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Discovery of a Neoproterozoic granite in the Northern Alxa region, NW China: its age, petrogenesis and tectonic significance

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Abstract – A Neoproterozoic granite (Western Huhetaoergai granite) from the Northern Alxa region, southern Central Asia Orogenic Belt (CAOB) is first recognized by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) U–Pb zircon dating (889 ± 8 Ma). It is a highly fractionated potassium-rich calc-alkaline pluton with low $\varepsilon_{Nd}(t)$ (−2.6 to −1.1) and high $(^{87}Sr/^{86}Sr)_t$ (0.727305–0.735626), and is probably derived from a mantle source and assimilated crustal rocks with very high $^{87}Sr/^{86}Sr$. Regional geology implies that it may reflect the existence of a microcontinent, and the formation of the Western Huhetaoergai granite is related to the assembly of Rodinia.

Keywords: Neoproterozoic, granite, Alxa, CAOB, zircon U–Pb dating.

1. Introduction

The Central Asia Orogenic Belt (CAOB), also called the Central Asian Mobile Belt, Central Asian Fold Belt or Altaids, is one of the largest accretionary orogens on the Earth. It is situated between the European, Siberian, Tarim and Sino–Korean cratons (Şengör', Natal'In & Burtman, 1993; Jahn, Wu & Hong, 2000; Khain *et al.* 2003; Kovalenko *et al.* 2004; Kröner *et al.* 2007; Windley *et al.* 2007) (Fig. 1a), recording a long history of accretionary growth from *c.* 1.0 Ga to *c.* 250 Ma (Jahn *et al.* 2004; Windley *et al.* 2007; Kröner *et al.* 2014). Most CAOB studies focus on two regions in its southernmost part: Northern Xinjiang in the west and Inner Mongolia in the east. Due to the barren environment and tough working conditions investigation of the central part of the southern CAOB (the Northern Alxa region) is limited, constraining its tectonic interpretation (Wang, Wang & Wang, 1994; Zheng *et al.* 2013*a*). In particular, very few Precambrian granites have yet been reported in the north of this region (Wang *et al.* 2001), yet Precambrian basement is important since it may be involved in the genesis of younger rocks in the region. In this study, we report a recently discovered Neoproterozoic granitic pluton from west of the Huhetaoergai area. Our study into the geochronology and geochemistry of this pluton not only constrains its age and petrogenesis, but also contributes to the understanding of tectonic affinities of the northernmost Alxa region.

2. Geological setting

In the Northern Alxa area there are three important ophiolitic belts or sutures (Fig. 1b). From north to south, they are: the Yagan Suture; the Engger Us Ophiolitic Belt; and the Qagan Qulu Ophiolitic Belt (Wang, Wang & Wang, 1994; Wu, He & Zhang, 1998). The Engger Us Ophiolitic Belt was regarded as the suture between the North China Plate and the Tarim Plate (Wu & He, 1992; Wang, Wang & Wang, 1994; Wu, He & Zhang, 1998). The southwards subduction of the Paleo-Asian Ocean led to the formation of a back-arc basin represented by the Qugan Qulu Ophiolitic Belt (Wu, He & Zhang, 1998; Feng *et al.* 2013; Zheng *et al.* 2014). The Yagan Suture was thought to be the extension of the Mingshui–Shibanjing–Xiaohuangshan Ophiolitic Belt from the Beishan area (Wu, He & Zhang, 1998), which is the main suture in the Beishan area that separated the Tarim Plate from the Kazakhstan Plate (He *et al.* 1994; Zheng *et al.* 2013*b*; Zuo & He, 1990). However, although rocks in the Yagan Suture Zone are highly fragmented and some ultramafic rocks are present (Wang, Wang & Wang, 1994; Wu, He & Zhang, 1998) (Fig. 1b), no other ophiolitic components have been recognized so far. In the north of the Engger Us Ophiolitic Belt, the Yagan Suture subdivides the area into Huhetaoergai Tectonic Zone (HZ) to the north and the Zhusileng Tectonic Zone (ZZ) and the Guaizihu Tectonic Zone (GZ) to the south (Wang, Wang & Wang, 1994; Wu, He & Zhang, 1998) (Fig. 1b). The Huhetaoergai Tectonic Zone was argued to be a palaeo-volcanic arc developed on oceanic crust preserved when the ocean closed during late Silurian – Devonian (Wang, Wang & Wang, 1994) or Permian (Wu, He & Zhang,

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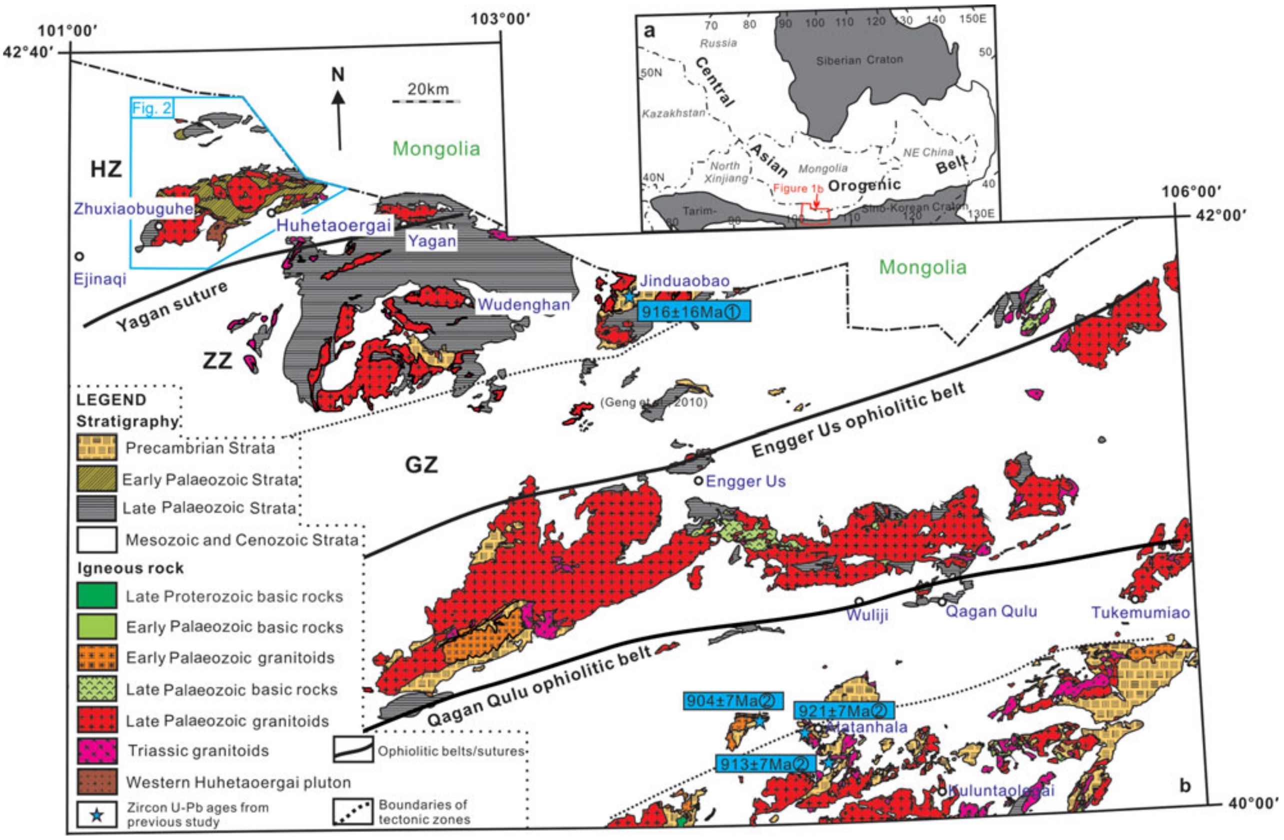

Figure 1. (Colour online) (a) The Northern Alxa region in the Central Asian Orogenic Belt (modified after Jahn, Wu & Chen, 2000). CAOB is area in white. (b) Simplified geological map of the Northern Alxa region (modified after BGGP, 1979, 1980, 1981*a*, *b*; BGIMAR, 1980; BGNHAR, 1976, 1980*a–d*, 1982*a*, *b*). HZ – Huhetaoergai tectonic zone; ZZ – Zhusileng tectonic zone; GZ – Guaizihu tectonic zone. References: 1. Wang *et al.* (2001); 2. Geng and Zhou (2010).

1998) time. The Zhusileng Tectonic Zone and Guaizihu Tectonic Zone were regarded as early Palaeozoic passive continental margin and late Palaeozoic oceanic basin, respectively (Wang, Wang & Wang, 1994; Wu, He & Zhang, 1998).

The Western Huhetaoergai granite is located in the Huhetaoergai Tectonic Zone (Fig. 2). The only Precambrian strata exposed in the Huhetaoergai Tectonic Zone are of Mesoproterozoic (Stenian–Estasian) age, into which the Western Huhetaoergai pluton intrudes. It includes sandstone, thick marble, some silicalite and slate. Its base contains purple-red sandstone with fine conglomerate (BGGP, 1980). More Precambrian strata are found in the Zhusileng Tectonic Zone (Fig. 1b). Mesoproterozoic (Stenian–Estasian) strata, only exposed south of the Wudenghan area, are composed of metasiltstone in the lower and upper parts and carbonate in the middle, in mutual fault contact (BGGP, 1981*a*). In the Jindouaobao area, an early Palaeoproterozoic marine regression sedimentary sequence is widely distributed. From bottom to top, it includes magnesium carbonates, intermediate–acidic volcanic rocks and clastic rocks (BGNHAR, 1982*a*). Minor late Palaeoproterozoic – early Neoproterozoic (Statherian–Calymmian) neritic carbonates and black siliceous rocks, early Neoproterozoic (Tonian) siliceous dolomites and late Neoproterozoic (Cryogenian) glacial till (*c.* 90 m) also occur (BGNHAR, 1982*a*; Wang, Wang & Wang, 1994).

2.a. Western Huhetaoergai granite

The Western Huhetaoergai pluton is in the Huhetaoergai Tectonic Zone and represents a batholith covering *c.* 80 km^2. It intrudes Mesoproterozoic sandstone in the SE and Ordovician strata in the north (Fig. 2). Banded structure and weakly developed gneissic fabric are present. The banded structure comprises light and dark parallel laminations of 2–3 cm width. Generally, coarse quartz, plagioclase and feldspar comprise the light bands and fine biotite and plagioclase form the dark bands. Most minerals are aligned parallel to the bands. Elongate marble xenoliths parallel to the gneissic schistosity or laminations are also present (BGGP, 1980).

The pluton is heterogeneous with variable composition and irregular lithofacies. However, it is predominantly composed of fresh red biotite granite and grey biotite granodiorite. The granodiorite emplaced into the granite is early Carboniferous in age (W. Zhang, unpub. Ph.D. thesis, Peking University, 2013). In this study we mainly focus on the biotite granite, which is fine to medium grained. The modal mineralogy includes plagioclase (15–25 %, minor alteration to sericite), perthitic

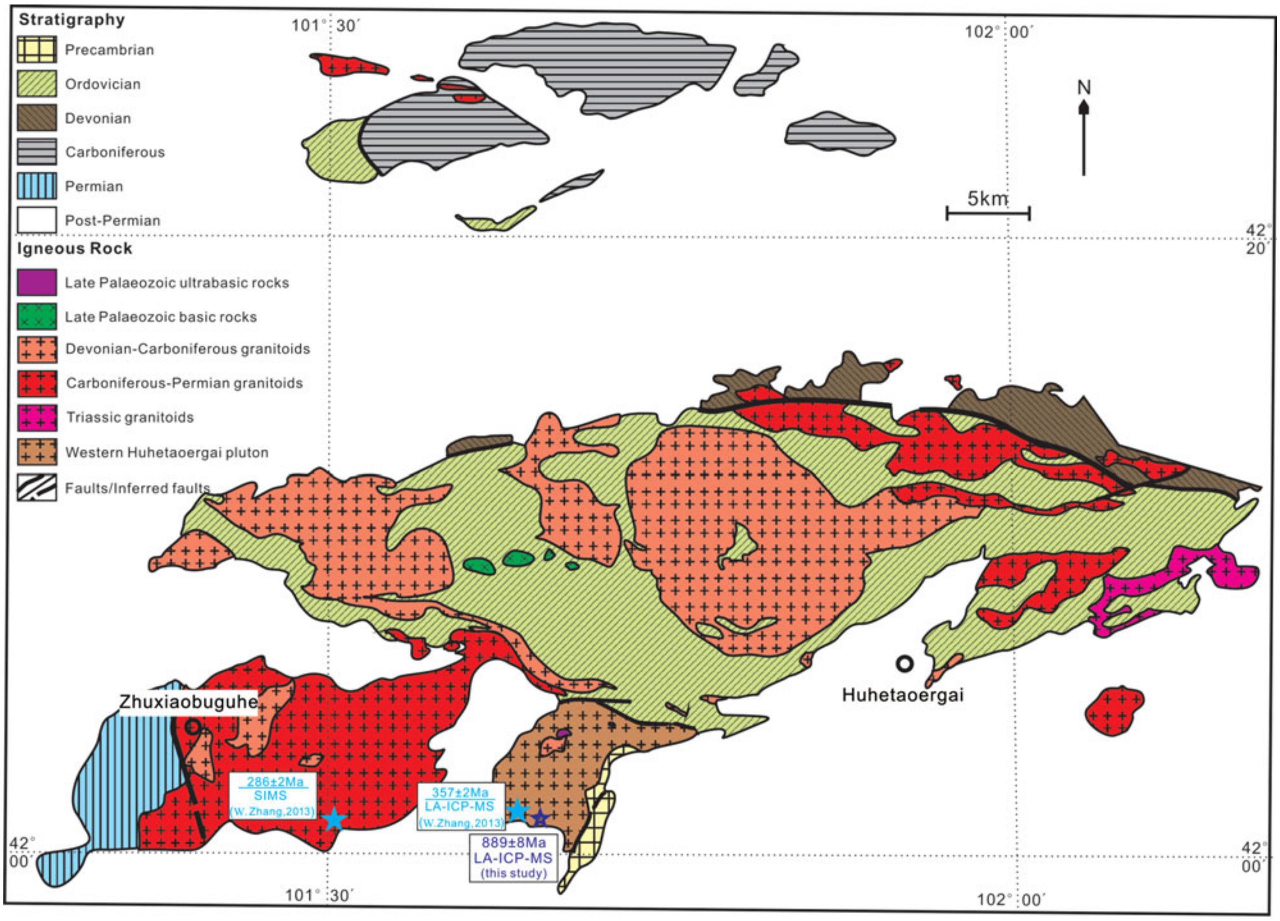

Figure 2. (Colour online) Geology of Western Huhetaoergai plutons, northernmost Alxa region (modified after BGGP 1980, 1981*a*).

feldspar (30–40 %), quartz (35–45 %), biotite (6–10 %, some altered to chlorite) and some muscovite. Garnet is also found in one sample (AB10-45). The main accessory minerals are zircon, titanite, apatite, hematite and magnetite.

3. Geochemistry and geochronology

Samples representing the principal compositional phases of the batholith were selected for major and trace element and Nd and Sr isotopic analyses. Analytical methods are described in Appendix S1 in the online Supplementary Material, available at http://journals.cambridge.org/geo. The results are given in supplementary Tables S1 & S2, available at http://journals.cambridge.org/geo.

3.a. Major and trace elements

The SiO_2 contents of the Western Huhetaoergai biotite granite ranges from 75.06 to 81.42 wt %; 9.59–12.76 wt % for Al_2O_3; 0.18–0.38 wt % for MgO with low Mg number (0.25–0.34; $Mg^{2+}/(Mg^{2+}+Fe^{2+})$) (Irving & Green, 1976); 0.15–0.25 wt % for TiO_2; and 0.57–0.69 wt % for CaO. All samples are peraluminous (A/NCK>1.0; for definition of notation see supplementary Table S1 notes, available at http://journals.cambridge.org/geo) (Shand, 1943; Zen, 1988) (Fig. 3a) and ferroan (Fe number = $FeO^T/(FeO^T + MgO)$ = 0.83–0.89) (Frost *et al.* 2001). The total alkali content ($Na_2O + K_2O$) is 7.89 wt % on average and all samples contain more K_2O than Na_2O ($Na_2O/K_2O<0.4$). They have high-K calc-alkaline to shoshonitic characteristics. On the $Na_2O + K_2O$ v. SiO_2 diagram (Fig. 3b), the Western Huhetaoergai biotite granite plots in the sub-alkaline field. Chondrite-normalized rare Earth element (REE) patterns (Fig. 4a) (Sun & McDonough, 1989) show enrichment of light REE (LREE) ($(La/Yb)_N$ = 1.9–4.3) and strongly negative Eu anomalies (δEu = 0.29–0.34). Normal mid-ocean-ridge basalt (N-MORB) -normalized trace element patterns (Fig. 4b) (Sun & McDonough, 1989) show that the samples are enriched in LREE, Rb, Th, K, Nd and Sm and depleted in Ba, Nb, Ti, P and Zr.

3.b. Nd and Sr isotopes

Determination of ‘initial’ data is based on the geochronology. Nd model ages have been calculated with $f_{Sm/Nd}$ values of –0.2 to –0.6. The Western Huhetaoergai granite has high initial $^{87}Sr/^{86}Sr$ of 0.727305–0.735626 and negative $\varepsilon_{Nd}(t)$ of -2.6 to -1.1. Both indicate components of modern to Proterozoic age when intrusive age is plotted against $\varepsilon_{Nd}(t)$ (Fig. 5a). Single-stage model age (T_{DM1}) is 2452–1707 Ma.

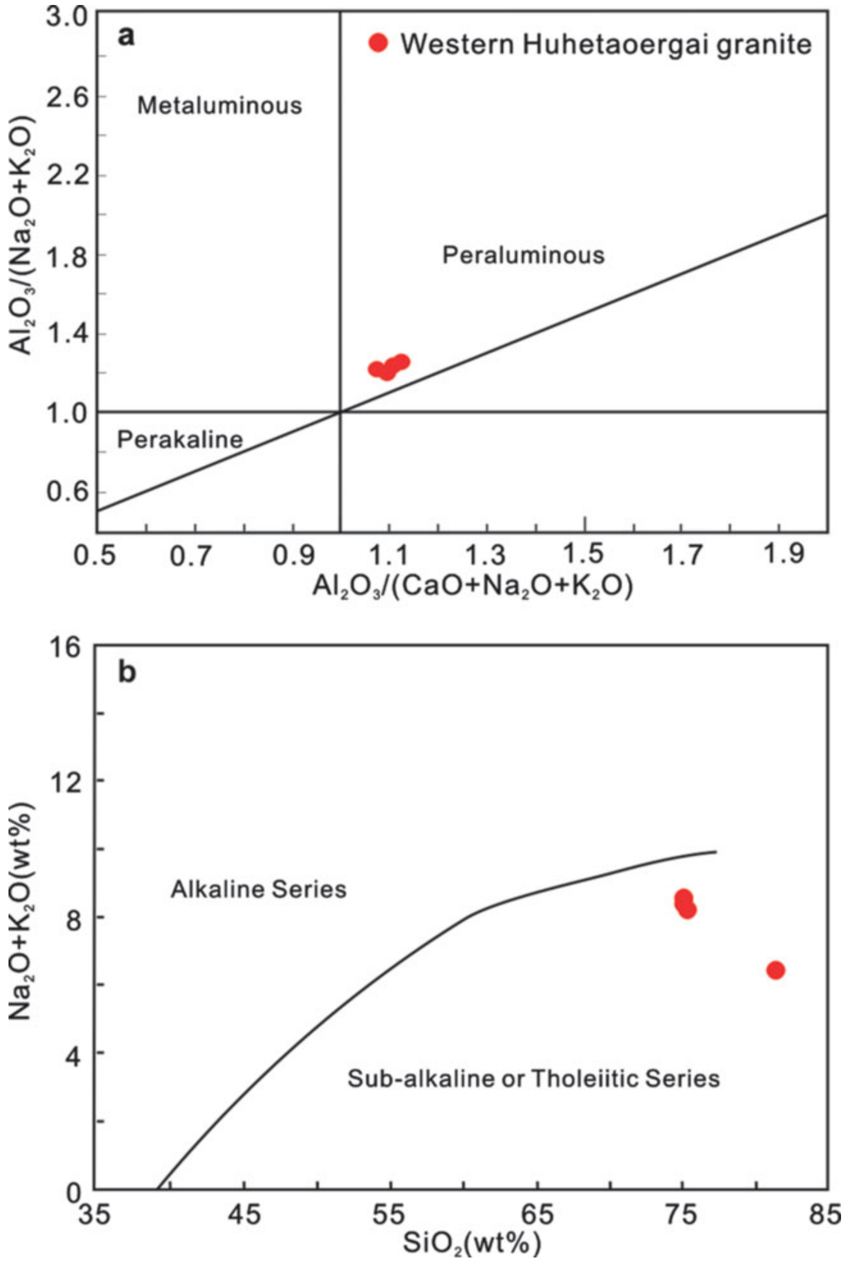

Figure 3. (Colour online) Major characteristics of the Western Huhetaoergai granite: (a) after Shand (1943); (b) after Irvine & Baragar (1971).

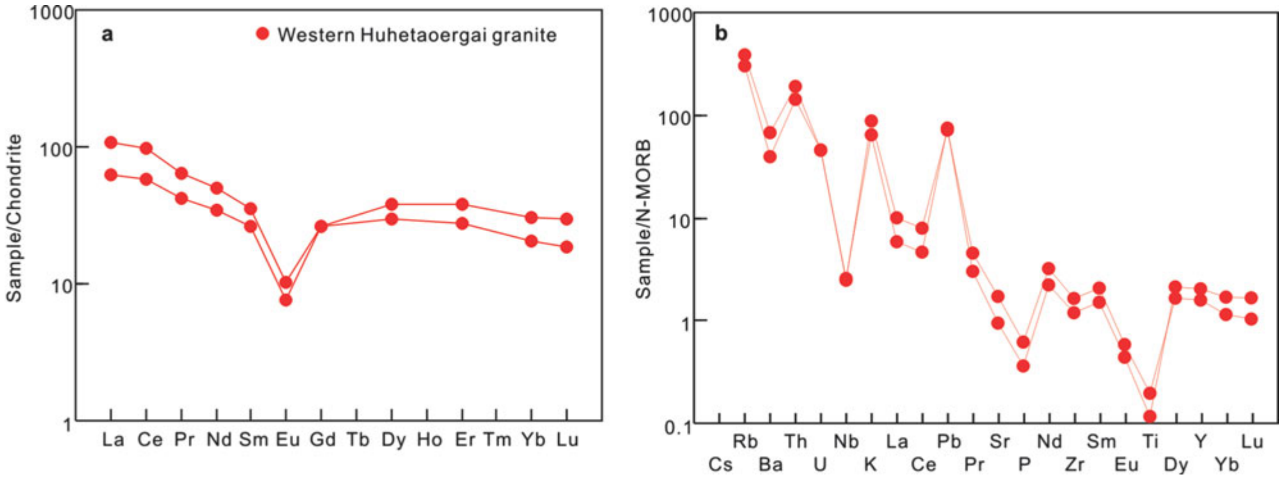

Figure 4. (Colour online) (a) Chondrite-normalized REE patterns and (b) N-MORB-normalized trace elements patterns for the Western Huhetaoergai granite (normalized values after Sun & McDonough, 1989).

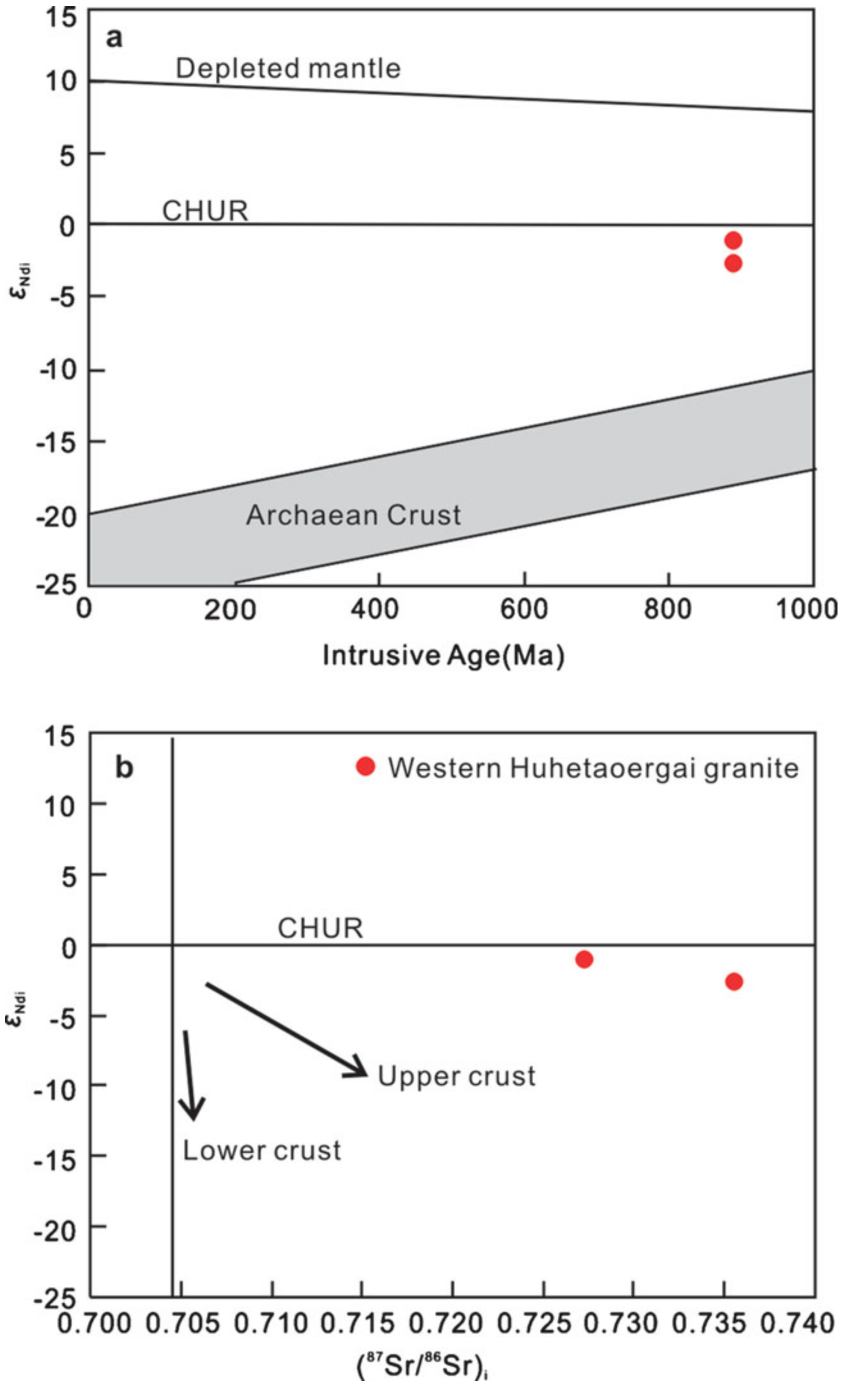

Figure 5. (Colour online) Isotopic data: (a) $\varepsilon_{Nd}(t)$ v. intrusive age; (b) $\varepsilon_{Nd}(t)$ v. $(^{87}Sr/^{86}Sr)_i$ ratios. The lower crust and upper crust fields are from Wu *et al.* (2003*a*).

3.c. Geochronology

After geochemical analyses, a representative sample (AB10–41) was selected for dating by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Analytical results are shown in supplementary Table S3, available at http://journals.cambridge.org/geo. Zircon grains are euhedral, clear to pink and transparent or euhedral to subhedral, brown and turbid to opaque. Aspect ratios (AR) range from 1:1 to 5:1. Some have inclusions and inherited cores. Most analyses represent idiomorphic grains with oscillatory zoning throughout the crystal (Fig. 6a). By integrating crystal shapes, textures and high Th/U ratios of the zircons, the majority of grains are presumed to be magmatic (Belousova *et al.* 2002; Corfu *et al.* 2003). One core was found and a slightly older age was obtained (1043_2_43). Analyses showing apparently older ages (1043_2_43) and those performed on grains on cracks (1043_2_46) are excluded from the age calculations. Sixteen analyses were combined to yield a concordia age of 889 ± 8 Ma (MSWD = 0.30) (Fig. 6b), which is interpreted as the crystallization age for sample AB10–41.

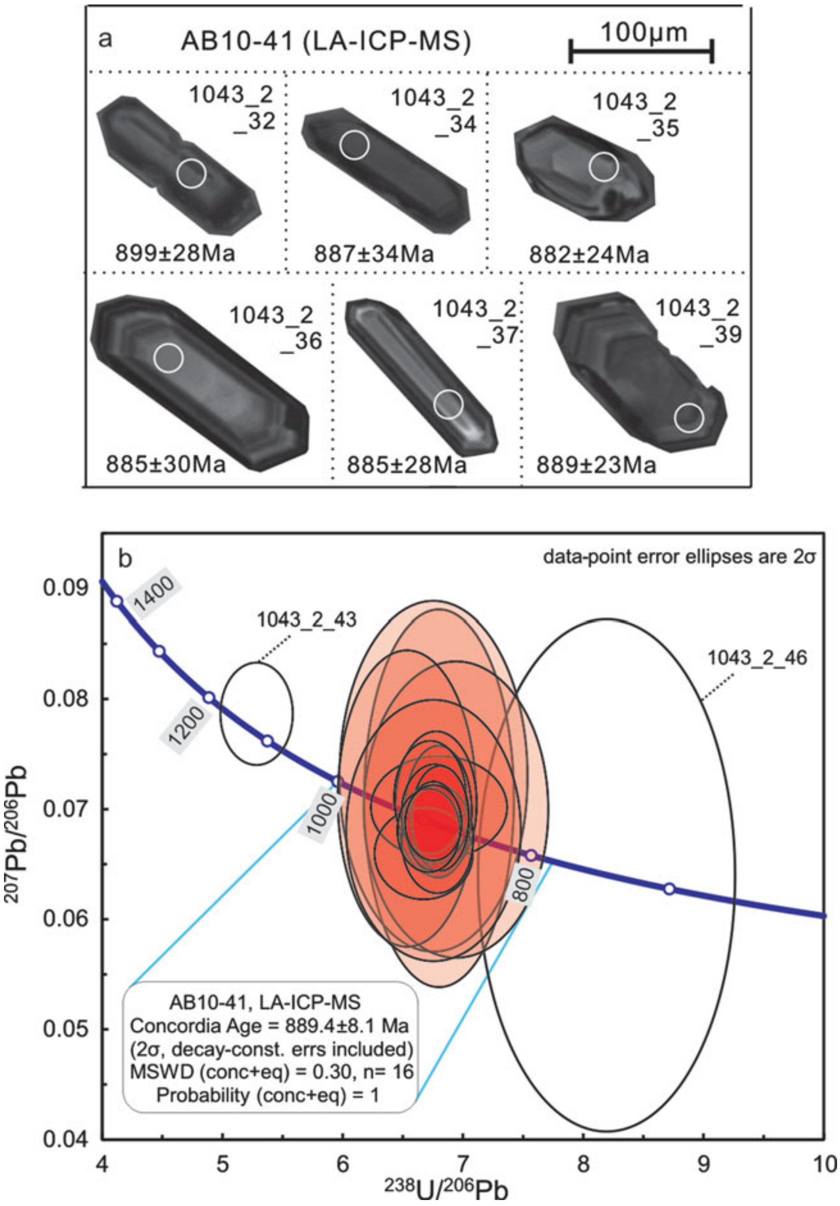

Figure 6. (Colour online) (a) Cathodoluminescence (CL) images of zircons and (b) U–Pb Concordia plot. Unfilled symbols excluded from final synthesis.

4. Discussion and conclusions

4.a. Petrogenesis

The pluton was previously regarded as being of early Palaeozoic (BGGP, 1980) or late Neoproterozoic (689 Ma, TIMS zircon U–Pb; Wang, Wang & Wang, 1994) in age. Our new LA-ICP-MS zircon U–Pb age of biotite granite (AB10–41) is 889 ± 8 Ma, which represents the age of the Western Huhetaoergai biotite granite pluton. Few Precambrian granitoids are reported in the Northern Alxa region, so the Neoproterozoic Western Huhetaoergai granite is significant in providing information about Precambrian basement and constraining Neoproterozoic evolution.

From the mineralogical and geochemical characteristics, such as the absence of alkaline minerals, the high SiO_2 and K_2O contents and the peraluminous nature, the Western Huhetaoergai granite is interpreted to represent a highly fractionated potassium-rich calc-alkaline rock (e.g. Sylvester, 1989). The low Fe/Mg, Ga/Al and contents of Zr, Nb, Ga, Y, Ce, Sr and CaO indicate that it is not an alkaline granite (A-type granite) but a fractionated felsic granite (Whalen, Currie & Chappell, 1987). This is also supported by the striking depletions in Ba, Nb, Eu, Ti and P (Fig. 4b). According to Wu *et al.* (2003*b*), negative Nb–Ti anomalies are related to fractionation of Ti-bearing phases (ilmenite, titanite, etc.), negative P anomalies result from apatite separation and strongly negative Eu anomalies require extensive fractionation of plagioclase and/or K-feldspar. The fractionation of K-feldspar would produce negative Eu–Ba anomalies.

The Neoproterozoic Western Huhetaoergai granite has $^{87}Sr/^{86}Sr$ values of 0.727305–0.735626, a T_{DM1} age of 2452–1707 Ma and slightly negative $\varepsilon_{Nd}(t)$ (−2.6 to −1.1). $\varepsilon_{Nd}(t)$ of value *c.* 0 shows that both a mantle (or juvenile) component and continental crust (or a sedimentary component) were involved in the genesis of the Neoproterozoic Western Huhetaoergai granite (Fig. 5b). Sr isotopic data suggest the important role of continental crust (or a sedimentary component).

Two possible processes may explain these isotopic characteristics. The first considers that the granite was generated from a high Rb/Sr source. Rb/Sr ratios of the Western Huhetaoergai granite ranges from 1.4 to 3.2 (supplementary Table S1, available at http://journals.cambridge.org/geo). To acquire high initial $^{87}Sr/^{86}Sr$, the source would have needed much higher Rb/Sr ratios. Sr-isotope evolution of the upper continental crust is determined by its age and Rb/Sr ratios (McDermott & Hawkesworth, 1990). Rocks with high Rb/Sr ratios are usually considered to be from the upper continental crust; however, upper continental crust would usually produce much lower initial ε_{Nd} than that recorded by the Western Huhetaoergai granite.

The second process considers that the granite was derived from a mantle source and assimilated/contaminated crustal rocks with very high $^{87}Sr/^{86}Sr$. As marble xenoliths are common in the pluton, they could be responsible for the high initial $^{87}Sr/^{86}Sr$. Previous studies show carbonate usually has high $^{87}Sr/^{86}Sr$ (0.71–0.73) (Metcalf *et al.* 1995; Plank & Langmuir, 1998; Faure & Mensing, 2010). According to Satish-Kumar *et al.* (2008), marble from East Antarctica has initial $^{87}Sr/^{86}Sr$ ratios between 0.7066 and 0.7582 (550 Ma) due to fluid–rock interactions. The assimilation of carbonate material may increase CaO and Sr concentrations, as well as the $^{87}Sr/^{86}Sr$ ratio (Barnes *et al.* 2005). The protolith of marble xenoliths in the Western Huhetaoergai pluton is probably dolomite ($CaMg(CO_3)_2$) (BGGP, 1980), but the granite has very low Sr, CaO and MgO. Consequently, it is difficult to explain its chemical characteristics by carbonate assimilation. However, minor carbonate assimilation must have occurred due to the presence of marble xenoliths. Crustal rocks with very high $^{87}Sr/^{86}Sr$ (e.g. Allègre & Othman, 1980) are not seen at the surface and may exist at depth. In addition, although few isotopic studies of contemporaneous granite in the CAOB are reported, the 880–864 Ma granite from Siberia's western margin has slightly lower initial ε_{Nd} (–2.6 to –5.1), similar to the Western Huhetaoergai granite but much lower initial $^{87}Sr/^{86}Sr$ (0.7070–0.7104) (Vernikovsky *et al.* 2007). It is interpreted as having been generated by melting and mixing of different source components (older and younger, lower and middle crustal meta-igneous or sedimentary rocks).

4.b. Tectonic implications

4.b.1. Tectonic setting

Enrichment of LREE and negative Nb–Ta–Ti anomalies of the Western Huhetaoergai granite indicate arc-related characteristics. It is post-collisional, both with respect to being unfoliated and as defined by its trace elements (Pearce, Harris & Tindle, 1984; Pearce, 1996), which is also consistent with its fractionated nature (e.g. Whalen, Currie & Chappell, 1987). From the geochemical and geochronological data, the HZ was in a post-collisional stage at *c.* 890 Ma. This is difficult to correlate with the sedimentary record as the Mesoproterozoic (Stenian–Estasian) sandstone into which the Western Huhetaoergai pluton is emplaced is the only Precambrian strata exposed in the Huhetaoergai Tectonic Zone (Fig. 1b). Future basement studies would be of great benefit in addressing granite genesis in the region.

A previous study argued that the Huhetaoergai Tectonic Zone represented a palaeo-volcanic arc developed on oceanic crust, preserved when the ocean closed and interpreted as 'juvenile' continental crust (Wang, Wang & Wang, 1994). The age of 689 Ma for the Western Huhetaoergai granite resulted in the interpretation that this 'juvenile' continental crust formed at *c.* 700 Ma. However, the new geochronology for the Western Huhetaoergai granite indicates that if the Huhetaoergai Tectonic Zone represents 'juvenile' continental crust, it should be older than *c.* 890 Ma. This is also supported by the presence of an additional fragment of Precambrian crystalline basement, the Mesoproterozoic strata with both marine and terrestrial components and the isotopic characteristics of the Western Huhetaoergai granite. The Huhetaoergai Tectonic Zone may therefore represent the same Neoproterozoic tectonic unit as the Zhusileng Tectonic Zone. The Western Huhetaoergai granite formed after the collision between the Huhetaoergai palaeo-volcanic arc and the Zhusileng Tectonic Zone.

4.b.2. Tectonic affinities of the northernmost Alxa region during early Neoproterozoic time

Granitoid gneiss of similar zircon U–Pb crystallization age (916 ± 16 Ma, conventional zircon age) is recognized in the Yagan–Onch Hayrhan metamorphic core complex, Jindouaobao area, Zhusileng Tectonic Zone (Fig. 1b) by Wang *et al.* (2001). The Neoproterozoic Jindouaobao granitoid gneiss has high SiO_2 and K_2O ($SiO_2 = 72–73$ wt %, $K_2O = 4.33–4.95$ wt %), peraluminous characteristics (A/CNK = 1.04–1.14) and negative Eu anomalies (δEu = 0.33–0.53), similar to the Western Huhetaoergai granite in this study. Wang *et al.* (2001) argued that the Jindouaobao granitoid gneiss implied the existence of a South Mongolian/South Gobi Microcontinent, which is consistent with a U–Pb zircon crystallization age of 952 ± 8 Ma for a gneissic granite from the South Gobi Block in south Mongolia (Hutag Uul Terrane of Badarch, Dickson Cunningham & Windley, 2002) reported by Yarmolyuk *et al.* (2005). In this case, it may be regarded as an extension of the Xilinhot gneiss (Xiao *et al.* 2003) located in a thrust belt near the Solonker Suture Zone, widely regarded to record the terminal evolution of the CAOB (Xiao *et al.* 2003; Chen, Jahn & Tian, 2009; Li *et al.* 2011). Our new zircon age data, together with the South Mongolian Microcontinent zircon age data

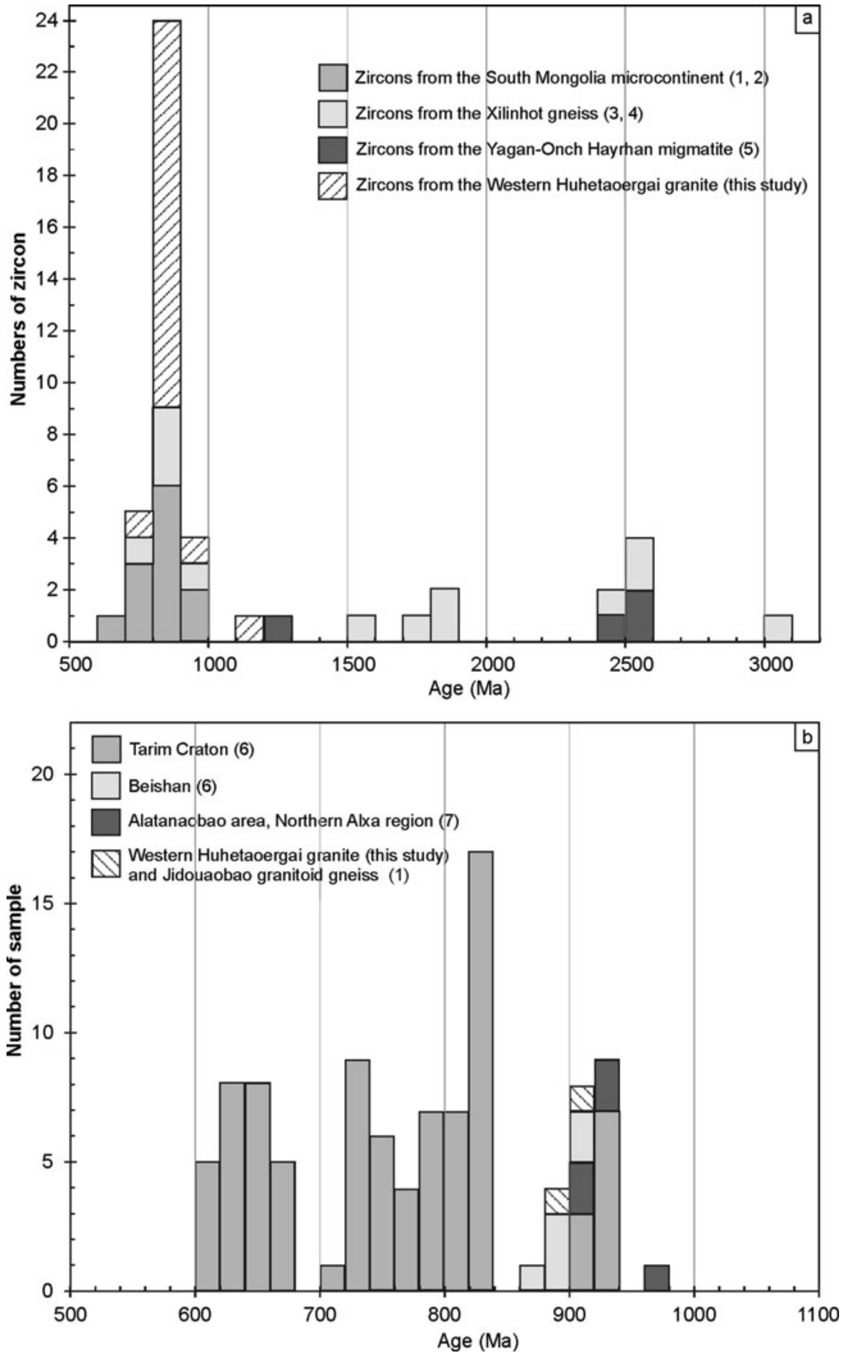

Figure 7. (a) Histogram of zircon age data for the Western Huhetaoergai granite, compared with the South Mongolia microcontinent-related zircon age data. (b) Age histogram for Neoproterozoic igneous rocks in the Northern Alxa region, Beishan area and Tarim Craton. Data from 1. Wang *et al.* (2001); 2. Yarmolyuk *et al.* (2005); 3. Shi *et al.* (2003); 4. Chen *et al.* (2009); 5. Taylor *et al.* (2013); 6. Liu *et al.* (2015); 7. Geng & Zhou (2010).

(Wang *et al.* 2001; Shi *et al.* 2003; Yarmolyuk *et al.* 2005; Chen, Jahn & Tian, 2009), are plotted in a histogram (Fig. 7a and supplementary Table S4, available at http://journals.cambridge.org/geo). Note that the Xilinhot metamorphic complex shows two groups of Precambrian ages: one with ages of 1524–2900 Ma, similar to those of the North China Craton, and the other with ages of 780–900 Ma, resembling those from the South Mongolian Microcontinent (Chen, Jahn & Tian, 2009). As shown in Figure 7a, the zircon ages of the Western Huhetaoergai granite overlap of that of the South Mongolian Microcontinent zircon age data, indicating their close affinities at that time. Consequently, it is possible that the Western Huhetaoergai granite reflects the existence of the South Mongolian Microcontinent and may also be an extension of the Xilinhot gneiss.

Tarim Craton provides an alternative possible interpretation for the tectonic affinity of Neoproterozoic northernmost Alxa region. Wang, Wang & Wang (1994) indicated that both Huhetaoergai and Zhusileng tectonic zones belonged to easternmost Tarim

Craton. When compared with the Neoproterozoic magmatism in the Beishan Orogenic Belt, Tarim Craton and the Alatanaobao area south of Northern Alxa region (Fig. 1), the Western Huhetaoergai granite and the Jindouaobao granitoid gneiss are more comparable with the Beishan samples in terms of their ages and rock associations (Fig. 7b). The Beishan Orogenic Belt may have been part of the Tarim Craton during early Neoproterozoic time (Liu *et al.* 2015). However, unlike highly fractioned Western Huhetaoergai post-collisional granite, 905–871 Ma Gubaoquan orthogneisses of the Beishan Orogenic Belt are suggested to be probably arc-related I-type granitoid geochemical affinities related to subduction tectonic settings (Liu *et al.* 2015). Referring to the similarity of the geochemistry, we favour the affinity of the northernmost Alxa region to the South Mongolian Microcontinent.

The existence of the South Mongolian Microcontinent has recently been questioned, however. From U–Pb zircon dating and microstructural analysis, Taylor *et al.* (2013) pointed out that previously suspected Precambrian protoliths of Totoshan–Ulanuul (Yarmolyuk *et al.* 2005) and Tsagaan–Khairkhan blocks (Tsaagan Uul Terrane of Badarch, Dickson Cunningham & Windley, 2002), which represent a substantial portion of the South Gobi Microcontinent (e.g. Salnikova *et al.* 2001; Wang *et al.* 2001; Kovalenko *et al.* 2004; Yarmolyuk *et al.* 2005, 2007, 2008), formed during Devonian–Triassic times and show no evidence to support the existence of the Precambrian basement. The only Precambrian zircons found are three of Archean and one of Mesoproterozoic age (Taylor *et al.* 2013) (Fig. 7a), interpreted to be sourced from the Tarim and North China cratons and associated accreted terranes (such as in the Qilian, Qaidam, Yin Shan and Yan Shan regions) located along the North China margin. Although these U–Pb zircon age data from Taylor *et al.* (2013) do not support the existence of exposed Precambrian rocks in the South Mongolian Microcontinent, the possibility of Precambrian rocks at deeper crustal levels cannot be ruled out entirely. Further evidence may be identified in a future study.

The Neoproterozoic age of the Western Huhetaoergai pluton may coincide with the assembly of Rodinia (Li *et al.* 2008; Lu *et al.* 2008; Demoux *et al.* 2009; Shu *et al.* 2011). From the study of magmatic zircons in gabbro, granite and paragneiss from Tarim, Shu *et al.* (2011) interpreted the assembly period of Rodinia to be the interval *c.* 1140–860 Ma (peak of 920 Ma). Synorogenic ages of 1050–844 Ma are recognized in Tarim (Lu *et al.* 2008). The protoliths of orthogneisses of age *c.* 900–870 Ma were also discovered in the Beishan Orogenic Belt (Jiang *et al.* 2013; Yu *et al.* 2013; Liu *et al.* 2015). Granitoid gneiss of similar age (972–904 Ma) with similar geochemical characteristics is also reported in the Alatanaobao area, Southern Alxa region (Geng *et al.* 2002; Geng & Zhou, 2010). The presence of rocks of age *c.* 1.0 Ga in the Alxa region and in the Tarim Craton demonstrates that these were joined at that time. This phase of magmatism is also documented by granite-gneiss with protolithic ages of 954 ± 8, 956 ± 3 and 983 ± 6 Ma in south Mongolia (Demoux *et al.* 2009). In Siberia's western margin, granites of age 880–864 Ma are interpreted to relate to the formation of the Rodinia supercontinent and the Central Asian Orogenic Belt (Vernikovsky *et al.* 2007). Granite formation at 1.1–0.8 Ga is also recorded in south Siberia (Berzin & Dobretsov, 1994). The genesis of the Western Huhetaoergai granite is therefore likely related to the assembly of Rodinia; at *c.* 890 Ma the Huhetaoergai area would have been under compression.

In summary, the Neoproterozoic Western Huhetaoergai granite is a highly fractionated potassium-rich calc-alkaline pluton with low initial $\varepsilon_{\mathrm{Nd}}$ (−2.6 to −1.1) and high initial $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ (0.727305 to 0.735626). The granite is probably derived from a mantle (or juvenile) source that assimilated very high $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ crustal rocks during the assembly of Rodinia. The Huhetaoergai and the Zhusileng tectonic zones were together during Neoproterozoic time. During early Neoproterozoic time, the northernmost Alxa region was closely linked to the South Mongolian Microcontinent.

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Supplementary material

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