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Petrogenesis and evolution of Quaternary basaltic rocks from the Wulanhada area, North China

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ABSTRACT

The origin of alkali basalts in eastern China has been the subject of considerable debate. Here we focus on the Wulanhada basalts located in the western block of North China Craton to provide new insights into recent deep mantle dynamics. The Wulanhada volcanic group has 30 volcanic cones with variable volumes, consisting of scoria cone (cinder cone + spatter cone) and lava. The Wulanhada volcanoes exhibit Strombolian eruption activities during late Pleistocene epoch and Holocene. The Wulanhada basalts are strongly alkaline rocks (tephrite). According to the characteristics of trace elements and Sr–Nd–Pb–Hf isotopic compositions, the Wulanhada magmas were mainly derived from garnet-bearing peridotite within the asthenosphere and underwent fractional crystallization of olivine and clinopyroxene without significant crustal contamination. Their elevated values of Na, Al, Sr/Sm, Sm/Hf, Zr/Hf, and Nb/Ta, positive Ba, K, Pb, and Sr anomalies and negative Zr, Hf anomalies, combined with a negative correlation between $^{176}Hf/^{177}Hf$ and $^{143}Nd/^{144}Nd$ and relatively low $^{87}Sr/^{86}Sr$, suggest that the magma source may be a mixture of garnet peridotites and carbonated melts. The presence of carbonated melts is likely associated with the sediments or fluids carried by the subducted or stagnant Pacific Plate.

1. Introduction

Extensive studies of the Cenozoic volcanic rocks from eastern China over the past 30 years have led to improved understanding of the origin of these basalts and provided new insights into mantle sources and processes. The Cenozoic volcanics in eastern China consist dominantly of alkali basalts and subordinate olivine/quartz tholeiites; The alkali basalts, usually containing abundant mantle/crust xenoliths, are generally thought to originate from variable degrees of partial melting of mantle peridotite in the asthenosphere, providing an ideal natural laboratory to constrain and determine the features of deep mantle source by investigating the petrogenesis of alkali basalts (e.g., Basu et al., 1991; Fan and Hooper, 1989, 1991; Tang et al., 2006; Xu et al., 2005; Zhang et al., 2009; Zhi et al., 1990; Zhou and Armstrong, 1982; Zou et al., 2000). Previous studies unanimously suggest that the alkali basalts are predominantly derived from the melting of mantle peridotite. However, additional types of potential magma sources of alkali basalts have been proposed recently (e.g., pyroxenite, amphibolite, carbonated peridotite, eclogite, or a mixture of them; Hirose and Kushiro, 1993; Dasgupta et al., 2007; Xu et al., 2012 and reference therein).

The Jining basalts located at the northern margin of the North China Craton (NCC) are associated with the well-known Hannuoba basalts. Generally, the Jining basalts mainly consist of olivine tholeiites, quartz tholeiites, alkaline olivine basalts, and basanites (e.g., Ho et al., 2011; Zhang et al., 2012). Zhang et al. (2012) proposed that alkali olivine basalt is predominantly derived from a depleted asthenosphere component without significant crustal contamination. However, according to Ho et al. (2011), the formation of alkali olivine basalt requires addition of a two-pyroxene granulite component. Thus, the petrogenesis of Jining alkali basalts is still a matter of debate.

The Wulanhada basalts, located in northern Jining, have been classified as part of Jining basalts (Ho et al., 2011; Zhang et al., 2012). Geochemical investigations of the Wulanhada basalts can potentially advance our understanding of the generation of alkali basalts in the within-plate setting. The Wulanhada volcanic field is generally characterized by more than 30 well-preserved Late Pleistocene–Holocene volcano cones (Bai et al., 2008). Here we present major and trace elements and Nd–Sr–Pb–Hf isotopic data for the Wulanhada basalts in order to constrain magma sources of recent magmatic activities, magma evolution and geodynamic setting in the western block of the North China Craton.

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2. Geological background

The Daxing'Anling–Taihangshan gravity lineament (DTGL) and Tan-Lu fault zone (TLFZ), spanning the North China Craton (NCC) and Central Asian Orogenic Belt (CAOB), are the principal tectonic belts that divide the east China from west China (Fig. 1a). Based on recent investigations of the North China Craton, the NCC can be divided into two blocks namely the Western Block and the Eastern Block and the two blocks collided at about 1.8 Ga, forming the Central Orogenic Zone (Zhao et al., 2001). During the Mesozoic, the northward subduction of the paleo-Asian Ocean Plate beneath the NCC and subsequent closure of the Mongol-Okhotsk Ocean formed the eastern part of the Central Asian Orogenic Belt (Yin and Nie, 1996). Furthermore, it's generally accepted that the subduction of the Pacific Plate beneath Eastern China is early or late Cretaceous (e.g., Mueller et al., 2008; Niu, 2005). Therefore, the NCC has been subjected to multistage of diverse subductions (Windley et al., 2010).

There are pronounced contrasts in the nature of lithosphere between the two sides of Daxing'Anling–Taihangshan gravity lineament. The 80–200 km thick lithospheric mantle in the western NCC, preserving some of the remnant old lithosphere, has been relatively stable, and began to thin during the Cenozoic era. In comparison, the lithospheric mantle in the eastern NCC underwent large-scale lithospheric thinning (the thickness of lithosphere <80 km) during both Mesozoic and the Cenozoic. The eastern NCC represents the mixture of old and new lithosphere mantle (e.g., Fan et al., 2000; Menzies et al., 1993; Xu, 2007; Xu et al., 2005; Zhang et al., 2005). Recent studies indicate that the stagnant Pacific slab is present beneath Eastern China, and its western edge is roughly in accordance with the DATG (Zhao et al., 2004), suggesting that the stagnant slab has a more significant effect on the Eastern Block than the Western Block. This feature is consistent with the contrasting nature of lithosphere between the Eastern Block and the Western Block.

Geographically, the Wulanhada volcanic area is located at the boundary between the northwestern North China Craton and the southern Central Asian Orogenic Belt, and is part of the broad Cenozoic Hannuoba basalts that include Wanquan basalts, Zhangbei basalts, Jining basalts, Fengzhen basalts, Zuoyun basalts, Youyu basalts, and Daihai basalts. The volcanic activity in the Jining area occurred during the Oligocene–Miocene era (Luo and Chen, 1990). Wulanhada is geographically located in the northernmost Jining area (Fig. 1a), and the Wulanhada volcanism started during the late Pleistocene (e.g, Huoshaoshan volcanic in Fig. 2a) and continued to Holocene (e.g., Zhongliandanlu volcano in Fig. 2b), as inferred from the presence of the lava flows, e.g., pahoehoe lava (Fig. 2c) and lava tumulus (Fig. 2d) directly covering the Holocene eolian sand and swamp deposits in some locations, such as Baiyinnao area.

3. The characteristics of volcanic geology

The Wulanhada volcanic field consists of more than 30 volcanic cones of variable volumes, including scoria cones (cinder cone + spatter cone) and lava (Fig. 1b). The eruption type is major Strombolian eruption and the volcanic activity is divided into late Pleistocene stage and Holocene stage (Figs. 2a–b; Bai et al., 2008).

The early-stage volcanism occurred in the southeastern Wulanhada, forming the Hongshan volcano and the Huoshaoshan volcano. Interestingly, these volcanoes occur as string of beads from the southeast to the northwest, illustrating the influence of geologic structure on the volcanism. In contrast, the late-stage Holocene volcanism migrated to the southwestern Wulanhada, formed 3 large volcanoes including, from the northeast to the southwest, Beiliandanlu volcano, Zhongliandanlu volcano, Nanliandanlu volcano, as well as 8 mini scoria cones in a north-east orientation southwest of Nanliandanlu volcano (Fig. 1b). The 3 large volcanoes are approximately 200 m in diameter and 70–90 m tall, and the 8 mini scoria cones are <20 m in diameter and <30 m tall. In addition, some smaller scoria cones in a S–N direction have also been found in the west of Beiliandanlu volcano. Heinaobao volcano, located between the Beiliandanlu volcano and Zhongliandanlu volcano, occurs as low conical cone and is 150 m in diameter and 50 m tall, as part of Late Pleistocene volcanism.

The early scoria cones consist predominantly of compositionally similar volcanic fallout and splashing accumulation and have been subjected to variable degrees of erosions, resulting in the formation of low

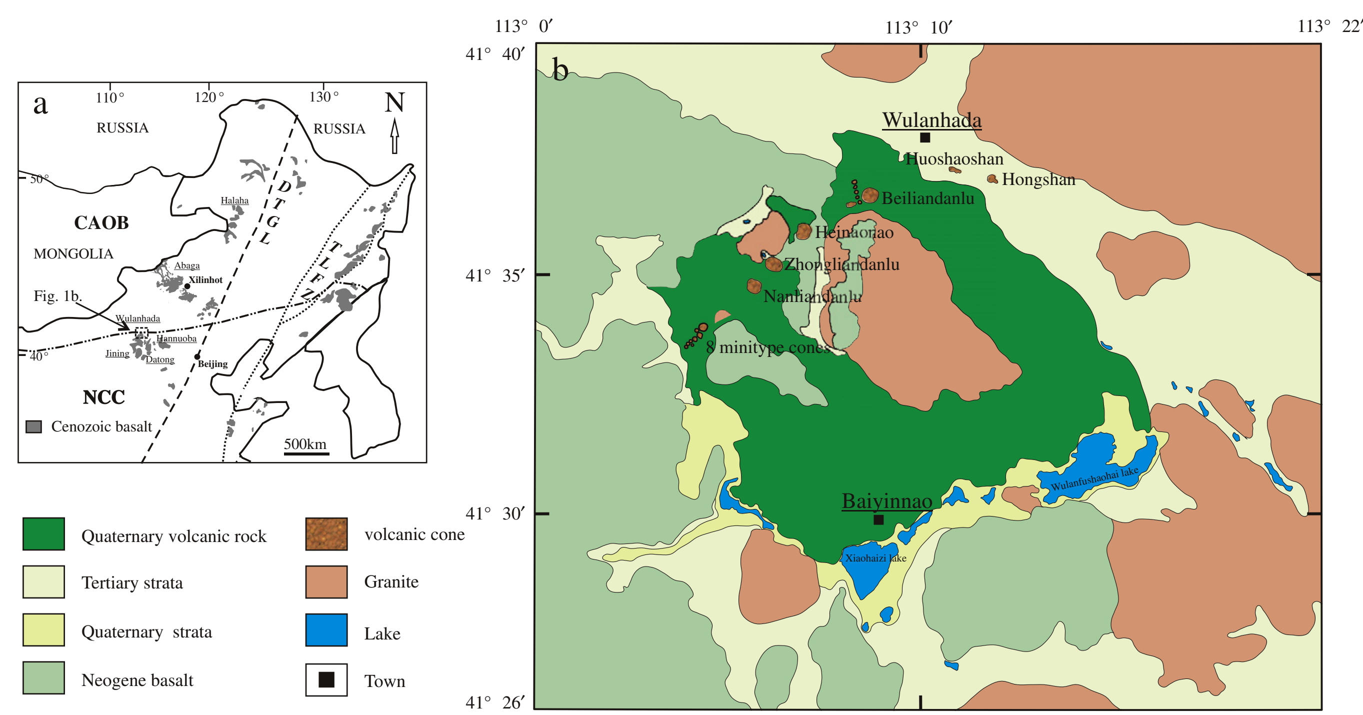

Fig. 1. (a) Distribution of the Wulanhada volcanic rocks and other major Cenozoic volcanic rocks in northern/northeastern China and (b) geological map of the Quaternary volcanoes at Wulanhada. Two noted geological and geophysical linear zones (e.g., Tan-Lu fault zone (TLFZ) and Daxinganlin–Taihang gravity lineament (DTGL)) traverse the North China.