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Petrology, structural setting, timing, and geochemistry of Cretaceous volcanic rocks in eastern Mongolia: Constraints on their tectonic origin

Batulzii Dash [a], An Yin [b,*], Neng Jiang [c], Bayartsengel Tseveendorj [a], Baofu Han [d]

[a] Department of Geology, Mongolian University of Science and Technology, Ulaan Baatar 210646, Mongolia
[b] Department of Earth and Space Sciences, University of California Los Angeles, CA 90095-1567, USA
[c] Key Laboratory for Mineral Resources Research, Institute of Geology and Geophysics, Chinese Academy of Sciences, P.O. Box 9825, Beijing 100029, China
[d] School of Earth and Space Sciences, Peking University, Beijing 10871, China

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ABSTRACT

Cretaceous volcanism occurred over a wide region of eastern Asia. Hypotheses for its development include intra-continental rifting, continental-arc magmatism, plume activities, and delamination of a previously thickened mantle lithosphere. One of the major obstacles in differentiating the above model is the lack of systematic studies of Cretaceous volcanic rocks in eastern Mongolia and far-east Russia. In this study, we address this issue by examining the timing and geochemistry of Cretaceous volcanic rocks in eastern Mongolia. Our $^{40}Ar/^{39}Ar$ dating of volcanic rocks together with the existing K–Ar ages of volcanic rocks indicate that Cretaceous volcanism in our study area occurred between 120 Ma and 104 Ma. Our field investigation and geochemical analysis reveal three types of volcanic rocks in the study area: (1) a bimodal series, (2) a shoshonite series, and (3) a basanite series. Geochemical analysis of the volcanic rocks indicates a highly heterogeneous source, which is characterized by a mixture of depleted, enriched and metasomatized mantle. At least three models may explain the timing, geochemistry, and regional tectonic setting of Cretaceous volcanism in eastern Mongolia: (1) partial delamination of a previously thickened mantle lithosphere generated by arc magmatism and collision tectonics, (2) back-arc extension and its related mantle upwelling due to rapid collapse of a flat subduction slab, and (3) mantle avalanche of a thick pile of cold subducted Paleo-Asian oceanic plates initially trapped at the 670-km endothermic phase transition triggered by westward Pacific subduction causing mixing of several mantle sources. Testing the above models require further studies on the spatial and temporal relationships between Cretaceous volcanism and structural history of NE Asia. In addition, a careful restoration of the position and history of past subducted slabs of the Paleo-Asian oceans may help differentiate the above competing models in the future.

1. Introduction

A 2000-km Cretaceous volcanic belt extends from eastern Mongolia, through the Greater Xing'an Mountains of NE China, to far-east Russia (Zonenshain et al., 1990; Badarch et al., 2002; Fan et al., 2003; Wu et al., 2005a; Wang et al., 2006; J.H. Zhang et al., 2008; L.C. Zhang et al., 2008; Ying et al., 2010a,b; Zhang et al., 2010, 2011) (Fig. 1). This belt can also be traced southward to SE Asia along the eastern margin of Asia (T.-D. Li, 2000; X.H. Li, 2000; Wu et al., 2005a). The northern part of the Cretaceous volcanic zone was constructed over a Neoproteorzoic to Early Mesozoic orogen variably named as the Central Asian Fold Belt (Zonenshain et al., 1990), Central Asian Accretionary Orogen (Sengör et al., 1993), Central Asian Orogenic Belt (Jahn, 2004), or Central Asian Orogenic System (Briggs et al., 2007, 2009) (Fig. 1). As the orogen is neither linear (i.e., not a belt) nor involving purely accretionary process (Kröner et al., 2014), we follow the usage of Briggs et al. (2007, 2009) and refer the orogen as the Central Asian Orogenic System (CAOS). The CAOS extends for >4000 km from the Tian Shan of central Asia in the west to the Sea of Okhotsk in the east (Sengör et al., 1993; Şengör and Natal'in, 1996; Briggs et al., 2007; Windley et al., 2007; Kelty et al., 2008; Briggs et al., 2009; Xiao et al., 2010; Wang et al., 2011; Kröner et al., 2014).

In eastern Mongolia, the Cretaceous volcanic rocks occur over Paleozoic accretionary complexes and turbidites (Badarch et al., 2002) (Fig. 2). In NE China, the Cretaceous volcanic rocks occurred across several Proterozoic terranes with metamorphic basement (e.g., Wang et al., 2011; Zhang et al., 2012) (Fig. 1). The tectonic evolution of eastern Mongolia and NE China has involved Late Paleozoic to Early Mesozoic subduction and closure of the Paleo-Asia oceans (e.g., Şengör and Natal'in, 1996; Yin and Nie, 1996; Zhang et al., 2012), followed immediately by the initiation of westward subduction of the Pacific plate below eastern Asia (e.g., Meng and Zhou, 1996; Şengör and Natal'in, 1996; Maruyama et al., 1997; Taira, 2001).

* Corresponding author.
E-mail addresses: ulziid@yahoo.com (B. Dash), yin@ess.ucla.edu (A. Yin), jiangneng@mail.igcas.ac.cn (N. Jiang).

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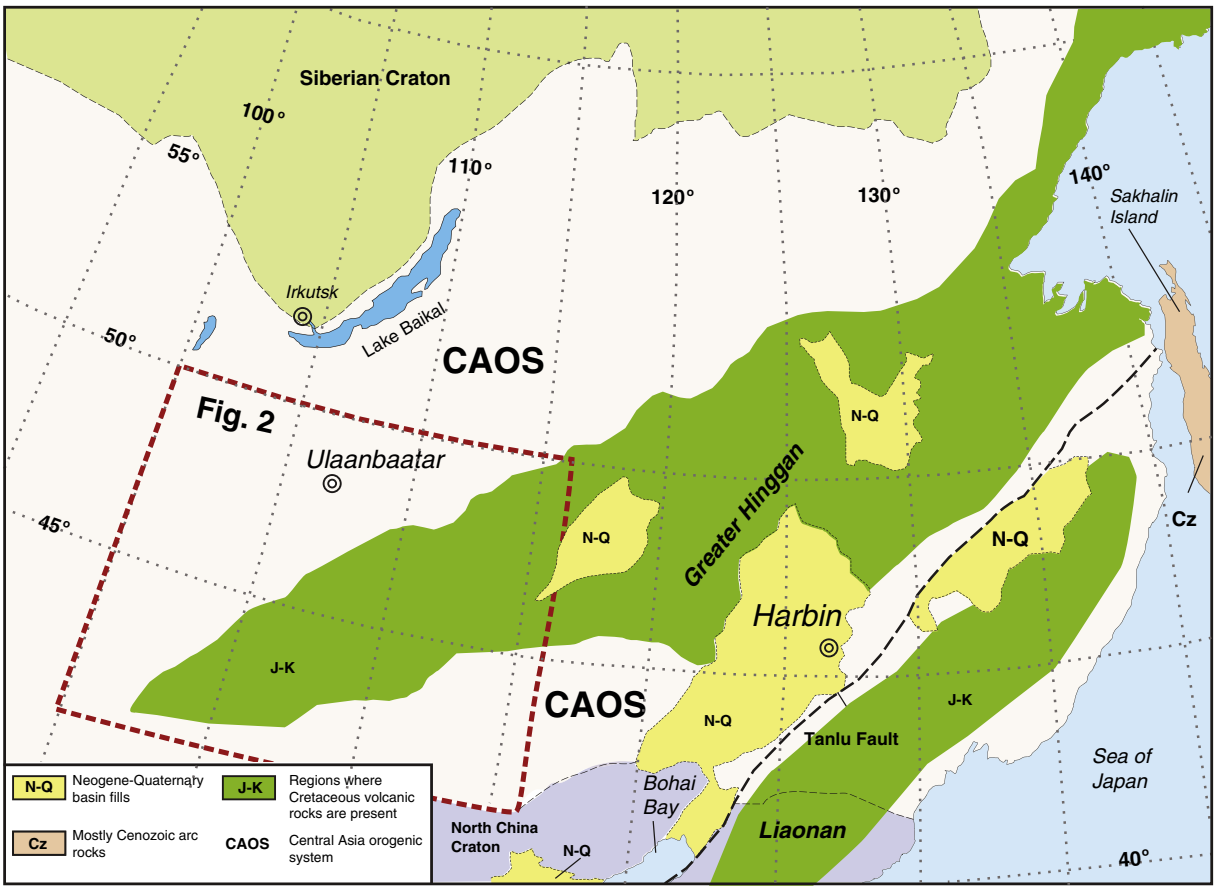

Fig. 1. Regions of Jurassic and Cretaceous volcanism superposed over the Central Asia Orogenic System (CAOS; also known as Central Asian Orogenic Belt or Central Asian accretionary orogen) in northeastern Asia. Geology is based on a compilation from Zonenshain et al. (1990), Li (2000), Badarch et al. (2002), and Wu et al. (2005a,b). Also shown is location of Fig. 2.

Despite being a prominent Mesozoic geologic feature, the origin of Cretaceous volcanism across a wide region of eastern Asia remains poorly understood. Existing hypotheses using geochemical and structural constraints were mostly constructed with the aim of explaining locally studied volcanic rocks. For example, models for the occurrence of Cretaceous volcanic rocks in eastern Mongolia and Siberia include (1) intra-continental rifting (Shatkov et al., 1980; Kovalenko and Yarmolyuk, 1990; Grahma et al., 2001), (2) formation of a continental arc resulting from westward subduction of the Pacific plate beneath Asia (Filippova et al., 1984; Zonenshain et al., 1990), and (3) mantle plume activities (Yarmolyuk et al., 1995). Similarly, models involving Cretaceous magmatism in the Greater Xing'an region of NE China (Fig. 1) emphasize the role of delamination (Wang et al., 2006), recycling of continental crust (Zhang et al., 2012), and regional extension (Wu et al., 2005b).

The southern segment of the Cretaceous volcanic zone in eastern Asia was well developed in SE China where four major episodes of igneous activities were documented during 136–146 Ma, 122–129 Ma, 101–109 Ma and 87–97 Ma (T.-D. Li, 2000; X.H. Li, 2000). T.-D. Li (2000), X.H. Li (2000) also noted that that the coeval high-K calc-alkaline rocks have geochemical signatures similar to those formed in continental back-arc and post-collision extensional settings and that the eruption centers are spatially associated with extensional basins and basin-bounding normal faults. These observations again support the causal linkage between lithospheric extension and resulting volcanism (T.-D. Li, 2000; X.H. Li, 2000). Zhou et al. (2006) noted that Cretaceous tholeiitic basalts occurred in the interior of the South China Craton in a back-arc setting. They are interlayered with red beds in extensional basins and were interpreted by Zhou et al. (2006) as resulting from interaction of back-arc extension and upper-mantle melting.

In contrast to the well-studied Mesozoic volcanic rocks in eastern China, there have been no systematic investigations of Cretaceous volcanic rocks in eastern Mongolia and far-east Siberia. The lack of modern geologic research in this region has hindered testing of the aforementioned competing models for the origin of Cretaceous volcanism in eastern Asia. For example, the progressive delamination model of Wang et al. (2006) predicts that the initiation of Mesozoic volcanism occurred at the final closure site of the Mongol-Okhotsk Ocean and the volcanic front had migrated from west to east between 160 Ma and 110 Ma across NE China. In order to test the various competing models, we conducted a reconnaissance investigation of volcanic rocks in the far-eastern region of Mongolia directly west of the Mesozoic Greater Xing'an volcanic field of Wang et al. (2006) and J.H. Zhang et al. (2008), Zhang et al., 2010). Our work involves $^{40}Ar/^{39}Ar$ dating and geochemical analysis of Cretaceous volcanic rocks from this region (Fig. 2). Our new age result, together with the existing K–Ar ages, suggests that volcanism in eastern Mongolia occurred at 120–104 Ma. Our geochemical analysis indicates that the volcanic rocks were derived from a highly heterogeneous mantle source that is characterized by a mixture of depleted, enriched and metasomatized mantle. This geochemical characteristic can be explained by site-specific processes such as partial delamination of a previously thickened mantle lithosphere or mantle avalanche across the 670 phase boundary. It may also be explained by a regional tectonic process such as back-arc extension induced by westward subduction of the Pacific plate below Asia.

2. Geological setting

We identified three Cretaceous volcanic associations in eastern Mongolia: (1) a bimodal series, (2) a shoshonite series, and (3) a basanite Series. Our field work focuses mainly on collecting volcanic samples at