Experimental constraints on the origin of potassium-rich adakites in eastern China *

Robert P. RAPP[1]   [2]   Nobu SHIMIZU[3]

Robert P. RAPP[1], Long XIAO[2] and Nobu SHIMIZU[3]

1. *Department of Geosciences and Mineral Physics Institute, State University of New York, Stony Brook, New York* 11794-2100, *USA*

2. *Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Wushan, Guangzhou* 510640, *China*

3. *Woods Hole Oceanographic Institution, Woods, Hole, Massachusetts* 02543, *USA*

2   510640

Abstract   Adakites are geochemically distinct volcanic and plutonic granitoid rocks found in intraoceanic island arc settings where relatively young, hot oceanic lithosphere has been subducted and melted (termed "slab melting"), and in continental arcs, such as the Andes, where melting has taken place at the base of tectonically- or magmatically-thickened lower crust (termed "lower crustal melting"). In both settings, the distinctive geochemical signature of adakitic granitoids is attributed to an origin by partial melting of a variably-hydrated metabasaltic protolith at sufficient depths for garnet to be stable within the residual crystalline assemblage (*i.e.*, residues of garnet-amphibolite and/or eclogite). Once generated, "pristine" or "parental" adakite melts may have their composition subsequently modified by processes of assimilation (of either mantle or continental material) and crystal fractionation during transport to and emplacement in the middle-upper crust. Late Mesozoic (early-mid Cretaceous,   160- 110Ma) adakites in eastern China are unusually rich in potassium (K_2O) and other large-ion lithophile elements (*e.g.*, Ba, Th, U), with low Na_2O/K_2O ratios (1.0- 1.1), in contrast to sodic adakites, found in eastern China and elsewhere, which resemble experimental adakite liquids produced by dehydration melting of basalt in the garnet-amphibolite to eclogite facies and which formed by either slab melting of oceanic crust, or by partial melting of broadly basaltic, lower crustal protoliths. Despite these compositional differences, their overall geochemical character defines the potassic granitoids of eastern China as adakites. We attribute the unique chemistry of these potassium-rich adakites to either peculiarities in the composition of their source, or to the processes, including assimilation and fractional crystallization (AFC), that subsequently modified parental adakite magmas. Although the apparent lack of proximity to a subduction zone suggests that adakites in eastern China formed by partial melting of underplated (magmatically-thickened) mafic lower crust, geodynamic scenarios involving "flat slab" subduction in eastern China during the Yanshanian period cannot be ruled out.
Key words   Potassium-rich adakites, Experimental constraints, Eastern China

Adakite   ,   ,
           ,   ("   "),   ,
("   ")   , adakite   ,
                                ;   (/   )
             "   " "   "adakite   ,   (,
)   (, 160- 110Ma)   adakite,
      adakite   ,   (K₂O)   (Ba Th U),   Na₂O/K₂O   (1.0- 1.1),

- adakite , ,
,
adakite adakite , , adakite
(AFC) , adakite ( )
" "
adakite; ;
P589. 1; P581; P588. 121

Introduction

Adakites as slab melts

For the past decade, the term adakite has been used to describe arc-related volcanic and plutonic rocks of andesitic-dacitic composition, possessing distinctive geochemical characteristics, including high Al_2O_3 and Na_2O contents, and high La/Yb and Sr/Y ratios coupled with strong depletions in Yb, Y, and high-field strength elements ("HFSEs", including Ti, Nb, Ta), suggestive of an origin by partial melting of basaltic ocean crust within downgoing slabs of oceanic lithosphere in subduction zones (Defant and Drummond, 1990; Drummond and Defant, 1991). Many of these key geochemical features were attributed to the presence of garnet in the residues of melting, and adakite petrogenesis was viewed as resulting from partial melting accompanying the dehydration of subducted oceanic crust, variably metamorphosed to a garnet-amphibolite and/or eclogite facies assemblage. Thus adakites occurring along convergent plate boundaries (in both intraoceanic and continental arc settings) were interpreted to be the products of "slab melting" (Defant and Drummond, 1990). Numerical models for the thermal regime in subducting slabs (Peacock et al., 1996; Molnar and England, 1995), however, suggested that slab melting would generally be restricted to unusually "hot" subduction zones, for example, those associated with subduction of an oceanic ridge (e.g., Stern and Killian, 1996; Kay et al., 1993), or of very young oceanic lithosphere (Sajona et al., 1994; Kepezhinskas et al., 1995; Morris, 1995); slow, oblique subduction, as in the western Aleutian arc (Kay, 1978; Yogodzinski et al., 1995), or subduction along a "slab tear", as in the Kamchatkan arc (Yogodzinski et al., 2001).

The geochemical basis for the "slab melting" model for adakite petrogenesis came from experimental studies that showed that 10% 30% melting of variably-hydrated MORB-like basalts at pressures of 1 - 4 GPa produced sodium-rich granitoid liquids that were, in terms of their major element components, similar to adakites from a number of continental and island arc settings (e.g., high SiO_2, Al_2O_3 and Na_2O contents; Na_2O/K_2O ratios > 2.0; low MgO and K_2O contents, and $Mg^\# < 0.5$, where $Mg^\# =$ molar $[Mg/(Mg + Fe)]$) (Rapp et al., 1991; Winther and Newton, 1991; Sen and Dunn, 1994; Rapp and Watson, 1995; Rapp, 1995;). Trace element geochemical features common to adakites worldwide, including strong enrichments in large-ion lithophile elements (LLEs), high ratios of La/Yb and Sr/Y coupled with strong relative depletions in heavy rare-earth elements (HREE), Y, and high field-strength elements (HFSEs, e.g., Ti, Nb and Ta) were, as a consequence, explicable in terms of equilibration between adakite liquids and garnet-bearing crystalline residues (eclogite or garnet amphibolite, with or without minor phases such as quartz or plagioclase); the presence of accessory titanate phases, such as sphene or rutile, are required to impart the strong relative depletion in HFSEs observed in adakites.

Although compositionally "pristine" adakites were described from some subduction zones (e.g., SW Japan, Morris, 1995; western Panama, Defant et al., 1991), in other cases, adakite magmas formed by slab melting appear to have undergone variable extents of interaction with rocks within the mantle wedge and lower arc crust (e.g., in the southern Andes, Stern and Killian, 1996 and Kay et al., 1993; in the Aleutians, the type-locality, Kay, 1978; and in the Philippines, Sajona et al., 1994), with the effects of these interactions manifested in the geochemical and isotopic attributes of "hybridized" adakites. Trace element analyses of "pristine" and "mantle-hybridized" adakitic liquids produced in laboratory experiments at 3 4 GPa (Rapp et al., 1999; this study) confirm the general legitimacy of petrologic models for adakite petrogenesis that begin with partial melting of a hydrous, mafic (i.e., basaltic) protolith in the garnet-amphibolite to eclogite facies. Limited interaction with peridotite in the overlying mantle wedge produces Mg-rich, hybridized liquids which retain the characteristic "adakitic" geochemical signature.

Adakites as crustal melts

An alternative to the slab melting model for adakite petrogenesis was proposed by Atherton and Petford (1993), to explain the origin of Na-rich plutonic and volcanic granitoids (i.e., ignimbrites, quatz diorites and tonalites) from the Cordillera Blanca complex in the Andes of NW Peru. At the time of adakite magmatism, the subducting slab at the trench (the Nazca Plate) was 55 65 Myr old, and therefore presumably "too old and too cold" to undergo melting; instead, it was suggested that the Cordillera Blanca granitoids were the products of partial melting of mafic lower crust at the base of the magmatically-thickened keel

of the Andes (Atherton and Petford, 1993; Petford and Atherton, 1996), similar to the model put forth by Smith and Leeman, (1987) for the petrogenesis of Na-rich dacites at Mt St Helens in the Cascade Range of North America. Adakite-like rocks from South Island, New Zealand (Muir *et al* , 1995), the Antarctic Peninsula (Wareham *et al* , 1997), and the Klamath Mountains of California and Oregon (Barnes *et al* , 1992; 1996) were subsequently interpreted as the products of partial melting of mafic lower crust, formed in response to crustal thickening achieved through underplating of mantle-derived mafic magmas (emplaced at the base of the existing arc crust). It was argued that displacement of this over-thickened "keel" of mafic crust to depths sufficient for garnet stability had led to partial melting attendant to dehydration, and adakite magmatism. Recent numerical models suggest that the appropriate *P-T* conditions can be achieved for partial melting of underplated "mafic lower (arc) crust" to take place, generating adakite parent magmas with mixed mantle- and crustal-like geochemical and isotopic signatures (Petford and Gallagher, 2001).

Intermediate-felsic volcanic and plutonic rocks of late-Creataceous age (160- 110 Myr old) from eastern China possess all of the characteristic geochemical attributes of adakites, including high SiO_2 and Al_2O_3 contents and high La/Yb and Sr/Y ratios, and strong relative depletions in the HREEs, Y, and HFSE. Yet many of the adakites in eastern China are distinctly more potassic than typical sodium-rich adakites associated with subduction, with Na_2O / K_2O ratios close to 1 (see Pan *et al* , 2001; Wang and Zhang, 2001; Wang *et al* , 2001; Zhang *et al* , 2001), and they are generally more potassic than the more typically sodic adakites from the Cascades, Antarctica, and the Andes. The "adakite-like" or "adakitic" granitoids which occur throughout eastern China have been termed continental or "C-type" adakites (Zhang *et al* , 2001), because they appear to lack any temporal or spatial association with subduction, and a lower crustal melting origin has been proposed. (Wang and Zhang, 2001; Pan *et al* , 2001; Wang *et al* , 2001). "C-type" adakites are contrasted with more sodic "oceanic" or "O-type" adakites (with Na_2O / K_2O ratios > 2 0) possessing a clear association with subduction (*e g.*, Xu *et al* , 2000; Xu *et al* , 2001). If the potassium-rich adakites of eastern China are also derived by partial melting of a garnet-bearing, hydrous mafic source, then their compositional differences with "O-type" adakites must be due either to differences in the source, or in the processes (*e g.*, assimilation and fractional crystallization; AFC) that subsequently modified the composition of "pristine" or parental adakite magmas. Melting experiments on hydrous basalt provide a geochemical reference point from which the geochemical effects of melt-rock reaction, wall rock assimilation, and intracrustal fractionation on adakite composition can be assessed.

Review of Experimental Studies

Whether formed by slab melting or lower crustal melting, a number of factors will control the composition of "parental" adakite magmas These include (1) the bulk composition of the source basalt, (2) the pressure-temperature conditions of melting, and (3) the exact mineralogy of the crystalline residue, especially the presence or absence of minor and accessory phases (*e g.*, rutile, zircon, or apatite) that can strongly affect the distribution of certain trace elements

Basalt compositions used in melting experiments

A variety of both natural and synthetic starting materials have been used to study the high-pressure melting behavior of hydrous basalt (Table 1). Rapp *et al* (1991) and Rapp and Watson (1995) conducted melting experiments at 0 8 - 3 2 GPa and 1000 - 1150 on four different natural amphibolites compositionally representative of variably altered and metamorphosed MORB. Potassium content in these starting materials ranges from < 0 1 wt% to 0 8 wt% K_2O, and Al_2O_3 contents range from 14 2 wt% to 17 0 wt% (Table 1). Adakitic liquids were produced by dehydration melting reactions involving hydrous minerals (primarily amphibole) whose breakdown produces silica-rich liquids at relatively low- to moderate-degrees of melting Dehydration melting experiments were also conducted by Sen and Dunn (1994) at 1 5 and 2 0 GPa, temperatures between 800 and 1150 , using a natural high-K amphibolitic basalt as starting material (Table 1), and Winther and Newton (1991) conducted melting experiments over a range of pressures (0 5- 3 0 GPa) and temperatures (850 - 1000), using two different low-K tholeiites (one a natural high-Al basalt, and the other a synthetic low-Al basalt representing "average Archean tholeiite") and variable amounts of water (from < 1 0 % to 15% H_2O).

Despite the fact that the various starting materials used in these experimental studies possessed a broad range in K_2O (0 1- 0 8 wt%), Na_2O (2 2- 4 3 wt%), and Al_2O_3 (14 2 - 19 3 wt%) contents, and highly variable Na_2O / K_2O (3 - 28), they all produced Na-rich granitoid liquids closely comparable to natural adakite by low- to moderate-degrees of melting (10- 30% by weight), leaving generally eclogitic crystalline residues Note however, that the Na_2O / K_2O ratio of average basalt from China is much lower than any of the starting materials used in the basalt melting experiments, with a K_2O content (2 51 wt%) much higher than the worldwide average (1 10 wt%).

Melting phase relations of hydrous basalt to 5 GPa

The melting phase diagram for hydrous basalt (Fig. 1) represent a composite constructed from the results of a number of experimental studies, on both natural and synthetic starting materials, and with variable amounts of water present Several of these studies focused on sub-solidus phase relations and the stability limits of important hydrous minerals, such as amphibole, lawsonite, zoisite and clinozoisite, and phengite (Poli and Schmidt, 1995; Schmidt, 1996; Kerrick and Connolly, 2001; Lopez and Castro, 2001). The actual position of the solidus for a given bulk composition will be determined by the form and
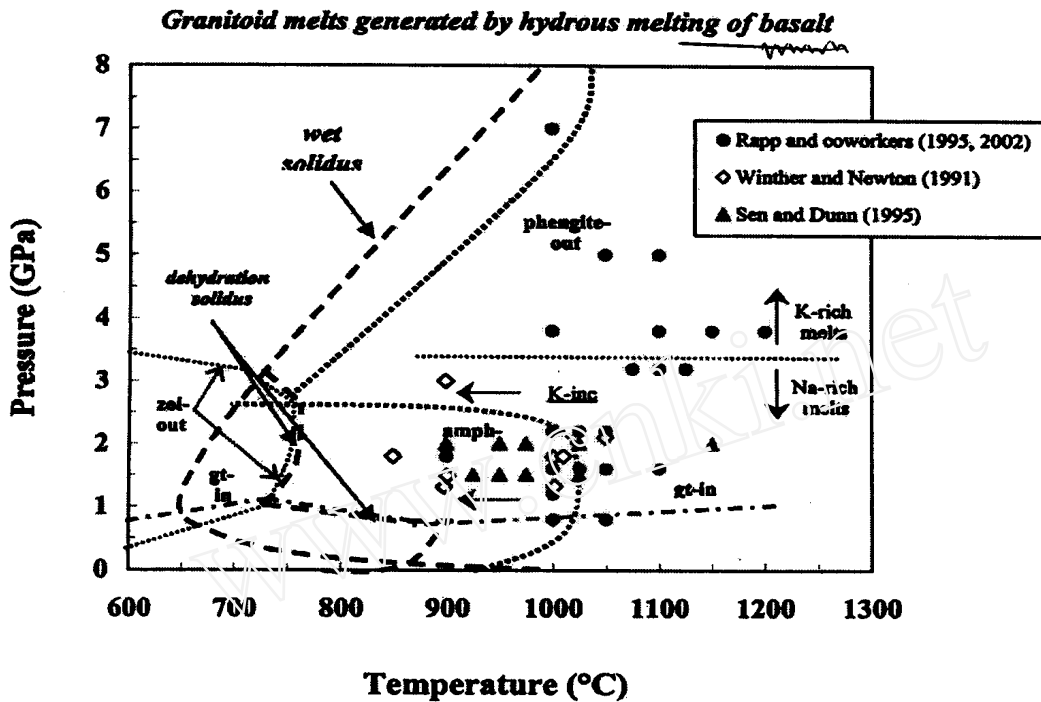
Fig. 1 Composite phase diagram for basalt-H₂O, with *P-T* locations of meltingexperiments in which adakitic granitoid liquids were formed (see references in text), the water-saturated or "wet basalt" solidus and the water-absent or dehydration melting solidus, and major phase boundaries for garnet and hydrous minerals. At pressures less than 3. 5 GPa, liquids formed by very low degrees of melting (< 10%) near the solidus have low Na_2O / K_2O ratios (< 1. 5); adakitic liquids with higher Na_2O / K_2O ratios form at higher temperatures and greater degrees of melting (10-30%). At higher pressures (> 3. 5 GPa), granitoid liquids formed by low- to moderate-degrees of melting possess high SiO_2 and K_2O contents, very low Na_2O / K_2O ratios, and low Al_2O_3 contents (see Table 2)

Table 1 Major-element oxide composition of starting material in melting experiments on hydrous basalts (wt%)

basalt	1	2	3	4	5	6	7	8
SiO_2	51. 19	48. 60	48. 30	47. 60	48. 20	49. 20	47. 09	48. 28
TiO_2	1. 18	2. 06	0. 72	1. 19	0. 85	1. 19	1. 23	2. 21
Al_2O_3	16. 62	17. 03	15. 30	14. 18	19. 30	15. 60	15. 07	14. 99
FeO^*	11. 32	10. 69	10. 70	13. 77	8. 94	13. 60	13. 20	11. 13
MnO	0. 23	0. 21	0. 19	0. 19	0. 11	0. 15	0. 26	0. 20
MgO	6. 59	6. 07	8. 40	6. 86	8. 72	6. 89	8. 29	7. 00
CaO	5. 49	9. 66	12. 60	10. 99	10. 50	10. 80	11. 33	8. 07
Na_2O	4. 33	3. 30	2. 27	2. 56	3. 11	2. 35	2. 52	3. 40
K_2O	0. 82	0. 21	0. 08	0. 19	0. 39	0. 26	0. 80	2. 51

availability of water in the source; if a free hydrous fluid phase is present, then the source can be considered to be "fully hydrated", and melting will commence at the "wet basalt" solidus. If no free fluid phase is present, all water will be bound in hydrous minerals, and melting will commence at the "fluid-absent" solidus through dehydration melting reactions involving amphibole, zoisite, and other water-bearing phases. The solidus for dehydration melting occurs at somewhat higher temperatures than the water-saturated or wet basalt solidus, with its exact location being

determined by the relative degree of hydration of the source, and the proportion of hydrous phases present (Lopez and Castro, 2001; Vielzeuf and Schmidt, 2001).

Melt compositions at 1- 4 GPa

   Also shown in Fig. 1 are the *P-T* locations of experiments in which granitoid melts (that is, liquid compositions that contain more than 10% quartz in a CIPW normative calculation) were reported (Winther and Newton,

1991; Sen and Dunn, 1994; Rapp and Watson, 1995). These experiments were generally conducted under fluid-absent conditions, where melting proceeds via dehydration reactions involving hydrous phases, primarily amphibole. Because potassium and the LLEs behave generally as highly incompatible elements during partial melting, the most potassic liquids, those richest in LLEs, will form at the lowest degrees of melting, nearest the solidus, and liquids formed by progressively higher degrees of melting will be less potassic and increasingly dilute with respect to the LLEs. Partial melts formed by very low-degrees of melting (< 10%), will thus be more potassic, with lower Na_2O/K_2O ratios (0.9- 1.2), than their sodium-rich counterparts (Na_2O/K_2O > 1.5- 2.0), formed at slightly higher temperatures and higher degrees of melting (10- 30 wt%). The amount of K_2O in the melt at a given degree of melting also appears to increase with increasing pressure (Winther and Newton, 1991), so that 20% melting at 3.8 GPa produces a more potassic liquid than 20% melting of the same basalt at 1.8 GPa (see Table 1). The lowest degrees of melting should also produce liquids with the highest Sr/Y and La/Yb ratios.

The amphibole-out phase boundary exerts strong control over the alumina saturation index (ASI, or A/CNK = molar $Al_2O_3/(CaO+ Na_2O + K_2O)$) of the partial melt, such that metaluminous adakitic liquids (*i.e.*, A/CNK < 1.0- 1.1) are only produced close to or beyond this boundary (Rapp, 1995). Most adakites, whether in a subduction zone or lower crustal setting, are metaluminous, and therefore they probably formed at temperatures at which residual amphibole was either a minor phase, or not present at all, and an eclogitic phase assemblage (garnet and clinopyroxene) was predominant. In this regard, we note that most of the adakites from eastern China possess A/CNK ratios less than 1.1 (Zhang *et al*, 2001).

Geochemical Comparisons with C-type Adakites

Geochemical comparisons between the experimental adakitic liquids, adakites from eastern China, and adakites formed either by slab melting or lower crustal melting of subducted slabs reveal important similarities and differences, as outlined below, providing some initial constraints on the petrogenesis of the compositionally-distinctive potassic adakites.

Major-element comparisons

Like "pristine" adakitic liquids in the basalt melting experiments, potassic adakites are typified by high SiO_2 and Al_2O_3 contents, $Mg^{\#}$'s less than 40- 45 (where $Mg^{\#} = 100$ x molar (Mg/[Mg+ Fe])), and A/CNK ratios generally < 1.0- 1.1. Adakites related to slab melting often have higher $Mg^{\#}$'s at lower SiO_2 contents, and A/CNK ratios less than 1.0, reflecting varying extents of interaction with peridotite in the overlying mantle wedge, but trace element abundance patterns remain largely unaffected (see discussion in Rapp *et al*, 1999, and Smithies, 2001). Clear

distinctions can therefore be made between relatively "pristine" and "mantle-hybridized" adakitic magmas, and although it is premature to call potassic adakites "pristine", it seems clear that they have experienced little interaction with a mantle component (as attested to by their low $Mg^{\#}$'s and low Cr and Ni contents). As shown by Wang *et al* (2001) and Zhang and Wang (2001), the primary difference, in terms of major-elements, between potassic adakite (C-type) and sodic adakite (O-type) is that the former is characterized by higher K_2O contents and lower Na_2O/K_2O ratios over a comparable range of SiO_2 contents (60- 73 wt%). When plotted on a ternary feldspar (Ab-An-Or) diagram, potassic adakites fall close to or within the granodiorite and granite fields, relative to the more typically tonalitic-trondhjemitic compositions of sodic adakites, as well as most experimental adakite liquids (Rapp *et al*, 1991; Winther and Newton, 1991; Sen and Dunn, 1994), with the exception of those produced from very low degrees of melting (*i.e.*, < 10 wt%).

Trace element comparisons

Trace-element data for experimental liquids is relatively scarce; ion microprobe data has been published for adakitic liquids produced at 1- 3 GPa (analyzing several samples from Rapp and Watson, 1995), and both "pristine" and "mantle-hybridized" adakitic liquids at 3- 4 GPa (Rapp *et al*, 1999). This data is combined with dditional unpublished data (Rapp and Shimizu, in prep.) in making trace element comparisons between experimental adakitic liquids, potassium-rich adakites from China, and Na-granitoids of the Cordillera Blanca batholith (to typify adakites derived by partial melting of thickened crust). Plots of La/Yb versus Yb and Sr/Y and Y were first used by Martin (1987) and Defant and Drummond (1990) to discriminate adakites and their Archean analogues (TTG) from normal calc-alkaline andesite-dacite-rhyolite volcanics. Mantle-normalized trace element abundance patterns for liquids formed at 3- 4 GPa, from melting of two different basalts, and taken to be representative of pristine adakite (unpublished data of Rapp and Shimizu), are used to make broader geochemical comparisons.

Sr/Y versus Y and La/Yb versus Yb

A relatively broad distribution is observed in La/Yb versus Yb (Fig. 2a) of the experimental adakites, a result of variable degrees of partial melting, at different P-T conditions, and different basaltic starting materials, but the overall fractionation of La from Yb coupled with the relative depletion in Yb is obvious. Similar to other adakites, associated with subduction, O-type adakites from China show variable but somewhat less pronounced fractionation of La from Yb, with comparable depletion in Yb. In contrast, C-type adakites show more highly variable, and in some cases extreme, degrees of REE fractionation and Yb depletion (comparable to the range seen in the experimental melts). Intermediate and felsic samples (tonalites and sodic ignimbrites) from the Cordillera Blanca are distributed over a range comparable to the experimental melts and C-type adakites.
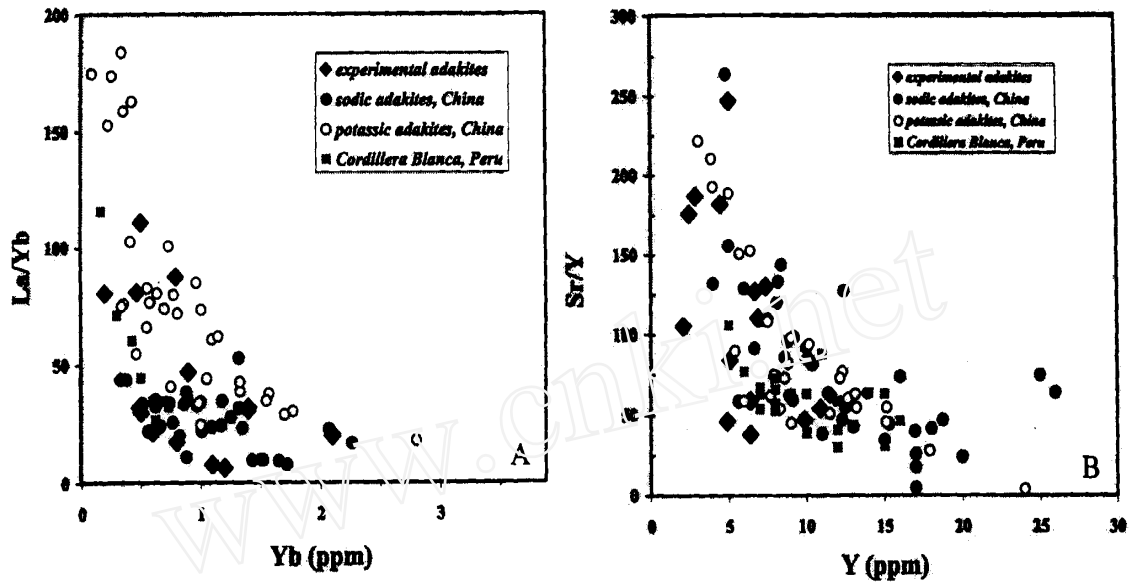
Fig. 2 La/Yb versus Yb (a) and Sr/Y versus Y (b) for: experimental melts at 1- 4 GPa (samples of Rapp and Watson (1995) and Rapp *et al.* (1999); "normal" sodic adakites from eastern and central China (data of Li *et al.*, 2001; Wang and Zhang, 2001; Xiaong *et al.*, 2001; Xu *et al.*, 2000, 2001; Zhang *et al.*, 2001), potassic adakites from eastern China (data of Pan *et al.*, 2001; Wang and Zhang, 2001; Wang *et al.*, 2001; Zhang *et al.*, 2001), and tonalites and quartz diorites, and leucogranodiorites from the Cordillera Blanca batholith (squares with cross, data of Atherton and Petford, 1993; Petford and Atherton, 1994)
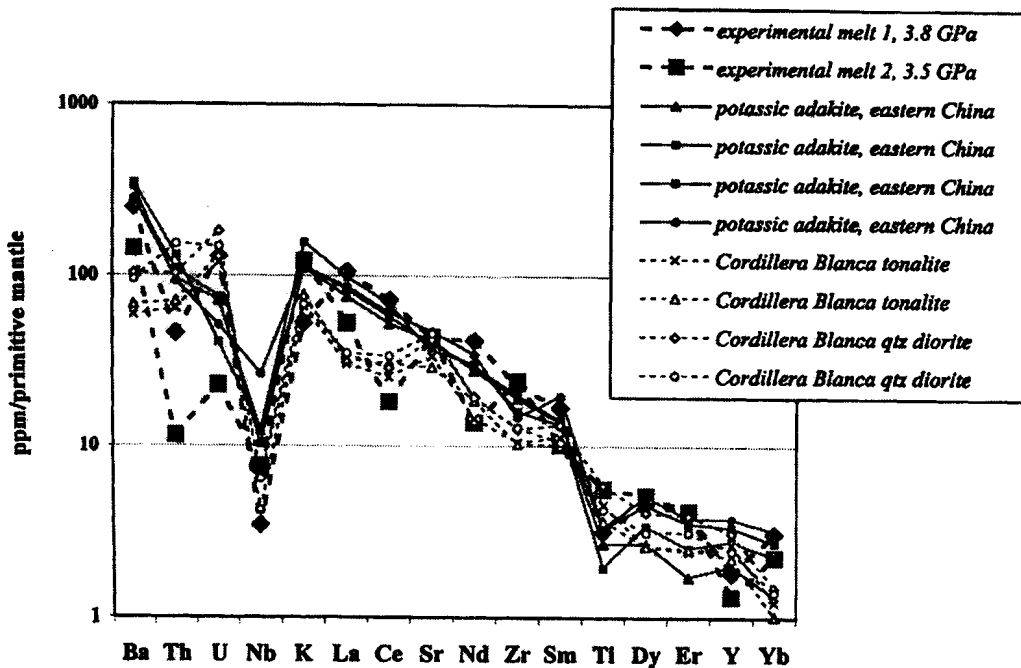

Fig. 3 Trace-element abundance patterns, normalized to primitive mantle (Sun and McDonough, 1989) for experimental adakite melts of basalt # 1 at 3.8 and # 2 at 3.5 GPa (Rapp and Watson, 1995; Rapp *et al.*, 1999), coexisting with rutile-bearing eclogite residues. Similar patterns are observed in adakite melts from lower pressure experiments at 1- 3 GPa (data of Table 2 and unpublished data of Rapp and Shimizu). Shown for comparison are the patterns for potassium-rich adakites from eastern China (data of Wang *et al.*, 2001; samples DBS 1019 and DBS JZ05); Pan *et al.*, 2001; sample 2174-1); Zhang *et al.*, 2001; sample 134a), and tonalites and quartz diorites from the Cordillera Blanca batholith, NW Peru (Petford and Atherton, 1996)

No clear distinctions are apparent between these data sets in terms of Sr/Y versus Y (Fig. 2b), with adakites from melting experiments, eastern China and the Peruvian Andes all showing the same general distribution trend, that of increasing fractionation of Sr from Y, coupled with decreasing Y concentrations. Based on the experimental samples, the range in the distribution of the data for the natural adakites is attributable to a combination of factors, including variable degrees of melting, at various P-T conditions, of compositionally variable yet broadly basaltic sources.

Mantle-normalized trace element abundance patterns

The overall distribution of trace elements during partial melting is controlled by mineral-melt partition coefficients for adakite liquids and crystalline phases present in the residue of melting (dominantly garnet, clinopyroxene, and rutile at pressures above 2 GPa). The characteristic trace element signature of adakite is distinguished by an overall enrichment in large ion-lithophile elements (including Ba, Th, U, K, LREEs, Sr), and strong depletions in HFSEs (*e. g.*, Nb, Ti) and the HREEs and Y (Defant and Drummond, 1990; Kay *et al*, 1993). These features are the consequence of equilibration between adakite melts and eclogitic residues containing rutile, typify adakite liquids in equilibrium with eclogitic residues at 1. 2- 3. 8 GPa, and are exemplified by the mantle-normalized trace-element abundance patterns (spidergrams) for two liquids from melting experiments at 3- 4 GPa (Fig. 3). Patterns for C-type adakites from eastern China (data from Pan *et al*, 2001; Wang and Zhang, 2001; Wang *et al*, 2001) show close similarities to the experimental melts, with general enrichment in LLEs, sharply negative Nb-anomalies, strong depletions in HREEs and Y, and variable relative depletion in Ti. The Chinese adakites, however, are distinguished by LREE and LLE abundances that are as high or higher than liquids formed at 3. 8 GPa from the most potassic basalt from Table 1; Ba, Th and K abundances are especially high in the Chinese samples. Potassic adakites have higher abundances of LREEs (La and Ce), MREE (Nd and Sm), Th and Ba, and lower U, when compared to tonalites and luecotonalites from the Cordillera Blanca. Similar comparisons with other Na-granitoids (*i. e.*, adakites) interpreted as lower crustal melts reveal similar compositional contrasts with the potassic adakites.

Nevertheless, the trace-element abundance patterns in Fig. 3 do strongly suggest that all these samples are related in the sense that they originated by partial melting of hydrous, garnet-bearing metabasalt, and the adakite geochemical signature was imparted through mineral-melt partitioning with the residual phase assemblage (garnet + clinopyroxene).

Discussion

Potassium-rich adakites from eastern China appear to be compositionally unique among granitoids possessing the adakite geochemical signature and interpreted as lower crustal melts. Similarities between the major- and trace-

element characteristics of adakites from eastern China and experimental melts clearly indicate an origin by dehydration melting of garnet-bearing metabasalt. The metaluminous A/CNK ratios (1. 0- 1. 1) and uniformly low Mg#'s (less than 40- 45) of the Chinese adakites suggest the following, respectively: (1) amphibole was absent or a minor phase in the residue of melting, and thus temperatures approached or exceeded the amphibole-out phase boundary (1000 at 2 GPa), and (2) the parental adakite magmas had limited interaction with mantle (peridotitic) assemblages. At pressures above 1. 5- 2. 0 GPa, sphene and/or rutile play a crucial role in effecting the sharp negative anomalies in Nb, Ti and other HFSEs apparent in Figure 3.

Liquids produced at pressures above 4 GPa (Table 2 and Fig. 1) have very low Na_2O/K_2O ratios (0. 5), but their Al_2O_3 contents are much lower than those of the potassic adakites, and implied crustal thicknesses are unrealistic (> 150 km). Potassium-rich granitoids formed at slightly lower pressure (3. 5- 3. 8 GPa; see Table 2) correspond more closely to C-type adakites in terms of Na_2O/K_2O ratios and Al_2O_3 contents, but would still require crustal thicknesses in excess of 120 km. Very low degrees of melting at pressures of 1- 3. 5 GPa (40- 120 km depth) can produce high-potassium liquids, but these liquids possess A/CNK ratios that are too high (< 1. 1- 1. 2) and Al_2O_3 concentrations that are too low to correspond to most adakites. Furthermore, such melts would also be expected to have the highest La/Yb and Sr/Y ratios, due to the partitioning effects of residual eclogitic phases, yet there is no obvious correlation between La/Yb or Sr/Y on the one hand, and Na_2O/K_2O ratios on the other. And adakites with low Na_2O/K_2O ratios occur over a range of SiO_2 contents, rather than at uniformly high SiO_2, which would be expected for very low-degree partial melts.

More likely, the compositional distinctiveness of potassic adakites is either attributable to a basaltic source that is unusually enriched in potassium and other LLEs, or to the effects of assimilation of intermediate lithologies in the lower-middle crust. Isotopic studies clearly indicate some level of crustal involvement in eastern China, but adakites from the Andean Austral Volcanic Zone which show isotopic evidence for significant interaction with the sub-arc crust (*e. g.*, Burney and Reclus volcanoes; Killian and Stern, 1996) still have "normal", adakitic, Na_2O/K_2O ratios (3- 5), and significantly lower LLE abundances than the potassic adakites of eastern China.

These considerations lead us to believe that the geochemical peculiarities that distinguish potassium-rich adakites arise from some unique aspect of either their source, or the lower crustal material with which they interacted. Potassium-rich shoshonites with high LLE abundances (*e. g.*, Ba, Th, U, LREEs), erupted in eastern China in the early Cretaceous (Wang and Zhang, 2001) attest to mantle activity and suggest a possible "enriched" source for the C-type adakites that followed upon magmatic underplating and crustal overthickening. Alternatively, assimilation of compositionally intermediate granulitic lithologies in the middle to lower crust (Taylor and

Table 2   Major-element compositions of near-solidus melts from 3.8 to 5 GPa

P(GPa)	1.8	3.2	3.8	3.8	3.8	3.8	5.0	5.0
Temp ( )	1000	1100	1000	1100	1200	1000	1100	1200
Oxide (wt%)								
SiO$_2$	67.88	65.93	71.10	67.52	66.61	73.15	67.20	69.29
TiO$_2$	0.49	1.31	0.79	1.72	1.88	0.68	1.78	2.19
Al$_2$O$_3$	18.01	17.55	14.43	17.60	13.84	14.68	12.01	11.58
FeO*	2.27	3.15	1.16	3.45	3.68	1.33	4.02	4.13
MnO	0.24	0.12	0.02	0.07	0.04	0.03	0.05	0.06
MgO	1.49	1.02	0.43	1.53	1.48	0.67	1.65	1.84
CaO	1.25	1.47	1.36	2.55	2.42	2.98	3.37	2.56
Na$_2$O	6.47	6.72	3.12	5.12	5.98	4.53	2.77	2.69
K$_2$O	2.62	2.55	7.03	4.13	3.66	1.59	6.46	5.66
P$_2$O$_5$	n.a	n.a	0.57	n.a	0.42	0.35	n.a	n.a
Mg$^\#$	0.28	0.37	0.40	0.44	0.42	0.47	0.42	0.44
A/CNK	1.14	1.06	0.95	1.00	0.76	1.01	0.68	0.76
Na$_2$O/K$_2$O	2.47	2.64	0.44	1.24	1.63	2.85	0.43	0.48
Melt(%)	20	30	12	17	36		8	13
Trace elements								
La	8.8	15	20	16.6	-	72	39.4	-
Yb	0.6	0.5	0.6	0.9	-	1.5	0.7	-
La/Yb	15	30	36	18	-	48	56	-
Sr	390	820	-	854	-	907	1663	-
Y	4.5	4.5	-	10	-	8.2	13.5	-
Sr/Y	87	182	-	85	-	111	123	-

McClennan, 1995) could explain the preferential enrichment in potassium and other LLEs. In either case, C-type adakites are considered to be the products of partial melting at the base of magmatically thickened lower crust; adakite magmatism was followed by a period of crustal extension and thinning, possibly in response to the foundering of dense eclogitic residues of melting, lower crustal delamination, and inflow of hot asthenospheric mantle (Wang and Zhang, 2001).

"Flat slab subduction" models based on seismic, geochemical and geochronologic evidence have recently been proposed for the Andes in Peru and southern Ecuador (Beate *et al*, 2001; Gutscher *et al*, 1999; Gutscher *et al*, 2000), offering an alternative to the lower crustal melting models of Atherton and Petford (1993). In these models, adakite magmatism is the result not of partial melting in the lower crust, but a consequence of slab melting. Subduction of the thick and buoyant "lost Inca Plateau" proceeded at a shallow angle and flattened out after penetrating 300 - 400 km inboard of the trench (Beate *et al*, 2001), providing an alternative (melting of the flat slab) to the lower crustal melting models for adakite volcanism in northern Peru and southern Ecuador. It remains to be seen whether or not such geodynamic models are applicable to eastern China. Kimura *et al* (1990) suggest that eastern Asia was being intensely deformed in the early Cretaceous as a consequence of collision between the Indochina Block and the Eurasian continent, arguing that these events controlled the evolution of subduction along the eastern continental margin. Yanshanian adakite magmatism in eastern China would then

have to be understood within the context of this more complex geodynamic setting, and any petrogenetic model for potassium-rich adakites would have to account for their compositional uniqueness.

Conclusions

Potassium-rich adakites of eastern China appear to be compositionally among adakites formed by either "slab melting" or "lower crustal melting" of broadly basaltic sources. The distinctiveness of the potassic adakites is attributable either to unique aspects of the source (alkalic basalt enriched in LLEs), or to the nature of the material with which it reacts during transport and emplacement. For most of the eastern China adakites, there is evidence for only limited mantle involvement in their petrogenesis, given their generally low Mg$^\#$'s (< 45); assimilation of granulitic lithologies in the lower to middle crust could explain both the low Mg$^\#$'s and the preferential enrichment in potassium and other LLEs, while being consistent with the isotopic evidence. Clearly, additional experimental study (including melting and assimilation experiments) is needed to better constrain the petrogenesis of potassium-rich adakites, and their role in crustal growth in eastern China, but their inclusion in the adakite family of granitoids, with origins in the dehydration melting of garnet-bearing metabasalt, seems appropriate.

Acknowledgements

References

Atherton M P and Petford N. 1993. Generation of sodium‑rich magmas from newly underplated basaltic crust. Nature, 362: 144- 146

Barnes C G, Barnes M A and Kistler R W. 1992. Petrology of the Caribou Mountain pluton, Klamath Mountains, California. Journal of Petrol, 33: 95- 124

Barnes C G, Petersen S W, Kistler R W, Murray R and Kays M A. 1996. Source and tectonic implications of tonalite‑trondhjemite magmatism in the Klamath Mountains. Contrib. Mineral Petrol, 123: 40- 60

Barth M G, Foley S F and Horn I. 2002. Partial melting in Archean subduction zones: constraints from experimentally determined trace element partition coefficients between eclogitic minerals and tonalitic melts under upper mantle conditions. Precambrian Res, 113: 323- 340

Beate B, Monzier M, Spikings R, Cotton J, Silva J, Bourdon E and Eissen J-P. 2001. Mio-Pliocene adakite generation related to flat subduction in southern Ecuador: the Quimsacocha volcanic center. Earth Planet. Sci. Lett, 192: 561- 570

Castillo P R, Janney P E and Solidum R U. 1999. Petrology and geochemistry of Camiguin Island, southern Philippines: insights to the source of adakites and other lavas in a complex arc setting. Contrib. Mineral Petrol, 134: 33- 51

Defant M J and Drummond M S. 1990. derivation of some modern arc magmas by melting of young subducted lithosphere. Nature, 347: 662- 665

Gutscher M -A, Maury R, Eissen J-P and Bourdon E. 2000. Can slab melting be caused by flat subduction?. Geology, 28: 535- 538

Gutscher M -A, Olivet J-L, Aswlanian D, Eissen J-P and Maury R. 1999. The " lost Inca Plateau ": cause of flat subduction beneath Peru? Earth Planet. Sci. Lett, 171: 335- 341

Johnston A D. 1986. Anhydrous P-T phase relations of near-primary high‑alumina basalt from the South Sandwich Islands: Implications for the origin of island arcs and tonalite-trondhjemite series rocks. Contrib. Mineral Petrol, 92: 368- 382

Kay R W. 1978. Aleutian magnesian andesites: melts from subducted Pacific ocean crust. Jour. Volcan. Geothermal Research, 4: 117- 132

Kay S M, Ramos V A and Marquez M. 1993. Evidence in Cerro Pampa volcanic rocks for slab melting prior to ridge‑trench collision in southern South America. Journal of Geology, 101: 703- 714

Kerrick D M and Connolly J A D. 2001. Metamorphic devolatilization of subducted oceanic metabasalts: implications for seismicity, arc magmatism and volatile recycling. Earth Planet. Sci. Lett. 189: 19- 29

Kepezhinkas P K, Defant M J and Drummond M S. 1995. Na metasomatism in the island-arc mantle by slab melt-peridotite interaction: evidence from mantle xenoliths in the North Kamchatka Arc. Journal of Petrology, 36: 1505- 1527

Kimura G, Takahashi M and Kono M. 1990. Mesozoic collision-extrusion tectonics in eastern Asia. Tectonophysics, 181: 15- 23

Li W P, Li X H and Lu F X. 2001. Genesis and geological significance for thr middle Jurassic high Sr and low Y type volcanic rocks in Fuxin area of west Liaoning, northeastern China. Acta Petrologica Sinica, 17 (4): 523- 532 (in Chinese with English abstract)

Lopez S and Castro A. 2001. Determination of the fluid-absent solidus and supersolidus phase relationships of MORB-derived amphibolites in the range 4- 14 kbar. American Mineral, 86: 1396- 1403

Molnar P and England P. 1995. Temperatures in zones of steady-state underthrusting of young oceanic lithosphere. Earth Planet. Sci. Lett, 131: 57- 70

Morris P A. 1995. Slab melting as an explanation of Quaternary volcanism and aseismicity in southwest Japan. Geology, 23: 395- 398

Muir R J, Weaver S D, Bradshaw J D, Eby G N and Evans J A. 1995. The Cretaceous Separation Point batholith, New Zealand: granitoid magmas formed by melting of mafic lithosphere. Journal Geol Soc. London, 152: 689- 701

Pan GQ, Lu XC and Yu HB. 2001. Petrological and geochemical characteristics of Mesozoic adakite from Northern Huaiyang and discussion on its genesis. Acta Petrologica Sinica, 17, 541- 550 (in Chinese with English abstract)

Peacock SM, Rushmer T and Thompson A B. 1994. Partial melting of subducting oceanic crust. Earth Planet. Sci. Lett, 121: 227 - 244

Petford N and Atherton M P. 1996. Na-rich partial melts from newly underplated basaltic crust: the Cordillera Blanca Batholith, Peru. Journal of Petrology, 37: 1491- 1521

Petford N and Gallagher K. 2001. Partial melting of mafic (amphibolitic) lower crust by periodic influx of basaltic magma. Earth Planet. Sci. Lett, 193: 483- 499

Rapp R P, Watson E B and Miller C F. 1991. Partial melting of amphibolite/eclogite and the origin of Archean trondhjemites and tonalites. Precambrian Res, 51: 1- 25

Rapp R P. 1995. The amphibole-out phase boundary in partially-melted metabasalt, its control over liquid fraction and composition, and source permeability. Jour. Geophys Res, 100: 15601- 15610

Rapp R P and Watson E B. 1995. Dehydration melting of metabasalt at 8- 32 kbar: implications for continental growth and crust-mantle recycling. Journal of Petrol, 36: 891- 931

Rapp R P, Shimizu N, Norman M D and Applegate G S. 1999. Reaction between slab-derived melts and peridotite in the mantle wedge: experimental constraints at 3.8 GPa. Chemical Geol, 160: 335- 356

Sajona F G, Bellon H, Maury R C, Pubellier M, Cotton J and Rangin C. 1994. Magmatic response to abrupt changes in geodynamic settings: Pliocene-Quaternary calc-alkaline and Nb-enriched lavas from Mindanao (Philippines). Tectonophysics, 237: 47- 72

Schmidt M W and Poli S. 1998. Experimentally based water budgets for dehydrating slabs and consequences for arc magma generation. Earth Planet. Sci. Lett, 163: 361- 379

Sen C and Dunn T. 1994. Dehydration melting of a basaltic composition amphibolite at 1. 5 and 2. 0 GPa: implications for the origin of adakites. Contrib. Mineral Petrol, 117: 394- 409

Smithies R H. 2000. The Archean tonalite-trondhjemite-granodiorite (TTG) series is not an analogue of Cenozoic adakite. Earth Planet Sci Lett, 182: 115- 125

Stern C R and Killian R. 1996. Role of the subducted slab, mantle wedge and continental crust in the generation of adakites from the Andean Austral Volcanic Zone. Contrib. Mineral Petrol, 123: 263- 281

Vielzeuf D and Schmidt M W. 2001. Melting relations in hydrous systems revisited: application to metapelites, metagreywackes, and metabasalts. Contrib. Mineral Petrol, 141: 251- 267

Wang Q, Xu JF, Zhao ZH, Wang RJ, Qiu JX and Bao ZW. 2001. The petrogenesis and geodynamic significance of HREE depleted granitoids during Yanshan period in the Dabie Mountains. Acta Petrologica Sinica, 17: 551- 564 (in Chinese with English abstract)

Wang Y and Zhang Q. 2001. A granitoid complex from Badaling area, North China: composition, geochemical characteristics and its implications. Acta Petrologica Sinica, 17: 533- 540 (in Chinese with English abstract)

Wang YL, Zhang Q and Wang Y. 2001. Geochemical characteristics of volcanic rocks from Ningwu area, and its significance. Acta Petrologica Sinica, 17: 565- 575 (in Chinese with English abstract)

Wareham C D, Millar IL and Vaughan A PM. 1997. The genration of sodic granite magmas, western Palmer Land, Antarctic Peninsula. Contrib. Mineral Petrol, 141: 81- 96

Winther K T and Newton R C. 1991. Experimental melting of hydrous low-K tholeiite: evidence on the origin of Archean cratons. Bull Geol Soc. Denmark, 39: 213- 228

Xiong XL, Zhao ZH, Bai ZH, Mei HJ, Xu JF and Wang Q. 2001. Origin of Awulale adakitic sodium-rich rocks in western Tianshan: Constraints for Nd and Sr isotopic compositions. Acta Petrologica Sinica, 17: 514- 522 (in Chinese with English abstract)

Xu JF, Wang Q and Yu X-Y. 2000. Geochemistry of high_Mg andesites and adakitic andesite from the Sanchasi block of the Mian-Lue ophiolitic mélange in the Qinling Mountains, central China: Evidence of partial melting of the subducted Paleo-Tethyan crust. Geochemical Jour, 34: 359- 377

Xu JF, Mei H, Yu X, Bai Z, Niu H, Chen F, Zhen Z and Wang Q.

2001. Adakites related to subduction in the northern margin of Junggar arc for the Late Paleozoic: Products of slab melting. Chinese Science Bull, 46: 1312- 1316

Xu JF, Wang Q, Xu YG, Zhao ZH and Xiong XL. 2001. Geochemistry of Anjishan intermediate-acid intrusive rocks in Ningzhen area: Constraint to origin of the magma with HREE and Y depletion. Acta Petrologica Sinica, 17: 576- 584 (in Chinese with English abstract)

Zhang Q, Wang Y, Qian Q, Yang J, Wang YL, Zhao T P and Guo GJ. 2001. The characteristics and tectono-metallogenic significance of the adakites in Yanshan period from eastern China. Acta Petrologica Sinica, 17: 236- 244 (in Chinese with English abstract)

Zhang Q, Wang Y and Wang YL. 2001. Preliminary study on the components of the lower crust in east China plateau during Yanshanian Period: Constraints on Sr and Nd isotopic compositions of adakite-like rocks. Acta Petrologica Sinica, 17, 505- 513 (in Chinese with English abstract)

,   ,   . 2001.   Sr   Y
                    .   , 17(4): 523- 532
,   ,   . 2001.   adakite
                    .   , 17(4): 541- 550
,   ,   ,   ,   ,   . 2001.
                                          .   , 17
(4): 551- 564
,   . 2001.
        , 17(4): 533- 540
,   ,   . 2001.
        , 17(4): 565- 575
,   ,   ,   ,   ,   . 2001.
                          : Nd   Sr   .   ,
17(4): 514- 522
,   ,   ,   ,   . 2001.
                                :
        .   , 17(4): 576- 584
,   ,   ,   ,   ,   ,   . 2001.
                                          -        .   , 17(2):
236- 244
,   ,   . 2001.   :
        Sr Nd   .   , 17(4): 505- 513