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RESEARCH PAPER

Reassessment of petrogenesis of Carboniferous–Early Permian rift-related volcanic rocks in the Chinese Tianshan and its neighboring areas

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Abstract The Carboniferous–Early Permian rift-related volcanic successions, covering large areas in the Chinese Tianshan and its adjacent areas, make up a newly recognized important Phanerozoic large igneous province in the world, which can be further divided into two sub-provinces: Tianshan and Tarim. The regional unconformity of Lower Carboniferous upon basement or pre-Carboniferous rocks, the ages (360–351 Ma) of the youngest ophiolite and the peak of subduction metamorphism of high pressure–low temperature metamorphic belt and the occurrence of Ni-Cu-bearing mafic-ultramafic intrusion with age of ∼352 Ma and A-type granite with age of ∼358 Ma reveal that the final closure of the Paleo-Asian Ocean might take place in the Early Mississippian. Our summation shows that at least four criteria, being normally used to identify ancient asthenosphere upwelling (or mantle plumes), are met for this large igneous province: (1) surface uplift prior to magmatism; (2) being associated with continental rifting and breakup events; (3) chemical characteristics of asthenosphere (or plume) derived basalts; (4) close links to large-scale mineralization and the uncontaminated basalts, being analogous to those of many "ore-bearing" large igneous provinces, display Sr-Nd isotopic variations between plume and EM1 geochemical signatures. These suggest that a Carboniferous asthenosphere upwelling and an Early

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Permian plume played the central role in the generation of the Tianshan–Tarim (central Asia) large igneous province.

1. Introduction

The Carboniferous–Early Permian rift-related volcanic rocks exposed in the Chinese Tianshan and its adjacent areas (Figs. 1 and 2) make up an important recently discovered large igneous province (LIP) in northwestern China (Xia et al., 2003, 2004, 2005c, 2007, 2008a,b). This LIP, which can be further divided into two sub-provinces: Tianshan and Tarim (Fig. 1a; Bryan and Ernst, 2008), has attracted a number of recent studies (Che et al., 1996; Chen et al., 1997b, 2006; Gu et al., 2000; Chen et al., 2001; Wang et al., 2002; Xia et al., 2002a, 2003, 2004, 2005b,c, 2007, 2008a,b; Zhao et al., 2003, 2004, 2006; Xing et al., 2004; Yang et al., 2005b, 2007; Zhu et al., 2005, 2009; Wang et al., 2006, 2007a,c, 2010, 2011; Zhou et al., 2006a; Pirajno, 2007; Bryan and Ernst, 2008; Pirajno et al., 2008, 2009; Zhou et al., 2009; Zhang et al., 2010a,b). The current studies include erosional unconformity between the volcanic rocks and underlying basement, radiometric dating, high pressure (HP)–low temperature (LT) metamorphic belt, petrologic and geochemical studies of basalts and their related rocks and mineralization. This study summarizes certain achievements in this domain and reassesses the petrogenesis of Carboniferous–Early Permian rift-related volcanic rocks and the links between LIP and regional-scale uplift, continental rifting and breakup, and large-scale mineralization events.

2. Geological background

The Carboniferous–Early Permian rift-related volcanic rocks are mainly exposed in a broom-shaped province of $\sim 1.7 \times 10^6$ km^2 within the Chinese Tianshan orogenic belt and its neighboring areas including Junggar, Turpan-Hami and Tarim basins (Fig. 2). This area represents a minimum estimate because the volcanic rocks extend west and east from China and also have a widespread distribution in Kazakhstan, Kyrgyzstan and Mongolia, respectively (Fig. 1b). Many mafic-ultramafic layered intrusions and widespread granitic magmatism also have developed in these areas during this period. This study focuses only on the Carboniferous–Early Permian rift-related volcanic rocks.

The Tianshan orogenic belt is part of a large-scale, composite orogenic belt located in northwestern China (central Asia). It was the product of accretion, subduction, and collision of various continental blocks during the formation, evolution, and disappearance of the Paleo-Asian Ocean between the northern Siberia craton and the southern Tarim and North China (i.e., Sino-Korean) cratons (Figs. 1 and 2). By the Early Mississippian, the Paleozoic ocean had closed along three main sutures, which are, from north to south, the Erqis suture (① in Fig. 3), the Northern Central Tianshan suture (② in Fig. 3) and the Southern Central Tianshan suture (③ in Fig. 3). The consequent suture zone became an area of thickened crust characterized by complex tectonic and magmatic activity and uplift. A major regional upwelling and partial melting event led to the development of the Carboniferous–Early Permian rift system and its associated large igneous province (Xia et al., 2002a,b, 2003, 2004, 2005b,c, 2007, 2008a,b).

The Carboniferous–Early Permian rift system comprises eight parts: the Kalpin rift situated in the northwestern margin of the Tarim craton; the western Tianshan Yili rift situated in the Yili Block; the Central Tianshan rift in the central Tianshan Block; the eastern Tianshan Bogda-Harlike rift; the eastern Tianshan Jueluotage rift; the Junggar rift located in the central-northern part of the Junggar basin; the Baishan rift located in the northeastern margin of the Tarim craton, and the Tarim rift located in the western part of the Tarim craton (Fig. 2).

The massive Carboniferous–Early Permian volcano-sedimentary successions were deposited (in form of an angular unconformity) on various types and ages of basement: the Proterozoic Yili Block (in the western Tianshan) that consists mainly of metamorphic rocks of Proterozoic age; the central Tianshan Block that consists of metamorphic rocks of Proterozoic and Early–Middle Ordovician age; the Junggar (in the Junggar area) and the eastern Tianshan mobile belt that consists mainly of Early Paleozoic–Devonian arc-basin formation; and the Tarim craton with a Precambrian basement formed in Archean and Proterozoic (Figs. 1 and 2).

The available isotopic dating data reveal that the Carboniferous–Early Permian volcanism may persist for 90 Ma (from 350 to 260 Ma), but the Tianshan–Tarim LIP event exhibit two pulses of high volume activity: a first main pulse that occurred at 335–325 Ma and a second main pulse at 285–275 Ma (Fig. 4).

The Carboniferous volcanic successions that consist mainly of basaltic lavas and subordinate amounts of intermediate and silicic lavas, and pyroclastic rocks are mainly exposed in the Tianshan and Junggar areas, and a small portion of them is buried beneath the Junggar basin (Fig. 2). The Carboniferous rift-related volcanism includes a bimodal distribution of dominant basic and subordinate silicic rocks in Junggar, central and eastern Tianshan, however the western Tianshan rift rocks display a spectrum of compositions from basic to silicic (Xia et al., 2004, 2005b,c, 2008a,b). The Early Permian volcanic successions are mainly developed in the Kalpin, the Tarim (subcrop) and the Baishan rifts, and they are also sporadically exposed in the Tianshan area (Fig. 2). These Early Permian volcanic rocks consist mainly of basaltic rocks and minor of dacites and syenites that display a compositional bimodality (Yang et al., 2005b, 2007; Zhou et al., 2009; Zhang et al., 2010a,b).

The thickness of the entire volcanic sequence varies from over 13,000 m in the eastern Tianshan, to several hundred meters in the central Tianshan, the Kalpin and the Tarim areas, to over 10,000 m in the western Tianshan (Xia et al., 2004, 2005b,c, 2008a,b; Zhou et al., 2009; Zhu et al., 2009; Zhang et al., 2010b). The average lava thickness of the Tianshan–Tarim (central Asia) LIP is estimated to be about 1000 m, thus the entire volume of the Tianshan basalts is $\sim 1.7 \times 10^6$ km^3. This represents a minimum estimate because: (1) erosion removed a significant portion of the eruptive sequences; and (2) the associated intrusives are not taken into account.

3. The final closure timing of the Paleo-Asian Ocean

There have been a wide variety of inferences on the termination age of the Paleo-Asian Ocean, such as the Late Devonian