Origin of Mesozoic adakitic intrusive rocks in the Ningzhen area of east China: Partial melting of delaminated lower continental crust?

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ABSTRACT

To the best of our knowledge, modern adakites have not been documented in a nonarc environment. We report geochemical and isotopic data for Early Cretaceous Anjishan adakitic intrusive rocks that are in a continental setting unrelated to subduction. The Anjishan adakitic intrusive rocks, which are exposed in the Ningzhen area of east China, have high Sr/Y and La/Yb ratios coupled with low Yb and Y as well as relatively high MgO contents and Mg numbers (Mg#; 0.4–0.6), similar to products from slab melting. However, low $\epsilon_{Nd(t)}$ values (−6.8 to −9.7) and high $(^{87}Sr/^{86}Sr)_i$ (0.7053–0.7066) are inconsistent with an origin by slab melting. The tectonics and geochemistry lead us to conclude that adakitic magmas were most likely derived from partial melting of mafic material at the base of the continental crust. High Sr/Y and La/Yb ratios of the adakitic intrusive rocks suggest that garnet was stable as a residual phase during partial melting, implying that the crustal thickness exceeded 40 km in the Early Cretaceous. The present thickness of the crust in the Ningzhen area is only 30 km, and therefore the crust appears to have been thinned by at least ~10 km since the Early Cretaceous. The relatively high MgO contents and Mg# of the Anjishan intrusive rocks suggest that adakitic magmas interacted with mantle rocks, possibly coinciding with lower-crustal delamination, which would also account for the observed thinning.

Keywords: adakite, lower-crustal melting, delamination, continental crust, slab melting, east China.

INTRODUCTION

It is generally considered that adakites (Defant and Drummond, 1990) are produced by slab melting (Kay, 1978) in subduction zones. However, some rocks with adakitic compositional features have been considered to have alternative origins, e.g., assimilation–fractional crystallization (AFC) processes involving a basaltic magma (Castillo et al., 1999), or partial melting of mafic lower crust (e.g., Atherton and Petford, 1993; Muir et al., 1995; Barnes et al., 1996). Atherton and Petford (1993) emphasized that basaltic magmas underplating the lower crust could generate adakites. Experimental studies (e.g., Rapp and Watson, 1995; Rapp et al., 1999) have also shown that mafic materials can melt to produce adakitic liquids at pressures equivalent to crustal thicknesses of >40 km (i.e., ~1.2 GPa), when the residual phases have garnet but no plagioclase. Although lower-crustal melting may be another way of generating adakites (in addition to slab melting), all reported adakites attributed to lower-crustal melting occur in arc settings (e.g., Atherton and Petford, 1993; Muir et al., 1995). Thus, there is still considerable debate over whether the source for these adakitic magmas is the slab (e.g., in a flat subduction setting, see Gutscher et al., 2000) or the lower crust. There are no geochemical criteria available that can distinguish adakites produced by lower-crustal melting from those generated by slab melting, and therefore it is still unclear whether and how lower-crustal melting leads to adakitic magmatism.

In this paper we show that the Ningzhen region of east China provides the first clear evidence of nonarc adakites. These rocks challenge the traditional slab-melting hypothesis for their generation. We document not only that the lower crust was partially melted, but also that the melting and adakitic magmatism coincided with delamination of amphibole-bearing eclogitic materials from the lower crust.

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GEOLOGIC SETTING

It is generally accepted that the region of east China has been a part of the present Eurasian continent since the North China and South China continental blocks were joined in the Triassic (Enkin et al., 1992; Ames et al., 1993). Extensive granitic and intermediate to acid volcanic rocks of Cretaceous and Jurassic age are exposed in this region (Fig. 1). Although it has been proposed that some volcanic rocks in southeast China (Fig. 1) are related to possible westward subduction of the Mesozoic paleo-Pacific plate (e.g., Lapierre et al., 1997; Zhou and Li, 2000), other studies have argued that these volcanic rocks, together with the granitic rocks, are not related to subduction, and indicate a nonarc setting for this region during the Mesozoic (Xu et al., 1987; Tao and Xue, 1989; Mao et al., 1990; Lu et al., 1997; Li, 2000, and references therein). The close association of A-type granites, within-plate mafic rocks, and high-K calc-alkaline intrusive and volcanic rocks as well as nontypical volcanic arc granites (VAG) led Li (2000) to suggest a within-continent extensional tectonic regime for southeast China during the Cretaceous. Moreover, Cretaceous peralkaline igneous rocks—phonolite and aegirite-augite syenite (Tao and Xue, 1989; Zhao et al., 1991)—have been found near the Ningzhen area. These peralkaline igneous rocks are associated with the adakitic intrusive rocks discussed herein, and their occurrence strongly argues against active subduction setting in the Cretaceous, because peralkaline magmatism is generally not associated with convergent plate margins. In summary, there is strong evidence that the Ningzhen area in east China was not within a subduction zone during the Cretaceous.

The Ningzhen area is geographically east of Nanjing City, and northwest of Shanghai City (Fig. 1A). A number of granitic plutons of Cretaceous age are exposed in the Ningzhen area; the Anjishan pluton is representative of these. It is a stock (~40 km^2) with an irregular

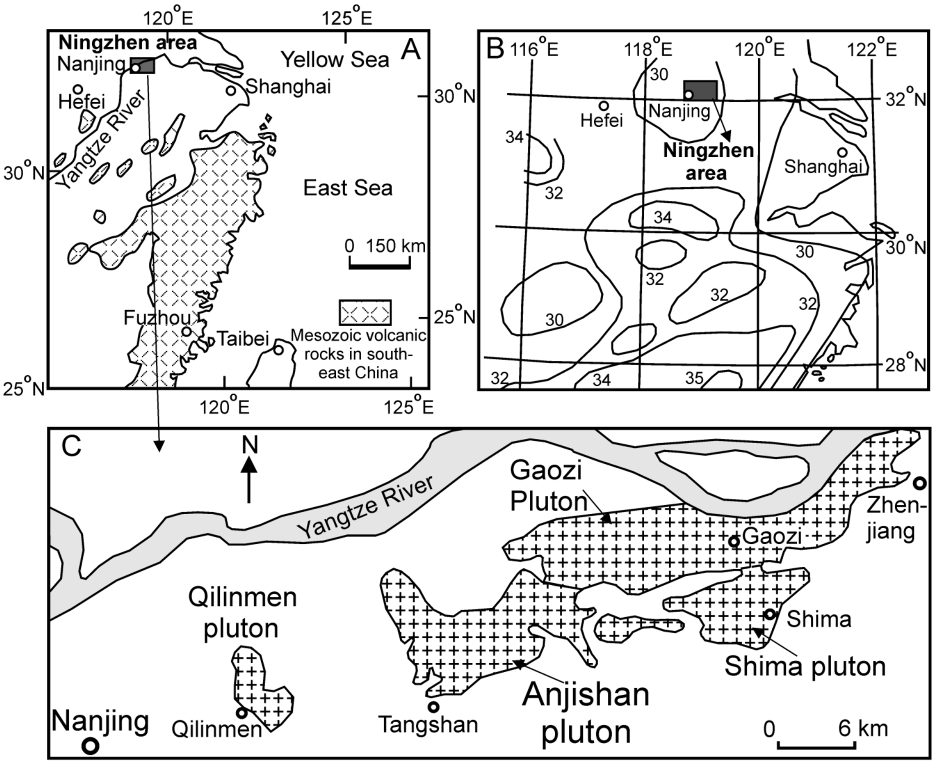

Figure 1. Simplified map of east China, showing distribution of Ningzhen plutons of Early Cretaceous age and volcanic rocks of Mesozoic age. A: Location of Ningzhen area in east China. B: Contour map of crustal thicknesses (km) in east China at present (after Wang, 1992). C: Simplified geologic map of Anjishan pluton and other plutons in Ningzhen area (after Xia, 2000). Location of map in C is shown in A and B by black rectangle.

shape (Fig. 1C). K-Ar isotopic dates indicate an Early Cretaceous age, i.e., 106–123 Ma (Mao et al., 1990; Xia, 2000). The Anjishan pluton mainly consists of quartz-diorite (quartz <20%) and granodiorite (quartz >20%). A small volume of mafic intrusive rocks, i.e., gabbroic and dioritic porphyries, occurs along the margin of the pluton. Other Early Cretaceous granitic plutons in the Ningzhen area, i.e., the Shima, Qilinmen, and Gaozi plutons (Fig. 1C), have rock types and mineral associations similar to the Anjishan pluton (Xia, 2000).

ANALYTICAL METHODS AND RESULTS

Fresh rock samples of the Anjishan pluton were collected for elemental and isotopic analysis. Major elements were determined by gravimetry (wet chemistry) and atomic absorption spectrometry (AAS). Trace elements were determined by inductively coupled plasma–mass spectrometry (ICP-MS) at the China University of Geosciences (Wuhan). The analytical procedure for the ICP-MS analyses is similar to that described by Hu et al. (2000). Nd, Sr, and Pb isotopic ratios of the rocks were analyzed on a Finnigan MAT-262 thermal ionization mass spectrometer (TIMS) at the University of the Ryukyus, Japan. The analytical procedure for the TIMS was described in detail by Shinjo et al. (2000).

On the basis of the major element data (Tables DR1 and DR2[1]), rocks in the Anjishan pluton can be divided into two groups. The first group consists of gabbros and diorites with SiO_2 contents ranging from 51 to 54 wt%. The second group, which makes up the bulk of the pluton and is referred to hereafter as the Anjishan rocks, consists of quartz diorite and granodiorite with SiO_2 content of >60 wt%. They are high in Al_2O_3 (>15 wt%), but show a range of K_2O contents (0.42–2.98 wt%), most of which are higher than adakites from slab melting (Defant and Drummond, 1990). In addition, the Anjishan rocks have relatively high MgO contents (1.52–3.99 wt%, Fig. 2A) and Mg numbers (Mg# = molar [Mg/(Mg + Fe)]; 0.4–0.6), similar to those of adakites derived from slab melting, but clearly higher than those of experimental low- to moderate-degree partial melts of hydrous basalt in the garnet stability field, and Archean tonalite-trondhjemite-diorite (TTD) (Fig. 2A).

[1]GSA Data Repository item 2002130, Tables DR1 and DR2, Elemental and isotopic analyses, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

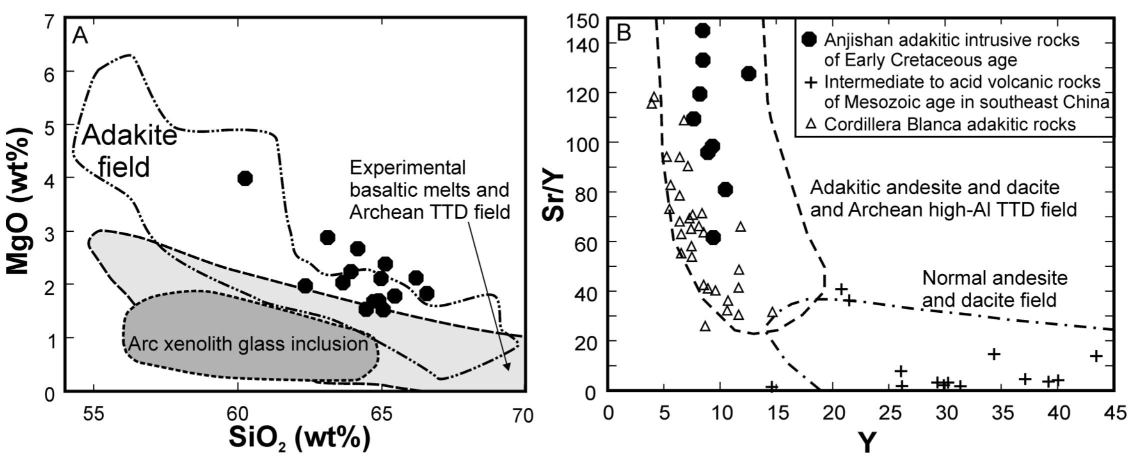

Figure 2. MgO vs. SiO_2 (A) and Y vs. Sr/Y (B) diagrams for Anjishan adakitic intrusive rocks. A: Anjishan adakitic intrusive rocks show MgO contents similar to those of adakites derived from slab melting, but clearly higher than those of experimental melts and Archean TTD (tonalite-trondhjemite-diorite). B: Anjishan rocks fall in adakite field similar to adakites of Cordillera Blanca. In contrast, volcanic rocks in southeast China fall in normal andesite and dacite field. Data of Cordillera Blanca rocks are after Petford and Atherton (1996); data of volcanic rocks in southeast China are from Lapierre et al. (1997). After Defant and Kepezhinskas (2001).

The Anjishan rocks have low heavy rare earth element (RRE) and Y contents (Yb, 0.78–1.16 ppm; Y, 7.4–12.5 ppm), and high Sr concentrations (820–1579 ppm), resulting in high La/Yb and Sr/Y ratios. They are in the adakite and high-Al TTD field on Sr/Y versus Y diagram (Fig. 2B) and show compositional characteristics that generally fit those of a slab melt as defined by Defant and Drummond (1990). However, the Nd and Sr isotopic data (Table DR2; see footnote 1) of the Anjishan rocks show low $\epsilon_{Nd(t)}$ (−6.8 to −9.7) and high $(^{87}Sr/^{86}Sr)_i$ (0.7053–0.7066), features that distinguish these adakites by partial melting of subducted mid-oceanic-ridge basalt (MORB) (e.g., on Cook Island, Stern and Kilian, 1996; and at Cerro Pampa, Kay et al., 1993). The Nd and Sr isotopic characteristics of the Anjishan rocks are similar to those of adakitic rocks in the Cordillera Blanca batholith, which were suggested to be derived from the lower crust (Petford and Atherton, 1996).

GENESIS OF THE ANJISHAN ADAKITIC INTRUSIVE ROCKS

Here we discuss the different possibilities for generating the Anjishan rocks. Castillo et al. (1999) proposed that assimilation–fractional crystallization (AFC) processes involving basaltic magma had produced rocks with adakitic characteristics at Camiguin Island in the Philippines. However, similar AFC processes seem unlikely to produce the Anjishan adakitic magmas. Coexisting mafic rocks within the Anjishan pluton and other plutons in the Ningzhen area occur in very small volumes, and it is unlikely that fractionation of such (apparently) small volumes of mafic magmas could be responsible for the large volumes of granitoid observed. Unlike the Camiguin suite of volcanic rocks, in which the acid members with adakite-like compositions are thought to be generated through AFC processes (Castillo et al., 1999), intermediate to acid and mafic rocks in the Anjishan pluton do not display continuous compositional variation; there an a SiO_2 gap from 54 to 60 wt%. The $\epsilon_{Nd(t)}$ values (>−4.9) of the mafic rocks are also higher than those of the Anjishan rocks (Table DR2; see footnote 1), suggesting a difference in the isotopic characteristics of their sources. Thus, it is difficult to explain the chemical signatures of these magmas through AFC processes.

Alternatively, the Anjishan rocks could have been produced by slab melting. As noted here, tectonic reconstructions do not favor a subduction-zone scenario at this time in east China (e.g., Lu et al., 1997; Li, 2000). In addition, Sr and Nd isotopic characteristics, low $\epsilon_{Nd(t)}$ and high $(^{87}Sr/^{86}Sr)_i$ values, of the Anjishan rocks do not show any indication of a MORB component, and the Anjishan rocks have low Pb isotopic age-corrected ratios [$(^{206}Pb/^{204}Pb)_i$ <17, Table DR2; see footnote 1], whereas Mesozoic MORB and oceanic sediments in the West Pacific have generally high $^{206}Pb/^{204}Pb$ (>18, Castillo et al., 1994; Shimoda et al., 1998). This indicates that the source for the Anjishan rocks was not subducted slab or sediments.

Lower-crustal melting is thought to be the most likely interpretation for the origin of the Anjishan rocks discussed here. Generally, adakitic rocks produced by lower-crustal melting are believed to come directly from a lower-crust source via heating from a basaltic melt that underplates the continent (e.g., Atherton and Petford, 1993). If adakitic magmas are derived directly from partial melting of mafic rocks in the lower crust, they should have a relatively low MgO content (or alternatively, Mg#), similar to the experimental melts of Rapp and Watson (1995). However, the Anjishan rocks show relatively high MgO contents (Fig. 2A) and Mg# values, suggesting that pristine adakitic melts must have interacted to some extent with mantle material (e.g., Rapp et al., 1999). The best scenario that can explain the elevated MgO (Mg#) of the Anjishan adakitic rocks seems to be delamination of the lower crust consisting of amphibole-bearing eclogitic materials, coinciding with dehydration melting of the delaminated crustal rocks in the subcrustal mantle. As the pristine adakitic melts rise, they pass through the mantle, elevating their MgO and Mg# values via reaction.

ADAKITE PRODUCED BY DELAMINATION OF THE LOWER CRUST

The Anjishan rocks are characterized by high Sr/Y and La/Yb ratios, indicating the residual presence of garnets and the loss of plagioclase in the source during partial melting. Because such a source is generally thought to occur at >40 km (>1.2 GPa) (Rapp and Watson, 1995; Petford and Atherton, 1996), the crustal thickness in the Ningzhen area was at least 40 km when the Anjishan adakitic magma was produced in the Early Cretaceous. However, the present crustal thickness in the Ningzhen area is only ~30 km (Fig. 1B), according to the geophysical survey by Wang (1992). These data imply that the Mesozoic continental crust in the Ningzhen area was thicker (>40 km) than the present crust, and the Ningzhen crust therefore has most likely undergone a thinning process. Mesozoic–Cenozoic volcanic and sedimentary rocks are still preserved in the Ningzhen area (Fig. 1A), suggesting that the upper crust in this area has not undergone extensive erosion since the Early Cretaceous. Thus, delamination could explain the thinning of the Mesozoic crust in the Ningzhen area. The standard explanation for delamination is that, as the continental crust thickened, the lower mafic section reached pressure and temperature conditions favorable to the formation of eclogite, which in the Ningzhen area would probably be amphibole-bearing eclogitic materials that were not fully dehydrated and had not undergone partial melting prior to delamination. These eclogitic materials were denser than the mantle rocks and could break away from the crust and sink, i.e., delaminate (Kay and Kay, 1993), resulting in the present thinner crust in the Ningzhen area.

It is generally accepted that at least 100 km of Archean to Proterozoic lithospheric mantle was removed from beneath large areas of east China during late Mesozoic to Tertiary time (e.g., Griffin et al., 1998; Xu et al., 2000). The thinning process was probably aided by upwelling of younger asthenospheric material, replacing a part of the old lithospheric mantle (Xu et al., 2000). When the hotter asthenospheric material rose and replaced the colder lithospheric mantle, the flux of heat from the underlying asthenosphere could trigger partial melting of the delaminated lower-crustal materials that were then within the subcrustal mantle. In addition, considering both the time of the lithospheric mantle thinning (late Mesozoic–Tertiary) and the age of the Ningzhen adakitic intrusive rocks (106–123 Ma), we conclude that the delamination of lower crust in east China also happened during the Cretaceous–Tertiary.

Thus, we suggest a model in which lower-crustal delamination coincided with adakitic magmatism (Fig. 3). We infer that source materials in the lower parts of thickened crust (>40 km) in the Ningzhen area consisted of amphibole-bearing eclogitic material that sank into the subcrustal mantle, and these delaminating blocks were heated by the relatively hot subcrustal mantle coupled with a flux of heat from upwelling asthenosphere, inducing dehydration melting and the generation of adakitic magmas. We also suggest that the delaminated crustal block melted, rather than the newly exposed new base of the crust, because the MgO content and Mg# value of the adakitic rocks collected require interaction with mantle rocks as the adakitic melts ascended.

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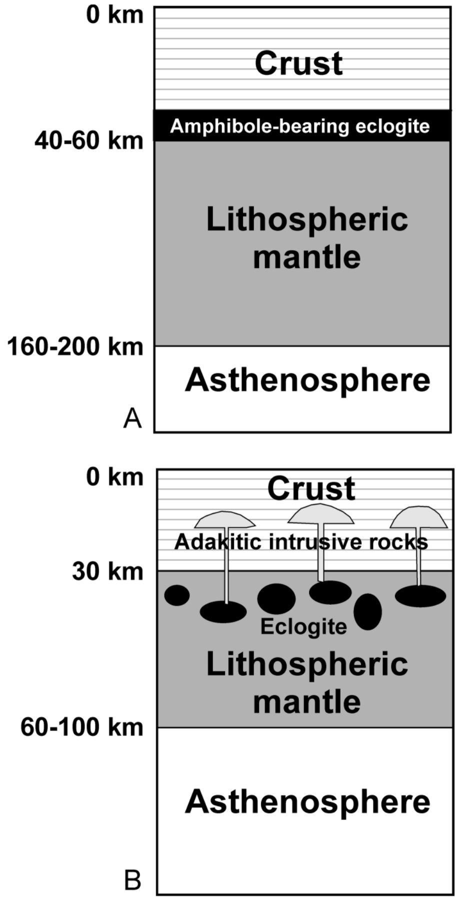

Figure 3. Suggested model to produce Anjishan adakitic intrusive rocks via delamination of lower crust. A: Relatively thick crust and lithospheric mantle in Jurassic (?) time. Lower part of thick crust is composed of amphibole-bearing eclogite that is not yet fully dehydrated. B: Thick crust was thinned through delamination in or after Cretaceous time. As amphibole-bearing eclogite bodies sank into underlying mantle, adakitic melt (light gray) was produced by dehydration melting of amphibole-bearing eclogite materials (black) that were heated by relatively hot mantle, coupled with flux of heat from upwelling asthenosphere. Adakitic melts pass through mantle, elevating MgO contents (and Mg#) of adakites via reaction. Thinning of lithospheric mantle during Mesozoic in east China is after Xu et al. (2000).

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