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Crust recycling in the sources of two parallel volcanic chains in Shandong, North China

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ABSTRACT

Recycled crustal components have been documented for many sources of hotspot-related ocean island basalts, but they have been difficult to identify in continental basalts, because in continental settings, hotspots are often obscured and recycled crustal sources are difficult to distinguish from crustal contamination. We show major, trace element and Sr–Nd–Hf isotopic compositions for two parallel chains of Cenozoic volcanoes from Shandong Province, North China, which are free of crustal contamination and show clear evidence for recycling of mafic lower crust. Sr, Nd, and Hf isotopes in the two volcanic chains form separate binary mixing arrays, which converge on the composition of Dashan, an isolated, nephelinitic volcano with the most depleted isotopic signature. The two chains have lower CaO values and significantly diverging isotope enrichment trends from this common endmember. Both trends deviate from the normal Sr–Nd and Hf–Nd mantle array toward lower $^{87}Sr/^{86}Sr$ and higher ε_{Hf} values, all features that point to a (recycled) eclogitic source.

We invoke a two-stage evolution model to generate the endmembers of these two mixing trends. In the first stage, recycled mafic crust (eclogite) is depleted by earlier (late Mesozoic) melt extraction, which elevates the Lu/Hf of the residue relative to Sm/Nd due to garnet control during melting. Subsequently, these silica-deficient residues are transported to the deeper mantle. Finally, in Cenozoic time, upwelling mantle (possibly a plume) transports lenses of residual eclogites into the shallow asthenosphere. The recycled crustal components beneath the two chains differ somewhat in isotopic composition due to different degree of the earlier melting. The upwelling mantle spreads beneath the lithosphere and flows toward regions of thinned lithosphere, e.g. the Tan–Lu Fault Zone in North China, where the recycled crust undergo remelting and mix with peridotite-derived melts to produce the two mixing trends observed.

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1. Introduction

The origin of wide-spread Cenozoic continental volcanism in eastern China is problematic because there is no obvious cause of melting, since only some of this volcanism is directly associated with rifting. Recent seismic tomography has identified a low velocity region in the upper mantle beneath the central part of the North China craton (NCC), reaching at least into the transition zone (Zhao et al., 2009), and this might represent a mantle plume. However, much of the volcanism is located hundreds of kilometers from this possible plume, and invoking a plume mechanism to account for all these melts might initially seem far-fetched. We will nevertheless argue that this represents perhaps the simplest mechanism for causing significantly older, recycled crustal material to melt and generate some of the Cenozoic magmatism discussed in this paper.

Major Cenozoic basaltic fields in the NCC include Hannuoba, Datong, Taihang, and Shandong. Previous studies suggest that alkaline basalts in the NCC have an asthenospheric source by their OIB-like geochemical and isotopic compositions, whereas the tholeiites may have been contaminated by the crust or the lithospheric mantle because of their more enriched isotopic compositions (Peng et al., 1986; Song et al., 1990; Xu et al., 2005). Tang et al. (2006) proposed that the geochemical signatures of alkaline basalts in Taihang, in particular their moderately enriched isotopic compositions, can be induced by asthenosphere–lithosphere interactions. Other authors have attributed the OIB-like signatures of alkaline basalts to the contributions of the recycled crust in their asthenospheric source (Chen et al., 2009a; Liu et al., 2008). In addition, our recent study of the basanites and nephelinites from Shandong has suggested that their asthenospheric source has been enriched by carbonatitic liquids (Zeng et al., 2010). Therefore, the nature of the source(s) of Cenozoic alkaline basalts in the NCC remains controversial, and the specific cause of melting has hardly been addressed in the recent literatures.

We focus here on a specific example of two parallel volcanic chains in the eastern part of the NCC, which superficially resemble the

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parallel volcanic chains on the Hawaiian islands, in that they are parallel, spaced about 40 km apart, and display consistent geochemical differences in a manner somewhat analogous to those described for the Kea and Loa trend volcanic chains on Hawaii (Abouchami et al., 2000; Abouchami et al., 2005). And although there are many obvious differences as well, such as the lack of time progression, the absence of an immediately obvious plume source, and a rather short length of the chains (50 km), there are additional similarities, such as inferred source compositions containing recycled crustal components, which are noteworthy. We show that the low-Ca contents of primary magmas are derived from an eclogitic source component, which is thought to be derived from older, recycled lower continental crust. These residual eclogite-derived melts are mixed with nephelinitic melts derived from a peridotitic source, which is also present in many of the isolated volcanic centers on the NCC.

Ebinger and Sleep (1998) proposed that much of the young volcanism occurring in Africa is related to a single plume rising in the Afar region and laterally flowing to shallow asthenospheric regions beneath thinned lithosphere, and we will argue that a similar mechanism can account for much of the Cenozoic volcanism in northern China. When the sublithospheric plume flow encounters regions of locally thinned lithosphere, it reaches sufficiently shallow levels to undergo melting and produce the observed chains of basaltic volcanoes. Thus we suggest that the consistent geochemical differences between the two volcanic chains are related to heterogeneities that have been severely stretched and elongated by plume flow, in a manner similar to those observed in the Hawaiian plume by Abouchami et al. (2005) and modeled by Farnetani and Hofmann (2010).

2. Geological setting and sample description

The North China Craton (NCC) is one of the world's oldest cratons, located in the central part of eastern China (Figure 1). The NCC is composed of two Archean blocks (the eastern block, and the western block) and one Proterozoic orogenic belt (the central part) (Figure 1) (Zhao et al., 2005). Cenozoic alkaline basalts in the NCC, as well as those in northeast and southeast China, represent the youngest magmatism in eastern China, and provide an ideal opportunity to study the chemical heterogeneities of the asthenosphere beneath a continent (see reviews by Chen et al., 2009a; Zou et al., 2000; and references therein) (Figure 1). The Shandong Province is located in the southeast of the NCC. The Cenozoic alkaline magmatism in Shandong took place during two periods: 24.0–10.3 Ma and 8.7–0.3 Ma (see the review by Luo et al., 2009). The early magmatism was profuse and characterized by large volcanoes densely distributed in a narrow area near the Tan–Lu Fault Zone (TLFZ) (Figure 1); the rocks of this age are mainly weakly alkaline basalts, including alkali olivine basalts and basanites. The later magmatism is characterized by small, isolated volcanoes, widely scattered in areas far from the TLFZ; the rocks of this group are dominated by basanites and nephelinites (Zeng et al., 2010), e.g. Dashan in Wudi. Mantle xenoliths are commonly contained in the alkaline basalts from Shandong. In particular, the early weakly alkaline basalts are arranged in two parallel volcanic chains: the north chain and the south chain (Figure 1). The parallel volcanic chains show a direction of north by east 55°, and the angle between these volcanic chains and the TLFZ is about 40°. They range about 40 km in length, and the distance between them is about 50 km.

We have chosen eight volcanoes from the two chains, including Niushan, Shanwang, Taohuashan, Fangshan, Fuyanshan of the north chain and Longshan, Chengdingshan, Liushan of the south chain, to study the genesis of basalts from chain-related volcanoes in Shandong. Samples from Niushan, Shanwang, Taohuashan, Chengdingshan and Fuyanshan are unaltered. Samples from Fangshan, Longshan, and Liushan are slightly altered, and olivine phenocrysts are partially altered to low-temperature iddingsite. All samples have minor olivine (<15%) as phenocrysts set in a groundmass of olivine,

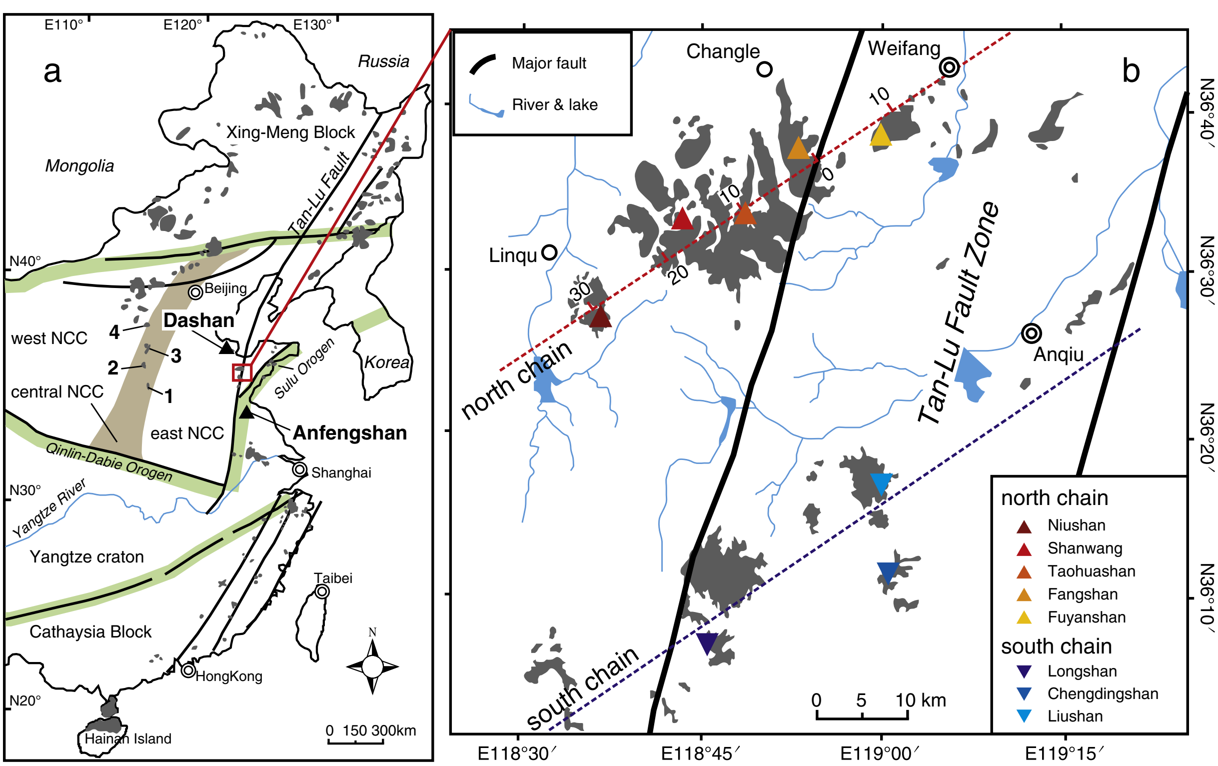

Fig. 1. (a) Simplified geological map of eastern China. Cenozoic basalts from Taihang Mountain area of central NCC include: 1 — Hebi basalts (4.3–4.0 Ma), 2 — Zuoquan basalts (5.6 Ma), 3 — Xiyang–Pingding basalts (7.9–7.3 Ma), and 4 — Fansi basalts (26–24 Ma) (Liu et al., 1992; Tang et al., 2006). (b) Distribution of the Cenozoic chain-forming volcanoes in Shandong. The red line and the blue line refer to the distributing directions of the north chain and the south chain, respectively. The distributions of Cenozoic basalts in eastern China and in Shandong are from Liu et al. (1992) and Shandong Institute of Geological Survey (2005), respectively.

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