

Na depletion in modern adakites via melt/rock reaction within the sub-arc mantle

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Abstract

Interaction between slab-derived melt and mantle peridotite and the role of slab melt as a metasomatizing agent in the sub-arc mantle is being increasingly recognized. Adakite, the slab melt erupted on the surface, usually exhibits anomalously high MgO, CaO, Cr and Ni contents that indicate interaction with mantle peridotite. Here we note that Cenozoic adakites have Na₂O contents below 5.8 wt.% with ~95% samples lower than 5.0 wt.%, and are generally depleted in this component relative to experimental basalt partial melts (mostly beyond 5.0 wt.% and up to 9.0 wt.% Na₂O) produced under 1.5–3.0 GPa conditions that are most relevant to adakite production. We interpret the adakite Na depletion to be also a consequence of the melt/rock reaction that takes place within the hot mantle wedge. During ascent and reaction with mantle peridotite, primary adakite melts gain mantle components MgO, CaO, Cr and Ni but lose Na₂O, SiO₂ and perhaps K₂O to the mantle, leading to Na-rich mantle metasomatism. Selective assimilation of predominately mantle clinopyroxene, some spinel and minor olivine at high T/P has been considered to be an important process in producing high-Mg adakites from primary low-Mg slab melts [Killian, R., Stern, C. R., 2002. Constraints on the interaction between slab melts and the mantle wedge from adakitic glass in peridotite xenoliths. *Eur. J. Mineral.* 14, 25–36]. In such a process, Na depletion in the assimilated melt is the result of dilution due to the increase in melt mass. Phase relationships in the reaction system siliceous melt+peridotite and quantitative calculation suggest that assimilation of mantle clinopyroxene, olivine and spinel and fractional crystallization of sodic amphibole and orthopyroxene, under conditions of moderate T/P and increasing melt mass, is also an important process that modifies the composition of adakites and causes the Na depletion.

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1. Introduction

Mantle metasomatism is of critical importance in the study of subduction magmatism. It is widely believed that arc volcanic rocks were predominately derived from the mantle peridotite metasomatized by a fluid or melt derived from the subducting slab. In the past 10 years, mantle metasomatism by slab-derived

melts has been highlighted in discussions of the origin of some Na-rich arc magmas (see Section 6 for the details) and considerable attention has been given to the nature of the slab-derived melt and to processes that occur in the mantle wedge (Yogodzinski et al., 1995; Kepezhinskas et al., 1995, 1996; Schiano et al., 1995; Kelemen, 1995; Kelemen et al., 1998, 2004; Drummond et al., 1996; Rapp et al., 1999; Sajona et al., 2000; Prouteau et al., 2001; Defant et al., 2002; Bourdon et al., 2002; Grove et al., 2002, 2003; Tsuchiya et al., 2005).

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During subduction the oceanic crust undergoes progressive metamorphism from greenschist to amphibolite and finally to the eclogite facies. It has been argued that, in general, the slab does not melt under normal thermal conditions of subduction zones, but dehydrates, releasing large ion lithophile element (LILE)-enriched hydrous fluids that metasomatise the overlying mantle wedge and instigate its melting (e.g. Gill, 1981; Kushiro, 1990; Tatsumi and Kogiso, 1997). Scenarios may be different, however, when the subducting slab is already hot or heated up, such as in the cases of young (Defant and Drummond, 1990; Drummond and Defant, 1990), fast and oblique (Yogodzinski et al., 1995; Yogodzinski et al., 2001) or flat subduction (Gutscher et al., 2000), or when slab melting is fluxed by water from subjacent hydrous lithologies (Prouteau et al., 1999, 2001). In these special cases, the slab geotherm may intersect the wet solidus of amphibolite/eclogite and the slab may melt to produce sodic felsic melts with high Sr but low Y and heavy REE concentrations. Defant and Drummond (1990) identified andesites and dacites in Cenozoic arcs with such slab-melt compositions and termed these rocks adakites after Adak Island in the Aleutians where they were first described by Kay (1978). Other examples are found in the Cascades, Baja California, Central America, south Andes, the Philippines, SW Japan, and the Kamchatka arcs (see Defant et al., 2002 and references therein). The ever-increasing number of locations where adakites are described suggests that conditions for slab melting are realized more often than previously believed (Defant et al., 2002).

During ascent to the surface, slab melt will react with the hot mantle peridotite through which it migrates and may even be consumed entirely via metasomatism (Beard et al., 1993; Rapp et al., 1999; Kelemen et al., 2004; Killian and Stern, 2002). Kay (1978) first noted anomalously high MgO, Ni and Cr concentrations in adakites from the Aleutian arc and attributed these features to interaction with the mantle wedge. Most adakites found since then in modern arcs appear to be the case, with more or less contamination by mantle components (Yogodzinski et al., 1995; Kelemen, 1995; Kelemen et al., 2004; Drummond et al., 1996; Stern and Killian, 1996; Sajona et al., 2000; Xu et al., 2000, 2002; Bourdon et al., 2002; Gao et al., 2004). By comparison to experimentally produced partial melts of basalt, Sen and Dunn (1994a) also noted enrichment of CaO in addition to MgO in most adakites. Killian and Stern (2002) demonstrated that experimentally produced trondhjemitic slab melts ($\text{CaO}/\text{Na}_2\text{O} < 1$) can become

tonalitic ($\text{CaO}/\text{Na}_2\text{O} > 1$) via selective assimilation of mainly clinopyroxene + spinel to explain the high MgO and CaO characteristics of adakitic glasses in the mantle xenoliths from Cerro del Fraile. The compositional anomalies in modern adakites indicate addition of mantle components to slab-derived melts. However, compositional contribution from slab melts to the mantle during the interaction is more essential in understanding the role of slab melt as a metasomatizing agent. Kelemen et al. (1992, 1998) noted silica enrichment in some peridotite xenoliths and attributed this to reaction of the mantle lithosphere with ascending melts. Here we have noted Na depletion in Cenozoic adakites relative to experimentally produced melts of hydrated basalt under P–T conditions most relevant to adakite generation. Average Cenozoic adakite is lower by 1–3% in Na_2O content than these “primitive” slab-melts. In this paper, we relate the Na depletion in Cenozoic adakites to melt/rock reaction within the mantle wedge, and discuss the possible reaction mechanism responsible for this Na depletion and the implication to the mantle sources of arc magmas.

2. Constraints of geochemistry and phase relation on the depth for adakite production

According to Defant and Drummond (1990, 1993) and Drummond et al. (1996), the distinctive geochemical characteristics of adakite include $\text{SiO}_2 > 56$ wt.%, $\text{Al}_2\text{O}_3 > 15$ wt.% (rarely lower), high Sr (>400 ppm and Sr positive anomaly), low Y (<18 ppm) and HREE (Yb <1.8 ppm) and thus high Sr/Y (>20–40) and La/Yb (>20) ratios, low HFSE (negative Nb–Ta and Ti anomalies), and small or negligible Eu anomaly. These geochemical characteristics provide the best constraint on the mineralogy of the source region and thus conditions for the adakite production. The Y and HREE depletion suggests that garnet is a necessary residual phase, whereas the lack of Eu anomaly and the high Sr, Na_2O and Al_2O_3 contents preclude significant plagioclase in the residue. In general, it was broadly accepted that adakites form by partial melting of hydrated MORB that leaves behind a garnet + clinopyroxene ± amphibole residue (e.g. Defant and Drummond, 1993; Peacock et al., 1994; Rapp and Watson, 1995).

Plagioclase stability during partial melting of basalt depends heavily on H_2O activity as well as pressure. For the low H_2O activity or fluid-absent melting (the melting instigated by the H_2O released from amphibole-breakdown), plagioclase remains stable at pressures up to at least 1.8 GPa (Rushmer, 1993; Rapp

and Watson, 1995). For the high H_2O activity or fluid-present (H_2O saturated or present but undersaturated) melting, the pressure stability of plagioclase is markedly lowered. For example, under the 5 wt.% H_2O condition, plagioclase is only stable below 1.0–1.2 GPa in the partial melting field of hydrated basalt (Xiong et al., 2005).

Garnet as a necessary residual phase was widely emphasized. Partial melting of hydrated basalts at low pressures (≤ 0.8 GPa; Beard and Lofgren, 1991; Rushmer, 1991) produce liquids in equilibrium with residues containing no garnet, whereas garnet is generally present as one of residual phases in melting experiments at pressures ≥ 1.0 GPa and temperatures of 850–1150 °C (Rapp et al., 1991; Sen and Dunn, 1994a; Rapp, 1995; Rapp and Watson, 1995; Winther, 1996; Liu et al., 1996; Prouteau et al., 2001). Wyllie and Wolf (1993) demonstrated that garnet-in reactions occur at pressures slightly less than 1.0 GPa, depending on the bulk basalt composition.

Recent experiments (Foley et al., 2000; Barth et al., 2002; Xiong et al., 2005) have confirmed that rutile dominates Nb and Ta budgets during the partial melting of subducted oceanic crust and only residual rutile can lead to marked negative Nb–Ta and Ti anomalies in derived liquids. Thus in addition to garnet, rutile is also an indispensable residual phase and the pressure or depth that favors the adakite production should simul-

taneously satisfy the conditions for stability of both rutile and garnet to explain the negative Nb–Ta and Ti anomalies as well as the Y and HREE depletion in adakites. The experiments of Xiong et al. (2005) have demonstrated that rutile appears at a pressure higher than the incoming of garnet (about 0.5 GPa above the garnet-in curve), and the rutile-in reaction boundary is generally at or a little higher than 1.5 GPa (Fig. 1) under both fluid-absent and present melting conditions. Thus the depth for the melting of subducted crust to yield adakite magmas must be deeper than about 50 km because only at a greater depth can both garnet and rutile be stable simultaneously whilst plagioclase is minor or absent.

The maximum depth for adakite production is also limited. Under fluid-absent condition, this depth is controlled by amphibole-out reaction or amphibolite-eclogite transformation, which intersects the wet solidus of basalt at 2.2–2.5 GPa (Fig. 1), depending on the bulk composition (e.g. Poli, 1993). Thus, the depth for the fluid-absent melting to produce adakite liquids ranges approximately from 50 to 85 km (1.5–2.5 GPa), under which the adakite liquid will be in equilibrium with a rutile-bearing garnet-amphibolite residue or a rutile-bearing amphibole-eclogite residue. Under fluid-present condition, the maximum depth for adakite production may exceed 85 km, with the adakitic liquid in equilibrium with a rutile-bearing eclogite residue. However,

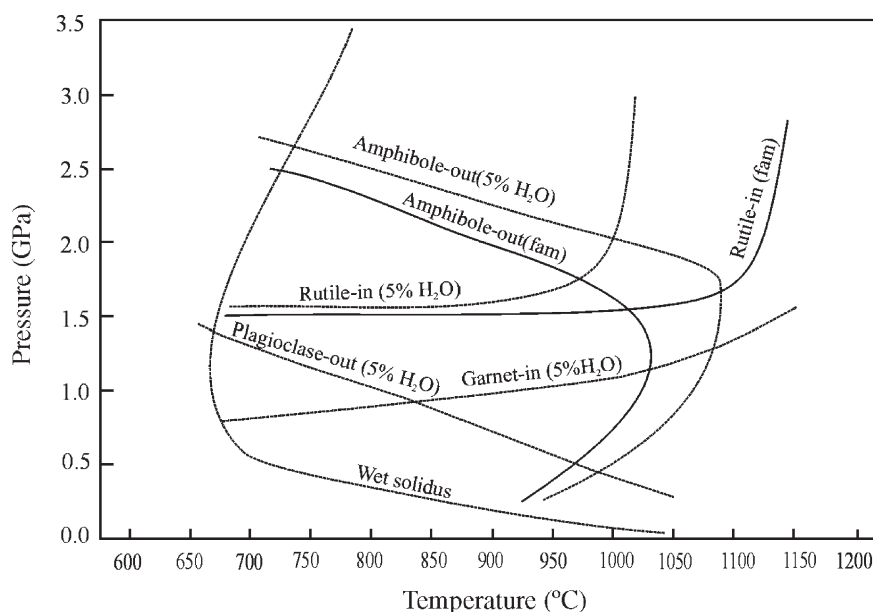


Fig. 1. Phase diagram showing the wet solidus of basalt and stability fields of plagioclase, garnet, amphibole and rutile in the partial melting field of hydrated basalt. Wet solidus, plagioclase-out (5% H_2O) and garnet-in (5% H_2O) from T. H. Green (1982); amphibole-out (fam) (fam=fluid-absent melting) from Rapp and Watson (1995) for their metabasalt #3; amphibole-out (5% H_2O), rutile-in (5% H_2O and fam) from Xiong et al. (2005).

the depth for the fluid-present melting in most cases should not exceed 100 km (~ 3.0 GPa) in consideration of the depth of subducted slab beneath arc volcanic fronts (100–120 km; Gill, 1981) and the location where most adakites occur in arc settings (in front of volcanic fronts; Drummond and Defant, 1990). Therefore, the depth range for adakite production is 50–85 km (1.5–2.5 GPa) under fluid-absent condition and 50 to 100 km (1.5–3.0 GPa) under fluid-present condition, and melting of basaltic protolith under these conditions will produce partial melts of adakite composition similar to those observed in modern arc settings. The 1.5–3.0 GPa pressure range demonstrated here covers those previously suggested for adakite production. For example, Peacock et al. (1994) suggested that the depth of possible adakite source regions in the subducted crust is 1.8–2.2 GPa,

and Drummond et al. (1996) estimated that the most likely pressure for adakite production is 2.3–2.6 GPa.

3. Na depletion in adakites

Fig. 2(A), (B) and (C) show the compositions of adakites, experimentally produced partial melts of hydrated or hydrous basalt (referred to as experimental slab melts hereafter) and adakitic glasses preserved in mantle xenoliths (referred to as natural slab melts hereafter), respectively, in ternary feldspar diagrams. The adakites (13 localities, 202 samples drawn from the literature) are those found in modern (Cenozoic) arc settings. The experimental slab melts (83 analyses of quenched glasses) were selected from available melting experiments on hydrated or hydrous basalt at pressures of 1.5–3.2 GPa, which approximately

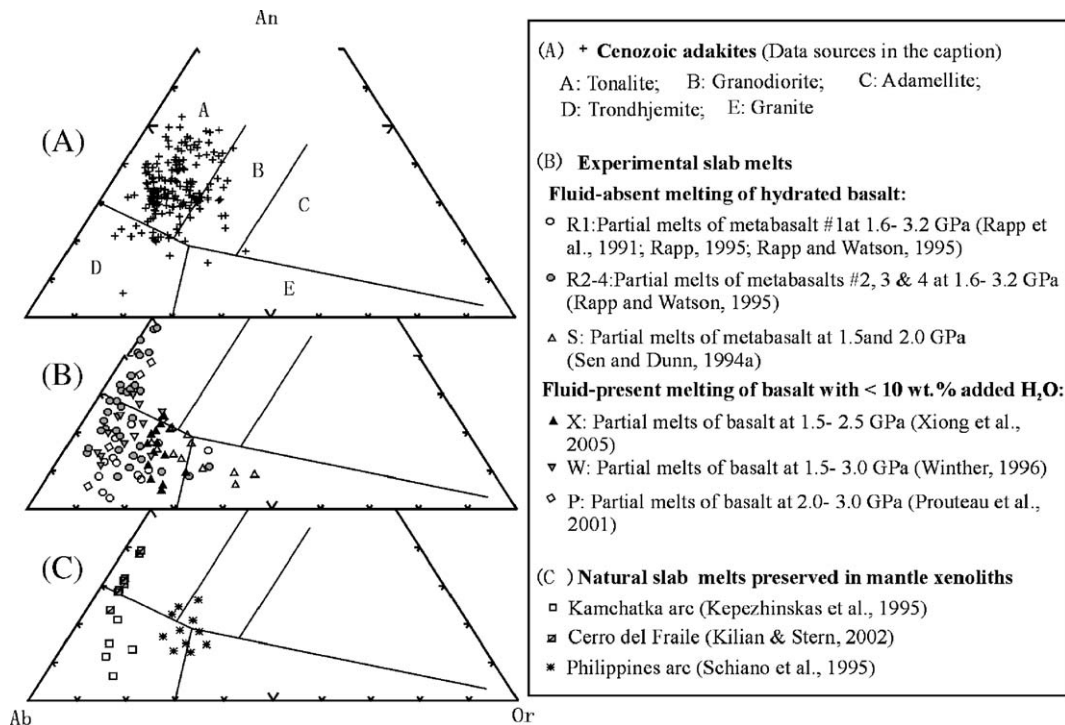


Fig. 2. CIPW normative Ab–An–Or granitic rock classification after Barker (1979). (A) Cenozoic adakite data, from the following localities: Aleutian Arc, Alaska (Kay, 1978; Yagodzinski et al., 1995); Cook Island, Chile (Puig et al., 1984); Baja of California, Mexico (Rogers et al., 1985; Aguillón-Robles et al., 2001); Sierra Madre, Mexico (Cameron and Cameron, 1985); Skagway, Alaska (Barker et al., 1986); El Valle and La Yeguada Volcanoes, Panama (Defant et al., 1991); Cerro Pampa, Argentina (Kay et al., 1993); Mindanao, Philippines (Sajona et al., 1994); Southwest Japan (Morris, 1995); Austral Andes (Stern and Killian, 1996); North Kamchatka Arc (Kepezhinskas et al., 1997); Quimsacocha, Ecuador (Beate et al., 2001); Mt. Shasta, California (Grove et al., 2002). (B) Experimental basalt partial melt data at pressures ≥ 1.5 GPa (for data sources, see the legends; for average compositions in Table 1 and for their protolith data in Table 2; fluid-absent melting: the melting instigated by the H₂O released from the breakdown of hydrous minerals (such as amphibole); fluid-present melting: H₂O saturated or H₂O present but undersaturated melting). These experimentally produced partial melts of basalt are referred to as experimental slab melts in this paper. (C) Data for adakite-glass veins in mantle xenoliths (Kepezhinskas et al., 1995; Killian and Stern, 2002) and adakite-glass inclusions in mantle minerals (Schiano et al., 1995). These adakitic glasses preserved in the mantle xenoliths are referred to here as natural slab melts. Data in (A), (B) and (C) show that Cenozoic adakites predominantly fall within the tonalite field, whereas most experimental and natural slab melts plot in the trondhjemite field.

corresponds to the pressure range (~1.5–3.0 GPa) for adakite production. Experimental melts produced at temperatures ≥ 1100 °C and thus containing <56% SiO₂ and those produced at pressures <1.5 GPa were excluded because the former are unlike adakite composition and the latter are not in equilibrium with garnet+rutile, which are two necessary residual phases during the generation of adakitic liquid. The natural slab melts are those from Kamchatka arc (Kepezhinskas et al., 1995), Cerro del Fraile in southernmost South America (Killian and Stern, 2002) and Philippines arc (Schiano et al., 1995). They were preserved in mantle xenoliths as glass veins or glass inclusions in mineral and have been interpreted to be quenched slab melts that have infiltrated the mantle wedge from below. The adakitic glasses (average compositions in Table 1) from Kamchatka arc have low MgO content (<1.0 wt.%) and Mg# (<35) and thus may represent least contaminated slab melts; whereas those from Cerro del Fraile have high MgO content (3.30 wt.%) and Mg# (84), indicating assimilation of mantle components; and those from Philippines arc contain crystalline phases (phlogopite, pargasite and hornblende) (Schiano et al., 1995), which have crystallized from the melt and have led to the low MgO content (<1.0 wt.%) and Mg# (<35).

It is clear from Fig. 2 that most adakite samples (over 80%) fall within the tonalite field with 8% in the trondhjemite field and ~9% in the granodiorite

field, whereas over 70% experimental slab melts fall in the trondhjemite field with only ~20% in the tonalite field and ~10% in the granite field. The least contaminated slab melts from Kamchatka arc also fall within the trondhjemite field and their range completely overlaps that of experimental slab melts. Thus, adakites are generally distinct from the experimental and least contaminated slab melts in terms of ternary feldspar composition, generally lower in Ab and to a lesser extent Or but higher in An than the latter.

Fig. 3 exhibits Na₂O vs. SiO₂ for adakites compared to the experimental slab melts. It is clear from this figure that adakites are generally lower in Na₂O content than the experimental and natural slab melts. Although there is overlap between adakites and the experimental slab melts, the overlapped adakite data are restricted to the lower portion of the experimental slab melt fields and at least 30% adakite samples are below these fields. We can also see from Fig. 3 that all adakite samples are lower in Na₂O content than 5.8 wt.% with ~95% samples lower than 5.0 wt.% (the only exception is that one sample from Mindanao, Philippines (Sajona et al., 1993) has Na₂O content of 7.36 wt.%), whereas over 70% experimental samples have Na₂O content exceeding 5.0 wt.% and up to 9 wt.%. Table 1 shows average compositional comparison between Cenozoic adakites, experimental slab melts and natural slab melts. The average Na₂O content (4.13%) of adakites is lower by

Table 1
Average compositional data on experimental and natural slab melts and adakites

	Fluid-absent melting			Fluid-present melting			Natural slab melt			Cenozoic adakite (n=202)
	R ₁ (n=13)	R ₂₋₄ (n=27)	S (n=13)	W (n=13)	P (n=5)	X (n=12)	Kamchatka (n=5)	Cerro del Fraile	Philippines (n=12)	
SiO ₂	63.85	66.38	65.75	72.05	66.48	61.45	64.76	60.30	64.08	62.23
TiO ₂	1.22	1.05	0.86	0.55	0.62	1.26	0.60	0.21	0.20	0.64
Al ₂ O ₃	18.03	16.69	17.59	15.31	18.34	18.49	18.52	20.30	19.17	17.22
FeO	4.13	4.21	3.24	2.43	2.28	4.15	2.41	1.10	2.83	4.76
MnO	0.08	0.09	–	0.07	–	0.12	0.05	0.05	–	0.08
MgO	1.11	1.06	0.90	0.61	0.48	1.85	0.70	3.30	0.76	2.61
CaO	2.37	4.15	2.68	2.82	5.0	3.40	2.13	6.60	4.38	5.68
Na ₂ O	6.96	5.32	5.42	5.08	5.56	5.79	6.88	6.20	4.86	4.13
K ₂ O	2.11	0.92	3.60	1.08	0.94	2.85	1.54	0.65	3.18	1.64
P ₂ O ₅	–	–	–	–	–	0.61	–	–	0.43	0.20
Mg#	32	32	36	31	27	39	34	84	34	50
Na ₂ O/CaO	2.94	1.28	2.02	1.80	1.11	1.70	3.23	0.94	1.11	0.73

Mg# = 100 * mol MgO / (mol MgO + FeO); R₁: average partial melt of metabasalt #1 at 1.6–3.2 GPa (Rapp et al., 1991; Rapp, 1995; Rapp and Watson, 1995); R₂₋₄: average partial melt of metabasalts #2, 3 and 4 at 1.6–3.2 GPa (Rapp and Watson, 1995); S: average partial melt of basaltic amphibolite at 1.5 and 2.0 GPa (Sen and Dunn, 1994a,b); W: average partial melt of basalt with about 0.8 to 5.0 wt.% added H₂O at 1.5–3.0 GPa (Winther, 1996); P: average partial melt of basalt with 6.0 wt.% or 10 wt.% added H₂O at 2.0 and 3.0 GPa (Prouteau et al., 2001); X: average partial melt of basalt with 2.0 or 5.0 wt.% added H₂O at 1.5–2.5 GPa (Xiong et al., 2005). For the protolith compositions of these experimental partial melts, see Table 2; for data sources for Cenozoic adakites and natural slab melts: see the caption and legends in Fig. 2. Data from Philippines arc (Schiano et al., 1995) have been normalized to 100%.

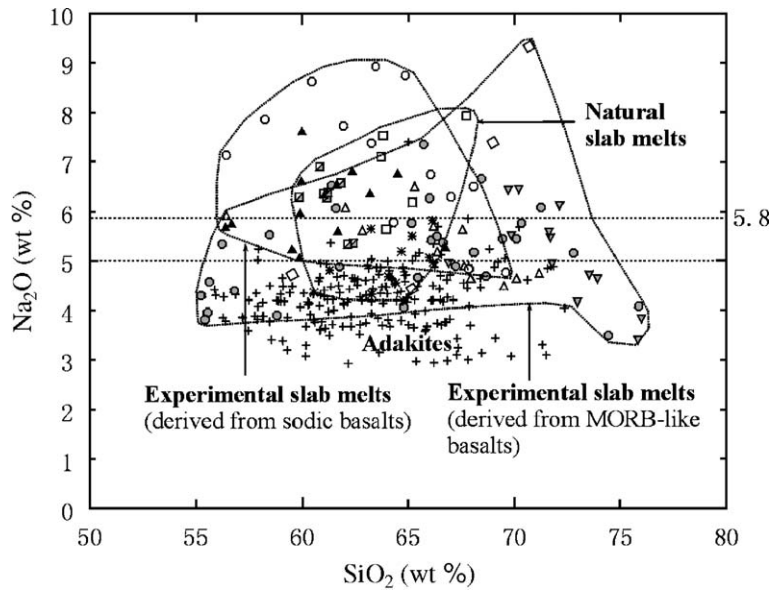


Fig. 3. Na_2O vs. SiO_2 for adakites compared with experimental and natural slab melts, showing that adakites are generally lower in Na_2O content than experimental and natural slab melts. All the adakite samples are lower in Na_2O content than 5.8 wt.%, whereas over 70% of the experimental slab melts have Na_2O content exceeding 5.0 wt.% and up to 9 wt.%. Symbols are shown as in Fig. 2. Compositions of the protoliths for the experimental slab melts are given in Table 2.

about 1–3% than those of experimental slab-melts (5.08–6.96%).

4. Possible causes for the Na depletion

4.1. Effect of protolith composition and P – T conditions on the Na_2O content of slab melt

Experimental workers have used many natural and synthetic materials compositionally representative of variably altered and metamorphosed MORB to study the high-pressure melting behavior of basalt under

fluid-absent or fluid-present conditions. Table 2 gives the protolith compositions for the experimental slab melts in Table 1 and Figs. 2 and 3. Most of these starting materials (Table 2) are compositionally close to the average N-MORB (Hofmann, 1988), exceptions are the alkali-rich basalt from Rapp and Watson (R_1 -B) and the potassic basalt (X-B), which have relatively high Na_2O contents and are considered to be representative of splitised oceanic crust (Rapp and Watson, 1995). From Tables 1 and 2 and Fig. 3, we can see that high Na_2O protoliths generally produce more sodic melts. However, all the experimental slab melts

Table 2

Protolith compositions of the experimental slab melts in Table 1 compared with the average N-MORB (Hofmann, 1988)

	Sodic basalts		MORB-like basalts						Average N-MORB
	R_1 -B	X-B	R_2 -B	R_3 -B	R_4 -B	S-B	W-B	P-B	
SiO_2	51.19	46.89	48.60	48.30	47.60	46.88	49.10	49.90	50.45
TiO_2	1.18	1.66	2.06	0.72	1.19	1.22	1.30	2.30	1.62
Al_2O_3	16.62	15.96	17.03	15.30	14.18	15.00	14.80	13.70	15.26
FeO	11.32	10.29	10.69	10.70	13.77	8.70	14.20	12.70	10.43
MnO	0.23	0.35	0.21	0.19	0.19	0.26	0.20	–	–
MgO	6.59	7.21	6.07	8.40	6.86	8.25	6.50	6.80	7.58
CaO	5.49	6.73	9.66	12.60	10.99	11.28	11.40	10.60	11.30
Na_2O	4.33	4.08	3.30	2.27	2.56	2.51	2.30	2.50	2.68
K_2O	0.82	1.38	0.21	0.08	0.19	0.80	0.30	0.30	0.11

R_1 -B, R_2 -B, R_3 -B and R_4 -B correspond to metabasalts #1 (alkali-rich basaltic amphibolite), #2 (high-Al basaltic amphibolite), #3 (low-K olivine tholeiitic amphibolite) and #4 (low-K Archean greenstone-amphibolite), respectively, in the Table 1 of Rapp and Watson (1995); X-B: potassic basalt from Tianshan, China (Xiong et al., 2005); S-B: basaltic amphibolite (Sen and Dunn, 1994a,b); W-B: synthetic tholeiite (Winther, 1996); P-B: mid-ocean ridge basalt from the Juan de Fuca ridge (Prouteau et al., 2001).

produced at pressures of 1.5–3.0 GPa have generally higher Na_2O contents compared to adakites, even though the experimental data on the high Na_2O basalts (open circles and filled up triangles in Fig. 3) are removed. Therefore, adakite is not derived from a particular low-Na source composition.

The effect of pressure is illustrated in Fig. 4. At a roughly constant temperature, the Na_2O content of the partial melt of basalt experimentally produced under the fluid-absent condition increases with increasing pressure until 2.0–2.5 GPa and then decreases as the pressure increases further. A similar result is also observed for the melts (from Xiong et al., 2005) experimentally produced via fluid-present melting. This trend is consistent with the effect of pressure on the stability and modal proportions of residual sodium-bearing crystalline phases (plagioclase, amphibole and clinopyroxene) during the partial melting of hydrated basalt. At pressures lower than 2.0–2.5 GPa, sodium-bearing residual phases are primarily plagioclase and amphibole whose stability and modal proportions decrease with increasing pressure, leading to an increase of Na_2O content in the derived liquid. At pressures higher than 2.5 GPa, the only sodium-bearing residual phase is clinopyroxene. Na_2O (or jadeite component) content in residual clinopyroxene increase with increasing pressure, but a substantial increase takes place only at pressures higher than about 2.5 GPa (Rapp and Watson, 1995), which explains the decrease of Na_2O content in derived liquids

at pressures higher than 2.5 GPa. We have demonstrated in Section 2 that the pressure range that dominates adakite production is 1.5–3.0 GPa. Fig. 4 shows that experimental melts produced in this pressure range have Na_2O contents generally higher than the highest Na_2O (5.8 wt.%) of adakites and higher than 95% of the adakites (below 5.0 wt.% Na_2O , see Fig. 3). Fig. 4 also shows that tonalitic melts with adakite Na_2O content level can be produced at pressures lower than 1.5 GPa, but these melts would not be in equilibrium with garnet+rutile and thus are not adakite liquids. It can be expected that at pressures greater than 3.0 GPa tonalitic melts with adakite Na_2O content level would also be produced due to the increasing solubility of jadeite component in residual clinopyroxene, but melting of subducted oceanic crust at pressures greater than 3.0 GPa would not dominate adakite production (see Section 2 for explanation).

The effect of temperature is also notable. Fluid-absent experiments on basaltic amphibolites (e.g. Sen and Dunn, 1994a; Rapp and Watson, 1995) have shown that under 1.5–2.5 GPa most partial melts generated at relatively low temperatures (≤ 950 – 1000 °C) are granitic, produced by very low degree ($<2\%$) of melting of amphibole+quartz or amphibole+plagioclase+quartz. Na_2O contents in such melts can overlap those of natural adakites, but then they are either too SiO_2 -rich ($\text{SiO}_2 > 72$ wt.%, see Fig. 3) or too potassic (see Table 4 in Sen and Dunn, 1994a). At relatively high

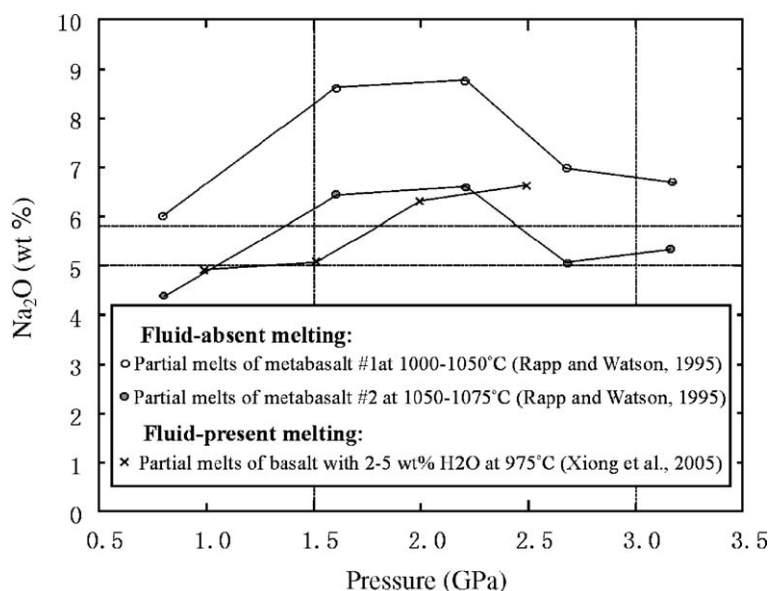


Fig. 4. Na_2O vs. pressure for experimental slab melts showing that Na_2O contents of experimental slab melts produced at pressures 1.5 to 3.0 GPa (corresponding to the pressure range of adakite production) are generally higher than the highest Na_2O value (5.8 wt.%) of adakites and are higher than 95% of the adakites (below 5.0 wt.% Na_2O , see Fig. 3).

temperatures (>1100 °C), high degree of melting takes place and would result in tonalitic liquids with low SiO_2 (such as those with $\text{SiO}_2 < 58$ wt.% in Fig. 3). However, high temperature melting cannot be the general case for adakite production because most adakites possess SiO_2 content exceeding 58 wt.% and because melting would become difficult at a relatively high temperature due to lack of H_2O (amphibole breakdown at temperatures below 1100 °C). Sen and Dunn (1994a) and Rapp and Watson (1995) demonstrated that slab melting caused by the amphibole dehydration under 1.5–2.0 GPa takes place between about 900–1075 °C, at which amphibole-breakdown leads to low- to moderate-degree melting of metabasalt to yield trondhjemite-dominated liquids, leaving amphibole-eclogite or eclogite residues. Under fluid-present condition, the effect of temperature on the melt Na_2O content is similar to that under fluid-absent condition, although the temperature appropriate to adakite production is lower at a given pressure (Proustau et al., 2001).

Fig. 5 shows Na_2O vs. SiO_2 for adakites compared with experimental melts produced by fluid-absent melting at 1.5–2.5 GPa (A) and those produced by fluid-present melting at 1.5–3.0 GPa (B). In this figure, data that are shown in Fig. 3 on fluid-absent melting at pressures >2.5 GPa and those with $\text{SiO}_2 < 58$ wt.% or >72 wt.% and/or $\text{K}_2\text{O} > \text{Na}_2\text{O}$ have been removed. Thus the experimental liquids remaining in Fig. 5(A) and (B) are representative of those produced at pressures and temperatures most relevant to the generation of typical adakites. Clearly, the experimental slab melts,

irrespective of whether they are produced by fluid-absent or fluid-present melting, have generally higher Na_2O contents than adakites. Therefore, adakites are generally Na-depleted relative to their experimental counterparts and such depletion must relate to the processes subsequent to magma generation on the way to the surface.

4.2. Fractional crystallization and contamination of felsic continental crust?

During ascent adakite magmas may undergo fractionation of mafic phases and/or Ca-rich plagioclase, but this will produce residual liquids with lower MgO and CaO but higher Na_2O contents, and so crystal fractionation cannot account for the Na depletion in adakites. Contamination by felsic continental crust might modify Na, K and Si values of primitive adakite liquids and such a contamination could lower the Na_2O content of adakite magmas, but it would also increase the K_2O and SiO_2 contents. However, most adakites are even depleted in SiO_2 and K_2O relative to the experimental slab melts (Drummond et al., 1996; Smithies and Champion, 2000; also see Fig. 6). Moreover, adakites have $^{87}\text{Sr}/^{86}\text{Sr}$ usually <0.7040 (Defant and Drummond, 1990) and Nd isotopic composition close to that of MORB (Li and Li, 2003), indicating limited contamination of continental materials. Thus crystal fractionation and/or contamination of felsic continental crust have little, if any, effect on the Na_2O content or Na depletion in adakites.

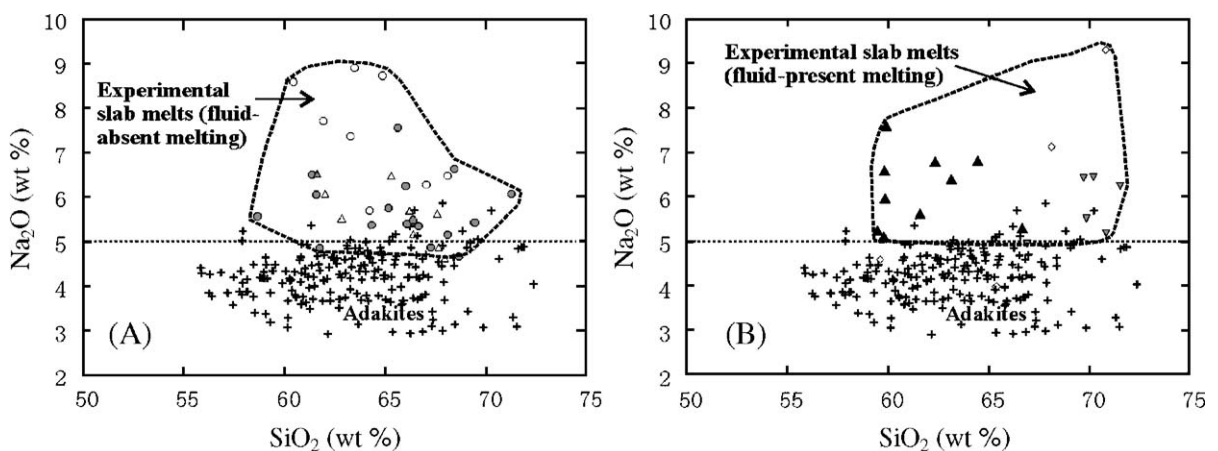


Fig. 5. Na_2O vs. SiO_2 for adakites compared with experimental melts produced by fluid-absent melting at 1.5–2.5 GPa (A) and those produced by fluid-present melting at 1.5–3.0 GPa (B). In this figure, data shown in Fig. 3 on fluid-absent melting at pressures >2.5 GPa and those with $\text{SiO}_2 < 58$ wt.% or >72 wt.% and/or $\text{K}_2\text{O} > \text{Na}_2\text{O}$ have been removed (see text for the detail). Thus the experimental liquids remaining in this figure represent those produced at pressures and temperatures relevant to the production of typical adakites. Clearly, these experimental melts, irrespective of whether they are produced by fluid-absent or fluid-present melting, have generally higher Na_2O contents than adakites.

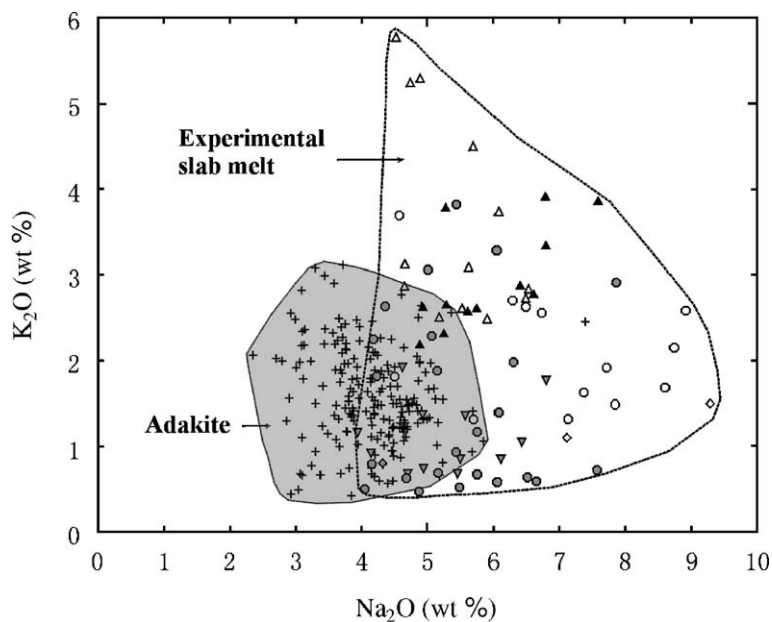


Fig. 6. K_2O vs. Na_2O for adakites and experimental slab melts, showing that the K_2O contents in adakites are generally lower than in experimental slab melts. Symbols as in Fig. 2.

4.3. Comparison with lower crust-derived adakitic rocks

The conditions under which adakitic magmas are generated are not unique to subduction zones (Atherton and Petford, 1993; Petford and Gallagher, 2001; Rapp et al., 2002). Atherton and Petford (1993) and Petford and Atherton (1996) suggested that the Cordillera Blanca felsic rocks, which are geochemically similar to adakite, were produced by melting of basaltic lower crust. Adakite-like rocks from the South Island, New Zealand (Muir et al., 1995), the Klamath Mountains of California and Oregon (Barnes et al., 1996), the Antarctic Peninsula (Wareham et al., 1997), and western and eastern China (Zhang et al., 2001; Lai and Liu, 2001; Xiong and Zhao, 2001, 2003; Wang et al., 2003) have also been interpreted as the products of partial melting of basaltic lower crust, formed in response to crustal thickening achieved through underplating of mantle-derived mafic magmas.

Adakite-like rocks derived from the lower continental crust do not pass through mantle and thus lack any direct mantle contribution or evidence for interaction with peridotite, being always low in MgO, Cr and Ni contents (Atherton and Petford, 1993; Smithies, 2000). Data collected in Fig. 7 show that many of them also have Na_2O contents in excess of 6 wt.%. These rocks exhibit generally higher Na_2O content compared to

Cenozoic adakites, though there is a large overlap with the adakites. This indicates presence of low-Na lower crustal melts, which are possibly derived from relatively shallow depth where plagioclase is still stable. Peacock et al. (1994) pointed out that at pressures corresponding to the base of the arc crust (1.0–1.2 GPa), fluid-absent melting of amphibolite will leave a residue of two-pyroxenes + plagioclase + garnet ± amphibole. In this case, garnet as a residual phase is still required to account for the heavy REE depletion in derived liquids, whereas rutile is not a necessary residual phase because mafic protoliths at arc settings may themselves be depleted in Nb, Ta and Ti and so partial melts derived from them would inherit the negative Nb–Ta and Ti anomalies. As shown in Fig. 4, partial melts with $Na_2O < 5.0$ wt.% can be produced at pressures lower than about 1.5 GPa, which explains why adakite-like rocks partially overlap the Cenozoic adakites. However, the presence of high-Na (>6 wt.% Na_2O) members of adakite-like rocks suggests that some of them may have been derived from deeper level and the processes within continental crust did not lead to Na depletion in these adakitic magma.

4.4. Slab melt-mantle peridotite interaction

Many adakites are Mg- and Ca-enriched and SiO_2 -depleted, which has been explained as a consequence of the interaction between primitive adakite magma

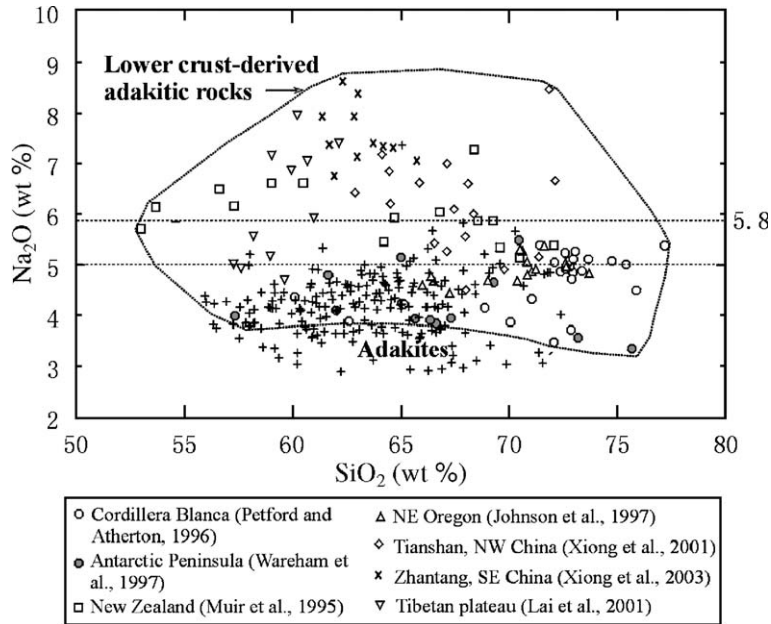


Fig. 7. Na_2O vs. SiO_2 for lower crust-derived adakitic rocks compared with Cenozoic adakites.

and peridotite within the hot mantle wedge (Kay, 1978; Yogodzinski et al., 1995; Kelemen, 1995; Drummond et al., 1996; Stern and Killian, 1996; Sajona et al., 2000; Xu et al., 2000; Bourdon et al., 2002). The Na depletion in adakites is also most

likely caused by this interaction. Data compiled here show that the Na depletion in adakites appears to be correlated to the Mg and Ca enrichment (Figs. 8 and 9). Adakites have only limited overlap with experimental slab melts in terms of Na_2O vs. MgO or CaO

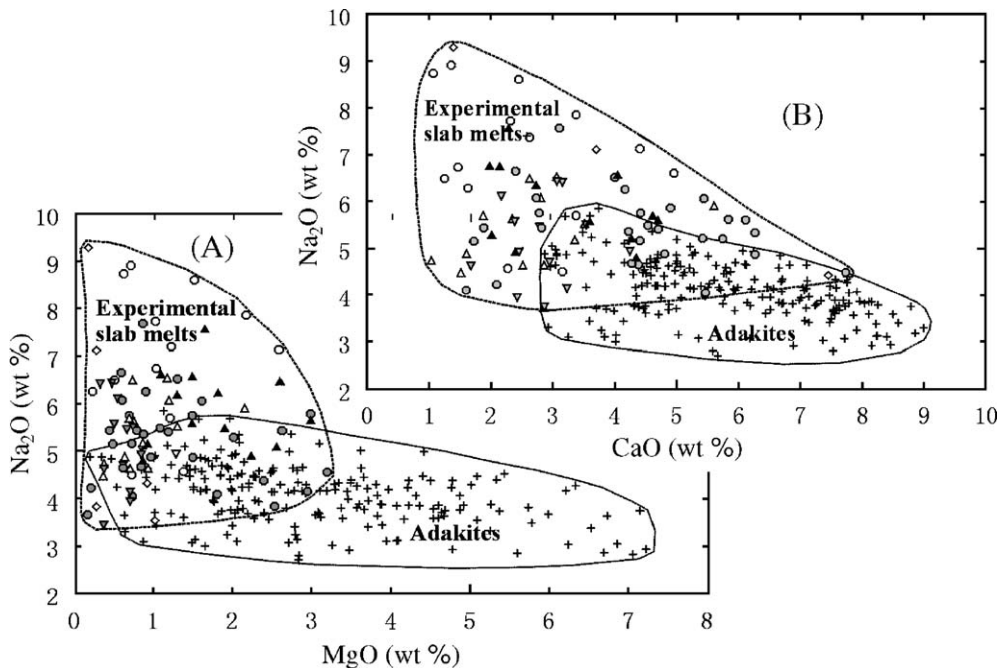


Fig. 8. Na_2O vs. MgO (A) and CaO (B) for adakites and experimental slab melts, showing that adakites are generally higher in MgO and CaO but lower in Na_2O than experimental slab melts and there is generally negative correlations between MgO (and CaO) and Na_2O contents of adakites. Symbols as in Fig. 2.

(Fig. 8 A and B), and the average adakite is remarkably lower in Na_2O content but higher in MgO and CaO contents than the average experimental slab melt (Table 1). The Na depletion and the Ca enrichment have led to considerable decrease in the $\text{Na}_2\text{O}/\text{CaO}$ ratio of adakites relative to the experimental slab melts. As shown in Fig. 9, the $\text{Na}_2\text{O}/\text{CaO}$ values of adakites are only 0.25 to 1.6, whereas those of experimental slab melts range from 0.5 to 8.1 with over 80% of them beyond the adakite field. In particular, there is a general positive correlation between $\text{Na}_2\text{O}/\text{CaO}$ ratio and SiO_2 content in adakites. Therefore, if the Ca enrichment with decreasing SiO_2 content in adakites is caused by the reaction with mantle peridotite, then the correlation suggests that the Na depletion may also be a consequence of this reaction.

5. Melt/rock reaction and the “fate” of slab melt in the mantle wedge

Slab-derived siliceous melts strongly contrast to ultramafic mantle peridotite in composition and they will be in chemical disequilibrium with hot peridotite during their passage through or residence in the mantle wedge (Beard et al., 1993). Extensive interaction between these melts and peridotite is expected and few will reach the surface unchanged; some even may be con-

sumed entirely via reaction, depending on the thermal regime, melt mass and melt/rock (reactant) ratio in the mantle wedge. The fate of a slab melt during going through the mantle wedge can be illustrated using Fig. 10 and Table 3. Fig. 10 shows the idealized cross-section of a subduction zone with a given thermal structure (A) and the schematic P–T phase relationships in the reaction system of hydrous siliceous melt plus 10% peridotite (B), in which several assumed reaction locations are marked. Table 3 gives the possible reactions and products in locations corresponding to those in Fig. 10.

5.1. Solidification and “thermal death”

Assume that a siliceous slab melt is produced at amphibolite–eclogite transition (~ 2.5 GPa) (Fig. 10) and then percolates into the overlying mantle wedge. At the initial stage (location “1”), the pressure in the reaction conduit is relatively high but the temperature is relatively low and the melt will react with olivine (ol) to produce orthopyroxene (opx)+clinopyroxene (cpx)+phlogopite (phl)+garnet (gt) \pm modified melt (Table 3). Under such a low temperature condition, reactions will consume more liquid than they produce. If the mass of the melt is small and the pressure and temperature are constant, reactions will ultimately lead to complete solidification, or “thermal death” (Wyllie and Sekine,

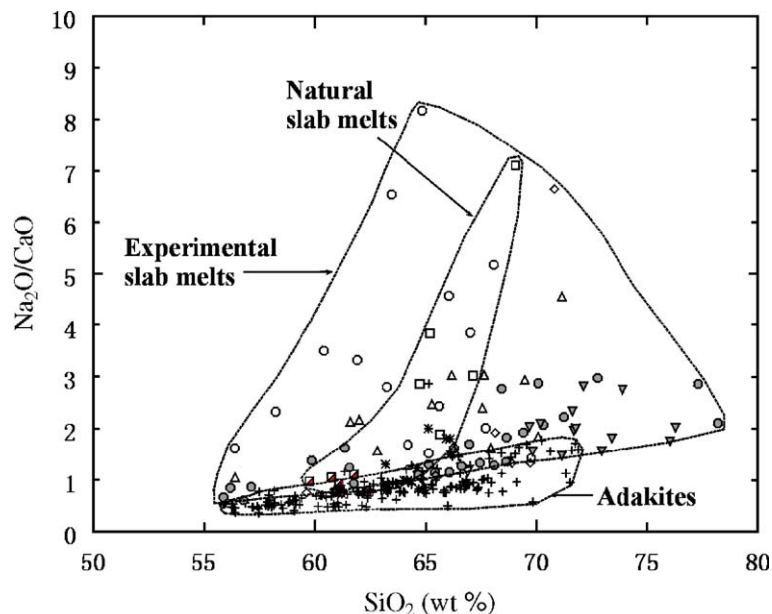


Fig. 9. $\text{Na}_2\text{O}/\text{CaO}$ vs. SiO_2 for adakites compared with experimental slab melts and natural slab melts. This plot shows that at a given SiO_2 content, the $\text{Na}_2\text{O}/\text{CaO}$ ratios of adakites are apparently lower than those of most experimental slab melts and the least contaminated slab melts preserved in the mantle xenoliths from Kamchatka arc (Kepezhinskis et al., 1995). Symbols as in Fig. 2.

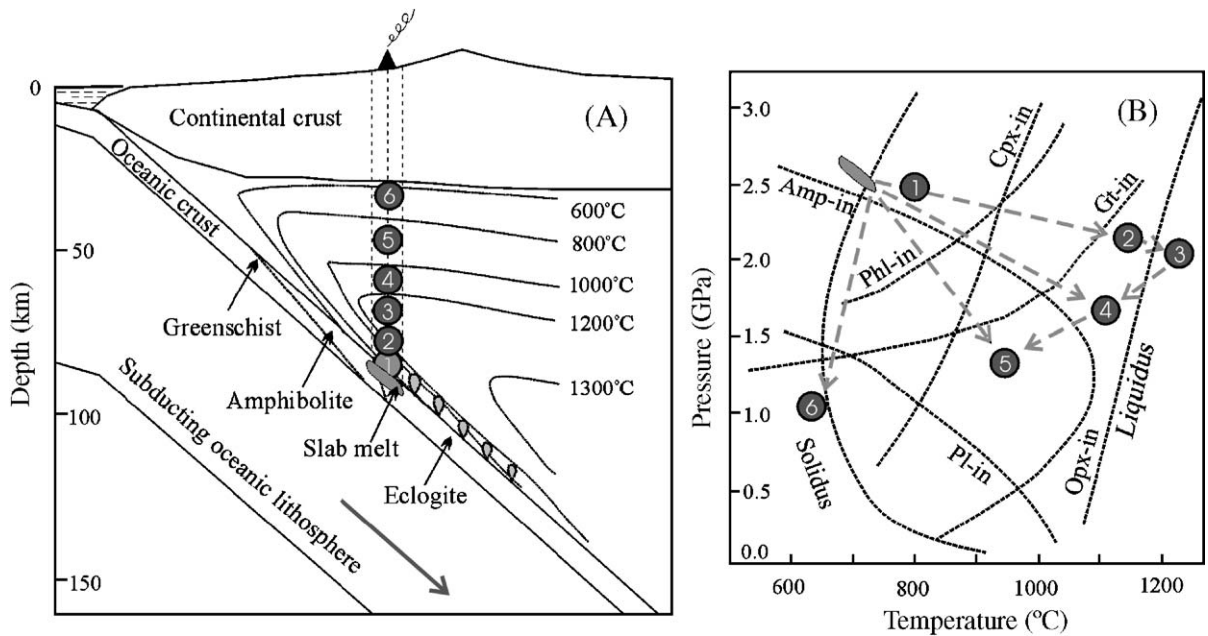


Fig. 10. Idealized cross-section through the subduction zone with a given thermal regime (A) and schematic phase relationships in the reaction system hydrous slab melt plus peridotite (B). (A) is similar to Fig. 1 of Wyllie and Sekine (1982) with an exception that a specific thermal regime is given in this figure. (B) is constructed based on experimental data in the reaction system of hydrous siliceous melt+10 wt.% peridotite at 3.0 GPa (Sekine and Wyllie, 1982) and at 1.5 GPa (Carroll and Wyllie, 1989; Sen and Dunn, 1994a,b). (A) shows the location of slab melting and several locations (“1”, “2”, “3”, “4”, “5” and “6”) where the slab melt may react with peridotite within the mantle wedge, while (B) displays the corresponding phase equilibrium relationships as the melt reacts with the peridotite at these locations. For detailed description of reaction processes, see Section 5 in the text and Table 3.

1982; Kelemen et al., 2004). The products of the hybridization and solidification would be phl (\pm gt)-pyroxenite (Wyllie and Sekine, 1982; Sekine and Wyllie, 1982), with metasomatic cpx being low in Mg and Ca and sodic relative to their primitive counterparts (Sekine and Wyllie, 1982; Carroll and Wyllie, 1989) and phl being anomalously Na-enriched (Zanetti et al., 1999; Prouteau et al., 2001) due to the comparatively high pressure and the high Na nature of the melt. It is possible that some slab melts do undergo thermal death at this initial stage, and then the hybridized peridotite carrying phl-pyroxenite masses circulate to other parts of the mantle wedge, later melting to give rise to enriched magmas (e.g., Ringwood, 1974; Wyllie and Sekine, 1982; Yogodzinski et al., 1994; Bourdon et al., 2002). In this paper, we note that all Cenozoic adakites have silica content lower than ~ 72 wt.% while at least 10% of experimental slab melts exceed this silica value (Figs. 3 and 9). Experimental studies (Sen and Dunn, 1994b; Prouteau et al., 2001) have demonstrated that low degree ($<2\%$) of partial melting of hydrated basalt will yield volumetrically minor high silica liquids. Such liquids would easily be modified in composition or even consumed completely via reaction with peridotite as

they percolate through the mantle wedge, which accounts for the lack of high silica end-member adakites in nature.

In addition to the low temperature zone just above the top of the slab, another likely thermal death site in the mantle wedge is the region just below the crust such as the location “6” where temperature would likely be below the solidus of slab melt. A slab melt may reach this subsolidus region via crack transport and will react with peridotite to form metasomatic opx, cpx, amphibole (amp) and sodic plagioclase (pl) or even be directly quenched as glass veins preserved in mantle peridotite, as the cases found in mantle xenoliths (Kepezhinskas et al., 1995; Killian and Stern, 2002).

5.2. Compositional modification and Na depletion

Kelemen and co-workers (Kelemen, 1986, 1990, 1995; Kelemen et al., 1992, 1998, 2004) emphasized that a key to considering reaction between slab-melt and peridotite is that melts must heat up as they rise and decompress in the mantle wedge. The combined effect of increasing temperature and decreasing pressure will move the melt away from its liquidus. This is often

Table 3

Possible reactions and products in the reaction system of hydrous slab melt + peridotite at locations corresponding to “1”, “2”, “3”, “4”, “5” and “6” in Fig. 10(A) and (B)

Location	Possible reactions	Solid products	“Fate” of the melt
“1” Low-T, high-P	ol + SiO ₂ (melt) = opx ol + Na ₂ O, CaO, Al ₂ O ₃ and SiO ₂ (melt) → cpx + MgO (melt) ol + CaO and Al ₂ O ₃ (melt) → gt + MgO (melt) ol + K ₂ O, Na ₂ O, Al ₂ O ₃ and H ₂ O (melt) → phl + MgO (melt)	opx + cpx + gt + phl (cpx and phl are unusually sodic due to the high pressure and the high Na nature of the slab melt)	Melt mass decreases, finally leading to complete solidification, or “thermal death”.
“2” High-T, high-P	ol + SiO ₂ (melt) = opx ol + cpx + sp dissolution	opx	Melt mass increases; Mg, Ca, Fe increase; Si, Al, Na, K decrease due to dilution.
“3” Superliquidus	ol + opx + cpx + sp dissolution		Melt mass increases; Mg, Ca, Fe increase; Si, Al, Na, K decrease due to dilution.
“4” High-T, moderate-P	ol + SiO ₂ (melt) = opx ol + cpx + sp dissolution	opx	Melt mass increases; Mg, Ca, Fe increase; Si, Na, K decrease due to dilution.
“5” Moderate-T, moderate-P	ol + SiO ₂ (melt) = opx ol dissolution cpx + sp + Na ₂ O, K ₂ O, Al ₂ O ₃ and H ₂ O (melt) → amp + CaO (melt) (ol + cpx + sp + melt ₁ = opx + amp + melt ₂)	opx + amp (amp are unusually sodic due to the high Na nature of the slab melt)	Melt mass increases; Si, Na, K and Al decrease, but Mg, Ca increase due to ol + cpx + sp dissolution and opx + amp precipitation.
“6” Subsolidus	ol + SiO ₂ (melt) = opx ol + Na ₂ O, CaO, Al ₂ O ₃ and SiO ₂ (melt) → cpx ol + K ₂ O, Na ₂ O, CaO, Al ₂ O ₃ , SiO ₂ and H ₂ O (melt) → amp Na ₂ O, CaO, Al ₂ O ₃ and SiO ₂ (melt) → pl	opx + cpx + amp + pl (cpx and amp are unusually sodic due to the high Na nature of the slab melt)	Complete solidification or veining.

ol: olivine, (Mg, Fe)₂SiO₄; opx: orthopyroxene, (Mg, Fe)₂Si₂O₆; cpx: clinopyroxene, (Ca, Mg, Fe²⁺, Fe³⁺, Al)₂(Si, Al)₂O₆; sp: spinel, MgAl₂O₄; amp: amphibole, (Na, K)(Ca, Na)₂(Mg, Mn, Fe²⁺, Fe³⁺, Al, Cr, Ti)₅(Si, Al)₈O₂₂(OH)₂; phl: phlogopite, KMg₃(Si₃AlO₁₀)(OH, F)₂; gt: garnet, (Mg, Ca, Fe)₃Al₂(SiO₄)₃; pl: plagioclase, NaAlSi₃O₈CaAl₂Si₂O₈.

referred to as “superheating” (temperature above liquidus of the melt). Kelemen et al. (2004) estimated that an ascending melt will attain ~65°C of superheat per GPa of pressure decrease, and can be heated from the melting temperature (just above the solidus of subducted metabasalt) to ~1300 °C in the hottest part of the wedge. Such a superheated melt would be able to dissolve a considerable mass of peridotite and could increase in mass until the change in composition brings the modified melt to its liquidus surface.

Slab melt can escape from thermal death and pass through the thin, low temperature mantle zone (“1” in Fig. 10) just above the top of the slab melting region if the melt mass is great enough or if the melt initially transports in cracks that cut through this low temperature zone and terminate within a hotter portion or in a reservoir in the mantle wedge. Most adakites exhibit limited contamination by mantle peridotite. Hence, here we consider several scenarios that slab melt reacts with small amount of peridotite once reaching a higher temperature location within the mantle wedge (e.g. “2”, “3”, “4” or “5” in Fig. 10).

We can see from Fig. 10 and Table 3 that as a slab melt reaches a higher temperature region such as “2” or “4” in the mantle wedge, it will interact with the peridotite to produce opx + modified melt via reaction ol + SiO₂ (melt) = opx and bulk or selective dissolution of ol, cpx and spinel (sp), with Mg and Fe increase and Si decrease in the melt and SiO₂ enrichment in the mantle [in the form of opx (Kelemen et al., 1992, 1998)]. As the slab melt reaches location “3” which is the hottest portion in the wedge, the temperature of the melt will be heated to >1200 °C, probably above the liquidus of a given bulk composition (slab melt + moderate amount of peridotite). The interaction at this location may only involve bulk or selective dissolution of mantle minerals and thus adds mantle components to the melt. In these three scenarios, Na (and Si and K likewise) “depletion” (content decrease) in the melt is due to the dilution caused by the increase in melt mass. By quantitative modeling, Killian and Stern (2002) demonstrated that only selective assimilation can explain the CaO enrichment in addition to the MgO enrichment in adakites. They showed

that the high MgO and CaO tonalitic glasses ($\text{Na}_2\text{O}/\text{CaO} < 1$) in the mantle xenoliths from Cerro del Fraile can be developed from a primitive trondhjemitic melt ($\text{Na}_2\text{O}/\text{CaO} > 1$) via the selective assimilation of $\sim 15\%$ of $\text{cpx} + \text{sp}$ ($\text{opx} : \text{sp} = 9 : 1$) + minor ol. This selective assimilation model must take place at scenario “3” based on the phase relationships described in Fig. 10(B). One can imagine that in addition to the reaction $\text{ol} + \text{SiO}_2$ (melt) = opx , if similar selective assimilation also takes place at scenarios “2” and “4”, the result will be similar except that the SiO_2 content in the assimilated melt will be still further lower.

As a slab melt reaches a moderate pressure and temperature region (“5” in Fig. 10) where amphibole in addition to opx becomes stable (< 1100 °C at 1.0–2.0 GPa), the melt will react with ol, cpx and sp to produce $\text{opx} + \text{amp} + \text{modified melt}$. The result is to form a hybridized mantle with mesomatic $\text{amp} + \text{opx}$ masses (Carroll and Wyllie, 1989; Sen and Dunn, 1994b) and the assimilated melt composition is governed by the ratio of consumed $\text{ol} + \text{cpx} + \text{sp}$ (solid reactants) to precipitated $\text{opx} + \text{amp}$ (solid products), which in turn depend on the specific temperature and pressure. Experiments at 950–1025 °C and 1.5–2.0 GPa (Sen and Dunn, 1994b) have demonstrated that melt/rock reaction in this case will lead to Na, Si and K depletion and Mg and Ca enrichment in the remaining melt, with Na loss from the melt via amp precipitation and Ca

addition to the melt via cpx decomposition. The possible reaction can be expressed as: $3\text{CaMgSi}_2\text{O}_6$ (diopside in cpx) + MgAl_2O_4 (sp) + $1/2\text{Na}_2\text{O} \cdot 1/2\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ (in melt) = $\text{NaCa}_2\text{Mg}_4\text{Al}_3\text{Si}_6\text{O}_{24}\text{H}_2$ (pargasitic amp) + CaO (in melt). This reaction reveals that $\text{cpx} + \text{sp}$ dissolution and amp crystallization must lead to Na and Al decrease and Ca increase in the remaining melt. We have quantitatively calculated the composition of an assimilated melt produced via the bulk reaction $\text{ol} + \text{cpx} + \text{sp} + \text{melt}_1 = \text{opx} + \text{amp} + \text{melt}_2$ (“5” in Table 3). The calculation used the equation and compositional data in Table 4, with mass of solid reactants/mass of solid products (Ma/Mc) = 3/1 and no change in phase proportions in the reactants ($\text{ol} : \text{cpx} : \text{sp} = 3 : 6 : 1$) and products ($\text{opx} : \text{amp} = 1 : 9$). As shown in Table 4 and Fig. 11, moderate amounts of reaction of primitive slab melts of metabasalt (~ 10 – 25% melting) with $\text{ol} + \text{cpx} + \text{sp}$ in peridotite, with $\text{amp} + \text{opx}$ crystallization and $\text{Ma}/\text{Mc} = 3/1$, can produce assimilated melts with Mg#, $\text{Na}_2\text{O}/\text{CaO}$ and other major element compositions identical to adakites. The mass of the assimilated melt will be 1.07 times to 1.2 times its initial mass as the melt/rock ratio (Mp/Ma , mass of primitive melt/mass of solid reactants) increases from 10/1 to 10/3. Most adakites exhibit Na depletion accompanied by Ca enrichment in addition to Mg enrichment. Hence, we consider the melt/rock reaction in field “5” to be an important process relevant to the behavior of slab melts in the mantle wedge in

Table 4
Results of major element modeling for the mantle AFC process of primitive slab melts

	Assimilating reactants			Crystalline products		Primitive	Calculated	Primitive	Calculated	Primitive	Calculated	Adakites
	ol	cpx	sp	opx	amp	Melt ₁	Melt ₁	Melt ₂	Melt ₂	Melt ₃	Melt ₃	
SiO_2	38.97	47.26	0.32	54.54	43.11	72.8	70.4–67.0	66.0	64.1–61.3	61.3	59.6–57.4	56–72
TiO_2	0.01	1.88	0.88	0.25	2.11	0.7	0.7–0.7	0.6	0.6–0.7	0.8	0.8–0.8	0.25–1.20
Al_2O_3	0.02	9.12	38.26	4.64	12.18	15.5	15.1–14.5	18.2	17.6–16.6	18.5	17.8–16.8	14.8–18.5
$\text{FeO}(\text{tot})$	12.9	7.48	18.26	10.12	10.97	2.8	3.2–4.0	3.3	3.7–4.4	5.5	5.8–6.2	1.8–7.0
MnO	0.11	0.12	0.42	0.38	0.13	0.04	0.05–0.06	0.03	0.04–0.05	0.00	0.01–0.02	0.05–0.15
MgO	47.35	13.05	16.88	28.94	14.77	0.5	2.2–5.0	0.9	2.6–5.3	1.6	3.2–5.9	0.5–6.2
CaO	0.22	19.77	0.06	1.12	10.4	1.7	2.4–3.6	4.2	4.7–5.7	5.4	5.9–6.7	2.8–8.5
Na_2O	0.01	0.25	0.0	0.07	3.5	5.2	4.7–4.1	6.3	5.8–5.0	6.0	5.6–4.8	3.0–5.8
K_2O	0.0	0.0	0.0	0	0.51	1.9	1.7–1.5	0.5	0.5–0.4	0.4	0.3–0.3	0.5–3.0
Mg#	87	76	62	84	71	23	54–69	32	55–68	34	50–63	30–72
$\text{Na}_2\text{O}/\text{CaO}$	0.05	0.01	0.00	0.06	0.34	2.98	1.94–1.12	1.5	1.22–0.88	1.12	0.94–0.72	0.25–1.6

The assimilated melt composition (Cam; columns 8, 10 and 12) was calculated by mass balance as follows: $\text{Cam} = ((\text{Ma}/\text{Mc}) \times (\text{Mp}/\text{Ma}) \times \text{Cp} + (\text{Ma}/\text{Mc}) \times \text{Ca} - \text{Cc}) / ((\text{Ma}/\text{Mc}) \times (\text{Mp}/\text{Ma}) + (\text{Ma}/\text{Mc})1)$ with a given $\text{Ma}/\text{Mc} = 3/1$ and $\text{Mp}/\text{Ma} = 10/1$ to $10/3$. Cp = elemental concentration of primitive melt (experimental slab melt); Ca = elemental concentration of the assimilating reactants (with $\text{ol} : \text{cpx} : \text{sp} = 3 : 6 : 1$); Cc = elemental concentration of the crystalline products (with $\text{opx} : \text{amp} = 1 : 9$); Mp/Ma = mass of primitive melt/mass of assimilating reactants; Ma/Mc = mass of assimilating reactants/mass of crystalline products.

Data sources: assimilating reactants and crystalline products: from the mantle xenoliths in Kamchatka Arc (ol: Val55/7; cpx: Val55/4; sp: Val55/10-1; opx: 8710-D; amp: Val4-2; Kepezhinskas et al., 1995); primitive melts: the experimentally produced high pressure partial melts of the metabasalt R_3 of Rapp and Watson (1995) (primitive melt₁: 1.6 GPa, 1000 °C, F (melting degree) = ~ 0.10 ; primitive melt₂: 2.2 GPa, 1025 °C, $F = \sim 0.20$; primitive melt₃: 1.6 GPa, 1050 °C, $F = \sim 0.23$); compositional range of adakites: from data in the caption of Fig. 2.

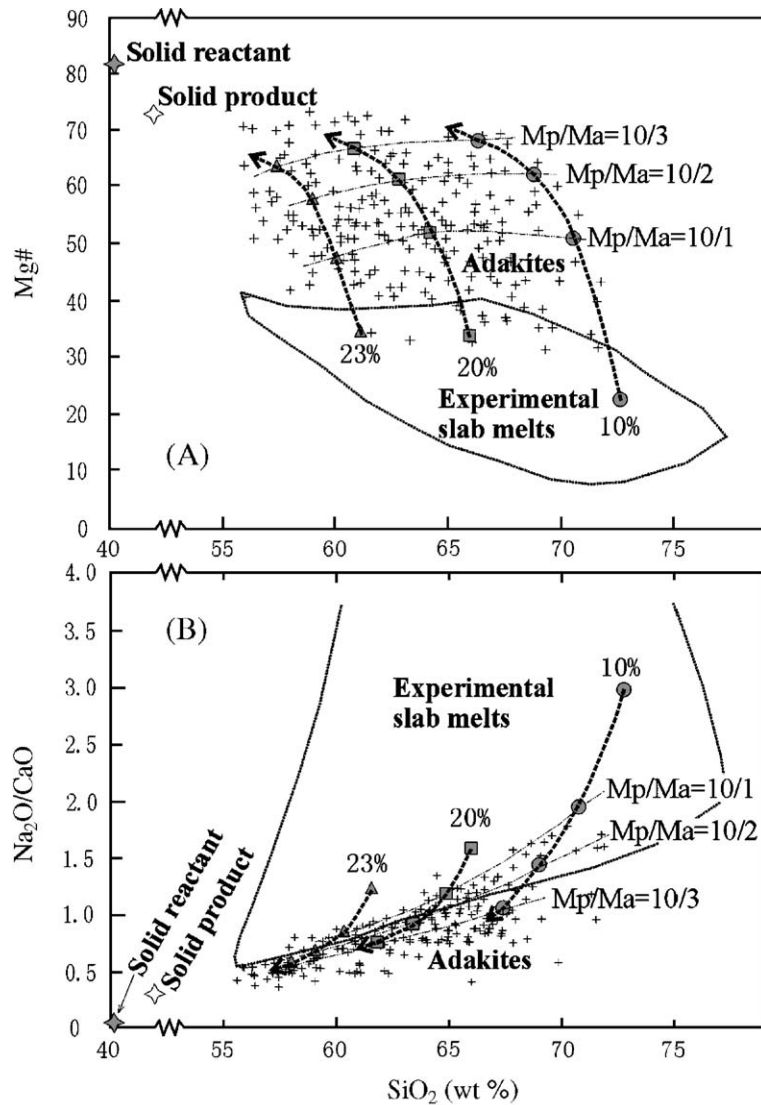


Fig. 11. Modeling results of SiO_2 versus Mg# (A) and $\text{Na}_2\text{O}/\text{CaO}$ (B) for the mantle AFC process of primitive slab melts, showing that reaction of primitive slab melts of metabasalt (~ 10 – 25% melting) with ol+cpx+sp in mantle peridotite, under conditions of increasing melt mass, produces amp+opx and assimilated melts with SiO_2 , Mg# and $\text{Na}_2\text{O}/\text{CaO}$ identical to adakites. The calculation uses the AFC equation and data in Table 4, with mass of solid reactants/mass of solid products (M_a/M_c)=3/1 and no change in solid phase proportions in the reactants (ol:cpx:sp=3:6:1) and products (opx:amp=1:9). The melt/rock ratio (M_p/M_a , mass of primitive melt/mass of solid reactants) ranges from 10/1 at which the melt mass is 1.07 times its initial mass to 10/3 at which the melt mass is 1.2 times its initial mass.

addition to the selective assimilation that has been described by Killian and Stern (2002).

6. Implication for mantle metasomatism and sources of arc magmas

Metasomatism of mantle wedge via slab melt is of particular importance in subduction zones. Ringwood and coworkers (Green and Ringwood, 1972; Nicholls and Ringwood, 1973; reviewed by Ringwood, 1974,

1975) early developed a hypothesis on slab–mantle interaction that hydrous siliceous melts, generated by partial melting of subducted crust, rise and react with the overlying peridotite, and the fertilized mantle region then melts to produce arc basalts and andesites. Wyllie and Sekine (1982) also proposed a model [as illustrated in Fig. 10(A)] that hydrous siliceous melts derived from subducted crust percolate upwards into and react with the overlying mantle, producing a series of discrete masses of phlogopite–pyroxenite which are

carried to deeper levels in the form of a heterogeneous layer above the subducted slab. They considered that alkalic magmas developed behind the volcanic front could be produced by incongruent melting of the phlogopite–pyroxenites at deep levels. In the past 10 years, the importance of slab-derived melts as a metasomatizing agent in sub-arc mantle is increasingly recognized (e.g., [Kepezhinskis et al., 1995](#); [Prouteau et al., 2001](#); [Defant et al., 2002](#) and references therein). The evidence in this paper suggests that most adakites have undergone interaction with mantle peridotite and one of results is to contribute SiO_2 , Na_2O and to a lesser degree K_2O to the peridotite mantle possibly via precipitation of orthopyroxene, amphibole and phlogopite. Such metasomatized mantle would possibly be the source region of some compositionally particular arc magmas.

Direct evidence for slab melt metasomatism in the mantle wedge comes from arc-mantle ultramafic xenoliths. [Kepezhinskis et al. \(1995\)](#) found that some arc-mantle xenoliths from north Kamchatka (Russia) contain high-Na and high-Al dacite veins with trace-element concentrations similar to adakite, and the metasomatic mineral phases (sodic amphibole, clinopyroxene and plagioclase) in the xenoliths are remarkably similar to those obtained during experimental runs in siliceous melt-peridotite reaction systems ([Carroll and Wyllie, 1989](#); [Johnston and Wyllie, 1989](#); [Sen and Dunn, 1994b](#)). They referred to this particular type of metasomatism as “Na metasomatism”. [Schiano et al. \(1995\)](#) also found that melt inclusions in mantle minerals of xenoliths from Luzon arc lavas, Philippines, are compositionally similar to adakites and that there is a linear chemical trend between these melt inclusions and their host lavas. They therefore concluded that slab melts must have contributed to metasomatism of the mantle below the Luzon arc. Mantle xenoliths from Cerro del Fraile in southernmost South America ([Killian and Stern, 2002](#)) also contain adakitic glass veins and many of the xenoliths are modified by modal Na-rich metasomatism, which produced elevated Sr/Y, La/Yb and La/Nb ratios typical of slab melts.

[Defant and Drummond \(1993\)](#) noted that adakites are sometimes associated with arc basalts that are rich in Nb and alkali compared with typical calc-alkaline and tholeiitic arc basalts and pointed out that these “Nb-enrich arc basalts” (NEAB) are sodic ($\text{Na}_2\text{O}/\text{K}_2\text{O} > 1$ and mostly $\text{Na}_2\text{O} > 3$ wt.%) and may be derived from a mantle source metasomatized by slab-derived melts. Defant and coworkers (see [Defant et al., 2002](#) and references therein) believed that Nb and Ta were transferred from slab melts, rather than hydrous fluids (since

the solubility of Nb and Ta in hydrous fluid is very low), to the mantle via precipitation of amphibole, and suggested that subsequent melting of such a metasomatized mantle produced basaltic magmas with high concentrations of Nb and other HFSE. The association of NEAB and adakites has been documented in several volcanic arcs including the Kamchatka (Russia), Philippines, Japan, western Aleutian Islands, Mount St. Helens, Mexico and Panama-Costa Rica ([Defant and Drummond, 1993](#); [Kepezhinskis et al., 1996, 1997](#); [Sajona et al., 2000](#); [Alfredo et al., 2001](#); [Defant et al., 2002](#)). In addition to NEAB, arc volcanic rocks thought to contain slab melt components include high-Mg andesites (HMA) and boninites ([Yogodzinski et al., 1994](#); [Drummond et al., 1996](#)). Together, these rocks have been termed the adakite metasomatic volcanic series by [Defant et al. \(2002\)](#). HMA includes both Adak- and Piip-types ([Yogodzinski et al., 1995](#)). The Piip-type in the western Aleutians were interpreted to represent volcanic rocks derived from a peridotite source that was generated by mixing depleted MORB mantle with minor adakite melts. The HMAs (or sanukites) from SW Japan ([Tatsumi and Ishizaka, 1982](#)) were included into this category ([Yogodzinski et al., 1995](#)). The Adak-type HMAs, which [Drummond et al. \(1996\)](#) referred to as transitional adakites, represent MgO- and CaO-rich adakites from the Adak Island in central Aleutians ([Kay, 1978](#)), the Austral Andes ([Stern and Killian, 1996](#)) and Baja California ([Saunders et al., 1987](#)). They were produced as slab melts incompletely reacted with mantle peridotite during ascent ([Yogodzinski et al., 1995](#)). The Archean high-Mg granodiorites from SW Superior Province of Canada ([Shirey and Hanson, 1984](#); [Stern and Hanson, 1991](#)) and the high-Mg diotites from Pilbara Craton, Western Australia ([Smithies and Champion, 2000](#)) were also thought to be the equivalents of the Adak-type HMA. In addition, boninites from Bonin Islands of Japan may have minor (2%) slab melt components in the mantle source to explain their high Zr/Sm ratios ([Taylor et al., 1994](#)).

In addition to the adakite metasomatic volcanic series, evidence for the slab melt as a metasomatizing agent of arc magmas is more extensive. Some arc magmas, though apparently not associated with adakites, indeed exhibit strong “slab melt” trace element imprint. For instance, variations of Nb/Ta ratios and other trace elements in basalts along the Indonesian arc ([Stolz et al., 1996](#)), the Luzon arc of Philippines ([Maury et al., 1998](#); [Castillo and Newhall, 2004](#)), and the Mariana arc ([Defant et al., 2002](#)), have been attributed to addition of variable amounts of slab-melt components to their mantle source regions.

7. Conclusions

Although adakites are sodic, here we have demonstrated that they are generally Na-depleted relative to their experimental equivalents. Average adakite is lower by 1–3 wt.% Na₂O than experimental slab melts. The Na depletion in adakites can be attributed to the melt/rock reaction as the magmas passed through the hot mantle wedge. The process added mantle components MgO and CaO to adakite magmas, with melt components Na₂O, SiO₂ and perhaps Al₂O₃ and K₂O being transferred to the mantle probably via precipitation of opx and sodic amp. Phase relationships in the reaction system siliceous melt+peridotite and quantitative calculation indicate that reaction of siliceous slab melts with mantle ol+cpx+sp under conditions of moderate T/P, with fractional crystallization of amp+opx and increasing melt mass, can produce assimilated melts with major element composition, Mg# and Na₂O/CaO identical to adakites. Hence, this mantle AFC process is responsible for the Na depletion in adakites.

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