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High-alumina basalts from the Bogda Mountains suggest an arc setting for Chinese Northern Tianshan during the Late Carboniferous

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ABSTRACT

Considerable debate persists as to the tectonic setting of the Tianshan Orogen during the Late Paleozoic, with active subduction system and intraplate large igneous provinces as two dominant schools. With aims of providing constraints on this issue, geochronological and geochemical analyses have been carried out on the Late Carboniferous high-Al basaltic lava (HAB) from the Bogda Mountains. These lavas, in conformable contact with the felsic rocks, belong to the Upper Carboniferous Liushugou Group. Zircon SHRIMP U–Pb dating of two felsic ignimbrites further suggest that they were mainly erupted during 315–319 Ma. The Bogda basaltic lava is classified as HAB given their high Al contents >16% and their chemical resemblance to those from modern arcs such as Aleutian and Kamchatka. They are characterized by strong enrichment in large ion lithophile elements (LILE), strong negative Nb–Ta and Ti anomalies, and distinct positive Pb anomalies. Hence, they are significantly different from the mantle plume-related basalts, as exemplified by those from Siberian, Emeishan, and Tarim large igneous provinces. Instead, their MORB-like Nd–Hf–Pb isotopes and arc-like trace elements indicate that the Bogda HABs may have been generated from a mantle wedge metasomatized by sediment-derived melts. The sector and oscillatory zoning in clinopyroxene phenocrysts in the Bogda HABs is attributable to rapid dynamic crystallization during magma ascent. High Al content is due to delayed plagioclase nucleation likely by the high crystallization pressure rather than water content. Collectively, our data lend support to an island arc environment during the Late Paleozoic, probably related to southward subduction of the Paleo-Tianshan Ocean.

1. Introduction

The Chinese Northern Tianshan is a key area for understanding the Paleozoic tectonics and long-lasting evolution of the Central Asian Orogenic Belt (CAOB; Sengör et al., 1993; Wilhem et al., 2012; Windley et al., 2007; W.-J. Xiao et al., 2004; Xiao et al., 2013). The E–W trending Bogda–Harlik (B–H) belt, occurring exclusively in the northern part of the Chinese North Tianshan, is an important tectonic belt separating the Juggar Basin to the north and the Tu–Ha Basin to the south (Fig. 1A). The key issues surrounding the B–H belt include 1) its tectonic nature in the Late Paleozoic and 2) the timing of final closure of the Paleo-Tianshan Ocean. Some researchers suggested that the Paleo-Tianshan Ocean closed by the end of Early Paleozoic (He et al., 1994) or Devonian (Xia et al., 2008, 2012). Accordingly, most part of the Carboniferous and Permian saw an intraplate setting, and the volcanic rocks erupted during this period may reflect responses to continental rifting (Che et al., 1996; Gu et al., 2000, 2001) or represent a large igneous province associated with a mantle plume (Xia et al., 2004, 2008, 2012). Others believed that it closed during the Late Carboniferous (Gao et al., 1998; Shu et al., 2011; Windley et al., 1990). This derives from the idea of a Carboniferous island arc setting to Permian post-collisional orogenic setting (Chen et al., 2011; Laurent-Charvet et al., 2003; Ma et al., 1997; Shu et al., 2011; W.-J. Xiao et al., 2004; Yuan et al., 2010; Zhu et al., 2009). Otherwise, some also argued that the Paleo-Tianshan Ocean closed at the end of Early Carboniferous given the occurrence of ~316 Ma A-type "stitching pluton" (Chen et al., 2011; Han et al., 2010).

Magmatism provides a clue to evaluate these competing models. Late Carboniferous–Permian volcano-sedimentary rocks are widely exposed in the Bogda Mountains, consisting of basaltic and rhyolite lava, felsic ignimbrite, breccia, and volcanic clastic sedimentary rocks (Fig. 1B; BGMRXUAR, 1993; Gu et al., 2001; Liang et al., 2011; Zhao et al., 2014). Among these volcanic rocks, high-Al basalt and basaltic andesite (HAB) are particularly interesting, because these rock types are generally associated with arcs or mid-ocean ridges on a global scale (e.g., Crawford et al., 1987; Eason and Sinton, 2006; Grove et al., 1988; Kuno, 1960; Ozerov, 2000; Sisson and Grove, 1993a).

Pioneering work by Tilley (1950) recognized HAB as a new magma type. Kuno (1960) reported the existence of three different primary magma types in the Japan arc (tholeiite, aphyric HAB, and alkali olivine

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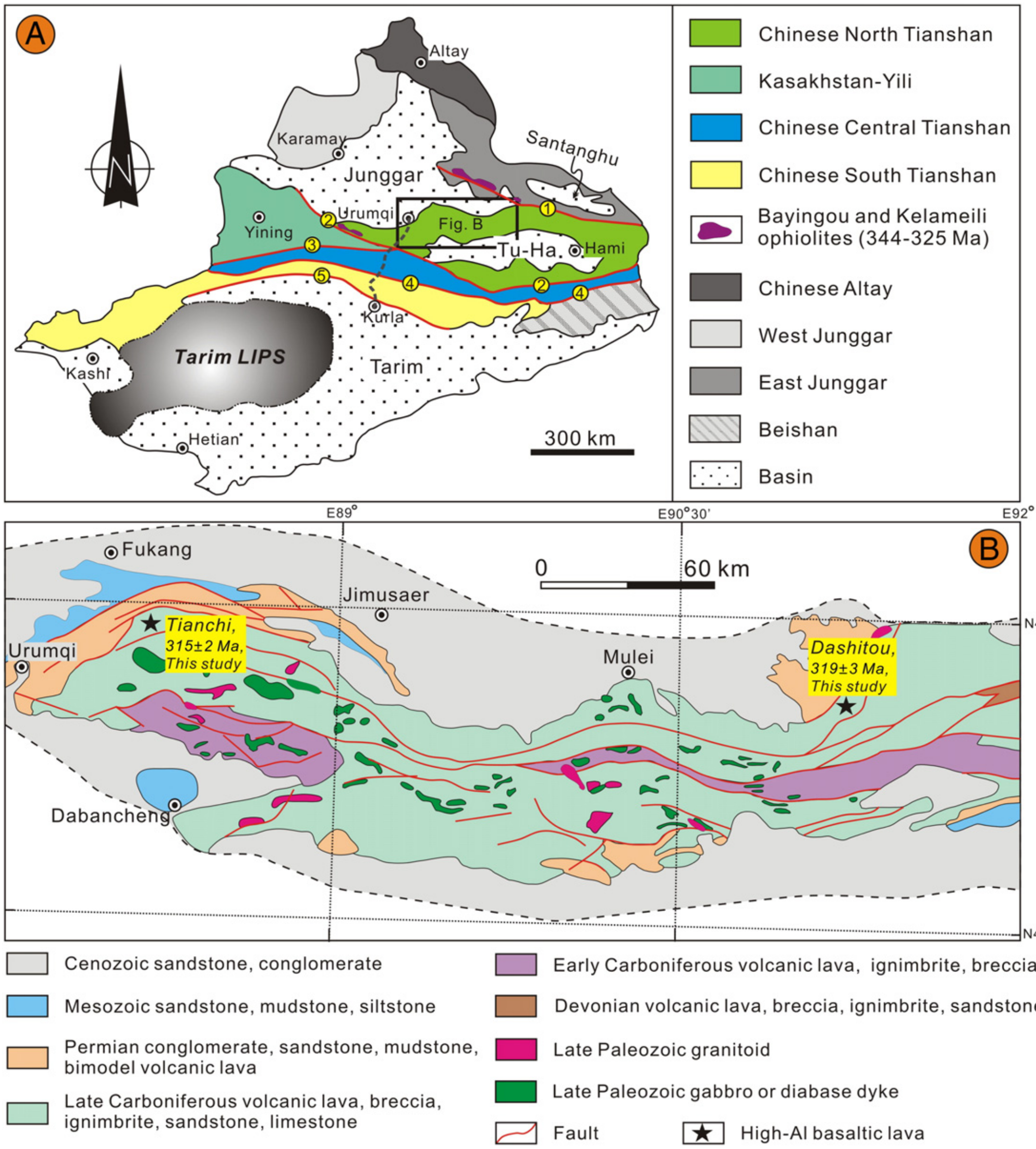

Fig. 1. A) Simplified tectonic sketch map of most part of Xinjiang province, NW China, modified after Pirajno et al. (2008), Wang et al. (2011), and Xiao et al. (2013), ① Kalameili Fault, ② North Tianshan–Aqikuduke–Shaquanzi Fault, ③ South Tianshan Future, ④ Kumishi–Kawabulake–Xingxingxia Fault, ⑤ North Tarim Suture; B) Geological map of the Bogda oregenic belt at the north margin of the Chinese North Tianshan, modified after Chen et al. (2011) and Zhao et al. (2014).

basalt). Subsequent research used "high-alumina basalt (HAB)" to refer to any sub-alkaline aphyric as well as porphyritic basaltic rock with $Al_2O_3 > 16\%$ (e.g., Crawford et al., 1987; Eason and Sinton, 2006; Ozerov, 2000; Sisson and Grove, 1993a). According to samples and experimental investigations, some workers further suggested that a slightly hydrous HAB ($H_2O < 2\%$) always was tholeiite with olivine + high-CaO pyroxene + plagioclase + magnetite (late crystallization) mineral assemblages, whereas a wet HAB ($H_2O > 2\%$) generally was calc-alkaline with olivine + high-CaO plagioclase + magnetite (early crystallization) + pyroxene/hornblende (Crawford et al., 1987; Hamada and Fujii, 2008; Sisson and Grove, 1993a, 1993b and references therein). Although some authors thought that the HAB might be generated by very high-degree partial melting of subducted oceanic slab (Brophy and Marsh, 1986; Johnson, 1986; Marsh, 1979, 1982), now most of researchers believe that it is likely generated by low-degree partial melting of mantle peridotite (Bartels et al., 1991; Crawford et al., 1987; Eason and Sinton, 2006; Green et al., 1967; Ozerov, 2000; Sisson and Grove, 1993a). The key factor for the genesis of high alumina may be due to the delayed plagioclase nucleation (Ariskin, 1999; Brophy, 1989; Crawford et al., 1987; Eason and Sinton, 2006; Green et al., 1967; Ozerov, 2000; Sisson and Grove, 1993a, 1993b), and/or preferential accumulation or flotation of plagioclase (Crawford et al., 1987; Yoder and Tilley, 1962). Furthermore, many workers believe that water ($H_2O > 2\%$) plays a dominate role for the delayed plagioclase nucleation (Ariskin, 1999; Beard and Lofgren, 1992; Grove et al., 2012; Sisson and Grove, 1993a, 1993b). Nevertheless, others proposed that high pressure can also suppress plagioclase fractionation (Bartels et al., 1991; Crawford et al., 1987; Draper and Johnston, 1992; Eason and Sinton, 2006; Grove et al., 1982).

In this paper, we present SHRIMP U–Pb ages and geochemistry for the Late Carboniferous HAB from the Bogda belt. We compare the Bogda basalts with HABs from modern arcs and typical mantle plume-related basalts. Then we combine mineral geochemistry to constrain the petrogenesis of these rocks. Our results suggest that the Bogda HABs represent magmas formed in a Late Carboniferous island arc system. Here, we also emphasize that high pressure rather than water content plays a dominate role to delay plagioclase nucleation in a tholeiite HAB.