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The Early Permian Tarim Large Igneous Province: Main characteristics and a plume incubation model

Yi-Gang Xu *, Xun Wei, Zhen-Yu Luo, Hai-Quan Liu, Jun Cao

State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, 510640, China

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ABSTRACT

The Early Permian magmatism in Tarim, NW China comprises diamondiferous kimberlites, lamprophyres, flood basalts, Fe–Ti oxide ore-bearing layered mafic–ultramafic intrusions, bi-modal dyke swarms, alkaline igneous complexes (including syenites and A-type granites), rhyolites and pyroclastic rocks. The extent of this intraplate magmatism exceeds 250,000 km^2, making it comparable to Large Igneous Provinces (LIPs). Screening of available radiometric ages reveals three main magmatic episodes in the Tarim LIP, with the first being marked by ~300 Ma small-volume kimberlites, followed by two phases of bimodal magmatism at ~290 Ma and at ~280 Ma, respectively. This relatively long time interval of the Early Permian magmatism is consistent with a low eruption rate of the Tarim LIP and is supported by the intercalation of volcanic rocks with sediments in outcrops and drill holes. Although the spatial distribution of each magmatic episode in the Tarim LIP is far from assessed, it seems that the ~290 Ma flood basalts are widespread across the province, whereas ~300 Ma kimberlites and ~280 Ma ultramafic–mafic–felsic intrusions and dyke swarms only occur in the Bachu Uplift and around the margins of the Tarim craton.

We propose that the ~300 Ma kimberlites were derived from deep part of the metasomatized sub-continental lithospheric mantle (SCLM), while the ~290 Ma flood basalts were likely formed as a result of mixing of plume-derived melts with SCLM-derived melts (e.g., lamproitic melt) as they rose through the SCLM. In contrast, the ~280 Ma magmas were most likely derived from the convecting mantle. A plume incubation model is proposed to account for the temporo-spatial distribution of the Tarim LIP, in which different styles of plume–lithosphere interaction are recognized. In the first two episodes, the mantle plume incubating the base of the craton provides the heat that triggered melting of the enriched components in the SCLM. In contrast, adiabatic decompression melting within the plume produced the ~280 Ma magmatic phase. Thermal modeling suggests that lithospheric thinning by thermal erosion might have been associated with the upwelling mantle plume, with the greatest thinning occurring in the Bachu area. Thinned spots and weak zones at the margins of cratons and mobile belts caused preferential channeling of plume flow and subsequent decompression melting. This explains the localized distribution of ~280 Ma magmas in the Tarim LIP.

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1. Introduction

Large igneous provinces (LIPs) are voluminous occurrences of dominantly mafic igneous rocks not directly related to plate tectonic processes (Coffin and Eldholm, 1994; Mahoney and Coffin, 1997; Bryan and Ernst, 2008). It has been widely accepted that the formation of LIPs is related to mantle plumes rising from a thermal boundary at the core–mantle boundary (e.g., Campbell and Griffiths, 1990; Morgan, 1971) or from the upper mantle/lower mantle transition zone (Courtillot et al., 2003; White and McKenzie, 1989).

There are two main competing hypotheses regarding the extent to which mantle plumes are involved in the formation of LIPs. One attributes the formation of LIPs to the arrival of a plume head at the base of the lithosphere, and subsequent decompression melting of a deflated plume head with a diameter reaching up to 2000 km (Campbell and Griffiths, 1990; Richards et al., 1989). The other proposes that a plume head grows more slowly (incubates) especially underneath thick continental lithosphere (>120 km) which inhibits melting of mantle plumes (Kent et al., 1992; Saunders et al., 1992). However, melting of a mantle plume in this scenario is possible when the overlying lithosphere is thinned and removed by conductive heating, melt injection and extension (White and McKenzie, 1989). These different modes of plume involvement create distinct features in LIPs. Specifically, flood basalts generated by adiabatic melting in a convecting mantle regime generally have rapid eruption rates (over a few million years) (Campbell, 2001, 2005; Gibson et al., 2006). In contrast, magmatism related to melting

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* Corresponding author at: Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, 510640 Wushan, Guangzhou, P. R. China. Tel.: +86 20 85290109; fax: +86 20 85290261.
E-mail address: yigangxu@gig.ac.cn (Y.-G. Xu).

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of the sub-continental lithospheric mantle (SCLM) due to conductive heating by an incubating mantle plume (Gibson et al., 1995a,b; Gallagher and Hawkesworth, 1992; Kent et al., 1992; Turner et al., 1996) commonly have a relatively low eruption rate (over tens million years) and display a lithospheric geochemical fingerprint. Investigations into LIPs thus provide information as to vertical transfer of mantle materials/heat. Moreover, evidence is mounting that the occurrence of LIPs correlates with profound changes in the surface environment, including crustal doming/changes in depositional facies (He et al., 2003; Rainbird and Ernst, 2001; Saunders et al., 2007) and mass biotic extinction (e.g., Courtillot and Renne, 2003).

The Permian is marked by the presence of four LIPs that cluster in eastern Asia, namely the Siberian traps (251 Ma, Kamo et al., 2003), Emeishan basalts (~260 Ma, He et al., 2007; Shellnutt et al., 2012; Xu et al., 2008; Zhong et al., 2014; Zhou et al., 2002), Tarim basalts (280–290 Ma, Wei et al., 2014) and Panjal traps (~290 Ma; Shellnutt et al., 2014). Interestingly, a number of major global events occurred almost simultaneously during the late Paleozoic, including the double (Permian–Triassic and end-Guadalupian) mass extinctions, ocean superanoxia, sharp C and Sr isotopic excursions, sea-level drop and Illawara geomagnetic reversal (Borisenko et al., 2006; Isozaki, 2009). These phenomena can be explained as the consequence of Permian superplume activity (Isozaki, 2009; Xu et al., 2013). Compared to intensive and systematic studies on the Siberian traps and the Emeishan basalts (e.g., Sharma, 1997; Xu et al., 2007), information on the Tarim basalts and Panjal traps still remains scarce, probably because of partial burial by the Taklamagan desert. Considerable controversy remains as to the age, extent, composition and geodynamic evolution of the Tarim LIP. Recent gas and petroleum exploration in the Tarim Basin has provided drill boreholes and seismic profiles of variable scale, offering an ideal opportunity to better understand this LIP (e.g., Li et al., 2011; Liu et al., 2014; Tian et al., 2010). In addition, there are sufficiently large amounts of data available from exposed lava sections, intrusions and numerous dykes, and kimberlite pipes in the NW and W Tarim (Bachu, Keping, Piqiang) for an integrated analysis to be undertaken (Chen et al., 1997; Jiang et al., 2006; Wei et al., 2014; Yang et al., 2005; Yu et al., 2011b; Zhang et al., 2008a, 2010b, 2013; Zhou et al., 2009). This review paper starts with a summary of the main characteristics of the Tarim LIP including its rock type, composition and emplacement ages. We show that the three magmatic episodes of this LIP display distinct geochemical features and, by inference, different mantle sources. By integrating the observational data with thermal modeling results, we attribute the evolution of the Tarim LIP to interaction between a plume and lithosphere over ~20 m.y.

2. Geological setting

Bounded by the Tianshan orogenic belt to the north and west, and the West Kunlun and Altyn orogenic belt to the south (Fig. 1a), the Tarim Basin in the southern part of Xinjiang Province is the largest basin in China, occupying an area of ~600,000 km^2. It is also the least known of the continental blocks (Tarim Craton) in Asia due to its extensive coverage by a thick succession of post-Permian sedimentary strata and Taklamagan desert. The craton was amalgamated with the southern Central Asian Orogenic Belt (CAOB) during the Late Paleozoic (Fig. 1; BGMRXUAR, 1993; Han et al., 2011; Li, 2006) and is composed of Precambrian crystalline basement and a thick Phanerozoic sedimentary cover, recording a long tectonothermal history ranging from ~2500 Ma to ~270 Ma (Hu et al., 2000; Long et al., 2011). The Precambrian basement is believed to be a fragment of the Rodinian Supercontinent (Li et al., 2003; Lu et al., 2008) and is overlain by a thick sedimentary sequence that includes Ordovician, Permian and Cretaceous strata (BGMRXUAR, 1993; Jia, 1997; Zhang, 2003). The Permian strata in the Tarim Basin consist mainly of a volcanic–sedimentary sequence, composed of clastic rocks, muddy limestones and mafic–felsic volcanic rocks. The basement and Paleozoic strata are folded and faulted by Cenozoic deformation, producing approximately E–W trending uplifts and depressions in northern and central Tarim basin (Jia, 1997).

The deep structure of the Tarim Craton still remains poorly characterized. Priestley and McKenzie (2006) converted seismic shear wave velocities into temperature profiles and then fitted a geotherm to the resulting temperature estimates to construct global/regional lithospheric variation maps. From this study it is clear that the present-day lithosphere beneath Tarim is relatively thick, ranging from 150 to 200 km. A similarly thick lithosphere beneath the Tarim Basin is also revealed by seismic tomography (Lei and Zhao, 2007; Xu et al., 2002) and by a receiver function analysis of S-to-P converted waves at the boundary between the lithosphere and asthenosphere (Kumar et al., 2005). Using the teleseismic data collected from digital seismograms, Lei and Zhao (2007) showed that the Cenozoic sediments of the Tarim Basin are characterized by some low Vp, low Vs and high Poisson anomalies, whereas at greater depths high Vp, high Vs and low s anomalies dominate, indicating the relatively strong craton-like structure. Lei and Zhao (2007) further demonstrated that the lithosphere becomes thicker from the margin of the Tarim Basin to its center, which is in agreement with the general features of basin tectonics. Although all these seismic data reflect the nature of the present-day lithosphere beneath Tarim, as we will discuss below, the observed variations in lithospheric architecture fit well with the different styles of magmatism as far back as the Early Permian.

A large volume of Early Permian volcanic rocks, as well as intrusive complexes and mafic dykes, are exposed in Keping, Bachu and Piqiang around the margins, and in the interior of the Tarim Basin (e.g., Chen et al., 1997; Jia, 1997; Jiang et al., 2006; Li et al., 2011; Zhang et al., 2008a, 2010a,b; Zhou et al., 2009). Because much of the volcanic sequence occurs in the subsurface (covered by the Taklamagan desert), the full extent of the Tarim LIP remains uncertain. However in recent years, industrial geophysical surveys and oil exploration provided new geophysical and borehole data that suggest that the Permian basalts (including related tuff and tuffaceous sedimentary rocks) may extend over an area of 250,000 km^2–300,000 km^2 (Fig. 1a) (Chen et al., 1997, 2006; Tian et al., 2010; Yang et al., 1996, 2005, 2007). Drill-hole data indicate that the thickness of volcanic rocks range from ~200 to ~800 m. If an average thickness of 600 m is assumed, the entire volume of the Tarim basalts is estimated to be ~1.5 × 10^5 km^3.

3. Main rock types and their temporo-spatial distribution

3.1. Diamondiferous kimberlites

Following a diamond prospecting program in the 1980s–1990s, several tens of kimberlitic pipes were discovered in the Wajilitag area in the western Tarim LIP (Fig. 1a; Du, 1983). The presence of micro-diamonds in some pipes makes the Wajilitag kimberlites (Fig. 1a) particularly significant in understanding the evolution of the Tarim LIP as it suggests the presence of a cold and thick diamond-facies (180–200 km) lithosphere at the time of kimberlitic eruption. Clustering in an area of 5 km^2, the Wajilitag kimberlitic pipes are deeply weathered to greenish clay. They intruded the flat-lying and metamorphosed continental clastic sequences of the upper Devonian Keziletag and Yimugangtawu Formations, and were in turn cut by dolerite dykes (Li et al., 2011; Zhang et al., 2013). Spatially, the kimberlitic intrusions are associated with the Wajilitag igneous complex, which comprises Fe–Ti oxide ore-bearing layered ultramafic–mafic intrusions (Cao et al., 2013; Li et al., 2012a) and syenites emplaced at ca. 274 Ma (Zhang et al., 2008a).

The Wajilitag kimberlites are brecciated with a porphyritic texture of euhedral to rounded macrocrysts and phenocrysts (0.5 to 5 mm) of clinopyroxenes, olivine and phlogopite setting in a fine-grained matrix. The matrix is composed of clinopyroxene, phlogopite, olivine, apatite, perovskite, baddeleyite, garnet, spinel, rutile, magnetite, calcite and graphite (Zhang et al., 2013). The Wajilitag kimberlites show fractionated

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