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An 850–820 Ma LIP dismembered during breakup of the Rodinia supercontinent and destroyed by Early Paleozoic continental subduction in the northern Tibetan Plateau, NW China

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ABSTRACT

Neoproterozoic intraplate magmatism is widely distributed in NW China and generally thought to be related to the breakup of the Rodinia supercontinent. Here we report a fragmented Large Igneous Province (LIP) formed at 850–820 Ma in the northern margin of the Qaidam block, northern Tibetan Plateau (named herein as the "North Qaidam LIP"). The associated rocks have undergone various grades of metamorphism from greenschist to ultrahigh-pressure (UHP) eclogite facies, including the greenschist-facies Yingfeng dolerite dikes and basalts (846–821 Ma), the amphibolite- to HP granulite-facies Aolaoshan meta-volcanic sequence (protolith age of 832 Ma and metamorphic age of 439 Ma), and the North Qaidam UHP eclogites (protolith age of 847–828 Ma and metamorphic age of 440–420 Ma). Geochemical data reveal that they resemble present-day E-MORB/OIB and typical continental flood basalts. These features, together with high potential temperatures (T_p = 1434–1524 °C) for "primary" magmas, suggest that these basaltic rocks were most likely derived from a mantle plume source and were emplaced in a continental extensional environment.

Their varying metamorphic facies record a range of locations along the underthrust continental slab from near-surface (Yingfeng dolerites/basalts), middle (Aolaoshan amphibolites) to deep (N. Qaidam UHP eclogites) sites with depths greater than 120 km. The large spatial distribution (potentially >0.1 Mkm^2), short duration (<30 Myr) and intraplate geochemical character suggest that these igneous rocks are remnants of the North Qaidam LIP caused by the upwelling of a mantle plume during 850–820 Ma. We consider that the North Qaidam LIP represents the onset of a protracted break-up history and precedes subsequent multiple episodes of rifting. These Neoproterozoic igneous rocks in the Qaidam block were separated from the contemporaneous magmatic suites over Australia, South China and Tarim by the breakup of Rodinia, and were further destroyed by the subduction of the passive continental margin of the Qaidam block in the Early Paleozoic (440–420 Ma).

1. Introduction

Large Igneous Provinces (LIPs) are exceptional intraplate igneous events that represent massive crustal emplacement of mafic magmas, generated by processes distinct from normal sea-floor spreading and plate convergence (Coffin and Eldholm, 1994; Ernst et al., 2005; Ernst and Jowitt, 2013; Ernst, 2014). Both continental and oceanic LIPs are likely to result from mantle plume heads arriving at the base of lithosphere, and are characterized by their large volume (at least 100,000 km^3), short duration (or short duration pulses), and geochemical and/or other affinities consistent with an intraplate tectonic setting (e.g., Richards et al., 1989; Coffin and Eldholm, 1994; Saunders, 2005; Bryan and Ernst, 2008; Ernst et al., 2008; Garfunkel, 2008; Bryan and Ferrari, 2013; Ernst, 2014). Most continental LIPs are dominated by flood basalts or their erosional/deformational remnants, a plumbing system of dikes and sills, and mafic–ultramafic layered

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intrusions (e.g., Bryan and Ernst, 2008). A substantial silicic component may be present in some cases, for example Sierra Madre Occidental (e.g., Bryan and Ferrari, 2013). Thick outpourings of flood basalts have been identified on rifted continental margins around the world and are closely connected with the onset of seafloor spreading (e.g., the Greenland traps and North Atlantic Igneous Province for the opening of the North Atlantic, the Deccan traps for the Indian Ocean, and the Paraná–Etendeka traps for the South Atlantic; White and McKenzie, 1989; Courtillot et al., 1999; Bryan and Ernst, 2008). Thus it is proposed that there are causal links between the formation of ancient LIPs and the growth, breakup and cycles of supercontinents, and they are critical for recognizing the episodes of continental breakup and constraining supercontinental reconstructions (White and McKenzie, 1989; Hill et al., 1992; Park et al., 1995; Saunders et al., 1996; Wingate et al., 1998; Courtillot et al., 1999; Li et al., 1999, 2008a; Ernst et al., 2005, 2008; Ernst and Jowitt, 2013).

In the last decades, the amalgamation, breakup and configuration of Rodinia have attracted much attention (e.g. Li et al., 2008a and references herein). It is widely accepted that the assembly of this supercontinent is associated with the worldwide Grenville-age orogeny (1.3–0.9 Ga) which has been recognized within North America, Scandinavia, Australia, South China, India, East Antarctica, Tarim and in the Qilian–Qaidam area (Li et al., 2008a; Song et al., 2012). However, the timing of the onset of the prolonged breakup process has been controversial. The first episode of Neoproterozoic plume activity was identified in light of the ca. 825 Ma mafic dikes and sills, komatiites, mafic–ultramafic intrusions, continental flood basalts (CFBs), and anorogenic granitoids in South China, Tarim and Australia (see Li et al. (2008a) for details). These magmatic events are also correlated to the initial rift phase of the Nanhua rift basin in South China and the Adelaide geosyncline in southeastern Australia (Powell et al., 1994; Preiss, 2000; Wang and Li, 2003; Li et al., 2003a). However, recent geochronological results suggest that the intraplate magmatism related to the breakup of Rodinia may have started earlier, perhaps at 870–850 Ma in South China, Qilian–Qaidam, Africa, India, Australia, the Scottish promontory of Laurentia and the Scandinavian Caledonides (Song et al., 2010 and references therein) or even at ca. 930 Ma in North China and West Africa (Peng et al., 2011; Ernst, 2014). Alternatively, Zhou et al. (2002, 2006a,b) and Wang et al. (2007) speculated that the magmatism of this period was formed in an active continental margin or a collisional orogen around the Yangtze Craton.

It is generally considered that the Qilian–Qaidam block was an integral component of Rodinia, and had a close relationship with South China (Xu et al., 2015 and references herein). In terms of the Grenville-age magmatism and metamorphism, Song et al. (2012) identified the link between the South China, Qilian–Qaidam and Tarim blocks, and named them as the "South-West China United Continent" (Fig. 1a). Nevertheless, the process of separation away from the rest of Rodinia for the Qilian–Qaidam block is still poorly understood due to the sparse intraplate magmatic records, not least because of later fragmentation, erosion, burial and metamorphism related to the Early Paleozoic collisional orogeny.

The North Qaidam ultrahigh-pressure metamorphic (UHPM) belt on the northern Tibetan Plateau is a continental subduction/-collisional suture, where the ancient passive continental margin of the Qaidam block was dragged to depths greater than 100 km and was destroyed during the period of 440–420 Ma (Song et al., 2006, 2012, 2014). However, the protoliths of eclogites in the North Qaidam UHPM belt have been controversial, as to whether they represent oceanic crust or continental basalts, which is significant for understanding the tectonic evolution from oceanic subduction to continental subduction-collision (Song et al., 2014 and references therein).

In this paper, we present petrological, geochronological, geochemical and Sm-Nd isotopic data for the Yingfeng dolerite dikes/basalts and the Aolaoshan meta-volcanic rocks in the western extension of the North Qaidam UHPM belt. By combining our data with the previous results on the North Qaidam eclogites and neighboring mafic–ultramafic intrusions, we suggest that these igneous rocks form in the within-plate environment with a mantle plume origin and are remnants of the 850–820 Ma North Qaidam LIP, associated with the initial breakup of Rodinia.

2. Geological setting

The Qaidam block in the northern margin of Qinghai-Tibet Plateau is located between the larger South China, Tarim and North China blocks (Fig. 1a) and is covered with Mesozoic to Cenozoic sedimentary sequences. To its north, the North Qaidam continental-type ultra-high pressure metamorphic (UHPM) belt has a NW-SE trend, and is offset about 400 km by the left-lateral Altyn Tagh Fault. The Quanji block is separated from the North Qaidam UHPM belt by the Wulan-Yuka Fault (Zhang et al., 2001; Li et al., 2003b; Chen et al., 2007, 2009a). This block consists of Archean to Early Proterozoic gneisses, amphibolites and granulites, and is unconformably covered by the less deformed and metamorphosed Neoproterozoic Quanji Group and Cambrian-Ordovician sequences (see Chen et al., 2009a; Fig. 1b). The Qilian block in the north contains Precambrian basement rocks formed from Archean to Neoproterozoic with Grenville-age (1000–900 Ma) intrusions, and has a close affinity with the Yangtze block (Wan et al., 2001, 2006; Lu et al., 2008; Song et al., 2013). Recent studies suggested that the combined Qilian–Qaidam microcontinent was a fragment of the Rodinia supercontinent, and rifted away from southeastern Australia at 600–550 Ma (Xu et al., 2015). Further to the north is the North Qilian oceanic suture zone, which consists of ophiolites, arc volcanic rocks and lawsonite-bearing eclogites and blueschists associated with the oceanic subduction in the Early Paleozoic era (see Song et al., 2013 for details).

The North Qaidam UHPM belt extends discontinuously for over 400 km from Dulan in the southeast, northwestward through Xitieshan and Lüliangshan to Yuka (see Fig. 1b for localities). The lithologies mainly consist of granitic and pelitic gneisses (~80%) with eclogite and garnet peridotite blocks. The granitic and pelitic gneisses recorded a Grenville-age orogenesis at ~1020–900 Ma (Wan et al., 2006; Song et al., 2012, 2014; Zhang et al., 2012, 2015; Yu et al., 2013). Coesite and diamond inclusions have been identified in zircons and garnets from the metapelites, eclogites and garnet peridotites, which suggest that the UHP metamorphism occurred at depths of 100–200 km at 438–420 Ma (Song et al., 2014 and references therein).

3. Occurrence and petrography

Three types/occurrences of the 850–820 Ma volcanic rocks were identified in the North Qaidam region as following: (1) Yingfeng low-grade meta-mafic dikes/basalts, (2) Aolaoshan medium-grade meta-volcanics and (3) eclogite blocks in the North Qaidam UHPM belt associated with continental subduction.

3.1. Yingfeng low-grade meta-mafic dikes/basalts

The Yingfeng mafic dikes and basalts (Site 5 in Fig. 1a) are located at the northwest of the Yuka eclogite-gneiss terrane (Fig. 1b). The Yingfeng mafic rocks mainly occur as sills, dikes and layered basalts (Fig. 2a-b). The dikes dominantly trend in a NW-direction, with lengths ranging from 1 to 3 km and widths from 2 to 5 m. Together with large sills (1 × 5 km), they intrude