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Transition zone origin of potassic basalts from Wudalianchi volcano, northeast China

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ABSTRACT

The origin of historic potassic basalts (from the 1719 to 1721 AD eruption) from the Wudalianchi volcanic field, northeast China, is investigated. The samples examined in this study are aphyric, and contain ~5 vol.% olivine microphenocrysts. Geochemical analyses of the samples, along with published data for material from the 1719 to 1721 AD eruption, show that the basalts exhibit linear compositional trends in whole-rock variation diagrams, and are characterized by K_2O enrichment (>4 wt.%) and an EM1-like isotopic signature. Using thermodynamic calculations and the observed petrological features of the basalts, the temperature of the magmas shortly before eruption is estimated to have been ~1250 °C, and the water content of the magma at depth is estimated to have been >~1.1 wt.%. Because the estimated temperatures are significantly higher than the projected maximum temperature of the lithospheric mantle beneath the Wudalianchi volcanic field, the magmas were likely derived from the asthenospheric mantle. We suggest that both the potassic- and EM1-like natures of the basalts originated from the mantle transition zone, metasomatized by K-rich sediment fluids ~1.5 Ga ago through a stagnation of an ancient slab. The linear whole-rock compositional trends of the basalts primarily reflect the geochemical heterogeneity in the mantle transition zone, with variable but coupled contributions of ~1.5 Ga sediments in the ancient stagnant slab, and recent sediments and peridotites in the stagnant Pacific slab. We infer that the Wudalianchi magmatism was caused by an upwelling of a hydrous mantle plume from the mantle transition zone, which was hydrated through the stagnation of the ancient subducted slab and the recent Pacific slab.

1. Introduction

In northeast (NE) China, Cenozoic intraplate volcanic products are widely distributed (Fig. 1), and magmatism in some volcanic fields is still active. These rocks have characteristic EM1 (enriched mantle-1: Zindler and Hart, 1986)-like isotopic signatures (e.g., Basu et al., 1991; Choi et al., 2006; Zou et al., 2000), and constitute one of the largest expressions of the DUPAL anomaly (Hart, 1984) in the Northern Hemisphere. The origin of the magmatism has previously been investigated extensively, and earlier studies have examined the nature of the source mantle as well as the tectonic processes responsible for the magmatism (e.g., Basu et al., 1991; Chen et al., 2003; Liu et al., 1994; Tatsumoto et al., 1992; Zhang et al., 1991, 1995; Zhou and Armstrong, 1982).

In NE China, the stagnant slab of the subducted Pacific plate is present in the mantle transition zone at depths of 410–660 km (e.g., Fukao et al., 1992; Zhao, 2004), and recent geophysical studies suggest that the transition zone under NE China is remarkably hydrous (Karato, 2011; Kelbert et al., 2009). On the basis of these geophysical observations, the Pacific slab stagnation and its relation to observed intraplate magmatism has received growing attention (Chen et al., 2007; Kuritani et al., 2011; Lei and Zhao, 2005; Ohtani and Zhao, 2009; Richard and Iwamori, 2010; Zhao et al., 2009; Zou et al., 2008). Currently, there are two contradicting proposals for the origin of the intraplate magmatism in NE China. On the basis of the absence of any island-arc geochemical signature in the erupted products, some of the studies have contended that the NE China magmatism was not affected by fluids derived from the stagnant Pacific slab (Chen et al., 2007; Zou et al., 2008). Alternatively, others have suggested a possible link between transition-zone processes and the overlying magmatism (Kuritani et al., 2011; Lei and Zhao, 2005; Ohtani and Zhao, 2009; Richard and Iwamori, 2010; Zhao et al., 2009).

Among Cenozoic basalts in NE China, the basalts from the Wudalianchi volcanic field (Fig. 1) show extreme geochemical features, characterized by high K_2O (absarokite to shoshonite) and incompatible trace element contents, as well as high $^{87}Sr/^{86}Sr$ and $^{207}Pb/^{206}Pb$ ratios, and low $^{143}Nd/^{144}Nd$ ratios (i.e., EM1-like signatures) (e.g., Basu et al., 1991). A number of geochemical studies have been carried out on Wudalianchi basalts, as well as mantle xenoliths hosted by the basalts, to elucidate the origin, source mantle characteristics, and magma generation processes (e.g., Chen et al., 2007; Zhang et al., 1991, 1995, 1998, 2011; Zou et al., 2003). These studies have suggested that the basalts were generated in the sub-continental lithospheric mantle (SCLM). Although geochemical data obtained in the

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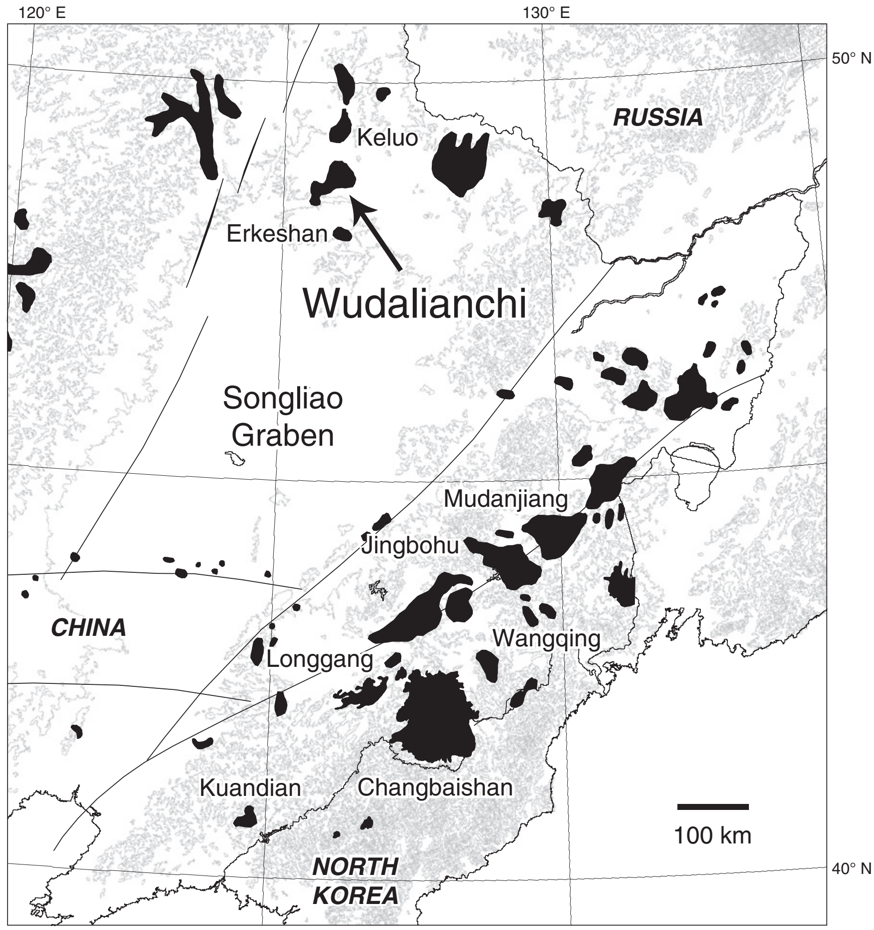

Fig. 1. A map showing the distributions of Cenozoic volcanic rocks and deep faults in northeast China after Liu et al. (2001). Topographic contour lines were drawn using generic mapping tools (e.g., Wessel and Smith, 1998) and global topographic data of the U.S. Geological Survey (2008).

studies appear to be consistent with the hypothesis of the SCLM origin of the magmas, the possibility that the magmatism was related to the Pacific slab stagnation has not yet been fully examined. It is worth revisiting the stagnant slab hypothesis, because new ideas and new experimental results regarding the origins of EM1-like signatures and highly potassic basalts have been proposed in the last decade (e.g., Murphy et al., 2002; Rapp et al., 2008), and the geochemical characteristics of the Wudalianchi basalts may be derived from a deep stagnant slab in the mantle transition zone.

In this study, we carried out a petrological study on the basalts from the 1719 to 1721 AD eruption period of the Wudalianchi volcanoes. To test the SCLM origin hypothesis for the Wudalianchi basalts, we estimated temperatures of the magmas by studying the petrological features of the basalts and performing thermodynamic analyses. We show that the Wudalianchi magmas cannot have been derived from the SCLM, because the estimated temperatures of the magmas are higher than the maximum temperature of the SCLM beneath the Wudalianchi volcano. On the basis of this result, we reexamine published geochemical data on the basalts and propose a stagnant slab origin for the geochemical characteristics of the Wudalianchi basalts.

2. Potassic basalts from Wudalianchi Volcano

2.1. Samples and methods

In NE China (Fig. 1), intraplate volcanic activities began in the Late Cretaceous, and have continued to the present time with minor interruptions (e.g., Liu et al., 2001). The Wudalianchi volcanic field, as well as the adjacent Erkeshan and Keluo volcanic fields, are located on the northern margin of the Songliao graben (Fig. 1), and are known for producing highly potassic basalt magmas (e.g., Basu et al., 1991) (hereafter, the three volcanic fields, Wudalianchi, Erkeshan, and Keluo, are referred to as "WEK"). The WEK volcanic activities occurred mainly in the Miocene (9.6–7.0 Ma), middle Pleistocene (0.56–0.13 Ma), and recent (1719–1721 AD) periods (e.g., Zhang et al., 1995). Among the products from the WEK volcanic fields, the basalts from the 1719 to 1721 AD activity are the target of this study. Because ample geochemical data have been previously obtained for these basalts (Basu et al., 1991; Chen et al., 2007; Zhang et al., 1991, 1995; Zou et al., 2003), we conducted a petrological study on two selected samples and discuss the magma genesis on the basis of the results of this analysis and the analysis of the published geochemical data. One sample (HK40090801), from one of the rock collections of the late Prof. Hisashi Kuno stored in the Tokyo University Museum, was collected from the 1719 to 1721 AD lavas, although the exact sampling locality is unknown. Another sample (KF-02) was collected from the Laoheishan volcano formed during the 1719–1721 AD activity. We selected these two samples because they are glassy and thermodynamically suitable for petrological analysis.

Whole-rock major and trace element compositions were determined by X-ray fluorescence (XRF) spectrometry, using a Rigaku RIX 2100 at the Graduate School of Science, Osaka City University. Rock specimens were crushed to coarse chips of diameter 3–5 mm. The chips were rinsed with deionized water in an ultrasonic bath, and then dried at 110 °C for more than 12 h. The washed chips were ground using an alumina mill. Powdered samples were kept at 950 °C for more than 12 h in a muffle furnace, and loss on ignition (LOI) was obtained gravimetrically. Glass beads were prepared by fusion with an alkali flux (2:1 sample dilution) consisting of a 4:1 mixture of lithium tetraborate and lithium