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Adakites: some variations on a theme

埃达克岩：关于其成因的一些不同观点*

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Abstract Adakites were proposed over a decade ago to be products of the melting of young subducted oceanic crust. In fact, several new localities have been discovered since the original work documented approximately ten localities in modern arcs (*e.g.*, southwestern Japan, Trans Mexican Volcanic Belt, *etc.*). But work over the past ten years has also shown that adakites can be generated by other processes during subduction (*e.g.*, along the edge of tears in the subducting slab, remnant slabs left in the upper mantle, *etc.*). In addition, adakites appear to be associated with a suite of rocks including high-Mg andesites resulting from either adakite interaction with the mantle (Adak-type) or melting of the mantle during adakite interaction (Piip-type), niobium enriched arc basalts (NEAB) that are believed to be derived from the partial melting of a mantle metasomatized extensively by adakites, and possibly boninites (several researchers have found an adakite component in boninites). A new rock suite, the adakite metasomatic volcanic series, has been proposed to account for the various associations. In addition, a large number of NEAB have been found to contain ultramafic mantle xenoliths with clear evidence of reaction between ultradepleted mantle and adakites.

Several alternative hypotheses have been proposed for the generation of adakites primarily involving the melting of the lower crust rather than the subducting slab. One model proposes that the melting of the lower crust occurs when basaltic melts underplate the lower crust. There are many reasons that appear to rule this method out. The other model proposes that in areas where the continental crust is thick, the lower crust can become eclogitic and separate and sink into the mantle (delaminate). This delamination process will bring the lower sections of the lower crust or the upper part of the delaminated lower crust in contact with relatively hot mantle, which could initiate melting, and the production of adakites. This has led us to conclude that many of the Cretaceous adakites not associated with subduction found in East China are the result of lower crustal melting via delamination. We also emphasize that, if true, the term adakite should not be restricted to processes related only to slab melting but must include those involving the melting of the lower crust.

The Archean continental crust consists of primarily trondhjemites, tonalities, and dacites (TTD). It remains problematic as to whether this continental crust was derived from slab melting or lower crustal melting. However, we believe that the higher mantle temperatures during the Archean led to more mid ocean ridges, which generated the subduction of "more" younger crust than today. Based on this, we suggest that the Archean TTD continental crust was generated primarily by slab melting. We also note that the Archean was a period of extensive gold mineralization. Several researchers have also found gold and copper mineralization associated with the adakite metasomatic volcanic series. This series may be an important indicator of ore deposits.

Key words Adakite, Slab melting, Na metasomatism, Lower crustal melting, Delamination, Gold and copper mineralization

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摘 要 埃达克岩的概念是十多年前提出来的，指由俯冲的年轻洋壳熔融形成的火成岩。自从最初在现代岛弧近十个地方报道埃达克岩以来，新近又在几个地方发现有埃达克岩（如日本西南部，外墨西哥火山岩带，等等）。但是，过去十多年的研究也表明，埃达克岩可以由俯冲期间的其它过程产生（例如，沿俯冲板片的撕裂边，留在上地幔中的板片残余等）。另外，埃达克岩似乎与一些岩石呈共生组合，这些岩石包括高镁安山岩、富 Nb 的弧玄武岩（NEAB），还可能有玻安岩（几个研究者已在玻安岩中发现有埃达克岩的组分）。高镁安山岩不是来自埃达克与地幔的相互作用（Adak-type），就是来自此相互作用期间地幔的熔融（Piip-type）；富 Nb 的弧玄武岩，据认为是来自一种被埃达克岩广泛交代的地幔的部分熔融。作为一个新的岩套，埃达克岩交代火山岩系列已被建议用来解释各种岩石组合。此外，大量的富 Nb 弧玄武岩也已被发现包含有超镁铁质的地幔包体，而这些包体有高亏损地幔与埃达克岩反应的明显证据。

关于主要与下地壳熔融而不是与俯冲板片有关的埃达克岩的起源已提出几种假说。一个模型认为，下地壳熔融出现在玄武质岩浆底侵下地壳时。但是，有许多理由似乎可以排除这种模式。另一种模型认为，在大陆地壳很厚的区域，下地壳可能变成榴辉岩，从而拆离并下沉到地幔中（拆沉）。这个拆沉过程将导致下地壳下部或拆沉的下地壳的上部与相对热的地幔接触，进而可引起下地壳熔融和埃达克岩的形成。这使我们认为，在中国东部发现的与俯冲作用无关的白垩纪埃达克岩可能是下地壳熔融与拆沉作用的产物。我们还要强调，如果下地壳熔融与拆沉作用真能形成埃达克岩，那么埃达克岩这一术语不应该仅仅局限于与板片熔融有关的过程，而应包括那些与下地壳熔融有关的过程。

太古宙的大陆地壳主要由奥长花岗岩、英云闪长岩和英安岩（TTD）组成。这种大陆地壳是来自板片熔融还是下地壳熔融仍是有争议的。然而，我们认为，太古宙期间地幔的较高温度会导致较多的洋中脊的形成，从而产生比今天“更多”的年轻洋壳的俯冲。据此，我们认为，太古宙 TTD 大陆地壳主要是由板片熔融形成。我们也注意到，太古宙是广泛金矿化的时期。有些研究者还发现，金和铜的矿化与埃达克质交代火山岩系列有关。因此，该火山岩系列可能是寻找金属矿床的一个重要标志。

关键词 埃达克岩；板片熔融；钠质交代；下地壳熔融；拆沉作用；金和铜矿化

中图法分类号 P588.121；P588.14；P597

Recently, Defant and Kepezhinskas (2001) completed a short review of adakites investigating the discoveries that have been made over the last decade. The limited space prevented them from elaborating on the details of the discoveries or a discussion of alternative hypotheses for the generation of adakites. In contrast, this paper has four objectives: 1) to explore the geochemical, petrological, and tectonic details of adakites; 2) discuss alternative hypotheses for the generation of adakites; 3) present an argument for the appropriate use of the term adakite — that is, should it be applied to all rocks with geochemical characteristics that suggest an amphibolite/eclogite source or be used strictly to specifically define a tectonic process (slab melting)?; and 4) to address the implications of the potential of lower crustal melting in China.

Kay (1978) and Stern *et al.* (1984) first called attention to geochemically distinct andesitic lavas erupted at Adak Island, Aleutian arc and the Andean Austral Volcanic Zone (southern Chile), respectively, and proposed that they were derived from the melting of the subducted slab. Martin (1986) subsequently noted that Archean tonalites had similar compositions to the Chilean volcanics and suggested that the siliceous Archean crust was derived from the melting of subducted oceanic lithosphere.

Drummond and Defant (1990) and Defant and Drummond (1990) proposed that the subducting slab could melt when the crust is relatively young and therefore elevated in temperature. They surmised, based on experimental and geothermal models (Peacock, 1990; also see refs. in Rapp *et al.* 1999), that the products would be andesitic and dacitic in composition with rather unusual geochemical imprints. They called these rocks adakites noting that Kay (1978) had been the first to attribute a slab-melt scenario to similar rocks at Adak Island. They identified approximately ten locations around the world where the subduction of young crust is associated with adakites (Fig. 1). They also predicted several other localities that had not been studied where they thought adakites would be found (*e.g.*, southwestern Japan) based on the subduction of young crust).

Defining Adakites

Kay (1978) and others worked out the major and trace-element compositions of slab melts based on geochemical modeling by the mid 1980s, and their work was eventually verified experimentally (Rapp *et al.*, 1999 and refs. therein). The combined work clearly showed that garnet was stable in the source at the pressure and temperature of melting — a garnet eclogite is the restite. Garnet preferentially incorporates the heavy rare-earth elements (HREE) and Y. Furthermore, as amphibolite is transformed into garnet eclogite during subduction, plagioclase breaks down. Elements enriched in plagioclase typically do not find “homes” in garnet eclogite and go into the melt (*e.g.*, Sr and Eu). This causes an unusual looking product from a geochemical perspective. Slab melts are enriched in Sr, Na, and Eu but depleted in Y and the HREE which is exactly what adakites show — geochemical features atypical of volcanic arcs. The fact that adakites are associated with the subduction of young crust bolstered the slab-melt hypothesis (Fig. 1).

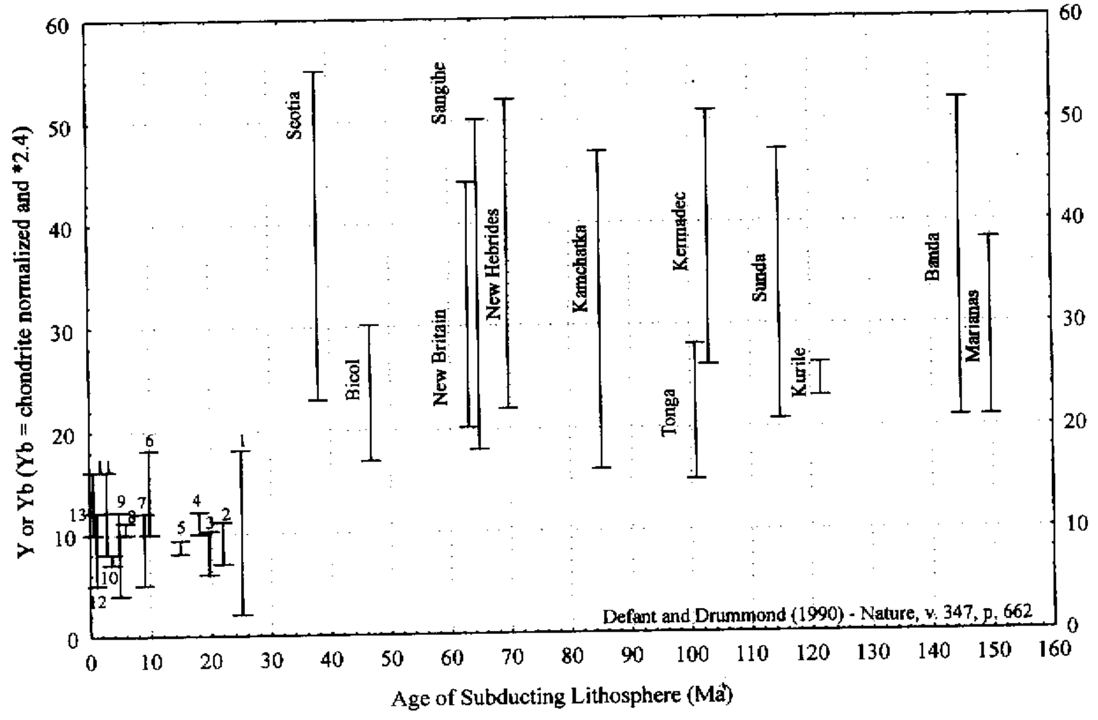

Fig. 1 Graph of the age of the subducting crust versus the Y (and Yb) concentrations in the associated subduction volcanoes. Note that the adakites (low Y and Yb) are associated with crust younger than 25 Ma (after Defant and Drummond, 1990).

Adakites typically have $SiO_2 \geq 56$ wt. %, $Al_2O_3 \geq 15$ wt. %, and $Na_2O \geq 3.5$ wt. % (pristine adakites are probably dacites not andesites) and are characterized petrographically by the presence of abundant plagioclase and amphibole phenocrysts. Trace elements worth noting are Sr ($>$ 400 ppm), Y ($\leq$ 18 ppm), HREE (*e.g.*, Yb $\leq$ 1.9 ppm), positive Eu anomalies (and positive Sr anomalies), and Sr/Y and La/Yb ratios of $\geq$ 40 and 20, respectively (Defant and Drummond, 1990). Adakites also contain the typical arc signature — depletion of Nb and Ta and, in most cases, MORB-like Sr and Nd isotope signatures. The spider diagram in Figure 2 accentuates the differences between adakites (and experimental metabasaltic melts) and "normal" island-arc dacite. As discussed later, the extreme variations in the more incompatible elements, such as Rb, Ba, K, *etc.* may be due to variations in the extent of the sediment incorporated into an adakite during slab melting (*e.g.*, Defant and Drummond, 1993). This may also affect the isotope composition of adakites (not all adakites have MORB-like isotopic signatures as discussed below).

In addition to the spider diagram in Figure 2, there are three widely used diagrams to differentiate between adakites and normal arc andesites, dacites, and rhyolites. Figure 3 shows a Na-K-Ca ternary diagram with the adakite (which includes various samples of Archean trondhjemites-tonalites-dacites — TTD) and island-arc fields superimposed. In addition, experimental metabasaltic melts from Rapp *et al.* (1999), the calc-alkaline trend of Nockholds and Reynolds (1953), and the trondhjemitic trend of Barker *et al.* (1981) are also included on the diagram. One of the most remarkable features of the diagram is the enrichment of adakites, Archean TTD, and experimental melts in Na compared with typical arc-related volcanism — a trend first noted in trondhjemites by Barker and his coworkers over two decades ago. Although adakites can be higher in K depending on how close the melt is to the solidous (Rapp, 2001), they rarely fall into the island-arc field toward high K in Figure 3. The breakdown of plagioclase during the formation of adakitic melts at the amphibolite-ecologite transition enriches the melt in Na relative to K. In contrast, differentiation of arc basalts toward andesites, dacites, and rhylolites tends to deplete Na (plagioclase fractionation) and enrich the melts in incompatible elements such as K.

The other two diagrams commonly used to distinguish adakites from other silicious rocks are Sr/Y versus Y and La/Yb versus Yb. We prefer Sr/Y versus Y but both diagrams emphasize the difference between partial melting of a metabasalt and the differentiation typical of arc melts. We display Sr/Y versus Y in Figure 4 with the adakite and arc andesite, dacite, and rhyolite fields superimposed (Archean TTD and experimental metabasalitc melts also fall within the adakite field on this diagram). Curve A emphasizes the direction that higher degrees of partial melting with an eclogitic restite source drive the subsequent melts — that is, toward higher Sr/Y and lower Y. The garnet depletes the Y and the breakdown of plagioclase increases the Sr.

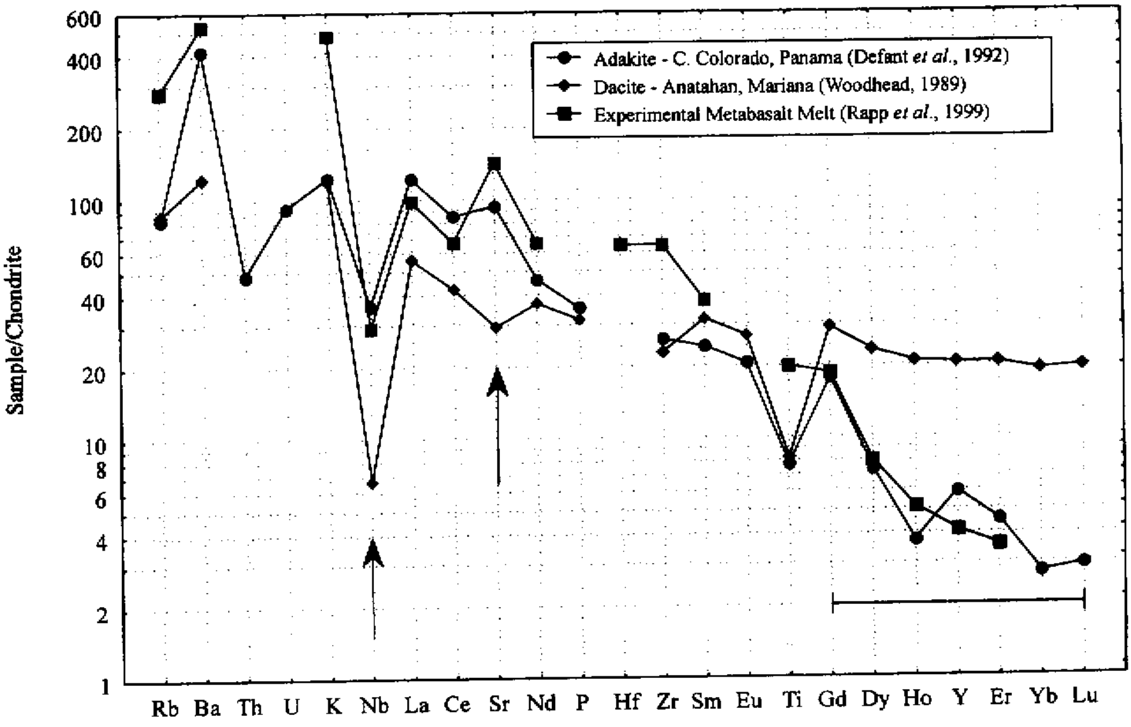

Fig. 2 Spider diagram of an adakite from Cerro Colorado, Panama (Defant *et al.*, 1992), an experimental melt from a metabasalt (Rapp *et al.*, 1999), and a typical island arc dacite from the Marianas (Woodhead, 1989).

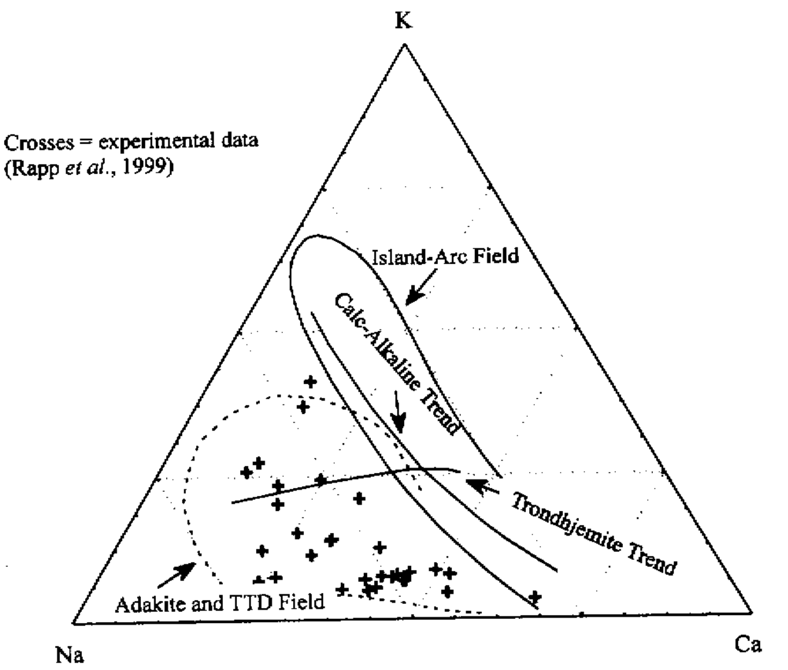

Fig. 3 Ternary diagram of Ca, Na, and K with calc-alkaline (Nockholds and Allen, 1953) and trondhjemitic (Barker *et al.*, 1981) trends superimposed. Experimental data — crosses — represent melts from metabasalts (Rapp *et al.*, 1999). The island arc field and the adakite and the Archean TTD fields are from Defant and Drummond (1993).

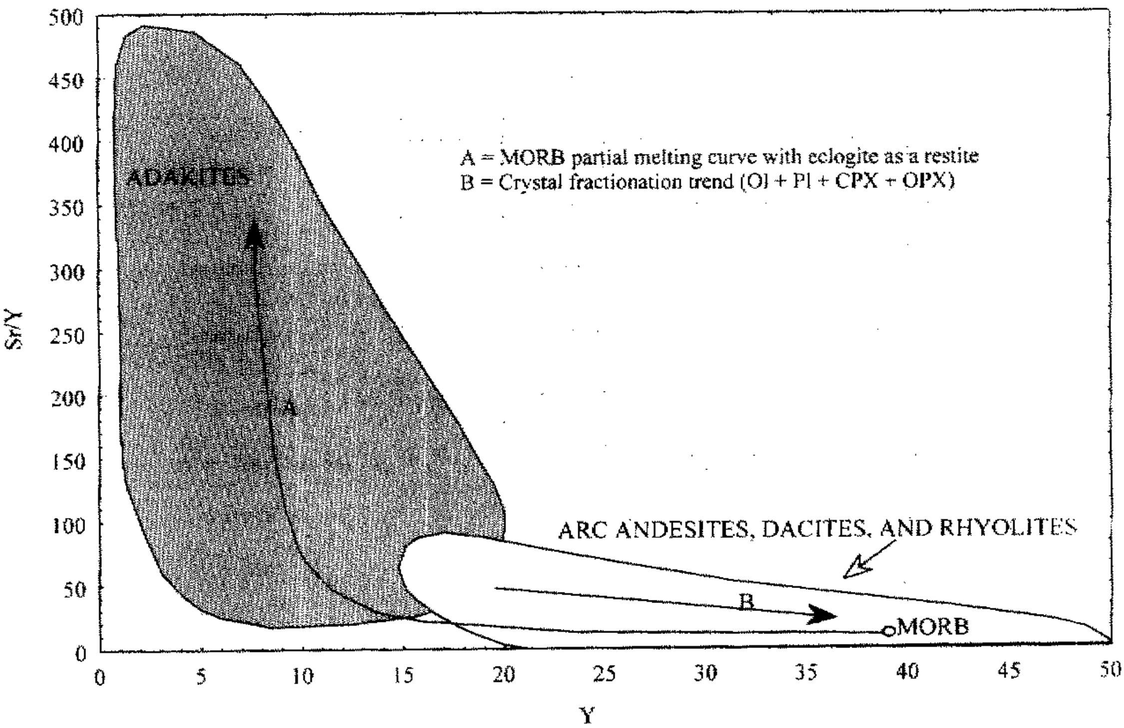

Fig. 4 Sr/Y versus Y. Fields for adakites (and Archean TTD) and island arc andesites dacites and rhyolites have been superimposed. In addition, experimental curves for the partial melting of a MORB and the differentiation trend have also been superimposed (after Defant and Drummond, 1993).

In stark contrast, curve B demonstrates the effects of differentiation including crystal fractionation with or without assimilation. In this case, Y behaves incompatibly and increases in concentration while Sr is removed primarily via plagioclase fractionation.

A number of new adakite localities associated with the subduction of young crust have been reported over the last decade, including Cerro Pampa (Kay *et al.*, 1993a), Andes; Talamancas, Costa Rica (de Boer *et al.*, 1995); southwest Japan (Morris, 1995), and the Mexican Trans-Volcanic Belt (Luhr, 2000).

Perhaps the best way to understand the process of slab melting is via field work on exposed subduction-zone terrains. Bebout *et al.* (1999 and refs. therein) found evidence for the involvement of partial melts of the subducted slab and sediments associated with the hydrous component in the Catalina schist, which represents an exposed subduction zone. Pegmatites with the chemical composition of adakites, were probably derived from the partial melting of the slab. The slab exists in the Catalina schist as garnet eclogitic restites. Based on their work, there is little doubt that adakitic melts can be products of slab melting within volcanic arcs.

One of the best examples of the juxtaposition of adakites with normal arc basalts, andesites, dacites, and rhyolites occurs along the coast of Kamchatka, Russia. In southern Kamchatka, subduction of extremely old oceanic lithosphere is associated with typical arc volcanism believed to be derived from hydrous metasomatism of the overlying mantle wedge. But in northern Kamchatka (north of the Aleutian islands) the crust off the coast is young and the volcanism changes to adakites (*e.g.*, Kepezhinskas *et al.*, 1997) (Fig. 1). Although it should be noted that Hochstaedter *et al.* (1996) indicated that the mantle below the Kamchatka arc may have been metasomatized by adakites (see our discussion below on small percents of slab melts in all arcs).

Finally in terms of examples, Mount St. Helens may be the best representation of the expected relationship between slab melts and normal arc-derived magmas. The Cascade arc is associated with one of the hottest subducting slabs in the world. Mount St. Helens erupts predominantly adakites (a short phase of niobium-enriched basalts occurred — see below) and sits in front of the Cascade arc (Defant and Drummond, 1993) (Fig. 5). The samples fall in the adakite field in Figures 3 and 4. In contrast, Mount Adams erupts regular arc basalts, andesites, and dacites but is located along the strike of the arc 50 km behind Mount St. Helens (the samples fall within the arc andesite, dacite, and rhyolite fields in Figs. 3 and 4). Experimental work has shown that slab-melting processes should occur at shallower depths than the normal dehydration melting of the mantle during regular arc volcanism. The frontal position of Mount St. Helens may be related to a shallow melting of the subducting lithosphere as opposed to the deeper melting which is producing magmatism at Mount Adams. Mount St. Helens began forming less than 40,000 years ago whereas the Cascade arc has existed in its present locality for the past

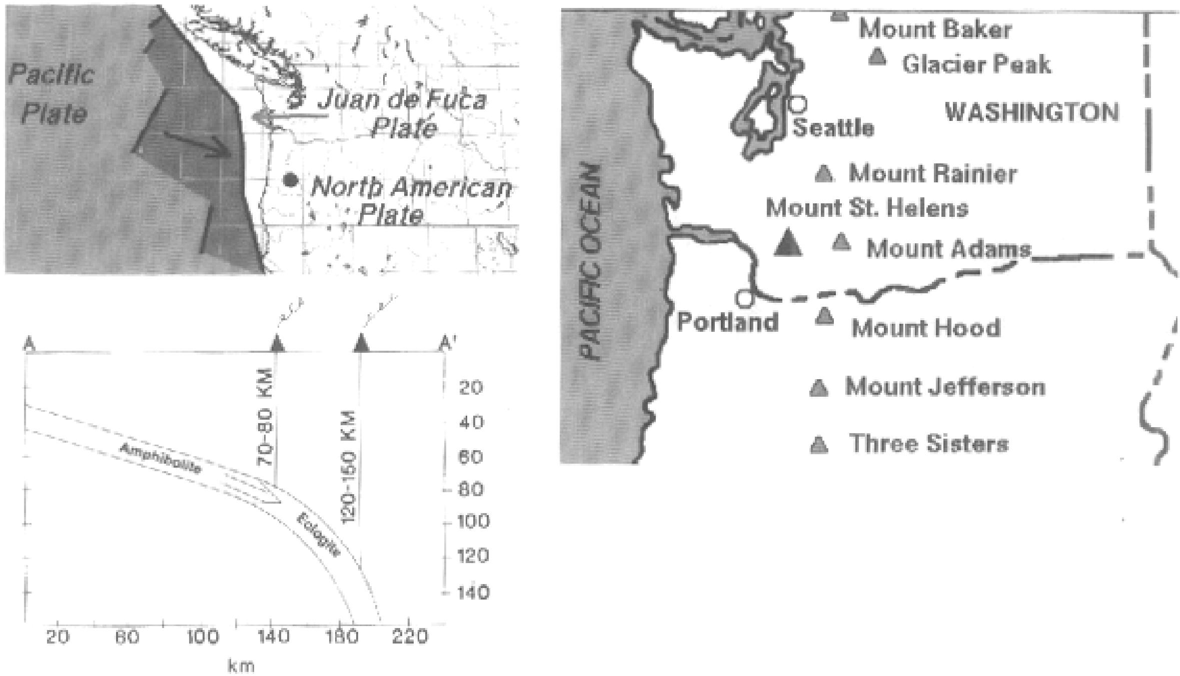

Fig. 5 Maps showing 1) the closeness of the ridge to North America and the subduction of young crust from the Juan de Fuca plate and 2) location of Mount St. Helens in front of the Cascade arc and Mount Adams within the strike of the Cascade arc. Cartoon shows the subducting plate below the Cascade range and approximate locations above the plate of Mount St. Helens and Mount Adams (the transect is from west to east). Mount St. Helens consists of primarily adakites and is approximately 70 to 80 kms above the Benioff zone whereas Mount Adams erupts primarily normal arc basalts through rhyolites and is located where most volcanoes are above the Benioff zone — approximately 120 km (after Defant and Drummond, 1993).

7 million years. As the North American plate approaches the mid-ocean ridge, the temperatures of the subducting plate have become hot enough to produce the copious amounts of adakites at Mount St. Helens (Defant and Drummond, 1993)(Fig. 5).

One of the most promising directions of study dealing with adakites over the past decade has been the discovery of variations in the concentration of the Mg content in adakites. Yogodzinski *et al.* (1994; 1995) discovered two types of high-Mg andesites in the western Aleutian Komandorsky Island region of Alaska and Russia: an Adak and Piip type. They suggested that the high-Mg found in some adakites results from limited interaction of adakites with peridotite in the mantle wedge before they are extruded — termed the Adak type. They pointed out that Adak Island, the Austral Andes, and Baja, California fall within the Adak category. The fact that adakites have higher MgO (and Cr and Ni) concentrations compared to experimental melt compositions (and Archean TTD) and adakitic inclusions in sub-arc mantle xenoliths supports their contention (Fig. 6).

In contrast, the Piip-type magnesium andesites are in equilibrium with olivine, which suggested to them that they formed from direct melting of the mantle wedge after metasomatism by slab melts. They attributed the enhanced adakite involvement in the western Aleutian Komandorsky Island region of Alaska to obique subduction (*i.e.*, slower subduction and higher shear stress). The Setouchi belt of southwest Japan is also believed to be a Piip-type high-Mg andesite, and they suggested that sanukitoids (another name for these high-Mg andesites in the Archean) are Piip-type adakites.

Several studies have suggested that both an adakite and hydrous slab fluid are involved in the formation of boninites (extremely high Mg andesites that are largely partial melts of hot and shallow mantle wedge) attesting to the involvement of the subduction of young crust (*e.g.*, Pearce *et al.*, 1992; Taylor *et al.*, 1994; Xu *et al.*, 2000)

Drummond *et al.* (1996) summarized the variations between pristine adakites, Piip and Adak-type high-Mg andesites, and boninites suggesting that pristine adakites only reach the surface if they follow pathways through the mantle that have already been extensively reacted with by previous adakite interaction (so no further reactions can affect the adaktite that reaches the surface). Otherwise the magmas pick up primarily Mg when they react with the mantle forming Adak-type magmas (Fig. 6).

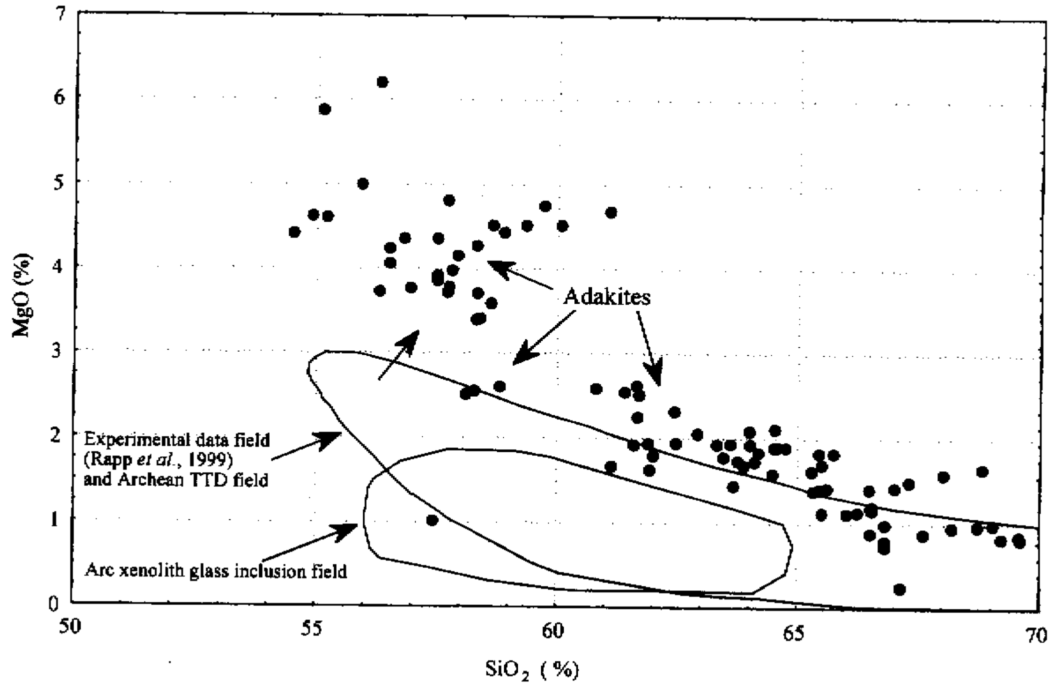

Fig. 6 MgO versus SiO_2 in adakites compared with the fields for experimental melts from metabasalts (Rapp *et al.*, 1999) and Archean TTD and glass inclusions in sub-arc mantle xenoliths.

If the reaction is so intense that the mantle is actually melted than the melt becomes intensely enriched in Mg and Piip-type adakites are generated (*i.e.*, HMA). Boninites, the ultra-high Mg andesites, appear to have the least adakitic component involved and probably reflect more hydrous conditions than during the generation of Piip-type magmas (and more melting).

Sigmarsson *et al.* (1998) found that young adakites from the southern Austral Andeans Volcanic Zone fall to the left of the Th-U disequilibrium equiline (on a graph of $^{230}Th/^{232}Th$ versus $^{238}U/^{232}Th$) suggesting a partial melting origin from the subducted slab and not a differentiation process from basalts derived from a hydrous metasomatized arc mantle. They found that the data was compatible with 20 percent partial melting of the subducted slab and noted that garnet in the residual eclogitic source during partial melting preferentially partitions U relative to Th. Mount St. Helens adakites fall to the left of the equiline also supporting the contention that they are derived from the slab.

Similar results have been recorded using Li isotopes from volcanism in western Panama, which can be divided into an old group (6 to 13 Ma) typical of normal arc volcanism and a young group (< 5 Ma) representing adakites (*e.g.*, Defant *et al.*, 1992 and refs. therein). The subduction parameters changed in the region about 5 Ma from an old slab to a young and hot slab. The older group has relatively high B/Be and δ^7Li isotopic ratios between +4.7 to +5.6 ‰ whereas the young group (the adakites) has low B/Be and δ^7Li isotopic ratios between +1.4 and +4.2 ‰. Old group arc volcanism is associated with the hydrous metasomatism of the mantle wedge (high B/Be and δ^7Li) whereas young and hot slabs tend to devolatilize their hydrous component early (prior to melting). Adakites (although hydrous) are lower in elements typically carried by hydrous fluids thus explaining the low B/Be and δ^7Li found in the young group (Tomascak *et al.*, 2000).

Additional Ways to Produce Adakites

Research over the last decade has decidedly shown that the subduction of young and hot slab is not necessary for the production of adakites. Six tectonic processes also appear to be able to produce adakites.

Remnant slabs: Several authors have postulated that adakites can be generated from a remnant of previously subducted slab incorporated in the mantle that becomes elevated in temperature by the surrounding mantle: *e.g.*, Evia, Greece (Pe-Piper and Piper, 1994) and Isla San Esteban, Gulf of California (Desonie, 1992).

Oblique or fast (8 to 10 cm/yr) subduction: Within some tectonic environments, older oceanic lithosphere subducts obliquely or at elevated rates which leads to adakite production. Shear stress related to fast subduction or oblique subduction can increase the temperature of the upper part of the subducting slab. The Aleutians and Komondorsky Island (*e.g.*, Yogodzinski *et al.*, 1995) and eastern Mindanao, Philippines (Sajona *et al.*, 1993; 1994) are probably the best examples.

Arc-arc collision: Adakites have been found in two major arc collisional zones — Arid Hills and northern coast of Papua New Guinea (*e.g.*, Maury *et al.*, 1996) and Central Mindanao, Philippines (Sajona *et al.*, 1997). It is important to emphasize that because the age of the crust can no longer be determined in these regions (it has subducted) we do not know its thermal history. The adakites may have been generated directly from young crust or the slab could still be below the collisional zone where it has heated to produce adakites. Alternatively, something specific to the process of arc-arc collision could generate adakites. More work is needed, particularly in Papua New Guinea, to better understand the relationship between tectonics and adakite production. In fact, we address this issue more below in discussions concerning eastern China.

Initiation of subduction: Peacock *et al.* (1994) showed that when the cold slab first plunges into the hot mantle, there is an increase in the temperature of the subducting slab which can produce partial melting. Sajona *et al.* (1993; 1994) suggested that adakites are probably derived from this process in eastern and southern Mindanao, Philippines.

Slab tears: Yogodzinski *et al.* (2000; 2001) demonstrated that a tear along the subducting slab below Shiveluch volcano, Kamchatka, Russia, has allowed the edge of the slab to be heated, producing adakites. Defant and Kepezhinskas (2000; in preperation) postulated a similar scenario where the Lesser Antilles volcanic arc terminates below Grenada. We believe that the end of the Central American arc in Costa Rica may reflect this process also but further work is needed.

Flat subduction: Adakites in Ecuador and Peru and perhaps in other arcs may be generated by flat subduction. During subduction, the slab literally flattens and travels horizontally. For example, Gutscher *et al.* (2000) suggested that the slab could heat enough to melt during this horizontal motion. There is currently an extensive amount of controversy regarding this subject. We delve further into lower crustal melting below as a potential alternative to flat subduction in certain sections of the Andes.

Na Metasomatism and the Arc Mantle

Defant and Drummond (1993, and refs. there in) noted that adakites are sometimes associated with Nb-enriched arc basalts (NEAB). They thought these basalts might be derived from a mantle source that was metasomatized by adakites, but lacked any direct evidence for their hypothesis. Kepzhinskas *et al.* (1996) looked carefully at NEAB associated with adakites from Mount St. Helens, northern Kamchatka (Russia), Panama and Costa Rica, and the southern Philippines. These basalts have Nb/La (HFSE/La) ratios higher than typical island-arc basalts, and even though NEAB have high absolute HFSE concentrations, they also have typical arc depletions in HFSE (relative to K and La). NEAB are also alkaline or transitional alkaline compared with typical calc-alkaline and tholeiitic arc basalts (most have $Na_2O + K_2O > 4.5$ wt. %) and all are sodic ($Na_2O/K_2O > 1$; most have $Na_2O >$ 3 wt. %).

It was within a group of these NEAB in northern Kamchatka, Russia, that Kepezhinskas *et al.* (1995) found rare arc-mantle xenoliths they believed represented the source of NEAB. Some ultramafic xenoliths contain high-Na and Al glasses with adakitic trace-element concentrations. In addition, the mineral phases in several of the xenoliths (*e.g.*, the garnet-bearing pyroxenites) are remarkably similar to those phases obtained during experimental runs when felsic melts (trondhjemites) are reacted with ultramafic material representative of the arc mantle (Carroll and Wyllie, 1989; Johnston and Wyllie, 1989; Sen and Dunn, 1994; Rapp, 2001).

Kepezhinskas *et al.* (1996) concluded that the xenoliths were the products of a newly discovered type of metasomatism they referred to as Na metasomatism. They envisioned this process occurring when slab melts percolate and interact with the sub-arc mantle.

Kepezhinskas *et al.* (1996) found HFSE-rich phases along the contact between the felsic veins and the mantle and concluded that the reaction preferentially increased the HFSE in the Na-metasomatized mantle. Nb and Ta actually correlate with incompatible elements such as La and Sr (Kepezhinskas and Defant, 1996) (Fig. 7) (traditionally believed to be transported by a hydrous component). Recent experimental determinations of partition coefficients between silicious melts and amphibole for Nb and Ta indicate that Nb and Ta are enriched in the mantle during silicic melt interaction via amphibole (Tiepolo *et al.*, 2000). Subsequent melting of this Na-metasomatized mantle produces basalts (or high-Mg andesites — Piip type) with high HFSE concentrations similar to NEAB.

Our current research focuses on the possibility of the existence of a genetically related volcanic suite of rocks that would incorporate adakites (both Adak and Piip types), perhaps boninites, NEAB, and the associated mantle xenoliths commonly found in these rocks. We propose the term adakite metasomatic volcanic series. Adakites and NEAB (plus or minus mantle xenoliths in the NEAB) have been documented in several distinct localities world wide including the Philippines, Japan; Kamchatka (Russia) and the far western Aleutian Islands, Alaska; Mount St. Helens; and Panama-Costa Rica.

Several other localities associated with ridge or oblique subduction or slab tears may also contain the adakite metasomatic volcanic series, namely Adak and Kanaga Islands (Aleutians), Grenada (Lesser Antilles), Baja California and the Trans Mexican Volcanic Belt (Mexico), and Simberi Island (Papua New Guinea).

Evidence in recent years has begun to suggest that slab melts may play a minor role in the metasomatism of all arc mantle. We are hesitant to extrapolate this idea too far for fear that we will be dismissed as attempting to apply our model to all situations. However, the evidence is compelling. Schiano *et al.* (1995) found melt inclusions in mantle xenoliths from Batan Island, northern Luzon arc, to be similar in composition to adakites. They concluded that slab melts must be a component during metasomatism of the arc mantle below the Luzon arc. Maury *et al.* (1998) proposed that the entire northern Luzon arc has been metasomatized by a small slab-melt component based on

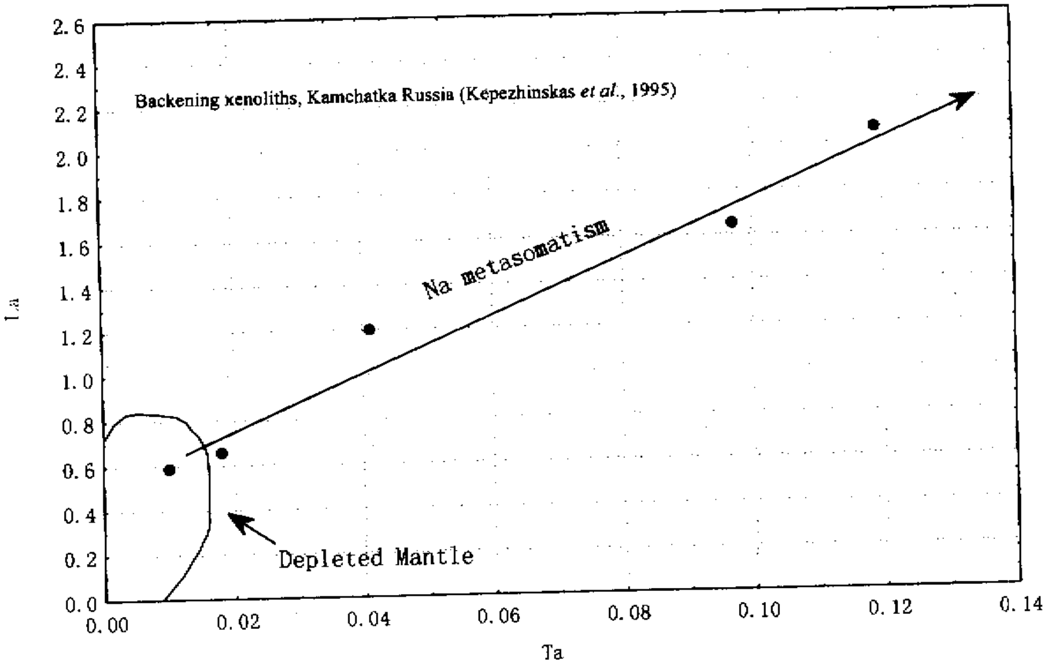

Fig. 7 Variations in Ta and La in mantle wedge xenoliths from the Kamchatka arc. La is typically carried by hydrous fluids whereas Ta is not. The fact that they correlate suggests that hydrous metasomatism is not the only process at work in the arc mantle (after Kepezhinskas and Defant, 1996).

their observation that temporal variations along the strike of the arc can only be explained through bulk mixing of a sediment and slab component which is consistent with the suggestions made by Schiano *et al*. (1995).

Is a slab-melt component limited only to the Luzon arc? We do not think so. We have studied xenoliths from the southern Kamchatka arc where the subducting slab is old and cold. Ionprobe analyses of melt inclusions with similar compositions to adakites seem to permeate the mantle below this arc (Kepezhinskas and Defant, in preparation).

Stolz *et al*. (1996) analyzed Indonesian volcanic samples for high precision Nb and Ta data and found that Nb/Ta ratios vary in basalts along the arc. The only way they could explain these changes was via variations in a slab-melt metasomatizing component. Other arcs also have these variations (*e.g.*, Marianas).

Our studies of PGE behavior in the sub-arc mantle (*e.g.*, Kepezhinskas and Defant, 2001; Kepezhinskas *et al*., 2002; Widom *et al*., in preparation) show that Kamchatka xenoliths form a continuous trend on a graph of Os versus Re/Os from high-Os harzburgites (restites) through lherzolites (refertilized mantle), pyroxenites (mantle veins) to adakites (metasomatizing component) indicating potential mantle-slab melt interaction.

It is difficult envisioning how PGE and/or HFSE can vary through hydrous metasomatism. Some authors, noting variations in the HFSE in arc basalts (NEAB), called upon an OIB mantle component present in arcs (*e.g.*, Reagan and Gill, 1989). But titanate phases stable in the source during melting are required to control HFSE variations. No such phases have ever been discovered in arc mantle xenoliths nor has there ever been an OIB mantle composition found in these xenoliths (*e.g.*, Maury *et al*., 1992). In addition, experimental work has shown that titanate phases are not stable during hydrous metasomatism or partial melting (*e.g.*, Ryerson and Watson, 1987). We cannot over emphasize this point. If NEAB are derived from an enriched "OIB" type mantle, than why are the hundreds of mantle xenoliths that we have collected in these basalts always ultra depleted or metasomatized ultra depleted mantle? We find it hard to understand how a plum-pudding model (*e.g.*, Morris and Hart, 1983) can withstand this scrutiny.

"OIBs probably come from a deep mantle that has had subducted lithosphere added to it. No wonder slab melt metasomatism of the arc mantle might appear to be similar to the source of OIBs. But what some authors suggest is an OIB mantle component in arcs, we believe is really an arc component in OIBs (*i.e.*, the deeply subducted slab)" (Defant and Kepezhinskas, 2001).

Archean Adakites and Adakites as a Prospecting Tool

Rapp (*e.g.*, 2001) has continually emphasized that the continental Archean crust consists of about 80 percent trondhjemitic rocks with adakitic characteristics. Martin (1986) showed that these trondhjemites have geochemical characteristics much different from arc suites being derived in present-day arcs. He has maintained that these rocks must be derived from the melting of the subducting slab, primarily because the subducting lithosphere in the Archean was, on average, much younger than it is today. Why? Because the Archean mantle was much hotter than the mantle is today and probably generated more mid-ocean ridges, which led to the subduction of much younger crust. Drummond and Defant (1990) showed that adakites increase in the rock record from the present to the Archean, which seemed to support Martin's hypothesis. In fact, they pointed out that today's adakite productivity is probably lower than at any time in the past, because the mantle has continually cooled since the Archean.

Martin (1999) has also noted that the Mg concentrations in Archean trondhjemites are lower than current-day adakites (Fig. 6). He postulated that the Archean adakites probably did not interact with the mantle as much and envisioned more adakite production and subsequently more adakite metasomatism of the Archean mantle preventing adakites that reach the surface from extensive interaction. The adakites produced today are much higher in MgO than not only the Archean adakites, but those produced experimentally and adakitic melt inclusions within mantle xenoliths (Fig. 6). In fact, we would argue that pristine adakites are rare at the surface in present arc systems, if they exist at all.

So, is the adakite metasomatic volcanic series present in the Archean? Until recently, no NEABs had been reported from the Archean. But in several papers submitted over the past year (*e.g.*, Wyman *et al.*, 2000) authors have reported NEABs from several Archean terrains noting their similarities to those found in present-day arcs.

We wish to emphasize that the Archean was a time of immense ore production. Numerous large gold deposits are found in Archean rocks greater than 2 to 2.5 billion years old. There may be a genetic relationship between slab melting and precious and base metal mineralization. In several cases, adakites have been linked to epithermal gold and porphyry copper deposits (*e.g.*, Sajona and Maury, 1998; Kepezhinskas and Defant, in preparation). We have also noticed the extensive gold and porphyry copper production associated with NEABs and adakites particularly along the northern coast of Papua New Guinea (*e.g.*, Porgera), Lihir, Bouganvilla, and several localities in western Panama. S. M. Kay and co-workers (Kay and Mpodozis, 1999; 2001; Kay *et al.*, 1999) have also noted recently that mineralization throughout the Andes is associated with rocks with steep REE patterns. We suggest that NEABs and adakites could be used for gold and copper exploration the way kimberlites are used to find diamonds.

Alternative Hypotheses for the Generation of Adakites

Before we continue further, we feel that it is important to emphasize that isotopes should be used with caution in explaining adakite generation and evolution. There are two sources that can control isotope ratios. 1) The amount of sediment incorporated into an adakite during melting can vary extensively depending on the amount subducted, the refractory nature of the material, and the isotopic concentration of the sediment. 2) AFC processes can increase the amount of assimilate and the extent of fractionation of plagioclase in adakites. Assimilation of the continental crust could increase Sr isotopic ratios while decreasing Nd isotopic ratios especially if one considers the fact that Sr will be reduced during plagioclase fractionation as the AFC proceeds. Pb isotopes would be affected accordingly by both processes.

Lower crustal melting via a basaltic melt: Several authors (*e.g.*, Atherton and Petford, 1993) have emphasized that the lower crust could melt via basaltic melts that underplate the continent thus generating adakites. There are three major reasons that argue against this scenario as the source of adakites. 1) The high MgO content of many modern-day adakites is not explained easily via melting of the lower crust and subsequent extrusion. The adakites must pass through the mantle and react to increase the MgO content and decrease the SiO_2 content. 2) The copious amounts of mantle xenoliths in adakite-associated NEAB is not easily explained by melting of the lower crust. The fact that the xenoliths are frequently metasomatized via adakite metasomatism strongly argues for a Na-metasomatized source (*i.e.*, adakites reacting with the source mantle of NEAB). 3) Modern-day adakites, to the best of our knowledge, have been described only from subduction environments (although we are currently working on adakites from Tibet that may be derived in a non-arc environment). This does not preclude adakites from being derived from the lower crust, but does emphasize the startling paucity of adakites in other tectonic environments. If basaltic melts cause melting of the lower crust in arcs, than why aren't adakites found in other tectonic environments such as hot-spot volcanism?

Lower crustal melting via delamination: Kay *et al.* (1993b; 1994) proposed that when the continental crust becomes thick enough, the lower crust would be converted to eclogite. Eclogite is denser than the mantle and may break away from the crust and sink (*i.e.*, delaminate). The process will bring relatively hot mantle in contact with newly exposed lower crust near the amphibolite/eclogite boundary either at the bottom of the crust or the top of the delaminated crust.

This could lead to partial melting, and the generation of adakites. We see no reason why this could not explain the generation of adakites where crustal thicknesses exceed approximately 40 km (based on experimental work — *e.g.*, Rapp, 2001). The process would allow adakites derived from the top of the delaminated crust to pass through mantle (thus potentially reacting and increasing their MgO content). The adakites could also metasomatize the mantle and possibly generate a source for NEAB and NEAB mantle xenoliths.

Nomenclature

Traditionally, adakites have been associated with partial melting of the subducted crust (*e.g.*, Defant and Drummond, 1990). But it now appears that adakite-like magmas, NEAB (potentially with mantle xenoliths), and the suite of Adak- and Piip-type adakites can be generated through delamination and subsequent partial melting of the lower crust. Therefore, we see no reason to restrict the use of the term adakite or the newly proposed rock suite "adakite metasomatic volcanic series" (Defant and Kepezhinskas, 2001) to the melting of the subducted oceanic crust.

East China: An Example of Non-Arc Adakites?

Several authors have recently noted the existence of early Cretaceous rocks with adakitic compositional signature, which they called adakite-like rocks, in east China (*e.g.*, Zhang, *et al.*, 2001a and b; Wang, *et al.*, 2001a and b; Xu *et al.*, submitted). Paleospastic reconstructions of the tectonics of this region indicate that only small sections were once associated with subduction during the period of adakite genesis (*e.g.*, Zhang *et al.*, 2001b). This has led researchers to suggest lower crustal melting as the source of the adakites rather than slab melting. In fact, we suggest that not only has the lower crust melted, but it probably occurred via delamination of eclogite (Fig. 8)(*e.g.*, Kay *et al.*, 1993a). It should also be noted that there are many Cu-Au metallogenic deposits in the East China apparently associated with adakites.

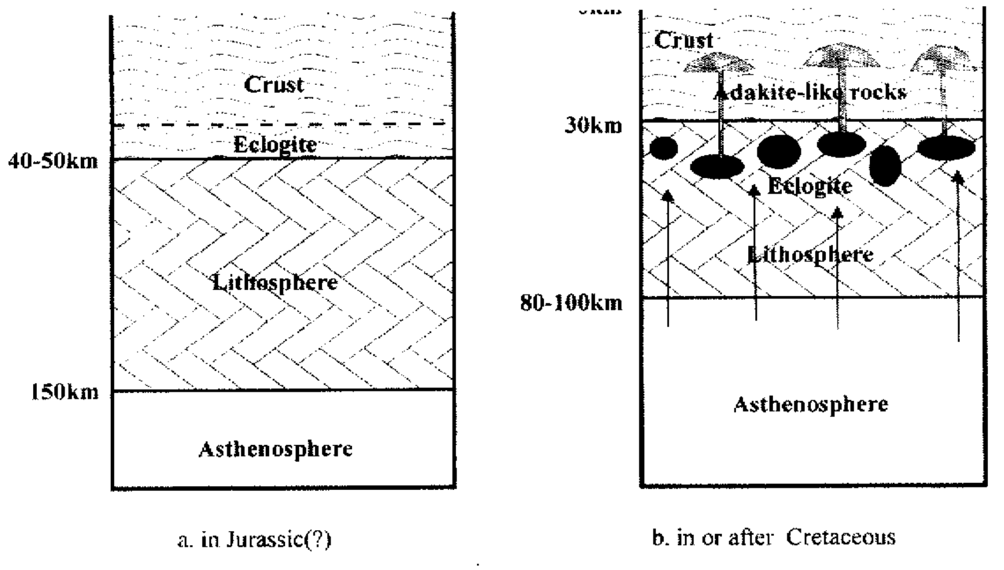

Fig. 8 Cartoon showing how the structure of East China lithosphere appeared in the Jurassic and how delamination led to the generation of adakites (after Xu *et al.*, in preparation).

However, there is still debate as to what the specific tectonic environment of East China was in the late Cretaceous. Some have suggested a subduction regime (*e.g.*, Deng *et al.*, 1992; Lapierre *et al.*, 1997; Zhou and Li, 2000). The problem is clear. In complex older tectonic environments, an understanding of the specific environment under which each rock type formed is problematic. In addition, the existence of adakites in the Andes volcanic arc where the crust is thick does not prove conclusively that melting of the lower crust or the subducted slab have generated the adakites as witnessed by the current debates on flat subduction versus lower crustal melting (see above). We suggest that the only conclusive way to determine if the lower crust actually melts is by studying a young tectonic region that is not associated with subduction. We have undertaken a project to work in a section of the Tibetan Plateau where volcanic rocks with adakite-like compositional signatures (0 to 20 Ma) have been reported (Zhang and Zheng 1996; Deng *et al.*, 1998). This may give us conclusive evidence of lower crustal melting via delamination.

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