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Large-scale liquid immiscibility and fractional crystallization in the 1780 Ma Taihang dyke swarm: Implications for genesis of the bimodal Xiong'er volcanic province

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ABSTRACT

Immiscibility is a potential mechanism for the formation of high-Fe–Ti–P rocks; however, whether large-scale segregation and eruption of high-Si lavas can occur in nature has yet to be proven. In this study, we investigate the possibility of immiscibility between the cogenetic 1780 Ma high-Fe–Ti–P-bearing Taihang dykes and the 'bimodal' Xiong'er volcanics in North China. The compositions of silicate melt inclusions in plagioclase megacrysts of the dykes provide a new approach to obtain the primary liquid. Mineral and bulk-rock compositions reveal that large compositional variations in the dykes are the result of plagioclase- and clinopyroxene-dominated fractional crystallization and of density-driven mineral sorting, which together caused the liquids to be poor in Ca–Al but rich in Fe–Ti–P–K, and thus chemically immiscible. Conjugate interstitial granophyric and ilmenite-rich intergrowths and reactive microstructures especially olivine coronas in the dykes, and Si–/Fe-Ti-rich globules in the volcanics, provide petrographic evidence for the presence of two coeval, coexisting liquids in equilibrium separated by a miscibility gap, and thus for immiscibility and segregation/migration. The fractional crystallization and subsequent segregation were responsible for the compositional diversity of the Taihang dykes and also of the 'bimodal' Xiong'er volcanics. Accordingly, the dacite and rhyolite lavas are potentially the high-Si counterparts of the high-Ti dykes, and the basalt and andesite lavas are the erupted equivalents of the relatively low-Ti dykes. It is likely that the sustained plagioclase- and clinopyroxene-dominated fractional crystallization, and the enhanced fO_2 were responsible for the immiscibility. The segregation probably took place during the ascent of the liquid in the pumping system (feeder dykes). This likely represents one natural example of crust-scale immiscibility from which many high-Ti dykes and silicic lavas (~1/3 volume of the Xiong'er volcanic province) were segregated and subsequently intruded/extruded over an areal extent of >0.1 Mkm^2.

1. Introduction

High-Fe–Ti–P-bearing compositions are common in gabbros of layered intrusions such as Bushveld (South Africa) (Cawthorn and Ashwal, 2009; Tegner et al., 2006; van Tongeren and Mathez, 2012), Skaergaard (Greenland) (Holness et al., 2011; Jakobsen et al., 2005, 2011; McBirney, 1975; Thy et al., 2006) and Sept Iles (Canada) (Higgins, 2005; Namur et al., 2012; Tollari et al., 2008), and in anorthositic complexes such as Rogaland (Norway) (Duchesne, 1999), Labrieville and St-Urbain (Quebec) (Owens and Dymek, 1992) and Damiao (North China) (Zhao et al., 2009b). Also high-Fe–Ti volcanic rocks occur in Columbia (USA) (Hartley and Thordarson, 2009), Parana–Etendeka (Brazil) (Rocha-Júnior et al., 2013), Kiirunavaara (Sweden) (Harlov et al., 2002), Emeishan (South China) (Xu et al., 2001), Dongargarh (India, andesites) (Sensarma and Palme, 2013) and Sinai (Egypt, dykes) (Essawy and El-Metwally, 1999) though most of these examples are not actually enriched in phosphorus. In the wide discussions about the origin of these distinctive high-Fe–Ti–(P) compositions it has commonly been suggested that many resulted from silicate liquid immiscibility (*e.g.*, Charlier and Grove, 2012; Charlier et al., 2013; Namur et al., 2012; van Tongeren and Mathez, 2012) and/or density-driven mineral sorting (*e.g.*, Tegner et al., 2006; Tollari et al., 2008). Liquid immiscibility is also considered to have played a crucial role in producing the compositional gap, which is indicated by the dearth of intermediate compositions, as reported in many of the above examples such as the Bushveld and Skaergaard complexes (though a possible alternative mechanism could be fractional crystallization). However, in some calc-alkaline arc magmatic systems, the missing compositions could not only be intermediate, but also intermediate to acidic transitional compositions (SiO_2 = 63–70/75 wt.%), *e.g.*, Okmok (Aleutian) and South Sister (Cascade) (*e.g.*, Brophy, 1991).

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However, the proposed liquid immiscibility in the above cases was only examined at relatively small scales (*e.g.*, within meters), and in particularly large examples such as the Bushveld Complex, where it reaches a hundred meter scale (van Tongeren and Mathez, 2012). Whether or not large-scale segregation and immiscible silica-rich components can occur in nature has yet to be verified (Charlier et al., 2013). Here we report a study from high-Fe–Ti–P compositions in the giant Taihang dyke swarm (1780 Ma) and in the coeval 'bimodal' Xiong'er volcanic province in North China (Fig. 1), because it is possible that these dykes and lavas originated from the same source, and their diverse compositions were driven by fractional crystallization and large-scale segregation. We will use data from silicate melt inclusions to constrain the primary compositions, and the differentiation processes, the (micro-)structures of rocks, and mineral and bulk-rock compositions in order to evaluate the possibility that compositional segregation was caused by immiscibility. This process may be a potential means to connect some mafic provinces with their felsic counterparts.

2. Background of the Taihang dyke swarm and the Xiong'er volcanic province

The 1780 Ma Taihang dyke swarm, which extends mainly NNW for over 1000 km with an area of >0.1 Mkm^2, is the biggest swarm in China, as shown in Fig. 1 (Qian and Chen, 1987; Halls et al., 2000; Hou et al., 2001, 2008a, b; Peng et al., 2004, 2007, 2008; Wang et al., 2004, 2008; Peng, 2015). The dykes have individual widths of up to 100 m (~15 m on average), and some crop out continuously along strike for up to 60 km (Peng et al., 2007). The dykes are mainly composed of plagioclase and clinopyroxene. They are characterized by a group of dykes enriched in Fe–Ti–P (FeO_t [total iron], TiO_2 and P_2O_5 up to 20 wt.%, 4 wt.% and 2 wt.%, respectively). It has long been debated whether this high Fe–Ti–P feature originated in the magma chamber through fractionation (*e.g.*, Peng et al., 2004, 2007) or from different sources (*e.g.*, Wang et al., 2004, 2008).

The Xiong'er volcanic province lies on the southern margin of the Eastern North China craton and is distributed around a triple-conjugation with two rift arms along the southern margin (the Xiong'er Group) and a third extending NNW into the Lvliang Mountains (the Xiaoliangling and Hangaoshan Groups) in the heart of the craton (Peng et al., 2008) (Fig. 1). The Xiong'er volcanics have a thickness of 3000–7000 m, an outcrop area of >6000 km^2 and an inferred area of 0.02 Mkm^2. They include basalt, andesite, trachyandesite, dacite, rhyodacite, rhyolite, with ~2 vol.% of volcanic clastic interlayers (Zhao et al., 2005), and comprise two compositional cycles, *i.e.* from mafic-intermediate to acidic for the lower two formations (the Xushan and Jidanping), and then from mafic-intermediate to intermediate for the third (upper) formation (the Majiahe) (Zhao et al., 2002). The rocks are mainly composed of plagioclase and clinopyroxene with variable amounts of quartz, K-feldspar and accessory minerals. Whether this volcanic province developed along a continental margin (*e.g.*, He et al.,

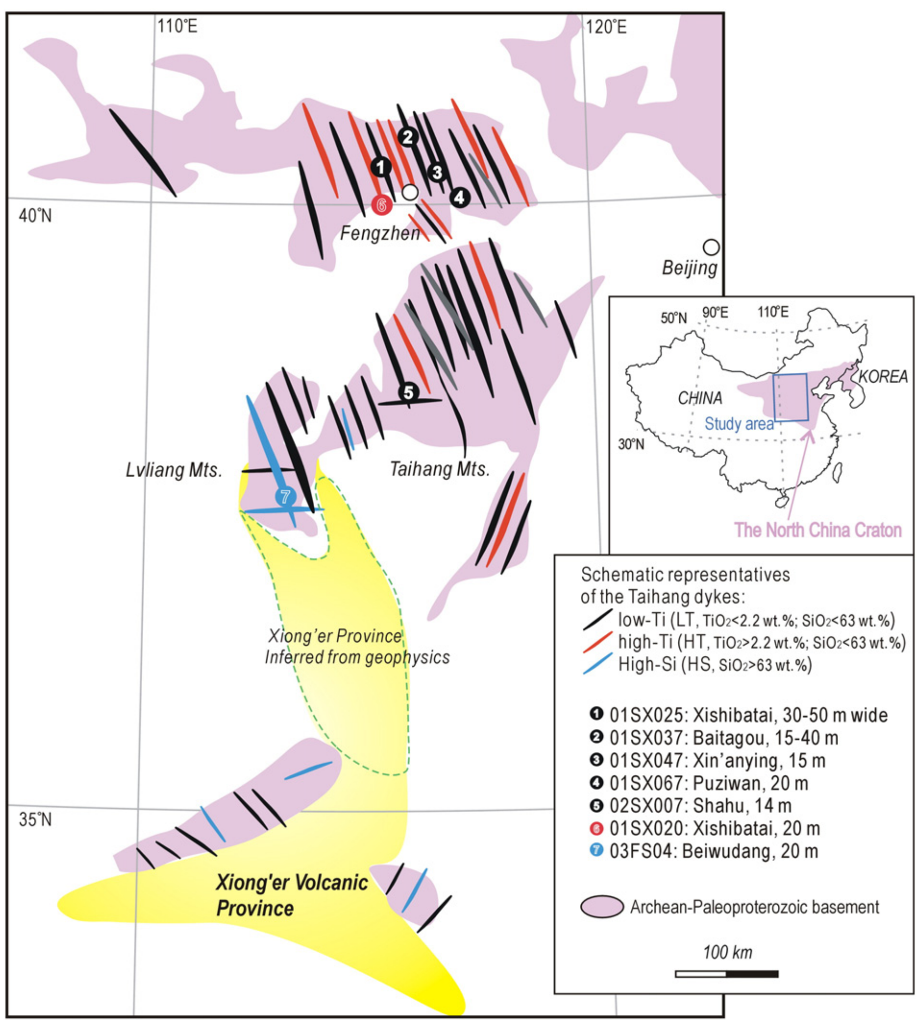

Fig. 1. Schematic maps showing the distribution of the Taihang giant dyke swarm and the Xiong'er volcanic province in the North China Craton. The approximate distributions of the low-Ti (*LT*), high-Ti (*HT*) and extremely high-Si (*HS*) groups (see Fig. 2 caption for classification) of the Taihang dykes and the localities of the seven selected samples are labeled. Note: the dykes in this map are schematic representations.