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Notes

Permian hornblende gabbros in the Chinese Altai from a subduction-related hydrous parent magma, not from the Tarim mantle plume

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ABSTRACT

In the Chinese Altai, on the northern side of the Erqis fault, the ~10-m-wide Qiemuerqieke gabbro is composed almost entirely of hornblende and plagioclase. Its relative crystallization sequence is olivine, hornblende, plagioclase, and it shows a narrow compositional range in SiO₂ (48.7–50.2 wt%), MgO (6.33–8.54 wt%), FeO (5.27–6.46 wt%), Na₂O (3.06–3.71 wt%), and K₂O (0.26–0.37 wt%). These contents result in a high Mg# value (68–72) and a low K₂O/Na₂O ratio of ~0.1. It has (⁸⁷Sr/⁸⁶Sr)_i ratios of 0.70339–0.70350, ε_{Nd(t)} values of 4.8–6.0, and zircon ε_{Hf(t)} of 11.4–15.8; these values demonstrate a mantle-derived source, and a whole-rock δ¹⁸O of ~6.7‰ suggests a mantle wedge origin. The presence of magmatic hornblende suggests a relatively high water fugacity, and the crystallization temperature (715–826 °C) calculated using Ti-in-zircon thermometry is considerably lower than that of a normal mafic melt but consistent with an origin from a water-bearing magma. The gabbro has a secondary ion mass spectrometry zircon U–Pb age of 276.0 ± 2.1 Ma, which is coeval with the 275 Ma mantle plume in the northern Tarim craton, but the Qiemuerqieke petrological and geochemical data do not indicate an abnormally high mantle temperature or a deep mantle signature, which would commonly characterize a mantle plume source. Our results integrated with published data support a model of juvenile crustal growth by a subduction-related process.

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INTRODUCTION

The Altaids or Central Asian orogenic belt is characterized by a huge amount of juvenile crust and a subordinate quantity of Precambrian crust, representing the largest Phanerozoic continental growth on Earth from ca. 1.0 Ga to ca. 250 Ma (Sengör et al., 1993; Jahn et al., 2004; Windley et al., 2007). However, there is little agreement on the tectonic environments in the Tarim–Tianshan–Chinese Altai region in the Pennsylvanian–Permian, when considerable growth took place, and ideas range from plate accretion–collision (Han et al., 2006, 2010; Charvet et al., 2007; Xiao et al., 2009), to mantle plume tectonics (Pirajno et al., 2008; Zhang et al., 2010; Qin et al., 2011). In order to constrain the competing models, some petrogenetic processes may be useful arbiters to enable discrimination. For example, subduction transports appreciable amounts of water into a mantle wedge, which metasomatizes and hydrates the mantle, and facilitates melting by decreasing the solidus. Magmas that originated from such a hydrated source crystallize water-enriched minerals like hornblende and mica. On the other hand, a mantle plume originated from the deep mantle, and even from the core–mantle boundary, may produce anhydrous magma, and high-temperature miner-

als may crystallize (Campbell, 2007). Hornblende/mica-bearing mafic-ultramafic complexes, which occur in many places in the Altaids, such as Kalatongke, Huangshan, Pobei, and Baishiquan (Fig. 1), many with magmatic Cu–Ni–sulfide deposits, make Central Asia one of the most important Ni provinces in orogenic belts worldwide (Pirajno et al., 2008), so understanding the mechanisms that were responsible for their metallogeny has important economic implications.

In this study, we report a plagioclase–hornblende gabbro at Qiemuerqieke, which is different from hornblende-bearing clinopyroxene–plagioclase gabbros that have been previously reported. The aims of our study are: (1) to determine the age and isotopic characteristics of the studied gabbro in order to constrain the character of its magma and source region; (2) to understand the role that the gabbro played in the considerable coeval magmatic activity in the region; and (3) to shed light on the controversial tectonic mechanisms (subduction–accretion vs. mantle plume) that contributed to the juvenile continental growth of this part of Central Asia in the Permian.

GEOLOGICAL BACKGROUND AND PETROLOGY

The Altaids in Northwest China encompass two mountain ranges, the NW-striking Chinese Tianshan and Altai and their enclosing basins, and the E–W–striking southern Tianshan, which is bounded by the Tarim craton to the south (Fig. 1, inset; Ren et al., 1999). The South and North Tianshan are two separate Paleozoic orogens (Gao et al., 2009), and the intervening Yili block is a Precambrian microcontinent (Wang et al., 2007).

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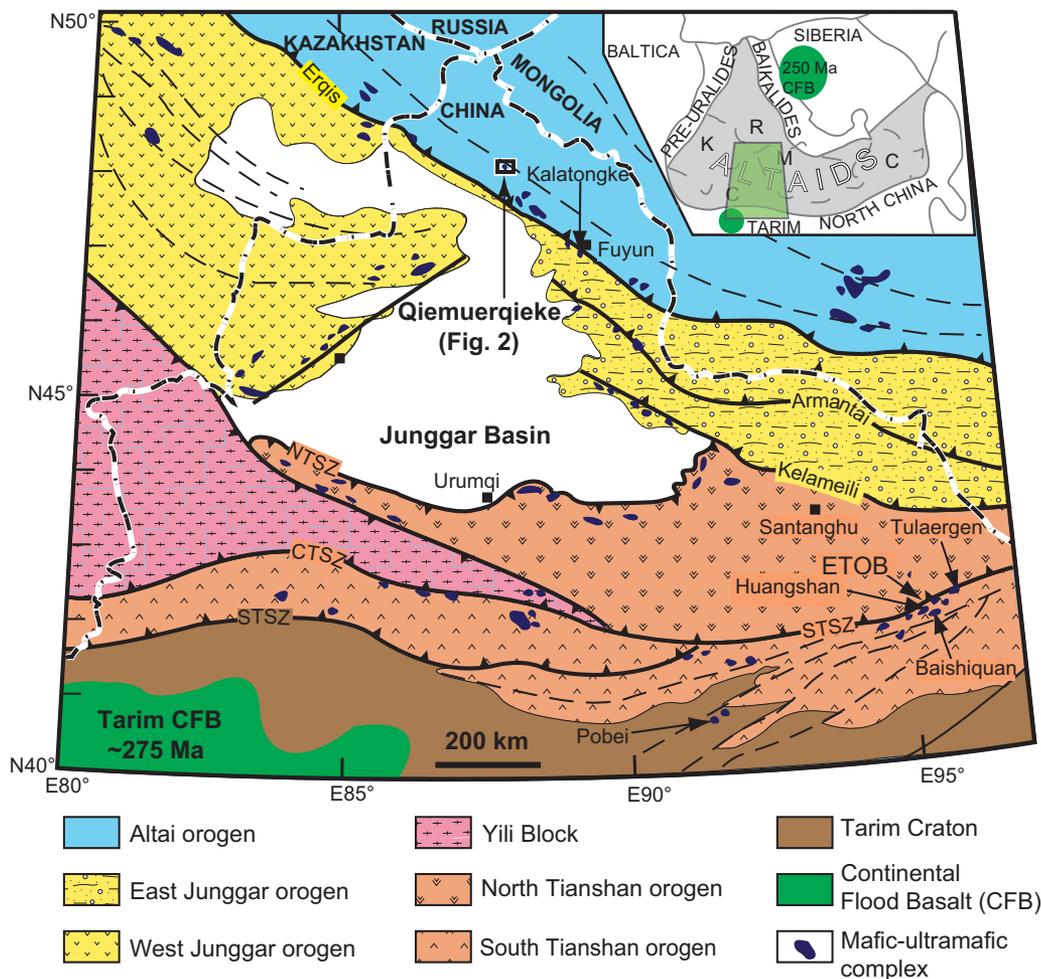


Figure 1. Simplified geological map of the western segment of the southern Altaids, showing the distribution of mafic-ultramafic intrusions and intraplate mafic volcanics. Figure is modified after Ren et al. (1999) and Pirajno et al. (2008). ETOB—East Tianshan ore belt; NTSZ, CTSZ, and STSZ—North, Central, and South Tianshan suture zones, respectively. K—Kazakhstan, R—Russia, C—China, M—Mongolia.

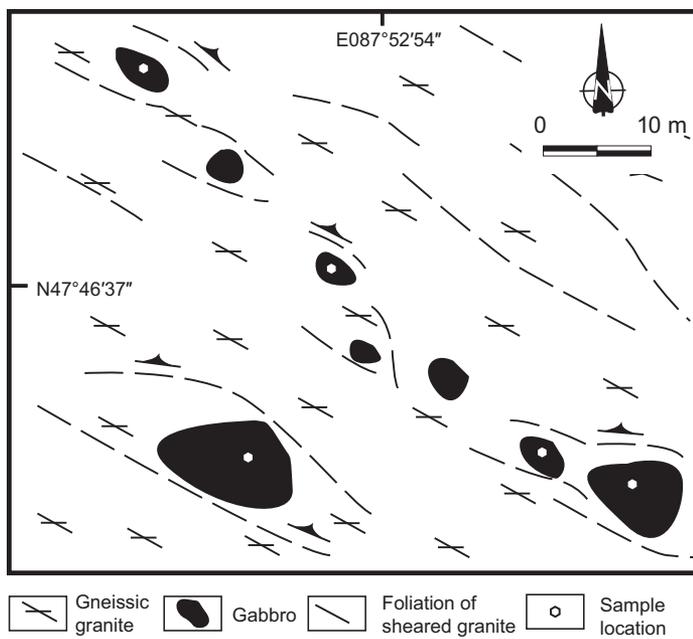


Figure 2. Sketch map of the hornblende gabbro at Qiemuerqieke; position is marked in Figure 1.

Many Permian mafic-ultramafic complexes (the East Tianshan ore belt; Zhou et al., 2004) were emplaced along the South Tianshan suture zone between the North and South Tianshan orogens (Fig. 1). The East Junggar orogen is bounded by the North Tianshan suture zone and Kelameili ophiolitic zone to the south, and the Erqis shear zone to the north. The West and East Junggar orogens are separated by the Junggar Basin, the tectonic setting of which is still unclear. The West and East Junggar orogens contain several late Paleozoic accretionary complexes (Xiao et al., 2009). The present study area is situated in the Altai orogen to the north, which contains major Paleozoic accretionary complexes (Xiao et al., 2009).

The Altai orogen mainly consists of arc-derived Cambrian–Silurian sediment and Devonian–Mississippian calc-alkaline volcanic rocks (Sun et al., 2008; Long et al., 2010). Many granitoids were intruded mainly from 462 ± 10 Ma to 210 ± 3 Ma (Wang et al., 2006; Cai et al., 2011), and many mafic, mostly gabbro, intrusions were emplaced along the Erqis shear zone at the contact between the East Junggar and Altai orogens (Zhang et al., 2010, 2012; Yuan et al., 2011); one of them hosts the largest magmatic Ni-Cu deposit (Kalatongke) in Xinjiang (Fig. 1). Many of these mafic intrusions have been studied in detail, especially those that host economic sulfide deposits as in Pobei (Song et al., 2011).

The hornblende gabbro of this study is located at Qiemuerqieke (Fig. 1). The Qiemuerqieke area is composed of a strongly sheared, gneissic granite batholith up to $60 \text{ km} \times 80 \text{ km}$, which has a pervasive NW-striking foliation (Fig. 2), folds, and mineral lineation. The late gneissic granite

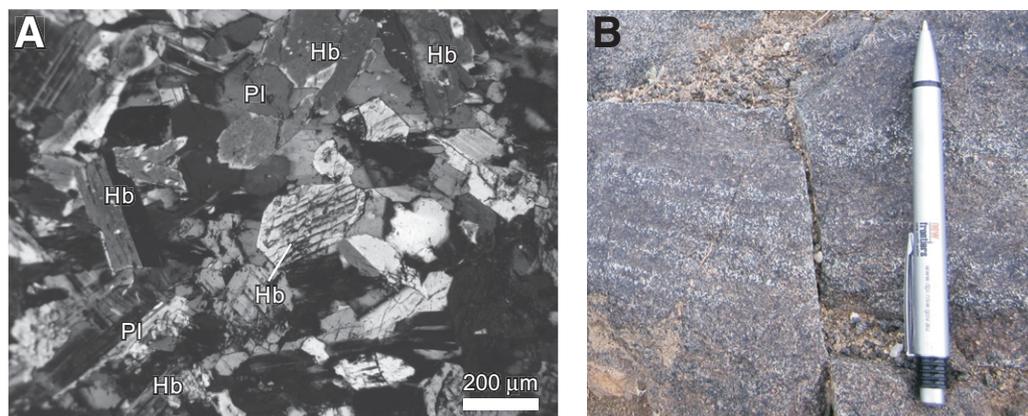


Figure 3. (A) Euhedral plagioclases and hornblendes of Qiemuerqieke gabbro. (B) Modal layering between white plagioclase layers and dark hornblende-plagioclase layers. Pl—plagioclase; Hb—hornblende.

has clear-cut discordant contacts with earlier regional gneisses (not shown in Fig. 2), indicating that the granite is intrusive. Many undeformed gabbro bodies in this strongly sheared gneissic granite are up to 10 m thick, extend for 2 km, and strike NNW (Fig. 2). The gneissic granite has a zircon emplacement age of 462 ± 10 Ma (Wang et al., 2006), whereas the gabbro has a zircon formation age of 276 ± 2.1 Ma (this study). The gabbro is fine-grained, undeformed, and is composed almost entirely of hornblende and plagioclase. Subhedral to anhedral hornblende grains make up 50–60 modal percent, plagioclase ~40%–50%, and clinopyroxene less than 1%. Minor phases are olivine and zircon, and accessories include Fe-Ti-oxides and apatite. The relative crystallization sequence is olivine, hornblende, plagioclase. Textural relationships (Fig. 3A) illustrate that plagioclase consistently crosscuts and postdates hornblende. Magmatic phase layering without grading (Fig. 3B) shows alternating layers, up to 2 cm wide, of hornblende and plagioclase-hornblende.

PETRO-MINERAL CHEMISTRY AND GEOCHRONOLOGY

Rock and Mineral Chemistry

The gabbroic rocks show a narrow compositional range in SiO_2 (48.7–50.2 wt%) and are characterized by high Na_2O (3.06–3.71 wt%) and MgO (6.33–8.54 wt%), and low FeO (5.27–6.46 wt%) and K_2O (0.26–0.37 wt%). These contents result in a low $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio of ~0.1, and a high Mg\# value (68–72) (supplemental Table 1¹). The alkaline- FeO_T - MgO contents indicate calc-alkaline characteristics (Fig. 4). The gabbros have a slight enrichment in light rare earth elements (LREE; $[\text{La}/\text{Yb}]_N = 1.9$ –2.4), and very low high field strength element (HFSE)/LREE ratios (e.g., Nb/La 0.36–0.46) (Fig. 5). The measured $^{87}\text{Sr}/^{86}\text{Sr}$ values are 0.703731–0.704021, and $^{143}\text{Nd}/^{144}\text{Nd}$ values are 0.512849–0.512892, corresponding to an initial Sr of 0.70339–0.70350 and $\epsilon_{\text{Nd}(276 \text{ Ma})}$ of 4.8–6.0 (supplemental Table 2 [see footnote 1]). The pyroxenes are characterized by high Al_2O_3 (2.3–5.3 wt%) and low TiO_2 (0.37–1.53 wt%) contents (Fig. 6). For a calculated formula of pyroxene based on 6 oxygens, the Al_T values (percentage of tetrahedral sites occupied by Al) are 0.06–0.14. Plagioclases have a high content of Ca (>10 wt%) and Al (>26 wt%) and a low content of K (<0.08 wt%), which give a moderate anorthite content of An 50–63 (see supplemental Table 2 [see footnote 1]).

¹GSA Data Repository Item 2013171, Geochemical data and analytical methods, is available at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

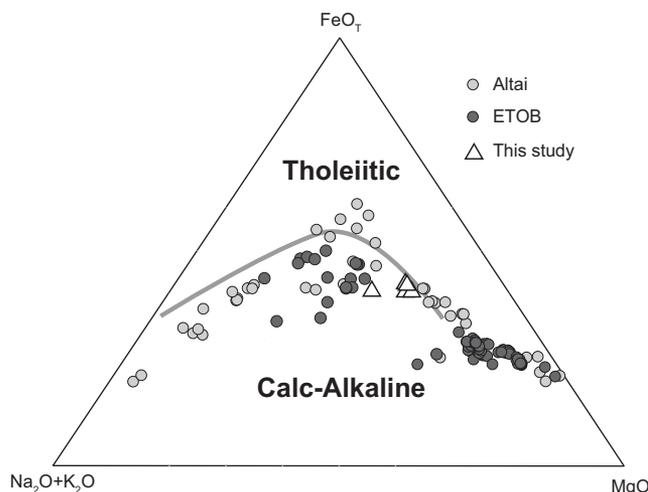


Figure 4. AFM ($\text{Na}_2\text{O} + \text{K}_2\text{O}-\text{FeO}_T-\text{MgO}$) diagram showing relevant gabbros that exhibit a calc-alkaline trend. Data for the Permian mafic rocks in the Chinese Altai are from Zhang et al. (2010), and those in the East Tianshan ore belt (ETOB) are from Zhou et al. (2004), Song et al. (2011), and Su et al. (2011).

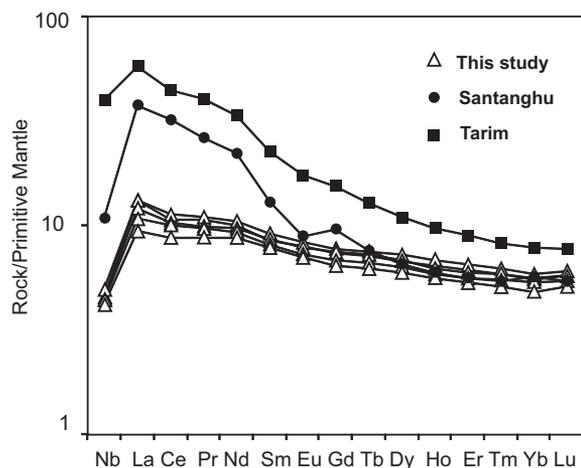


Figure 5. Primitive mantle-normalized Nb + rare earth element patterns for the Qiemuerqieke gabbro and Permian basalt from Santanghu in the Altai and Tarim. The normalized values are from Sun and McDonough, (1989). The Santanghu value is from Zhao et al. (2006), and Tarim data are from Tian et al. (2010).

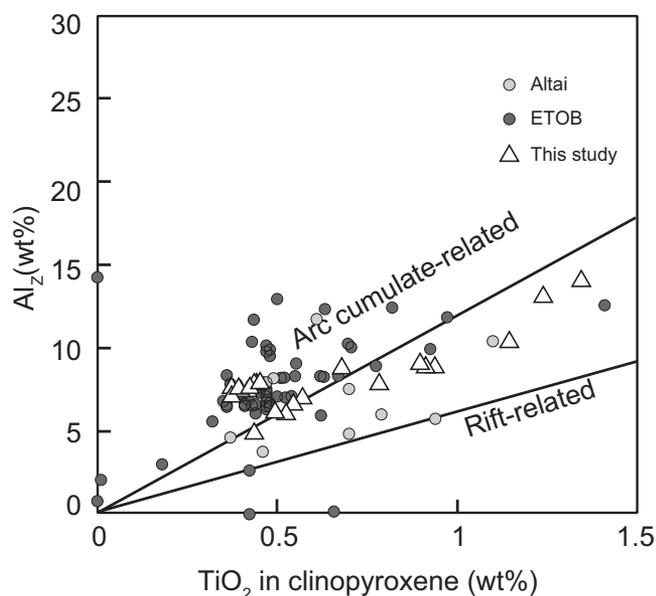


Figure 6. Al_z (percentage of tetrahedral sites occupied by Al) versus TiO_2 (wt%) in clinopyroxene from the Qiemuqie gabbro. Reference lines of arc-related and rift-related environments are from Loucks (1990). Samples from the Altai are from Zhang et al. (2009), and those in the East Tianshan ore belt (ETOB) are from Ao et al. (2010).

Zircon Secondary Ion Mass Spectrometry U-Pb Age, Apparent Crystallization Temperatures, and Hf-O Isotopes

Fourteen zircons selected from the gabbro are euhedral, colorless and transparent, mostly elongate-prismatic, and range up to 100 μm in diameter. Common Pb is low, with f_{206} values over total common $^{206}Pb < 0.22\%$; Th/U ratios are high (0.3–1.7) (supplemental Table 3 [see footnote 1]). The measured Pb/U ratios are concordant within analytical error (Fig. 7).

The weighted mean of $^{206}Pb/^{238}U$ is 0.0428 ± 0.00015 (1σ), corresponding to an age of 276.0 ± 2.1 Ma (mean square of weighted deviates [MSWD] = 0.76, 95% confidence level), which is interpreted as the time of crystallization of the gabbro. We also measured the Ti content on the same grains that were analyzed for U-Pb isotopes. The Ti concentration measurements of zircon were conducted using a Cameca-IMS 1280 large-radius secondary ion mass spectrometer (SIMS) at the Institute of Geology and Geophysics, Chinese Academy of Sciences. They were obtained using electron multiplier pulse-counting in mono-collection mode with magnetic peak switching, a 4 nA O^- primary ion beam, and 23 kV total accelerating voltage. Analytical conditions and standard calibration are similar to the description by Hiess et al. (2008). $SiO_4/^{49}Ti$ ratios from zircon (SL13) and glass (NIST 610) reference materials are consistent for concentrations at the ppm level. The internal precision of a single analysis is better than 10% (2 standard deviations). Ti contents of studied zircons are low (2.5–7.8 ppm), with an average value of 5.1 ppm (supplemental Table 3 [see footnote 1]). Based on the revised Ti-in-zircon thermometer by Ferry and Watson (2007), which applies to rocks without rutile and/or quartz, the apparent temperatures are 670–773 $^{\circ}C$, with an average value of 727 $^{\circ}C$, assuming a_{SiO_2} and a_{TiO_2} are 1 and 0.5, respectively. Taking into account the uncertainties of the formula, the maximum apparent temperatures are 715–826 $^{\circ}C$, and the average value is ~ 780 $^{\circ}C$.

Twenty in situ Hf and O isotopic analyses were conducted on the zircon grains (including the 14 zircons that were measured for U-Pb). The $^{176}Hf/^{177}Hf$ ratios range from 0.282951 to 0.283061, with a mean value of 0.282988 ± 0.000006 (1 standard deviation), corresponding to $\epsilon_{Hf(276Ma)}$ of 11.4–15.8 and a mean value of 13.6 ± 2 (1 standard deviation); most of the Hf model ages, T_{DM1} , are 280–460 Ma, with one exception of 176 Ma, which is unreasonable because it is younger than the emplacement age. The zircon Hf isotopes are consistent with the whole-rock Sr-Nd isotopes, and all systems show overall depleted characteristics (Figs. 8 and 9).

The measured oxygen isotope $\delta^{18}O$ ranges from 5.9‰ to 6.5‰, with an average value of $6.3\text{‰} \pm 0.3\text{‰}$ (1 standard deviation) (supplemental Table 4 [see footnote 1]). Illustrated by the Hf-O isotope diagram (Fig. 8), the samples are strongly depleted in Hf and slightly evolved in O. If these

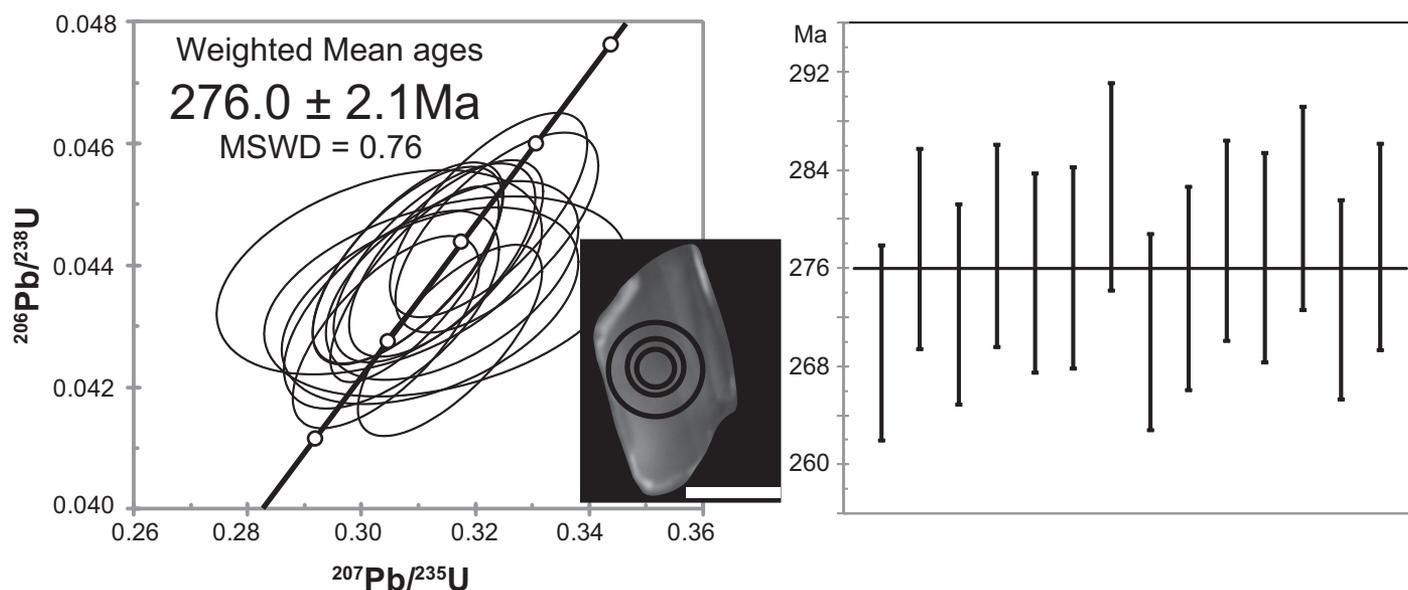


Figure 7. Concordia plots of our U-Pb zircon results from the Qiemuqie hornblende gabbro. Small circle is the oxygen analysis spot, medium circle is the U-Pb analysis spot, and the large circle is the Hf analysis spot. The bar is 50 μm . MSWD—mean square of weighted deviates.

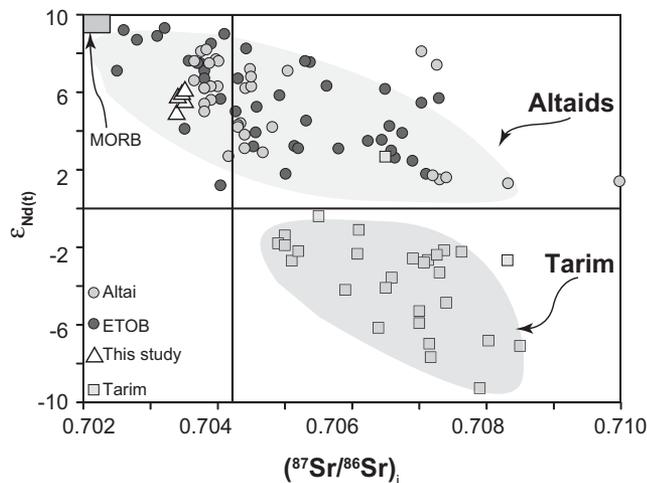


Figure 8. Sr-Nd isotope diagram. The Permian mafic rocks in the Chinese Altai are from Zhang et al. (2010), those in the East Tianshan ore belt (ETOB) are from Zhou et al. (2004) and Qin et al. (2011), and those in Tarim are from Tian et al. (2010). MORB—mid-ocean-ridge basalt.

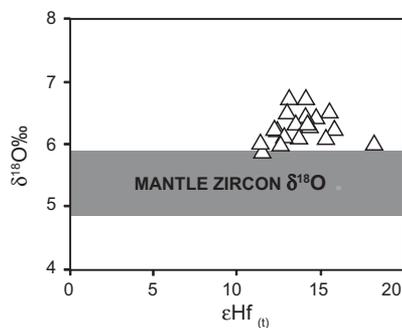


Figure 9. Plot of Hf vs. O isotopes of zircons from the Qiemuerqieke gabbro. The mantle oxygen value is from Valley (2003).

zircon $\delta^{18}\text{O}$ values are calculated based on the formula of Valley et al. (2005), the $\delta^{18}\text{O}$ of the average value of the whole rock is $6.8\text{‰} \pm 0.3\text{‰}$.

DISCUSSION

Did the Gabbro Originate from a Wet Basaltic Magma?

A cumulate gabbro can form from a dry basaltic magma (e.g., dunite-troctolite-gabbro) or from a wet basaltic magma (e.g., dunite-wehrlite-hornblende gabbro) (Gaetani and Grove, 1998). Considerable petrological and geochemical evidence from the Qiemuerqieke gabbro indicates that it accumulated from a water-enriched magma. First, the hornblende has a subhedral to anhedral texture, indicating that it crystallized directly from a magma, wet or dry. A high water content in a basaltic magma has the effect of suppressing plagioclase (Sisson and Grove, 1993), which occurs as a liquidus phase at a lower temperature in hydrous basaltic magmas than in anhydrous equivalents (Gaetani and Grove, 1998). Thus, water-enriched basaltic magmas often fractionate, in order of appearance, olivine, clinopyroxene, plagioclase (Sisson and Grove, 1993; Feig et al., 2006; Smith et al., 2009), and the most extreme end product of this process is the late crystallization of anorthite, as in the Fiskenaesset complex, West Greenland (Polat et al., 2009), and the Chimalpahad complex, India (Dharma Rao et al., 2011). In the Qiemuerqieke gabbro, plagioclase crystallized after and cuts across hornblende;

this relationship is consistent with the fact that the Qiemuerqieke gabbro crystallized from a water-enriched magma.

Second, the chemistry of clinopyroxene can also be an indicator of the water content of a magma source. In dry magmatic rocks, clinopyroxene in tholeiitic and silica-undersaturated rocks incorporates Al in the $\text{CaTiAl}_2\text{O}_6$ molecule by the charge-coupled substitution of ${}^{\text{vi}}\text{Mg}^{\text{iv}}\text{Si}_2$ to ${}^{\text{vi}}\text{Ti}^{\text{iv}}\text{Al}_2$. This substitution is promoted by high titanium activity relative to silica in the melt and, hence, is particularly characteristic of silica-undersaturated mafic rocks. In contrast, in hydrated mafic rocks, the high fugacities of H_2O and O_2 promote substitution between ${}^{\text{vi}}\text{Mg}^{\text{iv}}\text{Si}$ and ${}^{\text{vi}}\text{Fe}^{3+}\text{ivAl}$, and thus Al incorporated in clinopyroxene in the $\text{CaFe}^{3+}\text{AlSiO}_6$ molecule (Loucks, 1990). The clinopyroxenes in the Qiemuerqieke gabbroic rocks have high Al/Ti ratios that follow the normal arc-cumulate crystallization trend, consistent with other Permian gabbroic rocks in the Chinese Altai and East Tianshan ore belt (Fig. 5), further supporting that the derivative magma was water and oxygen enriched.

Third, if a magma is water enriched, the crystallization temperature will be considerably decreased. Attempts to estimate the melting temperature of mid-ocean-ridge basalt (MORB) have been relatively successful, commonly based on the distribution of Fe and Mg between olivine and a basaltic melt (e.g., Putirka et al., 2007), or on the Si and Mg contents of basalt (Lee et al., 2009). However, the chemical composition of a gabbro cannot represent the primitive magma composition, so these methods cannot apply. Zircon as an accessory mineral coexists with hornblende and plagioclase, and the crystallization temperature of zircon can represent the temperature at which the gabbro formed. Based on the revised Ti-in-zircon thermometers by Ferry and Watson (2007), which can apply to rocks without rutile and/or quartz, the maximum estimated apparent temperature of the Qiemuerqieke gabbro is $826\text{ }^\circ\text{C}$, which is considerably lower than the crystallization temperature of a normal basaltic magma ($>1200\text{ }^\circ\text{C}$; e.g., Lee et al., 2009); this further supports that the Qiemuerqieke gabbro magma was wet.

Based on the previous discussion, we conclude that the Qiemuerqieke gabbro formed from a wet basaltic magma, which raises a further question of whether the magma became hydrated in the mantle or crust. As mentioned already, the crystallization of hornblende requires the magma to have a high water content ($>3\text{ wt}\%$; Sisson and Grove, 1993). Both the lithospheric and asthenospheric mantle have very low water contents of $<0.1\text{ wt}\%$, and the continental crust has an even lower water content of $<0.001\text{ wt}\%$ (e.g., Williams and Hemley, 2001). However, a mantle wedge is commonly metasomatized by the introduction of subduction-derived fluids (e.g., McInnes et al., 2001), and therefore it can have a variable, but high, water content of up to $12\text{ wt}\%$ (Gaetani and Grove, 1998).

Accordingly, a mantle wedge is a highly likely source for the Qiemuerqieke gabbro magma. Moreover, isotopic compositions do not change during magma accumulation, and the Sr-Nd-Hf-O isotopes of the Qiemuerqieke gabbro change within a relatively small range, indicating that the magma source was very homogeneous. The initial $({}^{87}\text{Sr}/{}^{86}\text{Sr})_i$ ratio of ~ 0.703 , the $\epsilon_{\text{Nd}(t)}$ value of ~ 5.5 of the whole rock, and the zircon Hf isotope value $\epsilon_{\text{Hf}(t)}$ of ~ 13.6 all indicate a depleted source origin. The calculated $\delta^{18}\text{O}$ value of the whole rock is $\sim 6.6\text{‰} \pm 0.3\text{‰}$, which is only slightly higher than the upper limit of the mantle value of 6‰ (Valley, 2003). Eiler (2001) pointed out that a subduction process can increase the $\delta^{18}\text{O}$ value of mantle by input of crustal material, and the associated juvenile crustal $\delta^{18}\text{O}$ value could be 6‰ – 7‰ , as in the Sierra Nevada. Our oxygen data fall into that range, and the slightly enriched LREEs ($[\text{La}/\text{Yb}]_N = 1.9\text{--}2.4$), and the very low HFSE/LREE ratios ($\text{Nb}/\text{La} = 0.36\text{--}0.46$) strongly indicate that a mantle wedge could be the source of the Qiemuerqieke gabbro. As Figure 5 illustrates, the contrasting Nb/La pattern of the Qiemuerqieke gabbro is similar to that of the Permian

Santangu basalt in the Altaids (Fig. 1), which is different from that of the Permian basalt in Tarim.

Experimental Constraints

Considerable experimental work has been devoted to the problem of crystallization of hydrous minerals and rocks, like hornblende gabbros, from a hydrated tholeiitic magma typically derived from a metasomatized mantle wedge under an island arc (e.g., Takagi et al., 2005; Feig et al., 2006; Müntener and Ulmer, 2006). The results indicate that magmatic hornblendes can crystallize in gabbros from mafic magmas at the pressure-temperature and water pressure conditions expected in the magma chamber of Phanerozoic and Proterozoic island arcs (e.g., Zellmer et al., 2003). Experiments in a basaltic andesite system by Gaetani et al. (1993) demonstrated that the mineral crystallization order changes from olivine-plagioclase-clinopyroxene in a dry system to olivine-clinopyroxene-plagioclase in a water-saturated system. This was further quantified by Sisson and Grove (1993) and Feig et al. (2006), who showed that at pressures of >100 MPa, plagioclase crystallizes before clinopyroxene at low water contents of <3 wt%, whereas it forms after clinopyroxene when the water content in the melt is >3 wt%. Thus, it is not surprising that the plagioclases in the Qiemuerqieke gabbro postdate the other phases.

Several experimental studies have shown that the An content of plagioclase in a mafic magma increases with high water content (Sisson and Grove, 1993; Takagi et al., 2005; Feig et al., 2006). This relationship is confirmed by the presence of anorthitic plagioclase in amphibole-bearing complexes (Polat et al., 2009; Liu et al., 2010; Rollinson, 2010; Dharma Rao et al., 2011). The reason for the moderate An content (50%–63%) of plagioclase may be explained by the experimental study of Takagi et al. (2005), who found that at pressures of more than 4 kbar, crystallization of liquidus Ca-rich clinopyroxene decreases the CaO/Na₂O ratio of the liquid, thus prohibiting the crystallization of high-An plagioclase from a hydrous tholeiite.

Implications for Juvenile Crustal Growth in the Permian in the Southern Altaids

In the Altaids, juvenile crust was likely produced in two ways: accumulation of oceanic and arc assemblages in a trench and their lateral accretion onto imbricated accretionary prisms (Sengör et al., 1993), and vertical accretion achieved by addition of mantle-derived mafic rocks (Jahn, 2004). Considerable research has established that the principal mechanism of growth during the 750 m.y. history of the Altaids has been subduction-accretion (Jahn, 2004; Kröner et al., 2007; Windley et al., 2007; Xiao et al., 2010; Wilhem et al., 2012). However, since the discovery by Yang et al. (1997) of an Early Permian syenite in the Tarim craton, interpreted as a mantle plume product, many other authors have invoked the “mantle plume” hypothesis to explain the origin of other Permian-age granites and mafic-ultramafic complexes in the surrounding region of Junggar–Chinese Altai (Zhang et al., 2010) and southern Tianshan (Qin et al., 2011; Su et al., 2011). The answer to whether or not there is a plume in this region is related to the following factors, amongst which the Qiemuerqieke gabbro plays a role.

(1) An argument commonly used to support the idea of a Permian mantle plume in Central Asia is based on the assumption that all the plate-tectonic-controlled orogenesis terminated in the Pennsylvanian, and therefore that any Permian magma activity had to be intraplate and thus plume controlled (Fig. 10A) (e.g., Zhang et al., 2010). However, there is increasing multidisciplinary evidence to support the existence of an ocean until the Permian–early or mid-Triassic in the eastern branch of the Paleo-

Asian Ocean in Inner Mongolia (Xiao et al., 2003; Jian et al., 2008, 2010; Economos et al., 2012; Heumann et al., 2012). Therefore, that assumption cannot be valid, nor can it indicate plume activity in the region.

(2) Considerable evidence has been adduced to indicate the Tarim basalts formed from a mantle plume. For example, geophysical data suggest that at least 250,000 km² of Permian basalts lie beneath the Tarim Basin (Yang et al., 2007). Deep borehole data show that the seismological thickness of the basalt layer is more than 2.5 km, and the basalts have a trace-element and isotopic signature that is similar to that of mantle- and plume-derived oceanic-island basalt. Moreover, high MgO picrites have high ⁸⁷Sr/⁸⁶Sr and low ¹⁴³Nd/¹⁴⁴Nd isotopic ratios that resemble those of the Karoo plateau basalts; all these features point to eruption of a high-temperature picritic magma from a plume-generated deep mantle source (Tian et al., 2010).

(3) In addition to the volcanic rocks described earlier, in the Tarim–South Tianshan–Junggar–South Chinese Altai region, there are also many Permian plutonic rocks and complexes such as granites and mafic-ultramafic complexes, some of which contain Ni–Cu–platinum group element (PGE) mineralization, alkaline complexes, and mafic dikes. Pirajno (2010, p. 342) argued that all this Permian–Triassic plutonic magmatism “was not linked to subduction processes,” but rather to “postorogenic strike-slip zones linked to mantle plume activity.” However, several factors militate strongly against such a conclusion. For example, the presence of Alaskan-type concentrically zoned mafic-ultramafic complexes, which host PGE–Gu–Ni deposits (see Himmelberg and Loney, 1995) that consist of hornblende-bearing gabbros, peridotites, norites, and basalts, clearly indicates that the magmas were hydrous and could only be derived during or following the formation of subduction-generated Cordilleran-type magmatic arcs, probably from a hydrated mantle wedge (Xiao et al., 2004). Plume-derived magmas, which by their nature are dry, are generated from deep anhydrous mantle, which cannot give rise to such hydrated zoned Alaskan-type complexes. Of course, some of these complexes are situated today, as one would expect, on strike-slip faults and sutures, but that does not mean that they were not subduction generated and that they must have been emplaced by mantle plumes sited on strike-slip zones. Many Alaskan-type complexes are arranged in linear belts in subduction-arc settings, often in or close to suture zones, as in the Central Urals and southeast Alaska.

A good example in the Altaids to consider is the Huangshan complex, located today on the Kanggurtag fault in the eastern Tianshan, which consists of ultramafic rocks, hornblende gabbroic norites, and diorites; some bodies contain concentric zones with a dunite core surrounded by clinopyroxenite and hornblende gabbro, and Ni–Cu–PGE mineralization (Zhou et al., 2004; Z. Zhang et al., 2008; C.L. Zhang et al., 2011). The complex has secondary ionization mass spectrometry (SIMS) zircon ages of 278.6 ± 1.2 Ma and 284.0 ± 2.2 Ma (Qin et al., 2011), almost coeval with the 275 Ma Early Permian Tarim lavas. Although Zhou et al. (2004) considered that the complex was derived from a mantle source that was previously contaminated by subduction of oceanic crust, they concluded that the complex formed by plume-related activity within a continental setting. In other words, they considered that the plume was derived from a suprasubduction-zone mantle wedge. However, current understanding of plume tectonics (e.g., Maruyama et al., 2007) does not include a shallow mantle wedge as an acceptable source of traditionally accepted deep mantle plumes that give rise to, for example, Hawaiian volcanoes, the Siberian Traps, or the Deccan Traps.

The petrochemical features of the Huangshan hornblende-bearing complex are very similar to those of the nearby Early Permian Baishiquan and Pobei mafic-ultramafic complexes with their hornblende gabbros. Song et al. (2011) stated specifically that the trace-element and radiogenic isotope data of the Baishiquan and Pobei intrusions indicate

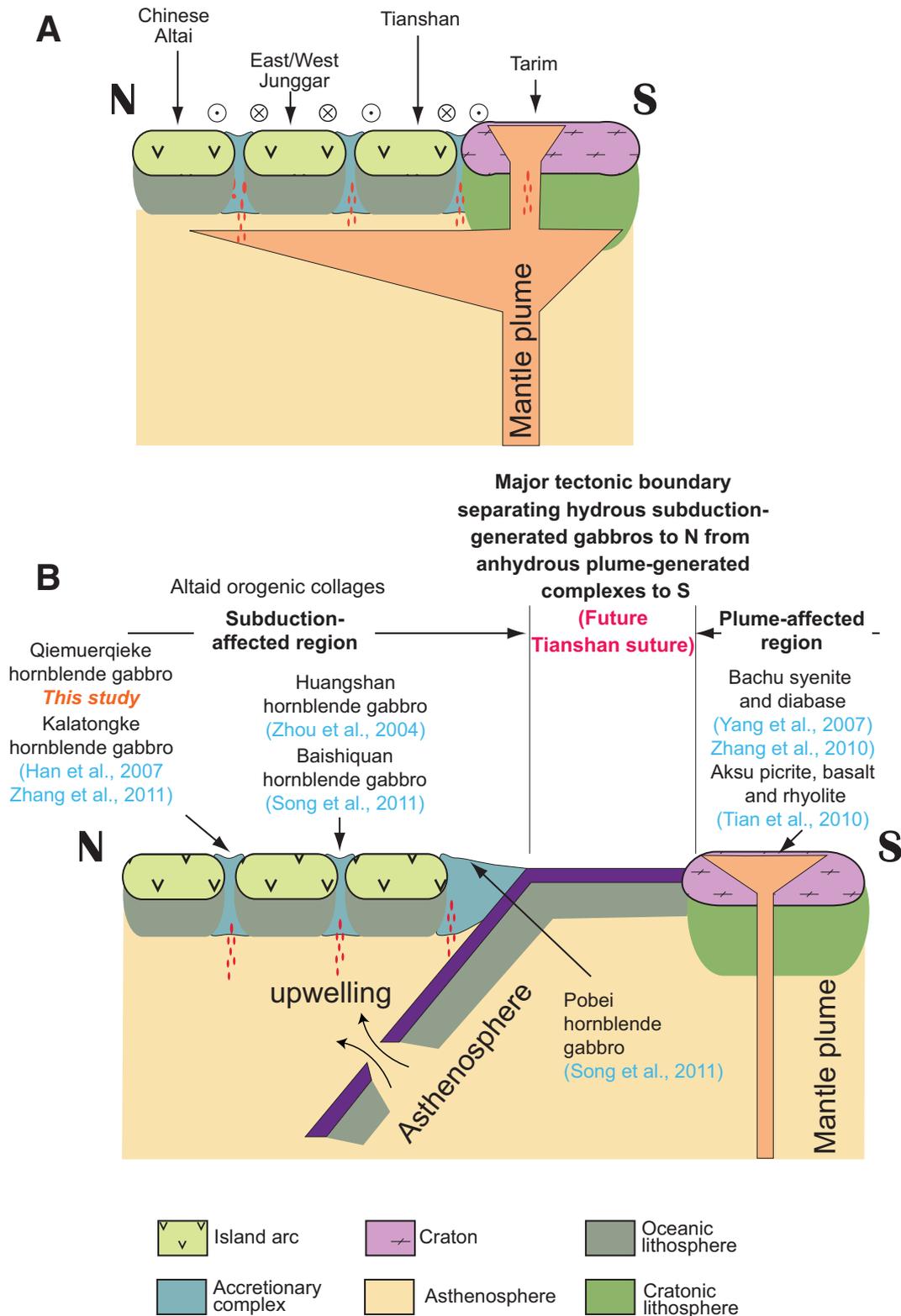


Figure 10. Cross-section view illustrating two possible continental growth models. (A) The Altai region was amalgamated with the Tarim craton before the Permian, and a ca. 275 Ma mantle plume affected both domains. (B) The Altaid collage was protected from the mantle plume by an ocean that was wide enough to separate it from the Tarim to the south. See text for detailed discussion.

that their parental magmas could not be plume related, and that the geochemical data strongly rule out any genetic link between them and the Tarim large igneous province magmatism. They further concluded that the geological and geochemical features of the two intrusions are most comparable to those of subduction-related mafic-ultramafic rocks, and that the parental magmas were derived from decompression melting of hydrated, subduction-modified lithospheric mantle during postcollisional extension, perhaps triggered by slab breakoff (Fig. 10B). We would add that the characteristics of these zoned complexes, such as Ni-Cu-PGE mineralization, minor orthopyroxene, ubiquitous hornblende, and in particular their hornblende gabbros, high chromium (chromite) only in the lowermost dunites, and negative Nb-Ta anomalies, are so extremely similar to those of the zoned hydrated Alaskan-type complexes that it would be spurious reasoning to argue that they were derived from an anhydrous mantle plume.

Another important, nearby hornblende gabbro-rich intrusion is the Kalatongke complex, which is situated in the East Junggar terrane ~15 km south of the Erqis fault, which is itself widely regarded as a suture (e.g., Zhang et al., 2010). The nine mafic-ultramafic Early Permian (290–280 Ma) intrusions have a downward and inward zonation from biotite diorite, biotite-hornblende norite with or without olivine hosting important Cu-Ni mineralization, and biotite-hornblende gabbro, to cores of clinopyroxenite and serpentinized harzburgite (Han et al., 2007). The published trace-element chemistry and isotopic data have led to diverse opinions about the geotectonic setting: (1) The intrusions have an island-arc geochemical signature formed as a result of subduction of oceanic crust in an Alaskan-type subduction-zone-arc setting (Han et al., 2007); (2) the primary magma was derived from metasomatized asthenospheric mantle modified by subduction-derived fluids, i.e., equivalent to a metasomatized mantle wedge (Zhang et al., 2009); and (3) the Cu-Ni ores were derived not from a metasomatized mantle wedge, but from a mantle-derived magma contaminated by crustal rocks in a postcollisional setting (Zhang et al., 2008). Significantly, all authors considered that the Kalatongke intrusions were not derived from a specific Tarim mantle plume, but from mantle-derived magmas contaminated by metasomatized mantle or by crustal material.

Having considered the character and tectonic setting of other, nearby Early Permian complexes that contain prominent hornblende-bearing gabbros, we return to the Qiemuerqieke hornblende gabbro, and its origin. First, the emplacement age of the gabbro (276.0 ± 2.1 Ma) is coeval with the broad range of the purported ca. 275 Ma mantle plume, but petrological and geochemical data indicate that the gabbro originated from a water-bearing magma, in common with the broadly coeval Early Permian Kalatongke, Huangshan, Baishiquan, and Pobei complexes. The Qiemuerqieke rocks and minerals are similar to those from typical subduction-related hornblende-bearing island arcs, as in the Solomon Islands (Smith et al., 2009), and Montserrat in the Lesser Antilles (Kiddle et al., 2010). Moreover, the Qiemuerqieke gabbro Sr-Nd isotopes are similar to many other Permian rocks in the Altaids that indicate a relatively depleted provenance, which is strikingly different from those in the Tarim craton (Fig. 8).

Second, the gabbro has a very low crystallization temperature (<1000 °C), in contrast to the high crystallization temperature (>1300 °C) to be expected in a mantle plume head or tail (Herzberg and O'Hara, 2002).

Third, although a high-temperature mantle plume can melt a refractory mantle beneath an old craton and give rise to a large igneous province like the Emeishan (Xu et al., 2004) and Siberian Traps (Sharma, 1997), if the mantle plume is emplaced beneath an orogenic belt in which mantle has been water enriched, it will more easily melt and produce a larger volume of rock and then penetrate the lithospheric mantle as in Yellowstone, United States (Coble and Mahood, 2012). However, this is not the case in the southern Altaids, where the Permian mafic rocks are sporadically distributed linearly along terrane boundaries like the Erqis fault and the South

Tianshan fault (Fig. 1), and the amount of these Permian mafic rocks is considerably less than that of the previous Carboniferous arc rocks.

Fourth, rocks that form from a mantle plume not only have a considerable volume and spatial extent, but also they evolve in a very short time period, like the Emeishan large igneous province at ca. 259 ± 3 Ma (Xu et al., 2004) and the Siberian Traps at ca. 249 ± 4 Ma (Renne and Basu, 1991). However, the relevant mafic-ultramafic complexes in the Altaids intruded over a long time period, for example, the Kalatongke gabbro at 287 ± 3 Ma (Han et al., 2004), and the Huanshanxi gabbro and the Tulaergen gabbro at 269 ± 2 Ma (Zhou et al., 2004) and at 300.5 ± 3.2 Ma (San et al., 2010), respectively. The available geological and isotopic age evidence from the Altaids does not indicate that the orogenesis terminated in the Carboniferous (Jian et al., 2008, 2010), and therefore that argument is invalid, and also the mafic-ultramafic complexes could not have intruded in a postorogenic extensional setting in a short period (e.g., Z. Zhang et al., 2008).

The Altaids and the Tarim craton were derived from very different mantle sources. If the Altaids and Tarim amalgamated before 275 Ma and evolved to a postcollisional or intracontinental stage (Fig. 10A), the deep mantle plume signature in the Tarim craton might have affected the lithosphere in the Altaids to a limited extent, but this possibility is not supported by our new data nor those of coeval ultramafic-mafic complexes.

It is clear that the Altaid orogenic collages were not affected by the plume. However, the Altaid orogenic collages were juxtaposed against the Tarim block. When the Altaid gabbros and the Tarim plume were emplaced, the Altaid collages and the Tarim craton must have been geodynamically separated; otherwise, both would have been affected by the plume (Fig. 10A). Therefore, they must have been separated by a major ocean, wide enough to protect the Altai from being affected by the plume (Fig. 10B). This indicates that the Tarim block and the Altaids in North Xinjiang came together after the intrusion of the gabbros and the plume, which was younger than at least ca. 276 Ma. Other lines of evidence indicate that the orogenesis lasted to the Late Permian (Xiao et al., 2010).

We consider that the contradictory data can be explained by the fact that the Altaids were separated from Tarim by an ocean or by a subducting slab in the Early Permian, for which we favor a slab breakoff model (Fig. 10B).

CONCLUSIONS

Based on our petrological, geochronological, and geochemical studies of the Qiemuerqieke hornblende gabbro in the Chinese Altai, we draw the following conclusions:

(1) The gabbro was emplaced at 276.0 ± 2.1 Ma based on in situ SIMS zircon dating, and it formed from a hydrous basaltic magma because: (a) the hornblende gabbro has a crystallization sequence of olivine, hornblende, feldspar; (b) a high Al/Ti ratio indicates that the gabbro originated from a water-enriched magma; and (c) the crystallization temperature ($715\text{--}826$ °C) calculated from the Ti content of zircons in the gabbro is considerably lower than that of anhydrous magmas in orogenic belts and, more importantly, much lower than that of a mafic magma crystallized from a hot mantle plume.

(2) Both whole-rock Sr-Nd and in situ zircon Hf isotope data indicate that the rocks originated from a relative depleted mantle source, and the $\delta^{18}\text{O}$ data, which are slightly heavier than the mantle source value, further constrain the mantle to be a subduction-metasomatized mantle wedge.

(3) The Qiemuerqieke hornblende gabbro is coeval with the purported 275 Ma Tarim mantle plume, but the petrological and geochemical data do not provide any convincing evidence of a high temperature or a deep mantle signature. Rather, the evidence points to a subduction-metasomatized

mantle wedge setting, more like that of an island arc or an Alaskan-type complex. Therefore, the evidence from Qienuerqie adds to the existing data from other hydrated hornblende gabbro complexes that do not support the mantle plume hypothesis in the southern Altai, at least in the Chinese Altai orogen.

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