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Slab melting in the Aleutians: implications of an ion probe study of clinopyroxene in primitive adakite and basalt

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Abstract

An ion probe study of trace elements in Mg-rich clinopyroxene phenocrysts in primitive Aleutian lavas provides constraints on the genesis of Aleutian adakites, and possible insights into the source of common Aleutian magmas. Clinopyroxene (cpx) phenocrysts in the primitive adakites have high Sr and Nd/Yb compared to cpx in Aleutian basalts. In the adakites, Sr and Nd/Yb are highest for high Mg# cpx, and these concentrations decrease toward lower Mg# compositions. These trends are the opposite of those seen in basalt cpx which generally show increasing incompatible trace element contents with decreasing Mg#, and are unlike antithetic compatible–incompatible trace element trends produced by chemical or kinetic effects of crystal growth. Petrographic observations and major and trace element zonation in cpx phenocrysts indicate that primitive Aleutian adakites are in part the product of mixing between primitive and relatively evolved magmas. The adakite trace element signature (high Sr, Nd/Yb) is clearly associated with the primitive mixing end-member. This observation supports the idea that adakites are derived by equilibration of slab melts with mantle olivine, and appears to rule out an origin by melting in the lower crust. Adakites are relatively rare in the Aleutians, but arc-wide correlations between Sr and La/Yb indicates that an adakite-type slab melt component may be present in the magmatic source throughout the arc. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Understanding the chemical contribution of subducted oceanic crust to arc magmas is essential to an overall understanding of global geochemical cycles, the thermal structure of subduction zones, and the origin of the continental crust. The classic model of Green and Ringwood [1] suggested that abundant calc-alkaline andesite found in volcanic arcs was produced by direct partial melting of basaltic oceanic crust that had been subducted to high pressures and metamorphosed to the eclogite facies. Subsequent experimental and geochemical studies cast doubt on this interpretation [2,3], and workers began to view the source of arc volcanic rocks as predominantly metasomatized peridotite in the mantle wedge above the subducting slab (e.g. Refs. [4–6]). Many workers now believe that the subducting slab is not hot enough to melt at all, and that it contributes only a hydrous fluid to the source mixture of arc volcanic rocks (e.g. Ref. [7]). Throughout, however, Marsh

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and co-workers continuously espoused an important role for slab melting in arc magmatism (e.g. [8,9]).

Some recent studies are now re-emphasizing slab melts as the important source for a geochemically distinctive group of calc-alkaline andesites and dacites termed ‘adakites’ (e.g. Ref. [10]). Adakites have high concentrations of Sr and La with low Y and steep rare earth element (REE) patterns (i.e. high La/Yb). Major element characteristics of adakites vary widely (e.g. Ref. [11]), but most Aleutian examples are primitive andesites with high Mg# and high Cr and Ni (i.e. magnesian andesites [12,13]). *Primitive adakites* have also been found in Patagonia [14–16], Baja, Mexico [17], and in Greece [18]. There are also dacitic and granodioritic adakites in the Aleutians [13], and we refer to these as ‘adakitic’ or ‘evolved adakites’ (see also Ref. [16]).

Cenozoic adakite occurrences worldwide are usually associated with subduction of young oceanic lithosphere [10], but adakites in the Aleutians appear to be associated with oblique and highly oblique subduction of oceanic lithosphere that is at least 55 My-old [13,19]. Adakites and adakitic rocks are common in certain Precambrian terranes [20,21], and they are abundant among Cenozoic-age volcanic rocks in the western Aleutians [13], Southwest Japan [22], Panama [23], Baja, California, Mexico [17,24], and parts of Patagonia [15,16]. Cenozoic adakites, nonetheless, make up a very small proportion of arc volcanic rocks world-wide. What then, is the importance of adakite to the genesis of common arc magmas? Is there any significant role for adakites in arc magma genesis outside of the relatively unusual tectonic situations where very young oceanic lithosphere is being subducted? In this paper, we begin to explore these questions with new results from ion microprobe analysis of trace elements in clinopyroxene phenocrysts from primitive adakites and basalts from the Aleutian island arc.

2. Sample selection

The objective of this study is to use trace element variation in cpx phenocrysts in geochemically distinctive Aleutian lavas to constrain alternative interpretations for their genesis. Samples were selected with the aim of studying relatively primitive rocks that are well characterized for their trace element and isotopic compositions and also contain phenocrysts of cpx. Partial whole-rock analyses for selected samples are provided in Table 1. Complete analyses can be found elsewhere [12,13,25,26].

Six Quaternary-age basalt lavas were selected for study. Three are from Umnak Island in the eastern Aleutians (UM4, UM10, UM11), one is from Kasatochi Volcano in the central Aleutians (KAS2A) and two are from Seguam Island (J87-36, B87-43), also in the central Aleutians (Fig. 1, Table 1). The Umnak and Seguam samples are from relatively large tholeiitic centers. These basalts are variably evolved (Mg# 0.55–0.71, see Table 1), but are broadly representative of the kinds of basalts that are believed to be parental magmas at many Aleutian volcanic centers [27,28]. The Kasatochi sample is a crystal rich basalt from a calc-alkaline center,

Table 1
Whole-rock information

Sample	Location	Type	Phenocrysts	SiO_2	Al_2O_3	FeO^*	MgO	Mg#	La	Yb	Sr	La/Yb
UM4	Umnak	basalt	olv, plag, cpx	51.7	17.7	8.92	5.45	0.58	11.6	2.36	442	4.92
UM10	Umnak	basalt	olv. plag, cpx	51.3	16.2	8.30	7.45	0.67	6.70	1.34	557	5.00
UM11	Umnak	basalt	olv, plag, cpx									
KAS7A	Kasatochi	basalt	olv, plag, cpx	49.1	15.8	8.82	8.77	0.69	5.43	1.49	482	3.64
J87-36	Seguam	basalt	olv, plag, cpx	51.1	18.2	7.15	8.01	0.71	4.93	1.12	315	4.40
B87-34	Seguam	basalt	olv, plag, cpx	51.9	19.9	7.42	4.05	0.55	4.09	1.44	377	2.84
V3842Y3	Bering dredge	adakite	cpx	58.9	15.7	3.35	4.44	0.75	29.6	0.70	2446	42.29
V3841Y3	Bering dredge	adakite	cpx	60.1	15.5	3.40	4.52	0.75	33.0	0.68	2302	48.53
ADK53	Adak	adakite	cpx, plag	55.5	15.5	6.21	5.58	0.67	29.2	0.94	1783	31.01
KCPY1	Medny	adakite	cpx, plag, amph	59.7	16.4	6.08	5.54	0.67	16.3	0.96	1199	16.98
KCPY4	Medny	adakite	cpx, plag, amph	59.1	16.7	6.16	5.45	0.66	16.3	0.87	1170	18.74

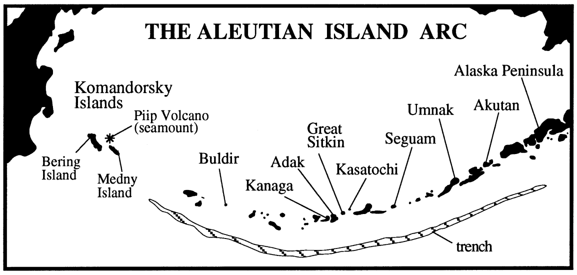

Fig. 1. Simplified map of the Aleutian island arc showing the locations of geographic features mentioned in the text.

but it has major element and mineral characteristics that are also typical of parental high Mg# Aleutian basalts. All of the basalts contain phenocrysts of olivine, plagioclase, and cpx. Phenocrysts of cpx are augite, which generally show normal and continuous (rim-to-core) major element zonation, indicating relatively simple growth histories [29,30]. With respect to trace elements, all of the basalts are slightly enriched in the light REE (La/Yb = 2.8–5.0), and have low-to-moderate concentrations of La (4.09–11.6 ppm), Yb (1.12–2.36 ppm), and Sr (315–557 ppm). Incompatible element and isotopic ratios in these rocks vary significantly, but all are broadly like those of common basalts and andesites found throughout the modern Aleutian arc (e.g. Ref. [26]).

Five adakites were selected for this study. Sample ADK53 (age unknown) is from the original adakite location described by Kay [12] at the northeast foot of Mt. Moffett on Adak Island in the central Aleutians (Fig. 1, Table 1). Two adakites (V38 sample names; Table 1) were selected from a dredge location in the far western Aleutians, northwest of Bering Island (Fig. 1). Scholl et al. [31] estimated a middle Miocene age (12–14 My) for adakite sample 70-B49 from this location. Two adakites from Medny island (KCP sample names; Table 1) were also selected. These are among the Miocene age (8- to 16-My-old) calc-alkaline rocks that occur throughout the western Aleutians (e.g. Ref. [32]). The V38 adakite samples contain phenocrysts of clinopyroxene only, the ADK samples contain clinopyroxene and plagioclase phenocrysts, and the KCP adakites contain phenocrysts of plagioclase, amphibole, and clinopyroxene (Table 1). Augite phenocrysts in the ADK and V38 adakite samples have high Mg-numbers that vary toward diopside (Mg# mostly 0.78–0.91). These phenocrysts commonly contain rounded cores that are more Fe-rich than the surrounding rims [12]. These Fe-rich cores are usually cpx (augite), but in sample ADK53, we observed at least one Fe-rich core of orthopyroxene (hypersthene) that was rimmed by Mg-rich cpx. All of the adakites have relatively high Mg-numbers (0.66–0.75) with very high concentrations of Sr (1170–2450 ppm), and La (16–30 ppm), low Yb ($<$1 ppm), and steep REE patterns (La/Yb = 17–48). Whole-rock trace element and isotopic ratios in these samples readily distinguishes them from common Aleutian basalts and andesites [12,13].

3. Analytical methods

The trace element determinations for cpx phenocrysts were obtained on the Cameca IMS 3f ion microprobe at the Woods Hole Oceanographic Institution. Analytical procedures are described in Shimizu [33] and references therein. A primary beam of negative oxygen ions with a current of about 20–30 nA was focused to a spot of 30 μm diameter. Positive secondary ions were analyzed by a double focusing mass spectrometer; energy filtering to reduce molecular interference involved a nominal secondary accelerating voltage of 4500 eV plus a high energy offset of -60 eV for REE, and -90 eV for other trace elements, with a bandpass of ±10 eV. Under these conditions, the isotope abundance corrected count rate for Si in clinopyroxene standard KH1 is about 6–10 million counts/s. After several minutes of preliminary sputtering, secondary beam intensities were measured in five cycles, ratioed to Si intensity, and averaged to obtain a mean intensity ratio. These were combined with standard working curves to calculate abundances in ppm, relative to clinopyroxene with a nominal SiO_2 concentration of about 50 wt%. Mg, Fe and Ca intensities were also collected, and used to calculate Mg# via an empirical relationship developed on the MIT/Woods Hole ion probe (Shimizu, personal communication, 1989). These were used to calculate the Mg# for each point; they are only accurate to ±2 mol%. However, precision is much higher than this, so that differences in Mg# determined by our empirical method are accurate to about ±0.1 mol%.

4. Results

Trace element concentrations and interelement ratios in cpx phenocrysts in Aleutian basalts and adakites broadly reflect whole-rock compositions for several important trace elements. Specifically, high whole-rock concentrations for Sr and light REE in Aleutian adakites can be seen in high Sr and Nd concentrations in adakite cpx relative to basalt cpx (Fig. 2A,B). Low Yb and Y concentrations and steeply sloping heavy REE patterns (as indicated by high Nd/Yb), are also clearly present in adakite cpx but not basalt cpx (Fig. 2C,D). These first-order observations indicate that trace element concentrations in cpx phenocrysts are a broad indicator of mineral-melt equilibrium in these distinctive rock types.

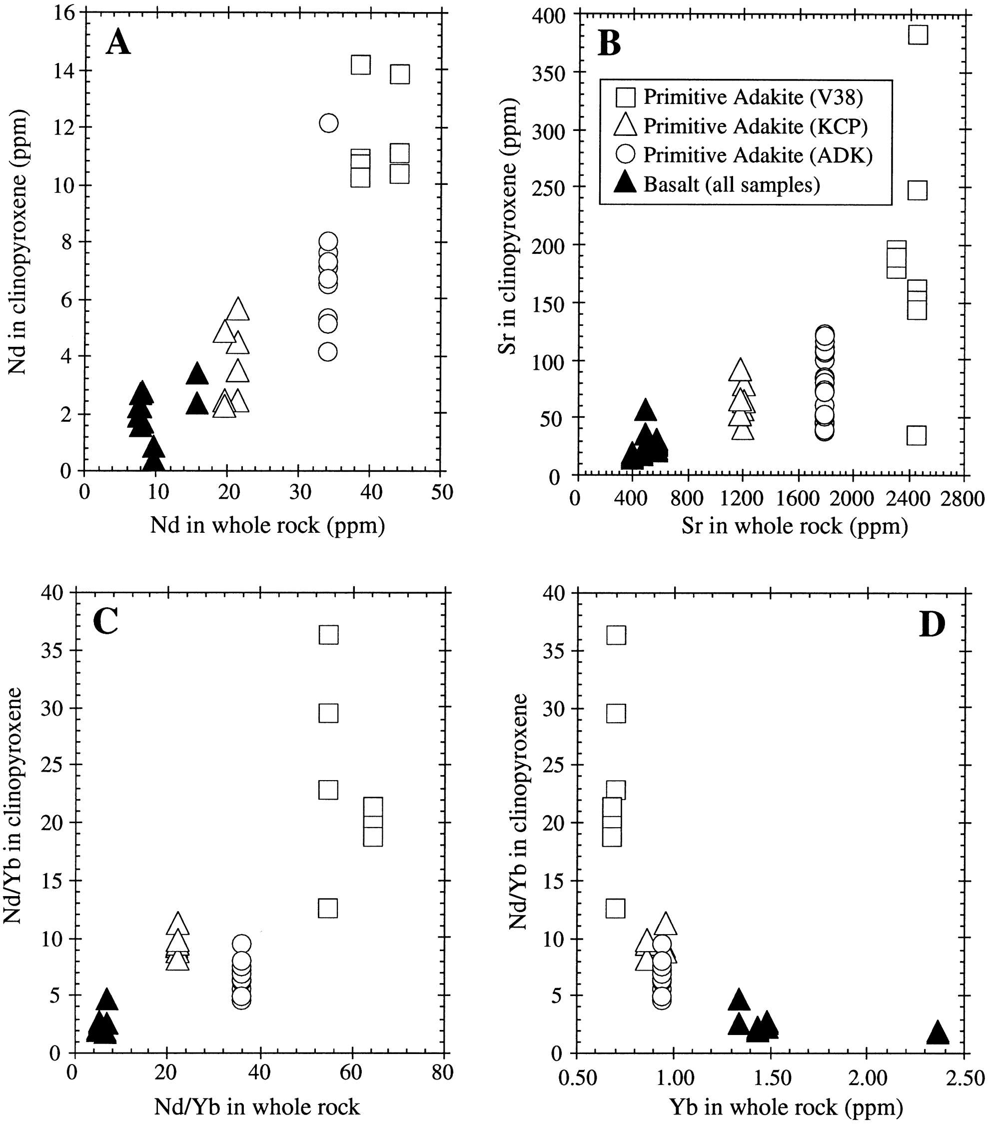

Fig. 2. Trace elements in clinopyroxene plotted against trace elements in whole-rock samples. In A, B, and C, relatively high Nd, Sr, and Nd/Yb in adakite clinopyroxene correspond to relatively high whole-rock values for these parameters in adakites compared to basalts. In D, high Nd/Yb in adakite cpx corresponds to low whole-rock Yb concentrations in adakites compared to basalts. These data imply that trace elements in clinopyroxene phenocrysts are a broad indicator of mineral-melt equilibria in these distinctive rock types.

Table 2
Trace element analyses of clinopyroxene phenocrysts in Aleutian basalts

Sample no.:	B87-34	B87-34	J87-36	J87-36	KAS7A	KAS7A	UM-10	UM-10	UM-11	UM-11	UM-11	UM-4	UM-4
Analysis no.: [a]	1c	1r	1	3	1c	1r	5	6	4	1c	1r	1	2
Location:	Seguam	Seguam	Seguam	Seguam	Kasitochi	Kasitochi	Umnak	Umnak	Umnak	Umnak	Umnak	Umnak	Umnak
Rock type:	basalt	basalt	basalt	basalt	basalt	basalt	basalt	basalt	basalt	basalt	basalt	basalt	basalt
Mg#	0.79	0.79	0.82	0.83	0.78	0.76	0.79	0.84	0.79	0.87	0.82	0.73	0.76
Sc	136	111	130	106	146	139	96	85	138	94	95	130	123
Ti	1996	1616	2029	1528	2610	3154				928	1356	3297	3089
V	377	323	390	313	316	330	235	189	344	160	228	530	441
Cr	809	741	3730	2495	2100	546	414	848	2200	2731	1329	1215	1911
Sr	19.2	16.1	17.9	15.5	26.0	38.0	32.5	31.8	37.4	33.7	34.0	19.5	21.0
Y	9.28	8.09	7.62	6.43			6.19	3.57	8.81				
Zr	8.76	7.09	8.34	6.67	12.5	19.2	11.3	7.92	16.7	2.50	6.26	13.8	13.8
La		0.28	0.31	0.57	0.36	0.36	0.25	0.09	0.56	0.08	0.14	0.50	0.38
Ce		1.39	1.21	2.32	1.04	1.04	0.76	0.32	2.60	0.28	0.57	1.84	1.38
Nd		1.95	1.75	2.79	1.63	2.30	0.89	0.48	2.70	0.57	1.28	3.45	2.43
Sm		1.05	0.86	1.53	0.75	0.88	0.48	0.16	1.42	0.27	0.63	1.38	1.15
Eu		0.45	0.35	0.53	0.26	0.36	0.20	0.11	0.56	0.09	0.21	0.49	0.39
Dy		1.71	1.40	2.24	1.07	1.39	0.59	0.27	1.78	0.28	0.76	2.68	1.90
Er		0.98	0.82	1.32	0.56	0.81	0.42	0.16	0.92	0.16	0.38	1.59	1.17
Yb		0.95	0.73	1.29	0.67	0.79	0.31	0.10	0.93	0.11	0.39	1.80	1.14

[a] Letters 'r' and 'c' after analysis number indicates a core or rim analysis.

Compatible element concentrations and Mg# in cpx phenocrysts in adakites and basalts are positively correlated, and in general, both compatible elements and Mg# are inversely correlated with incompatible elements (Tables 2 and 3). These trends may form by mineral-melt equilibria for phenocrysts growing in magmas that are evolving by fractional crystallization, or they may be produced by crystal chemical or kinetic effects of crystal growth [33]. For Aleutian basalts, the concentrations of Sc, Ti, V, Sr, Zr, Y, and the REE all generally show this kind of inverse correlation with cpx Mg#.

In contrast, the Sr concentrations in adakite cpx show a strong positive correlation with cpx Mg# (Fig. 3A, Table 3), a trend that cannot be produced by fractional crystallization or crystal growth effects. A similar trend is seen for Nd/Yb in adakite cpx (Fig. 3B). Equally important is the wide range of Sr, and Nd/Yb seen in the adakite cpx and the contrasting small variation in basalt cpx. Within one adakite sample (V3841Y3), the Sr concentration in cpx phenocrysts varies from 36 to 384 ppm, whereas the variation in cpx Sr for nearly all of the basalts studied is between 15 and 40 ppm (on outlier at 59 ppm). Perhaps most important is the trace element zonation in adakite cpx phenocrysts. Fig. 3A illustrates the presence of both normal and inverse major element zonation in adakite cpx, and it shows that the high Mg# cpx (usually the rim composition) have higher Sr concentrations than the more Fe-rich cpx (usually the core compositions). The same overall trends are present for Nd/Yb in cpx (Fig. 3B, Table 3), though the details are less clear because fewer data are available.

5. The genesis of adakites and adakitic rocks

The common presence of reverse major element zonation in cpx phenocrysts in the primitive adakite samples from both the western and central Aleutians implies that these lavas were evolving in open magmatic systems immediately prior to eruption. Kay [12] suggested that the reverse zonation in cpx phenocrysts was produced by reaction between a silicic melt of the subducting slab and hot peridotite in the mantle wedge. This interpretation is similar to that proposed by Myers [8], and Myers and Frost [8] for a wide variety of chemical and petrographic features in Aleutian volcanic rocks. Yogodzinski et al. [13] suggested a model in which reverse major element zonation in adakite cpx might be produced by the

Table 3
Trace element analyses of clinopyroxene phenocrysts in primitive Aleutian adakites

Sample no.	V3842Y3	V3842Y3	V3842Y3	V3842Y3	V3842Y3	V3842Y3	V3841Y3	V3841Y3	V3841Y3	ADK53	ADK53	ADK53	ADK53
Analysis no.: [a]	1c	1r	2c	2r	3c	3r	1	2	3	1c	1r	3c	3r
Location:	dredge	dredge	dredge	dredge	dredge	dredge	dredge	dredge	dredge	Adak	Adak	Adak	Adak
Rock type:	adakite	adakite	adakite	adakite	adakite	adakite	adakite	adakite	adakite	adakite	adakite	adakite	adakite
Mg#	0.75	0.87	0.91	0.88	0.85	0.88	0.87	0.8782	0.8649	0.60	0.83	0.67	0.80
Sc	33	21	<1	10	41	17	18	13	19	101	107	87	108
Ti	1587	1855	1802	1517	2400	1720	1522	1723	2392	2157	2528	2699	3767
V	195	76	40	50	159	58	44	52	65	367	206	473	222
Cr	397	1644	1295	1287	1179	705	1713	1517	1490	96	4538	189	1167
Sr	36	154	384	162	153	145	181	197	190	47	61	32	131
Y							5.71	5.00	7.85				
Zr	9.17	20.9	30.9	12.5	18.3	14.2	15.8	17.9	35.0	137	27.1	39.2	55.0
La	1.68		2.83		2.00		2.11	2.25	3.03	0.78	0.59	2.34	1.15
Ce	8.56		11.5		9.00		9.25	9.69	12.5	3.99	3.00	7.76	5.07
Nd	10.9		10.7		10.3		10.4	11.2	13.9	5.36	4.22	7.64	6.54
Sm	3.45		2.97		3.20		3.26	3.62	4.18	2.28	1.70	2.78	2.65
Eu	1.18		0.92		1.14		1.23	1.29	1.55	0.70	0.58	0.96	0.97
Dy	1.53		0.95		1.99		1.52	1.60	1.67	2.09	1.22	2.34	1.98
Er	0.58		0.32		0.89		0.62	0.63	0.70	1.15	0.74	1.36	1.08
Yb	0.48		0.30		0.82		0.54	0.65	1.14	1.14	0.57	1.36	1.02

Sample no.:	ADK53	ADK53	ADK53	ADK53	ADK53	KCPY1	KCPY1	KCPY1	KCPY1	KCPY1	KCPY4	KCPY4	KCPY4
Analysis no.: [a]	5c	5r	6c	6r	8r [b]	1	2	3	4c	4r	1	2	3
Location:	Adak	Adak	Adak	Adak	Adak	Medny	Medny	Medny	Medny	Medny	Medny	Medny	Medny
Rock type:	adakite	adakite	adakite	adakite	adakite	adakite	adakite	adakite	adakite	adakite	adakite	adakite	adakite
Mg#	0.65	0.86	0.68	0.86	0.85	0.82	0.83	0.78	0.86	0.86	0.84	0.84	0.80
Sc	82	45	84	38	62	80	57	58	41	41	53	67	92
Ti	2992	1448	3297	1326	1569	2247	1977	1212	1206	1266	1426	1348	2833
V	469	172	581	186	137	214	191	184	170	154	180	138	283
Cr	182	5728	149	5698	2683	3272	1366	455	2219	3108	4247	1616	1059
Sr	33	56	32	54	119	112	101	76	99	110	125	85	109
Y	21.4	5.71	16.7	5.47	6.90						3.33	4.28	11.2
Zr	57.5	11.3	27.1	11.3	17.1	17.9	12.9	23.8	6.67	7.51	12.5	13.3	45.9
La	3.45	0.86	1.96	1.04	3.93	0.79	0.48	1.64		0.76	0.72	0.51	1.27
Ce	13.6	3.96	7.59	4.49	10.4	3.76	1.99	6.31		3.14	2.67	1.99	4.56
Nd	12.2	4.18	8.07	5.16	7.35	4.53	2.52	5.73		3.54	2.46	2.31	4.94
Sm	3.71	1.46	3.07	1.90	2.30	1.63	0.91	1.69		1.04	0.83	0.72	1.55
Eu	1.16	0.51	1.21	0.66	1.07	0.59	0.35	0.64		0.38	0.36	0.32	0.66
Dy	3.02	1.00	3.08	1.56	1.55	1.04	0.60	1.24		0.60	0.61	0.55	1.07
Er	1.96	0.57	1.80	0.67	0.83	0.49	0.30	0.67		0.37	0.32	0.29	0.71
Yb	1.87	0.54	1.63	0.74	0.76	0.49	0.27	0.64		0.31	0.25	0.28	0.50

[a] Letters ‘r’ and ‘c’ after analysis number indicates a core or rim analysis.
[b] Analysis number 8r in ADK53 was clinopyroxene rim surrounding a core of low Mg# orthopyroxene (hypersthene).

mixing of a silicic melt from the slab and a primitive basaltic melt of the mantle wedge.

Trace element zonation in cpx phenocrysts revealed by this study clearly show that the high Mg# cpx rims hold the adakite trace element signature (high Sr, Nd/Yb), and the more Fe-rich cores have trace element characteristics similar to those seen in cpx phenocrysts in Aleutian basalts (Fig. 3). Therefore, the ion probe data indicate that neither of the previous interpretations of cpx major element zonation are correct in detail. Instead, a simple magma mixing interpretation is more appropriate. Two mixing end-members are required: a primitive end-member with high Mg#, Sr, and Nd/Yb, and an evolved end-member with relatively low Mg#, Sr, and Nd/Yb. The primitive end-member was apparently a high Mg# adakite. The evolved end-member must have contained phenocrysts of relatively Fe-rich cpx. In addition, the presence of hypersthene phenocryst cores mantled by high Mg# (and high Sr) cpx in one of the western Aleutian samples (see ‘sample selection’) indicates that the evolved mixing

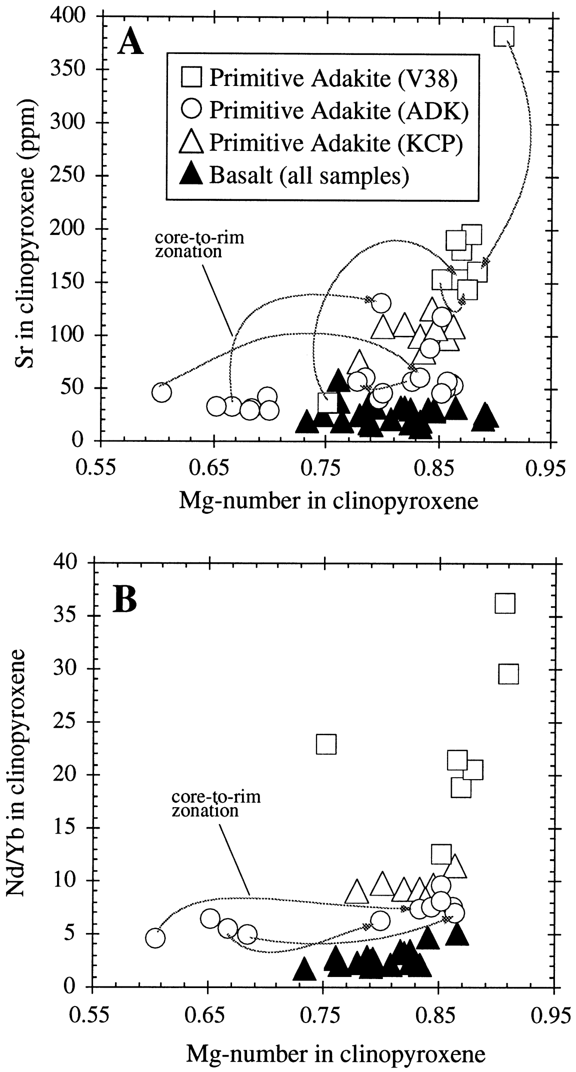

Fig. 3. Strontium concentration and Nd/Yb plotted against Mg# for clinopyroxene phenocrysts in Aleutian adakites and basalts. The figure highlights the narrow range of Sr and Nd in basalt clinopyroxene compared to clinopyroxene in adakites, and it shows the strong positive relationship between Mg# and Sr–Nd/Yb in adakite clinopyroxene. The overall trend of the data indicates that the adakite trace element signature (high Sr, Nd/Yb) is linked to high Mg# in adakite clinopyroxene phenocrysts. Major and trace element zonation within individual clinopyroxene phenocrysts in adakites (shown by gray arrows which point from core to rim compositions) also draw a connection between high Mg# and high Sr or Nd/Yb compositions.

end-member also contained phenocrysts of hypersthene, and was, therefore, probably an evolved basalt or basaltic andesite. The evolved end-member apparently had incompatible trace element abundances similar to those of common Aleutian volcanic rocks (i.e. comparable to those seen in the basalts studied here).

Co-variation of trace elements and Mg# in cpx phenocrysts (Fig. 3) suggest that the adakite component equilibrated with the sub-arc mantle. In short, our data support the interpretations of Kay [12] and Myers and Frost [34], in which the incompatible element characteristics of Aleutian adakites are derived by melting of the subducting slab (e.g. high Sr) and compatible element characteristics (e.g. high Mg# and high Cr, Ni) are derived by interaction of the slab melt with peridotite in the mantle wedge (Fig. 4). This may be a common process in forming adakites world-wide (e.g. [35–37]). In fact, there are substantial differences between the various slab melt/mantle interaction hypotheses. We prefer the idea that a silicic slab melt component originates by small degrees of partial melting in the presence of garnet and rutile, and therefore has high La/Yb and La/Ta prior to interaction with the mantle wedge (e.g. [12,13,36]). At the same time, we concur with Myers and Frost [34] and Yogodzinski et al. [38], that many characteristics of adakites in particular, and Aleutian magnesian andesites in general, may reflect extensive melt/mantle interaction at low pressure, just beneath the base of the arc crust.

Our data appear to rule out an origin for primitive Aleutian adakites through lower crustal melting. Models for lower crustal melting suggest that mixing between mafic and silicic magmas should be relatively rare [39]. If the primitive adakites were produced by lower crustal melting, their high Mg# and high Cr–Ni character would be the product of mixing/mingling between primitive basalts and silicic melts of the lower crust. However in this scenario, the distinctive adakite trace element signature would be linked to the low Mg# component – the opposite of what we observe.

It is clear from Fig. 3 that the most primitive Aleutian adakites mixed with and evolved by concomitant crystal fractionation, toward melts with 'normal' trace element characteristics. One likely outcome of this evolution can be seen among the Miocene-and-younger rocks in the western Aleutians. In this area, primitive adakites are associated with adakitic calc-alkaline dacites and granodiorites.

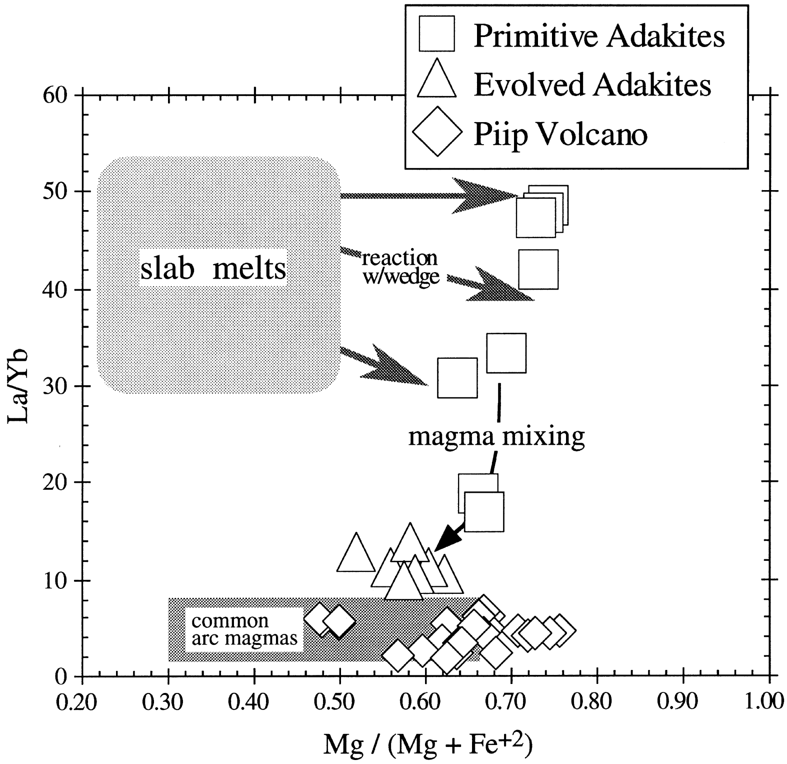

Fig. 4. Interpretation of whole-rock Sr and La/Yb for primitive adakites Miocene–Recent volcanic rocks of the western Aleutian Komandorsky region including evolved adakites and volcanic rocks of the Piip Volcano area. Small percentage melts of the subducting slab are relatively silicic with high La/Yb and low Mg#. These slab melts react with peridotite as they rise through the mantle wedge. Arrow labeled 'magma mixing' indicates that some (but probably not all) of the range in La/Yb in primitive adakites is produced by mixing with common arc magmas within or immediately below the arc crust. Evolved adakites are Miocene-age dacites and granodiorites from the Komandorsky region [13]. Modeling of volcanic rocks at Piip Volcano [38] indicates that they too contain a slab melt component, even though they have trace element and concentrations and inter-element ratios that are broadly like those of common Aleutian magmas.

The primitive adakites have the highest Sr, La, and La/Yb, and these parameters decrease progressively in the evolved adakites which have higher SiO_2 and lower Mg# (Fig. 4; see also Ref. [13]). These relationships imply that the adakite signature was diluted by shallow magma mixing accompanied by crystal fractionation to produce the adakitic dacites. At Piip Volcano, an active calc-alkaline seamount in the western Aleutians, modeling of incompatible elements and isotopes [13] shows the presence of the an adakite component in calc-alkaline andesites and dacites that have overall trace element abundances that are broadly like those of common Aleutian volcanic rocks (Fig. 4). In the case of Piip Volcano, the adakite component made a relatively small contribution to the dominantly MORB-type source in the mantle wedge [38]. The relationship between the adakite component and calc-alkaline magma genesis is unusually clear in the western Aleutians, because in the absence of subducted sediment [13,38] the remaining source components may be discerned.

The Aleutian results indicate that the primitive aspect of adakite compositions (high Mg#, Cr, Ni) may be the key to distinguishing between an origin involving slab melting and an origin by melting in the lower crust. Relatively cool slab melts (<1050ºC) must rise through the hot mantle wedge (>1100ºC) above the subducting slab [36,37,40]. Under these circumstances, slab melts will interact with and acquire some characteristics of the mantle wedge (e.g. high Mg#, Cr, Ni; [8,36,37,40]). By contrast, in anatexis of lower continental crust or arc crust followed by mixing with basalts, the high silica, anatectic end-member will have low Mg#, Cr and Ni.

This means that magnesian andesites and dacites (or intrusive equivalents) will commonly be the parental melts in adakitic rock suites formed by slab melting followed by mantle interaction, and that evolved adakites (dacites, tonalites, trondjhemites, granodiorites) will generally be derived from these parental melts through shallow magmatic processes. This seems to be the case for Cenozoic adakitic suites in the western Aleutias [13], and Patagonia [14,16], as well as in Archean age adakitic rocks in the Superior Province, Canada [21].

Some of the evolved adakites in the western Aleutians retain elevated Cr contents relative to SiO_2 (up to 56 ppm at 64% SiO_2) as a memory of their relation to primitive (andesitic) adakites. Elevated Cr is also seen among dacitic adakites from Patagonia [14,16] and Greece [18], and high Cr is common in evolved (granodioritic) Archean adakites of the Superior Province [21]. In our view, this may indicate that they are related to more primitive adakitic rocks which were produced by melting of the subducting slab and interaction with the mantle wedge. The absence of any semblance of a mantle-derived signature (e.g. high Cr) from dacitic rocks of an area may indicate that a lower crustal melting interpretation is more appropriate (e.g. the Novarupta system [41]).

6. Slab melts in the Aleutian arc source?

Plank and Langmuir [42] conclude that the basaltic part of the subducting slab dehydrates and therefore contributes fluid (not melt) to the source mixture beneath arcs. The MORB-like isotopic character of adakitic rocks in the Aleutians shows, however, that the basaltic part of the subducting oceanic crust has indeed melted. It seems clear that in some parts of the arc, the subducting slab is adding magma (not just fluid), to the mantle wedge. Is it possible that an adakite component is present in the source mixture of common volcanic rocks throughout the Aleutian arc?

The strongest imprint of an adakite component in the common volcanic rocks is likely to be in Sr and La/Yb which are the most distinctive trace element characters in the adakites. Relatively high La/Yb among certain evolved calc-alkaline rocks is probably produced by crystal fractionation of amphibole [26,43], but the arc-wide correlation of La/Yb and Sr for Aleutian rocks with Mg# > 0.60 (Fig. 5A), and a similar correlation for Sr and Nd/Yb in cpx phenocrysts studied here (Fig. 5B), suggest that slab melts may be present throughout the Aleutians. Mixing between the slab melt and MORB-like mantle wedge components could result from magmatic mantle metasomatism, melt/mantle interaction, and/or magma mixing.

Other trace element and isotopic criteria may or may not support the idea of slab melting throughout the Aleutians. The adakites have (by far) the highest La–Ta ratios in the arc (e.g. fig. 5 in [13]), so the presence of an adakite component in the source could account for the relative depletion of Ta and Nb in common Aleutian volcanic rocks. In contrast, the limited available data suggest that the Ce–Pb ratios of adakites are relatively high [12,44], indicating that the adakites may not be an appropriate mixing end-member for Pb isotopes [45].

Alternative interpretations of the strong arc-wide correlation between Sr and La/Yb (Fig. 5A) include fluid metasomatism, sediment input, and/or variable degrees of melting in the mantle wedge (e.g. [45–47]). These interpretations do not, however, address the key point that the high Sr–La/Yb end of the correlation is controlled by adakitic rocks which are isotopically MORB-like and andesitic-to-dacitic in composition (i.e. chemically dominated by slab melting; [12,13]). A more thorough understanding of the role of adakites in Aleutian magma genesis will await more complete analysis of available adakites and adakitic rocks (e.g. Pb concentrations). In this context, samples from the western Aleutians will be of particular interest because the absence of subducted sediment there [38] has created a relatively simple source mixture compared to the central and eastern arc where subducted sediment is abundant and the source is complex.

7. Conclusions

Kay [12] concluded that the key geochemical features of Aleutian adak-type magnesian andesites (primitive adakites) were produced by small degree

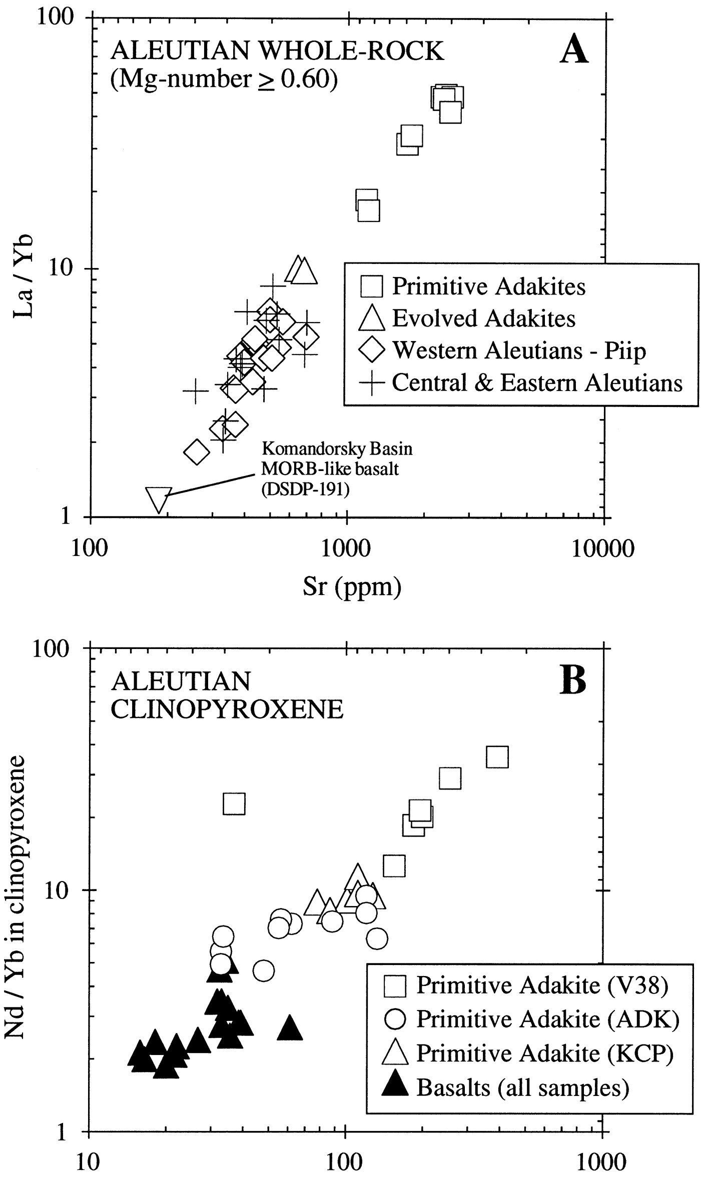

Fig. 5. In A, La/Yb plotted against Sr for Aleutian whole-rock samples with Mg# > 0.60 indicates that a slab melt component may be present in the source mixture throughout the Aleutian island arc. The same relationship can be seen in B where Nd/Yb and Sr are strongly correlated for clinopyroxene phenocrysts in Aleutian adakites and basalts (Tables 2 and 3). Eastern Aleutian data are from Okmok Island [26,27,47], Akutan [50], and Seguam [25]. Central Aleutian data are from Kanaga, Adak (Mt. Moffett and Mt. Adagdak), Great Sitkin, and Buldir ([26,27]). Western Aleutian data from the Piip Volcano area are from Yogodzinski et al. [38]. Evolved adakites are dacites and granodiorite from the Komandorsky islands [13]. Whole-rock data for primitive adakites are from Kay [12], Yogodzinski et al. [13].

melting of basalt in the subducting slab beneath the arc. The results of this study support his conclusion with the added caveat that primitive adakites appear to evolve by magma mixing within or immediately below the arc crust (Fig. 4). This study also appears to rule out lower crustal melting as a viable interpretation for the genesis of Aleutian adakites. Arc-wide correlations for key trace elements (Sr, La/Yb) and an important role for magma mixing, appear to link adakite genesis to that of common Aleutian volcanic rocks. This suggests that slab melting, not just slab dehydration, may be occurring throughout the Aleutian subduction system, even though the subducting oceanic lithosphere is relatively old.

If significant quantities of frictional heat are required to melt old subducting slabs [48], then the presence of slab melts beneath the central Aleutians (Adak island) implies that the generation of substantial subduction-related frictional heat is possible. If slab melting is possible in modern subduction systems, then it must have been relatively common in the Archean when the earth was significantly hotter [49]. This suggests that through all of earth history, high Mg# andesites and dacites generated in subduction zones (through slab melting and reaction with peridotite) may have been an important contributor in the genesis of the continental crust [37].

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