Earth and Planetary Science Letters 286 (2009) 426–435

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Sources of Anfengshan basalts: Subducted lower crust in the Sulu UHP belt, China

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ARTICLE INFO

Article history:
Received 12 December 2008
Received in revised form 6 July 2009
Accepted 6 July 2009
Available online 3 August 2009

Editor: R.W. Carlson

Keywords:
continental subduction
eclogite
crustal recycling
alkaline basalt
mantle heterogeneity

ABSTRACT

Deep subduction of lower continental crust to mantle depths has been recognized in outcrops and drill cores of eclogites and other ultra-high pressure (UHP) rocks of the Sulu intra-continental orogenic belt. In a search of evidence for such subducted crustal sources of melts, we study the elemental and isotope geochemistry of basalts from Anfengshan, a Miocene volcano located in the Sulu UHP belt, as well as Nd–Hf isotopes of eclogites from the Sulu belt itself. The Anfengshan basalts are basanites and nephelinites with low SiO_2, high incompatible element contents, positive Nb, Ta, Sr, and negative K, Pb, Zr, Hf, and Ti anomalies. Radiogenic isotopes ($^{87}Sr/^{86}Sr = 0.70337–0.70359$, $\varepsilon_{Nd} = +5.1–+6.7$, $\varepsilon_{Hf} = +10.6–+12.3$, $^{206}Pb/^{204}Pb = 17.5–18.0$) show some highly unusual correlations: ε_{Nd} correlates positively with $^{87}Sr/^{86}Sr$, but negatively with ε_{Hf}. $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, and $^{206}Pb/^{204}Pb$ ratios all correlate negatively with $\Delta\varepsilon_{Hf}$ (= deviation from the global ε_{Hf}–ε_{Nd} correlation). The correlations form two distinct mixing arrays with one common, high-ε_{Nd} end-member. Superchondritic Zr/Hf ratios (~55), and negative Zr, Hf, Ti anomalies indicate that the common mantle source component has been metasomatized by carbonatitic liquids. We suggest that the other two source components are eclogites derived from subducted lower crust: both of these differ from ordinary mantle components by their low $^{87}Sr/^{86}Sr$ and low ε_{Nd} and $^{206}Pb/^{204}Pb$, but high $\Delta\varepsilon_{Hf}$.
The ε_{Nd}–ε_{Hf} values of the eclogites form two groups, both of which lie close to the Hf–Nd mantle array, and are therefore not direct analogues of possible source eclogites for the basalts. We explain the shift toward high $\Delta\varepsilon_{Hf}$-basalt sources as follows: an early Cretaceous igneous event extracted partial melts from the eclogites residing in the mantle, thereby increasing their (residual) Lu/Hf ratios, while changing Sm/Nd only slightly. During the Anfengshan melting event, these garnet-rich sources produced melts with low Zr/Hf and increased Nb/Nb*, Hf/Hf*, Sm/Yb ratios relative to the peridotitic source end-member. We therefore suggest that the eclogites represent the residues of mafic lower continental crust subducted during the Triassic continent–continent collision. This interpretation is supported by recent seismic tomography, which revealed a high-velocity anomaly in the uppermost mantle beneath the Sulu belt.

1. Introduction

Subduction recycles crustal rocks into the mantle, and the chemical heterogeneity of the mantle observed in the composition of oceanic basalt is largely due to the recycling of subducted oceanic crust (Hofmann, 1997). In addition to oceanic subduction, continental subduction has also been observed with the recognition of ultra-high pressure (UHP) rocks in intra-continental collisional zones, especially in the Eurasian continent, e.g. the Qinling–Dabie–Sulu belt of eastern China, Kokchetav Complex of northern Kazakhstan, Maksyutov Complex of the southern Urals, the Dora–Maira massif of the Western Alps, and the Western Gneiss Region of southwestern Norway (Ernst and Liou, 2000). Mineral evidence from UHP eclogites shows that continental crust can be subducted into the deep asthenospheric mantle (>200 km) (Ye et al., 2000). Although some of the UHP rocks have been exhumed, most of them, especially mafic eclogites transformed from lower crust, are expected to remain in the mantle because of their high density. However, it is still poorly understood whether and how such subducted continental materials contribute to the compositions of the mantle and to the sources of mantle-derived basalts.

The Qinling–Dabie–Sulu orogen is the world's largest UHP belt (Zhang et al., 2007). The continent–continent collision between the North China craton and the Yangtze craton in the Triassic produced this giant UHP terrain in central China. The geochemistry of the eclogites suggests that the protoliths of these UHP metamorphic rocks are mainly lower crustal cumulates (Liu et al., 2008b), which implies that the lower crust of the Yangtze craton has been subducted into the mantle beneath the North China craton. Recent seismic tomography revealed a high-velocity anomaly (eclogite?) in the uppermost mantle (40–110 km) beneath the Sulu (Xu et al., 2001). Does this high-velocity anomaly possibly represent the subducted lower crust of the

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doi:10.1016/j.epsl.2009.07.006

Yangtze craton? Since basalts offer the best opportunity to understand the chemical/lithological heterogeneity of the uppermost mantle, and lower continental crust has distinct isotopic signatures, we use Sr–Nd–Pb–Hf isotopes and major and trace element geochemistry of Anfengshan basalts, a Cenozoic volcano in the Sulu orogenic belt, to investigate the contribution of recycled lower continental crust in their mantle sources.

2. Geological setting and sample description

The early-Mesozoic Qinling–Dabie–Sulu orogenic belt is the boundary between the North China craton and the Yangtze craton (Fig. 1). Ultrahigh-pressure coesite-bearing eclogites are widespread in this orogenic belt, providing evidence for the northward subduction of crustal rocks of the Yangtze craton down to mantle depths (>100 km) (see a review by Zheng et al., 2003). Since Triassic time, the central part (the Dabie UHP belt) and the eastern part (the Sulu UHP belt) of this giant orogenic belt have been dislocated by approximately 500 km of left-lateral strike-slip displacement along the Tan-Lu fault (Fig. 1). In the late-Mesozoic, the eastern part of the North China craton experienced a tectono–thermal reactivation with intensive magmatism and the development of extensional basins (Menzies and Xu, 1998).

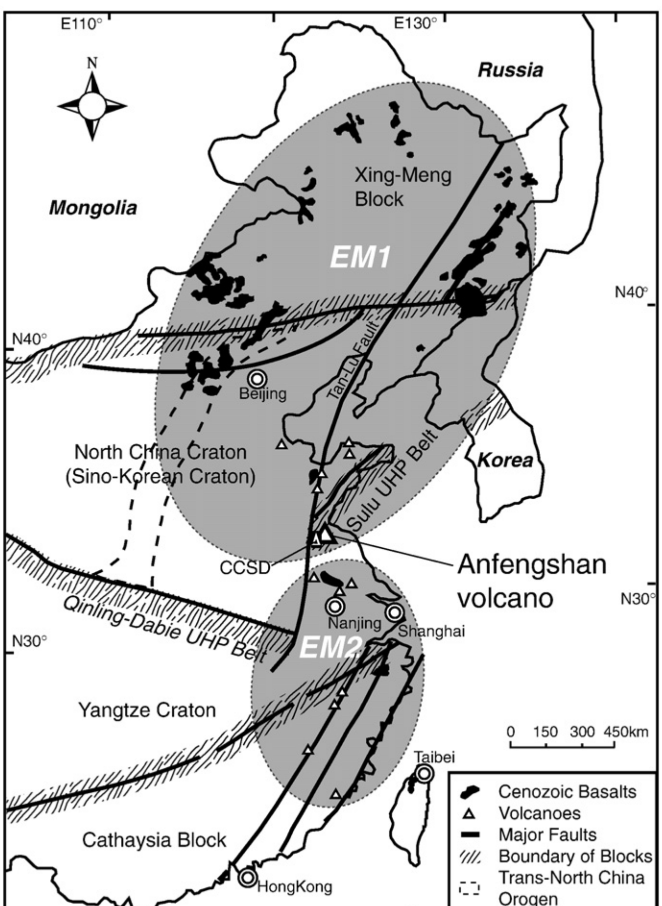

Fig. 1. Simplified geological map of eastern China. The distributions of Cenozoic basalts in eastern China are shown as dark area and triangles (isolated volcanoes). Anfengshan volcano (large triangle) is located in the west end of the Sulu UHP belt. Cenozoic basalts from North China and Northeast China (upper shadowed area) show isotopic affinities with EM1-type oceanic basalts, while Cenozoic basalts from South China (lower shaded area) show EM2-type isotopic affinities.

In Eastern China, Cenozoic basalts are widely distributed along the coastal provinces and adjacent offshore shelf and constitute the Eastern China volcanic belt (Fig. 1). This magmatism is closely associated with major regional faults, e.g. the Tan-Lu fault. The Cenozoic volcanic rocks are mainly composed of alkaline basalts. Strongly alkaline rocks, e.g. basanite, nephelinites can be found in some Neogene/Quaternary isolated volcanoes (Fig. 1). These alkaline basalts are geochemically characterized by enrichment of large ion lithophile elements (LILEs), light rare earth elements (LREEs), and Nb and Ta. Isotopic compositions of the alkaline basalts from southeast China show EM2 affinities, while those from north China and northeast China show EM1 affinities (see Fig. 2 and a review by Zou et al., 2000).

The research area of Donghai County is located in the eastern part of the Sulu UHP belt, near the Tan-Lu fault (Fig. 1), and is famous as the location of the Chinese Continental Scientific Drilling (CCSD) project (N34º25′, E118º40′). There are two Cenozoic volcanoes, Pingmingshan and Anfengshan, in this county. Anfengshan is the larger one with an area of ~5.5 km^2; it is located only 10 km to the east of the main hole of the CCSD (N34º21′, E118º44′). K–Ar dating yielded an early Miocene age (12.3–7.3 Ma) for this volcano (Jin et al., 2003). Samples of this paper were collected in quarries around the Anfengshan, and all are fresh without obvious alteration. No peridotite xenoliths are found in Anfengshan, whereas there are many such xenoliths in the Pingmingshan volcano. Here we only discuss Anfengshan. The Anfengshan basalts contain olivine as the principal phenocryst phase (<15 vol.%) that exists in a groundmass (>85%) composed of olivine, ilmenite, nepheline, and glass. Plagioclase and clinopyroxene phenocrysts are not observed.

Our study also includes a comparison between Anfengshan basalts and UHP eclogite samples from the drilling site (CCSD) nearby. Detailed descriptions of the eclogite samples of this study can be found elsewhere (Qiu et al. 2006; Wang et al., in press).

3. Analytical methods

Nine fresh samples were selected for whole-rock analysis. The measurements of whole-rock major and trace elements were carried out at the Department of Geology, Northwest University in Xi'an, China. We used a RIX-2100 X-ray fluorescence spectrometer (XRF) to measure the major elements. According to the measured values of standards (GSR-1 and GSR-3), the uncertainties are about ±1% for

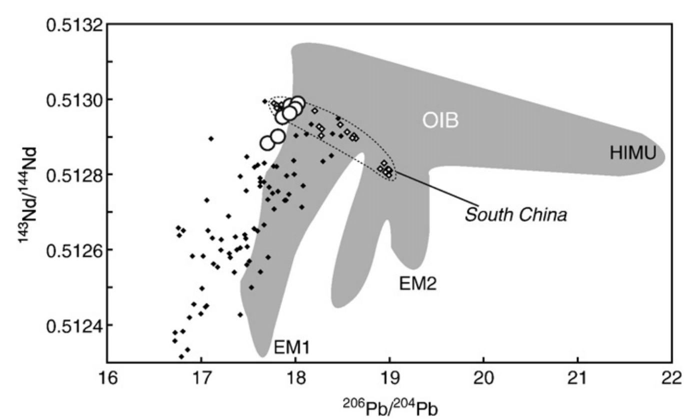

Fig. 2. Pb–Nd isotopic compositions of Cenozoic basalts in North China and Northeast China. Anfengshan basalts are shown as large open circles. Data for North China and Northeast China (filled diamonds) are from (Peng et al., 1986; Song et al., 1990; Basu et al., 1991; Zhang et al., 1995, 2005; Tang et al., 2006), data for South China (open diamonds) are from (Zou et al., 2000). The OIB fields are from the Georoc database (http://georoc.mpch-mainz.gwdg.de/georoc/).