Magnesian andesite in the western Aleutian Komandorsky region: Implications for slab melting and processes in the mantle wedge

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ABSTRACT

The role of the subducting lithospheric slab in the genesis of mantle-derived (primitive) magmas is investigated through a study of volcanic rocks formed in the tectonically strike-slip–dominated western Aleutian arc. Two types of chemically and petrologically distinctive primitive andesites have been found among the Miocene–late Pleistocene–age volcanic rocks in the western Aleutians. These are termed the "Adak-type" and "Piip-type" magnesian andesites. Trace element and isotopic characteristics indicate that Adak-type magnesian andesites (adakites) formed principally as small percentage melts of the basaltic portion of the subducting oceanic crust, leaving a clinopyroxene-garnet-rutile residual mineralogy. The resulting slab melt signature (high La/Yb, Sr) distinguishes Adak-type magnesian andesites from all other Aleutian volcanic rocks. Primitive characteristics (high Mg#, Cr, Ni) and intermediate compositions (~59% SiO_2) of Adak-type magnesian andesites were acquired by interaction with peridotite and/or basalt in the mantle wedge. The absence of olivine phenocrysts from Adak-type magnesian andesites indicates that they were not equilibrated with peridotite and so are unlike Piip-type magnesian andesites, which appear to have equilibrated under low pressure and hydrous conditions in the subarc mantle. Piip-type magnesian andesites also contain a slab melt component, but reaction-equilibration with peridotite has lowered La/Yb and Sr to levels like those of common Aleutian volcanic rocks.

Miocene-age calc-alkaline rocks of the Komandorsky Islands have chemical characteristics transitional between those of Adak-type magnesian andesites and common Aleutian volcanic rocks from the central and eastern arc. In a source mixture of depleted mantle wedge, slab melt, and sediment, the Komandorsky rocks have a relatively large contribution from the slab melt endmember. The strong slab melt signature among western Aleutian rocks is attributed to highly oblique convergence that produced a slow subduction path into the subarc mantle. Geochemically, the slab melt provided a high Sr, La/Yb, La/Ta, and low Ti/Hf endmember to the western Aleutian source mixture. The enhanced role for slab melting in the western Aleutians may be like that predicted for Archean systems and for modern systems where the subduction zone is warm. In this regard, Adak-type magnesian andesites are probably the appropriate analog to sanukitoids and other primitive andesitic rocks of Archean age.

INTRODUCTION

The chemical contributions of oceanic crust to the source of arc volcanic rocks and the thermal structure of the subducting oceanic lithosphere and overlying mantle wedge are central issues in the study of modern and ancient subduction magmatic systems. It is widely believed that the source of modern arc volcanic rocks is predominantly metasomatised peridotite in the mantle wedge above the subducting slab (Gill, 1973; Kay, 1980; Perfit et al., 1980; Morris et al., 1990; for an alternative view see Marsh, 1982; Brophy and Marsh, 1986; Myers, 1988). Interest in the geochemistry of arc volcanic rocks has increasingly focused on the nature of the slab-derived metasomatizing agent (is it a melt or fluid?) and on processes that occur in the mantle wedge (e.g., Defant and Drummond, 1990; Kelemen et al., 1990; Morris et al., 1990). These issues relate to the origin of the subduction geochemical component in arc volcanic rocks, to the thermal structure of subduction zones in modern and ancient times, and ultimately to the origin of the continental crust (e.g., Martin, 1986; Drummond and Defant, 1990; Kay and Kay, 1991; Peacock et al., 1994).

Kay (1980) argued that a source mixture of marine sediment, depleted mantle, and subducting oceanic crust (± seawater) was required to explain the chemistry of arc volcanic rocks worldwide. But the complexity of this source mixture in most arcs has made it difficult to identify in detail the nature of the chemical endmembers. In this regard, the western Aleutians are of interest, because oblique subduction in this region has produced a source mixture that is nearly devoid of sedimentary components (Yogodzinski et al., 1993; Yogodzinski et al., 1994). Furthermore, Aleutian magnesian andesites, which have geochemical characteristics indicating that they are important endmembers in the Aleutian source mixture (Kay, 1980), appear to be more common in the western Aleutians than in other parts of the arc (Yogodzinski et al., 1993; Yogodzinski et al., 1994).

Two types of magnesian andesites are known among Miocene–Holocene volcanic rocks of the western Aleutian arc. These are the Adak-type magnesian andesites, named for the type-locality on Adak Island in the central Aleutians, and the Piip-type magnesian andesites, named for their occurrence

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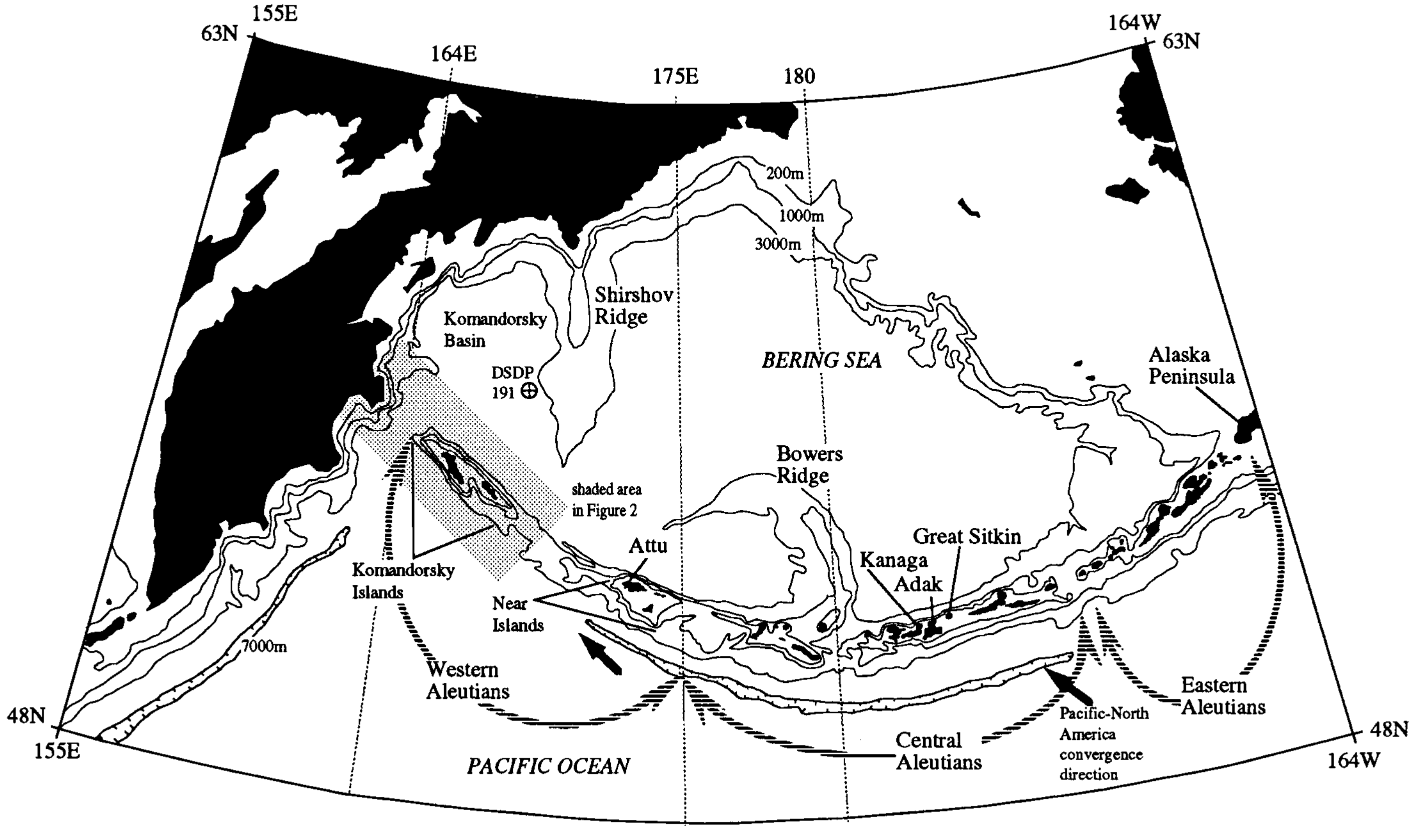

Figure 1. Insular Aleutian arc and surrounding region. Pacific–North America convergence directions in the western Aleutians (N49°W, 92 mm/yr) and central Aleutians (N42°W, 87 mm/yr) are from Engebretson et al. (1985). Shaded area is detailed in Figure 2.

at Piip Volcano, a hydrothermally active seamount located immediately north of the far western Aleutian Komandorsky Islands (Fig. 1). The term "adakite" (Defant and Drummond, 1990) may be used interchangeably with our term "Adak-type magnesian andesite." We prefer the term "magnesian andesite" because it emphasizes the primitive and andesitic nature of the rocks, and it distinguishes them from more silicic and less primitive rocks that are commonly included under the broadly defined term "adakite" (Defant and Drummond, 1990).

In a previous paper (Yogodzinski et al., 1994) we focused on the origin of Piip-type magnesian andesites, we noted their similarity to the well-studied magnesian andesites of the Japanese Setouchi Belt (Tatsumi, 1982), and we emphasized an origin by basalt-peridotite interaction under low pressure and hydrous conditions in the uppermost subarc mantle. The focus of this paper is on western Aleutian Adak-type magnesian andesites and associated calc-alkaline rocks of the Komandorsky Islands. We argue that all Miocene–Holocene volcanic rocks in the western Aleutians contain a significant slab melt component, and that the geochemical signature of the slab melt is variably diluted by reactions in the mantle wedge. General implications of western Aleutian–style arc volcanism for mantle wedge processes in modern and ancient subduction systems are discussed.

MAGMATIC AND TECTONIC DEVELOPMENT OF THE KOMANDORSKY REGION

Relative motion of the Pacific plate in the western Aleutians is nearly parallel to the strike of the arc (western Aleutians defined here as long 164°–175°E; Fig. 1). The general seismic, structural, and magmatic character of the arc in this region led Newberry et al. (1986) to conclude that it was not underlain by subducting oceanic crust. More recently, Boyd and Creager (1991) have imaged the aseismic extension of a subducting slab beneath all of the western Aleutian arc. Their findings, which are in broad agreement with regional magmatic studies (Kay et al., 1989; Yogodzinski et al., 1993), suggest that oblique subduction in the central Aleutians during the past 15–20 m.y. has carried a slab to great depths beneath most of the western Aleutian–Bering Sea region.

The Komandorsky Islands (Bering and Medny; Fig. 2) are the crest of a bathymetrically distinct crustal block (the Komandorsky block) located at the Aleutian-Kamchatka junction. Borusk and Tsvetkov (1982) and Tsvetkov (1991) identified three geochemically and stratigraphically distinctive volcanic episodes in the Komandorsky Islands. The first and earliest episode was a bimodal association of basalt and rhyolite (middle Eocene–middle Oligocene). The second magmatic episode was an alkaline series, which lasted until approximately the early Miocene (15–25 Ma). The third and final episode (middle Miocene–early Pliocene) was a calc-alkaline series of andesite, dacite, and subvolcanic granodiorite.

Trace element and isotopic features of all three series clearly imply a subduction environment (Tsvetkov, 1991), but the early and middle Tertiary tectonic conditions in the western Aleutians remain poorly understood. This is in part because the Komandorsky block appears to be an allochthonous

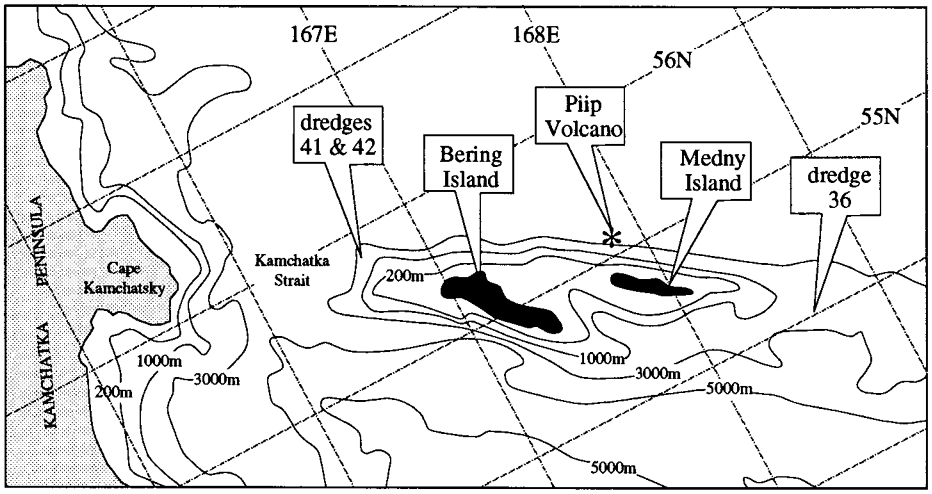

Figure 2. Aleutian-Kamchatka junction, Komandorsky Islands, modified from Scholl et al. (1976). Piip Volcano is a hydrothermally active seamount (see also Baranov et al., 1991; Yogodzinski et al., 1994).

terrane. Low paleomagnetic inclinations on Paleogene sedimentary rocks suggest that the Komandorsky block may have originated at low latitudes (Bazhenov et al., 1992), but most workers (Cooper et al., 1992; Yogodzinski et al., 1993; Geist and Scholl, 1994) favor an origin immediately to the east, as a fragment of Aleutian crust that was transported by strike-slip motion from the Aleutian-Shirshov junction (Fig. 1). This kind of model is consistent with regional tectonics, the structure of the Kamchatka-Aleutian junction, and with the magmatic development of the Near Islands portion of the western Aleutian arc (Watson and Fujita, 1985; Baranov et al., 1991; Yogodzinski et al., 1993).

The timing of tectonic transport as it relates to the early magmatic development of the Komandorsky Islands remains poorly understood, but it appears that the Komandorsky terrane arrived at its present location by middle–late Miocene time (Watson and Fujita, 1985; Cooper et al., 1992; Yogodzinski et al., 1993; Geist and Scholl, 1994). This is consistent with the age of thrusting in eastern Kamchatka (Sukhanov and Zindevich, 1987), and with regional east-west geochemical trends along the Aleutian arc (especially in Pb isotopes), which show a close kinship between Miocene-age rocks in the Komandorsky Islands and late Pleistocene rocks of Piip Volcano (Yogodzinski et al., 1994). The youngest magmatic rocks of the Komandorsky Islands (this study) are also middle–late Miocene in age and appear, therefore, to have formed during and/or immediately after strike-slip tectonic transport along the western arc.

PETROLOGY AND GEOCHEMISTRY

Data presented here are from Miocene–Pliocene age volcanic and subvolcanic rocks from the Komandorsky Islands and from dredges taken in the Komandorsky region by the Russian research vessel *Vulkanolog* on Leg 38 (1990). These data are presented in two groups.

The first group is composed of Adak-type magnesian andesites dredged from the Kamchatka Strait area northwest of the Komandorsky Islands (dredges 41–42; Fig. 2). This is the 70-B49 dredge location of Scholl et al. (1976). Whole-rock K-Ar and fossil evidence indicate a middle–late Miocene age for these rocks (Scholl et al., 1976). Wet chemical analyses and new trace element and isotopic data presented here (Tables 1 and 2) augment previously published analyses of Adak-type magnesian andesites from this locality (Scholl et al., 1976; Kay, 1978).

The second group is a series of amphibole-bearing volcanic and subvolcanic rocks of andesitic and dacitic composition, which were collected on Medny Island and during dredging of an area southeast of Medny Island (dredge #36; Fig. 2). This is the calc-alkaline diorite-granitoid series of Borusk

TABLE 1. ADAK-TYPE MAGNESIAN ANDESITE WHOLE-ROCK ANALYSES

	V3841Y3	V3841Y2	V3841Y1	V3842Y2	V3842Y3	ave. anhyd.
SiO_2	60.06	59.70	58.63	59.32	58.88	61.07
TiO_2	0.92	0.89	0.95	0.89	0.89	0.93
Al_2O_3	15.52	15.43	15.25	15.32	15.71	15.90
Fe_2O_3	0.88	1.65	1.95	1.92	1.54	
FeO	2.61	1.89	1.52	1.66	1.98	3.46
MnO	0.05	0.04	0.05	0.05	0.05	0.05
MgO	4.52	4.76	4.52	4.52	4.44	4.69
CaO	6.94	7.48	7.48	7.32	7.32	7.52
Na_2O	3.63	3.69	3.63	3.53	3.48	3.70
K_2O	2.22	2.08	2.35	2.17	2.12	2.25
P_2O_5	0.43	0.39	0.44	0.42	0.38	0.42
H_2O^-	0.24	0.24	0.48	0.28	0.58	N.A.
H_2O^+	2.40	1.96	2.20	2.44	N.A.	N.A.
LOI	N.A.	N.A.	N.A.	N.A.	2.44	N.A.
Total	100.42	100.20	99.45	99.84	99.81	100.00
FeO*/MgO	0.75	0.71	0.72	0.75	0.76	0.74
CaO/Al_2O_3	0.45	0.48	0.49	0.48	0.47	0.47
La	33.0	30.3	33.6	33.7	29.6	
Ce	80.0	70.9	78.4	79.8	70.3	
Nd	44.0	39.8	41.7	45.5	38.3	
Sm	7.55	6.85	7.52	7.55	6.62	
Eu	1.93	1.74	1.95	1.95	1.73	
Tb	0.51	0.48	0.57	0.50	0.50	
Yb	0.68	0.62	0.70	0.71	0.70	
Lu	0.084	0.074	0.072	0.090	0.079	
Sr	2302	2366	2529	2309	2446	
Ba	323	320	327	365	297	
Rb	17	13	24	20	30	
Cs	0.11	0.09	0.15	0.15	0.19	
U	1.02	0.97	1.09	1.12	1.00	
Th	3.22	2.88	3.29	3.18	2.86	
Hf	4.53	4.01	4.89	4.49	3.99	
Ta	0.26	0.23	0.26	0.24	0.19	
Co	17.8	17.0	17.7	22.1	17.0	
Sc	9.4	8.9	9.1	10.0	9.0	
Cr	164	161	166	184	163	
Ni	119	126	124	133	126	
La/Yb	48.5	48.9	48.0	47.5	42.3	
Ba/La	10	11	10	11	10	
La/Ta	127	132	129	140	156	

Note: Major element analyses were performed at the Russian Institute of Volcanic Geology and Geochemistry (Petropavlovsk, Kamchatka) by wet chemistry, except Na_2O and K_2O, which were analyzed by flame photometry. Rubidium was analyzed by X-ray fluorescence at the Institute of Geology and Geophysics, Novosibirsk, Russia. All other trace elements were determined by neutron activation analysis at Cornell University. Procedure descriptions, and standard analyses and precision are published elsewhere (Kay et al., 1987; Kay and Kay, 1988; Romick et al., 1992). N.A. = not applicable.

TABLE 2. ISOTOPE ANALYSES

	^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb	^{208}Pb/^{204}Pb	^{87}Sr/^{86}Sr	^{143}Nd/^{144}Nd	εNd
			Adakites			
V3841Y3	17.874	15.398	37.291	0.70 280	0.513 073	+8.5
V3842Y3	17.877	15.399	37.300	0.70 282	0.513 075	+8.6
			Komandorsky calc-alkaline			
8-6-78	17.922	15.404	37.338	0.703 10	0.513 144	+9.9
8-4-78	17.883	15.395	37.247	0.703 02		
V38/36G3	17.895	15.387	37.274	0.703 16	0.513 170	+10.4
V38/36G1	17.871	15.415	37.325	0.703 05		
KCP/Y1	17.772	15.377	37.167	0.702 92	0.513 077	+8.6
KCP/Y4				0.702 93	0.513 066	+8.4
			Komandorsky Basin			
DSDP 191	17.785	15.381	37.302	0.702 71	0.513 182	+10.7

Note: All isotope analyses by thermal ionization mass spectrometry at Cornell University. Measured values for NBS SRM-981 Pb standard were ^{206}Pb/^{204}Pb = 16.896 ± 0.020, ^{207}Pb/^{204}Pb = 15.436 ± 0.022, and ^{208}Pb/^{204}Pb = 36.523 ± 0.061 (± indicates two standard deviation precision based on 28 analyses). Mass fractionation correction based on values of ^{206}Pb/^{204}Pb = 16.937, ^{207}Pb/^{204}Pb = 15.493, and ^{208}Pb/^{204}Pb = 36.705. Nd analyses were done on Ta single filaments by quintuple collector dynamic procedure. Correction for mass fractionation based on ^{146}Nd/^{144}Nd = 0.7219. Measured values for LaJolla Nd standard were ^{143}Nd/^{144}Nd = 0.511 859 with analytical precision of ±0.000 015 based on eight analyses. Epsilon Nd (εNd) are deviations in 10^4 from present-day chondritic ^{143}Nd/^{144}Nd assuming LaJolla εNd = −15.15. Sr analyses were done on W single filaments by quadruple collector dynamic procedure. Correction for mass fractionation based on ^{86}Sr/^{88}Sr = 0.119 40. Strontium isotope analyses based on NBS SRM-987 Sr standard value of ^{87}Sr/^{86}Sr = 0.710 248 with analytical precision of ±0.000 012 based on 45 analyses.

and Tsvetkov (1982) and Tsvetkov (1991). These are the youngest magmatic rocks of the Komandorsky Islands, dated at middle–late Miocene age (Borusk and Tsvetkov, 1982; Tsvetkov, 1991).

Adak-Type Magnesian Andesite

Western Aleutian Adak-type magnesian andesites (Table 1) are intermediate in composition (SiO_2 = ~59%), with low FeO* (3.3%) and TiO_2 (0.9%); moderate MgO (4.5%), CaO (7%), and Al_2O_3 (15.3%); and high Na_2O (3.6%) and K_2O (~2%). Low FeO*/MgO (0.75) and high Cr (165 ppm) and Ni (125 ppm) indicate that these rocks are among the most primitive in the Aleutian arc (e.g., Table 1 in Kay and Kay, 1994). Major element characteristics that distinguish these and other magnesian andesites from primitive basalts are high SiO_2 and low CaO/Al_2O_3 and CaO/Na_2O relative to FeO*/MgO (Fig. 3).

Petrographically, the western Aleutian Adak-type magnesian andesites are fresh, showing only fracture-controlled hydrous alteration of groundmass glass. They contain phenocrysts of clinopyroxene only (10%–20% diopside and endiopside), which typically show normal compositional zonation (Table 3). Groundmass phases include plagioclase (~An51), orthopyroxene (Mg-no. = ~86), clinopyroxene (Mg-no. = ~78), and interstitial glass (~69% SiO_2; see also Scholl et al., 1976; Kay, 1978).

Very high Sr (~2400 ppm) and steep rare earth element patterns (La/Yb = 45) are the trace element characteristics that distinguish Adak-type magnesian andesites from all other volcanic rocks in the Aleutians (Figs. 4 and 5; and see Kay and Kay, 1994). Ratios among the large ion lithophile elements and Sr are broadly like mid-oceanic-ridge basalt (MORB), but concentrations of the high field strength elements are relatively low (Fig. 5). There is also strong fractionation among the high field strength elements (Fig. 6). In particular, La/Ta in the Adak-type magnesian andesites is the highest, and Ti/Hf is the lowest among mafic- and intermediate-composition volcanic rocks in the Aleutian arc (Fig. 6).

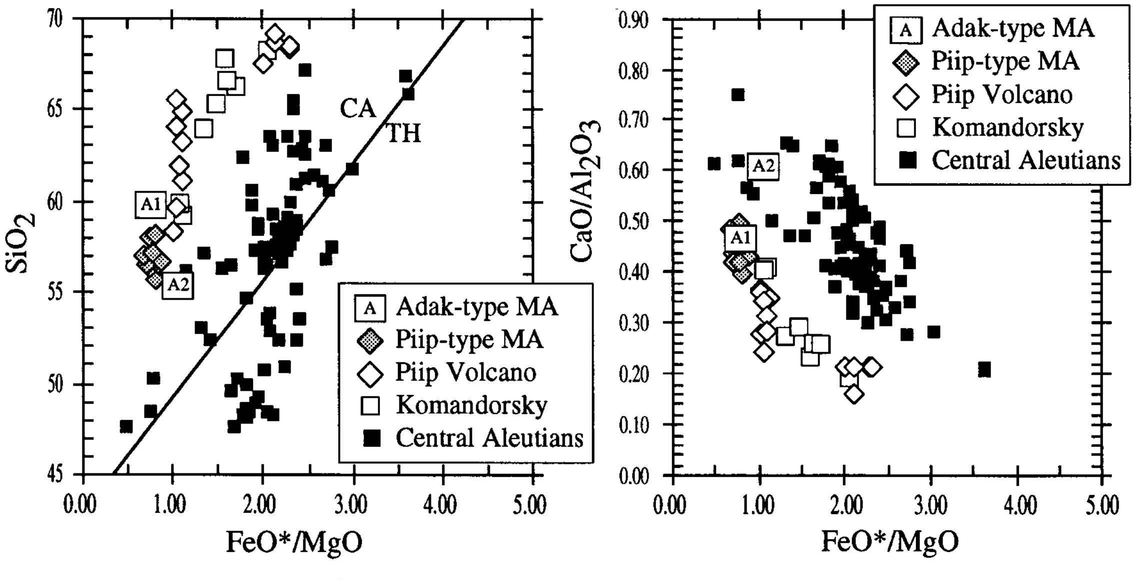

Figure 3. Major element characteristics of the Komandorsky calc-alkaline series compared to Piip Volcano and central Aleutians calc-alkaline volcanic rocks. Note the strongly calc-alkaline trend (low average FeO*/MgO and CaO/Al_2O_3 relative to SiO_2) of the western Aleutian data (Piip, Komandorsky) compared to the central Aleutian data. Adak-type magnesian andesites are marked by "A1" (western Aleutians, Table 1) and "A2" (central Aleutians; Kay, 1978). Komandorsky data are from Table 4. Piip Volcano data are from Yogodzinski et al., 1994). Central Aleutian data are from calc-alkaline volcanoes Moffett and Adagdak (Adak Island), Kanaga and Great Sitkin (locations in Fig. 1; data from Kay and Kay, 1994).

TABLE 3. CLINOPYROXENE ANALYSES: WESTERN ALEUTIAN ADAK-TYPE MAGNESIAN ANDESITES

	55c	57r	52c	54r	23c	24r	72c	74r
SiO_2	53.38	51.15	54.08	53.04	55.15	51.87	52.79	52.55
TiO_2	0.15	0.59	0.17	0.40	0.47	0.97	0.18	0.25
Al_2O_3	1.42	2.78	1.08	1.81	1.57	3.65	1.55	1.85
Cr_2O_3	1.36	0.02	0.67	0.09	0.11	0.00	0.08	0.53
FeO	1.98	4.93	2.43	4.42	3.59	6.02	4.16	4.54
MnO	0.13	0.28	0.03	0.07	0.05	0.07	0.11	0.09
MgO	16.75	15.93	16.96	17.03	16.56	15.14	16.43	16.51
CaO	22.90	22.22	23.06	21.34	22.84	21.59	22.32	21.25
Na_2O	0.35	0.19	0.28	0.19	0.24	0.26	0.06	0.09
K_2O	0.00	0.02	0.01	0.02	0.02	0.04	0.01	0.02
total	98.42	98.11	98.77	98.41	100.60	99.61	97.69	97.68
Mg-no.	0.94	0.85	0.93	0.88	0.89	0.82	0.88	0.87
Wo	0.48	0.46	0.48	0.44	0.47	0.46	0.46	0.44
En	0.49	0.46	0.49	0.49	0.47	0.44	0.47	0.48
Fs	0.03	0.08	0.03	0.07	0.06	0.10	0.07	0.07

Note: Clinopyroxene analyses by electron microprobe at the Institute of Volcanic Geology and Geochemistry (Petropavlovsk, Kamchatka, Russia). Phenocryst core compositions are designated by "c," and rim compositions are designated by "r" after analysis number.

Despite the variably fractionated trace element signature, available isotopic data (Table 2) require that the source for the Adak-type magnesian andesites was broadly MORB-like and, therefore, chemically depleted (Kay, 1978). Strontium isotope ratios are low ($^{87}Sr/^{86}Sr = 0.7028$), falling between northeast Pacific MORB and normal volcanic rocks from the central and eastern Aleutian arc (Fig. 7). Lead isotope ratios in the western Aleutian Adak-type magnesian andesites ($^{206}Pb/^{204}Pb = {\sim}17.9$) are substantially less radiogenic than northeast Pacific MORB (Fig. 8). Regionally, the western Aleutian Adak-type magnesian andesites are at the nonradiogenic limit of an east-west trend of decreasing Pb isotope ratios along the Aleutian arc (Fig. 8). In comparison to Sr and Pb, the Nd isotopes in western Aleutian Adak-type magnesian andesites are relatively radiogenic ($\varepsilon Nd = {\sim}{+}8.5$). The overall isotopic characteristics of these rocks are more similar to certain western Pacific marginal basin basalts than to eastern Pacific MORB (Figs. 7 and 8).

Komandorsky Calc-Alkaline Series

Miocene age magmatic rocks of the Komandorsky Islands are a medium-K, calc-alkaline assemblage of andesite (~59% SiO_2), dacite (64%–68% SiO_2), and subvolcanic granodiorite (~66% SiO_2). Dacite and granodiorite dominate the assemblage. The andesites have 10%–20% phenocrysts of amphibole, plagioclase, and minor clinopyroxene. The dacites are phenocryst-rich (20%–35%) with abundant plagioclase and amphibole and minor biotite, clinopyroxene, and Fe-Ti oxides. Groundmass glass is generally hydrated and devitrified, and sericite, calcite, and chlorite partially replace most feldspars and amphiboles. The granodiorites are mineralogically similar to the dacites (plagioclase-amphibole-biotite) but generally show less alteration than the volcanic rocks.

High SiO_2, Na_2O, and Al_2O_3, and low-moderate CaO, MgO, and FeO* (compared to FeO*/MgO) are the major element features that distinguish the Komandorsky rocks from those of the central Aleutian arc. These features produce a more strongly calc-alkaline series (lower average FeO*/MgO) in the Komandorsky rocks than in any volcano of the central arc. These major element characteristics are similar to those at Piip Volcano (Fig. 3).

Trace element and isotopic characteristics of the Komandorsky calc-alkaline rocks are broadly transitional between those of Adak-type magnesian andesites and normal Aleutian calc-alkaline rocks. This is clearest in the Komandorsky andesites that have lower Ba/La (~24 ppm) and higher La/Yb (~18 ppm) and Sr (~1200 ppm) than any volcanic rock in the central arc (Figs. 9 and 10, and Table 4). The Komandorsky dacites and granodiorites have La/Yb (10–13 ppm) and Ba/La (28–57 ppm) that are more similar to typical Aleutian volcanic rocks, but still are outside the main central Aleutian trend (Figs. 9 and 10).

Isotopic characteristics of the Komandorsky rocks (Table 2) are also more similar to Adak-type magnesian andesites (more MORB-like) than to typical volcanic rocks of the central and eastern arc. Strontium isotopes in the Komandorsky rocks are at the nonradiogenic limit of normal Aleutian volcanic rocks ($^{87}Sr/^{86}Sr = 0.7029–0.7031$), and neodymium isotopes in the Komandor-

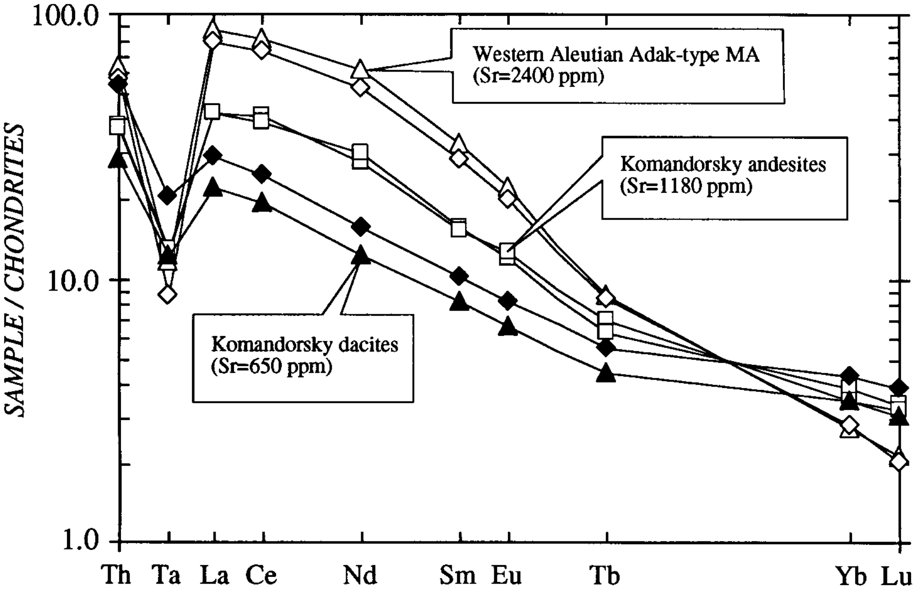

Figure 4. Chondrite-normalized rare earth elements, Th, and Ta in western Aleutian Adak-type magnesian andesites (Table 1) and Komandorsky calc-alkaline series rocks (Table 4). Note the high La/Yb, high La/Ta, and low Th/La of Adak-type magnesian andesites relative to the Komandorsky andesites and dacites. Normalizing values are Leedy chondrite (ppm): Th (0.050), Ta (0.022), La (0.378), Ce (0.976), Nd (0.716), Sm (0.230), Eu (0.0866), Tb (0.0589), Yb (0.249), Lu (0.0387).

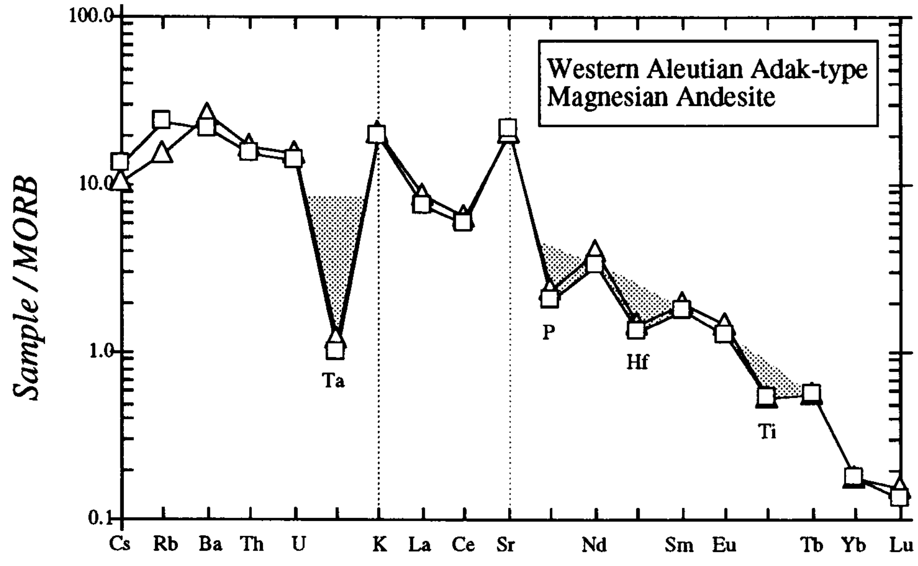

Figure 5. Incompatible elements in western Aleutian adakites normalized to average mid-ocean ridge basalts. Note that ratios among the large ion lithophile elements (including Sr) are broadly MORB-like, and that the high field strength elements (and phosphorus) are depleted relative to the smoothly varying rare earth elements. Normalizing values and plotting order are from Sun and McDonough (1989).

sky rocks are high (εNd = 8.5–10.4), extending well above the range of central and eastern Aleutian volcanic rocks (Fig. 7). Finally, Pb isotopes in the Komandorsky rocks are nonradiogenic, with a low ^{206}Pb/^{204}Pb (17.9–18.4) signature that is a distinctive feature of Miocene–Holocene volcanic rocks throughout the western Aleutian arc.

ORIGIN OF MAGNESIAN ANDESITE AND ITS IMPORTANCE IN THE WESTERN ALEUTIANS

Trace Elements and Isotopes in Adak-Type Magnesian Andesite: The Slab Melt Signature

Isotopic and large ion lithophile element ratios in Adak-type magnesian andesites indicate that they were derived from a chemically depleted source similar in most respects to normal MORB. Kay (1978) showed that small percentage melts of eclogite with MORB chemistry could produce the appropriate rare earth element and large ion lithophile element characteristics. A model of this kind is reproduced here in Figure 11. Tantalum is included in this model because, as noted earlier, Aleutian Adak-type magnesian andesites are the most strongly high field strength element–depleted rocks in the arc (Figs. 5 and 6). To account for the depletion in high field strength elements, a small quantity of rutile (0.80%) must be included in the residual eclogite mineralogy. Residual rutile will produce relative depletions in all of the high field strength elements (Green, 1981), but the greatest effects will be in Ta and Nb (Green and Pearson, 1987). Because the quantity of residual rutile in the model is small (<1%), only the most rutile-compatible elements will be affected. It is thus a critical assumption that the light rare earth elements and large ion lithophile elements (including Th) are not substantially partitioned into rutile under high-pressure melting conditions.

The presence of residual rutile in the model is consistent with experimental work, which has shown that small percentage melts of eclogite are silicic (Green and Ringwood, 1968; Rapp et al., 1991) and, therefore, may be rutile saturated (Green and Pearson, 1986; Ryerson and Watson, 1987). Dehydration melting experiments of Rapp et al. (1991) provide direct observation of rutile saturation in high-pressure melts of basaltic rocks and lend support to the simple eclogite melting model illustrated in Figure 11.

Slab Melt–Peridotite Reaction and Formation of Magnesian Andesite

Trace element and isotopic characteristics provide good evidence that Adak-type magnesian andesites originated as partial melts of the subducting slab, but the primitive features of these rocks (e.g., low FeO*/MgO, high Cr-Ni) and their intermediate composition (55%–59% SiO$_2$) imply that the slab-derived melts must have somehow interacted with peridotite in the mantle

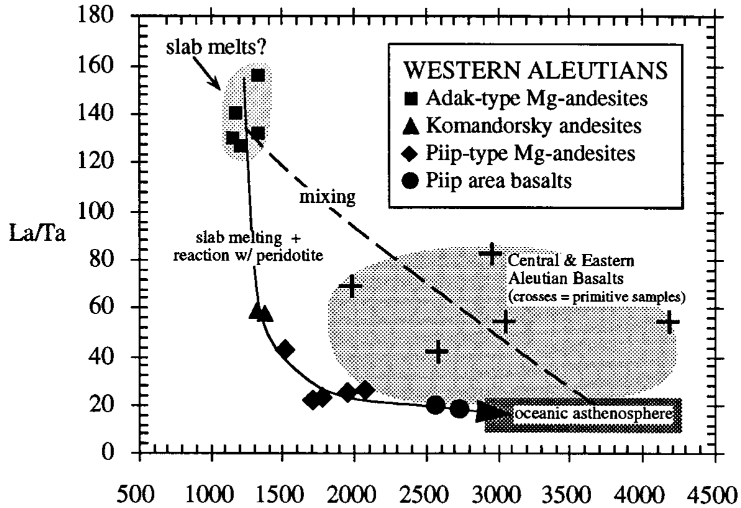

Figure 6. La/Ta versus Ti/Hf for western Aleutian volcanic rocks compared to oceanic asthenosphere and basalts from the central and eastern Aleutian arc. Values for oceanic asthenosphere are from Table 1 in Sun and McDonough (1989). Aleutian basalt data are from Kay and Kay (1994).

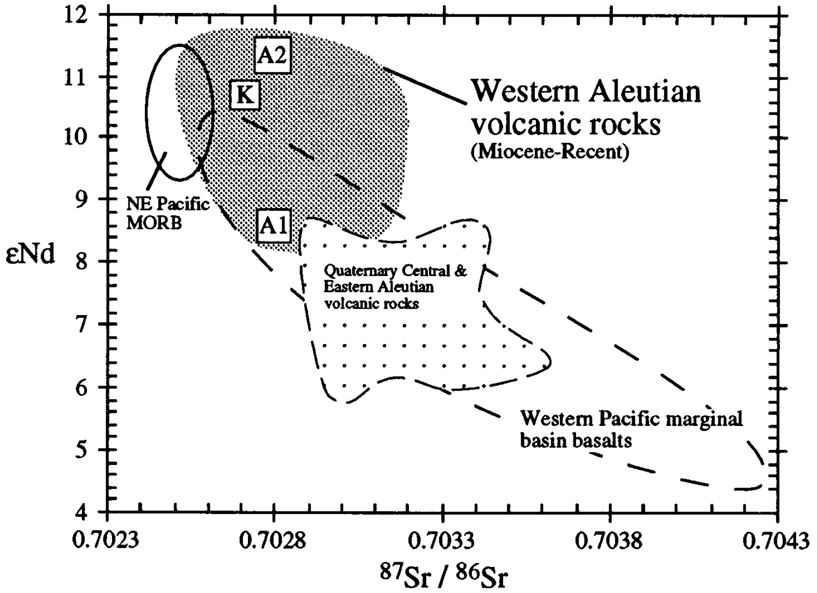

Figure 7. εNd versus $^{87}Sr/^{86}Sr$ for Aleutian volcanic rocks compared with mid-ocean ridge basalts (MORB) from the Northeast Pacific (White et al., 1987; Hegner and Tatsumoto, 1989) and selected marginal basin basalts of the Western Pacific (Hickey-Vargas, 1991; Tatsumoto and Nakamura, 1991). Samples A1 and A2 are Adak-type magnesian andesite (see Fig. 2). Sample K is a tholeiitic basalt from the Komandorsky Basin (Deep Sea Drilling Project Leg 191; location in Fig. 1). The western Aleutian field includes Miocene age samples from the Komandorsky Islands (Table 1) and the Near Islands (Table 3 in Yogodzinski et al., 1993), and Quaternary age rocks from Piip Volcano (Table 4 in Yogodzinski et al., 1994). Central and Eastern Aleutian data are from Kay and Kay (1994) and references therein.

wedge (Kay, 1978). This is because small percentage melts of a basaltic source (e.g., eclogite) are silicic (>63% SiO_2) and will generally have low concentrations of compatible elements (Cr, Ni, MgO).

In modelling magnesian andesite formation through reactions between silicic slab melts and peridotite in the mantle wedge, Kelemen et al. (1993) showed that the primary effects on incompatible elements are to lower their concentrations and to dampen most of the inter-element fractionation produced by eclogite melting. For example, slab melt–peridotite reactions lower La/Yb in the melt even when the solid residue is a garnet harzburgite (Kelemen et al., 1993). In the reactions outlined by Kelemen et al. (1993), the mass assimilated is greater than the mass crystallized, and the amount of magnesian andesite produced is greater (by a factor of 3–8) than the initial mass of the slab melt. Physically, this may be reasonable because of the inverted geothermal gradient that is anticipated in the mantle wedge. In this kind of model, the solid products of the reactions are peridotites (lherzolite, harzburgite, dunite, etc.), so the minerals crystallizing in the reaction are broadly similar to those that are being assimilated (Kelemen et al., 1993).

Reactions of this kind can produce the major element characteristics of Adak-type magnesian andesites. For example, 72% pyrolite assimilation by a trondhjemite, with 58% fractional crystallization of olivine + orthopyroxene, will accurately produce the major element features of Adak-type magnesian andesites and leave a harzburgite residue (calculations outlined in model 2, Table 5). If we assume that the incompatible element concentrations in the initial (unreacted) slab melt were substantially higher than those observed in the magnesian andesites (e.g., Fig. 10), then this kind of model might also account for the trace elements. Recall, however, that Adak-type magnesian andesites from both the central and western

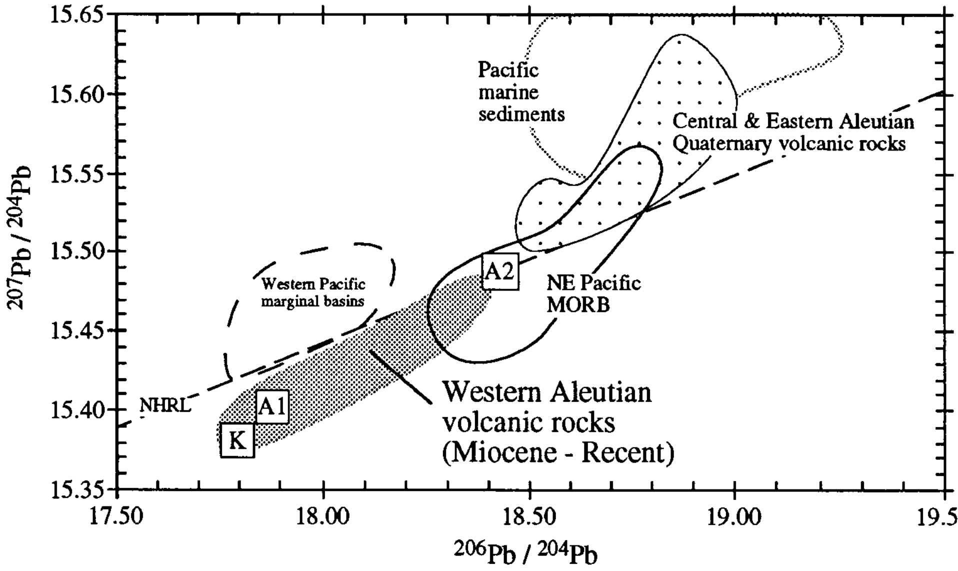

Figure 8. Pb isotopes in Miocene–Holocene western Aleutian volcanic rocks compared to northeast Pacific mid-ocean ridge basalts (MORB), and volcanic rocks of the central and eastern Aleutian arc. Samples A1 and A2 are Adak-type magnesian andesite (see Fig. 2). Sample K is Komandorsky Basin basalt (DSDP 191; Table 4). Data sources for this figure are the same as those in Figure 7. NHRL is the northern hemisphere reference line (Hart, 1984).

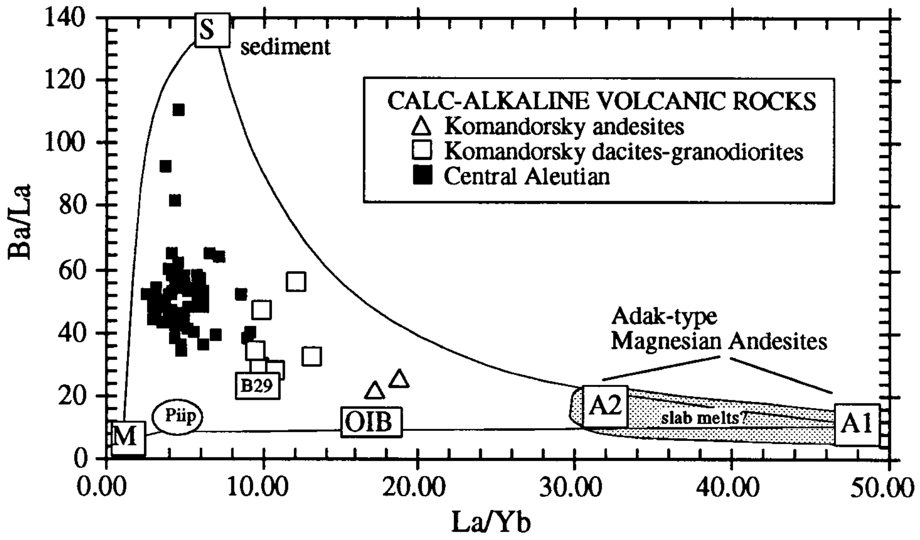

Figure 9. Ba/La versus La/Yb for Aleutian Adak-type magnesian andesites and western Aleutian Komandorsky calc-alkaline series rocks (Tables 1 and 4) compared to calc-alkaline volcanic rocks of the central Aleutian arc. Mixing lines connect depleted mantle (M), sediment (S), and proposed slab melts (Adak-type magnesian andesites). Sample B29 is a Quaternary western Aleutian hornblende dacite dredged by Scholl et al. (1976). Trace elements for B29 from Kay and Kay (1994). Central Aleutian data from calc-alkaline volcanoes Moffett and Adagdak (Adak Island), Kanaga, and Great Sitkin (locations in Fig. 1; data from Kay and Kay, 1994) Trace element values (in ppm) for sediment endmember are La (15.7), Yb (2.29), and Ba (2135) (composite A3 from Kay and Kay, 1988). Values for depleted mantle are La (0.206), Yb (0.347), and Ba (0.734). Trace element values for slab melt endmember are La (33.0), Yb (0.68), and Ba (323) (sample V3841Y3, Table 1).

Aleutian arc contain phenocrysts of clinopyroxene only. These phenocrysts may have formed during the melt's ascent through the crust, and so may tell little about processes in the mantle wedge, but it is an important point that as the melt encountered lower pressures, the stability of liquidus olivine would have been greatly expanded, especially under hydrous conditions (Nicholls and Ringwood, 1973). It is therefore difficult to explain how the Adak-type magnesian andesites could have reacted with a large mass of solid peridotite (Kelemen et al., 1993) without becoming saturated in olivine prior to eruption.

It seems more likely that Adak-type magnesian andesites have been produced by limited interaction between a slab melt and peridotite than by extensive assimilation and crystallization of peridotite. The argument for limited interaction with peridotite is supported by the important observation that clinopyroxene phenocrysts in Adak-type magnesian andesites from the central Aleutians show reverse compositional zonation, indicating that the melt was becoming more Mg rich as the crystallization proceeded. If Adak-type magnesian andesites are formed by reaction with a large mass of peridotite, then any mafic minerals crystallizing from the melt should be buffered at a uniformly primitive composition (Mg-no. = >88).

If we assume that the initial slab melt was tonalitic (SiO_2 = 59%–64%, CaO/Na_2O = >1), then major element mass balance indicates that Adak-type magnesian andesites can be produced by limited interaction with peridotite. Model 3 (Table 5) summarizes the features of this calculation. In this model, 26% peridotite is assimilated into a tonalite, and 34% orthopyroxene is crystallized. The mass assimilated is relatively high compared to the mass fractionated (Ma/Mc = 0.76), but for an assimilation-fractional crystallization reaction occurring in a subduction zone this is expected if the hot peridotite in the mantle wedge thermally dominates the system (see Johnston and Wyllie, 1989; Kelemen et al., 1993). Petrologically the model is reasonable because we know from experimental work that assimilation of peridotite by a tonalitic melt at relatively high temperatures will produce saturation in orthopyroxene only (Carroll and Wyllie, 1989). The important feature of model 3 is that a relatively small amount of hybridization of the tonalite is required to produce Adak-type magnesian andesites. This is consistent with experimental work, which indicates that large amounts of hybridization of slab melts may be difficult to achieve (Sekine and Wyllie, 1983; Johnston and Wyllie, 1989), and it means that the characteristic trace element pattern produced by slab melting is not substantially disrupted by the hybridization process.

Melt–Melt Interaction and Formation of Magnesian Andesite

Having outlined two different types of slab melt–peridotite (melt-rock) reactions that can explain the broad geochemical characteristics of Adak-type magnesian andesites, we look to alternative successful models that might outline other processes occurring in the mantle wedge. One alternative may be the interaction of silicic and mafic melts.

Experiments at 15–30 kbar in the hybrid system indicate that mixtures of silicic or intermediate and mafic melt endmembers will produce hybrid melts that are mostly saturated in garnet and clinopyroxene (Stern and Wyllie, 1978; Carroll and Wyllie, 1989). Mass-balance calculations indicate that the major element features of the western Aleutian Adak-type magnesian andesites can be reproduced by mixing and crystal fractionation in this kind of hybrid system. Examples of major element mixing-crystallization models of this kind are summarized in Table 5. In all cases these models begin with basalt–slab melt mixtures in proportions that produce andesitic hybrid systems (53%–61% SiO_2). In the simplest case, removal of garnet from the hybrid systems can reproduce the features of Adak-type magnesian andesites (models 4–5, Table 5). The amount of garnet removed in this kind of model depends on the relative CaO-Na_2O content of the slab melt used. In model 4, the slab melt endmember has CaO/Na_2O = 1.52 (a dacite), and removal of 21% garnet is required to produce the major element features of the western Aleutian adakites. In contrast, model 5 (Table 5) requires the removal of only 5% garnet, because the Na content of the slab melt in these models is relatively high (CaO/Na_2O = 0.80–0.35 in trondhjemites). When garnet + clinopyroxene are removed from the hybrid systems, residuals are generally lower, and there is a

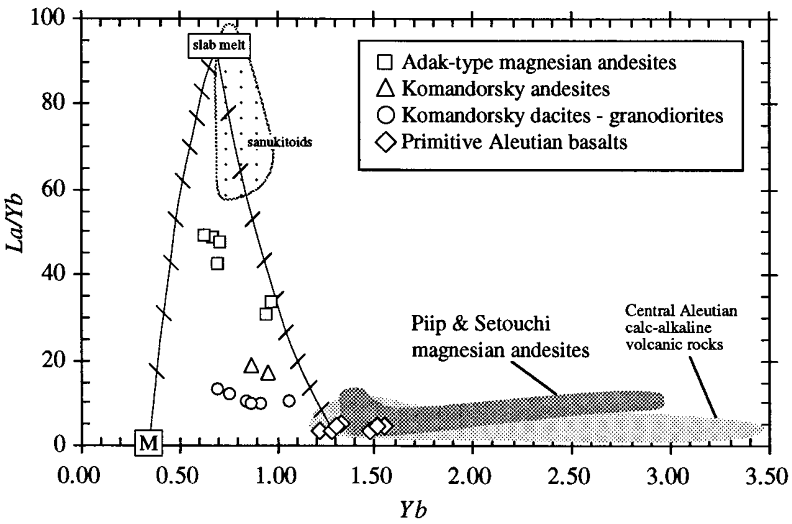

Figure 10. La/Yb versus Yb for Adak-type magnesian andesites (Table 1; Kay and Kay, 1994) and Komandorsky calc-alkaline rocks (Table 4) compared with Piip-type magnesian andesites (Yogodzinski et al., 1994), primitive Aleutian basalts and calc-alkaline volcanic rocks from the central Aleutians (Kay and Kay, 1994, and references therein). Mixing lines connect hypothetical slab melt, depleted mantle (M) and primitive Aleutian basalt. Slashes on mixing lines are at 10% intervals. Setouchi magnesian andesites data are from Ishizaka and Carlson (1983) and Tatsumi and Ishizaka (1982). Slab melt composition is produced by 3% melting of average MORB (La = 3.895 ppm, Yb = 3.90 ppm; Hofmann, 1988). Melting mode and distribution coefficients as in Figure 11. Depleted mantle mixing endmember has La = 0.21 ppm, and Yb = 0.35 ppm. Primitive basalt mixing endmember has La = 4.29 ppm, and Yb = 1.29 ppm.

TABLE 4. KOMANDORSKY CALC-ALKALINE WHOLE-ROCK ANALYSES

	Andesite		Dacite		Granodiorite		Dacite	
	KCP/Y4	KCP/Y1	8-6-78	KCP/Y3	8-4-78	KCP/Y2	38/36G1	38/36G3
SiO_2	59.08	59.69	64.02	65.33	66.35	66.67	67.84	68.27
TiO_2	0.72	0.73	0.52	0.48	0.46	0.46	0.34	0.26
Al_2O_3	16.69	16.35	17.18	17.01	16.87	17.05	16.9	16.98
FeO*	6.16	6.08	3.88	3.79	3.71	3.38	2.94	2.86
MnO	0.14	0.06	0.11	0.12	0.17	0.12	0.12	0.15
MgO	5.45	5.54	2.89	2.55	2.16	2.07	1.84	1.39
CaO	6.78	6.6	4.79	5.07	4.37	4.41	3.98	3.29
Na_2O	3.06	3.17	4.38	4.2	4.48	4.43	4.37	4.45
K_2O	1.92	1.78	1.71	1.45	2.04	1.41	1.67	2.35
Total	100.00	100.00	99.48	100.00	100.61	100.00	100.00	100.00
FeO*/MgO	1.13	1.1	1.34	1.49	1.72	1.63	1.6	2.06
CaO/Al_2O_3	0.41	0.4	0.28	0.3	0.26	0.26	0.24	0.19
La	16.3	16.3	8.46	8.97	10.9	8.33	9.22	9.2
Ce	40.3	38.9	18.8	20.2	24.4	18.8	20.1	19.9
Nd	19.6	21.3	8.6	10.5	11.3	9.0	9.6	8.7
Sm	3.53	3.58	1.94	2.18	2.38	1.87	1.87	1.78
Eu	1.08	1.03	0.65	0.64	0.72	0.58	0.59	0.54
Tb	0.42	0.37	0.28	0.31	0.33	0.26	0.23	0.23
Yb	0.87	0.96	0.85	0.92	1.07	0.87	0.7	0.76
Lu	0.123	0.121	0.124	0.136	0.15	0.119	0.092	0.123
Sr	1170	1199	627	666	734	620	630	516
Ba	417	356	409	254	321	301	308	525
Cs	0.19	0.08	0.08	0.13	0.33	0.10	0.22	0.17
U	0.2	0.09	0.08	0.14	0.35	0.1	0.99	0.95
Th	1.85	1.94	1.61	1.77	2.71	1.44	1.74	1.79
Ta	0.28	0.28	0.33	0.36	0.45	0.27	0.28	0.26
Hf	3.2	3.17	2.45	2.5	3.26	2.59	2.26	2.67
Sc	21	21	10	11	9	7	6	5
Cr	85	82	56	28	18	19	16	5
Ni	42	41	28	23	17	13	17	6
Co	23	25	14	13	12	10	9	8
La/Yb	19	17	10	10	10	10	13	12
Ba/La	26	22	48	28	29	36	33	57
La/Ta	59	58	25	25	24	31	33	36

Note: Major elements by electron microprobe, trace elements by neutron activation analysis, all at Cornell University. Procedure descriptions, and standard analyses and precision are published elsewhere (Kay et al., 1987; Kay and Kay, 1988; Romick et al., 1992).

wider variety of models that produce a good fit (models 7–8, Table 5).

It appears that in addition to melt-peridotite reaction processes like those advocated by Kelemen (1990, 1993), Adak-type magnesian andesites may also be produced by mixtures of slab melt and basalt that fractionate garnet ± clinopyroxene. This kind of mixing-crystallization model may be physically appropriate if peridotite of the mantle wedge is warm enough to undergo decompression melting within a broad zone of upwelling surrounding a batch of low density, silicic slab melt. Under these conditions, hybridization of the slab melt would be accelerated, because the exchange of components would be enhanced by the presence of a continuous mafic melt phase throughout the system (Sekine and Wyllie, 1983). In this model, hybridization of the slab melt occurs not only by diffusive transfer of heat and peridotite components into the slab melt, but also by mass and heat advection through magma mixing.

Slab Melting Throughout the Western Aleutian Arc

Kay (1980) showed that three component source mixtures of depleted peridotite, marine sediment, and partial melts of the subducting oceanic crust are required to explain the chemistry of arc volcanic rocks worldwide. For any given arc locality, these endmembers are normally difficult to characterize, but in the western Aleutians, the slab melt and mantle wedge endmembers are relatively well understood. We know, for example, that the western Aleutian subarc mantle is depleted peridotite, broadly similar to that which produces MORB (Kay et al., 1986; Yogodzinski et al., 1993; Yogodzinski et al., 1994). It is also apparent that slab melting has occurred in the western Aleutians, and that these slab melts have distinctive Pb isotopic signatures that appear in arc volcanic rocks throughout the region (Fig. 8).

The important feature of Miocene-age calc-alkaline rocks in the Komandorsky Islands is their similarity to the geochemically distinctive Adak-type magnesian andesites. In particular, the nonradiogenic Pb isotope composition is regionally distinctive (Fig. 8), and the combination of MORB-like isotopes with high Sr and La/Yb (Figs. 7–10) seems to require a slab melting origin. In our view, the Komandorsky andesites, dacites, and granodiorites (Table 4) were formed by crystal fractionation (at mid-lower crustal

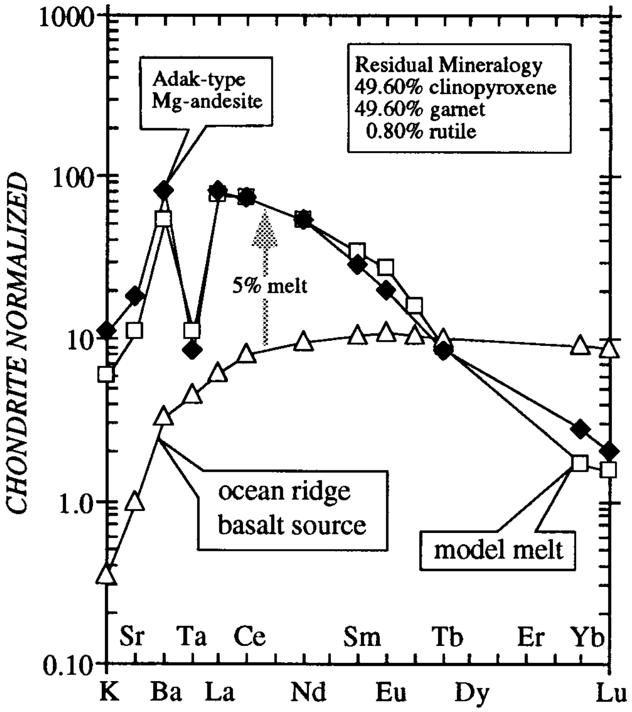

Figure 11. Eclogite batch melting model (Shaw, 1970) for the trace element features of western Aleutian Adak-type magnesian andesite (modified from Kay, 1978). Residual mineralogy (including rutile) is similar to that in 32 kbar melts of a basalt source from Rapp et al. (1991). Note that a small quantity of residual rutile (0.80%) produces a large Ta depletion relative to the light rare earth elements. Mineral/melt distribution coefficients for clinopyroxene are: 0.002 (K), 0.078 (Sr), 0.001 (Ba), 0.008 (Ta), 0.050 (La), 0.096 (Ce), 0.182 (Nd), 0.261 (Sm), 0.250 (Eu), 0.307 (Tb), 0.227 (Yb), 0.200 (Lu). For garnet, mineral/melt distribution coefficients are: 0.015 (K), 0.012 (Sr), 0.023 (Ba), 0.01 (Ta), 0.014 (La), 0.028 (Ce), 0.090 (Nd), 0.290 (Sm), 0.490 (Eu), 2.07 (Tb), 11.5 (Yb), 11.9 (Lu). With the exception of Ta, clinopyroxene coefficients are from Kay (1978), and garnet coefficients are from Arth and Hanson (1975). Coefficients for Ta in clinopyroxene and garnet are from Kelemen et al. (1993; assumed here to be similar to Nb). Rutile/melt distribution coefficient for Ta (44.0) is from Green and Pearson (1987). Other coefficients for rutile are assumed to be zero. Normalizing values for Ta and the rare-earth elements are the same as in Figure 4. Other normalizing values are K (1650), Ba (3.77), Sr (135).

depths) from parental magmas similar to the Adak-type magnesian andesites. In this interpretation, the parental magmas originated as melts from the subducting slab that underwent variable degrees of interaction with peridotite or basalt in the mantle wedge. Geochemical variation in the Komandorsky calc-alkaline rocks (e.g., La/Yb = 10–20) probably reflects different degrees of partial melting in the subducting slab and/or different degrees of interaction of the slab melts with peridotite in the mantle wedge. We rule out crystal fractionation as a key process in controlling the chemistry of the Komandorsky rocks because, in general, the andesites have higher concentrations of compatible and incompatible elements (e.g., Cr, Ni, La, Ba, Sr, and La/Yb; Table 4) than do the dacitic rocks. The essential point is that the source mixture that produced the Komandorsky calc-alkaline rocks had a relatively large slab melt contribution compared to volcanic rocks in the central and eastern parts of the Aleutian arc.

The presence of a slab melt endmember appears to be an important feature of all Miocene and younger volcanic rocks in the western Aleutian arc. In late Pleistocene-age calc-alkaline rocks at Piip Volcano, nearly all inter-element and isotopic ratios can be explained by simple mixing of depleted peridotite and small percentage melts of the subducting oceanic crust (Yogodzinski et al., 1994). The Piip-type magnesian andesites and related rocks do not, however, show the high Sr and La/Yb fingerprint of slab melting (Fig. 10), and in this way they are unlike Komandorsky calc-alkaline rocks. The essential difference between the Piip and Komandorsky rocks is that the trace element signature of slab melting in the Piip rocks has been diluted by more interaction between the slab melt and peridotite or basalt in the mantle wedge. In the case of the Piip rocks, the slab melt contribution is relatively small, so in effect it acts only to metasomatize and fertilize the source peridotite (Yogodzinski et al., 1994). In the Komandorsky rocks (including the Adak-type magnesian andesites), the slab melt endmember is relatively large, so it contributes not only to the trace element and isotopic features of the rocks but also to their major element (e.g., high SiO_2 relative to FeO*/MgO) and in some cases their mineralogical characteristics (e.g., clinopyroxene phenocrysts in Adak-type magnesian andesites).

DISCUSSION

Alternatives to a Slab-Melting Origin for Adak-Type Magnesian Andesites

Alternatives to the slab-melting interpretation for the origin of Adak-type magnesian andesites may be garnet fractionation from a basaltic magma or melting of a thick, garnet-bearing lower crust. Both of these alternatives require thicker crust and higher crustal pressure (>20 kbar) than is present in the Aleutians, and neither provides a comprehensive explanation for the distinctive isotopic and trace element characteristics of Adak-type magnesian andesites. If, for example, the lower crust of the Aleutian arc is gabbroic and chemically related to the volcanic and plutonic rocks exposed at the surface (e.g., Kay and Kay, 1981; Kay and Kay, 1991), then melting of the Aleutian lower crust should produce rocks with average Aleutian isotopic values. Adak-type magnesian andesites from both the central and western Aleutians are, however, among the most isotopically extreme in the arc (most MORB-like; see Figs. 7 and 8). This is clearest in the western Aleutian Adak-type magnesian andesites, which have nearly the lowest $^{206}Pb/^{204}Pb$ in the arc (17.9) and are less radiogenic than most of the earlier magmatic rocks in the Komandorsky Islands (see also Housh et al., 1989). The only conceivable crustal source for Adak-type magnesian andesites is in the Cretaceous-age(?) oceanic foundation upon which the arc was

TABLE 5. MAJOR ELEMENT MASS BALANCE CALCULATIONS*

No.[†]	Reactants	Products	Σres.^{2}[§]
1	1.000 (bslt1)	−0.290 (gnt1) −0.450 (cpx1) = 0.264 (adk1)	0.639
2	0.720 (prlt) + 0.280 (smlt1)	−0.355 (olv1) −0.241 (opx1) = 0.395 (adk1)	0.335
3	0.240 (prlt) + 0.760 (smlt2)	−0.343 (opx2) = 0.661 (adk1)	0.514
4	0.500 (smlt3) + 0.500 (bslt1)	−0.211 (gnt2) = 0.791 (adk1)	0.619
5	0.520 (smlt4) + 0.480 (bslt1)	−0.054 (gnt3) = 0.963 (adk1)	0.774
6	0.360 (smlt4) + 0.640 (baslt1)	−0.111 (gnt4) −0.236 (cpx2) = 0.672 (adk1)	0.258
7	0.440 (smlt1) + 0.560 (bslt1)	−0.095 (gnt4) −0.053 (cpx3) = 0.851 (adk1)	0.201
8	0.200 (smlt3) + 0.800 (bslt1)	−0.240 (gnt2) −0.278 (cpx1) = 0.482 (adk1)	0.158

Note: Abbreviations: bslt = basalt, gnt = garnet, cpx = clinopyroxene, prlt = pyrolite, smlt = slab melt, olv = olivine, and opx = orthopyroxene.

*Least squares analysis of major element components are aimed at producing the features of Adak-type magnesian andesites. The amount of magnesian andesite produced by calculation is shown to the right of the equal sign under "Products." The "adk1" composition is the average anhydrous analysis from Table 1. Other rock and mineral compositions used in these calculations are presented in Table 6.

[†] (1) Fractionation of clinopyroxene + garnet from primitive Aleutian basalt; (2) assimilation of pyrolite by trondhjemite with fractionation of olivine + orthopyroxene; (3) assimilation of pyrolite by tonalite with fractionation of orthopyroxene; (4) mixing of dacite with Aleutian basalt and fractionation of garnet; (5) mixing of trondhjemite with primitive basalt and fractionation of garnet; (6) mixing of trondhjemite with primitive basalt and fractionation of garnet + clinopyroxene; (7) mixing of high pressure melt (trondhjemite) with primitive basalt and fractionation of garnet + clinopyroxene; and (8) mixing of dacite with primitive basalts and fractionation of garnet + clinopyroxene.

[§] This is the sum of the mass balance residuals squared: $\Sigma(\text{observed} - \text{calculated})^2$.

built (Kay et al., 1986), but melting of this isotopically MORB-like basement without significant incorporation of lower crust formed by Aleutian arc magmatism seems unlikely.

The major element features of Adak-type magnesian andesites can be modeled by garnet-clinopyroxene fractionation from a primitive Aleutian basalt (mass balance calculations in model 1, Table 5). A model of this kind could also explain some of the trace element characteristics of Aleutian adakites (e.g., high La/Yb), but garnet fractionation cannot produce extreme La/Ta and Ti/Hf and cannot account for the distinctive isotopic characteristics of Adak-type magnesian andesites relative to other volcanic rocks in the arc. Rutile fractionation from basalt would produce low relative TiO_2 and Ta, but the high TiO_2 contents required for rutile saturation in a basaltic melts ($>3\%$ TiO_2; Ryerson and Watson, 1987) are unlike those observed in primitive arc basalts ($<1\%$ TiO_2; e.g., Perfit et al., 1980). The basalt fractionation model is, therefore, regarded as improbable. We conclude that the slab melting model of Kay (1978) is consistent with a broad range of experimental and observational data and that it remains the most plausible explanation for the trace element and isotopic characteristics of Adak-type magnesian andesites.

Two Kinds of Magnesian Andesite

We have argued that in the western Aleutians there are two petrologically and geochemically distinct magnesian andesites types, both of which are related to melting of the subducting slab in the eclogite facies. In general, there is probably a range of magma types that may be produced by slab melting and reaction of those melts in the mantle wedge. If a silicic slab melt reacts and equilibrates with a large mass of peridotite, then the result may be a magnesian andesite or it may be a basalt (Marsh, 1982; Brophy and Marsh, 1986; Myers, 1988; Kelemen, 1990). The difference will depend to a large degree on the final conditions of equilibration; in general, low pressure (<10 kbar) and hydrous conditions will favor magnesian andesite formation. In any case, a melt formed by equilibration or near-equilibration with peridotite will be saturated in forsteritic olivine when it erupts. This is because olivine is abundant in the mantle, and the stability of liquidus olivine is greatly expanded at low pressures, especially under hydrous conditions (Nicholls and Ringwood, 1973; Kelemen, 1990).

Because Adak-type magnesian andesites do not contain phenocrysts of olivine, they cannot have been near equilibrium with peridotite. The presence of only clinopyroxene phenocrysts in Adak-type magnesian andesites is, however, consistent with an origin in the tonalite-peridotite hybrid system. On the pseudoternary liquidus diagram of this system at 15–30 kbar (e.g., Figs. 3 and 14 in Carroll and Wyllie, 1989), Adak-type magnesian andesites plot in the clinopyroxene field, adjacent to the clinopyroxene-garnet cotectic. The mineralogy of Adak-type magnesian andesites, therefore, provides strong evidence that these rocks were produced by limited and incomplete reaction between a silicic slab melt and mantle peridotite or basalt (Kay, 1978). This interpretation is well supported by the trace element patterns in Adak-type magnesian andesites (Figs. 4–6), which retain the signature of basalt melting in the eclogite facies, and by isotopic and large ion lithophile element ratios that are consistent with a chemically MORB-like source (Figs. 7 and 8).

TABLE 6. ROCK AND MINERAL COMPOSITIONS USED IN MASS BALANCE CALCULATIONS[†]

	Pyrolite	Basalt	Hypothetical slab melts				Olivine	Orthopyroxene		Clinopyroxene			Garnet			
	1[§]	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	prlt	bslt1	smlt1	smlt2	smlt3	smlt4	olv1	opx1	opx2	cpx1	cpx2	cpx3	gnt1	gnt2	gnt3	gnt4
SiO_2	44.32	48.97	70.10	63.11	64.80	73.80	40.83	54.28	53.16	46.90	50.50	52.41	40.40	40.20	38.02	39.32
TiO_2	0.16	0.72	0.94	0.73	0.73	0.04	0.00	0.21	0.33	1.30	0.90	0.31	0.30	0.70	1.30	1.19
Al_2O_3	4.33	16.27	15.54	16.50	17.60	16.30	0.01	3.74	8.34	12.70	12.50	5.24	22.90	22.50	21.29	21.42
FeO*	9.82	8.78	1.78	5.26	4.10	0.39	9.09	11.09	12.28	8.40	10.10	9.78	12.30	16.30	23.84	17.72
MgO	36.84	9.62	0.43	2.48	2.25	0.16	49.99	29.33	22.17	10.20	8.10	18.53	13.00	11.60	4.88	11.37
CaO	3.34	12.86	1.89	5.72	4.14	2.65	0.01	0.58	2.35	17.90	12.50	13.35	10.40	10.90	10.00	7.80
Na_2O	0.39	2.11	5.44	3.42	2.73	6.24	0.00	0.05	0.16	1.50	3.80	0.80	0.00	0.00	0.08	0.07

[†] Mass balance calculations are summarized in Table 5, which also has explanation of abbreviations.

[§] (1) MORB-pyrolite (Falloon and Green, 1988); (2) primitive Aleutian basalt sample OK4 (Kay and Kay, 1994); (3) trondhjemite melt from eclogite source at 32 kbar (Rapp et al., 1991); (4) tonalite from the Peninsular Ranges Batholith (Gromet and Silver, 1987); (5) dacite from the Puna-Altiplano plateau (Kay and Kay, 1991); (6) trondhjemite from Minnesota (Arth and Hanson, 1975); (7) forsteritic olivine; (8–9) orthopyroxene compositions from tonalite-peridotite experiments (Carroll and Wyllie, 1989); (10–12) clinopyroxene compositions from the system tonalite-basalt-peridotite (Carroll and Wyllie, 1989; Stern and Wyllie, 1978); and (13–16) garnet compositions from the system tonalite-basalt-peridotite (Carroll and Wyllie, 1989; Stern and Wyllie, 1978).

In contrast, the Piip-type magnesian andesites are saturated in forsteritic olivine, and thus may have been near equilibrium with peridotite prior to eruption, but our understanding of the physical process that produced the Piip-type magnesian andesites remains incomplete. They may have formed by direct melting of a relatively fertile lherzolite (Tatsumi, 1982), they may have formed by equilibration of arc basalt with depleted peridotite (Yogodzinski et al., 1994), or they may have formed by the incremental reaction and equilibration of a silicic slab melt in the mantle wedge (Kelemen, 1993). The major element and mineralogic features of Piip-type magnesian andesites, which are similar to the well-studied Setouchi magnesian andesites (Tatsumi, 1982), suggest only that they last equilibrated with the mantle under relatively low pressure and hydrous conditions. We conclude that the andesitic character of the Piip-type magnesian andesites may have come entirely from the equilibrium features of peridotite melts (e.g., Mysen et al., 1974; Tatsumi, 1982), and in this way they may be unlike Adak-type magnesian andesites, where the andesitic and mineralogic compositions are attributed to incomplete reaction between silicic slab melt and peridotite or basalt. This is the primary justification for distinguishing the Piip-type and Adak-type magnesian andesites.

Oblique Subduction and Melting of the Slab

It is likely that an enhanced role for slab melting in the Komandorsky region stems from the highly oblique nature of the subduction path, because, in general, slower subduction produces a warmer pressure-temperature-time path for the down-going lithosphere (Peacock et al., 1994). According to Creager and Boyd (1991), oblique subduction into the Komandorsky region carries the slab from the trench to 100 km depth in 6–10 m.y. In the central Aleutians, subduction to 100 km depth is accomplished in 2.5–3.0 m.y. We suggest that this three-fold difference in subduction rate is significant and that the lower rates for subduction in the western Aleutians increase the likelihood that the subducting slab will intersect the basalt solidus beneath the arc.

Most workers agree that frictional heat production in the subduction zone is required to produce melting in basaltic oceanic crust at the surface of the slab (e.g., Turcotte and Schubert, 1973). Peacock et al. (1994) argue further that shear stresses in subduction zones are relatively low (<30 MPa) and that these stresses will produce enough heat so that only young lithosphere (<5 m.y. old) subducting at low rates (1–3 cm/yr) will generally reach thermal conditions required for slab melting. Molnar and England (1990) argue, however, that shear stresses in subduction zones may be relatively high (30–100 MPa), and, under these conditions, melting of the subducting slab would be more common (Peacock et al., 1994). In this regard it is an important point that Adak-type magnesian andesites from the central Aleutians (those from Adak Island) were produced in an area where the subducting lithosphere was relatively old (40–50 Ma; Lonsdale, 1988) and where subduction rates are relatively high (>5 cm/yr; Fig. 1). If the thermal models are correct, this would seem to argue for relatively high shear stresses in the central Aleutian subduction zone.

In addition, the overall geometry of the Aleutian subduction system is such that the region of highest strain and highest strain rate within the subducting slab is located beneath the central part of the arc (Creager and Boyd, 1991). If high strain and high strain rates in the slab can be related to high shear stresses and shear heat production (e.g., Peacock et al., 1994), then the overall geometry of the subducting slab might partially explain why the slab has apparently melted beneath Adak Island in the central part of the arc (Kay, 1978).

Overall, the effect of oblique subduction on the thermal structure of the down-going lithosphere is not well known, because thermal models for subduction zones assume an orthogonal subduction geometry (e.g., Peacock et al., 1994). It is an interesting point, however, that some other proposed slab melting (adakite) localities are also in areas where subduction is oblique (e.g., Panama and Cook Island; Stern et al., 1984; Defant and Drummond, 1990). Even at the central Aleutian Adak location, subduction since the middle Miocene has been oblique (45°–57° from the trench; Engebretson et al., 1985). We conclude from our studies in the western Aleutians and from the occurrence of adakite localities worldwide that oblique subduction may be an important control over the thermal structure of subduction zones.

Slab Melting and the Subduction Component in Arc Volcanic Rocks

If we accept the interpretation that Adak-type magnesian andesites are produced largely by the melting of the subducting slab in the eclogite facies, then we can draw some important conclusions about the possible geochemical effects of slab melting in subduction systems. Figure 12 shows, for example, that the addition of small percentage melts of the subducting slab to a depleted mantle wedge will produce an arc magma source that is enriched in light rare earth elements, depleted in the high field strength elements, and has K/La and Sr/La nearly identical to primitive Aleutian basalts. Steep rare earth element patterns, low to moderate Ba/La (10–20), and high concentrations of the large ion lithophile elements and light rare earth elements may be attributed to oceanic-island basalt-type mantle in the source of arc magmas (Morris and Hart, 1983), but these features can also be attributed to small percentage melts of the subducting oceanic crust (Kay, 1980; Fig. 9 here). Anticipated variation in Sr isotope composition ($^{87}Sr/^{86}Sr = \sim 0.7025–0.7040$, depending on seawater alteration in oceanic crust) also make slab melts an attractive endmember in source mixtures for arc volcanic rocks.

With regard to large ion lithophile element-enrichment in the arc source, it is an important point that a mixture of subducted MORB and peridotite will not produce a source with appropriately high Cs, Rb, Ba, or Th (e.g., Ba/La will be too low; Fig. 12). The high large ion lithophile element/light rare earth element aspect of the subduction component apparently requires the addition of a third mixing endmember that contains components from sediment (Kay, 1980). It is commonly argued that this component is added to the source mixture as a fluid (Tatsumi et al., 1986; Morris et al., 1990). We note, however, that elements like Ba and Th, which behave very similarly in arc volcanic rocks (e.g., McCulloch and Gamble, 1991; Kay and Kay, 1994), are generally thought to have different solubilities under hydrothermal conditions. The idea that large ion lithophile elements are transported from the slab to the mantle wedge dominantly by fluids therefore seems problematic (Kay and Kay, 1988).

For many of the western Aleutian rocks, the sedimentary component appears to be absent (e.g., low Ba/La in Piip Volcano rocks and Adak-type magnesian andesites;

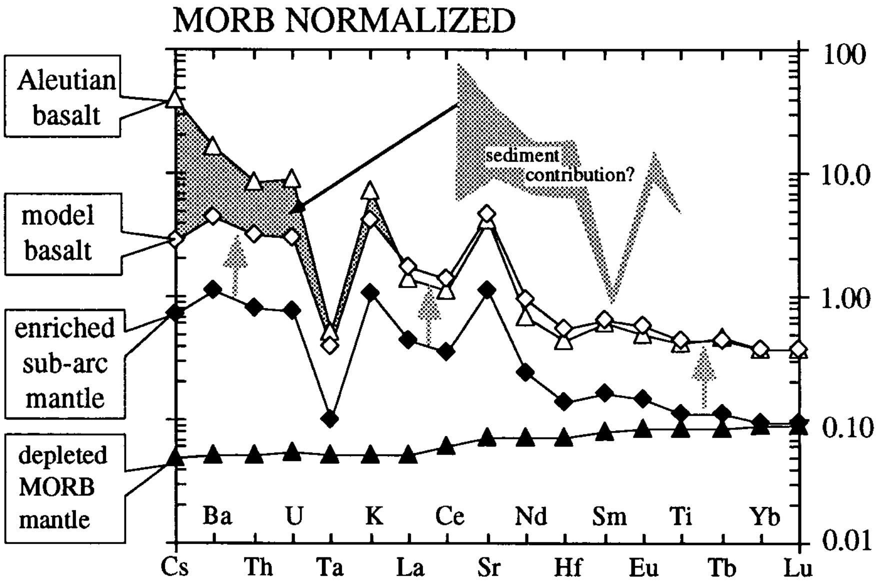

Figure 12. Slab melt plus mantle wedge model basalt compared to primitive Aleutian basalt. Mixture of 5% Adak-type magnesian andesite (sample V3842Y3 in Table 1, not shown here) and 95% depleted MORB mantle to produce an enriched subarc mantle source. The concentration level of the model basalt is set by placing the enriched mantle pattern over the Aleutian basalt at Yb-Lu (approximately equivalent to 15%–25% batch melting of the enriched source). The model melt and arc basalt have similar K, Sr, rare earth element and high field strength element characteristics, but the basalt has higher relative concentrations of Cs, Ba, Th, and U (i.e., Ba/La is higher in the basalt than the model). This deficiency implies the existence of a third mixing endmember derived from sediment (Kay, 1980). The sediment contribution is apparently quite large for the Cs, Ba, Th, and U, but is relatively small for K, Sr and the rare earth elements. All values in this figure are normalized to average mid-ocean ridge basalt (Hofmann, 1988). Depleted mantle values (in ppm) are: Lu(0.054), Yb(0.347), Tb(0.077), Ti(1020), Eu(0.115), Sm(0.299), Hf(0.220), Nd(0.815), Sr(8.25), Ce(0.722), La(0.206), K(46.7), Ta(0.010), U(0.004), Th(0.010), Ba(0.734), Cs(0.0007) (see also Fig. 15 in Yogodzinski et al., 1994). Primitive Aleutian basalt is sample KAS-7A (Kasatochi basalt, table 1 in Kay and Kay, 1994).

Fig. 9). In the presence of an enhanced role for slab melting, this implies that subduction has not carried sediment into the western Aleutian subarc mantle, because in most cases the sediment will be more easily melted than the basaltic portion of the slab. We attribute the minor role for subducted sediment in the western Aleutian source mixture primarily to the oblique subduction trajectory and long subduction path that carries the slab into the subarc mantle (see Yogodzinski et al., 1993; Yogodzinski et al., 1994).

With regard to high field strength elements and the arc rock source, it is an essential point that melts of the subducting slab are silicic and relatively cool and may, therefore, be saturated in accessory phases that cannot be retained through melting of peridotite (e.g., Watson, 1980; Green and Pearson, 1986; Ryerson and Watson, 1987; Ringwood, 1990). Slab melts saturated in rutile, apatite, amphibole, or garnet will be substantially fractionated in their high field strength element/rare earth element characteristics and may impart those characteristics to the depleted mantle wedge by metasomatism. McCulloch and Gamble (1991) have argued that ratios among Zr, Nb, and Ti indicate that rutile is not an important accessory phase in the source of arc basalts. It seems unlikely, however, that the combined roles of rutile, garnet, apatite, and/or amphibole have been adequately evaluated. The Adak-type magnesian andesites probably do contain a rutile-saturated melt component, and they do show the kind of interelement fractionation anticipated by McCulloch and Gamble (1991) (low La/Ta and Ti/Hf; Figs. 5 and 6). Low relative P in the Adak-type magnesian andesites (Fig. 5) suggests that these rocks may also contain an apatite-saturated component (e.g., Watson, 1980). It is an important point, however, that volcanic rocks at Piip Volcano probably also contain a slab melt (rutile-saturated) component (Yogodzinski et al., 1994), but that fractionation among high field strength elements in these rocks is not extreme because the signature has been dampened by reaction with peridotite or basalt in the mantle wedge (compare mixing and reaction lines in Fig. 6).

Finally, it appears that chromatographic effects and fractionation of high field strength elements from rare earth elements by melt-peridotite interaction (Kelemen et al., 1990) cannot be the process that produced low relative Ta concentrations in Adak-type magnesian andesites. This is because high melt-rock ratios required to produce large La-Ta fractionation would have brought the major elements of the slab melt into near equilibrium with peridotite. The absence of olivine phenocrysts from the Adak-type magnesian andesites indicates that this has not occurred. Kelemen et al. (1993) have shown that the primary effect of slab melt reaction with peridotite is to lower the overall incompatible element concentrations of the initial slab melt and to dampen the strong trace element fractionation that is produced by small percentage melting in the eclogite facies. In general, this is the process that we believe has produced the range of trace element characteristics that we see in Miocene and younger volcanic rocks of the western Aleutian arc.

Ancient Analogs to Modern Magnesian Andesites

Subduction of young and, therefore, warm oceanic lithosphere is believed to be a fundamental control over slab melting in modern subduction systems (Rogers et al., 1985; Defant and Drummond, 1990; Drummond and Defant, 1990; Kay et al., 1993). In the Archean, subducting oceanic lithosphere was on average much younger than today; thus it is believed that slab melting was relatively important in Archean time (Martin, 1986). We have argued here that oblique subduction in modern systems may also promote slab melting, even when the down-going lithosphere is relatively old (>25 Ma).

An important consequence of oblique subduction and an enhanced role for slab melting appear to be the formation of igneous rock series wherein magnesian andesites are the most common parental magma types. Interestingly, magnesian andesites also appear to have been more common in the Archean than today (Shirey and Hanson, 1983; Martin, 1986; Stern et al., 1990; Kelemen, 1993).

Archean-age sanukitoids (monzodiorites and trachyandesites) of the southwest Superior Province (Shirey and Hanson, 1983) are examples of magnesian andesite–like igneous rocks that are important parental rocks in an Archean igneous series. Shirey and Hanson (1983) and Stern and Hanson (1991) have interpreted sanukitoids of the southwest Superior Province as shallow and hydrous melts of mantle peridotite that was enriched by fluids or melts of a subducting slab (or the Archean equivalent of a subducting slab). These authors argue on isotopic grounds that source enrichment must have preceded melting by no more than 100–200 m.y., but they specify that enrichment and melting were discrete events in time. They were discrete in time because the enrichment process reflects garnet equilibria (high La/Yb), whereas the melting process (in their view) reflects hydrous melting of peridotite under low-pressure conditions that are outside of the garnet stability field.

This is also the paradox presented by Adak-type magnesian andesites in the Aleutians. We resolve this paradox, however, by recognizing that the major element, trace element, and isotopic systems can be substantially decoupled by a continuous process of eclogite (or garnet amphibolite) melting, followed by reaction of the resultant silicic melt with peridotite or basalt. In this view, the trace elements reflect equilibration with a garnet-bearing residue from melting of a basaltic source, the major elements reflect incomplete equilibration of a silicic melt with peridotite or basalt, and the isotopes are a weighted average of the total source mixture. Parent-daughter isotopic disequilibria of this kind are particularly well illustrated in Adak-type magnesian andesites from the central Aleutians, where $^{238}U/^{204}Pb$ is high (~20), but $^{206}Pb/^{204}Pb$ is low (~18.4; see Kay, 1978; Sun, 1980, and references therein). The Sm-Nd system is similarly decoupled (low Sm/Nd but high εNd).

Shirey and Hanson (1983) and Stern and Hanson (1991) emphasize that sanukitoids are analogous to magnesian andesites of the Japanese Setouchi belt (the term "sanukitoid" is derived from the Setouchi location in Japan). Major elements and isotopes do not uniquely distinguish between Piip- and Adak-type magnesian andesites, but trace elements do, and in this regard, Archean sanukitoids are far more similar to Adak-type magnesian andesites than to magnesian andesites from Piip Volcano or the Japanese Setouchi belt (e.g., Fig. 10). We suggest on these grounds that the appropriate modern analogs to Archean sanukitoids are likely to be the Adak-type magnesian andesites. In this interpretation, magnesian andesite–like igneous rocks of Archean age would be produced primarily through melting of a basaltic source in the eclogite facies. This could occur in a subduction environment (as it apparently has in the modern Aleutians), or it could occur at the base of thickened continental crust where underplated basalt supplies heat and melts a garnet-bearing lower crust to form a silicic magma, which then interacts with the basalt (Carroll and Wyllie, 1989; Kay and Kay, 1991).

CONCLUSIONS

Results from the western Aleutians indicate that, among Miocene and younger volcanic rocks, there are two petrologically distinctive magnesian andesite types that both contain a geochemical component formed by melting of the basalt-gabbro portion of the subducting oceanic crust. The trace element signature produced by slab melting in the eclogite facies (high Sr, La/Yb, La/Ta, low Ti/Hf) is well expressed in the Adak-type magnesian andesites (adakites), but reaction with peridotite and/or basalt in the mantle wedge has diluted the strong slab-melt signature so that the trace-element features of Piip-type magnesian andesites are similar to those in common volcanic rocks of the central and eastern Aleutian arc.

It appears that all Miocene and younger volcanic rocks in the western Aleutians contain a slab melt component in their source mixture. With regard to mantle wedge processes, it seems that in the western Aleutians the geochemically important metasomatizing agent has been a silicic melt (not a slab-derived fluid). A slab melt geochemical end-member of this kind may also be present in volcanic rocks throughout the Aleutians and in other subduction systems.

Slab melting is a prominent aspect of western Aleutian magmatism despite the fact that the subducting slab in this region is relatively old (>40 Ma). The enhanced role for slab melting in this region is attributed to highly oblique subduction and low convergence rates, which produce a long, slow subduction path into the subarc mantle. Magmatic consequences of this tectonic setting appear to be the formation of igneous series wherein the most common parental magma is a magnesian andesite (not a basalt). With regard to the predominance of slab melting and the common occurrence of magnesian andesites, the western Aleutians bear some resemblance to Archean-age magmatic systems (e.g., Shirey and Hanson, 1983; Martin, 1986). Magmatism in the Miocene–Holocene western Aleutian arc may, therefore, be like that in Archean subduction systems and/or modern subduction systems where the down-going slab is young.

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