the plumbing system itself has been removed or chemically modified. Lavas erupted at this stage are petrographically and chemically homogeneous

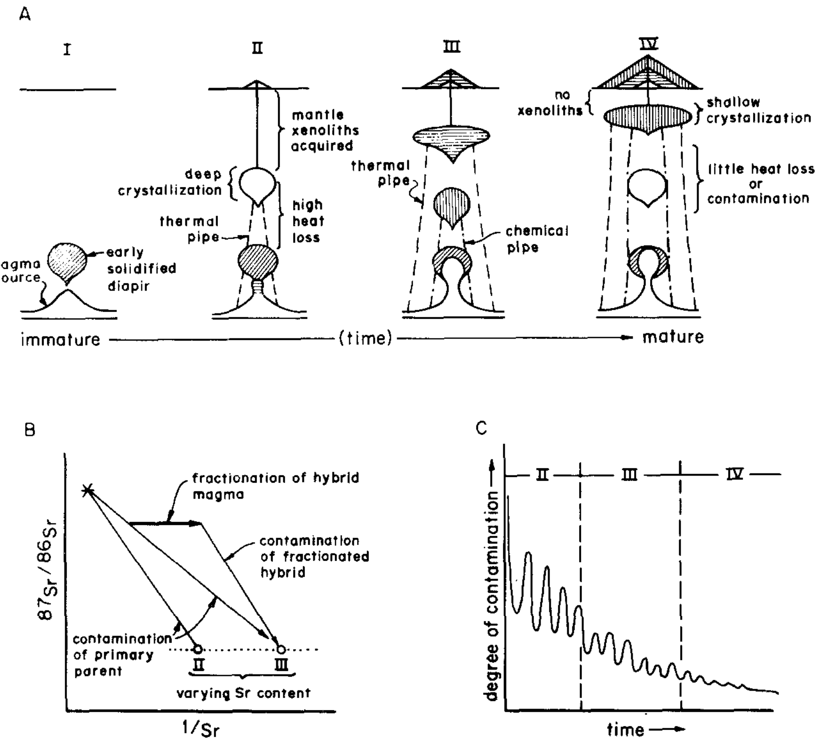

Fig. 9A–C. Diagrammatic illustration of the details of lithospheric contamination.
A Evolution of a conduit with time. Initial diapirs do not reach the surface but begin the development of chemical and thermal pipes (I). With continued use, the thermal pipe develops but heat loss is still rapid and magma emplacement occurs at relatively deep levels (II). By stage III, the thermal pipe is well established, however, the chemical conduit is still in its formative stage. At maturity (IV), the thermal and chemical pipes are fully developed and magmatic evolution occurs in a shallow level chamber.
B Illustration of the complexity that can characterize isotopic systematics. Hybrid liquids may be produced by lithospheric contamination of parent, fractionated parent or fractionated hybrid. Due to variations in the degree of melting and/or wallrock melting histories, successive contaminants may vary in Sr content thereby imparting unique isotopic relations to each diapir.
C With time, the degree of contamination in the lavas decreases but in a highly non-systematic manner. Symbols: star – parent; dotted line – isotopic composition of lithospheric contaminant

intereacting with virgin lithospheric wallrock (Fig. 8). Small centers, like Adak, should, therefore, emit lavas with significant chemical variability. In essence, the plumbing system is "dirty", i.e., it contains a significant wallrock component that is chemically unlike the ascending magmas.

As the magmatic pathway is repeatedly used, the thermal and chemical character of the lithosphere around the conduit is progressively altered (Fig. 8). While the passage of successive magma bodies heats the region, they also alter the composition of the lithospheric wallrock. At the same time, diapirs that have solidified during their ascent (Marsh 1978, 1982b, 1984) displace lithospheric material thereby reducing the chemical contrasts experienced by subsequent diapirs (Fig. 9a). These changes in the character of the lithospheric wedge serve to insulate successive magma bodies from heat loss and significant chemical contamination. Because successive magmas have cleaned the system of contaminants (Fig. 8), later lavas of large mafic centers, such as Atka, should show much less chemical and isotopic variability.

Since the thermal structure of the region above the magma source has not been altered, initial magma diapirs encounter relatively low temperatures and the development of incipient volcanic centers will be dominated by rapid heat loss. In addition, the relatively small volume of magma emplaced also facilitates magma cooling. This rapid heat loss has two important petrologic consequences. First, initial magma emplacement is confined to relatively deep levels

(Fig. 9a). Equally important, the heat loss promotes extensive, early crystallization. Lavas erupted at this developmental stage will be characterized by abundant phenocrysts of relatively high pressure origin. At the same time, extensive crystallization may also promote fractionation. Because heat loss is extreme and crystallization rapid, successive early lavas may vary considerably in composition causing immature centers to be marked by an unusual abundance of andesites. Their extensive crystallization and relatively deep level of emplacement also suggests these early magmas have the greatest chance of generating a trapped vapor phase which, upon exceeding the strength and pressure of the overburden, may produce explosive eruptions containing large amounts of xenolithic wallrock (Fig. 9). As additional magmas traverse the passageway, the wedge is continually heated and a thermal aureole established around the conduit. Until a steady-state system is established, successive diapirs experience different thermal regimes and undergo different degrees of crystallization and hence fractionation. Lavas erupted from successive diapirs may differ markedly in compositional characteristics. During the mature stage of development, a steady-state thermal structure is achieved and major heat loss is confined to shallow levels (Fig. 9a). The reduced heat loss allows parental magmas to rise (density permitting) increasingly higher within the lithosphere without undergoing significant crystallization and fractionation. Thus, lavas characteristic of mature centers will, on average, contain fewer phenocrysts but these phenocrysts will be indicative of low-pressure crystallization. In addition, the lavas will exhibit more coherent, systematic geochemical trends. Due to these changes, the dominant erupted magma will become more mafic and homogeneous as the volcanic center evolves. (We do not mean to imply that individual stratigraphic sequences erupted from a single vent (i.e., sampling a single diapir) progress from andesite to basalt, but that the dominant lava of the center as a whole becomes more mafic.) The chemical characteristics of these later more mafic lavas will more intimately reflect the nature of their source region.

In addition to crystal fractionation, ascending magmas are compositionally modified by lithospheric contamination. Due to its dynamic nature, quantitatively modeling this process is extremely difficult. To illustrate this complexity consider the evolution of a single diapir ascending soon after initiation of magmatic activity. During ascent, the magma interacts with the wallrock producing changes in major and trace element as well as isotopic composition. Assuming contamination is a single stage event (it probably isn't), the isotopic systematics of the parental magma are altered only at this stage (Fig. 9b). Although it will modify hybrid magma major and trace element compositions, subsequent fractionation will leave isotopic characteristics unchanged. Eruptions from this contaminated magma body will produce a succession of lavas characterized by uniform isotopic ratios but a range in major and trace element characteristics (Fig. 9b). Essentially, the isotopic and other compositional systems are effectively decoupled. Due to this complexity, reconstructing the petrologic history of a single diapir from its resultant lavas will be extremely difficult. And yet, these lavas will be spatially related to lavas derived from other diapirs with different evolutionary histories. For example, consider the diapir that ascends immediately after the one just discussed. Because the ascent of the first body alters the thermal and chemical structure of the conduit, this later diapir experiences an environment considerably different from that of its predecessor. As a result of these changes, contamination produces hybrid magma compositional ranges different from those of the preceding body. Changes in thermal structure may also alter subsequent fractionation paths. Due to these changes, lavas erupted from this diapir will have no simple petrogenetic relation to those preceding them. This process is repeated with decreasing degrees of contamination until a mature system is established (Fig. 9c). Even with the relatively simple model discussed, extremely complex petrogenetic relations will be evident in the resultant lavas. Since lithospheric contamination and crystal fractionation within an individual diapir are probably concurrent processes, subsequent compositional trends will be orders of magnitude more complex than those described (DePaolo 1981). The spatial superposition of such lavas coupled with an inability to identify lavas from different diapirs complicates attempts to unravel the petrogenetic history of immature centers.

Despite these complexities, two general comments about lithospheric contamination can be made. Although its exact character (i.e., fertile or depleted) is uncertain, the major element composition of the mantle wedge is most certainly ultramafic. At small degrees of partial fusion ($\leq 20\%$), melts of ultramafic rocks have major element characteristics that are distinctly different from those of arc lavas (Mysen and Kushiro 1977). If contamination occurs when the dominant magma of the diapir is still mafic, shifts in hybrid magma composition will be subtle and perhaps difficult to resolve (Fig. 10). In contrast, small degrees of contamination when the magma is more evolved produce marked increases in MgO and decreases in Al_2O_3. Since differences in the slopes of the trends for FeO^T, CaO and to a lesser degree Na_2O are small, the shifts in these oxides due to contamination may not be readily apparent. If the ultramafic rocks of the mantle wedge have typical relatively non-radiogenic strontium isotopic compositions (Mengel et al. 1984), contamination of arc magmas (~ 0.70330) will also produce hybrid lavas with low isotopic ratios. Lithospheric contamination may, therefore, produce significant changes in MgO and Al_2O_3, particularly in intermediate and siliceous magmas, and decreases in $^{87}Sr/^{86}Sr$ ratios, an isotopic shift *opposite* to that described for most contamination processes.

The progession from immature to mature plumbing systems requires the repeated passage of ascending diapirs. With each magma ascent, the wedge is heated as well as chemically processed. The time required to establish a mature plumbing system is a function of the rate of magma flux. Large fluxes alter the wedge more effectively thereby producing mature systems rapidly. Correspondingly longer time intervals are required when flux rate is small. Consequently, the age or duration of volcanic activity at a given center is of secondary importance and centers of similar age may represent completely different evolutionary stages. Presumably, this transition from immature to mature plumbing systems will be recorded in the lavas. Ideally, volcanic products characteristic of large centers should range from highly porphyritic, heterogeneous lavas typical of immature plumbing systems through the more mafic, less crystalline volcanics indicative of mature systems. Given sufficient magma flux, the early "dirty" lavas of immature stages may become buried as later volcanics are erupted (Fig. 8 and 9a). It is also possible that this critical transition

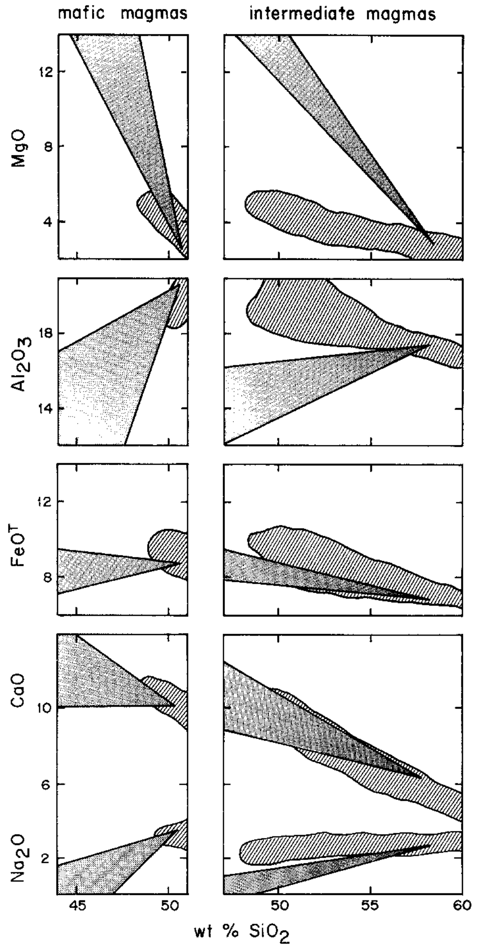

Fig. 10. Subtraction diagram illustrating the effect of lithospheric contamination on magma major element composition. The strongest effects are evident for MgO and Al_2O_3 and increase with the silica content of the magma being contaminated. The compositions of the contaminant correspond to partial melts (5–20%) of a spinel peridotite (Mysen and Kushiro 1977) compositionally similar to the Adak ultramafic nodule. Lined areas are compositional fields of the Atka basalts while the shaded regions show the directions of compositional shifts produced by contamination

may occur in the near subsurface. Lavas exposed at mature centers that have not been extensively dissected by erosion may, therefore, reflect only recent evolutionary stages. Conversely, extensive erosion or caldera formation may expose the earlier lavas. Volcanic products of a large center, therefore, may or may not visibly record the evolution from dirty to clean (i.e., immature to mature) plumbing systems.

The first indication of a volcanic center's maturity is its volume. Since large volumes of magma must have used the magmatic passageway, large centers are likely to be mature. Due to the possible exposure of immature and mature lavas within such centers, confirmation of their evolutionary stage requires a considerable body of geologic, petrographic, geochemical and isotopic data. Detailed knowledge of stratigraphic relations, geographic distribution of lavas as well as their respective volumes are crucial to determining the spatial and temporal framework within which the analytical data must be interpreted. (Since the synthesis of the analytical data rests on this framework, the importance of geologic mapping cannot be overemphasized.) Petrographic observations (e.g., phenocryst types and modes, textural variations, presence/absence of xenoliths/xenocrysts, etc.) coupled with quantitative data on phenocryst compositional ranges and zoning are necessary to evaluate conditions of crystallization. Lastly, extensive major and trace element and isotopic analyses are needed to define the compositional range of the volcanics as well as their geochemical trends. While all major compositional units must be analyzed, the number of analyses from any compositional unit should broadly reflect its volume. Without such information, different evolutionary stages within a large center may not be recognized and the transition of lava characteristics from immature to mature missed. For example, strontium isotopic analyses from all evolutionary stages will show a significant isotopic range. If geologic, petrographic and geochemical data to differentiate different evolutionary stages are not available, such an isotopic range may be interpreted as evidence for an immature evolutionary stage. Using the volume of a small center as an indicator of the degree of maturity is not as straightforward as for large centers. While significant volumes of magma may have been emplaced at shallow levels, it may be represented by little surface expression, e.g. erupted lavas. Thus while the plumbing system may be well-developed, maturity must be established using the lines of evidence discussed earlier. Large isotopic variations accompanied by other characteristics of lavas of immature centers are indicative that the center (or at least its present plumbing system) is immature and its volume closely tied to the subsurface plumbing system. Small variations in isotopic ratios, systematic geochemical – SiO_2 trends coupled with other "mature" characteristics suggest significant magma volumes at depth and a mature plumbing system only weakly tied to the surface. We do, however, note a caveat to this monotonic advance from small and dirty to big and clean. In some instances, a system may become so big and its plumbing so well used that it is unusually hot throughout. This condition can lead to magma generation within the wallrock. In comparison to the original deeper source, the resultant lavas may appear dirty within an otherwise mature system.

Adak – Atka

All the characteristics of the volcanic centers of Adak and Atka are consistent with this petrogenetic model. Because of its small volume, Adak represents an immature stage of lithospheric plumbing evolution. The high crystal contents of its lavas as well as abundance of andesites strongly suggest crystallization in a relatively cold environment characteristic of incipient volcanic centers, i.e. strong subsurface magmatic evolution. At the same time, lithospheric contamination is indicated by the major and trace element heterogeneity of the Adak volcanics. For example, one lava (AD-116) containing abundant nodules is characterized by low Al_2O_3 (14.9 wt%) and high MgO (6.73%). The significant strontium isotopic variability as well as low $^{87}Sr/^{86}Sr$ ratios of Adak lavas are also consistent with contamination by non-radiogenic lithospheric wallrock. Both of these compositional characteristics are exactly like those predicted by the petrogenetic model.

On the other hand, the size as well as petrographic, geochemical and isotopic characteristics of Atka suggest it is supplied by a mature or clean plumbing system. The lower phenocryst content of its lavas as well as the abundance of basaltic lavas suggests crystallization in a relatively

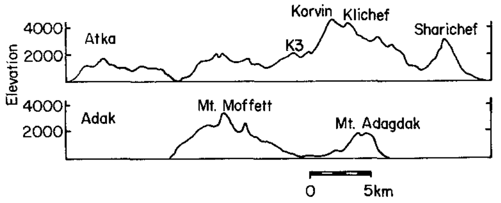

Fig. 11. Topographic profiles of the two volcanic centers illustrating the higher average elevation of Atka. Profiles are oriented east-west and were constructed by superimposing cross-sections drawn through all major topographic features

Table 6. Division of Aleutian volcanic centers into evolutionary classes

<50 km^3 Immature	50–130 km^3 Uncertain	>130 km^3 Mature
Akun (15)	Akutan (80)?	Shishaldin (400)
Islands of Four Mtns. (70[a])	Seguam (75)?	Westdahl and Pogromni (315)
Adagdak (5) + Adak (25)	Great Sitkin (60)	Makushin (145)
Kanaga (25)		Okmok (210–310)
Gareloi (15)		Vsevidof and Recheshnoi (265)
Semisopochoni (35)?		Atka (200)
Little Sitkin (12.5)		Tanaga (160)
Segula (5)		
Kiska (12.5)		
Buldir (2.5)		
Amak (<5)		
Bogoslof (<5)		
Bobrof		

Numbers in parentheses are volume estimates (km^3) from Marsh (1982a)

[a] Total of four islands

hot environment. The smooth systematic major and trace element-silica trends and lack of significant strontium isotopic variability are also consistent with an evolutionary history dominated by crystal fractionation not contamination. The absence of such compositional variability suggests the early, heterogeneous lavas of Atka's immature stage have been buried by the volcanic products of the later evolutionary stages. A study of a basal sequence of mafic lavas along Atka's northeast coast, which has failed to identify any unusual lavas even at the lowest stratigraphic levels exposed, supports this conclusion (Myers et al. 1985). Because Atka covers approximately four times the surface area of Adak (Fig. 1), has a greater average elevation (Fig. 11) and has not been cut by significant caldera formation, burial of the earlier lavas is highly probable. Atka appears to be an example of a mature volcanic center at which evidence of the earlier, immature evolutionary stages has apparently been buried.

Maturity of other Aleutian centers

The Aleutian arc contains approximately thirty-six major volcanoes (Fig. 1; Marsh 1982b) that vary considerably in size and petrographic and geochemical characteristics. Estimated volumes range from 400 km^3 at Shishaldin to 2.5 km^3 for Buldir (Marsh 1982b). Thirteen centers, located mostly in the western part of the arc, are the same size or smaller than Adak and presumably represent immature centers (Table 6). In contrast, seven centers with volumes similar to that of Atka are most likely mature. Three centers have volumes intermediate between Adak and Atka. Although these centers may represent a stage of intermediate maturity, they are not built on older volcanics like other Aleutian centers and may, therefore, also be mature. As discussed earlier, determining the maturity of a volcanic center requires a large body of geologic, petrographic, geochemical and isotopic data. For most Aleutian centers, these data simply do not exist and tests of our predictions of the evolutionary stage of other Aleutian centers must thus await these data.

Discussion

Using a limited number of analyses from a large number of Aleutian volcanic centers, Kay et al. (1982) recognized petrographic, major and trace element and volumetric differences similar to those described for Atka and Adak between other volcanic centers in the arc. Because of the character of their data set, these authors did not distinguish variations in major element, trace element or isotopic heterogeneity between different centers. Based on this regional study, Kay et al. (1982) termed small centers calc-alkaline and large centers tholeiitic. A comparison of our classifications with those of Kay et al. (1982) reveals a nearly perfect correspondence between calc-alkaline and immature centers and tholeiitic and mature centers. As with our model, differences in crystallization depth are cited for some of the petrographic variations. This difference was, however, attributed to differences in tectonic setting not maturity of magmatic plumbing. Because they are supposedly located in regions of compression, magma ascent beneath calc-alkaline centers is slow thereby resulting in deeper emplacement levels. In contrast, the location of tholeiitic centers in regions of extension permits a faster ascent and a shallower depth of emplacement (Kay et al. 1982). Since much of the Aleutians are located on thin (5–10 km), oceanic crust (Grow 1973; Helmberger 1977), regional stresses can be maintained only to relatively shallow depths. Because intensive parameters derived from arc lavas suggest that crystallization occurs below the base of the oceanic crust (Marsh 1976, 1982), differences in regional stresses must be unimportant in determining the deep-seated rate of magma ascent and emplacement depth. At the same time, differences in emplacement depth and fractionation paths alone cannot explain the isotopic variability of Adak and Atka. These characteristics, if common throughout the arc, preclude the model of Kay et al. (1982) from being the dominant process responsible for the evolution of arc magmas. It is thus immediately obvious that all of these characteristics are more easily explained by the age and cumulative volume of magma associated with any center.

Our terms, i.e. immature and mature, carry petrogenetic implications. That is, they imply a particular evolutionary stage as well as distinctive petrographic, geochemical and isotopic characteristics. Since considerable geologic and analytical data are required to identify a center's maturity, knowledge of the developmental stage of a center may often be uncertain (the present state for most Aleutian centers). Employing terms such as immature and mature in such cases would be misleading. Although they convey some of the observed characteristics, immature and mature would imply an evolutionary stage that remains unconfirmed. A means of describing the overall characteristics of a volcanic suite without implying evolutionary stage is, therefore, needed. Because the terms calc-alkaline and tholeiitic as used by Kay et al. (1982) describe the same characteristics (except compositional heterogeneity) as immature and mature and have historically been descriptive terms, we propose using these terms to describe volcanic centers whose evolutionary stages are uncertain. As a classification scheme emphasizing the observed differences between Aleutian volcanic centers, these terms are quite useful (Kay et al. 1982).

Considerable compositional heterogeneity observed in small seamounts has led several investigators to suggest that small scale heterogeneities exist within the mantle (Staudigel et al. 1984; Zindler et al. 1984). Since it has often been suggested that arc magmas are dominated by components from the mantle wedge (Kay 1980; Perfit et al. 1980b; Morris and Hart 1983), the possibility exists that the compositional differences distinguishing Adak and Atka may arise from melting a heterogeneous mantle wedge. Although the source of parental arc magmas is addressed in detail by Myers et al. (1985), a few comments about magma source are appropriate.

Based on a detailed petrographic, geochemical and isotopic examination of a basal sequence of mafic lavas from Atka, Myers et al. (1985) concluded that parental Aleutian magmas could not be generated from the mantle wedge. In a regional isotopic (Sr, Nd) study, von Drach et al. (1985) compared the Aleutian arc lavas with basic, nodule-bearing lavas from well behind the arc (i.e., Pribilofs, Nunivak and St. Lawrence Islands) and found that the source of these back-arc volcanics is heterogeneous and is probably the wedge but that the source of the arc lavas is, comparatively, exceedingly homogeneous. Experimental phase relations are also inconsistent with derivation by fractionation of partial melts of the mantle wedge (Baker and Eggler 1983). Thus, mantle heterogeneity alone cannot explain the differences between Adak and Atka. This type of heterogeneity could, however, produce a secondary variation in the proposed petrogenetic model by adding a measure of compositional heterogeneity to the lithospheric contaminant.

Because the mechanics of magma ascent from mantle depths is the same regardless of tectonic setting, evolution of magmatic plumbing systems should be a common petrologic process. The greater compositional variability of the small Loihi seamount relative to the much larger Hawaiian volcanoes is consistent with such a process (Frey and Clague 1983; Staudigel et al. 1984). Young Pacific seamounts of similar volume to Adak are also marked by considerable compositional heterogeneity (Zindler et al. 1984). Since such characteristics could be produced by contamination during ascent in a compositionally layered mantle, small-scale mantle heterogeneities may not be necessary to explain these variations. Clearly, magma evolution is a very dynamic process and magma characteristics may be acquired during magma ascent as well as from the source region and shallow level evolution.

Conclusions

The characteristics of Aleutian magmas are influenced by several igneous processes operating at different times and locations along the ascent path. Initially, source melting, mantle contamination and fractionation all act in conjunction to produce the lavas observed at the earth's surface. Isotopic heterogeneity is inherited from the source and lithospheric contamination; trace element concentrations and major oxide trends are controlled by source melting, lithospheric contamination and crystal fractionation. Because the plumbing system is dirty, the source is obscured. Later, with the passage of a sufficient volume of magma the plumbing system matures and becomes increasingly clean; the influence of contamination decreases and source melting and fractionation are mostly responsible for observed compositional variations. Isotopic heterogeneity is now inherited only from the source region and major and trace element characteristics reflect crystal fractionation. Because of these complexities, unraveling the source and evolution of arc magmas will be difficult unless special attention is paid to the evolutionary stage of individual volcanic centers. Combining data from volcanic centers at different stages of maturity will yield incorrect interpretations and obscure the recognition of the truly valuable petrogenetic features. Studies of small centers with immature plumbing systems give useful information about the means of magmatic ascent and the nature of the wallrock through which the magmas ascended, but they are unsafe to use in unraveling the ultimate origin of the lavas themselves (Conrad et al. 1983; Conrad and Kay 1984). That is, we must be particularly cautious not to construe debris from the underlying oceanic crust as essential material of an earlier, more primitive, magmatic stage of the arc itself.

To evaluate the maturity of a plumbing system as well as that of the arc volcanic centers themselves, detailed field, petrographic, geochemical, and isotopic studies of individual centers are needed. Once the geochemical and isotopic characteristics of a center are known, its stage of subsurface maturity can be determined and these data used in conjunction with information from other centers to deduce the origin and evolution of arc magmas. The detailed investigations of Adak and Atka are examples of the information needed and the conclusions that can be made from such studies.

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