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Subducted slab-plume interaction traced by magnesium isotopes in the northern margin of the Tarim Large Igneous Province

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ABSTRACT

Incorporation of subducted slabs may account for the geochemical and isotopic variations of large igneous provinces (LIPs). However, the mechanism and process by which subducted slabs are involved into magmas is still highly debated. Here, we report a set of high resolution Mg isotopes for a suite of alkaline and Fe-rich rocks (including basalts, mafic–ultramafic layered intrusions, diabase dykes and mantle xenoliths in the kimberlitic rocks) from Tarim Large Igneous Province (TLIP). We observed that δ^{26}Mg values of basalts range from −0.29 to −0.45‰, −0.31 to −0.42‰ for mafic–ultramafic layered intrusions, −0.28 to −0.31‰ for diabase dykes and −0.29 to −0.44‰ for pyroxenite xenoliths from the kimberlitic rocks, typically lighter than the normal mantle source (−0.25‰ ± 0.04, 2 SD). After carefully precluding other possibilities, we propose that the light Mg isotopic compositions and high FeO contents should be ascribed to the involvement of recycled sedimentary carbonate rocks and pyroxenite/eclogite. Moreover, from basalts, through layered intrusions to diabase dykes, $(^{87}Sr/^{86}Sr)_i$ values and $\delta^{18}O_{V\text{-}SMOW}$ declined, whereas $\varepsilon_{(Nd)t}$ and δ^{26}Mg values increased with progressive partial melting of mantle, indicating that components of carbonate rock and pyroxenite/eclogite in the mantle sources were waning over time. In combination with the previous reported Mg isotopes for carbonatite, nephelinite and kimberlitic rocks in TLIP, two distinct mantle domains are recognized for this province: 1) a lithospheric mantle source for basalts and mafic–ultramafic layered intrusions which were modified by calcite/dolomite and eclogite-derived high-Si melts, as evidenced by enriched Sr–Nd–O and light Mg isotopic compositions; 2) a plume source for carbonatite, nephelinite and kimberlitic rocks which were related to magnesite or periclase/perovskite involvement as reflected by depleted Sr–Nd–O and extremely light Mg isotopes. Ultimately, our study suggests that subducted slabs could make important contributions to LIP generation, and establishes a potential linkage between plate tectonics and mantle plume.

1. Introduction

Plate tectonics and mantle plume were adopted to interpret the plate boundary's (e.g., arc magma and mid-ocean ridge basalt (MORB)) and intraplate magmatism, respectively (e.g., Morgan, 1971). Compared to arc magma and MORB, intraplate magma tends to represent a later stage magmatism that was derived from a metasomatized mantle and occurred after the termination of subduction. High resolution seismic images show that subducted slabs can reach mantle transition zone and accumulate as stagnant stabs, which then fall into lower mantle and ultimately settle down above the core–mantle boundary (CMB; e.g., Maruyama et al., 2007). In this case, crustal materials including oceanic crusts (e.g., oceanic basalts, pelagic sediments, and sedimentary carbonate rocks) are expected to enter mantle sources at different levels, modify the physical and chemical properties, and generate mantle heterogeneity (e.g., Thomson et al., 2016). Thus, magmas derived from these different zones would potentially show signatures of crustal materials. Characterized by massive eruption of mafic–ultramafic rocks within a short period of time (area $>10^5$ km^2, volume $>10^5$ km^3, with the note that the duration can be relatively long, but >75% volume will be accomplished in 1–5 Ma; Bryan and Ernst, 2008), Large Igneous Province (LIP) is one of the most typically intraplate magmas. Even though many mechanisms were proposed for the formation of LIPs, they are generally considered to be related to mantle plume originating from the CMB or upper-lower mantle boundary (e.g., Campbell, 2005). Based on the reconstruction of supercontinent and ancient LIPs, the spatio-temporal coupling of LIPs and subduction abyssal system suggests

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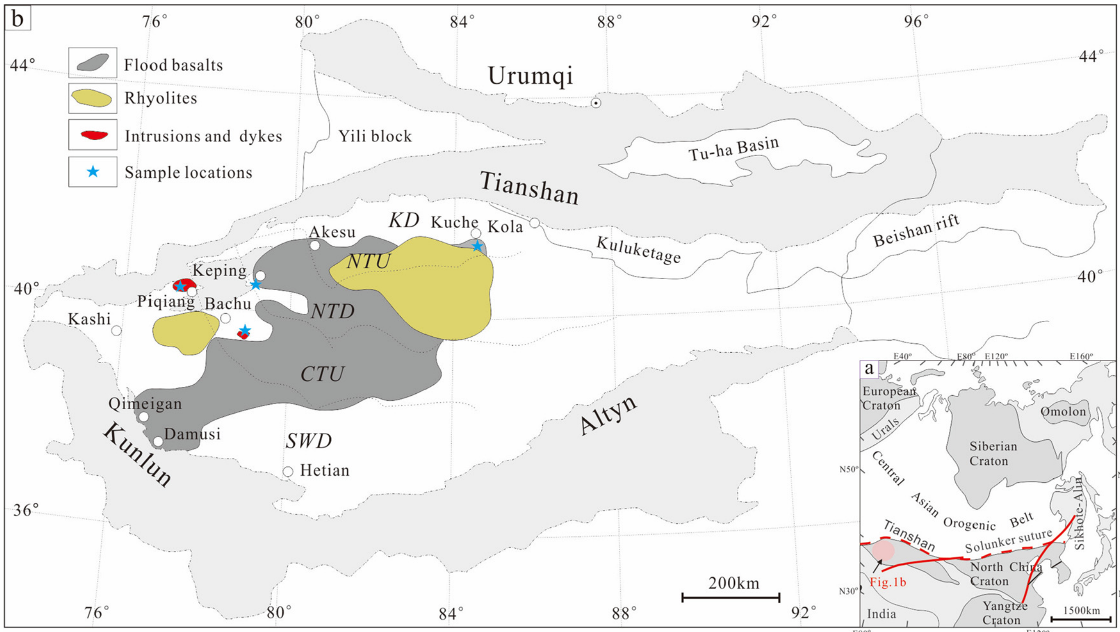

Fig. 1. (a) Distribution of TLIP (modified after Cheng et al., 2017); (b) Sketch geological map of TLIP showing sample locations (modified after Xu et al., 2014). Therein, basalts are from Keping and Kuche drill cores, mafic–ultramafic layered intrusions are from Bachu and Piqiang, diabase dykes and pyroxenite xenoliths of the kimberlitic rocks are from Bachu. Abbreviation: *KD*, Kuche Depression; *NTU*, Northern Tarim uplift; *NTD*, Northern Tarim Depression; *CTU*, Central Tarim Uplift; *SWD*, Southwestern depression.

a close genetic connection (Wang et al., 2013). The unique massive basaltic magma can effectively transfer deep mantle materials to surface. If we can establish the direct linkage between subduction slabs and LIPs, it will improve our understanding knowledge of the Earth material circulation system. However, the exact mechanism by which subducted slabs were incorporated into intraplate magmas is still highly controversial, and we also lack robust evidence and efficient methods to trace the role of subducted slabs for LIPs.

Permian Tarim Large Igneous Province (TLIP) is a recently recognized LIP (Fig. 1) in NW China. In comparison with the other LIPs, the igneous units of TLIP show typically alkaline affinity (Fig. 2a) and are relatively iron-rich (Fig. 2b; most of basaltic rocks are ferrobasaltic in composition with total FeO (referred as TFeO) contents >12.5 wt. %; e.g., Zhou et al., 2009; Tian et al., 2010). Based on the previous studies, alkaline rocks are suggested to be derived from low degree ($<10\%$) partial melting (e.g., Spera, 1980). This inference results in a paradox that low-degree melting of mantle hardly produce voluminous magmas and form a LIP. Hence, more fusible components in the magma source are expected. On the other hand, previous experimental studies also proposed that the involvement of eclogite/pyroxenite may play an important role in the formation of Fe-rich primary melts, e.g., ferropicrite (e.g., Hirose and Kushiro, 1993; Tuff et al., 2005). Moreover, these more fusible components are commonly related to subduction. Therefore, both alkaline and iron-rich features possessed by TLIP could provide a rare opportunity for us to elucidate the contribution from ancient subduction to LIPs.

Magnesium (Mg) isotope is a newly developed stable isotope tool. Previous studies reveal that the normal mantle and oceanic basalts (average value of $\delta^{26}Mg = -0.25‰$; e.g., Teng et al., 2007; Bourdon et al., 2010) exhibit distinct isotopic compositions from sedimentary carbonate rocks ($\delta^{26}Mg = -5.54‰$ to $-0.47‰$; e.g., Galy et al., 2002; Wombacher et al., 2011). Mg isotope is therefore sensitive to contributions from recycled carbonates (Yang et al., 2012; Huang et al., 2015; Li et al., 2016; Cheng et al., 2017). Moreover, during the dehydration of subducted slab, although significant isotopic fractionation cannot be observed for the entire slab, different components (i.e., carbonate and eclogite) can alter their isotopic composition by isotopic exchange (Wang et al., 2014). The isotopic exchange results in a slightly heavier δ^{26}Mg values for metamorphosed carbonates ($-2.51‰$ to $-0.53‰$), leaving silicate component with lighter δ^{26}Mg values ($-1.93‰$ to $-0.65‰$). These components with lighter Mg isotopes are expected to change the surrounding mantle, and hence provide critical supports to trace signatures of subducted slabs.

In this contribution, we mainly focused on the mafic–ultramafic rocks along the northern margin of TLIP, including basalts, layered intrusions, diabase dykes and mantle xenoliths in the kimberlitic rocks. We present the systematic Mg isotope study, in combination with major and trace elements and conventional Sr–Nd–O isotopes, to examine the contribution of subducted slabs to LIPs, and further provide evidence for the linkage between subducted slabs and mantle plume.

2. Permian Tarim Large Igneous Province

Tarim craton (TC) is located in Xinjiang Uygur Autonomous Region, northwestern China (Fig. 1a). It is surrounded by Tianshan Mountain to the north and Kunlun Mountain to the South. TC is composed of Precambrian basement and thick Phanerozoic cover. Therein, Precambrian basement is suggested to be related to the breakup of Rodinian supercontinent, while Phanerozoic cover consists of Ordovician, Devonian, Carboniferous, Permian and Cretaceous strata (Xu et al., 2014). The Permian strata is mainly a volcanic-sedimentary sequence, comprising clastic rock, limestone and basic-felsic volcanic rocks. Due to the remote effect of Cenozoic India–Eurasia collision, folds and faults in large scales were well developed, and the TC generally formed several E–W trending uplifts and depressions, which are Kuche depression, Northern Tarim uplift, Northern Tarim depression, Central Tarim uplift and Southwestern depression from north to south (Fig. 1b; Tian et al., 2010). Voluminous Early Permian basalts, mafic–ultramafic layered intrusions and mafic dykes are widespread in the Tarim basin (Xu et al., 2014 and the reference therein). The best outcrops of basalts are from Keping, Qimeigan and Damusi around the Tarim basin, and layered mafic–ultramafic intrusions are mainly from Piqiang and Bachu (Fig. 1b). Detailed geological description of these outcrops could be referred to the Supplementary