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Are continental "adakites" derived from thickened or foundered lower crust?

Qiang Ma [a,b], Jian-Ping Zheng [b,*], Yi-Gang Xu [a,*], William L. Griffin [c], Rui-Sheng Zhang [b]

[a] State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
[b] State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan 430074, China
[c] ARC CoE for Core to Crust Fluid Systems/GEMOC, Macquarie University, NSW 2109, Australia

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ABSTRACT

The geochemical signatures of "adakites" are usually attributed to high-pressure (≥50 km) partial melting of mafic rocks, and accordingly the occurrence of adakitic magmas in continental settings is frequently used as an indicator of a thickened or foundered lower crust at the time of magma emplacement. These premises are built on experiments and modeling using an MORB-like source, but the probable source of continental "adakites" (i.e., continental lower crust) is compositionally different from MORB. To elucidate the effect of source inheritance and pressure on resultant melts, geochemical analyses and trace-element modeling have been carried out on Jurassic adakitic rocks from the northern part of the North China Craton. The results show that these continental adakitic melts can be generated at depths less than 40 km, and their "adakitic" signature is most likely inherited from their source rocks. Such conclusions can be applied to the Mesozoic adakitic magmas from the interior of the North China Craton. Only the "adakites" from collisional orogens (i.e., Tibet, Dabie UHP belt) require crustal melting at depths greater than 50 km, consistent with collision-induced crustal thickening in these areas. This study therefore highlights the importance of source composition when defining the formation conditions of magmatic rocks in general, and in particular questions the common use of "adakites" as an indicator of specific geodynamic situations.

1. Introduction

"Adakite" is used to describe a group of intermediate-felsic igneous rocks found in modern subduction zones; they are characterized by high Sr/Y (>40) and La/Yb (>20), depletion in Nb–Ta relative to light rare earth elements (LREEs) and large-ion lithophile elements (LILEs) and a lack of obvious Eu anomalies (Kay, 1978; Defant and Drummond, 1990). Melting experiments and modeling based on MORB-like basaltic source regions have shown that this adakitic geochemical signature can be achieved via high-pressure melting (≥1.5 GPa, Xiong et al., 2005; Nair and Chacko, 2008) of mafic rocks. In recent years, many igneous rocks with compositions similar to adakites have been identified in continental settings (Xu et al., 2002; He et al., 2011) and are inferred to be the products of similar high-pressure melting of mafic rocks. Thus, partial melting of thickened or foundered lower continental crust (LCC) at depths greater than 50 km is often invoked in the genesis of continental adakitic magmas (Chung et al., 2003; Gao et al., 2004). However, source composition, which is critical in the petrogenetic evaluation of magmatic rocks, has not been fully considered in these models. In particular, continental "adakites" tend to have radiogenic initial Sr and unradiogenic Nd isotopes (Fig. 1a), suggesting a source in ancient lower continental crust, which probably differs drastically in composition from MORB (Fig. 1b). More importantly, experiments have shown that adakitic melts can be produced by lower-pressure (10–12.5 kbar) melting of lower crust without leaving eclogitic residues (Qian and Hermann, 2013). It is therefore necessary to reassess the relative contributions of source inheritance *vs* high-P melting to the genesis of intra-continental adakitic melts.

To address this issue, we have carried out geochemical analyses and trace-element modeling on Jurassic adakitic volcanic rocks from the Yanshan belt in North China (Fig. 2), which have previously been interpreted as melts derived from a thickened lower crust (Zhang et al., 2008). We present a new petrogenetic model for continental adakitic rocks, in which the importance of source composition in the formation of "adakitic" magmas is emphasized.

* Corresponding authors.
E-mail addresses: jpzheng@cug.edu.cn (J.-P. Zheng), yigangxu@gig.ac.cn (Y.-G. Xu).

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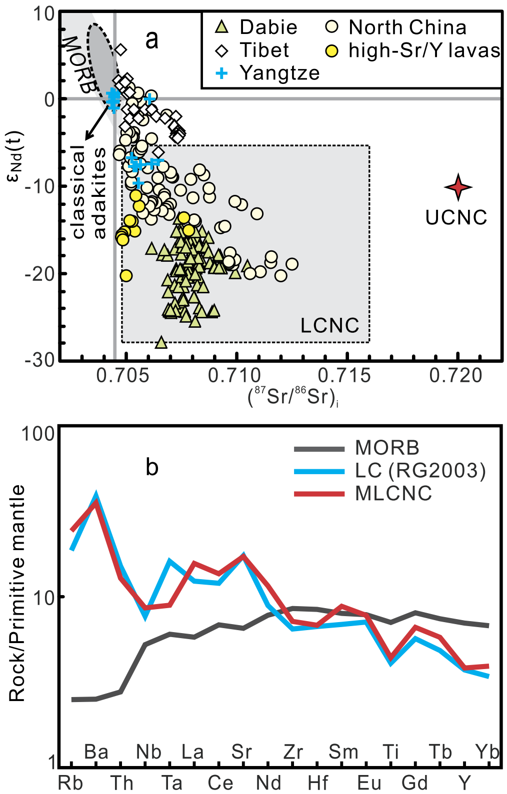

Fig. 1. (a) Sr–Nd isotopic compositions of Mesozoic–Cenozoic continental adakitic rocks from China. (b) Primitive mantle (PM) normalized trace-element patterns of mafic lower crust of the NCC (MLCNC), lower continental crust (RG2003) and MORB. Data sources: North China Craton, Gao et al. (2004), Yang and Li (2008), Ma et al. (2012), Chen et al. (2013), Xu et al. (2006) and this study; Yangtze Craton, Xu et al. (2002) and Wang et al. (2006a); Tibet Plateau, Chung et al. (2003), Hou et al. (2004) and Wang et al. (2005); Dabie Orogen, He et al. (2013) and references therein; lower continental crust, Rudnick and Gao (2003); MORB, Arevalo Jr. and McDonough (2010). Upper (UCNC) and lower crust (LCNC) of the North China after Jahn et al. (1999) and Jiang et al. (2013). Classical adakites, attributed to partial melting of subducted oceanic crust in modern arcs, are from the GeoRoc database (http://georoc.mpch-mainz.gwdg.de/georoc). Sr–Nd isotopes of MORBs (include both N-MORB and E-MORB) in (a) are from (http://www.earthchem.org/petdb). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Geological background

The North China Craton (NCC; Fig. 2a) is well known worldwide for several reasons. It is one of the oldest (≥3.8 Ga, Liu et al., 1992) Archean cratons in the world. It has lost its lithospheric keel (>100 km) during the Phanerozoic, and represents the best example of craton-root destruction (Menzies et al., 1993; Griffin et al., 1998; Xu, 2001; Zheng et al., 2007). It is located between two major orogenic belts: the Qingling–Dabie–Sulu Orogenic belt to the south and the Central Asian Orogenic Belt to the north. The EW-trending Yanshan belt (Fig. 2a) is located in the northern part of the NCC. This region was tectonically dominated by post-collisional extensional regimes in the early Mesozoic, intraplate contractional environment in late Jurassic and crustal extension in early Cretaceous. Mesozoic terrestrial volcanic and clastic strata (Fig. S1, Supplementary online materials) unconformably overlie an Archean–Paleoproterozoic basement and Cambrian–Permian sedimentary units in this area. Volcanic rocks, varying from mafic to andesitic–felsic in composition, have been identified and interpreted as the results of cratonic destruction (Yang and Li, 2008; Ma et al., 2012). The middle-late Jurassic volcanic rocks across the Yanshan belt (Fig. 1b) mainly consist of intermediate-felsic lavas and pyroclastic rocks of the Haifanggou Formation (∼173 Ma, this study; Fig. S2) and the overlying Lanqi Formation (166–153 Ma, Ma and Zheng, 2009).

3. Analytical methods

Geochemical data presented here include whole-rock compositions, Sr–Nd isotopes and zircon U–Pb and Hf isotopes; these are listed in Tables S1–S3. All the analyses were conducted at State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences (Wuhan). Major- and trace-element compositions of whole rocks were measured by XRF and ICPMS, respectively. Sr and Nd isotopic ratios were analyzed using a Finnigan Triton TIMS. In-situ U–Pb and Hf isotope analyses of zircons were conducted by LA-ICPMS and MC-LA-ICPMS, respectively. Full details of the analytical methods are provided in Supplementary online materials.

4. Geochemistry

The samples collected range in composition from trachyandesite to rhyolite (Fig. 3a) with SiO_2 of 56.1–74.5 wt% and total alkalies ($Na_2O + K_2O$) of 5.7–9.7 wt%. These lavas show enrichment of LREEs over HREEs (Fig. 4a). They are enriched in LREEs, LILEs and Pb, with negative anomalies in high-field-strength elements (HFSEs) in the PM-normalized trace element plots. The lavas also have whole-rock Sr–Nd and zircon Hf isotopes (initial $^{87}Sr/^{86}Sr = 0.70434$ to 0.70787, $\varepsilon_{Nd}(t) = -20$ to -11, and $\varepsilon_{Hf}(t) = -21.7$ to $+4.1$; Tables S2–S3) indicative of derivation from older crustal rocks. Based on their compositions (Table S1), they can be subdivided into two groups (Figs. 3–5). Most of them, defined as high-Sr/Y lavas in this study, are characterized by high Sr (>540 ppm) and LREEs, low Y (8–21 ppm) and heavy rare earth elements (HREEs), a lack of obvious Eu anomalies (Fig. 4a), and low contents of MgO (<4.9 wt%), Ni (<41 ppm) and Cr (<57 ppm except 2 samples) (Fig. 3b); in all these features they are broadly similar to the high-silica adakites (Martin et al., 2005) and to experimental melts of mafic lower crust at 1–1.5 GPa (Qian and Hermann, 2013). The second group, defined as low-Sr/Y lavas, has higher Y (12–43 ppm) and HREEs and thus lower Sr/Y and La/Yb compared to the first group; it is similar to normal arc-related andesites, dacites and rhyolites (ADRs) (Fig. 5). The lavas of the second group also show enrichment in Th and U, lower Ba/Th and more variable Rb/Ba than the high-Sr/Y lavas, and have been interpreted as partial melts of upper lower-crustal to middle-crustal intermediate rocks (Yang and Li, 2008). This second group of rocks is not the focus of this study.

5. Petrogenesis of the Jurassic high-Sr/Y lavas

5.1. Assessing the role of AFC in petrogenesis of high-Sr/Y lavas

Crustal assimilation and/or fractional crystallization (AFC) can change the chemical and isotopic compositions of magmas and is considered as an important process in “adakite” petrogenesis (Castillo et al., 1999). However, the lack of correlation between initial Sr isotopic compositions and SiO_2 contents (Fig. S3) shows that crustal contamination or assimilation of intermediate-felsic crustal rocks is not appreciable in most of the investigated lavas. Using an adakitic dacite (C4-4-88) from a modern arc (Defant et al., 1992) as representative of “adakites” before continental crust assimilation, the modeled Sr–Nd isotopes of melts resulting from contamination are dramatically different from those of the Jurassic high-Sr/Y lavas (Fig. S3), which also suggests their Sr–Nd isotopes are not the product of crustal interaction. Moreover, AFC modeling on the representative lavas (Supplementary online materials) suggests that AFC processes would drive the