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Oxygen isotope evidence for slab melting in modern and ancient subduction zones

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Abstract

We measured oxygen isotope compositions of 34 adakites, high-Mg andesites, and lavas suspected to contain abundant slab and sediment melts from the Western and Central Aleutians, the Andes, Panama, Fiji, Kamchatka, Setouchi (Japan), and the Cascades. This suite covers much of the diversity of arc lavas previously hypothesized to contain abundant 'slab' melts. Measured and calculated values of $\delta^{18}O$ for olivine phenocrysts in these samples vary between 4.88‰ and 6.78‰, corresponding to calculated melt values of 6.36‰ to 8.17‰. Values of $\delta^{18}O$ for these samples are correlated with other geochemical parameters having petrogenetic significance, including Sr/Y, La/Yb, $^{87}Sr/^{86}Sr$, and $^{143}Nd/^{144}Nd$. Archetypical adakites from Adak Island (Central Aleutian) and Cook Island (Andean Austral zone), previously interpreted to be nearly pure melts of basaltic and gabbroic rocks in subducting slabs, have values of $\delta^{18}O$ slightly higher than those of normal mid-ocean-ridge basalts, and in oxygen isotope equilibrium with typical mantle peridotite (i.e., their subtle ^{18}O enrichment reflects their Si-rich compositions and low liquidus temperatures, not ^{18}O-rich sources). Other primitive adakites from Panama and Fiji show only subtle sub-per mil enrichments in the source. This finding appears to rule out the hypothesis that end-member adakites are unmodified partial melts of basaltic rocks and/or sediments in the top (upper 1–2 km) of the subducted slab, which typically have $\delta^{18}O$ values of ca. 9–20‰, and also appears to rule out them being partial melts of hydrothermally altered gabbros from the slab interior, which typically have $\delta^{18}O$ values of ca. 2–5‰. One explanation of this result is that adakites are mixtures of partial melts from several different parts of the slab, so that higher- and lower-$\delta^{18}O$ components average out to have no net difference from average mantle. Alternatively, adakites might be initially generated with more extreme $\delta^{18}O$ values, but undergo

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isotopic exchange with the mantle wedge before eruption. Finally, adakites might not be slab melts at all, and instead come from differentation and/or partial melting processes near the base of the arc crust in the over-riding plate. High-Mg andesites and Setouchi lavas are commonly higher in $\delta^{18}O$ than equilibrium with the mantle, consistent with their containing variable amounts of partial melts of subducted sediments (as we conclude for Setouchi lavas), slab-derived aqueous fluid (as we conclude for the Cascades) and/or crustal contaminants from the over-riding plate (as we conclude for Kamchatka).

1. Introduction

Convergent margin magmas are believe to be derived from variable proportions of: partial melting of the mantle wedge in response to addition of aqueous fluid evolved from the subducting ocean lithosphere (or 'slab'); decompression-melting of mantle upwelling beneath the upper plate; direct melting of the slab; and melting of pre-existing crustal rocks within the upper plate [1]. The relative contributions of these processes to the overall magmatic output of arcs vary widely. Most basaltic lavas in recent convergent margins appear to be products of hydrous melting of the mantle wedge, containing only trace, cryptic components derived from the slab (e.g., [2]). However, three types of recent arc lavas have been interpreted to be products of high-degree slab melting:

(1) 'Adakites', initially identified on Adak Island in the Central Aleutians [4] and subsequently recognized on Cook Island, in the Andean Austral zone [5], and several other arcs (Table 1). Near-end-member adakites, including those from Adak and Cook islands, Panama, and Fiji are characterized by unusually high Sr concentrations and low Y concentrations (and thus extremely high Sr/Y ratios), unusually high La/Yb ratios, and low heavy-rare-earth (HREE) concentrations. These characteristics appear to require that adakites are derived from garnet-rich residues having initial trace-element compositions resembling mid-ocean-ridge basalts (or MORBs [6]), which is often interpreted that they are high-degree melts of mafic rocks in subducting slabs. Adakites are the modern lava types that are most commonly identified as being analogous to Archean TTG suites. For the purposes of this study, we define adakites as lavas having broadly andesitic major element composition ($SiO_2 = 57 \pm 3$ wt.%; Table 1), Sr/Y ratios greater than 100, and La/Yb ratios greater than 20.

(2) High-Mg andesites—lavas containing between ~53 and 63 wt. % SiO_2, having Mg#'s (molar[$Mg/(Mg + Fe^{+2})$] > 0.7, high Ni and Cr concentrations compared to more typical island arc andesites, and trace-element compositions resembling, but less extreme than adakites (e.g., Sr/Y ratios less than 100, but still unusually high). Furthermore, high-Mg andesites often contain amphibole phenocrysts whereas adakites do not. It has been hypothesized that high-Mg andesites are produced by reaction between adakitic melts and peridotites in the mantle wedge [7], or by partial melting of the mantle wedge in response to unusually high fluxes of aqueous, slab-derived fluid [8], or the combination of these two processes [9].

(3) Lavas from Setouchi, Japan, are characterized by isotopic compositions of Sr, Nd, Pb, and Hf approaching those of subducting sediment and have been hypothesized to sample a large (ca. 10%) component of sediment melt (the remainder being partial melt of the mantle wedge [10–12]). Setouchi lavas are more mafic than either adakites or high-Mg andesite, but have similarly high Mg# (Table 1). Unlike adakites and high-Mg andesites, Setouchi lavas do not have extremely high Sr/Y and La/Yb ratios. They might be an end-member example of the same process responsible for cryptic 'sediment melt' components recognized in the trace elemental geochemistry of many subduction-related lavas [11]. Setouchi lavas were considered to be modern analogues of Archean 'sanukitoids' [13].

Table 1
Oxygen isotope composition of olivine phenocrysts, calculated values of melt, and relevant geochemical parameters

	Sample type	$\delta^{18}O \pm 1std$ (olivine)	n	Com	Sr/Y	La/Yb	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$	ε_{Nd}	SiO$_2$ (wt.%)	Mg# (molar)	$\delta^{18}O_{melt}$, calculated	
												Method 1	Method 2
Panama													
M65	Santo Domingo	A	5.08 ± 0.08	3		163	58.0	0.70336	0.512965	6.38	55.90	0.64	6.38	6.43
M99a	San Felix	A	5.21 ± 0.13	3		80	44.0	0.70354	0.513002	7.10	53.67	0.67	6.51	6.36
M44	El Baru volcano	A	5.22 ± 0.11	3		119	26.0	0.7035	0.512986	6.79	54.90	0.69	6.52	6.48
M91a	El Baru volcano	A	5.55 ± 0.11	4		144	68.0	0.7035			56.49	0.68	6.85	6.95
Fiji													
N64	Ngaloa I	A	5.39 ± 0.07	2		141	40.5	0.70288	0.51302	7.45	52.03	0.71	6.69	6.39
NG-1	Ngaloa I	A	5.61 ± 0.03	2		106	26.7	0.70292	0.51305	8.04	51.25	0.70	6.91	6.55
ST-44	E. Kudavu I	A	5.89 ± 0.05	2		125	22.2	0.70332	0.51301	7.26	56.39	0.75	7.19	7.28
ST-43	E. Kudavu I	A	5.64 ± 0.07	2		127	26.4	0.70321	0.51304	7.84	56.53	0.75	6.94	7.04
Aleutians													
V35G5a	Piip V, dredge	HMA	5.32 ± 0.01	2		21	4.4	0.70265	0.513139	9.77	58.00	0.74	6.62	6.85
KCPY1	Komandorsky I	HMA	5.00	2	1	80	17.0	0.70292	0.513077	8.56	59.69	0.66	6.30	6.68
ADK-53	Adak I	A	5.10	1	2	240	45.0	0.7028	0.513244	11.82	55.50	0.66	6.40	6.41
V3841Y3	W. Aleutians, dredge	A	5.22	1	3	329	48.5	0.7028	0.513073	8.49	60.06	0.74	6.52	6.94
Japan													
SDSYB	Shodo-Shima I	S	6.04 ± 0.04	2		15		0.70439	0.512747	2.13	48.95	0.71	7.34	6.78
SD261	Shodo-Shima I	S	6.14 ± 0.07	4		18		0.7049	0.51270	1.21	55.31	0.68	7.44	7.44
SD411	Shodo-Shima I	S	6.24 ± 0.08	2		16		0.70491	0.512717	1.54	55.80	0.70	7.54	7.58
SD249	Shodo-Shima I	S	6.78 ± 0.02	2		23		0.7051			56.33	0.71	8.08	8.17
Cascades													
MSH-18	Mt. S.Helens, 1980	HMA	5.49 ± 0.11		4	37	11.1	0.70364	0.51293	5.70	63.23	0.47	6.79	7.48
97-7	Mt. Shasta	HMA	5.76		5	118	13.4	0.702871	0.512939	5.87	63.02	0.63	7.06	7.74
8294a	Mt. Shasta	HMA	5.78 ± 0.01	2		42	8.0	0.703659	0.512905	5.21	52.50	0.74	7.08	6.83
8541b	Mt. Shasta	HMA	5.59 ± 0.10	3		68	10.2	0.702993	0.512974	6.55	57.87	0.77	6.89	7.11
Kamchatka													
1002/4	Zarechny	A/C	6.45 ± 0.03	2		38	6.2	0.70339	0.513083	8.68	53.00		7.75	7.54
K01/22	Zarechny	A/C	6.37	1		42	6.3	0.703522	0.513084	8.70	52.60		7.67	7.43

K2-92	Kharchinsky	A/C	6.36 ± 0.01	2		13	4.5	0.70359	0.513091	8.84	50.78		7.66	7.26
1188/1	Shiveluch	A/C	5.72 ± 0.03	3		23	5.3	0.703805	0.513039	7.82	50.06	0.79	7.02	6.56
K01/19	Shiveluch	A/C	5.87 ± 0.06	3		36	5.3	0.703362	0.513115	9.30	57.00		7.17	7.31
K01/14	Shiveluch	A/C	5.62 ± 0.07	2		33	4.1	0.70333	0.513100	9.02	53.60		6.92	6.76
5734	Shiveluch	A/C	5.83 ± 0.02	2		21	5.2	0.7037	0.513059	8.21	51.18	0.75	7.13	6.76
5764	Shiveluch	A/C	5.65 ± 0.02	2		33	5.4	0.70347	0.513089	8.80	53.87	0.70	6.95	6.82
South America														
Ck-3-198	Cook I	A	*5.32*		*6*	334	35.7	0.7028	0.51314	9.79	59.56	0.72	6.62	6.99
Ck-1-468	Cook I	A	*4.98*		*7*	318	32.8	0.70268			61.36	0.68	6.28	6.81
Ck-3-197	Cook I	A	*4.88*		*8*	443	30.3				61.51	0.67	6.18	6.72
CP-1	Cerro Pampa	A	*5.10*		*9*	306	33.0	0.7029	0.512887	4.86	64.55	0.67	6.40	7.21
Pich-70c	Pichincha, Ecuador	HMA	5.61 ± 0.06	2							57.40		6.91	7.09
Pich-135	Pichincha, Ecuador	HMA	5.85 ± 0.05	2							58.10		7.15	7.39
Averages			stdev	*n*										
Adakites			5.30 ± 0.29	14		212	38.4	0.70309	0.51304	7.8	57.121 ± 3.8	0.70	6.60	6.75
HMA:			5.55 ± 0.28	8		61	10.7	0.70312	0.51299	6.9	58.726 ± 3.4	0.71	6.79	7.12
S, Sediment melts:			6.30 ± 0.33	4		18	n.d.	0.70483	0.51272	1.6	54.10 ± 3.5	0.70	7.60	7.49
A/C, Crustally contaminated			5.98 ± 0.35	8		30	5.3	0.70352	0.51308	8.7	52.761 ± 2.2	0.75	7.28	7.06
			Total	34										

The numbers in italics are calculated Ol-equivalent values based on other phenocrysts and assuming equilibrium at 1000 °C using Chiba et al. [30] calibration. The melt in equilibrium with measured or calculated olivine was calculated (see text). Reconstructed olivine and melt values are accurate to within 0.1‰ and 0.2‰ based on internal reproducibility of standards and calculations respectively.

Sample type: A—adakitic; HMA—high-Mg andesitic; S—sediment melt–wedge interaction; A/C—adakite/crust interaction.

Comments 1–9: duplicated analyses of phenocrysts. 1: Plag (An50–65): 5.72‰ ± 0.01‰; 2: Cpx: 5.6‰ ± 0.2‰ (UV-laser); 3: Cpx: 5.7‰ ± 0.2‰ (UV-laser); 4: Plag: 6.937 ± 0.129, Amph: 5.921 ± 0.046; Mt: 3.8 ± 0.031, T (°C)=970–1020 °C using Chiba et al. [30] Plag (An50)–Mt and Amph (Cpx)–Mt A values; 5: Opx: 6.17 ± 0.1‰; 6: Cpx: 5.8‰ (UV-laser); 7: Cpx: 5.4 ± 0.1 (UV-laser); 8: Amph: 4.88 ± 0.39 (4); 9: Plag: 6.591 ± 0.081, Amph: 5.664 ± 0.103, T (Δ^{18} O$_{\text{Plag-Amph}}$)=907 °C.

Sample numbers, sample descriptions, and major, trace, and radiogenic isotopic parameters are from the following sources: Japan: Shimoda et al. [10]; Hanyu et al. [11]. Cascades: Grove et al. [8]; Aleutians: Yogodzinski et al. [7]; Yogodzinski and Kelemen [40]; Astral zone of South America: Stern and Killian [5]; Kay et al. [14]; Fiji: S. Tetroeva and L. Danyshevsky, unpublished data; Panama: K. Hoernle, unpublished; Kamchatka: Bindeman et al. [32]; M. Portnyagin and I. Bindeman (unpublished); Volynets et al. [38]; Ecuador: Bourdon et al. [9,17].

Radiogenic isotope data for Fiji and Cerro Pampa is for similar sample of the same units, others are for the same samples.

These three types of putative slab melts are rare in modern subduction zones, being restricted to convergent margins subducting exceptionally young, hot ocean crust [6], or having oblique subduction, slab 'tears' [4,14], mantle corner flow around the slab [15], delamination and slab window formation [16], or exceptionally shallow subduction [17].

Oxygen isotope data have the potential to constrain the amounts of slab melt contributing to arc lavas, and possibly even the part of the slab from which that melt is derived. This usefulness stems from two factors: (1) All common rocks and geological fluids contain similar concentrations of oxygen, making it relatively easy to relate variations in $\delta^{18}O$ of lavas to mixing ratios of isotopically distinct components in their sources; and (2) most mantle peridotites span a narrow range of $\delta^{18}O$ values (ca. 5.5‰ ± 0.2‰; see [18,19]) whereas ocean lithosphere contains several materials that are distinct from this range (and from each other): Marine carbonates ($\delta^{18}O = 25$–32‰), siliceous oozes ($\delta^{18}O = 35$–42‰), pelagic clays ($\delta^{18}O = 15$–25‰) [20], and weathered and hydrothermally altered upper oceanic crust ($\delta^{18}O = 7$–15‰) are all richer in ^{18}O than peridotites, whereas hydrothermally altered lower oceanic crust ($\delta^{18}O = 0$–6‰) [21–23], hydrothermally altered ultramafic rocks (e.g., serpentinites) from deeper in the ocean lithosphere ($\delta^{18}O = 0$–6‰, although these are poorly known) [24,25], and pore waters in marine sediments ($\delta^{18}O = 0$‰ to -3‰; perhaps as low as -15‰) [26] are all poorer in ^{18}O. Oxygen isotopes therefore have the potential to provide information on the causes of slab melting. If slabs heat only in response to under-thrusting the hotter mantle wedge, then their upper several kilometers should be the only portion that warms enough to melt, and slab melts should only come from ^{18}O-enriched sediments and altered basalts. If, instead, the slab is torn or otherwise structurally disrupted, then it might heat throughout its thickness and could also generate partial melt from low-$\delta^{18}O$ hydrothermally altered rocks in the slab interior. In this case, it is possible that contributions of melt from ^{18}O-rich and ^{18}O-poor parts of the slab might balance to produce a $\delta^{18}O$ value no different from the mantle wedge, although such mixing would have to be surprisingly constant and balanced not to produce per mil level ranges in $\delta^{18}O$ of those mixtures.

We present here oxygen isotope analyses of phenocrysts from 34 adakites, high-Mg andesites and Setouchi lavas, most of which are previously characterized for their major-element, trace-elemental, and radiogenic isotope compositions (Table 1). The samples we analyzed are geographically widely distributed and most have been the basis of recent hypotheses regarding slab melting.

2. Samples and methods

Rock types and geographic locations of samples examined in this study are given in Table 1 and major element compositions in Appendix A; further details regarding their settings and compositions can be found in references provided in the footnotes of these tables. Some of the samples examined in this study have undergone post-eruptive alteration that almost certainly changed the $\delta^{18}O$ values of their glass, groundmass, and other easily weathered components (e.g., Adak Island adakites are of Miocene age and are chloritized). Therefore, we have focused our analyses on hand-picked phenocryst fragments that appear under a $30\times$ binocular microscope to be free of alteration minerals and glass. We particularly focus on olivine, which is resistant to oxygen isotope exchange when it has not undergone serpentinization or other alteration reactions (which can be selected against during hand picking). Olivine is also an early liquidus phase in many primitive magmas, is a major constituent of the mantle, and has no recognized solid-solution variations of its oxygen isotope reduced partition coefficient ratio. Therefore, it is a good reference mineral for comparing $\delta^{18}O$ values of basalts, andesites, and their sources, and for calculation the equilibrium melt values. In olivine-free rocks we utilized other phenocrysts.
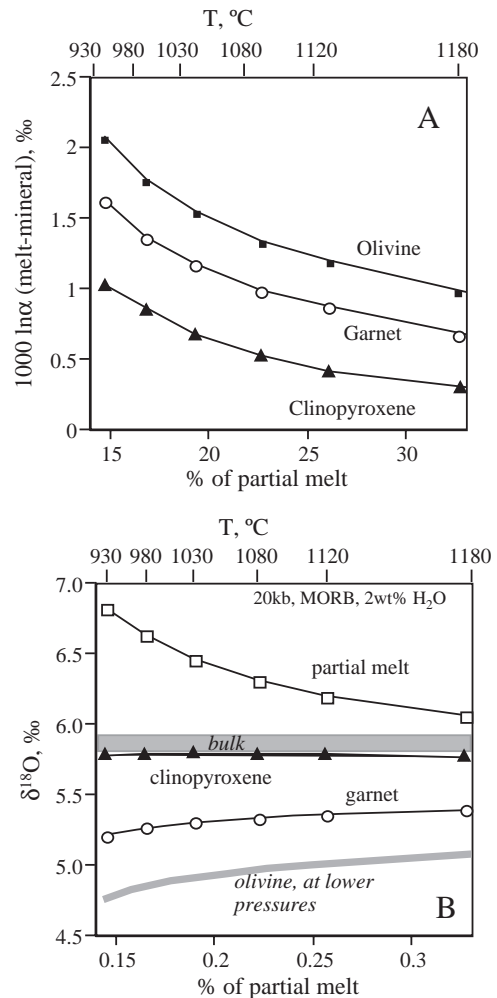
Rock chips of each sample were lightly crushed in a percussion mortar, sieved, and hand-picked for fresh phenocrysts. Recovered phenocrysts were ultrasonically washed in acetone and dried in a drying oven prior to analysis. 1–2 mg aliquots of these separates were analyzed at Caltech stable isotope lab by laser fluorination using BrF_5 as a reagent and methods previously described in [27–29]. Analyses were standardized based on measurements of Gore Mountain Garnet (UWG-2, 5.75‰) and San

Carlos Olivine (SCO-2, 5.35‰) secondary reference materials. Analyses of unknowns were corrected by the average difference between measured and accepted values for these standards measured on the same day. The absolute value of these corrections averaged 0.10‰. External precision for replicate analyses of standards on a given day varied between ±0.03‰ and 0.12‰, 1σ, and averaged ±0.08‰ (see Appendix A). All samples were analyzed in duplicate or triplicate, with an average reproducibility of ±0.06‰ (Table 1). We analyzed amphibole, plagioclase, magnetite, and/or pyroxene in several samples (principally those that lacked olivine). All of these phases other than pyroxene were analyzed as described above. Clinopyroxenes were analyzed by UV-laser (157 nm) fluorination in an F_2 atmosphere, which we believe is more consistently accurate than CO_2 laser fluorination for this phase. We calculated an equivalent olivine $\delta^{18}O$ value for each sample in which a mineral other than olivine was analyzed, based on previous estimates of the relevant inter-mineralic oxygen isotope fractionations at magmatic temperatures [30]. This calculation introduces an additional uncertainty (est. ±0.10‰, 1σ), so these 'olivine equivalent' values are printed in italics in Table 1.

Fig. 1. Calculation of oxygen isotope effects (values and reduced partition functions ratios) during melting of typical MORB basalt (Basalt-2 in [32]) with bulk oxygen isotope composition of 5.8‰. Calculations of batch melting were made in pMELTS program at 20 kbar and 2 wt.% H_2O. In these conditions restite/cumulate assemblage is eclogitic (jadeitic clinopyroxene plus garnet). The melt proportions and temperatures are consistent with adakite petrochemistry (e.g., [49]). The calculation algorithm includes treating the melt as a mixture of CIPW norms and calculating the isotopic fractionations between clinopyroxene, garnet and olivine and these fictive compounds in the melt; weighed proportion of each compound determines the resulting $\delta^{18}O_{melt}$ value (see [32] for more details), and the results are shown in A. B—$\delta^{18}O$ values of minerals and melts. Olivine is not present in the assemblage at 20 kbar, but will appear on liquidus as a phase when the adakitic partial melt is moved to lower pressures. Pressure produces negligible effects on oxygen isotope partitioning. Notice that $\delta^{18}O_{olivine}$ values range from 4.8‰ to 5.1‰ depending on the degree of melting; $\delta^{18}O_{cpx}$ is largely unchanged as it is close to the bulk composition; $\delta^{18}O_{melt}$ is getting progressively heavier with decrease in the degree of melting. It is important to stress that these rather heavy 6.1–6.6‰ melts are in oxygen isotopic equilibrium with the eclogitic mantle source and mantle peridotite (which is parental to the MORB eclogite), and do not record exotic high-$\delta^{18}O$ sources.

3. Calculated $\delta^{18}O$ values of silicate melts

A key goal of our study is to establish whether the oxygen isotope compositions of putative slab melts are in high-temperature equilibrium with typical mantle rocks, or are instead enriched or depleted in ^{18}O relative to the mantle due to isotopically exotic source components. It is relatively straightforward to do so for primitive basalts, because their olivine phenocrysts should be indistinguishable in $\delta^{18}O$ from olivine in their mantle peridotite sources. However, $\delta^{18}O$ values of phenocrysts from olivine-undersaturated magmas require corrections for high-temperature equilibrium fractionations during partial melting and/or crystallization–differentiation. As an example of these effects, Fig. 1 plots

the expected variations in $\delta^{18}O$ of minerals and melts during partial melting of an eclogite having a major-element composition similar to normal MORBs and an initial whole-rock $\delta^{18}O$ value of 5.8‰. This calculation assumes that melting occurs as a batch process at 20 kbar, and uses the pMELTS program to estimate mineral and melt abundances as functions of temperature. We find that the $\delta^{18}O$ value of clinopyroxene in the residue varies little as a function of the degree of partial melting; this is because it is the most abundant component of the eclogite source before melting and remains abundant in the residue throughout melting. In contrast, the $\delta^{18}O$ values of silicate melt and garnet vary significantly with the temperature and degree of melting. Most notably, small degrees of partial melting (~10–15%) produce siliceous, high-$\delta^{18}O$ (~6.8‰, Fig. 1) partial melts. Furthermore, if these melts undergo crystallization–differentiation at low pressure, the first olivine they precipitate (note some melts may be olivine understaturated at any pressure) will actually be lower in $\delta^{18}O$ than typical mantle olivine. This reflects the large equilibrium thermodynamic fractionation between siliceous melt and olivine at the relatively low liquidus temperatures of these melts. Because of this effect of melt composition on $\delta^{18}O$ values of both siliceous melts and minerals precipitated from those melts, olivine in oxygen isotope exchange equilibrium with typical adakites at their liquidus temperatures should have $\delta^{18}O$ values of ca. 4.9‰, rather than the values of 5.0–5.2 that are typical of upper mantle olivine or olivine phenocrysts in basalts.

As a means of addressing the effect of high-temperature equilibrium fractionations on oxygen isotope compositions of siliceous melts and their phenocrysts, we discuss two oxygen isotope parameters: (1) The $\delta^{18}O$ value of olivine, either measured in the sample or 'fictive' olivine calculated to be in oxygen isotope exchange equilibrium with another phenocryst phase that was measured in that sample (plagioclase, clinopyroxene, or amphibole) at the estimated liquidus temperature of the lava; and (2) the $\delta^{18}O$ value of melt calculated to be in oxygen isotope exchange equilibrium with measured phenocrysts (olivine, plagioclase, clinopyroxene, or amphibole) at the estimated liquidus temperature of the lava. The first of these parameters is the best means of showing the variations in $\delta^{18}O$ required for the sources of lavas having broadly similar major element compositions (e.g., all ada-
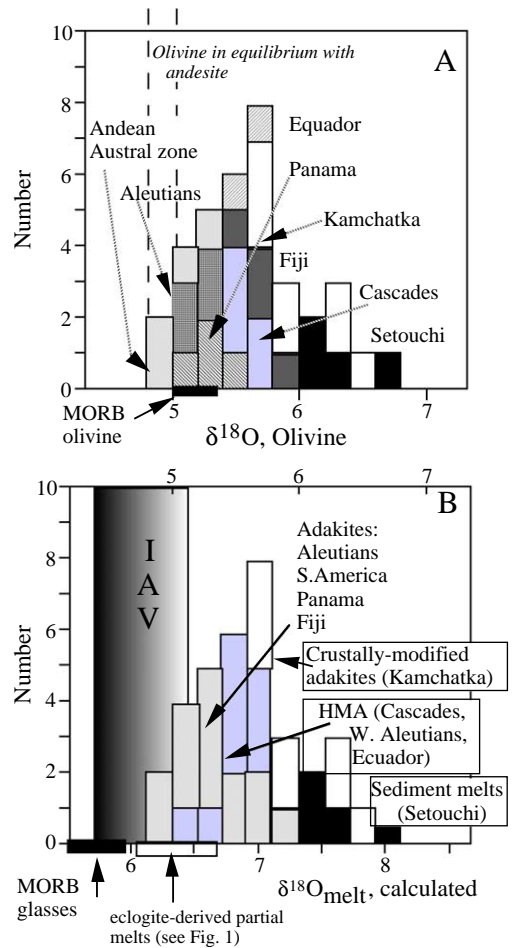

Fig. 2. Histogram of $\delta^{18}O$ values of the world's adakites, high-Mg andesites, and geochemically exotic melts from Setouchi, Japan. A—Comparison of measured $\delta^{18}O$olivine values for each locality. Samples from the Aleutians, South America, Fiji, and Panama are "end-member" slab melts with the highest Sr/Y and La/Yb ratios; Setouchi belt of Japan is the best example of sediment melt interaction with the mantle wedge; Cascades, Ecuador, and W. Aleutians are high-Mg andesites; Kamchatkan adakites show evidence of melting and assimilation of the lower crust. B—Comparison of calculated $\delta^{18}O$ melt values and its comparison with MORB glasses and the range of $\delta^{18}O$ in island arc volcanic rocks that are produced by variable degrees of partial melting of the MORB-like mantle wedge and variable degree of subsequent fractional crystallization without interaction with any other $\delta^{18}O$ reservoir. It is assumed that 90% fractional crystallization will produce rhyolitic melt which is 0.4–0.5‰ heavier than the original 5.8‰ basalt. Notice that slab and sediment melts considered here are subtly to significantly higher in $\delta^{18}O$ than other mantle-derived island arc volcanic rocks and products of their closed-system differentiation. This reflects higher $\delta^{18}O$ values of their source rather than other effects.
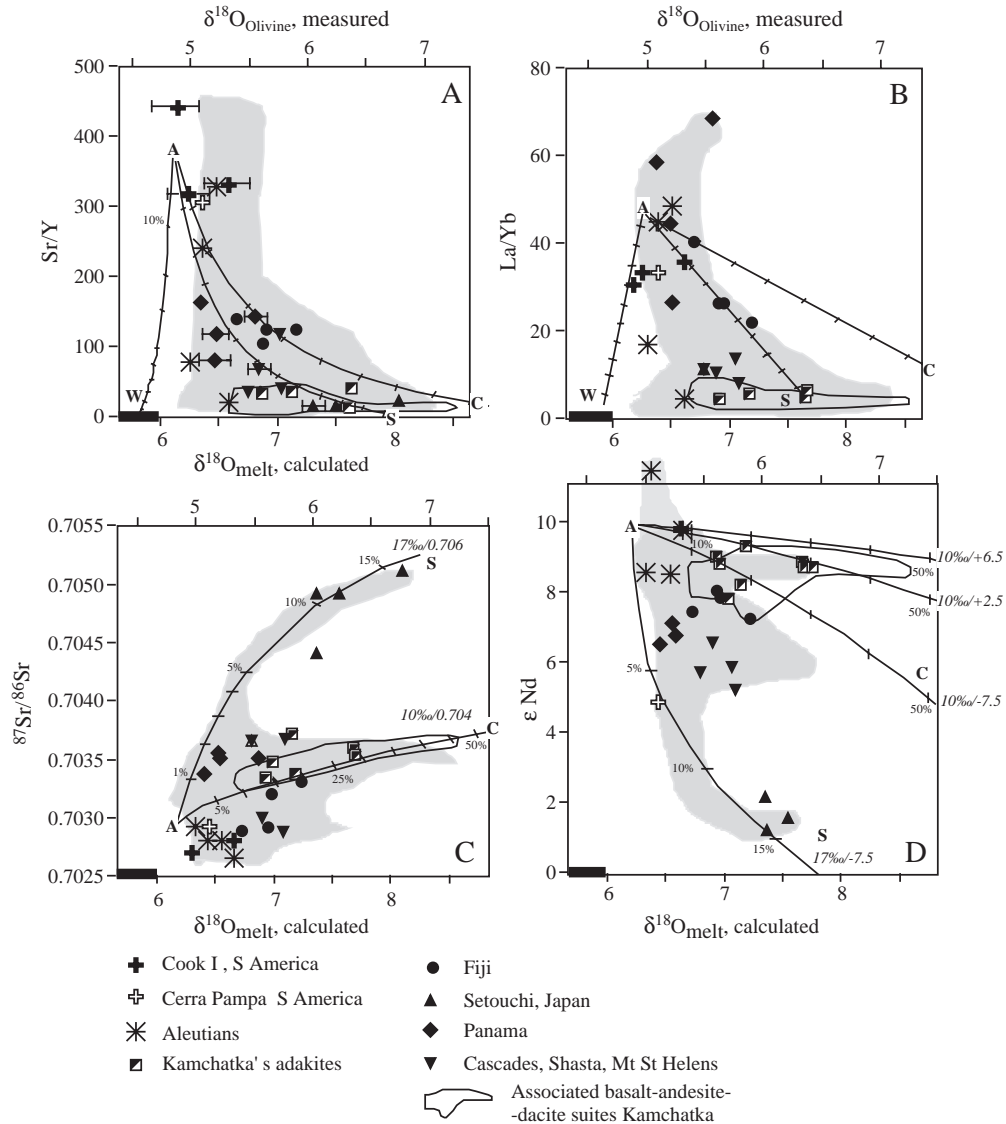
Fig. 3. Sr/Y, La/Yb, $^{87}Sr/^{86}Sr$, and ε_{Nd} correlations with $\delta^{18}O$ in world's adakites, high-Mg andesites, and sediment melts. Data is from Table 1. The lower scale denotes $\delta^{18}O_{melt}$ calculated from $\delta^{18}O_{olivine}$, which is shown on the upper scale. The gray field (upper scale) denotes the melt in equilibrium with olivine at given SiO_2 content of the whole rock that indirectly includes temperature dependence (see Table 1, model 2). Thick black bars at the bottom and the top of each graph show the accepted range values of $\delta^{18}O$ for mantle derived basaltic melt. Notice that adakitic melts of the present study are higher than MORB, while sediment melts (Setouchi) are significantly higher than MORB. Other typical island arc magmas are shown on the example from Kamchatka basalts to andesites that are derived from the garnet-free shallower lower crustal assimilation overlap in $\delta^{18}O$ with the adakitic range but are distinct in all other parameters. Curves shown are bulk mixing of end members: A—adakitic (slab) melts, W—melts derived from the mantle wedge, C—crustal melts, and S—sediment melts ± fluids. A–B: Correlation with trace elemental ratios; mixing of "end-member" adakitic melt with mantle wedge melt (steeper curve) and the sediment and crust (shallower curves). C–D: ▢Correlation with radiogenic isotope ratios; mixing curves with and sediment melts (upper curve) and crustal melts which explain genesis of Setouchi high-Mg andesites, and Kamchatkan adakites respectively. Notice clear distinction of source-contamination trend by sediment melt vs. crustal assimilation trends in C and D. 10‰/0.706 and 10‰/−7.5 are end-member isotopic compositions of O/Sr and O/Nd respectively. Concentrations of elements in end members (ppm) is as follow: Sr: 160 (W), 300 (S), 300 (C), 2200 (A); Nd: 2.5 (W), 15 (S), 10 (C), 10 (A); La: 2.5 (W), 6 (C, S), 72 (A); Y: 20(W), 35 (C, S), 5.5 (A); Yb: 0.7 (W), 1 (C, S), 0.9 (A).

kites and high-Mg andesites). The second parameter is convenient for comparing $\delta^{18}O$ values of our samples with other common lavas (e.g., MORB glasses and island arc volcanics). We have undertaken two approaches in this regard.

The first approach uses the average offset of reduced partition function ratios (fractionation factors) between olivine–basalt and olivine–andesite melts. The basaltic melt–olivine fractionation at 1200–1300 °C is in the 0.4–0.8‰ range [19,31], the average calculated (see below) andesitic melt–olivine fractionation is 1.3‰, based on the average adakitic and high-Mg andesitic melt with 57‰ SiO_2 as is given in Table 1. These larger calculated values account for the more siliceous and lower temperature adakitic and high-Mg andesitic melts of the present study. The calculated melt values are plotted in Figs. 2 and 3 of this paper, along with olivine $\delta^{18}O$ values (see upper and lower scales and 1.3‰ offset). The second approach calculates the $\delta^{18}O$ value of each melt as a function of its silica content in an attempt to correct for the compositional diversity of melts of this study. We made this calculation using a parameterization previously described in [32]: $\delta^{18}O_{melt} = \delta^{18}O_{olivine} + 0.088 * SiO_2 - 3.57$, where SiO_2 is in weight percent, which yields 1.3‰ at 57 wt.% SiO_2. This parameterization assumes that the liquidus temperature of the magma is 1000–1100 °C, which we believe is a reasonable approximation for the samples we examined, and results in a typical melt–olivine fractionation for adakites of ~0.8‰ to 1.7‰. The melt $\delta^{18}O$ values calculated this way are shown in Table 1, and are plotted as fields in Fig. 3. This second method of calculation allows better comparison among compositionally diverse melts, but introduces an additional uncertainty in the calculated values (0.088‰ for 1 wt.%). Nevertheless, the two methods produce broadly similar results (Fig. 3). In the following discussion, we focus on $\delta^{18}O_{melt}$ values estimated using the first method described above.

4. Results

4.1. Adakites

Most prototypical adakites, such as those from the Adak and Cook Islands, lack olivine and contain only clinopyroxene as phenocrysts. This alone suggests that

they might be derived from olivine-free sources, like subducted eclogites, and have not equilibrated with the olivine while passing through the mantle wedge. The $\delta^{18}O$ values of measured or calculated olivine in the 14 adakites analyzed in this study range from 4.88‰ to 5.89‰ and average 5.30‰ ± 0.30‰—only 0.1‰ higher in average to, but more variable than, olivine from basaltic lavas from MORB, oceanic arcs and ocean islands [33,34]. The $\delta^{18}O$ values we estimate for the silicate melts hosting these phenocrysts vary between 6.36‰ and 7.28‰—considerably higher than most basalts (ca. 5.5–5.8‰). This is because the SiO_2-rich compositions and low liquidus temperatures of adakites result in relatively large melt–olivine fractionations. The average estimated $\delta^{18}O$ value of melt for these samples—6.65‰ ± 0.31‰ (Table 1, Fig. 2) is 0.3–0.4‰ higher than expected for andesitic melt in equilibrium with mantle peridotite or similarly SiO_2-rich partial melts of eclogite having the $\delta^{18}O$ of MORBs (see Fig. 1). Thus, adakites as a group are ^{18}O enriched compared to both MORBs and typical IABs, but these enrichments are generally subtle (several tenths of per mil). The highest $\delta^{18}O$ values estimated for model adakitic melts are in oxygen isotope exchange equilibrium at liquidus temperatures with the highest-$\delta^{18}O$ olivine and plagioclase phenocrysts previously observed in intraoceanic island-arc basalts, basaltic andesites, and boninites [27]. The following paragraphs detail oxygen isotope results for each suite of Adakites examined in this study.

4.1.1. Andean Austral zone (Cook Island and Cerro Pampa)

Adakites from Cook Island erupted through relatively thin crust and are believed to have undergone little or no crustal assimilation, unlike Ecuadorian and other Andean adakites that erupted through the exceptionally thick crust [17]. Thermal models of convergent margins indicate that partial melting of the subducted oceanic crust is probable below the Austral Andes due to the slow subduction rate (2 cm/yr) and the young age (0.24 Ma) of the subducted oceanic lithosphere [5,14]. Geochemical models for adakites are consistent with a large material contribution from subducted oceanic crust (35–90% slab-derived mass, see [5,35,36]), and those from Cerra Pampa may additionally contain up to 6% of sediment contribution (Fig. 3D).

These samples from South America, along with those from the Aleutians (below) exhibit the most extreme 'adakitic' trace element chemistry of any samples examined in this study. The model melt $\delta^{18}O$ values (Fig. 2) are the lowest among other adakites and are near the inferred oxygen isotope equilibrium with the typical mantle. We also note that the Sr and ε_{Nd} isotopic compositions of these lavas (but not in other adakites) are the most 'MORB-like' (0.7026 and +10 respectively) of any lavas examined in this study, and this contradicts their inferred derivation by remelting of the MORB slab, which has higher Sr isotopic values due to interaction with seawater.

4.1.2. Aleutians

Adakites from the Central and Western Aleutians, including ADK-53—the sample from Adak Island of Tertiary age originally used to coin the term 'adakite' [4], occur at a convergent margin where relatively old, cold ocean lithosphere is subducted obliquely. This margin appears to be inconsistent with thermal models suggestion that adakites should form only by melting of young, hot subducted lithosphere [6]. However, the precise tectonic and thermal regime at the time of sample derivation in the Tertiary remains unknown. These Aleutian adakites are similar in trace element and radiogenic isotope composition to the Andean Austral adakites described above (Fig. 3A–D), and likewise also have $\delta^{18}O$ values consistent with isotope exchange equilibrium with average mantle.

4.1.3. Panama

Panamanian adakites occur above the subducting Panama Fracture Zone, which forms the boundary between the Cocos and Nazca Plates [37]. Panamanian adakites have high Sr/Y ratios typical of other adakites, but are unusual in that their La/Yb ratios are higher than any other adakites examined in this study. This characteristic might reflect derivation from a high La/Yb source, perhaps because the ocean crust in the Panama Fracture Zone (and adjacent parts of the Cocos and Nazca Plates) formed near the Galapagos hotspot and compositionally resembles ocean-island basalt, including La/Yb higher than MORBs [37]. The $\delta^{18}O_{Olivine}$ values of Panamanian adakites range from 5.08‰ to 5.55‰; i.e., ranging from values similar to those typical of average NMORBs up to values ca.

0.5‰ higher. Similarly, the estimated $\delta^{18}O$ values of melts parental to Panamanian adakites range from 6.36‰ to 6.95‰; i.e., ranging from values similar to Andean Austral and Aleutian adakites up to values ca. 0.5‰ higher.

4.1.4. Fiji

The origins of Fijian adakites are not clear, but are hypothesized to reflect partial melting of South Fiji Basin lithosphere (~30 Ma) after it was subducted into unusually hot mantle beneath the North Fiji Basin [Tetroyeva et al., in preparation]. Fijian adakites have $\delta^{18}O$ values for olivine phenocrysts of 5.39‰ to 5.89‰ and estimated magma of 6.39‰ to 7.28‰— both higher than 'end-member' adakites from the Andean Austral zone and Aleutians. Fijian adakites are similar in Sr/Y to these adakites, but higher in $^{87}Sr/^{86}Sr$ and lower in ε_{Nd}.

4.1.5. Kamchatka

Adakites from Kamchatka have been interpreted as partial melts of the subducted Cretaceous Pacific slab, formed in response unusual slab heating by flow of mantle around its edge, west of the Aleutians [15,38]. The $\delta^{18}O$ values for Kamchatkan adakites are higher and more variable than any other suite examined in this study, with $\delta^{18}O_{Olivine}$ ranging from 5.65‰ to 6.45‰ corresponding to calculated melt values of 6.56‰ to 7.54‰. The oxygen isotope compositions of Kamchatkan adakites form continuous geochemical trends with even higher $\delta^{18}O$, non-adakitic basalts from the nearby large volcanoes, Klyuchevskoy, Tolbachik, and Bezymianny (and their associated monogenetic cones) in plots involving indices of magmatic differentiation (Fig. 2). Furthermore, Kamchatkan lavas define an end member to the trends defined by all samples examined in this study in plots of $\delta^{18}O$ vs. $^{87}Sr/^{86}Sr$ or ε_{Nd} (Fig. 3C–D), extension of which approach the compositions of higher $\delta^{18}O$ more evolved, non-adakitic Kamchatkan lavas. These results are consistent with contamination of lower $\delta^{18}O$, primary adakitic magmas (resembling Andean Austral and Aleutian adakites) by higher-$\delta^{18}O$ crustal rocks of Cretaceous to Miocene age in the thick crust of the upper plate [32]; thus, these samples do not provide clear evidence for high-$\delta^{18}O$ primary adakitic magmas, despite their extreme oxygen isotope compositions.

In summary, adakites with the highest Sr/Y ratios and most MORB-like radiogenic isotope compositions are consistently characterized by $\delta^{18}O$ values in or near high-temperature exchange equilibrium with average mantle peridotites. Adakites from Panama and Fiji, have higher $\delta^{18}O_{Olivine}$ values, consistent with derivation from a source ca. 0.1–0.8‰ higher than average mantle peridotites, thus reflecting subtle enrichment in the deep source, is as evidenced by the high La/Yb ratios of these lavas. Kamchatkan adakites have consistently higher $\delta^{18}O$ values but are also less 'adakitic' in their trace element chemistry, and can be explained by contamination of adakites having 'normal' $\delta^{18}O$ values by higher-$\delta^{18}O$ crustal rocks from the upper plate.

4.2. High-Mg andesites from the cascades and western aleutians

High-Mg andesites are similar in many respects to adakites and the difference between the two is somewhat arbitrary. For the purpose of this study, high-Mg andesites are generally lower in Sr/Y and La/Yb ratios (<100 and 20 respectively) and contain abundant amphibole phenocrysts. These observations are consistent with them being eclogite melts with or without subsequent reaction with peridotites in the mantle wedge [39], or products of melting the mantle wedge in the presence of abundant (presumably slab derived) aqueous fluids [8].

We examined high-Mg andesites from Shasta and Mt. St. Helens in the Cascades, two dredged samples from the Western Aleutians [7,40], and two from Pichincha volcano in Ecuador. High-Mg andesites and dacites of Mt. St. Helens and Pichincha were interpreted as slab melts by Defant and Drummond [6] and Bourdon et al. [17]. Those from Shasta were interpreted by Grove et al. as partial melts of peridotite in response to fluxing by unusually large amounts of slab-derived aqueous fluids (i.e., more slab fluid than is added to the sources of typical island arc basalts; [8]). We find these lavas have $\delta^{18}O_{Olivine}$ values of 5.49‰ to 5.78‰, in equilibrium with calculated model melt values of 6.83‰ to 7.74‰; i.e., they are 0.5–0.8‰ higher than expected for oxygen isotope exchange equilibrium with typical mantle peridotites. Analyses of $\delta^{18}O$ values for olivines from magnesian basalts throughout the Cascade's

are uniformly MORB-like (5.0–5.2‰, Leeman and Bindeman unpublished), including those that have unusually high Sr/Y ratios (one of the properties characteristic of Adakites).

The high-Mg andesites examined here are higher and more variable in $^{87}Sr/^{86}Sr$ (0.7030 to 0.7041) than NMORBs or most end-member adakites (Fig. 3C). Borg et al. [41] interpreted high $^{87}Sr/^{86}Sr$ in similar Cascades lavas as evidence of addition to their sources of a slab-derived aqueous fluid containing radiogenic Sr [42]. Chmeleff and Sigmarsson suggested a similar process is responsible for ^{226}Ra excesses in Pichincha lavas [44]. Previous oxygen isotope studies of western Pacific arcs have found evidence for additions of high-$\delta^{18}O$ slab-derived fluids to their sources [27,45]. Thus, it seems reasonable to attribute the ^{18}O-rich character of high-Mg andesites to the addition of high-$\delta^{18}O$, high-$^{87}Sr/^{86}Sr$, ^{226}Ra-rich slab-derived aqueous fluids to their mantle sources. However, high $^{87}Sr/^{86}Sr$ and ^{226}Ra excesses in arc lavas are not universally associated with high $\delta^{18}O$ values, and so it also seems possible that ^{18}O enrichments of high-Mg andesites are unrelated to their Sr and Ra isotope compositions. Furthermore, contamination of primary Cascades magmas (and in Mt. St. Helens in particular) by high-$\delta^{18}O$, high-$^{87}Sr/^{86}Sr$ lower crustal rocks in the upper plate could also explain the trend defined by these samples Fig. 3C–D [43] (see also [9,17]).

4.3. Putative sediment melts from Setuchi, Japan

Island arc lavas from Setouchi, Japan, have particularly radiogenic isotope composition of fluid-immobile elements such as Nd and Hf [11,12], that have been attributed to unusually large amounts (up to 10 wt.%; Fig. 3C) of sediment melt in their sources (see [10–12]). The Sr/Y and La/Yb ratios of Setouchi lavas are lower than in typical adakites and high-Mg andesites; i.e., there is no obvious reason to suspect that they also contain an abundant component of eclogite melt. The $\delta^{18}O_{olivine}$ values of these lavas vary from 6.04‰ to 6.78‰—the most consistently high values of any suite observed in this study and corresponding to $\delta^{18}O$ values of host melt of 6.78‰ to 8.17‰. Setouchi lavas are an extreme to the population of samples examined in this study when viewed in plots of $\delta^{18}O$ vs. $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ vs. ε_{Nd} (Fig. 3C–D). These properties are consistent with

addition of sediment melt to their mantle sources, and differ from the geochemical signatures we expect for contamination by crustal rocks in the upper plate. A mass-balance calculation fit to the correlation between oxygen, strontium and neodymium isotopes for these samples (Fig. 3C–D) requires up to 15% addition of high-$\delta^{18}O$ sediment melt to a depleted peridotite mantle wedge. Thus, our data are broadly consistent with previous interpretations, but appear to require a higher fraction of sediment melt than was previously surmised based on Pb, Nd, and Hf isotope data [10–12]. One simple explanation of this discrepancy could be that the incompatible trace element concentrations in the sediment melt component are lower than previously suggested.

5. Discussion: types and origins of modern slab melts, and comparisons with Archean TTG suites

Fig. 3 plots the oxygen isotope compositions and other geochemical properties of all lavas examined in this study. The trends observed on these diagrams show that the minimum $\delta^{18}O$ defined by end-member adakites and increasing $\delta^{18}O$ with decreasing Sr/Y, La/Yb, $^{143}Nd/^{144}Nd$ and increasing $^{87}Sr/^{86}Sr$. This result is contrary to our expectation that the most extreme oxygen isotope signatures should be associated with the most extreme 'adakite-like' trace element compositions (i.e., because these lavas are suspected to contain the largest mass fractions of slab melts). Instead, the end-member adakites are in or close to oxygen isotope exchange equilibrium with average mantle peridotite. The higher $\delta^{18}O$ values are associated with trace element and radiogenic isotope compositions that might reflect components of slab-derived aqueous fluids (as we conclude for the Cascades), partial melts of subducted sediment not having the characteristic 'adakitic' chemistry (as we conclude for Setouchi), and/or contaminants coming from assimilation or melting of the upper plate (as we conclude for Kamchatka).

Adakites are widely hypothesized to be nearly pure melts of subducted crustal rocks. How, then, can they have $\delta^{18}O$ values closely approaching equilibrium with mantle peridotite when subducted rocks vary widely in $\delta^{18}O$ and generally differ from the mantle? The following paragraphs explore three hypotheses

that we believe better explain the oxygen isotope compositions of adakites.

5.1. Differentiation and/or melting processes in the upper plate?

It is possible that some adakites are not slab melts at all, but instead are differentiation products of melts of the mantle wedge, much like the tholeiitic and calc-alkaline basalts and basaltic andesites that make up most of the primitive lavas in magmatic arcs. This answer challenges a commonly held interpretation of adakite petrogenesis, and requires some other explanation of their trace-element compositions. The distinctive properties of adakites – high Sr/Y and La/Yb in lavas with andesitic or dacitic composition – can be explained by 15–25%-degree partial melting of garnet-rich, plagioclase-poor mafic rocks (so these 10s of % partial melting leaves a garnet-bearing, plagioclase-free residue) having trace element and radiogenic isotope compositions broadly similar to MORBs. These constraints are generally interpreted as evidence for partial melting of the subducted ocean crust after it has passed into the eclogite stability field at depths beneath the arc (generally ≥100–150 km). However, adakitic melts might instead be generated from differentiation and/or partial melting near the base of the thick subcontinental arc crust on the over-riding plate by one of two means:

(1) By re-melting basalts that previously ponded near the base of the arc crust and/or mafic cumulates that precipitated from ponded basalts. Garnet amphibolite which is poor in plagioclase can form at midcrustal pressures—(ca. 12 kbar), corresponding to a depth of ca. 32–35 km, although stable Grt+Cpx eclogitic assemblage is not formed until 18 kbar, based on our pMELTS modeling with MORB compositions. This is deeper than the suspected depth to the geophysical petrologic MOHO in many arcs (although this depth is generally poorly known), but within the suspected depth for arcs built on thick pre-existing crust (e.g, the Andes and Kamchatka). Alternatively, deep arc crust is known to contain mafic cumulates rich in hornblende and garnet, and it is possible that

re-melting of some subset of these composition-ally diverse materials might produce adakites. Green and Ringwood [61,62] described a subset of rhyodacitic calc alkaline igneous rocks that contain almandinic garnet [62], and their experiments suggest pressure in excess of 13.5 kbar for a stable garnet bearing cumulate assemblage to exist. This limits the adakite genesis to areas of thickened subcontinental crust with siliceous compositions, such as Tibet. Finally, mafic lower crust might convert to eclogite and partially melt even in convergent margins with thin arc crust (<30 km) if it either delaminates and sinks into the underlying asthenosphere or is dragged to great depth by subduction erosion [51]. The delamination hypothesis has been put forward to explain highly radiogenic intraplate adakites in Tibet [50], while adakites from Adak Island in the Aleutians could be explained by subduction-erosion [51].

(2) By high-pressure crystallization–differentiation of wedge-derived calc-alkaline hydrous basaltic magmas. However, this scenario is less likely as it requires early crystallization of garnet on liquidus of basalts, which only happens at high pressures (ca. >35 kbar) when garnet substitutes omphacitic clinopyroxene on liquidus [61]. At lower pressures of ca. 13.5–18 kbar that are compatible with MOHO in areas of thickened crust, garnet only crystallizes after clinopyroxene ([62], our pMELTS modeling). Many tens of percent of fractional crystallization of eclogitic garnet–clinopyroxene assemblage might be needed to produce broadly andesitic differentiate with high Sr/Y and La/Yb ratios. Such extensive degrees of fractionation are complementary to the 15–25% proportions of the partial melting above.

These mechanisms for creating adakites in the upper plate should generate siliceous magmas in or near oxygen isotope exchange equilibrium with the mantle, because they involve re-melting common basaltic arc rocks (or their differentiation products). These rocks are generally similar in $\delta^{18}O$ to normal MORBs, rather than parts of the subducted ocean crust that have been subjected to extensive near-surface hydrothermal alteration and weathering.

5.2. Equilibration with the mantle wedge

It is known that the mantle wedge is importantly involved in providing high-Mg signature to many slab melts ("high-Mg, or Piip-type adakite" end member, e.g., [7]), while preserving their petrochemical (e.g., high SiO_2) and trace elemental signatures. Fig. 3A–B demonstrates that interaction with the mantle wedge may lower the Sr/Y and La/Yb ratios and in effect provides transition from the accepted end-member adakite-like to high-Mg andesite-like (and boninite-like) melts. However, our global data set (Fig. 3) clearly shows that adakites with the highest Sr/Y and La/Yb ratios have narrower range in $\delta^{18}O$, and that with lowering these characteristic trace elemental ratios, the $\delta^{18}O$ values either remains the same, or are getting higher. Perhaps the strongest argument against complete reequilibration with the mantle wedge is that the archetypical adakites lack olivine on liquidus, a mineral that would be expected if such equilibration has taken place.

Eclogites found in kimberlites are known to exhibit wide variety of $\delta^{18}O$ values spanning the entire range found in the oceanic crust (e.g., Fig. 1 in [52]). The relatively narrow range of $\delta^{18}O$ in adakites as compared to diversity seen in eclogite nodules may indicate that adakites might be slab melts that have come into partial to complete oxygen isotope equilibrium with peridotites in the mantle wedge. It is known that melts with exotic $\delta^{18}O$ can came from, or pass through the mantle wedge without equilibrating with, normal peridotites as is observed in Setouchi suite examined here. However, what if adakites sample a class of melts that do so? If this interpretation were correct, then the $^{18}O/^{16}O$ ratio should exchange faster than the Sr/Y, La/Yb, and be able to preserve high SiO_2 values of output melts. The example of Setouchi suggests that this is not correct, as sediment melts, or slab melts travel the similar distance from the slab to the surface do interact with the mantle wedge, but retain clear geochemical spike signatures, including elevated $\delta^{18}O$, but low Sr/Y ratios. This comes, perhaps, as no surprise, as oxygen is slower diffuser than Sr and should suffer less diffusive exchange with mantle wedge during transport. Additionally, against the complete equilibration with the wedge hypothesis contradicts the evidence that at least some lavas with adakite affinities exhibit significant excesses of $(^{226}Ra/^{230}Th)$, $(^{234}U/^{230}Th)$,

and [10]Be [35,36,44], which suggests that melting, and transfer rates to the surface may be sufficiently rapid (e.g. 10^3–10^4 yr), and warrant chanellized or diapir-like flow that carry out subduction-related geochemical signal without complete equilibration with the mantle wedge.

5.3. Whole-slab melting

It is important to stress that, while end-member adakites are only slightly elevated in $\delta^{18}O$, suspected slab melts such as adakitic high-Mg andesites and Setouchi lavas are consistently some of the highest $\delta^{18}O$ arc lavas known. Part of this enrichment is related to the thermodynamics of the partial melting of an eclogitic source (see Fig. 1), but we have demonstrated above that even when accounted for this, the high-$\delta^{18}O$ source characteristics are still required in adakites from Fiji and Panama. This [18]O enrichment and rarity of similarly high $\delta^{18}O$ values in other intraoceanic island-arc basalts and basaltic andesites of Circum-Pacific arcs (e.g., [27,45–47]) suggest the common involvement of high-$\delta^{18}O$ components with garnet trace elemental signatures in the petrogenesis of these lavas.

Convergent margin lavas with adakitic signatures that are lightly enriched in $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ may contain higher abundances of aqueous fluids and/or silicate melts extracted from the ^{18}O-rich top of the slab. Given that the adakitic and high-Mg andesitic melts of the present study are broadly andesitic in composition, comparison of their chemical composition with the partial melts generated experimentally in eclogite melting experiments [48] require at least 20% melting. These amounts can clearly be classified as "high" degree partial melts of the subducted slab, these degrees generate broadly andesitic in composition melts with high Sr/Y ratios that are capable of rapid segregation and dynamic mixing.

Therefore, many adakites especially those in intraoceanic environment or areas of thin crust (e.g., Fiji and Panama) might be mixtures of melts of high- and low-$\delta^{18}O$ rocks in the subducted slab in proportions, balanced in such a way to yield an integrated value similar to slightly higher than fresh normal MORBs. This does not amount to special pleading because the weighted average of low-$\delta^{18}O$ and high-$\delta^{18}O$ rocks throughout the basaltic and gabbroic sections of the ocean crust is thought to equal that of fresh MORBs (although this is generally not strictly true in any one crustal section) [21,22,58]. Nevertheless, in order from slab melting to consistently yield magmas having $\delta^{18}O$ values equal to less than 1‰ higher than MORBs, mafic rocks from throughout the slab must melt. In this scenario, the thin and high-$\delta^{18}O$, high-$^{87}Sr/^{86}Sr$ top part of the slab contributes slightly more to the bulk melt than does its thick low-$\delta^{18}O$ interior, and, more importantly, the lack of low-$\delta^{18}O$ adakites suggests that melting of the interior never proceeds alone. This rather delicate $\delta^{18}O$ balance is likely not possible in most convergent margins if partial melting is in response to conductive heating of structurally intact slabs (which should preferentially heat the high-$\delta^{18}O$ sediments and weathered basalts near the slab top surface). Instead, adakite genesis would have to usually or always involve melting of torn or delaminated slabs. There are modern convergent margins where this is believed to take place (e.g., northern Kamchatka) [15].

We do not believe we can discriminate among these possible origins for adakites based on existing constraints. However, these models do make predictions that could be tested with further work, using lithium and osmium isotope for example. Finally, it is important to note that these various hypotheses to explain adakites with 'normal' $\delta^{18}O$ values need not to be mutually exclusive.

5.4. Archean TTG suites

It has been widely suggested that the growth of continental crust during the Archean involved relatively large contributions from slab melts [3,6,53]. Archean trondhjemite–tonalite–granodiorite (TTG) suites are the most plausible candidates for these slab melts (and their differentiation products). Members of TTG suites are characterized by highly fractionated REE patterns and high Sr/Y and La/Yb ratios (i.e., like adakites), implying derivation from garnet-rich and plagioclase-poor residues (e.g., [54]). The oxygen isotope compositions of members of TTG suites can be estimated using previous analyses of zircons from these rocks [55,56], which have been suggested to preserve magmatic oxygen isotopic compositions in even very old
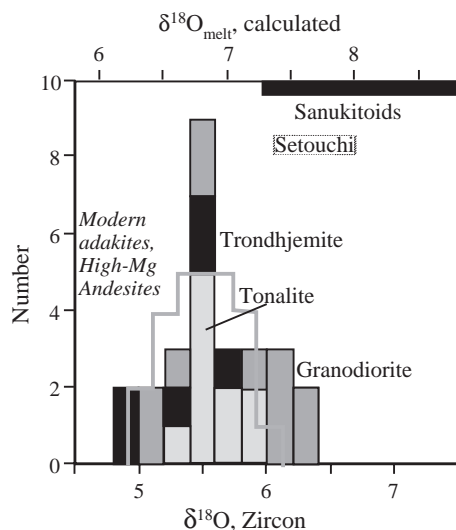
Fig. 4. Compiled $\delta^{18}O$ values of zircons for Archean orogenic TTG suites (trondhjemite, tonalite–granodiorite) and postorogenic sanukitoids suites predominantly from the Superior province in Canada, data is from [55,56]. These suites exhibit high Sr/Y and La/Yb ratios and are interpreted to represent slab melts (e.g., [13,59]). Stippled pattern denotes $\delta^{18}O$ values of olivine in adakites and high-Mg andesites of this study for comparison. At 1000 °C reference temperature, the $\Delta^{18}O(zircon–olivine)$ fractionation is 0.64‰ [30,60], but the calculated $\Delta^{18}O(olivine–melt)$ at 1100 °C for olivine-bearing adakites, and $\Delta^{18}O(melt–zircon)$ at 950 °C for zircon-bearing TTG are approximately similar. Thus, plotted zircon and olivine $\delta^{18}O$ values serve as good proxies for $\delta^{18}O(melt)$, which is shown on the top of the histogram. Notice that the Archean examples of slab melts have similar $\delta^{18}O$ range, which can suggest similarity of $\delta^{18}O$ values of the subducted slab and slab melting mechanisms, thus confirming that adakites serve as a modern analog for the Archean TTG suite. Setouchi samples overlap in $\delta^{18}O$ with the range for Archean sanukitoids.

rocks. Fig. 4 compares the oxygen isotope compositions of Archean TTG suites to younger adakites and high-Mg andesites examined in this study. The two groups of samples have broadly similar distributions in $\delta^{18}O$ values, re-enforcing the previous interpretation that adakites are recent analogues for TTG petrogenesis. This suggests that melting of garnet-bearing roots of continental margins and/or whole-sale melting of eclogitized delaminated slab were much more common in the Archean than today. Viewed in light of the apparent constancy of seawater-$\delta^{18}O$ from the Archean to the present [57,58], this similarity suggests to us that hydrothermal alteration of oceanic crust and its subsequent re-melting in Archean subduction zones resembled the wholesale slab melting we suggest is responsible for adakite genesis. Finally, 'sanukitoids' are Archean granitoids with composition similarities to recent arc lavas from Setouchi in Japan, and thus are suspected of being ancient convergent margin magmas with an unusually large fraction of sediment melt [13,59]. We note that sanukitiods have higher $\delta^{18}O$ values than other coeval TTG rocks, just as Setouchi lavas are higher in $\delta^{18}O$ than adakites, high-Mg andesites and other more common arc lavas.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2005.04.014.

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