Hf isotopic characteristics of the Tarim Permian large igneous province rocks of NW China: Implication for the magmatic source and evolution

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Abstract

The Tarim large igneous province (TLIP) in northwestern China, covering an area of ca. 250,000 km², includes large volumes of basalts, basic dyke swarms, mafic-ultramafic intrusion and minor picrite. Here we report systematic Hf isotope data from basalt, diabase, olivine pyroxenite and syenitic porphyry from the TLIP and address the source components and magma evolution. The subdivision of the Tarim basalts shows that the Group 1 and Group 2 basalts are clearly differentiated based on different Nb/Y values, with two subgroups (Group 1a, Group 1b) identified based on distinct P2O5 vs. Mg# trends. The 176Hf/177Hf isotopic composition of the basalts ranges from 0.282584 to 0.282837. The εHf(t) of the basaltic lavas of the Pitcairn hotspot. These features, together with the enriched signature of the Tarim basalts might reflect the incorporation of partial melting of lithospheric mantle source in the early stages of the plume activity. The TLIP basalts show low εNd(t) and moderate εHf(t) OIB-like source. The 176Hf/177Hf-143Nd/144Nd values of the Group 1a and Group 1b basalts of the TLIP basalts are comparable to those from the Karoo high-Ti basalts, and those of the Group 2 basalts are comparable to the features of the Karoo low-Ti basalts and diabases. The Group 1a and Group 1b basalts fall in the same εNd(t) array, whereas the Group 2 basalts fall in a different array with much higher εNd(t). The olivine pyroxenite, diabase and syenitic porphyry fall in the higher εNd(t) and εHf(t) field, with the olivine pyroxenite and diabase having features close to OIB-like source. Our new Hf isotopic results suggest distinct sources for the Tarim basalts (285–290 Ma) and the intrusive rocks (274–284 Ma). Furthermore, the εHf(t) vs. εNd(t) plots show that the basalts and intrusive rocks might correspond to two different periods of magmatic activity in the Tarim Basin during the Early Permian, being comparable to the temporal evolution of different rock units in the TLIP. The εHf(t) and εNd(t) combined with other evidences address that the basalts could be explained by being derived from the asthenospheric (or plume) mantle and having interaction with lithospheric mantle source by mainly lower degree of partial melting in the early stage before the eruption, and should be much less proportion of crustal contamination during the period of 285–290 Ma, and the intrusive rocks might be derived from the primary magma and/or OIB-like mantle sources and underwent a magma process mainly by fractional crystallization and/or cumulation during the period of 274–284 Ma.

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1. Introduction

Continental flood basalts (CFBs) and large igneous provinces (LIPs) have received considerable attentions recently in relation to mantle dynamics as well as plate and plume tectonics (Carlson et al., 2006). The continental flood-basalt volcanism has been
linked to an anomalously hot, enriched mantle reservoir (White and McKenzie, 1989), the effects of mantle flow close to the lithospheric mantle boundaries (Carlson and Hart, 1987; King and Anderson, 1998), mantle plumes (e.g., Richards et al., 1989; Campbell and Griffiths, 1990; Ernst and Buchan, 2003), and by delamination of the lower parts of continental lithosphere (e.g., Elkins-Tanton and Hager, 2000; Hales et al., 2005) under continental extensional setting (Harry and Leeman, 1995). Continental flood basalts show elemental and isotopic compositional range similar to either mid-ocean-ridge basalts (MORBs) or ocean-island basalts (OIBs) (e.g., Condie, 2001). The interaction among end-member components of mantle plume and/or asthenosphere, heated lithosphere mantle, and continental crust plays an important role for the LIPs and/or CFBs. The lithosphere can modify asthenosphere (plume)-derived melts through contaminating the melts with sub-lithospheric mantle and continental crust (e.g., Arndt and Christensen, 1992), and may serve as an important site of melt generation for the formation of continental flood basalts provinces (e.g., Campbell and Griffiths, 1990; Turner and Hawkesworth, 1995; Turner et al., 1996; Wang et al., 2008). Furthermore, systematic Hf isotope study combined with Sr–Nd–Pb–Os–O isotopes and major and trace elemental data for the basalts and intrusive rocks can provide a good trace for the contributions of the magmatic source components of the end-members of the OIB-MORB-EM (enriched mantle)-DMM (depleted MORB mantle) system and even magmatic evolution of the CFBs and LIPs as well as the genetic link with mantle plume. The recent advancements in analytical techniques has led to the application of Hf-isotope geochemistry in a variety of problems related to petrogenesis and tectonics, and studies on the Lu–Hf system because it is a sensitive monitor of source components and mineralogy, as the different chemical behavior of the parent and daughter elements results in larger variations in $^{176}\text{Hf}/^{177}\text{Hf}$ relative to $^{143}\text{Nd}/^{144}\text{Nd}$ ratios.

Permian continental flood basalts and other related igneous rocks in the Tarim Basin and surrounding regions of northwestern China have been well studied in terms of petrology, geochemistry and Sr–Nd–Pb isotopes, particularly in the Keping area of northwestern Tarim Basin (Fig. 1). The rocks constitute the ~274–290 Ma Tarim Large Igneous Province (TLIP) with a large-scale distribution of basalts (ca. 250,000 km²), including picrite, and widely developed basic dyke swarms and coeval mafic-ultramafic intrusions as documented from the surface outcrops and drilling data (Chen et al., 1997; Jiang et al., 2004a,b, 2006; Yang et al., 2006a,b, 2007a,b; Li et al., 2008, 2011; Zhang et al., 2008, 2010; Zhou et al., 2009; Tian et al., 2010; Yu et al., 2011). The TLIP can be compared to the ~250 Ma Siberian Traps in Russia (Campbell et al., 1992; Lightfoot et al., 1993; Ivanov, 2007) and the ~258–260 Ma Emeishan LIP in southwestern China (Chung and Jahn, 1995; Xu et al., 2001; Xiao et al., 2003), with probable link to mantle plume activity (Zhang et al., 2008; Yu et al., 2009; Pirajno et al., 2009; Zhou et al., 2009; Li et al., 2011).

The Hf isotope characteristics of the various units in the TLIP have not yet been investigated in detail. In this paper, we present a detailed Hf isotope study for the 285–290 Ma basalts and 274–284 Ma intrusive rocks (olivine pyroxenite, diabase, syenite, total 32 samples) collected from the field outcrops of the Yingan (Yg), Sishichang (Ssc) and Xiahenan (Xhn) sections of Keping areas, and Xiaohaizi and Wajilitag of Bachu areas of the northwestern Tarim, the Taxinan section (Txn) of southwestern Tarim, and the Shengli (SL), Yangta (YT), He, Hadexun (H) and Yingmai (YM) drill holes of the Northern and Central Tarim Basin (Fig. 1). Rocks belonging to the 289 Ma (285–290 Ma) and 275 Ma (274–284 Ma) groups were used in the calculation of $e^{\text{Hf}}(t)$ and $e^{\text{Nd}}(t)$ because these ages represent the eruption timing of the basalts and the emplacement of the intrusive suite. The purpose of our

![Fig. 1. A simplified tectonic map of the Tarim Basin, northwestern China, showing the distribution of Permian basalts in the Tarim Basin and the locations of some outcrops and drill holes sections with the samples in this study. The distribution of Permian basalts is after Yang et al. (2005), mainly based on available drill core data and outcrops in and around the basin.](image-url)
Hf isotopic study on the TLIP is threefold: (1) to record the Hf isotopic signature of the TLIP rocks; (2) to determine the temporal Hf isotope variations in the TLIP rocks; and (3) to discuss the implications on the magma source of the basalts and intrusive rocks from the different areas of the Tarim Basin using the characteristics of Hf–Nd isotopes, as well as to make a comparison of Hf isotope signature in the TLIP rocks with that of the Siberia, Hawaii and Yellowstone volcanic rocks related with the CFB, mantle plumes and hotspots.

2. Regional geology and Permian igneous rocks in the Tarim Basin

The Permian magmatic event was as a large scale magmatic activity in the Tarim Basin (Yang et al., 2007a; Zhang et al., 2011). The TLIP is widely distributed in the Keping, Bachu, Tabei (northern Tarim Basin), Tazhong (central Tarim Basin) and Taxinian (southwestern Tarim Basin) areas (Fig. 1), and covers an area of ca. 250,000 km² (Yang et al., 2005; Chen et al., 2006), comparable to that of the Emeishan LIP in SW China (Chung and Jahn, 1995; Xu et al., 2001). Lithological units of the TLIP are mainly continental flood basalts and diabases as well as layered mafic–ultramafic intrusions, mica-olivine pyroxenite breccia pipes, diabases and ultramafic dykes, quartz syenites, quartz syenite porphyry and bimodal dykes (Yang et al., 1996; Chen et al., 1997; Jiang et al., 2004a,b; Yang et al., 2006a,b, 2007a,b; Zhang et al., 2008; Li et al., 2010; Li et al., 2011). Permian basalts in the Tarim Basin occur in the outcrops around the basin (Keping and Taxinan areas) and have also been identified from drilled cores within the basin (Jiang et al., 2004b; Yang et al., 2005, 2006a; Li et al., 2008; Yu et al., 2009, 2011). The basalts have been recognized in the Kupukuziman Formation in the lower part and the Kaipaiizele Formation in the upper part of the Early Permian (Jiang et al., 2006; Yu et al., 2011). Li et al. (2008) argued that the basalts exposed in the lower Permian Qipan Formation of the southwestern Tarim Basin have geochemical affinity with those from the Keping area. The data from the drill holes and 3D seismic cross-sections pose in the lower Permian Qipan Formation of the southwestern Tarim Basin using the characteristics of Hf–Nd isotopes, as well as to make a comparison of Hf isotope signature in the TLIP rocks with that of the Siberia, Hawaii and Yellowstone volcanic rocks related with the CFB, mantle plumes and hotspots.

3. Sample description

The samples analyzed were collected from five field sections of the Yingan, Sishichang, Xiahenan, Wajilitag, and Xiaoaihaizi areas, and the drill holes of He4, H1, YT6, SL1, YM5 and YM8 (Fig. 1, Table 1). In addition to the surface exposures of the flood-volcanics, several boreholes drilled for oil and gas exploration have sampled basaltic rocks at the depths of 810–5900 m in the central and northern parts of the Tarim Basin.

The various units of basaltic rocks identified are coeval and chemically similar (Li et al., 2008; Tian et al., 2010; Li et al., 2012). Their geological features are given in Jia (1997), Zhang et al. (2003), Yang et al. (2005) and Li et al. (2008). In general, the basalts have been classified into various compositional groups. The Group 1 (a, b) basalts are aphyric and locally hyaloclastitic, occasionally vesicular/amygdaloidal, and sometimes with rare phenocrysts of plagioclase (<3%). They show interlayering of porphyritic and aphyric varieties. The groundmass is composed of plagioclase (30–50%), basaltic glass (30–45%) and Fe–Ti oxides (5–10%). The basalts belonging to compositional Group 2 basalts are augite- (<1–2%) and plagioclase (<2%)-phyric, with minor olivine, and occasional lavas are aphyric with rounded vesicles. Some lavas are more strongly porphyritic, with 2–10% plagioclase phenocrysts and sparse phenocrysts of olivine (<1–2%) and augite (<1–3%). Groundmass textures vary from interstitial, through microlitic, to devitrified glassy, and the crystalline groundmasses are typically composed of plagioclase (30–45%), clinopyroxene (30–45%), olivine (<45%) and Fe–Ti oxides (5–10%). The magmatic stratigraphy of the Yingan section of Keping area was described in detail in Yu et al. (2011) and YQ Li et al. (2012). The Yingan section in the Keping County (Fig. 1) is one of the best Permian basalt outcrops in the study area and was hence selected for Hf-isotopic investigation in this study. The stratigraphy and geochemistry, including PGE were described by Yu et al. (2011) and YQ Li et al. (2012), where the eight basaltic lava flow units of a total thickness of ca. 400 m were recorded. Among these, the 2 units are exposed in the Kupukuziman Formation and 6 units in the Kaipaiizele Formation. Individual basaltic unit ranges from 10 to 70 m in thickness, with intercalations of terrestrial sediments such as alternating reddish mudstone and siltstone, volcanic breccia, tuff and non-marine limestone (Yu et al., 2011). A total of 32 representative samples were selected from more than 120 samples collected. The samples were analyzed for major, trace and rare earth elements as well as Sr–Nd–Pb isotopes, followed by Hf isotope study. Among these, 2–3 basalt samples were collected from individual lava flow units in the Group 1a basalts of the Yingan section to evaluate the Hf isotope variations among the individual units. The basalts from the middle and upper parts of the 5th unit is exceptional in that they carry abundant plagioclase phenocrysts (ca. 40 modal%).

The olivine-pyroxenite and diabase near the southern part of the Xiaoaihaizi reservoir in Bachu area occur as dykes intruding...
The Carboniferous sedimentary rocks, which the latter underwent contact metamorphic effect (sample locations described in Yang et al., 2007a,b). The diabase dykes intruded into the Devonian to Carboniferous sedimentary rocks, which the latter underwent metamorphism.

### 4. Geochemical characteristics of the Tarim Permian basalts and intrusive rocks

#### 4.1. Tarim Permian basalts

In general, the TLIP basalts show SiO₂ contents from 43.7 to 53.6 wt.%, with K₂O contents always lower than Na₂O. The basalts belong to both alkaline and subalkaline series. All the basalts are rather evolved (100 Mg# from 22.3 to 59.3), and most of them show high TiO₂ contents (mainly 3–5 wt.%), classifying as high-Ti series basalts. According to the classification by ZL Li et al. (2012), three compositional groups have been identified for the TLIP basalts as defined from their HFSE and P₂O₅ contents. The Groups 1 and 2 basalts are clearly differentiated on the basis of their different Nb/Y values, with two subgroups (Group 1a, Group 1b) identified within the Group 1 basalts, based on their distinct P₂O₅ vs. Mg# trends and P₂O₅/Ce ranges (not shown here). The Group 1 basalts include alkaline and moderately subalkaline rocks and have distinctly lower SiO₂ and generally lower K₂O, and higher FeOT, TiO₂, P₂O₅ than those of the Group 2 lavas. The Group 1 basalts show a limited range (0.8–1.1), indicating only weak or no Eu anomaly. The Group 2 basalts show slightly steeper LREE enrichment and more HREE depletion than the Group 1 basalts, though there is effectively no significant difference in REE patterns of both the groups show LREE-enrichment, with moderate HREE depletion ([Ca/Lu]₅_N of 1.7–3.3) and their Eu/Eu’ ratios show a limited range (0.8–1.1), indicating only weak or no Eu anomaly. The Group 2 basalts show slightly steeper LREE-enrichment and more HREE depletion than the Group 1 basalts, although there is effectively no significant difference in REE patterns between the two sub-groups despite their markedly different P₂O₅/Ce values. A more detailed description of the geochemical features of the three groups of basalts is given in ZL Li et al. (2012).

#### 4.2. Tarim Permian intrusive rocks

The olivine-pyroxenite with an average abundance of SiO₂ around 42%, 100 Mg# = 67–69 was probably derived from a primary basaltic magma rich in iron and magnesium, with significant fractionation as suggested by the enrichment of the marked slope from LREE to HREE. These rocks show geochemical features similar to those of within-plate basalts, with LREE enrichment and lack of

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**Table 1**

<table>
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<tr>
<th>Rock types</th>
<th>Samples</th>
<th>Rock name</th>
<th>t²⁶⁹Hf/t²⁷⁰Hf</th>
<th>εHf</th>
<th>t²⁶⁹Sm/t²⁷⁰Sm</th>
<th>SiO₂</th>
<th>FeO₂</th>
<th>MgO</th>
<th>Mg#</th>
<th>εNd</th>
<th>εNd(Cr)</th>
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<td>15.02</td>
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<td>0.000009</td>
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<td>3.91</td>
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<td>2.88</td>
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<td>0.000007</td>
<td>5.0</td>
<td>46.61</td>
<td>15.57</td>
<td>5.03</td>
<td>3.65</td>
<td>3.73</td>
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<td>48.02</td>
<td>12.35</td>
<td>2.42</td>
<td>2.88</td>
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<td>0.7062</td>
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<td>Group 2a basalt</td>
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Note: ε values calculated using CHUR (today) with ¹⁴⁷Nd/¹⁴⁴Nd = 0.512847; ¹⁴⁷Sm/¹⁴⁴Nd = 0.1967, t²⁶⁹Hf(t) being calculated at t = 289 Ma and t = 275 Ma for the basaltic and intrusive rocks, respectively. σ = Standard error of the mean and Mγ# = Mγ/Mγ + Fe²⁺. The t²⁶⁹Hf(⁴⁴) being from this study, and SiO₂, FeO₂, and MgO and Sr–Nd isotope values of basalts are from Li et al. (2008), Yu et al. (2011), ZL Li et al. (2012) and of intrusive rocks from Yang et al. (2006a,b, 2007a,b) and authors’ unpublished data. Nd isotope data not reported in this paper. Ol: olivine, Hf: initial Hf.
Eu anomaly. Their trace elements ratios suggest a potential magma source from the mantle. It is possible that the magma was derived from partial melting of asthenospheric mantle, and intruded along fractures in the basement rocks (Yang et al., 2007b). The diabase dykes which occur in close proximity to the olivine pyroxenite dyke, show geochemical characteristics broadly similar to those of the Keping basalts suggesting that they might have been derived from a similar magma source in the same within-pllate setting. Yang et al. (2007a) showed that the geochemistry of the quartz syenite porphyry in Bachu Shuigongtuan indicates A-type affinity, formed under within-pllate rifting environment and derived from mantle sources at ca. 277 Ma, and probably representing the last major magmatic event in the Tarim Basin. The quartz syenite porphyry has almost the same geochemical features with the Xiaohai-zi syenite, and both of them show similar source characteristics and tectonic setting. The chemical characteristics of the diabase indicate derivation from mantle source and formation under within-pllate environment, with probable affinity with mantle plumes. The formation of the quartz syenite porphyry and diabase are genetically linked with the voluminous Permian (285–290 Ma) basalts occurring in the Tarim Basin.

5. Analytical methods

The 32 whole-rock samples selected for this study were crushed by jaw crusher and roller mill, and then powdered in agate mortars in order to minimize potential contamination of transitional metals. The amygdules in some basalt samples were carefully removed as best as possible to minimize the effect of post-eruption hydrothermal alteration.

Hf isotopes were determined using a Finnigan Neptune multi collector (MC)-ICP-MS at the Guangzhou Institute of Geochemistry of Chinese Academy of Sciences. The measured $^{176}$Hf/$^{177}$Hf ratios were normalized to $^{176}$Hf/$^{177}$Hf = 0.713393, and the reported $^{176}$Hf/$^{177}$Hf ratios were further adjusted relative to the JB-3 standard of 0.282160. The analytical procedures used are similar to those described by Li et al. (2005, 2007). The Hf isotopic results are listed in Table 1. The $\varepsilon$Hf(t) values were calculated with reference to the chondritic reservoir (CHUR) with present-day $^{176}$Hf/$^{177}$Hf = 0.282772 and $^{176}$Lu/$^{177}$Hf = 0.0332 (Blichert-Toft and Albarède, 1997).

6. Analytical results

The $^{176}$Hf/$^{177}$Hf isotopic ratios of the basalt samples range from 0.282584 to 0.282837. The Group 1a, Group 1b, and Group 2 basalts have $^{176}$Hf/$^{177}$Hf ratios of 0.282584–0.282733, 0.282611–0.282658, and 0.282649–0.282684, respectively (Table 1). The pyroxenites, diabases, and felsic dykes show $^{176}$Hf/$^{177}$Hf ratios of 0.282789–0.282776, 0.282765–0.282621, and 0.282785–0.282835, respectively. The $\varepsilon$Hf(t) in the Group 1a, Group 1b, and Group 2 basalts are -0.4–4.4, 0.5–2.1, and 1.9–3.1, respectively, and the intrusive olivine pyroxenite, diabase and syenitic porphyry show 6.0–6.5, 4.5–5.7 (except the value of 0.6 for a sample of diabase), and 6.5–8.3, respectively.

7. Discussion

7.1. Spatial and temporal comparison of Hf isotopic systems from the three group basalts and intrusive rocks

As summarized in a previous section, the Tarim basalts show an age range of 285–290 Ma. The results from present study show that the Hf isotopes ($^{176}$Hf/$^{177}$Hf and $\varepsilon$Hf(t)) of the three groups basalts (Group 1a, Group 1b and Group 2) do not display any marked contrast. However, the $\varepsilon$Hf(t) of the Group 1a rocks show a much wider range, and overlap with the ranges of the Group 1b and Group 2 rocks. The Tnx basalts from the southwestern Tarim Basin show almost the same Hf isotope features to those from Keping area (Yg, Ssc). The Hf data combined with trace elements and Sr–Nd–Pb isotopes, suggest that these basalts may be derived from the same OIB-like magmatic sources, but underwent evolved magmatic processes in some extent. In the Yingan section, there is a discontinuous change of the trace element ratios and Sr–Nd isotopes from the bottom unit to the top unit of the basalts, suggesting probable a mixing process between the evolved magma and a relatively primitive magma source (YQ Li et al., 2012). Hf isotopes of the basalts from the Yingan section show variation from 0.282654 to 0.282679 at the top of the Kai2 unit to the bottom of the Kai3 unit, from 0.282653 to 0.282678 to the top of the Kai3 to Kai4, and from 0.282696 to 0.282637 from the top of the Kai4 to the bottom of the Kai5 unit. Variation also exists within individual units, such as an increase in Hf isotope from 0.282593 to 0.282672 in Kai1 and from 0.282696 to 0.282723 in Kai5 (from the bottom to the top). The Hf isotope variation from the bottom unit to the top unit as recorded in the present study shows an abrupt and pronounced change from the beginning of the unit Kai1 till Kai6, with the exception of the Kai2 unit (Fig. 4b).

However, the intrusive units formed during 274–284 Ma, and are much younger than the basalts (Li et al., 2011). The intrusive suite show much higher $^{176}$Hf/$^{177}$Hf and $\varepsilon$Hf(t) values than the three groups of basalts (Fig. 2 and 3), indicating that they may be derived from a different componental proportion of magma sources. Furthermore, the $\varepsilon$Hf(t) in the olivine pyroxenite is relatively higher than the diabase, and the syenitic porphyry has the highest $\varepsilon$Hf(t) values compared to those from the basalts and olivine pyroxenite and diabase although they are plotted in similar or the same field with relatively high $\varepsilon$Nd(t) and $\varepsilon$Hf(t) among the various units in the Tarim LIP. The mafic intrusive rocks (olivine pyroxenite and diabase) and the syenite porphyry have the similar age between 274 Ma and 284 Ma, and have genetic affinity in the sources and magmatic evolution as described by Zhang et al. (2008). Zhang et al. (2008) argued that the Bachu layered igneous complex including mafic rocks and syenite were derived from mantle source by crystal fractionation and accumulation, and is similar to those of many oceanic and continental alkaline primary suites having positive $\varepsilon$Nd(t) in association with LREE enrichments relative to Normal-MORB-mantle-derived rocks (N-MORB; Wedepohl and Baumann, 1999). In this context, the high $\varepsilon$Nd(t) and...
176Hf/177Hf in them further support Zhang et al. (2008)'s argument in the present study.

Combined with the previous major, trace and Sr–Nd isotope study, the Taxinan basalts show similar geochemical and Sr–Nd isotope characteristics, and are regarded to have been derived from the same magma source and/or varied magmatic evolution. The Hf isotope data presented in this study support the assumption that the Taxinan basalt belongs to the Group 1a basalts being from the same magma source and witnesses similar magmatic processes with those of the Keping basalts (Yg and Ssc and Xhn basalts), constituting a flood basaltic province in the Tarim Basin during Early Permian.

With regard to the spatial and temporal distribution of HF isotope characteristics in the Tarim Basin, the intrusive rocks in the Bachu area formed during the age of 274–284 Ma show higher 176Hf/177Hf isotope data presented in this study. The fields for the Hawaii basalt (Blichert-Toft et al., 1999), Karoo basalt (HT, LT) and swarm dykes (Ellam, 2006; Jourdan et al., 2007); Siberian melilitites and kimberlites (Carlson et al., 2006); Yellowstone hotspot tuffs (Nash et al., 2006); Galapagos Islands (Blichert-Toft and White, 2001); and Kerguelen Archipelago volcanic rocks (Mattielli et al., 2002). The regression line of the terrestrial array from the Group 1a, Group 1b and Group 2 basalts and intrusive rocks (274–284 Ma) (Fig. 3). In the en-echelon arrays for the Tarim basalts and intrusive rocks, the Hf isotope characteristics, and are regarded to have been derived from the same magma source and/or varied magmatic evolution. The Hf isotope characteristics and evolved magmatic process in the Tarim Basin during Early Permian.

Our new Hf isotopic data may provide important clues to evaluate the differences between the basalts (285–290 Ma) and the intrusive rocks (274–284 Ma) (Fig. 3). In the eHf(t) vs. ɛNd(t) plot, the en-echelon arrays for the Tarim basalts and intrusive rocks might correspond to two different periods of magmatic activity and evolved magmatic process in the Tarim Basin during Early Permian.
try, Yu et al. (2011) and Zhou et al. (2009) proposed that the Tarim characteristics. Based on trace element and Sr–Nd isotope chemistry, the source is suggested from the Hf–Sr–Nd isotope and geochemical features, the basaltic melts was 1200°C chondritic Hf/Sm ratios (0.7 ± 0.1) preclude the possibility of significant crust contamination. The weak Nb anomaly and the nearly linear slope of 0.76, being much gentler than that of the terrestrial array. Individual oceanic island arcs (Salters and White, 1998; Blichert-Toft et al., 1999; Kempton et al., 2000) are commonly characterized by shallower slopes (e.g. Pitcairn Island and Hawaiian basalts, S ~ 1.00, Eisele et al., 2002), whereas the arrays for Walvis Ridge, another EMI-type locality, and Iceland (Kempton et al., 2000), have steeper slopes (S > 1.5). The slope of the eHf(t) vs. Sm/Sr ratio and source components from the TLIP Group 1a and Group 1b basalts can be compared to the Karoo CFB basalt (HT), although the former has a much higher eHf(t). The TLIP ultramafic–mafic intrusive rocks can be compared to the Siberian LIP meimechite and kimberlite, and Kerguelen Archipelago volcanic rocks. A sample from the drill hole of the He4 with lower eNd(t) has distinct eHf(t) and eNd(t) values as compared to the other samples, with a good correlation between the eHf(t) and eNd(t), indicating the He4 rock was derived from a source distinct from that of other Group 1a basalts. However, such a distinction does not exist in the Sr–Nd relations, and the He4 sample coincides with the Group 1a basalts in 147Nd/144Nd vs. 87Sr/86Sr ratio (not shown). However, the TLIP Group 2 basalts are similar to those of the Karoo CFB basalt (LT) and Karoo CFB Dyke swarm and Kerguelen Archipelago volcanic rocks. There is no systematic trend and correlation between the HF and alkalinity index (Al = (Na2O + K2O) – 0.37SiO2 – 14.43; Rhodes, 1996). However, the high eHf(t) from the olivine pyroxenite show subalkaline feature, whereas the low eHf(t) from the Group 1a basalts (except for the He sample) and diabase are dominantly alkaline. The Group 1b and Group 2 basalts are tholeiitic and subordinately alkali. Furthermore, in the eHf(t) vs. Sm/Sr (t) plot, the syenitic porphyry components are different compared to those from the felsic tuffs from the Yellowstone hotspots, with the former having higher eHf(t) and eNd(t) values (Fig. 3).

The possibility that the Tarim basalts were derived from enriched lithosphere mantle and OIB-like asthenosphere mantle source is suggested from the HF–Sr–Nd isotope and geochronological characteristics. Based on trace element and Sr–Nd isotope chemistry, Yu et al. (2011) and Zhou et al. (2009) proposed that the Tarim basalts were derived from OIB-like mantle source with less continental crust contamination. The weak Nb anomaly and the nearly chondritic HF/Sm ratios (0.7 ± 0.1) preclude the possibility of significant contribution from continental crust material.

According to the highest Fo values (85) of olivine from the ultramafic dykes at the Bachu area, the liquidus temperature of olivine was as high as 1303°C, and the corresponding liquidus temperature of the basaltic melts was 1200°C (Ko = 0.30 ± 0.03); and such high-Mg parental magmas with a high temperature further suggest that the magmas were generated from an upwelling mantle plume (Zhao et al., 2009). To estimate the role of the Tarim plume, we use chemical signatures generated by the plume and its interaction with shallow lithosphere materials during the rising of the plume to the surface. Previous studies show some evidences from isotopes and geochemistry that the Tarim basalts have OIB-like components, which indicate that these basalts suffered different degrees of interaction between plume melts and the underlying lithospheric mantle (Li et al., 2008, 2012; Zhang et al., 2008; Zhou et al., 2009; Tian et al., 2010). An important tool in deciphering the interaction of the plume magmas with the lithospheric mantle and oceanic crust is the relationship between the uncontaminated isotopic ratios of the source magmas and their major element chemistry. However, it is not easy for CFB to remain uncontaminated. Also, the data so far reported from Tarim suggest a weak crustal contamination. The geochemical and isotopic data such as alkalinity, MgO and other major element contents of basaltic magmas can be used to deduce the degree of interaction between the plume mantle and overlying lithospheric mantle during melting and differentiation processes. Typically, variation in MgO contents results from shallow-level olivine fractionation, whereas variation in alkalinity results from changes in degree of melting in the lithosphere (Chen and Frey, 1985), depth of melting, or clinopyroxene fractionation in the deeper part of the suboceanic lithosphere (Mattioni et al., 2002). Correlation between isotopic ratios and major elements can yield information about the interaction of plume magmas with the lithosphere. Good correlations between eHf(t) and major-element compositions (e.g., SiO2, MgO, FeO) and arc-shaped distribution in the Lu/Hf vs. Hf/Yb plot (Fig. 5d) in the Group 1a, Group 1b and Group 2 basalts indicate that the Group 1a, 1b and 2 basalts were generated by partial melting of a two-component mantle source and partly mixing process (Fig. 5d) except for a sample from the He4 drill hole and another sample from the Yg section (yg0512-4a, andesitic basalt) which show different chemistry (Fig. 5, Table 2). Although a good correlation exists between eHf(t) and SiO2, the eHf(t) does not show a good correlation with MgO and FeO in the Group 1a basalt. Here we argue that the good correlation between eHf(t) and major elements might be a reflection of the interaction of the two-component melt sources. The Sr and Nd isotopic compositions of the basalts from the Keping area overlap with those of typical OIB previously studied by Jiang et al. (2004a) and Zhou et al. (2009). The Group 1a and Group 1b basalts have similar 87Sr/86Sr ratios and initial 87Sr/86Sr (Sr1) values; however, Group 2 basalts have much lower 87Sr/86Sr ratios and Sr1 values than those from the Group 1a and Group 1b basalts. Zhou et al. (2009) argued that the Keping basalts are OIB-like, and proposed a genetic link with mantle plume. Therefore, combined with the previous data and our present results, we suggest that the basalts were derived from the same primary magmas of asthenosphere mantle or mantle plume and had an interaction with the lithospheric mantle during its rising, although they subsequently underwent different evolutionary processes. Hf and Nd isotopic compositions are well correlated in the Group 1a, Group 1b, and Group 2 basalts samples, and olivine pyroxenite and diabase with the data falling within the array observed for OIB, except for the syenitic porphyry samples. A diabase sample (sample Xhn3-1) from Xiaohaizi of Bachu area fall in the field close to the Group 1a basalt (Figs. 2, 3) and could be explained through a genetic link between the basalts and diabases although they formed in different time. The other sample of the diabase shows positive eNd(t) and falls in the similar field of the olivine pyroxenite but with a lower eHf(t) than that of the olivine pyroxenite. The isotopic variability among different igneous rocks can reflect distinct magma source proportions, as these rocks are also characterized by low 143Nd/144Nd and 176Hf/177Hf values, and high 87Sr/86Sr ratios (Jiang et al., 2004b; Zhou et al., 2009 and Fig. 6b in this study). In general, according to the above study, the basalts and intrusive rocks from the TLIP might be derived from different compositional proportion of magma sources with different degree of partial melting of lithospheric mantle while the magmas upwell- ing from the OIB-like asthenospheric mantle and/or plume mantle, and the magma process by mainly fractional crystallization and
cumulation from the primary magma and/or OIB-like mantle source, respectively (Fig. 7).

### 7.3. Magma evolution and comparison with other large igneous provinces in the world

As the majority of the flood basalts in the Tarim Basin were erupted at around 285–290 Ma (Li et al., 2011), based on the Hf isotopic features as well as the relatively homogenous character of the CFB and their widespread distribution, we suggest that the isotopic compositions of the Tarim Group 1a basalts are likely to reflect the mantle source composition of the main volume of the Tarim plume and might include less recycled oceanic crust and/or continental crust.

We selected $\varepsilon_{\text{Hf}}(t)$ and $\varepsilon_{\text{Nd}}(t)$ values of the Karoo CFB basalt (HT and LT), Karoo CFB dyke swarm, Siberian LIP meimechite and kimberlite, Yellowstone hotspot felsic tuff, Hawaii basalt, Galapagos basalt, Kerguelen Archipelago volcanic rocks, and SW Australia flood basalt for comparison. From Fig. 3, the Group 1a, Group 1b and Group 2 basalts fall in the end member of OIB with low $\varepsilon_{\text{Hf}}(t)$ and $\varepsilon_{\text{Nd}}(t)$ values close to the enriched mantle source. The $\varepsilon_{\text{Hf}}(t)$ and $\varepsilon_{\text{Nd}}(t)$ of the basalts are comparable to the Karoo CFB basalt (HT), Kerguelen Archipelago volcanic rocks, and Yellowstone hotspot, and those of the intrusive rocks are similar to the Siberian LIP meimechite and kimberlite with mixing components of low $\varepsilon_{\text{Hf}}(t)$-$\varepsilon_{\text{Nd}}(t)$ and high $\varepsilon_{\text{Hf}}(t)$ and $\varepsilon_{\text{Nd}}(t)$ of the OIB. The Tarim Group 1a basalts have similar $\varepsilon_{\text{Hf}}(t)$ and $\varepsilon_{\text{Nd}}(t)$ values close to the enriched mantle source.

### Table 2

Sequences of the Ka1–Ka6 unit basalts from the Yg section.

<table>
<thead>
<tr>
<th>Rock types</th>
<th>Samples</th>
<th>Rock name</th>
<th>Sequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1a</td>
<td>yg0512–3b Basalt</td>
<td>6th unit of the Kpz FM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>yg0512–4a Basalt</td>
<td>Top of the 5th unit of the Kpz FM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>yg0512–4k Basalt</td>
<td>Bottom of the 5th unit of the Kpz FM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>yg0512–5c Basalt</td>
<td>4th unit of the Kpz FM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>yg0512–5f Basalt</td>
<td>Bottom of the 4th unit of the Kpz FM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>yg0512–6b Basalt</td>
<td>Top of the 3rd unit of the Kpz FM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>yg0512–6c Basalt</td>
<td>3rd unit of the Kpz FM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>yg0512–7a Basalt</td>
<td>Top of the 2nd unit of the Kpz FM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>yg0512–7f Basalt</td>
<td>Bottom of the 2nd unit of the Kpz FM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>yg0512–8i Basalt</td>
<td>Top of the 1st unit of the Kpz FM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>yg0512–8d Basalt</td>
<td>1st unit of the Kpz FM</td>
<td></td>
</tr>
</tbody>
</table>

Note: Kpz FM = Kaipaizileike Formation.
kimberlite have much higher $\varepsilon$Hf($t$) and $^{206}$Pb/$^{204}$Pb than those from the Tarim flood basalts. The low $\varepsilon$Nd($t$) is distinct from that of MORB and OIB, and is therefore attributed to the continental plate (ZL Li et al., 2012), suggesting that an enriched subcontinental lithospheric mantle might be a source candidate for the formation of the Tarim basalts. The olivine pyroxenite, diabase and felsic rocks from the Tarim Basin might have been derived from different magma source/magma process compared to the basalts because they show much higher $\varepsilon$Hf($t$), $\varepsilon$Nd($t$) and $^{206}$Pb/$^{204}$Pb than those from the Tarim basalt lavas. But we suggest that they may be derived from the similar magma sources and suffered evolved magmatic processes, such as the different evolved stages during the process of fractional crystallization after partial melting of mantle sources.

The Tarim flood basalts (including Groups 1a, 1b, and 2) have lower $^{143}$Nd/$^{144}$Nd and higher $^{87}$Sr/$^{86}$Sr values than the Xiaohaizi and Wajilitag ultramafic–mafic rocks (Zhang et al., 2008; Li et al., 2012a,b). This phenomenon is comparable to that in the Siberian Traps, where most of the flood basalts have lower $^{143}$Nd/$^{144}$Nd and higher $^{87}$Sr/$^{86}$Sr values than the high-MgO Maymecha-Kotuy samples (Lightfoot et al., 1990; Sharma et al., 1991; Wooden et al., 1993). The isotopic range of the Maymecha-Kotuy samples overlaps the isotopic variation seen in intraplate OIB. In the Tarim Basin, flood basalts also have much lower $^{143}$Nd/$^{144}$Nd and higher $^{87}$Sr/$^{86}$Sr values than the high-MgO olivine pyroxenite and diabase with same MgO (except for one sample of the diabase). The mafic intrusive rocks which show distinct geochemistry and isotopes, support the models proposed for the Siberian flood basalts and Maymecha-Kotuy samples (Carlson et al., 2006) with either a larger percentage of the pyroxene-rich component present in the Maymecha-Kotuy source, or crustal contamination of the basalts. We favor that the mafic intrusive rocks should be derived from an OIB-like asthenospheric (plume) mantle in an extensional regime by crystal cumulation and fractionation (with negligible crustal contamination) of alkali basalts using the data of trace elements and Sr–Nd isotope features in the Bachu layered intrusions by Zhang et al. (2008).

Clinopyroxene, amphibole and garnet exert major control on the fractionations of Lu/Hf and Sm/Nd values. For example, the fractionation of Lu/Hf and Sm/Nd controlled by clinopyroxene results in too low $f$(Lu/Hf)/$f$(Sm/Nd) values for shallow level melting (Salters and Hart, 1991). Garnet and amphibole are the two most obvious phases that can affect $f$(Lu/Hf)/$f$(Sm/Nd). Although amphibole does fractionate Lu/Hf more than clinopyroxene, there is a concomitant change in Sm/Nd fractionation (Salters and Hart, 1991). Garnet is able to fractionate Lu/Hf more significantly and melting in the presence of garnet will result in higher $f$(Lu/Hf)/$f$(Sm/Nd) values. Only modest amounts of garnet (modal garnet-clinopyroxene ratios of 0.15–0.25) are required to result in the appropriate $f$(Lu/Hf)/$f$(Sm/Nd) values and will explain the slope of the OIB array (Salters and White, 1998), although amphibole does fractionate Lu/Hf more than clinopyroxene, and Garnet is able to fractionate Lu/Hf more significantly and melting in the presence of garnet will result in higher $f$(Lu/Hf)/$f$(Sm/Nd) values. Only modest amounts of garnet (modal garnet-clinopyroxene ratios of 0.15–0.25) are required to result in the appropriate $f$(Lu/Hf)/$f$(Sm/Nd) values and will explain the slope of the OIB array (Salters and White, 1998). Based on these studies, we presume that the higher $f$(Lu/Hf)/$f$(Sm/Nd) values and the $\varepsilon$Hf($t$)/$\varepsilon$Nd($t$) values in the Tarim Group 1a and Group 1b basalts are mainly controlled by garnet, and not by clinopyroxene and amphibole. However, in the Tarim Group 2 basalts, clinopyroxene fractionation is significant. Alternatively, the low end of the OIB array can also be explained by the recycling of a fixed mixture of sediment and ancient basalt as described by Salters and White (1998). Mixtures of asthenosphere (OIB-like components) with continental crust or continentally derived sediments could produce sources that would fall in the low end OIB field with low $^{176}$Hf/$^{177}$Hf and low $^{143}$Nd/$^{144}$Nd for the Tarim basalts.
Li et al. (2008, 2011), Zhang et al. (2008), Zhou et al. (2009) and Tian et al. (2010) suggested that the trace element ratios and Sr–Nd–Pb isotopes and the wide distribution of the basalt of the TLIP support a mantle plume origin. The continuously evolved trend for the $^{87}$Sr/$^{86}$Sr and $^{143}$Nd/$^{144}$Nd values may imply a continuous magma evolution process for the formation of the Groups 1a, 1b and 2 basalts during the peak time of a flood-basalt episode, and even extend to those of olivine pyroxenite and diabase in the subsequent late stage of magma evolution.

8. Conclusion

HF isotopes can provide a further evidence to limit magmatic origin and evolution combined with major and trace elements and Sr–Nd–Pb isotopic compositions of the basalts. In general, the basalts and intrusive rocks from the TLIP might be derived from different componental proportion of magma sources and/or underwent evolved magmatic processes.

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References


