Petrogenesis of the Piqiang mafic-ultramafic layered intrusion and associated Fe-Ti-V oxide deposit in Tarim Large Igneous Province, NW China

Jun Cao\textsuperscript{a,b}, Xuan Wang\textsuperscript{b} and Jihua Tao\textsuperscript{a,b}

\textsuperscript{a}Fundamental Science on Radioactive Geology and Exploration Technology Laboratory, East China University of Technology, Nanchang, Jiangxi, China; \textsuperscript{b}School of Earth Sciences, East China University of Technology, Nanchang, Jiangxi, China

ABSTRACT

The Piqiang intrusion is one of the two important mafic-ultramafic layered intrusions that host giant Fe-Ti-V oxide deposits in the Permian Tarim Large Igneous Province, NW China. The intrusion mainly consists of gabbro, anorthosite and minor plagioclase-bearing clinopyroxenite in the marginal zone. Disseminated to massive Fe-Ti oxide ores occur as layers and lenses within the gabbro. SHRIMP zircon U-Pb results from both a gabbro from the Piqiang intrusion and a granite from the surrounding granitic dyke yield ages of \textasciitilde270 Ma. Geochemically, the Piqiang silicate rocks are enriched in light rare earth elements (LREE) and large ion lithophile elements (LILE), moderately depleted in high field strength elements (HFSE), and have a large range of Sr-Nd-Hf isotopic compositions. The similar mineralogy, mineral compositions, and trace element characteristics of the layered units suggest that all the rocks are co-magmatic. The parental magma is Fe-Ti-rich and is akin to the most primitive diabasic dyke which is associated with the Piqiang intrusion. Partial melting of the Tarim mantle plume with involvement of a subduction-metasomatized lithospheric mantle source best explains the geochemistry and petrogenesis of the parental magmas of the Piqiang intrusion. We propose that the lithospheric mantle source may have been metasomatized by subduction-related materials and the metasomatic enrichment of this source region which may be correlated with oceanic sediment recycling during southward subduction of the South Tianshan oceanic slab during the Early-Middle Paleozoic. Crystal settling and mechanical sorting is the predominant process responsible for the formation of the massive Fe-Ti oxide ores in the Piqiang intrusion. Central to ore formation is a combination of the protracted differentiation history of a Fe-Ti-enriched parental magma and the later addition of external H\textsubscript{2}O from the country rocks to the slowly cooling magma chamber.

1. Introduction

Layered intrusions are the most voluminous plutonic expressions of many, if not all large igneous provinces (LIPs) and have been intensively studied for their unique metal endowment [i.e., PGE (platinum group elements), Cr, Ni, V, Ti] (Ernst and Jowitt 2013; Nebel et al. 2013). Notable examples include the Merensky reef and Main Magnetite Layer of the Bushveld Complex in the Bushveld LIP (Ernst and Jowitt 2013), the Platinova reef of the Skaergaard intrusion in the North Atlantic LIP (Andersen et al. 2002; Holwell and Keays 2014) and the Panzhihua and Hongge Fe-Ti-V oxide deposits in the Emeishan LIP (Zhou et al. 2005, 2013; Pang et al. 2008; Zhang et al. 2009; Bai et al. 2012). However, there are obvious differences between layered intrusions with respect to metal enrichment, volatile contents, and characteristics of their mantle sources, all of which potentially affect the crystallization sequence and therefore zoning and focusing of ore metals into oxide or sulfide ore horizons (Nebel et al. 2013). Origin of mineral accumulation in specific horizons, differences in chemical composition within minerals, and the roles of source variability and crustal assimilation remain elusive, yet they are crucial for economic prospecting and for the understanding of the formation of the orthomagmatic deposits hosted by layered intrusions.

Early Permian Tarim LIP is a newly recognized LIP in NW China after the recognition of Late Permian Emeishan LIP in SW China (Figure 1(a); Yang et al. 2013; Yu et al. 2017). LIPs are highly prospective for magmatic Fe-Ti-V oxide deposits that occur within mafic-ultramafic layered intrusions, as exemplified by the Bushveld and Emeishan LIPs (Ernst and Jowitt 2013). In the Tarim LIP, Fe-Ti oxide mineralization has been recently identified in the Wajilitag and Piqiang layered intrusions (Zhang et al. 2013).
2010, 2014; Cao et al. 2014, 2017a); these represent a major breakthrough in the exploration for orthomagmatic deposits in this LIP. In contrast to the Wajilitag intrusion, which contains only disseminated Fe-Ti oxide ores in the clinopyroxenite, both massive and disseminated Fe-Ti oxide ores are present in the Piqiang intrusion and closely associated with the gabbroic rocks (Zhang et al. 2018). In this respect, the Piqiang intrusion provides an excellent opportunity to identify the critical factors that led to the formation of the massive ores. Although some work has been done on the Piqiang intrusion (e.g., Zhang et al. 2010, 2016, 2018), the origin of the intrusion and its Fe-Ti-V deposits is still a matter of debate.

In this contribution, we carried out detailed petrological, geochemical, and geochronologic investigations on the Piqiang intrusion and associated Fe-Ti oxide ores. These new data are used to constrain the nature and origin of the parental magma and to shed new light on the genesis of massive Fe-Ti oxide ores in layered intrusions.

2. Geological background

The Tarim Craton in northwestern China is surrounded by the Tianshan orogenic belt to the north and west, and the Kunlun and Altyn orogenic belt to the south (Figure 1(b)). It was amalgamated with the southern part of the Central Asian Orogenic Belt during the Late Paleozoic and is composed of a Precambrian crystalline basement, including volcano-sedimentary and high-grade metamorphic rocks, and a thick Phanerozoic sedimentary cover which comprises Ordovician, Devonian, Carboniferous, Permian and Cretaceous strata (BGMRXUAR 1993; Long et al. 2010). Along the northern margin of the Tarim Craton, Ordovician to Devonian arc rocks (ca. 460–400 Ma) are sporadically exposed, and are generally correlated to the southward subduction of the South Tianshan oceanic lithosphere plate beneath the Craton (Huang et al. 2013; Ge et al. 2014).

The Tarim LIP consists of diverse lithologies including kimberlites, flood basalts, mafic-ultramafic layered intrusions, bimodal dyke swarms, lamprophyres, nephelinites, carbonatites and the full spectrum of volcanic and plutonic silicic rocks (i.e. rhyolites, syenites, granites) (Tian et al. 2010; Liu et al. 2014a; Xu et al. 2014; Cheng et al. 2015, 2017; Zhang et al. 2016; Yu et al. 2017). The estimated areal extent of these magmatic products exceeds $3 \times 10^5$ km$^2$ with a thickness ranging from several hundred meters to 3 km (Tian et al. 2010). However, most areas of the Tarim basin is covered by the Taklamakan desert, and thus the present extent of the Tarim LIP is largely deduced from geophysical studies and boreholes. The best outcrops of flood basalts are from Kepeing, Xiahenan, Qipan and Damusi around the western Tarim basin, and mafic-ultramafic layered intrusions and dykes together with minor kimberlites,

Figure 1. (a) Distribution of the Permian Tarim and Emeishan LIP (modified from Zhou et al. 2009). (b) Regional geological map of the Tarim LIP and locations of the mafic-ultramafic layered intrusions associated with Fe-Ti-V oxide deposits (modified from Xu et al. 2014; Cao et al. 2017a; Yu et al. 2017). Abbreviations for exposed sections: Ssc-Sishichang section, Kpz-Kaipaizileike section, Yg-Yingan section, Xhn- Xiahenan section, Dms-Damusi section, Qp-Qipan section. Abbreviations for boreholes: Yt6-Yata 6, Dh6-Donghe 6, Sl1-Shengli 1, Ym4-Yimin 4, Hd5-Hade 5, Mx2-Manxi 2, He4- He 4, Mc1-Macan 1, Tz22-Tazhong 22, B4-Ba 4, Q5-Qun 5.
syenites, granites, lamprophyres, nephelinites and carbonatites are mainly from Piqiang and Bachu (Xu et al. 2014; Cheng et al. 2017). Some of mafic-ultramafic layered intrusions host economically important Fe-Ti-V oxide deposits, including the Wajilitag and Piqiang deposits (Figure 1(b)). Previous field studies and geo-chronological investigations have identified the time sequence of Permian magmatism of the Tarim LIP is as follows: kimberlites (~300 Ma) → flood basalts and low Nb-Ta type rhyolites (292−287 Ma) → mafic-ultramafic layered intrusions and high Nb-Ta type rhyolites (284−273 Ma) → diabasic dykes, syenites, syenite porphyries and granites (278−273 Ma) → lamprophyric dykes (272 Ma) → carbonatites, nephelinites (268−266 Ma) (Liu et al. 2014a; Xu et al. 2014; Zou et al. 2015; Zhang et al. 2016; Cao et al. 2017b; Song et al. 2017). This Permian massive magmatism in the Tarim Craton is believed to have resulted from a deep mantle plume activity (Yang et al. 2013; Xu et al. 2014; Cheng et al. 2017; Yu et al. 2017).

3. Geology of the Piqiang intrusion and associated Fe-Ti oxide ores

The Piqiang (also known as Puchang) intrusion is located in the northwestern part of the Tarim LIP, ~120 km north-east of the Atushi city (Figure 2(a)). It is an ~6.1 × 3.5 km oval-shaped body in plan and crops out over an area of ~16.7 km². The intrusion was emplaced into limestone and intercalated calcareous sandstone of the Upper Carboniferous Kangkelin Formation and the northwestern part of the intrusion is overlain by Neogene sedimentary rocks (Figure 2(a)). Xenoliths of country rock are found in the Piqiang intrusion close to the contact (Zhang et al. 2014). Numerous diabasic, dioritic and granitic dykes occur within the intrusion (Figure 2(a−b)); some of these may have been displaced by later faulting. To the south-east lies the neighbouring 282 ± 4 Ma (Cao et al. 2017b) Wajilitag layered intrusion that is the sixth largest Fe-Ti-V oxide deposit identified to date in China (Bai et al. 2018; Pang and Shellnutt 2018).

The Piqiang intrusion mainly consists of gabbroic rocks with variable amount of Fe-Ti oxides, and volumetrically subordinate anorthosite and plagioclase-bearing clinopyroxenite (Figure 2). Anorthosite is found only as small separated cupolas in some parts of the intrusion, and plagioclase-bearing clinopyroxenite dominates the margin of the intrusion (Figures 2 and 3(a)). The contact relationship between the anorthosite and gabbro is gradational, whereas the plagioclase-bearing clinopyroxenite and gabbro are in sharp contacts against each other. Anorthosite and plagioclase-bearing clinopyroxenite are coarse-grained massive rocks without prominent layering. Gabbroic rocks are fine- to coarse-grained and locally exhibit well-defined layering (Figure 3(b−c)). Igneous layering displays a regular alternation of dark and light layers (Figure 3(c)). Dark layers are enriched in olivine, clinopyroxene and Fe-Ti oxides, whereas light layers consist mostly of clinopyroxene and plagioclase.
observed in the Piqiang intrusion is typical of layered intrusions and similar features have been described from the Skaergaard intrusion (McBirney 1996), the Sept Iles intrusion (Namur et al. 2010) and the Panzhihua intrusion (Zhou et al. 2005; Zhang et al. 2009).

In the Piqiang intrusion, Fe-Ti oxide mineralization is mainly concentrated in the gabbroic rocks with fine-
grained texture. Oxide bodies occur as occur as layers or lenses, and are in sharp contact with adjacent gabbros (Figure 3(d–f)). The massive and disseminated ores also have sharp contacts with each other. Some of the massive ore layers occur as centimeter-scale ore bands in disseminated ore layers (Figure 3(g)). The silicate-rich portions of the oxide bodies commonly show planar lamination of elongated plagioclase (Figure 3(h)). This deposit has a total ore resource of 120 million tons with an average ore grade of 20 wt.% total FeO and 11 wt.% TiO₂ (Zhang et al. 2014).

The plagioclase-bearing clinopyroxenite exhibits a hetero-granular cumulate texture and are composed essentially of euhedral clinopyroxene (up to 2.4 mm in length; 70–85%) and variable amounts of interstitial plagioclase (5–15%) with minor Fe-Ti oxides and amphibole (Figure 4(a)). Contiguous clinopyroxene grains typically have 120° triple junctions (Figure 4(a)). Clinopyroxene grains exhibit sporadic and patchy replacement by brown amphibole. Plagioclase is tabular to platy with irregular wavy edges (Figure 4(a)). Oxide minerals including titanomagnetite and ilmenite in roughly sub-equal amounts occur as inclusions in the rim of clinopyroxene or as interstitial phases between silicate minerals (Figure 5(a)).

Gabbros are fine- to coarse-grained cumulate rocks composed mainly of plagioclase (30–70%), clinopyroxene (20–50%) and small amounts of Fe-Ti oxides, amphibole and biotite (Figure 4(b–d)). However, the modal proportions in this rock type vary considerably, and either Fe-Ti oxides or olivine locally reaches as much as 25% in some gabbroic samples (Figure 4(d–e)). Plagioclase is an ubiquitous phase with a grain size ranging from 0.1 to 7 mm, forming sub-equant to strongly tabular subhedral to euhedral grains. In fine-grained gabbroic samples (Figure 4(d)), planar foliation and lineation are shown by a marked preferred orientation of plagioclase laths and small elongated clinopyroxene crystals. In places, plagioclase laths may be slightly deformed, displaying kinked twinning (Figure 4(c–d)), which is probably caused by compaction (Godel et al. 2011). Clinopyroxene grains are subhedral and sometimes contain small euhedral-subhedral plagioclase grains (Figure 4(b–c)) and exsolution lamellae of ilmenite along its prismatic cleavages (Figure 4(d)). Olivine appears as very large (up to 2.5 mm) subhedral to locally poikilitic grains (Figure 4(e)) in olivine gabbro. The entrapment of olivine in plagioclase and the abundance of cumulus olivine in these gabbros (Figure 4(e)) indicate that the olivine has crystallized before plagioclase. Similarly, entrapment of plagioclase within clinopyroxene in most gabbroic samples (Figure 4(b)) indicate that the plagioclase has crystallized before clinopyroxene. Fe-Ti oxide minerals occur either as small (<1 mm) patches of anhedral titanomagnetite with minor ilmenite or two-phase intergrowths (Figure 5(b–c)). Irregular Fe-Ti oxide grains have locally been observed as inclusions in silicate minerals (Figure 4(b–e)). Reaction rims of brown amphibole and biotite are in places well-developed along contacts between silicate and Fe-Ti oxide minerals (Figure 4(b–c)).

Anorthosite is medium- to coarse-grained, and consists predominantly of euhedral-subhedral plagioclase (>90%) and minor anhedral olivine, Fe-Ti oxides, amphibole and biotite (Figure 4(f)). Plagioclase occurs either as large (1–7 mm), elongated crystals or aggregates of small (0.1–0.3 mm) grains because of recrystallization. In some cases, it exhibits undulose extinction and deformation twins. Olivine and Fe-Ti oxides typically account for less than 5%, and amphibole and biotite accounts for less than 2%. Orthopyroxene was observed as coronitic rims around olivine in a few anorthositic samples (Figure 4(f)).

Disseminated Fe-Ti oxide ore dominates the ore horizons (Rui et al. 2002) and are composed of Fe-Ti oxides (25–50%), plagioclase (25–40%) and clinopyroxene (10–25%), with minor olivine and amphibole (Figure 4(g)). The massive Fe-Ti oxide ore is also an important component of the ore horizons; it is fine-grained (Figure 4(h)), and contains less silicate minerals but more Fe-Ti oxides (>80%) than the disseminated Fe-Ti oxide ore. The silicate minerals occur as isolated grains, or aggregate of grains, surrounded completely by Fe-Ti oxides. It is worthy to note that both plagioclase and clinopyroxene in the disseminated Fe-Ti oxide ore exhibit the same preferred orientation (Figure 4(g)). In the oxide ores, the major ore minerals consist of titanomagnetite and ilmenite (Figure 5(d–e)) and are interstitial to the main rock-forming minerals (Figure 4(g–h)), suggesting that they crystallized at a late stage. Titanomagnetite occurs as polygonal grains and accounts for ~75–80% of the oxide minerals (Figure 5(e)). It contains exsolution lamellae including ilmenite and hercynite (Figure 5(d–e)). Ilmenite occurs as fine-grained irregular to polygonal crystals and makes up ~15% of the oxide minerals. Most boundaries between the oxide grains are straight to slightly curved and meet at distinct triple junctions with ~120° interfacial angles (Figure 5(d–e)). Subordinate hercynite (<2%) is also present as micro-patches along the rims of titanomagnetite or as single irregular crystals at the boundaries between titanomagnetite and ilmenite (Figure 5(d–f)). Occasionally, some inclusions composed of ilmenite and sulphide have been observed within silicate minerals (Figure 5(f)). Reaction rims of amphibole, and to a lesser extent olivine, are well-developed along contacts between silicates and oxide minerals (Figure 5(g–h)), indicating...
Figure 4. Photomicrographs of rocks from the Piqiang intrusion. (a) Interstitial plagioclase (Pl) and Fe-Ti oxides between cumulus clinopyroxene (Cpx) in plagioclase-bearing clinopyroxenite (Sample PQ1136, plane-polarized light). Euhedral to sub-rounded Fe-Ti oxides is also enclosed by large clinopyroxene crystals. Note that the clinopyroxene grain is locally replaced by patches of amphibole (Amp), and that some aggregate of clinopyroxene grains are in ~120° triple junctions to each other. (b) Coarse-grained gabbro showing the occurrence of granular clinopyroxene and plagioclase laths surrounded by Fe-Ti oxides (Sample PQ1113, plane-polarized light). Note that large clinopyroxene encloses tabular plagioclases. (c) Cumulus clinopyroxene and plagioclase with minor fine-grained olivine (Ol) and interstitial Fe-Ti oxides in medium-grained gabbro (Sample PQ1103, crossed-polarized light). Biotite (Bi) rims are present surrounding the plagioclase when contact with the Fe-Ti oxide minerals. (d) Typical fine-grained gabbro showing orientated plagioclase (Sample PQ1119, crossed-polarized light). Clinopyroxene has significant exsolution lamellae of ilmenite, and the presence of deformed twin of plagioclase should be noted. (e) Cumulus olivine, clinopyroxene and plagioclase with minor interstitial Fe-Ti oxides in olivine gabbro (Sample PQ1174, crossed-polarized light). Sub-rounded Fe-Ti oxide inclusions occur in olivine grains. (f) Anorthosite consisting of plagioclase, clinopyroxene and olivine with subordinate interstitial Fe-Ti oxides, biotite and amphibole (Sample PQ1143, crossed-polarized light). Orthopyroxene rims are present surrounding the olivine. Note the presence of deformed twin of plagioclase. (g) Opaque Fe-Ti oxides occur as an interconnected network enclosing cumulus olivine, clinopyroxene and plagioclase in disseminate Fe-Ti oxide ore (Sample PQ1111, plane-polarized light). Insert is scanned picture. Amphibole rims along boundaries between Fe-Ti oxides and clinopyroxene or plagioclase. (h) Isolated grains of olivine, clinopyroxene and plagioclase are surrounded by Fe-Ti oxides in massive Fe-Ti oxide ore (Sample PQ1105, plane-polarized light). Note that the silicates are commonly rimmed by amphibole in places.
disequilibrium textures between oxide minerals and coexisting silicates (Holness et al. 2011; Howarth et al. 2013). Also, these silicate grains are typically embayed and resorbed, which appear to have crystallized prior to oxides.

4. Sample preparation and analytical methods

A total of 55 samples were collected from the exposed section of the open-pit mine in Piqiang, and one sample (PQ1126) was collected from a granitic dyke cross-cutting the Piqiang intrusion. Their locations are indicated in Figure 2. Weathered or altered surfaces were removed from the samples before jaw-crushing. Fresh chips were then selected for analysis using a binocular microscope and pulverized into powders using agate mortars.

Zircons were separated from a gabbro sample (PQ1113) and granite sample (PQ1126) using conventional heavy liquid and magnetic techniques and purified by handpicking under a binocular microscope. They were mounted in an epoxy resin, and then polished. Cathodoluminescence and back-scattered images were used to select undeformed zircon crystals that show regular growth patterns plus lack of inherited cores and sector compositional zoning for U-Pb dating. U-Pb isotopes of the selected zircon crystals were determined using a SHRIMP-II in the Chinese Academy of Geological Sciences, Beijing, following procedures of Compston et al. (1992) and Williams (1998).

Whole-rock major elements were analysed on fused glass discs using a Rigaku RIX 2000 X-ray fluorescence spectrometer in the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (GIG-CAS). The analytical uncertainties are mostly between 1% and 5%. Trace elements were analysed by solution inductively coupled plasma mass spectrometry (ICP-MS) in the GIG-CAS. The solutions were prepared by complete digestion of rock powders in HF + HNO₃ in Teflon bombs at 100°C for 7 days. The precision for most elements was typically better than 5% RSD (relative standard deviation), and the measured values for Zr, Hf, Nb and Ta were within 10% of the certified values of the two employed standards (diabase W-2 and basalt BHVO-2).

Sr, Nd and Hf isotopes were determined in the GIG-CAS, using a Neptune Plus multicollector ICP-MS. The Sr, Nd and Hf isotopic analyses followed the procedure of Wei et al. (2002), Li et al. (2006) and Lu et al. (2007). Sr, Nd and Hf isotopic ratios were normalized against ⁸⁶Sr/⁸⁸Sr = 0.1194, ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219 and ¹⁷⁶Hf/¹⁷⁷Hf = 0.7325, respectively. ⁸⁷Sr/⁸⁶Sr for the NIST987 Sr standard was 0.710256 ± 10 (2σ; N = 9), ¹⁴³Nd/¹⁴⁴Nd for the Shin Etsu JNd-1 Nd standard was 0.512092 ± 7 (2σ; N = 10), and ¹⁷⁶Hf/¹⁷⁷Hf for the JMC-14374 Hf standard was 0.282180 ± 6 (2σ; N = 7).

Electron microprobe analyses of major rock-forming minerals were obtained using the JEOL Superprobe JXA-8100 electron microprobe in the GIG-CAS. The operating conditions are 15 kV accelerating voltage, 20 nA beam current, 1–2 μm beam diameter. Elements were analysed with wavelength-dispersive spectrometers and were calibrated by reference to oxide and mineral standards using the ZAF correction routine. The precision for oxide concentrations is better than 1%. The counting times were 20 s on the peak and 10 s on the background.

Trace element concentrations in clinopyroxene were determined on thin sections by laser ablation ICP-MS in the GIG-CAS, using an Agilent 7500a ICP-MS system coupled with a Resolution M50-HR 193 nm ArF-excimer laser sampler. The analytical procedures, operating conditions, calibration, and data reduction are the same as those given in Tu et al. (2011).

5. Analytical results

5.1 Zircon U–Pb ages

Zircon U–Pb isotope data for the Piqiang gabbro and the surrounding granite dyke are given in Supplementary Table 1. Zircon crystals of a gabbro sample PQ1113 are mostly subhedral with variable lengths of 30 to 200 μm. Most of them are dark in CL images. Some of them show oscillatory zoning and some others are structureless. Thirteen analyses on different zircon grains have a wide range of Th (158–8775 ppm) and U (1262–8699 ppm) contents with Th/U ratios between 0.05 and 1.04. Except for Spot 9, 11 and 14 with an exceptionally high common Pb, the analytical results (Supplementary Table 1) yield a concordia U–Pb isotopic age of 270.8 ± 2.3 Ma (mean square weighted deviation (MSWD) = 0.76; Figure 6(a)). Zircon crystals of a granite sample PQ1126 are mostly euhedral and prismatic, with lengths between 100 and 300 μm. These zircon grains are characterized by either sector or oscillatory zoning in CL images. The Th/U ratios of 12 analyses on the selected zircon grains range from 0.22 to 0.85. Except for Spot 11 with a slightly young apparent ⁴⁰Ar/³⁹Ar age of 245.2 ± 4.4 Ma (1σ; Supplementary Table 1), the U–Pb results form a coherent cluster and yield a concordia age of 270.3 ± 2.6 Ma (MSWD = 1.3; Figure 6(b)). The concordia ages, which consider the ²⁰⁶Pb/²³⁸U age of 245.2 ± 4.4 Ma (1σ; Supplementary Table 1), the U–Pb results form a coherent cluster and yield a concordia age of 270.3 ± 2.6 Ma (MSWD = 1.3; Figure 6(b)). The concordia ages, which consider the ²⁰⁶Pb/²³⁸U age of 245.2 ± 4.4 Ma (1σ; Supplementary Table 1), yield a concordia age of 270.3 ± 2.6 Ma (MSWD = 1.3; Figure 6(b)).
Figure 5. BSE images and photomicrographs of microstructures in rocks of the Piqiang intrusion. (a) Euhedral to sub-rounded titanomagnetite (Mt) occur as inclusions within the clinopyroxene as well as interlocking grains with silicate minerals in plagioclase-bearing clinopyroxenite. Note that many titanomagnetite grains contain exsolution of sandwich-textured ilmenite (Ilm) lamellae, and rare occurrence of polygonal ilmenite is present at titanomagnetite grain boundaries. (b) Sandwich-textured ilmenite lamellae exsolution in titanomagnetite and patches of hercynite at the edge of granular ilmenite in olivine gabbro. Small sulphide inclusion is trapped in ilmenite. (c) Partial melts interpreted from trails of fine-grained, symplectites between clinopyroxene and titanomagnetite or plagioclase across boundaries between other silicates in gabbro. The clinopyroxene-plagioclase symplectites are sometimes partially replaced by biotite. (d) A discrete grain of ilmenite show ~120° triple junction with titanomagnetite in disseminated Fe-Ti oxide ore. (e) Polygonal grains of titanomagnetite and ilmenite in massive Fe-Ti oxide ore show straight or slightly-curved boundaries that are in contact through ~120° interfacial angles. (f) A sub-rounded sulphide (Sul) and ilmenite composite inclusion in olivine from the massive Fe-Ti oxide ore. (g) Amphibole rims along boundaries between Fe-Ti oxides and embayed clinopyroxene or plagioclase in massive Fe-Ti ore. (h) Composite reaction rims of amphibole and olivine along boundaries between Fe-Ti oxides and plagioclase. Other mineral abbreviations as in Figure 4.
synchronous with the spatially associated granite dykes. Notably, both of these ages are consistent with previous reported SHRIMP and SIMS zircon U–Pb ages of 276 ± 4 Ma (Zhang et al. 2010) and 273.3 ± 2.0 Ma (Zhang et al. 2016) for the Piqiang intrusion, and laser ablation ICP-MS zircon U–Pb ages of 268.6–272.4 Ma (Zhang and Zou 2013) for the adjacent Halajun and Kezile granitic plutons within error.

5.2 Whole-rock major and trace elements
All analysed samples have low or negligible LOI values (<1.3 wt.%; Supplementary Table 2) consistent with their fresh nature observed under microscope. As one would expect from strongly modally layered cumulates, the bulk-rocks exhibit large compositional variations (Supplementary Table 2). Specifically, the plagioclase-bearing clinopyroxenites have low Al₂O₃ and high CaO, consistent with the high content of clinopyroxene in these rocks. They also have the highest P₂O₅ contents (Supplementary Table 2). The anorthosite samples are characterized by high SiO₂, Al₂O₃, (Na₂O+K₂O) and relatively low contents of total Fe₂O₃ and TiO₂ compared with the plagioclase-bearing clinopyroxenites and gabbros. Generally, the compositional variations can be attributed to the varying proportions of olivine, clinopyroxene, plagioclase, titanomagnetite and ilmenite (Figure 7). In particular, the disseminated and massive Fe-Ti oxide ores plot out of the trajectories of the olivine, clinopyroxene and plagioclase (Figure 7), suggesting that the titanomagnetite and ilmenite within these samples are cumulus phases that crystallized directly from the magma rather than being intercumulus phases formed as a result of trapped liquid saturation. Total Fe₂O₃ (Figure 7(c)) and TiO₂ (Figure 7(d)) contents negatively correlate with SiO₂ contents, whereas Al₂O₃ (Figure 7(e)) and CaO (Figure 7(b)) contents positively correlate with SiO₂. This is consistent with a crystal sorting process that caused the segregation of dense Fe-Ti oxides and less dense silicate minerals within the Piqiang magmatic system (Bai et al. 2018).

In the TiO₂ (Figure 8(a)) and V (Figure 8(b)) versus total Fe₂O₃ diagrams, two trends indicative of titanomagnetite control and titanomagnetite-ilmenite control are observed in the Piqiang samples. It is notable that the disseminated and massive Fe-Ti oxide ores follow the titanomagnetite-only trend, suggesting that titanomagnetite is the only dominant oxide mineral.

Representative trace element compositions of the Piqiang intrusive rocks are given in Supplementary Table 2 and illustrated in Figure 9. The intrusive rocks are all enriched in the light rare earth elements (REE) relative to the heavy REE and have positive Eu anomalies (Eu/Eu* = 0.88–4.30) (Figure 9(a–b)). In the primitive mantle normalized immobile trace element diagram (Figure 9(c)), the plagioclase-bearing clinopyroxenite, gabbro and anorthosite samples display moderate negative Nb, Ta, Zr, Hf anomalies and variable Ti anomaly. In comparison, the disseminated and massive Fe-Ti oxide ores have strongly positive Nb-Ta and weakly positive Zr-Hf anomalies (Figure 9(d)). These differences in Nb-Ta and Zr-Hf anomalies are consistent with the fact that Nb and Ta are compatible but Zr and Hf are slightly incompatible in ilmenite within basaltic systems (Klemme et al. 2006; Dygert et al. 2013).

5.3 Sr-Nd-Hf isotopes
The analysed Piqiang rocks show limited variations in Sr, Nd and Hf isotopic compositions (Supplementary Table 3). The age-corrected ⁸⁷Sr/⁸⁶Sr ratios (t = 270.8 Ma) range from 0.70492 to 0.70662, and εNd (t) values vary from −3.2 to +0.9; εHf (t) values range from −6.1 to −0.5. Our data (Supplementary Table 3) are consistent with those of previous isotopic studies on the rocks from the layered series (Zhang et al. 2010, 2018).

The Sr-Nd data for our samples overlap the field of Group 2 basalts from the Tarim LIP as well as the Bachu diabasic dykes, and plot above the fields of the Group 1 basalts in the Tarim LIP (Figure 10(a)). The Mazaertag and Wajilitag intrusions in the Tarim LIP have much higher εNd (t) and lower (⁸⁷Sr/⁸⁶Sr) ratios. Notably, the Piqiang samples have a more enriched Sr-Nd isotopic signature compared with the uncontaminated Tarim plume-derived melts represented by Bachu diabasic dyke-hosted clinopyroxene macrocrysts (Wei et al. 2015). The Nd-Hf data for the Piqiang intrusion plot within the OIB field and but slightly below the mantle array line (Figure 10(b)) (Chauvel et al. 2008), showing weak decoupling (∆εHf = −4.1 to −0.6).

5.4 Mineral chemistry
5.4.1 Major elements
Representative chemical compositions and structural formulae of olivine, clinopyroxene, plagioclase, titanomagnetite and ilmenite from Piqiang intrusion are listed in the Supplementary Tables 4–8 and are shown in Figure 11. Olivine within the Piqiang intrusion has forsterite (Fo) contents that range from 61 to 79 mol%. The olivine crystals from the disseminated and massive Fe-Ti oxide ores have higher Fo values (70–79) than those of the silicate rocks (Fo61–69) (Supplementary Table 4). Individual crystals in the massive Fe-Ti oxide ores are reversely zoned with high Mg rims, probably reflecting late-stage subsolidus re-equilibrium between olivine and the surrounding oxide.
Figure 6. Concordia diagrams for SHRIMP zircon U–Pb analyses of the Piqiang gabbro (a) and surrounding granite dyke (b).

Figure 7. Co-variations of MgO (a), CaO (b), total Fe$_2$O$_3$ (c), TiO$_2$ (d), Al$_2$O$_3$ (e), and P$_2$O$_5$ (f) with SiO$_2$ contents for the Piqiang intrusion. Ol, olivine; Cpx, clinopyroxene; Pl, plagioclase. The solid lines are the least square linear regression lines calculated from the compositions of major rock-forming minerals. Data of the Piqiang alkali diabasic dykes are from Zhang et al. (2010). The alkali diabasic dykes plot in the field of the Piqiang intrusion, indicating the dykes may have formed from a magma with composition similar to the Piqiang intrusion.
minerals (Shellnutt and Pang 2012). This is supported by a positive correlation between the olivine Fo content and whole-rock total FeO content (Figure 11(a)). All the analysed clinopyroxenes are Ca-rich and belong to the diopside-augite variety. They show similar compositions with a limited range of Wo_{29.1-53.2}En_{31.7-47.1}Fs_{12.9-24.4} (Supplementary Table 5). The Mg#(= 100*Mg/(Mg+ total Fe), in atoms per formula unit) varies from 58 to 77. Al₂O₃ and TiO₂ contents of the clinopyroxenes are moderately high, reaching maxima of 9.58 wt.% Al₂O₃ and 2.66 wt.% TiO₂. Values are similar to those in other clinopyroxene analyses from rocks of alkali basalt parentage (Deer et al. 1978). Piqiang clinopyroxenes have low octahedral Al consistent with their formation in situ, at low pressure, and the excess tetrahedral Al is probably due to the presence of substitutions such as CaCrAlSiO₆ and CaFe³⁺AlSiO₆ (Chambers and Brown 1996). TiO₂ concentrations (0.28–2.66 wt.%) generally correlate with the change of Mg# (Figure 11(b)). Plagioclase within the intrusion belongs to the bytownite to anorthite series with anorthite (An) contents from 48.4 to 88.8 mol% (Supplementary Table 6). Plagioclase in the plagioclase-bearing

Figure 8. Plots of TiO₂ (a), and V (b) versus total Fe₂O₃ contents of the Piqiang intrusion. Data of the Mazaertag and Wajilitag intrusions in the Tarim LIP are from Cao et al. (2014) and Cao and Wang (2017).

Figure 9. Chondrite-normalized REE patterns (a, b) and primitive mantle-normalized alteration-resistant trace element patterns (c, d) for the Piqiang intrusion. The chondrite, primitive mantle and ocean-island basalt (OIB) compositions are from Sun and McDonough (1989). Data of the Bachu diabasic dykes (represented by sample BC-6) are from Wei et al. (2015). Data of the Piqiang diabasic dykes are from Zhang et al. (2010).
clinopyroxenite has the highest An content (An_{74.7-88.8}) among the entire intrusion. Minor zoning within plagioclase crystals of a normal or reversed nature are present (Supplementary Table 6). Both the Fo contents of olivine and Mg\# of clinopyroxene from the Piqiang intrusion exhibit positive correlations with the An contents of plagioclase.
Titanomagnetite shows a wide compositional range with \( \text{TiO}_2 \) contents ranging from 1.2 to 17.5 wt. %, 0.0–2.9 wt.% \( \text{MgO} \), 0.6–7.4 wt.% \( \text{Al}_2\text{O}_3 \) and 0.0–0.6 wt.% \( \text{MnO} \) (Supplementary Table 7). Titanomagnetite in the disseminated and massive Fe-Ti oxide ores tend to have higher \( \text{TiO}_2 \), \( \text{MgO} \), \( \text{Al}_2\text{O}_3 \) and \( \text{MnO} \) than in silicate rocks, a phenomenon also known in the Panzhihua intrusion (Pang et al. 2008). Besides, a positive correlation exists between \( \text{MgO} \) contents of titanomagnetite and \( \text{Fo} \) contents of olivine (Figure 11(e)). It is worth noting that the titanomagnetite in the oxide inclusions has a low \( \text{Cr}_2\text{O}_3 \) content (0.0–0.9 wt.%), similar to the interstitial titanomagnetite (Figure 11(f); Supplementary Table 7). Ilmenite in the disseminated and massive Fe-Ti oxide ores also have higher \( \text{MgO} \) (4.3–6.3 wt.%) than the silicate rocks (Supplementary Table 8). These compositional trends of Fe-Ti oxide minerals are presumably caused by the subsolidus Fe-Mg equilibration between mafic silicates and Fe-Ti oxides as suggested for the Panzhihua intrusion (Pang et al. 2008, 2009).

5.4.2 Trace elements

Clinopyroxenes in the three units of the Piqiang intrusion have total REE contents ranging from 32.6 to 96.1 ppm (Supplementary Table 9) and shows similar, ‘hump-shaped’ light REE-enriched chondrite-normalized REE patterns (Figure 12(a)), coupled with negative Nb-Zr anomalies in primitive mantle-normalized trace element patterns (Figure 12(a)).

Figure 11. Plots of whole-rock total FeO versus Fo of olivine (a), \( \text{TiO}_2 \) versus Mg# of clinopyroxene (b), Fo content of olivine versus An content of plagioclase (c), Mg# of clinopyroxene versus An content of plagioclase (d), MgO contents of titanomagnetite versus Fo content of olivine (e) and \( \text{V}_2\text{O}_3 \) versus \( \text{TiO}_2 \) contents of titanomagnetite (f). Trends for Bushveld, Panzhihua olivines and clinopyroxenes against plagioclase are included for comparison (Tegner et al. 2006; Pang et al. 2009). Literature data for the Piqiang intrusion are from Zhang et al. (2018).
6. Discussion

6.1 Parental magma composition

The similarities in mineralogy, mineral compositions, chondrite-normalized REE patterns (Figure 9(a–b)) and Sr-Nd-Hf isotopic compositions (Figure 10) observed in the three units of the Piqiang intrusion suggest that all the rocks were derived from a common parental magma by similar processes of magmatic differentiation. Unfortunately, no chilled margins have been found that could help to constrain the compositions of the parental magma. A suite of alkali diabasic dykes are exposed in the vicinity of the Piqiang intrusion and they were thought to have compositions similar to the Piqiang parental magma (Zhang et al. 2010, 2018). Though the ages of these dykes are unknown, they are spatially associated with the Piqiang layered intrusion and their textural resemblance to the mineral phases within the layered sequences strongly suggest that they belong to the same magmatic event. Applying a K0 of 0.3 ± 0.03 to the distribution of Fe and Mg between olivine and liquid (Roeder and Emslie 1970) indicates that the most Mg-rich olivine (Fo = 76) from the Piqiang intrusion rocks were in equilibrium with a liquid with an Mg# [= molar 100× MgO/(MgO+FeO)] of between 38 and 42. The Mg# value quoted for the least fractionated alkali diabasic dyke (Sample 08KT01-14) discussed by Zhang et al. (2010, 2018) is 38, again supporting the contention that such a dyke may share similar compositions with the parental magma of the Piqiang intrusion. The parental magma was thus a ferrobasaltic melt that was relatively low in SiO2 (51.56 wt.%), highly enriched in total FeO (12.48 wt.%) and TiO2 (2.28 wt.%) (Zhang et al. 2010). This composition is close to the estimate of the Panzhuhua layered intrusion (c.51.72 wt.% SiO2; 13.03 wt.% total FeO; 4.37 wt.% TiO2) by Howarth and Prevec (2013).

On the basis of the partition coefficients of trace elements between clinopyroxene and silicate melt (Supplementary Table 10), we calculated the trace element composition of the melt in equilibrium with the most primitive clinopyroxenes from both the massive Fe-Ti oxide ore and barren silicate units. The calculated trace element patterns (Figure 12(c)) are similar to those of the surrounding diabasic dykes (Zhang et al. 2010). Therefore, we propose that the parental magma of the Piqiang intrusion is compositionally similar to that of the surrounding diabasic dykes.

6.2 Crustal contamination

Crustal contamination is a potential process for mantle-derived melts during their ascent through continental crust or their evolution within a magma chamber in a continental environment (He et al. 2016). All the silicate rocks in the Piqiang intrusion are characterized by negative Nb-Ta anomalies and enrichment in light REE and LILE in the primitive mantle-normalized trace element diagram (Figure 9(c)). The depletion of these elements could potentially be explained by crustal contamination, because continental crust is poor in these elements (e.g., Rollinson 1993). The relatively high δ18O values in zircon from the various layered units of the Piqiang intrusion (5.6 to 7.1‰ with mean value of 6.4 ± 0.06‰; Zhang et al. 2016) also indicate the possibility of crustal contamination. However, extensive crustal contamination would have produced positive Zr-Hf anomalies and high (La/Nb)PM and (Th/Nb)PM ratios (Sun and McDonough 1989). Thus, the weak negative Zr-Hf anomalies of the Piqiang silicate rocks (Figure 9(c)), their low (La/Nb)PM and (Th/Nb)PM ratios indicate that crustal contamination was not an important process in the formation of this body. Moreover, contamination of crustal materials can result in variable isotopic compositions due to the inhomogeneity of crustal rocks. However, the Piqiang rocks have relatively uniform (87Sr/86Sr)i and εNd (t) values, and follow a crystal fractionation (FC) rather than an assimilation crystal fractionation (AFC) trend (Figure 10(c–d)).

The country rocks of the intrusion (limestones of the Kangkelin Formation; Figure 2(a)) and deep crustal materials (e.g., Neoproterozoic gabbros and granites, and Early-Middle Paleozoic granites) are the main potential contaminants. We use the average Sr-Nd isotopic compositions of Bachu diabasic dyke-hosted clinopyroxene macrocrysts ([87Sr/86Sr)i = 0.70352; εNd (t) = 4.6; Sr = 39.28 ppm; Nd = 3.74 ppm, Wei et al. 2015] to represent the composition of the uncontaminated mantle-derived magma. Using the Sr-Nd isotopic compositions of both the Tarim lower and upper continental crust (e.g., Neoarchean granitic gneiss, and Neoproterozoic-Early Paleozoic granite) as the the composition of the possible contaminant, modelling calculations show that <5% of upper crustal contamination is required to explain the observed isotopic composition of the studied intrusion (Figure 10(a)). Nevertheless, a limited degree of crustal contamination (7–13%) at source is suggested by the combined Sr-O isotopic characteristics of the Piqiang samples (c.f. Zhang et al. 2016) which show relatively higher initial Sr isotopic values compared with O isotopic values. This variability of Sr-O isotopic compositions could be indicative of variable amounts of crustal components in the mantle source in addition to shallow-level assimilation. This is similar to the model proposed for the ultrapotassic Fanshan intrusion in the North China Craton that also show a crustal signature in their mantle source (Hou et al. 2015).
Figure 12. Chondrite-normalized REE patterns (a) and primitive mantle-normalized trace element patterns (b) for the clinopyroxenes of the Piqiang intrusion. (c) Calculated parent magma compositions compared with that of the surrounding diabasic dykes (represented by sample 08KT01-14; Zhang et al. 2010).
6.3 Modelling of magma evolution

The parental magmas of the Piqiang intrusion may have experienced variable degrees of fractional crystallization, en route from source to surface. Compared with the mantle-derived olivine (Fo = ~90; Gibson et al. 2000), the low Fo content in most magnesian olivines (Fo\textsubscript{crv}) in silicate rocks indicates that the parental magma has experienced extensively fractional crystallization before it emplaced into the current magma chamber. Moreover, Cr depletion in titanomagnetite in the Piqiang intrusion compared with the Mazaertag and Wajilitag intrusions in the Tarim LIP (Cao et al. 2014; Cao and Wang 2017) most probably indicate a Cr-depleted magma resulting from a previous Cr-rich titanomagnetite fractionation process of a primitive magma.

The Piqiang magma intruded into the slightly older Upper Carboniferous Kangkelin Formation and Lower Permian Bieliangjin Formation, the maximum thickness of which is estimated as ~2.7 km (Zhang et al. 2013b). This is the best constraint on the final emplacement depth of the Piqiang intrusion and gives a maximum value of ~1 kbar. H\textsubscript{2}O has a significant effect on the differentiation paths of basaltic magmas, mainly by suppressing plagioclase crystallization and therefore decreasing its cotectic proportion in the cumulus mineral assemblage (Sisson and Grove 1993; Botcharnikov et al. 2008). Compared to the absence of plagioclase as a cumulus phase in the Mazaertag intrusion (Wei et al. 2014), the presence of abundant cumulus plagioclase throughout much of the Piqiang intrusion suggest that the Piqiang parental magma contained much less initial H\textsubscript{2}O content than the Mazaertag intrusion (~1.5 wt.% H\textsubscript{2}O in the Mazaertag parental magma; Wei et al. 2014). This is also consistent with the fact that the Piqiang gabbros contain much less primary hydrous phases (generally <5% principally amphibole and to a lesser extent biotite) than the Mazaertag wehrlites, in which the interstitial amphibole and biotite are up to 8–10% (Wei et al. 2014; Cao and Wang 2017). Low water content (<0.5%) in the Skaergaard parental magma enhances the liquidus volume of plagioclase and suppresses those of mafic silicates and oxides, and is thought to be responsible for producing significant volume of cumulate rocks (59.7% of the Skaergaard intrusion; Nielsen 2004) before the appearance of Fe-Ti oxides (Botcharnikov et al. 2008). By contrast, the Piqiang intrusion was characterized by the occurrence of Fe-Ti oxides throughout the intrusion (Zhang et al. 2010, 2014, 2018; this study), implying that the Piqiang parental magma contained significant amounts (e.g., ≥0.5 wt.%) of H\textsubscript{2}O. Evidence presented here indicates that the initial H\textsubscript{2}O content of the Piqiang parental magma was likely 0.5 wt.%. The initial redox state of the Piqiang magma is uncertain. Application of the magnetite-ilmenite thermometer and oxygen barometer [using the QUILF program of Andersen et al. (1993)] to the magnetite-ilmenite mineral pairs from the Fe-Ti oxide ores of the Piqiang intrusion yields temperatures ranging between 394 and 592°C and f\textsubscript{O\textsubscript{2}} ranging between FMQ-5.6 and FMQ-1.8 (Figure 13; Supplementary Table 11). All the data follow trends of decreasing f\textsubscript{O\textsubscript{2}} with decreasing temperature that lie close to the U-30 isopleth (Figure 13). The result also indicates that the end of subsolidus re-equilibration for magnetite and ilmenite of the Piqiang and Wajilitag Fe-Ti oxide ores occurred at similarly low f\textsubscript{O\textsubscript{2}}. In addition, the magnetite within the Piqiang intrusion contain low concentrations of V (3331–6594 ppm) that are indicative of formation from magmas under relatively low f\textsubscript{O\textsubscript{2}} conditions (<FMQ+0.5; Xing et al. 2013). In addition, experiments by Toplis and Carroll (1995) have indicated that magnetite-dominated oxide phases crystallize from a ferrobasaltic system at high f\textsubscript{O\textsubscript{2}} conditions (FMQ–FMQ+1.5), and those containing cumulus magnetite and ilmenite crystallize at f\textsubscript{O\textsubscript{2}} conditions at FMQ. Data from this study and from Cao et al. (2014) show that the Fe-Ti oxide minerals from the Piqiang intrusion are dominated by titanomagnetite, whereas both magnetite and ilmenite are present in the Wajilitag intrusion (Figure 7). This means that it is probable that f\textsubscript{O\textsubscript{2}} of the Piqiang parent magma is somewhat higher compared with the Wajilitag parent magma, despite the relatively dry nature of the Piqiang magma. The occurrence of coexisting ilmenite and sulphides gives an indication of moderate f\textsubscript{O\textsubscript{2}} conditions, likely close to FMQ, since sulphides are stable only at f\textsubscript{O\textsubscript{2}} condition <FMQ+1.5 in various magmatic systems (Jugo et al. 2005).

We use the geochemical modelling program MELTS (Ghiorso and Sack 1995) to test if a parent magma composition similar to an alkali diabasic dyke from the vicinity of the Piqiang intrusion (Sample 08KT01-14 of Zhang et al. 2010) could model successfully the evolution of the Piqiang magma. The result of the MELTS modelling is shown in Figure 14. In the model, we use f\textsubscript{O\textsubscript{2}} = FMQ, a starting temperature of 1200°C, a final temperature of 900°C, H\textsubscript{2}O = 0.5 wt.% and a pressure of 1 kbar. The MELTS modelling shows that the crystallization sequence of the melt is orthopyroxene → plagioclase → clinopyroxene+Fe-Ti spinel → apatite. This is not consistent with the observations from the Piqiang intrusion, where orthopyroxene is only found as a minor intercumulus phase in anorthosites (Figure 4 (f)). Notably, olivine, which is a significant cumulus phase in most of the Piqiang rocks (Figure 4), is not present in the modelled assemblage. It is probable that the high SiO\textsubscript{2} content in the model parent magma results in orthopyroxene rather than olivine appearing...
on the liquidus at the very early stage of differentiation. To justify this, we conducted another model run using the same starting composition with a low SiO\(_2\) content (49.2 wt.% according to sample ZK4-2-15-3; Zhang et al. 2018) under similar conditions. The modelling of the evolution of the parental magma suggests that the sequence of mineral crystallization is olivine → plagioclase → clinopyroxene → Fe-Ti spinel → apatite, which is generally consistent with petrographic observations. The calculated compositions of olivine (Fo = 67–70), plagioclase (An = 34–63), and clinopyroxene (Mg# = 60–74) are roughly comparable to the measured range of cumulus mineral compositions (Fo = 61–69, An = 48–68, and Mg# = 58–77).

### 6.4 Magma generation and nature of the mantle source

It has been demonstrated that the Tarim LIP has two main magmatic pulses, i.e. ~290 Ma and ~280 Ma. The ~290 Ma basalts were generated from shallow melting of the metasomatized sub-continental lithospheric mantle (SCLM) by conductive heating from the deep-seated plume, whereas the ~280 Ma Bachu layered intrusions (such as Wajilitag and Mazaertag) and contemporaneous diabasic dykes are products of deep melting of the plume head (Wei et al. 2014; Xu et al. 2014; Yu et al. 2017). In addition, Zhang et al. (2013a) and Xu et al. (2014) suggested the existence of small-volume ~300 Ma magmatism represented by Wajilitag kimberlites and it might represent the earliest eruption resulting from the melting of the metasomatized base of the Tarim SCLM during plume-lithosphere interaction. As noted earlier, the Piqiang layered intrusion has been dated at 270.8 ± 2.3 Ma. At Wajilitag, there is also a limited number of carbonatitic, lamprophyric and nephelinitic dykes with an age between 266 and 272 Ma (Wang 2014; Cheng et al. 2015; Song et al. 2017). These ages suggest that a weak but significant mantle-derived magmatism indeed occurred ~10–20 Ma later than the main stage of Tarim plume magmatism. Campbell and Griffiths (1990) have proposed that plume magmatism lasts a relatively short time, with the bulk of magmas emplaced over a period of 1–3 Ma and then followed by less voluminous mantle melting products during a further 5–25 Ma. This scenario agrees well with time scale of the Tarim LIP.

Generally, the cumulate rocks of the Piqiang intrusion has REE and incompatible trace element patterns similar to those of Bachu alkali diabasic dykes and OIB (Figure 9 (a–c)). The Sr, Nd and Hf isotope compositions of the Piqiang intrusion fall into the ranges for Bachu alkali diabasic dykes and OIB (Figure 10(a–b)). These lead us to conclude that the Piqiang intrusion was genetically related to the Tarim mantle plume activity. However, the cumulate rocks also have negative Nb-Ta and Zr-Hf anomalies, possibly indicating a fingerprint of lithospheric mantle or crustal materials. As stated earlier, the Piqiang rocks show minor crustal contamination, and these signatures probably reflect the true character of their mantle.

**Figure 13.** log\(f_O(\Delta \text{FMQ})\)–temperature diagram constructed from compositions of coexisting titanomagnetite and ilmenite pairs of the Piqiang rocks. Oxygen fugacity is normalized to that of the fayalite-magnetite-quartz (FMQ) buffer, where log \(f_O(\Delta \text{FMQ}) = \log f_O(\text{FMQ}) - \log f_O(\text{FMQ})\). Solid lines labeled ‘I’ or ‘U’ are isopleths of ilmenite and ulvöspinel, respectively, adapted from Frost et al. (1988). Dashed lines are extrapolated lines representing possible temperature and oxygen fugacity conditions. Data of the Mazaertag and Wajilitag intrusions are shown for comparison and from Cao et al. (2014) and Cao (2015), respectively.
Thus, the negative Nb-Ta and Zr-Hf anomalies of the Piqiang mafic-ultramafic rocks could be attributed to the involvement of lithospheric mantle. It can further be noted that the negative to slight positive whole-rock $\varepsilon_{\text{Nd}}(t)$ values (−3.2 to +0.9), enrichment of LILE (e.g. Rb, K, Th, and U) and light REE, and depletion of HFSE (e.g. Nb, Ta, Zr, and Hf) of the Piqiang mafic-ultramafic rocks suggest a chemically enriched SCLM. On the other hand, the Hf-Nd isotopic systems are decoupled (Figure 10(b)) with negative $\Delta_{\varepsilon_{\text{Hf}}}$ values (−4.1 to −0.6), signatures typically observed from zircon-bearing sediments (Bayon et al. 2009; Guo et al. 2014). The rather high (Ta/La)$_{\text{PM}}$ and (Hf/Sm)$_{\text{PM}}$ ratios indicate that mantle source metasomatized by subduction-related processes (Figure 10(e)). As stated above, the northern margin of the Tarim Craton, where the Piqiang intrusion is located, was strongly influenced by the southward subduction of the South Tianshan oceanic plate during Ordovician to Devonian times (Huang et al. 2013; Ge et al. 2014). This is evidenced by the occurrence of Early-Middle Paleozoic Andean-type continental arc magmatism on the northern margin of the Craton (460–400 Ma; Ge et al. 2014; Kong et al. 2019). Hence, the enriched SCLM source was probably metasomatized by subduction melts or fluids derived from subducted zircon-bearing marine sediments during the Early-Middle Paleozoic when the South Tianshan oceanic slab was subducted beneath the northern margin of the Tarim Craton. The subduction and metasomatic events affecting lithospheric mantle during the Early-Middle Paleozoic are also supported by the noble gas isotope studies on olivine and clinopyroxene separated from the ~268 Ma Wajilitag nephelinite, which is ~150 km southeast of Piqiang (Figure 1(b); Kong et al. 2017). We thus propose that the parental magmas of the Piqiang intrusion were generated by plume-lithosphere interaction or ascending plume-derived melts contaminated by the enriched SCLM, analogous to models proposed for the origin of Group 2 basalts from the Tarim LIP (Yu et al. 2017) and Panzhihua intrusion from the Emeishan LIP (Hou et al. 2013).

The elevated (Tb/Yb)$_{\text{PM}}$ ratios (Figure 10(f)) indicate that the magmas parental to the Piqiang intrusion were
probably derived from a garnet-bearing source region rather than a spinel-bearing source (Xu 2001). Since both Rb and Ba are compatible in phlogopite and Rb, Sr and Ba are moderately compatible in amphibole, melts in equilibrium with amphibole are expected to have extremely high Ba contents and Ba/Rb values (Furman and Graham 1999). The mafic-ultramafic rocks of the Piqiang intrusion have low Rb/Sr values (<0.07) and high Ba/Rb (mostly >20) values, consistent with melting of an amphibole-bearing lherzolite. Thus, the Piqiang magmas could have been derived from an amphibole-bearing garnet lherzolite mantle source. Class and Goldstein (1997) have discussed evidence for the presence of amphibole and phlogopite in the mantle sources for some ocean island basalts, and suggest that metasomatism of the oceanic lithosphere by small volume silicate melts plays an important role in ocean island magmatism. As discussed previously, the lithospheric mantle underneath the Tarim Craton has likely been metasomatized by slab-derived melts or fluids during Early-Middle Paleozoic subduction. The subducted oceanic slab likely underwent eclogite-facies metamorphism (Qu et al. 2011) and generated slab melts, a scenario supported by the presence of the ca. 430 Ma Baicheng dioritic pluton on the northern margin of the Tarim Craton (Zhao et al. 2015). On the Ba versus Nb/Y diagram (not shown), the Piqiang silicate rocks have the relatively large variation of Nb/Yb (0.12–2.13) with restricted Ba contents (29.6–267 ppm), suggesting that the source of the Pi qiang intrusion was plausibly metasomatized by melts derived from the subducted slab and overlying sediments as well (Kepezhinskas et al. 1996). The infiltration of subduction-related melts into the lithospheric mantle would lead to the formation of metasomatic minerals, such as pyroxene, amphibole, garnet and/or phlogopite (e.g. Yaxley 2000; Herzberg 2006). This scenario is supported by the presence of peridotite and clinopyroxenite mantle-derived xenoliths as well as clinopyroxene, garnet, amphibole and phlogopite entrained xenocrysts in the Wajilitag kimberlitic rocks (Cheng et al. 2014). Experimental studies have revealed that the formation of primitive Fe-rich magmas is genetically related to the presence of garnet pyroxenite in the source under high pressure (~5 GPa) and temperature (~1550°C) (Tuff et al. 2005). The garnet pyroxenite, which may occur as blocks or veins in the shallow lithospheric mantle (Hirschmann and Stolper 1996), may be produced by the reaction of subduction-related melts with lithospheric peridotites (Herzberg 2006). Therefore, the Piqiang ferrobasaltic parental magmas could have been generated by partial melting of a mixture of an ascending mantle plume and the garnet pyroxenite-

loaded, enriched SCLM that was metasomatized by subduction-related melts prior to magma generation.

### 6.5 Origin of the Fe-Ti oxide ores

Compared with Fe-Ti oxide mineralization hosted by the Wajilitag intrusion in the Tarim LIP, massive Fe-Ti oxide ores are more common in the Piqiang intrusion (Cao et al. 2017a; Zhang et al. 2018). Cumulates with very high Fe-Ti oxide modes (>85 vol.%) approaching monomineralic facies have been reported from other Fe-Ti-V oxide deposits in mafic-ultramafic layered intrusions such as the Bushveld complex in the Bushveld LIP (Cawthorn and Ashwal 2009) and Panzhihua and Hongge intrusions in the Emeishan LIP (Zhou et al. 2013). Two competing models have been proposed for the genesis of massive Fe-Ti oxide ores: (1) crystallization of a distinct Fe-Ti-(P) rich immiscible liquid segregated from the evolved basaltic magma (Reynolds 1985; Wang and Zhou 2013; Liu et al. 2014b; Zhou et al. 2013), and (2) gravitational settling and sorting of Fe-Ti oxide minerals from the Fe-Ti-enriched magmas (Pang et al. 2008; Bai et al. 2012; Cawthorn 2013; Song et al. 2013; Luan et al. 2014).

Silicate liquid immiscibility has been proposed for the genetic mechanism for some Fe-Ti-V-(P) oxide deposits in various magmatic intrusions, including the Upper Zone of the Bushveld Complex (VanTongeren and Mathez 2012), Skaergaard intrusion (Jakobsen et al. 2011), Sept Iles layered intrusion (Charlier et al. 2011; Namur et al. 2012), Panzhihua-type layered intrusions (Wang et al. 2013; Zhou et al. 2013; Liu et al. 2014b), and Duluth Complex (Ripley et al. 1998). This has been verified by laboratory experiments showing that immiscibility usually develops at very late stage of tholeiitic magma differentiation and Fe, Ti and P are preferentially partitioned into the immiscible Fe-rich liquids during immiscible separation of Si-rich and Fe-rich silicate liquids (Charlier and Grove 2012). However, in these cases the immiscible Fe-rich liquids commonly contained 33.4 to 52.6 wt.% SiO₂, 5.60 to 36.0 wt.% total Fe₂O₃, 0.08 to 12.2 wt.% TiO₂ and 0.07 to 10.2 wt.% P₂O₅. In the Piqiang case, the massive Fe-Ti oxide ores are extremely enriched in total Fe₂O₃ (62.8–72.5 wt.%), TiO₂ (14.0–17.6 wt.%), but poor in SiO₂ (3.0–10.2 wt.%), P₂O₅ (<0.01 wt.%). P strongly partitions into the Fe-rich liquid (D_pFe⁴⁺/LSi⁴⁺=8–10, Watson 1976; Schmidt et al. 2006). If massive Fe-Ti oxide ores were formed from an Fe-rich liquid, they would have had cumulus apatite. The coexistence of apatite with Fe-Ti oxides is indeed observed in the Bushveld Complex (Eales and Cawthorn 1996), Skaergaard intrusion (Jakobsen et al. 2005) and Sept Iles layered intrusion (Namur et al. 2014).
Therefore, the absence of coexisting apatite and Fe-Ti oxides indicates liquid immiscibility is not the mechanism for producing Piqiang massive Fe-Ti oxide ore layers. Moreover, our field observation that the base of massive Fe-Ti oxide ore layers is typically gabbro, rather than anorthosite as is common in the Bushveld Complex (Cawthorn and Ashwal 2009), which is also a strong argument against silicate liquid immiscibility at Piqiang. Thus, silicate liquid immiscibility is incapable of explaining the formation of Piqiang massive Fe-Ti oxide ores, and alternative genetic model involving crystal settling and mechanical sorting of dense Fe-Ti oxide minerals is preferred.

According to our studies, the Piqiang rocks exhibit a large range of major element compositional variation (Figure 7), yet all have similar Sr-Nd isotopic and trace element characteristics (Figures 9 and 10), suggesting that the parental magmas have experienced varying degrees of fractional crystallization and crystal accumulation after emplacement. The order of crystallization can be deduced from the field relations, petrographic observations and MELTS modelling. The following crystallization sequence in the Piqiang intrusion is proposed: Olivine is the earliest phase on the liquidus, followed by plagioclase, clinopyroxene and then Fe-Ti oxides. Olivine, plagioclase and clinopyroxene began to crystallize during cooling of the magma chamber. Continuous fractionation of silicate minerals (in particular plagioclase) may have driven the elevated concentrations of Fe and Ti in the residual magma (Figure 15(a)). In this way, the residual magma becomes strongly enriched in the total FeO, TiO$_2$ and depleted in SiO$_2$ (Figure 14), which may promote subsequently extensive Fe-Ti oxide crystallization. This is in accordance with the occurrence of massive Fe-Ti oxide ores in the middle-upper parts of the Piqiang gabbroic section (Figure 2(c)) and ilmenite exsolution lamellae in the clinopyroxene crystals (Figure 4(d)). The anorthositic rocks were probably formed at this stage by flotation of plagioclase to the top of the magma chamber (Figure 15(a)).

As fO$_2$ is thought to significantly influence the Fe-Ti oxide saturation of mafic magmas (Toplis and Carroll 1995), the formation of the massive Fe-Ti oxide ores in the Panzhihua and Hongge intrusions is therefore attributed to the early crystallization and extensive accumulation of Fe-Ti oxides as a result of elevated fO$_2$ in magmas (Ganino et al. 2008; Pang et al. 2008; Bai et al. 2012). Ganino et al. (2008) suggested that the higher fO$_2$ conditions recorded by the Panzhihua intrusion were associated with the release of abundant CO$_2$ from carbonate wall-rocks during contact metamorphism. Although assimilation of the footwall limestones might result in significant elevation of fO$_2$ and mass crystallization of the Fe-Ti oxides immediately after emplacement of the Piqiang intrusion, such a hypothesis cannot explain that why the massive Fe-Ti oxide ore horizons in this intrusion are not in direct contact with the limestone wall-rocks (Figure 2). Furthermore, we found no evidence for significant bulk assimilation of limestone wall-rocks in the Piqiang intrusion based on our calculations, suggesting that oxidation of basaltic magma by CO$_2$-rich fluids released from limestone wall-rocks did not play a major role in the formation of the massive Fe-Ti oxide ores in the Piqiang case.

Recently, Howarth and Prevec (2013) and Howarth et al. (2013) have suggested that Fe-Ti oxides crystallizes late in dry (<0.5 wt.% H$_2$O) magmas and early in wet (>1.5 wt.% H$_2$O) magmas and that hydration is a key factor affecting the stability of Fe-Ti oxides over silicate phases (in particular plagioclase) in the evolution of the ferrobasaltic magmas. This in turn suggests addition of H$_2$O would result in extensive crystallization of Fe-Ti oxides prior to silicates and resultant consumption of previously crystallized silicate phases (Howarth et al. 2013). The hypothesis could be reconciled with the silicate disequilibrium textures observed in the Piqiang Fe-Ti oxide ores. The widespread planar foliation and lineation shown by the orientation of plagioclase and clinopyroxene in the Piqiang Fe-Ti oxide ores (Figure 4(g)) may indicate that magmatic currents and a laminar flow regime may have resulted from the replenishment of magma (e.g. Wager and Brown 1967; Irvine 1987). Furthermore, the high abundances of the interstitial amphibole (~2–5%) in the Piqiang Fe-Ti oxide ores indicated that the pre-existing residual magma was H$_2$O-enriched (2–3 wt.%), probably when Fe-Ti oxides crystallized (Luan et al. 2014). Likewise, symplectites between clinopyroxene and Fe-Ti oxides or plagioclase (Figure 5(c)) clearly indicated the presence of ‘new’ hydrated melts introduced during intrusion solidification, which is likely associated with multiple replenishment of Fe-Ti-magma from a deeper source (Gao et al. 2017). Thus the Piqiang Fe-Ti oxide ores could be produced by large scale Fe-Ti oxide crystallization at the expense of silicates because of an introduction of additional H$_2$O to the initially dry (~0.5 wt.% H$_2$O) magma (Howarth et al. 2013). Considering that the wall-rocks of the Piqiang intrusion are limestone and sandstone and the intrusion is directly intruded into them, it is likely that external H$_2$O was introduced into the Piqiang intrusion during the assimilation of the wall-rocks, although the amounts of crustal contamination are small (Ganino et al. 2008; Luan et al. 2014). Addition of H$_2$O is known to reduce melt viscosities (Giordano et al. 2008), which could effectively facilitate rapid transport
and accumulation of the Fe-Ti oxides in the H$_2$O-enriched magma during the late stages of magma differentiation. This process, coupled with successive Fe and Ti enrichment in the Piqiang fractionating magma, would have created favorable conditions for the precipitation of large quantities of Fe-Ti oxides at late-stage and resulted in the generation of quantities of dense, Fe-Ti oxide-rich slurries (Howarth et al. 2013). These dense Fe-Ti oxide crystal slurries with low viscosity infiltrated downwards through the unconsolidated crystal pile that occurs below them. During this stage, they sorted during settling to form massive Fe-Ti oxide ore layers at various stratigraphic levels in the gabbroic section. It is implied, therefore, in this model that massive Fe-Ti oxide ores should be be intrusive into lower lithologies within the intrusion. In fact, the main Fe-Ti oxide ore bodies in Piqiang generally show clear intrusive boundaries with the host gabbros (Figure 3(d–e)). The compaction of the crystal mush by gravitational accumulation further leads to expulsion of residual interstitial liquid (Figure 15(b)) and formation of essentially monomineralic titanomagnetite layers that exhibit polygonal grain boundaries which meet in triple junctions with interfacial angles of 120° (Figure 5(d–e); Reynolds 1985). The residual liquid from the main magma body was likely silicic and might be responsible

![Diagram](attachment:image.png)

**Figure 15.** Proposed petrogenetic model for the formation of major Fe-Ti oxide ores in the Piqiang intrusion. (a) Fractional crystallization of magmas developed a dense Fe-Ti-(V) enriched liquids. (b) Further crystallization of the Fe-Ti-(V) enriched liquids, in combination with addition of H$_2$O-rich ferrobasaltic magma, led to the formation of major Fe-Ti oxide ores.
for the intrusion of a series of granitic dykes that intersected the Piqiang layered intrusion (Zhang et al. 2010; Cao et al. 2013).

Therefore, it is reasonable to infer that a lengthy period of fractional crystallization of a Fe-Ti-enriched parental magma, involving later addition of water to the fractionating magma after its final emplacement, finally results in large amounts of Fe-Ti oxide precipitation and gave rise to the growth of distinct massive Fe-Ti oxide ore layers in this case.

7. Conclusions

The Piqiang intrusion was formed at ~270 Ma and may represent the last pulse of the Tarim LIP magmatism. The parental magmas are deduced to be ferrobasaltic in composition. Partial melting of the Permian Tarim plume that interacted with the garnet pyroxenite component in an enriched lithospheric mantle source could explain the petrogenesis of the ferrobasaltic parental magma. Lithospheric mantle enrichment probably resulted from metasomatism associated with oceanic sediment recycling during southward subduction of the South Tianshan oceanic slab during Early-Middle Paleozoic. The Piqiang rocks are clearly cumulates and we consider that crystal settling and mechanical sorting is the predominant process responsible for their formation. The presence of silicate disequilibrium textures and symplectites between clinopyroxene and plagioclase indicates later addition of external H₂O from the wallrock to the more fractionated magma during the late-stage of magma differentiation. We propose a model in which abundant dense Fe-Ti oxide crystals formed from the fractionated parental magma during the late stages of magma differentiation and then rapidly settling to the underlying unconsolidated silicate crystal pile. The dense Fe-Ti oxide crystal slurries further tended to effective accumulate Fe-Ti oxides to form massive Fe-Ti oxide ores under a H₂O-rich environment. The formation of massive Fe-Ti oxide ores could plausibly result from a combination of the protracted differentiation history of a Fe-Ti-enriched parental magma and the later addition of water to the fractionating magma after its final emplacement.

Acknowledgments

We acknowledge Prof. Zhaochong Zhang and one anonymous reviewer for their helpful and constructive suggestions that assisted us to improve the original manuscript. Hangqiang Xie and Wei Xie are thanked for their assistance with zircon U–Pb dating analysis; Changming Xing is thanked for his help in the field.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was funded by the National Natural Science Foundation of China (41703030) and research grants from the East China University of Technology [DHBK2015323 and RGET1803].

References

Andersen, D.J., Lindsley, D.H., and Davidson, P.M., 1993, QUILF: A pascal program to assess equilibria among Fe–Mg–Mn–Ti oxides, pyroxenes, olivine, and quartz: Computers and Geosciences, v. 19, p. 1333–1350. doi:10.1016/0098-3004(93)90033-2.

Andersen, J.C.Ø., Power, M.R., and Momme, P., 2002, Platinum-group elements in the palaeogene north atlantic igneous province: canadian institute of mining, Metallurgy and Petroleum, Special Volume 54, p. 637–667.

Bai, Z.J., Zhong, H., Naldrett, A.J., Zhu, W.G., and Xu, G.W., 2012, Whole-rock and mineral composition constraints on the genesis of the giant Hongge Fe–Ti–V oxide deposit in the Emeishan Large Igneous Province, Southwest China: Economic Geology, v. 107, p. 507–524. doi:10.2113/econgeo.107.3.507.

Bai, Z.J., Zhong, H., Zhu, W.G., Hu, W.J., and Chen, C.J., 2018, The genesis of the newly discovered giant Wuben magmatic Fe–Ti oxide deposit in the Emeishan Large Igneous Province: A product of the late-stage redistribution and sorting of crystal slurries: Mineralium Deposita. doi:10.1007/s00126-018-0801-9.

Bayon, G., Burton, K.W., Soulet, G., Vigier, N., Dennielou, B., Etoubleau, J., Ponzevera, E., German, C.R., and Nesbitt, R.W., 2009, Hf and Nd isotopes in marine sediments: Constraints on global silicate weathering: Earth and Planetary Science Letters, v. 277, p. 318–326. doi:10.1016/j.epsl.200810028.

BGMRXUAR (Bureau of Geology Mineral Resources of Xinjiang Uygur Autonomous Region), 1993, Regional geology of the Xinjiang Uygur autonomous region: Geological Publishing House, Beijing, p. 1–468. [in Chinese].

Botcharnikov, R.E., Almeev, R.R., Koepke, J., and Holtz, F., 2008, Phase relations and liquid lines of descent in hydrous ferrobasalt—implications for the Skaergaard intrusion and columbia river flood basalts: Journal of Petrology, v. 49, p. 1687–1727. doi:10.1093/petrology/egn043.

Campbell, I.H., and Griffiths, R.W., 1990, Implications of mantle plume structure for the evolution of flood basalts: Earth and Planetary Science Letters, v. 99, p. 79–93. doi:10.1016/0012-821X(90)90072-6.

Cao, J., 2015, Origin of the Fe-Ti oxide mineralization and the host mafic-ultramafic layered intrusions in the Tarim Large Igneous Province, NW China: Dissertation of Doctoral Degree for University of Chinese Academy of Sciences, 1–180pp. [in Chinese with English abstract] (Cao, J., Tao, J.H., and Wang, X., 2017b, SHRIMP zircon U–Pb ages of the Wajililtag igneous complex: Constraints on the origin of A-type granitoids in the Tarim Large Igneous Province: Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 54, p. 637–667. doi:10.1016/j.epsl.200810028.)
Province, NW China: Acta Geologica Sinica, v. 91, p. 2318–2320. doi:10.1111/1755-6724.13471. (English edition)

Cao, J., Wang, C.Y., Xing, C.M., and Xu, Y.G., 2014, Origin of the early Permian Wajijtag igneous complex and associated Fe–Ti oxide mineralization in the Tarim Large Igneous Province, NW China: Journal of Asian Earth Sciences, v. 84, p. 51–68. doi:10.1016/j.jseaes.2013.09.014.

Cao, J., Wang, C.Y., Xu, Y.G., Xing, C.M., and Ren, M.H., 2017a, Triggers on sulfide saturation in Fe–Ti oxide-bearing, mafic-ultramafic layered intrusions in the Tarim Large Igneous Province, NW China: Mineralium Deposita, v. 52, p. 471–494. doi:10.1007/s00126-016-0670-z.

Cao, J., and Wang, Q.M., 2017b, Petrogenesis and metallogeny of the Mazaertag layered intrusion in the Tarim Large Igneous Province, NW China: Acta Geologica Sinica, v. 91, p. 1653–1679. doi:10.1111/1755-6724.13404. (English edition)

Cao, J., Xu, Y.G., Xing, C.M., and Li, H.Y., 2013, Origin of the early Permian gabbroic plutons from the Piquiang region in the northern Tarim block: Implications for the origin of A-type granites of the Tarim Large Igneous Province: Acta Petrologica Sinica, v. 29, p. 3336–3352. [in Chinese with English abstract].

Cao, X.F., Lü, X.B., Liu, S.T., Zhang, P., Gao, X., Chen, C., and Mo, Y.L., 2011, LA-ICP-MS zircon dating, geochemistry, petrogenesis and tectonic implications of the Dapingliang Neoproterozoic granites at Kuluketage block, NW China: Precambrian Research, v. 186, p. 205–219. doi:10.1016/j.precamres.2011.01.017.

Cawthorn, R.G., 2013, Rare earth element abundances in apatite in the Bushveld complex—a consequence of the trapped liquid shift effect: Geology, v. 41, p. 603–606. doi:10.1130/G34026.1.

Cawthorn, R.G., and Ashwal, L.D., 2009, Origin of anorthosite and magnetitite layers in the Bushveld complex, constrained by major element compositions of plagioclase: Journal of Petrology, v. 50, p. 1607–1637. doi:10.1093/petrology/egp042.

Chambers, A.D., and Brown, P.E., 1996, The Lillooet intrusion, East Greenland: Fractionation of a hydrous alkali picritic magma: Journal of Petrology, v. 36, p. 933–963. doi:10.1093/petrology/36.4.933.

Charlier, B., and Grove, T., 2012, Experiments on liquid immiscibility along tholeiitic liquid lines of descent: Contributions to Mineralogy and Petrology, v. 164, p. 27–44. doi:10.1007/s00410-012-0723-y.

Charlier, B., Namur, O., Toplis, M.J., Schiano, P., Cluzel, N., Higgins, M.D., and Auwera, J.V., 2011, Large-scale silicate liquid immiscibility during differentiation of tholeiitic basalt to granite and the origin of the daly gap: Geology, v. 39, p. 907–910. doi:10.1130/G32091.1.

Chauvel, C., Lewin, E., Carpentier, M., Arndt, N.T., and Marini, J. C., 2008, Role of recycled oceanic basalt and sediment in generating the Hf–Nd mantle array: Nature Geoscience, v. 1, p. 64–67. doi:10.1038/ngeo.2007.51.

Cheng, Z.G., Zhang, Z.C., Hou, T., Santosh, M., Zhao, D.Y., and Ke, S., 2015, Petrogenesis of nephelinites from the Tarim Large Igneous Province, NW China: Implications for mantle source characteristics and plume-lithosphere interaction: Lithos, v. 220–223, p. 164–178. doi:10.1016/j.lithos.2015.02.002.

Class, C., and Goldstein, S.L., 1997, Plume-lithosphere interactions in the ocean basins: Constraints from the source mineralogy: Earth and Planetary Science Letters, v. 150, p. 245–260. doi:10.1016/S0012-821X(97)00089-7.

Compston, W., Williams, I.S., Kirschvink, J.L., Zhang, Z.C., and Guogan, M.A., 1992, Zircon U–Pb ages for the Early Cambrian timescale: Journal of the Geological Society, v. 149, p. 171–184. doi:10.1144/gsjgs.149.2.0171.

Deer, W.A., Howie, R.A., and Zussman, J., 1978, Rock-forming minerals, Single-chain silicates. Volume 2A (2 ed.). London: Longman. p. 668.

Dyglyt, N., Liang, Y., and Hess, P., 2013, The importance of melt TiO2 in affecting major and trace element partitioning between Fe–Ti oxides and lunar picritic glass melts: Geochimica et Cosmochimica Acta, v. 106, p. 134–151. doi:10.1016/j.gca.2012.12.005.

Eales, H.V., and Cawthorn, R.G., 1996, The Bushveld complex, in Cawthorn, R.G., ed., Layered igneous rocks: Amsterdam: Elsevier, p. 181–229.

Ernst, R.E., and Jowitt, S.M., 2013, Large igneous provinces (lips) and metallogeny: society of economic geologists special publication, v. 17, p. 17–51.

Frost, B.R., Lindsley, D.H., and Andersen, D.J., 1988, Fe–Ti oxide-silicate equilibria: Assemblages with fayalitic olivine: American Mineralogist, v. 73, p. 727–740.

Furman, T., and Graham, D., 1999, Erosion of lithospheric mantle beneath the East African Rift system: Geochemical evidence from the Kivu volcanic province: Lithos, v. 48, p. 237–262. doi:10.1016/S0024-4973(99)00031-6.

Ganino, C., Arndt, N.T., Zhou, M.F., Gaillard, F., and Chauvel, C., 2008, Interaction of magma with sedimentary wall rock and magneteite ore genesis in the Panzhuhua mafic intrusion, SW China: Mineralium Deposita, v. 43, p. 677–694. doi:10.1007/s00126-008-0191-5.

Gao, W.Y., Ciobanu, C.L., Cook, N.J., Huang, F., Meng, L., and Gao, S., 2017, Petrography and trace element signatures in silicates and Fe–Ti oxides from the Lanjiahuoshan deposit, Panzhuhua layered intrusion, Southwest China: Lithos, v. 294–295, p. 164–183. doi:10.1016/j.lithos.2017.10.003.

Ge, R.F., Zhu, W.B., Wilde, S.A., He, J.W., Cui, X., Wang, X., and Zheng, B.H., 2014, Neoproterozoic to Paleozoic long-lived accretionary orogeny in the northern Tarim Craton: Tectonics, v. 33, p. 302–329. doi:10.1002/2013TC003501.

Ghiorsio, M.S., and Sack, R.O., 1995, Chemical mass transfer in magmatic processes iv. A Revised and Internally Consistent Thermodynamic Model for The Interpolation and Extrapolation Of Liquid–solid Equilibria in Magmatic Systems at Elevated Temperatures and Pressures: Contributions to Mineralogy and Petrology, v. 119, p. 197–212. doi:10.1007/BF00307281.

Gibson, S.A., Thompson, R.N., and Dickin, A.P., 2000, Ferropicrites: Geochemical evidence for Fe-rich streaks in upwelling mantle plumes: Earth and Planetary Science Letters, v. 174, p. 355–374. doi:10.1016/S0012-821X(99)00274-5.
Giordano, D., Russell, J.K., and Dingwell, D.B., 2008, Viscosity of magmatic liquids: A model: Earth and Planetary Science Letters, v. 271, p. 123–134. doi:10.1016/Feps.2008.03.038.

Godef, B., Barnes, S.J., and Maier, W.D., 2011, Parental magma composition inferred from trace element in cumulus and intercumulus silicate minerals: An example from the lower and lower critical zones of the Bushveld Complex, South-Africa: Lithos, v. 125, p. 537–552. doi:10.1016/j.lithos.2011.03.010.

Guo, F., Fan, W.M., Li, C.W., Wang, C.Y., Li, H.X., Zhao, L., and Li, J.Y., 2014, Hf–Nd–O isotopic evidence for melting of recycled sediments beneath the Sulu Orogen, NW China: Chemical Geology, v. 381, p. 243–258. doi:10.1016/j.chemgeo.2014.04.028.

He, P.L., Huang, X.L., Xu, Y.G., Li, H.Y., Wang, X., and Li, W.X., 2016, Plume-orogenic lithosphere interaction recorded in the Haladala layered intrusion in the Southwest Tianshan Orogen, NW China: Journal of Geophysical Research: Solid Earth, v. 121, p. 1525–1545. doi:10.1002/2015JB012652.

Hirschmann, M.M., and Stolper, E.M., 1996, A possible role for garnet pyroxenite in the origin of the “garnet signature” in MORB: Contributions to Mineralogy and Petrology, v. 124, p. 185–208. doi:10.1007/s004100050184.

Holness, M.B., Stripp, G., Humphreys, C.S., Vekslers, I.V., Nielsen, T.F.D., and Tegner, C., 2011, Silicate liquid immiscibility within the crystal mush: Late-stage magmatic micro-structures in the Skaergaard Intrusion, East Greenland: Journal of Petrology, v. 52, p. 175–222. doi:10.1093/petrology/egq077.

Holwell, D.A., and Keays, R.R., 2014, The formation of low-volume, high-tenor magmatic pge-au sulfide mineralization in closed systems: evidence from precious and base metal geochemistry of the platinova reef, skaergaard intrusion, east greenland: Economic Geology, v. 109, pp. 387–406. doi:10.2113/econgeo.109.2.387.

Hou, T., Zhang, Z.C., Encarnacion, J., Santosh, M., and Sun, Y.L., 2013, The role of recycled oceanic crust in magmatism and metallogeny: Os–Sr–Nd isotopes, U–Pb geochronology andgeochemistry of picritic dykes in the Panzhihua giant Fe–Ti oxide deposit, central Emeishan large igneous province, SW China: Contributions to Mineralogy and Petrology, v. 165, p. 805–822. doi:10.1007/s00410-012-0836-3.

Hou, T., Zhang, Z.C., Keiding, J.K., and Vekslers, I.V., 2015, Petrogenesis of the ultrapotassic Fanshan intrusion in the North China Craton: Implications for lithospheric mantle metasomatism and the origin of apatite ores: Journal of Petrology, v. 56, p. 893–918. doi:10.1093/petrology/egv021.

Howarth, G.H., and Prevec, S.A., 2013, Hydration versus oxidation: Modeling implications for Fe–Ti oxide crystallisation in mafic intrusions, with specific reference to the Panzhihua Intrusion, SW China: Geoscience Frontiers, v. 4, p. 555–569. doi:10.1016/j.gsff.2013.03.002.

Howarth, G.H., Prevec, S.A., and Zhou, M.F., 2013, Timing of Ti-magnetite crystallisation and silicate disequilibrium in the Panzhihua mafic layered intrusion: Implications for ore-forming processes: Lithos, v. 170–171, p. 73–89. doi:10.1016/j.lithos.2013.02.020.

Huang, H., Zhang, Z.C., Santosh, M., Zhang, D.Y., Zhao, Z.D., and Liu, J.L., 2013, Early paleozoic tectonic evolution of the South Tianshan collisional belt: Evidence from geochemistry and Zircon U–Pb geochronology of the Tie’reke monzonite pluton, Northwest China: Journal of Geology, v. 121, p. 401–424. doi:10.1086/670653.

Irvine, T.N., 1987, Layering and related structures in the Duke Island and Skaergaard intrusions: Similarities, differences, origins, In Parsons, I. (ed) Origins of Igneous Layering: D. Reidel Publ. Co., Dordrecht, pp. 185–245.

Jakobsen, J.K., Vekslers, I.V., Tegner, C., and Brooks, C.K., 2005, Immiscible iron- and silica-rich melts in basalt petrogenesis documented in the Skaergaard intrusion: Geology, v. 33, p. 885–888. doi:10.1130/G21724.1.

Jakobsen, J.K., Vekslers, I.V., Tegner, C., and Brooks, C.K., 2011, Crystallization of the Skaergaard intrusion from an emulsion of immiscible iron- and silica-rich liquids: Evidence from melt inclusions in plagioclase: Journal of Petrology, v. 52, p. 345–373. doi:10.1093/petrology/egq083.

Jugo, P.J., Luth, R.W., and Richards, J.P., 2005, An experimental study of the sulfur content in basaltic melts saturated with immiscible sulfide or sulphate liquids at 1300°C and 1.0 GPa: Journal of Petrology, v. 46, p. 783–798. doi:10.1093/petrology/egh097.

Keppezhinskas, P., Defant, M.J., and Drummond, M.S., 1996, Progressive enrichment of island arc mantle by melt-peridotite interaction inferred from Kamchatka xenoliths: Geochemica et Cosmochimica Acta, v. 60, p. 1217–1229. doi:10.1016/0016-7037(96)00001-4.

Klemme, S., Günther, D., Hametner, K., Prowatke, S., and Zack, T., 2006, The partitioning of trace elements between ilmenite, ulvospinel, armalcolite and silicate melts with implications for the early differentiation of the moon: Chemical Geology, v. 234, p. 251–263. doi:10.1016/j.chemgeo.2006.05.005.

Kong, W.L., Zhang, Z.C., and Cheng, Z.G., 2017, Noble gas isotopic characteristics and geological significance of Wajilitag nephelinites in Tarim Large Igneous Province: Acta Petrologica Et Mineralogica, v. 36, p. 581–592. in Chinese with English abstract.

Kong, W.L., Zhang, Z.C., Huang, H., Cheng, Z.G., and Santosh, M., 2019, Geochemistry and zircon U–Pb geochronology of the Oxidaban intrusive complex: Implication for Paleozoic tectonic evolution of the South Tianshan orogenic belt, China: Lithos, v. 324–325, p. 265–279. doi:10.1016/j.lithos.2018.11.013.

LaFleeche, M.R., Camire, G., and Jenner, G.A., 1998, Geochemistry of post-acadian, Carboniferous continental intraplate basalts from the Maritimes basin, Magdalen Islands, Quebec, Canada: Chemical Geology, v. 148, p. 115–136. doi:10.1016/S0009-2541(98)00002-3.

Li, P.C., Chen, G.H., Zeng, Q.S., Yi, J., and Hu, G., 2011, Genesis of lower ordovician dolomite in central Tarim basin: Acta Sedimentologica Sinica, v. 29, p. 842–856. in Chinese with English abstract.

Li, X.H., Li, Z.X., Wingate, M.T.D., Chung, S.L., Liu, Y., Lin, G.C., and Li, W.X., 2006, Geochemistry of the 755 Ma Mundine well dyke swarm, Northwestern Australia: Part of a Neoproterozoic mantle superplume beneath Rodinia?: Precambrian Research, v. 146, p. 1–15. doi:10.1016/j.precamres.2005.12.007.
Li, Y.Q., Li, Z.L., Yu, X., Langmuir, C.H., Santosh, M., Yang, S.F., Chen, H.L., Tang, Z.L., Song, B., and Zou, S.Y., 2014, Origin of the Early Permian zircons in Kepping basalts and magma evolution of the Tarim Large Igneous Province (Northwestern China): Lithos, v. 204, p. 47–58. doi:10.1016/j.lithos.2014.05.021.

Liu, H.Q., Xu, Y.G., Tian, W., Zhong, Y.T., Mundil, R., Li, X.H., Yang, Y.H., Luo, Z.Y., and Shangguan, S.M., 2014a, Origin of two types of rhyolites from Tarim Large Igneous Province: Consequences of plume incubation and melting: Lithos, v. 204, p. 59–72. doi:10.1016/j.lithos.2014.02.007.

Liu, P.P., Zhou, M.F., Chen, W.T., Boone, M., and Cruizile, V., 2014b, Using multiphase solid inclusions to constrain the origin of the Baima Fe–Ti(V) oxide deposit, SW China: Journal of Petrology, v. 55, p. 951–976. doi:10.1093/petrology/egu012.

Long, X.P., Yuan, C., Sun, M., Zhao, G.C., Xiao, W.J., Wang, Y.J., Yang, Y.H., and Hu, A.Q., 2010, Archean crustal evolution of the northern Tarim Craton, NW China: Zircon U–Pb and Hf isotopic constraints: Precambrian Research, v. 180, p. 272–284. doi:10.1016/j.precamres.2010.05.001.

Lu, Y., Makishima, A., and Nakamura, E., 2007, Purification of Hf in silicate materials using extraction chromatographic resin, and its application to precise determination of $\text{Hf}^{177}/\text{Hf}^{176}$ by MC-ICP-MS with $\text{Hf}^{179}$ spike: Journal of Analytical Atomic Spectrometry, v. 22, p. 69–76. doi:10.1039/b610197f.

Luan, Y., Song, X.Y., Chen, L.M., Zheng, W.Q., Zhang, X.Q., Yu, S.Y., She, Y.W., Tian, X.L., and Ran, Q.Y., 2014, Key factors controlling the accumulation of the Fe–Ti oxides in the Hongge layered intrusion in the Emeishan Large Igneous Province SW China: Ore Geology Reviews, v. 57, p. 518–538. doi:10.1016/j.oregeorev.2013.08.010.

Ludwig, K.R., 1998, On the treatment of concordant uranium-lead ages: Geochimica et Cosmochimica Acta, v. 62, p. 665–676. doi:10.1016/S0016-7037(98)00059-3.

McBirney, A.R., 1996, The Skærgaard intrusion, In Cawthorn, R. G. (ed.), Layered Intrusions: Developments in Petrology, Elsevier, Amsterdam, v. 15, p. 147–180. doi:10.1016/S0167-2894(96)80007-8.

Namur, O., Charlier, B., and Holness, M.B., 2012, Dual origin of Fe–Ti–P gabbros by immiscibility and fractional crystallization of evolved tholeiitic basalts in the sept i les layered intrusion: Lithos, v. 154, p. 100–114. doi:10.1016/j.lithos.2012.06.034.

Namur, O., Charlier, B., Toplis, M.J., Higgins, M.D., Liégeois, I.P., and Vander Auwera, J., 2010, Crystallization sequence and magma chamber processes in the ferrobasaltic sept i les layered intrusion, canada: Journal Of Petrology, v. 51, p. 1203-1236. doi:10.1016/j.petrol.2007.06.003.

Nebel, O., Arculus, R.J., Ivanic, T.J., Rapp, R., and Wills, K.J.A., 2013, Upper Zone of the Archean Windimurra layered mafic intrusion, Western Australia: Insights into fractional crystallisation in a large magma chamber: Neues Jahrbuch für Mineralogie, v. 191, p. 83–107. doi:10.1127/0077-7575/2013/0249.

Nielsen, T.F.D., 2004, The shape and volume of the Skærgaard intrusion, Greenland: Implications for mass balance and bulk composition: Journal of Petrology, v. 45, p. 507–530. doi:10.1093/petrology/egg092.

Pang, K.N., and Shellnutt, J.G., 2018, Magmatic sulfide and Fe–Ti oxide deposits associated with mafic-ultramafic intrusions in China, in Mondal, S.K., and Griffin, W.L., eds., Processes and ore deposits of ultramafic-mafic magmas through space and time: Elsevier, Amsterdam, p. 239–259.

Pang, K.N., Li, C.S., Zhou, M.F., and Ripley, E.M., 2009, Mineral compositional constraints on petrogenesis and oxide ore genesis of the late Permian Panzhihua layered gabbroic intrusion, SW China: Lithos, v. 110, p. 199–214. doi:10.1016/j.lithos.2009.01.007.

Pang, K.N., Zhou, M.F., Lindsley, D., Zhao, D.G., and Malpas, J., 2008, Origin of Fe–Ti oxide ores in mafic intrusions: Evidence from the Panzhihua intrusion, SW China: Journal of Petrology, v. 49, p. 295–313. doi:10.1093/petrology/egm082.

Qu, J.F., Xiao, W.J., Windley, B.F., Han, C.M., Mao, Q.G., Ao, S.J., and Zhang, J.E., 2011, Ordovician eclogites from the Chinese Beishan: Implications for the tectonic evolution of the southern Altaiids: Journal of Metamorphic Petrology, v. 29, p. 803–820. doi:10.1111/j.1525-1314.2011.00942.x.

Reynolds, I.M., 1985, The nature and origin of titaniferous magnetite-rich layers in the upper zone of the Bushveld complex: A review and synthesis: Economic Geology, v. 80, p. 1089–1108. doi:10.2113/gsecongeo.80.4.1089.

Ripley, E.M., Severson, M.J., and Hauck, S.A., 1998, Evidence for sulfide and Fe–Ti–P rich liquid immiscibility in the Duluth complex, Minnesota: Economic Geology, v. 93, p. 1052–1062. doi:10.2113/gsecongeo.93.7.1052.

Roeder, P.L., and Emslie, R.F., 1970, Olivine-liquid equilibrium: Contributions to Mineralogy and Petrology, v. 29, p. 275–289. doi:10.1007/BF00371276.

Rollinson, H.R., 1993, Using geochemical data: evaluation, presentation, interpretation. Longman, Singapore, pp. 352.

Rui, X.J., He, J.R., and Guo, K.Y., 2002, Mineral resources of Tarim block: Beijing, Geological Publishing House, p. 56–157. [in Chinese with English abstract].

Schmidt, M.W., Connolly, J.A.D., Gunther, D., and Bogaerts, M., 2006, Element partitioning: The role of melt structure and composition: Science, v. 312, p. 1646–1650. doi:10.1126/science.1126690.

Shellnutt, J.G., and Pang, K.N., 2012, Petrogenetic implications of mineral chemical data for the Permian Baima igneous complex, SW China: Mineralogy and Petrology, v. 106, p. 75–88. doi:10.1007/s00710-012-0217-7.

Sissons, T.W., and Grove, T.L., 1993, Experimental investigations of the role of H2O in calc-alkaline differentiation and subduction zone magmatism: Contributions to Mineralogy and Petrology, v. 113, p. 143–166. doi:10.1007/BF00283225.

Song, W.L., Xu, C., Chakhmouradian, A.R., Kynicky, J., Huang, K. J., and Zhang, Z.L., 2017, Carbonatites of Tarim (NW China): First evidence of crustal contribution in carbonatites from a Large Igneous Province: Lithos, v. 282–283, p. 1–9. doi:10.1016/j.lithos.2017.02.018.

Song, X.Y., Qi, H.W., Hu, R.Z., Chen, L.M., Yu, S.Y., and Zhang, J. F., 2013, Formation of thick stratiform Fe–Ti oxide layers in layered intrusion and frequent replenishment of fractionated mafic magma: Evidence from the Panzhihua intrusion, SW China: Geochemistry, Geophysics, Geosystems, v. 14, p. 712–732. doi:10.1002/ggge.20068.

Sun, S.S., and McDonough, W.F., 1989, Chemical and isotopic systematics of oceanic basaltic: Implications for mantle composition and processes, in Saunders, A.D., and Norry, M.J., eds., Magmatism in the ocean basaltic: London, Geological Society Special Publication, p. 313–345.
Tegner, C., Cawthorn, R.G., and Kruger, F.J., 2006, Cyclicity in the main and upper zones of the Bushveld Complex, South Africa: Crystallization from a zoned magma sheet: Journal of Petrology, v. 47, p. 2257–2279. doi:10.1093/petrology/egl043.

Tian, W., Campbell, I.H., Allen, C.M., Guan, P., Pan, W.Q., Chen, M.M., Yu, H.J., and Zhu, W.P., 2010, The Tarim picrite-basalt-rhyolite suite, a Permian flood basalt from northwest China with contrasting rhyolites produced by fractional crystallization and anatexis: Contributions to Mineralogy and Petrology, v. 160, p. 407–425. doi:10.1007/s00410-009-0485-3.

Toplis, M.J., and Carroll, M.R., 2001, Experimental constraints on the role of garnet pyroxenites in the genesis of high-Fe mantle plume derived melts: Journal of Petrology, v. 42, p. 259–289. doi:10.1007/s10909-001-0120-6.

Tu, X.L., Zhang, H., Deng, W.F., Ling, M.X., Liang, H.Y., Liu, Y., and Sun, W.D., 2011, Application of resolution in-situ laser ablation ICP-MS in trace element analyses: Geochimica, v. 40, p. 83–89. [in Chinese with English abstract].

Tuff, J., Takahashi, E., and Gibson, S.A., 2005, Experimental constraints on the role of garnet pyroxenites in the genesis of high Fe-Ti oxide stability, phase relations, and mineral-melt equilibria in ferrobasaltic systems: Journal of Petrology, v. 36, p. 1137–1170. doi:10.1093/petrology/36.5.1137.

Tu, X.L., Zhang, H., Deng, W.F., Ling, M.X., Liang, H.Y., Liu, Y., and Sun, W.D., 2011, Application of resolution in-situ laser ablation ICP-MS in trace element analyses: Geochimica, v. 40, p. 83–89. [in Chinese with English abstract].

Van Tongeren, J.A., and Mathez, E.A., 2012, Large-scale liquid immiscibility at the top of the Bushveld complex, South Africa: Geology, v. 40, p. 491–494. doi:10.1130/G32980.1.

Wager, L.R., and Brown, G.M., 1967, Layered igneous rocks: Freeman, San Francisco.

Wang, C.Y., and Zhou, M.F., 2013, New textural and mineralogical constraints on the origin of the Hongge Fe-Ti-V oxide deposit, SW China: Mineralium Deposita, v. 48, p. 787–798. doi:10.1007/s00126-013-0457-4.

Wang, K., Plank, T., Walker, J.D., and Smith, E.I., 2015, Contributions to the origin of the Hongge Fe-Ti-V oxide deposits, SW China: Earth Science Frontiers, v. 20, p. 105–206. doi:10.1007/s11430-013-4653-y.

Xia, Y.G., Wei, X., Luo, Z.Y., Liu, H.Q., and Cao, J., 2014, The Early Permian Tarim Large Igneous Province: Main characteristics and a plume incubation model: Lithos, v. 204, p. 20–35. doi:10.1016/j.lithos.2014.02.015.

Yang, S.F., Chen, H.L., Li, Z.L., Li, Y.Q., Yu, X., Li, D.X., and Meng, L.F., 2013, Early permian tarim large igneous province in northwest china: science china: Earth Sciences, v. 56, p. 2015–2026. doi:10.1007/s11430-013-4653-y.

Yaxley, G.M., 2000, Experimental study of the phase and melting relations of homogeneous basalt-peridotite mixtures and implications for the petrogenesis of flood basalts: Contributions to Mineralogy and Petrology, v. 139, p. 326–338. doi:10.1007/s004100000134.

Yu, X., Yang, S.F., Chen, H.L., Li, Z.L., and Li, Y.Q., 2017, Petrogenetic model of the Permian Tarim Large Igneous Province: Science China: Earth Sciences, v. 60, p. 1805–1816. doi:10.1007/s11430-016-9098-7.

Zhang, C.J., Wang, H.J., and Shi, G.H., 2013b, The geological features and mine prospecting significance of Puchang ilmenite mine in Atushi, Xinjiang: Xinjiang Geology, v. 31, p. 29–33. [in Chinese with English abstract].

Zhang, C.L., Li, X.H., Li, Z.K., Ye, H.M., and Li, C.N., 2008, A Permian layered intrusive complex in the western Tarim block, Northwestern China: Product of a ca275 Ma mantle plume?: Journal of Geology, v. 116, p. 269–287. doi:10.1086/587726.

Zhang, C.L., Xu, Y.G., Li, Z.K., Wang, H.Y., and Ye, H.M., 2010, Diverse Permian magmatism in the Tarim block, NW China: Genetically linked to the Permian Tarim mantle plume?: Lithos, v. 119, p. 537–552. doi:10.1016/j.lithos.2010.08.007.

Zhang, C.L., and Zou, H.B., 2013, Permian A-type granites in Tarim and western part of Central Asian Orogenic Belt (CAOB): Genetically related to a common Permian mantle plume?: Lithos, v. 172–173, p. 47–60. doi:10.1016/j.lithos.2013.04.001.

Zhang, D.Y., Zhang, Z.C., He, H., EncarnacioN, J., Zhou, N.W., and Ding, X.X., 2014, Platinum-group elemental and Re-Os isotopic geochemistry of the Wajiltag and Puchang Fe-Ti oxide deposits, Northwestern Tarim Large Igneous Province: Ore Geology Reviews, v. 57, p. 589–601. doi:10.1016/j.oregeorev.2013.08.004.

Zhang, D.Y., Zhang, Z.C., Huang, H., Cheng, Z.G., and Charlier, B., 2018, Petrogenesis and metallogenesis of the Wajiltag and Puchang Fe-Ti oxide-rich intrusive complexes, Northwestern Tarim Large Igneous Province: Lithos, v. 304–307, p. 412–435. doi:10.1016/j.lithos.2018.02.019.
Zhang, D.Y., Zhang, Z.C., Mao, J.W., Huang, H., and Cheng, Z. G., 2016, Zircon U-Pb ages and Hf-O isotopic signatures of the Wajilitag and Puchang Fe-Ti oxide-bearing intrusive complexes: Constraints on their source characteristics and temporal-spatial evolution of the Tarim Large Igneous Province: Gondwana Research, v. 37, p. 71–85. doi:10.1016/j.gr.2016.05.011.

Zhang, D.Y., Zhang, Z.C., Santosh, M., Cheng, Z.G., Huang, H., and Kang, J.L., 2013a, Perovskite and baddeleyite from kimberlitic intrusions in the Tarim Large Igneous Province signal the onset of an End-Carboniferous mantle plume: Earth and Planetary Science Letters, v. 361, p. 238–248. doi:10.1016/j.epsl2012.10.034.

Zhang, Y., Wei, X., Xu, Y.G., Long, X.P., Shi, X.F., Zhao, J.X., and Feng, Y.X., 2017, Sr-Nd-Pb isotopic compositions of the lower crust beneath northern Tarim: Insights from igneous rocks in the Kuluketage area, NW China: Mineralogy and Petrology, v. 111, p. 237–252. doi:10.1007/s00710-016-0470-2.

Zhang, Z.C., Mao, J.W., Saunders, A.D., Ai, Y., Li, Y., and Zhao, L., 2009, Petrogenetic modeling of three mafic-ultramafic layered intrusions in the Emeishan Large Igneous Province, SW China, based on isotopic and bulk chemical constraints: Lithos, v. 113, p. 369–392. doi:10.1016/j.lithos2009.04.023.

Zhao, Z.Y., Zhang, Z.C., Santosh, M., Huang, H., Cheng, Z.G., and Ye, J.C., 2015, Early Paleozoic magmatic record from the northern margin of the Tarim Craton: Further insights on the evolution of the Central Asian Orogenic Belt: Gondwana Research, v. 28, p. 328–347. doi:10.1016/j.gr.2014.04.007.

Zhou, M.F., Chen, W.T., Wang, C.Y., Prevec, S.A., Liu, P.P., and Howarth, G.H., 2013, Two stages of immiscible liquid separation in the formation of Panzhihua-type Fe-Ti-V oxide deposits, SW China: Geoscience Frontiers, v. 4, p. 481–502. doi:10.1016/j.gsf.2013.04.006.

Zhou, M.F., Robinson, P.T., Lesher, C.M., Keays, R.R., Zhang, C.J., and Malpas, J., 2005, Geochemistry, petrogenesis and metallogenesis of the Panzhihua gabbroic layered intrusion and associated Fe-Ti-V oxide deposits, Sichuan province, SW China: Journal of Petrology, v. 46, p. 2253–2280. doi:10.1093/petrology/egi054.

Zhou, M.F., Zhao, J.H., Jiang, C.Y., Gao, J.F., Wang, W., and Yang, S.H., 2009, Oib-like, heterogeneous mantle sources of permian basaltic magmatism in the western tarim basin, nw china: implications for a possible permian large igneous province: Lithos, v. 113, p. 583–594. doi:10.1016/j.lithos.2009.06.027.

Zou, S.Y., Li, Z.L., Song, B., Ernst, R.E., Li, Y.Q., Ren, Z.Y., Yang, S. F., Chen, H.L., Xu, Y.G., and Song, X.Y., 2015, Zircon U–Pb dating, geochemistry and Sr-Nd-Pb-Hf isotopes of the Wajilitag alkali mafic dikes, and associated diorite and syenitic rocks: Implications for magmatic evolution of the Tarim Large Igneous Province: Lithos, v. 212–215, p. 428–442. doi:10.1016/j.lithos2014.09.005.