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Role of lithosphere–asthenosphere interaction in the genesis of Quaternary alkali and tholeiitic basalts from Datong, western North China Craton

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Abstract

The geochemistry of Quaternary volcanic rocks from Datong provides important constraints on the petrogenesis of continental alkali and tholeiitic basalts and lithospheric evolution in the western North China Craton. Alkali basalts in north Datong have trace element compositions similar to oceanic island basalts (OIB). They show nearly homogenous isotopic compositions (ε_{Nd} = 5.4–6.8 and $^{87}Sr/^{86}Sr$ = 0.7035–0.7037) that resemble the nearby Hannuoba Miocene basalts, indicating that the two lava suites share a similar asthenospheric source. However, Datong basalts have conspicuously lower Al_2O_3 and CaO, higher SiO_2 and HREE contents and Na/Ti ratios, compared to Hannuoba lavas at comparable MgO. This compositional difference is attributable to the combined effect of source difference and temporal decrease in melting depth. The latter reflects Cenozoic lithospheric thinning of the western North China Craton.

Tholeiitic basalts in southeast Datong have incompatible element ratios that differ from OIB; they have lower ε_{Nd} (1.3–3.7) and higher $^{87}Sr/^{86}Sr$ (0.7039–0.7046) compared to alkali basalts. These moderately evolved rocks (MgO < 7%) display unusually high Cr concentrations (>200 ppm), a nearly flat LREE pattern and a fractionated HREE with the "kink" occurring at Gd. A shallow melting depth (<60 km), suggested by their Q-normative composition, is in conflict with the residual garnet in the source (>75 km) as required by REE modeling. This paradox, which is reminiscent of that for Hawaiian tholeiites, can be reconciled if garnet lherzolite melts react with refractory peridotites during which orthopyroxene is dissolved and olivine precipitates. The diagnostic consequence of this melt–rock reaction includes increases in SiO_2 and Cr, decreases in Al_2O_3 and CaO, and formation of "kinked" REE patterns. Involvement of lithospheric mantle in the genesis of Datong tholeiites may be related to the Cenozoic lithospheric thinning/erosion in the western North China Craton. The spatial distribution of Datong alkali and tholeiitic basalts may be related to enhanced extension along the lithospheric boundary between the Western Block of the North China Craton and the Trans-North China Orogen.

Keywords: Alkali basalt; Tholeiite; Petrogenesis; Geochemistry; Lithospheric thinning; Lithosphere–asthenosphere interaction; Western North China craton

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1. Introduction

Continental basalts commonly show a wider compositional diversity than oceanic counterparts (Perry et al., 1987; Song et al., 1990; Zhi et al., 1990; Fan and Hooper, 1991; Fitton et al., 1991; Wilson and Downes, 1991; Zhou and Mukasa, 1997; Jung and Masberg, 1998; Zou et al., 2000; Barry et al., 2003). There is ample evidence that the continental lithosphere (crust+mantle) plays a central role in creating this compositional diversity. Continental lithosphere may serve as a passive mechanical barrier to continuous upwelling of the asthenosphere, thereby defining the final depth of melting (e.g., Langmuir et al., 1992; Fram and Lesher, 1993), or it may have a more direct role in determining magma composition by serving as a source component (e.g., Perry et al., 1987; Fitton et al., 1991) or a magma contaminant (e.g., Glazner and Farmer, 1992). These possible roles for continental lithosphere must be evaluated when using the geochemistry of continental basalts to constrain the magma sources and accompanying mantle processes (e.g., Cox and Hawkesworth, 1984; Perry et al., 1987; DePaolo and Daley, 2000). For example, the effect of a thick lithospheric lid on the composition of asthenosphere-derived basalt is indicated by indicators of the mean pressure of melt segregation, such as FeO, SiO_2 and Na/Ti (Langmuir et al., 1992; Putirka, 1999a). The effect of wallrock contamination during ascent of magmas through lithosphere is especially important for tholeiitic basalt which ascends relatively slowly due to low volatile contents (Cox and Hawkesworth, 1984). Clearly, determining the relative contribution of continental lithospheric mantle (CLM) and crust to basaltic composition is a formidable task for petrologists.

The alkali and tholeiitic basalt in the Quaternary Datong volcanic field in North China provides new information about the relative roles of asthenosphere and lithosphere in the generation of continental basalt. Like many other volcanic terrains, the two rock types from this locality display different geochemical signatures. In addition, the two basalt types show distinct spatial provinciality, rather than intercalation as at Hannuoba, 100 km north of Datong (Zhi et al., 1990; Song et al., 1990). On the other hand, it is well established that the Archaean North China Craton (NCC) experienced widespread thermotectonic reactivations during the Late Mesozoic and Cenozoic, which resulted in replacement of the old, cold, thick and depleted lithospheric mantle by young, hot, thin and fertile mantle (Menzies et al., 1993; Griffin et al., 1998; Xu, 2001). More importantly, the lithospheric thinning in the NCC may have proceeded in a diachronous way. While the lithosphere is progressively thinned in the western NCC (located east to the Daxinganling–Taihangshan gravity lineament, Fig. 1) during the Cenozoic, it is thickened in the eastern NCC, probably related to regional thermal decay following peak magmatism in the Late Cretaceous (Xu et al., 2004a). Datong Quaternary basalts are emplaced in western NCC and are compositionally distinct from Oligocene and Miocene lavas in the region (Xu et al., 2004a). Petrogenetic characterization of Datong lavas is therefore the key to understand the lithosphere–asthenosphere interaction during the dramatic change in lithospheric architecture in the NCC (Menzies et al., 1993; Griffin et al., 1998; Xu, 2001). The objectives of this study are:

(a) to present major, trace element and Sr–Nd isotopic composition of alkali and tholeiitic basalts from Datong and to discuss their petrogenesis with emphasis on defining the role of lithosphere–asthenosphere interaction in continental basaltic volcanism;
(b) to compare geochemical data of the Datong lavas with the well-studied Miocene basalts from Hannuoba, to define the temporal change in mantle melting conditions in the NCC using forward and inverse REE modeling techniques and to test the proposed model on the Cenozoic lithospheric evolution of the NCC; and
(c) to propose a tectonomagmatic model to explain the spatial distribution of the Datong basalts.

2. Geologic background and petrographic characteristics

Traditionally, the NCC is separated into two different tectonic domains by the N–S trending Daxinganling–Taihangshan gravity lineament (DTGL) (Ye et al., 1987; Ma, 1989; Menzies and Xu, 1998). This division was recently refined on the basis of lithological, geochemical and metamorphic *P–T* path data of the basement rocks (Zhao et al., 2001). The basement of the NCC is now divided into three blocks, namely Eastern and Western Blocks and the intervening Trans-North China Orogen (Fig. 1a). The Eastern Block consists predominantly of Early to Late Archean tonalitic–trondhjemitic–granodiotitic (TTG) batholiths. The Late Archean lithological assemblage, structural style and metamorphic history in the Western Block are similar to those of the Eastern Block. The Trans-North China Orogen is composed of Late Archean to Paleoproterozoic TTG gneisses and granitoids, inter-