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Oceanic lithospheric mantle beneath the continental crust of the Chinese Altai

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Abstract: Although subduction–accretion is proposed as a major regime in making new continental crust, how the lithospheric mantle forms remains unclear. Formed after the closure of the Palaeo-Asian Ocean, the Ashele basalt shows normal mid-ocean ridge basalt (N-MORB)-like characteristics with light REE-depleted patterns and extremely low contents of high field strength elements. The low Zr/Y and Nb/Y ratios of the basalt are significantly different from those of asthenosphere-derived melts, and the excess Eu and Sr suggest that the basalt was probably derived from accreted oceanic lithospheric mantle. The presence of the N-MORB-like terrestrial basalt implies that subduction–accretion is an effective mechanism in building the refractory lithospheric mantle of Phanerozoic continents.

Supplementary material: A photograph of the outcrop, and age and geochemical data are available at http://www.geolsoc.org.uk/SUP18464.

The longevity of continental blocks is commonly ascribed to refractory and buoyant subcontinental lithospheric mantle, which must have experienced high degrees of melt extraction (Poudjom Djomani *et al.* 2001; Arndt *et al.* 2009). As an alternative to a mantle plume, which can produce refractory lithosphere by widespread melt extraction (Wyman & Kerrich 2002; Griffin *et al.* 2009), subduction stacking of oceanic lithosphere is considered as a possible regime for forming the refractory subcontinental lithospheric mantle (James & Fouch 2002; Horodyskyj *et al.* 2007; Wittig *et al.* 2008). However, oceanic lithosphere is heterogeneous and generally characterized by a low fraction of harzburgite and dunite, and partial melting of oceanic lithosphere can hardly produce peridotite residues with high-Fo olivine (Arndt *et al.* 2009). Therefore, whether a refractory lithospheric mantle can be achieved by subduction–accretion remains to be tested. Another key issue for the subduction stacking model is whether relatively fertile oceanic lithosphere can evolve into refractory continental lithosphere by subsequent melt extraction after accretion to continental margins. Mafic magmas may provide important constraints on their mantle sources. If post-accretionary mafic magma shows oceanic lithosphere-derived signatures, it would suggest that oceanic mantle can not only be incorporated in, but can also have potential to finally evolve into, continental lithosphere. Unfortunately, like most peridotite massifs in young mobile belts (Pearson & Wittig 2008; Griffin *et al.* 2009), post-accretionary, mantle-derived magmas generally reflect metasomatized mantle sources that can hardly be related to accreted oceanic lithosphere, and the finding of post-accretionary mafic rocks with oceanic lithosphere signatures has been a primary task in unravelling the above enigma. The Altaids (Sengör & Natal'in 1996), also called the Central Asian Orogenic Belt, are a huge tectonic collage and represent one of the largest accretionary orogens on Earth (Kröner *et al.* 2007; Windley *et al.* 2007). This orogenic belt is formed by accretion of juvenile materials towards the south margin of the Siberian craton (Sengör & Natal'in 1996), and can hence be treated as a Phanerozoic analogue to test the subduction stacking hypothesis for formation of the continental lithospheric mantle. Here we report a late Triassic terrestrial basalt of the Chinese Altai, a mountain range that was an archipelago in Palaeozoic time but now represents one of the youngest continental blocks on Earth (Windley *et al.* 2007), and the mid-ocean ridge basalt (MORB)-like compositions of the basalt allow us to infer the nature of the lithospheric mantle of the newly formed continent.

Geological background

The Altaids occupies a vast area between the Siberia and North China–Tarim cratons (Fig. 1). Its evolution began in the Neoproterozoic (Kröner *et al.* 2007) and ended in the late Palaeozoic, possibly as late as the end of the Permian as suggested by a study of the Solonker suture (Xiao *et al.* 2003). The long-lasting subduction-related processes resulted in accretion of juvenile blocks, dominated by arcs, oceanic islands and plateaux, to the southern margin of the Siberian craton, representing the most important crustal growth event in the Phanerozoic (Sengör & Natal'in 1996; Kröner *et al.* 2007). Geochemical studies have revealed that the Altai mountain range, at least the portion in China, consists mainly of juvenile materials accreted during the consumption of the Palaeo-Asian Ocean (Sun *et al.* 2008). The Altaids underwent oroclinal bending after the closure of the Palaeo-Asian Ocean (Sengör & Natal'in 1996), and Late Permian to Jurassic tectonothermal events in the Chinese Altai have been widely interpreted as large-scale translation of terranes (Briggs *et al.* 2009). The Chinese Altai is divided into several units (Xiao *et al.* 2004), and

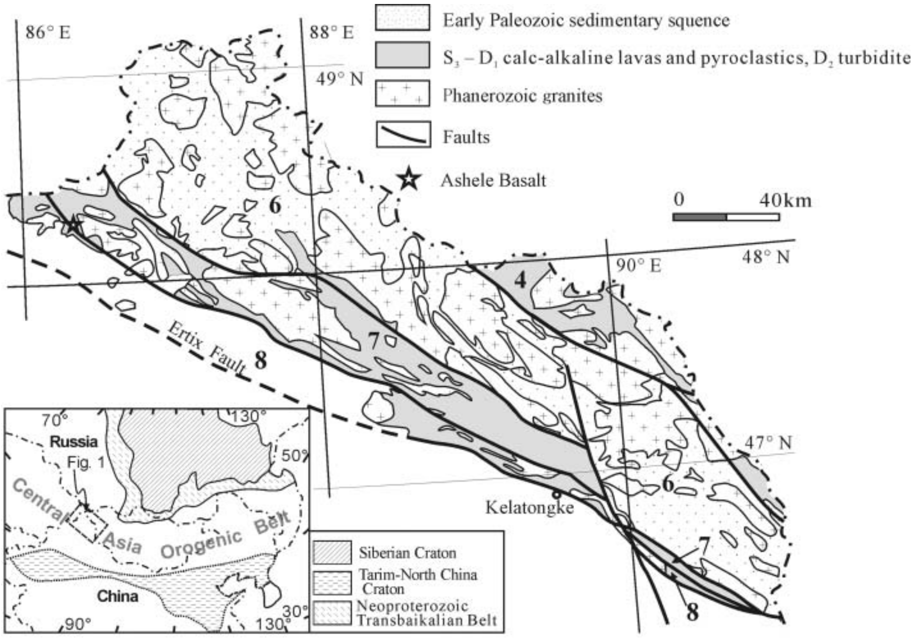

Fig. 1. Geological map of the Chinese Altai (geological division following Xiao *et al.* 2004). Terranes: 4, Altaishan; 6, Halong; 7, Abagong; 8, Erqis.

the Ashele basalt covers a small area (<0.1 km^2) and is located in the Abagong Unit dominated by an accreted Silurian–early Devonian island arc (Fig. 1). Rocks in this unit are characterized by high εNd_T values ($> +1.4$) and low $^{87}Sr/^{86}Sr$ ratios (<0.705) (Wang *et al.* 2009), consistent with a juvenile arc terrane. The Ashele basalt unconformably overlies the Late Silurian to Early Devonian strata, which consist mainly of andesitic clastic rocks intercalated with minor limestones and andesites. The basalt is undeformed and clearly shows vertical columnar joints that suggest terrestrial eruption. The basalt is very fine-grained, fresh, and consists of plagioclase, clinopyroxene and minor iron–titanium oxides, with an intergranular texture.

Ar–Ar dating results

After cleaned with deionized water in an ultrasonic bath, rock chips of the Ashele basalt were irradiated in the 49-2 reactor in Beijing for 54 h with a standard DRA1 sanidine of 25.26 ± 0.07 Ma. Mass spectrometry analysis was performed at Guangzhou Institute of geochemistry, Chinese Academy of Sciences (GIGCAS). The $^{40}Ar/^{39}Ar$ dating results were calculated using the ArArCALC software package of Koppers (2002). Both incremental-heating and total fusion techniques were used. In total, 16 steps were conducted for sample ASL06-15 and the $^{40}Ar/^{39}Ar$ age spectrum is shown in Figure 2a. Seven out of nine incremental-heating stages form an integrated and stable plateau, which corresponds to an age of 225 ± 6 Ma (Fig. 2a). The plateau also yields a consistent normal and inverse isochron age of 223 ± 17 Ma, and gives an initial $^{40}Ar/^{36}Ar$ ratio (297 ± 44) consistent with the Nier ratio (295.5), suggesting a negligible influence of excess argon. This plateau age therefore represents the timing of emplacement of the basalt.

Terrestrial basalt with normal (N)-MORB characteristics

The basaltic samples possess rather homogeneous compositions, with SiO_2 generally between 47.4 and 51.9 wt%. The rock samples contain consistent TiO_2 contents (around 1.0 wt%) and their MgO contents are generally lower than 5.5 wt%. Except for three with relatively high K_2O (0.17–0.22 wt%), most samples are characterized by extremely low K_2O contents (mostly <0.07) and K_2O/Na_2O ratios (most around 0.01), showing features of tholeiitic basalt (Fig. 2b and c). The basaltic samples contain low Cr (<15 ppm) and Ni (<10 ppm), but relatively high V (355–449 ppm). Their V/Sc ratios (8.3–14.9) are significantly higher than those of N-MORB rocks (6.74 ± 1.11, Li & Lee 2004). The rocks contain low REE (23–27 ppm) and are characterized by light REE (LREE)-depleted ($(La/Yb)_N = 0.7–1.0$) and unfractionated heavy REE (HREE) ($(Gd/Yb)_N \sim 1$) patterns (Fig. 3a). Other striking features include positive Eu, Sr and Pb anomalies ($Eu/Eu^* = 1.06–1.29$) and remarkable troughs for Nb–Ta (Fig. 3a and b), analogous to those observed in subduction-related rocks. Their high field strength element (HFSE; Nb, Ta, Zr and Hf) and Rb contents are considerably lower than those of N-MORB, although they have relatively high Sr, Ba, Th and U. They also possess relatively low Nb/Ta (12–16) and Zr/Hf (26–31) ratios, whereas their Zr/Nb (51–57), Th/Ta (15–19) and Ba/Rb (mostly >50) ratios are significantly higher than those of N-MORB.

The Ashele basalts possess initial εNd_T values (+4.3 to +5.2) strikingly lower than those of Permian, asthenosphere-derived zoned mafic–ultramafic rocks in the Eastern Tianshan and Chinese Altai, although they show similar initial $^{87}Sr/^{86}Sr$ ratios (0.7047–0.7052) (Fig. 4a). The basaltic samples mostly exhibit Proterozoic T_{DM} ages (0.52–1.85 Ga).

Asthenospheric v. lithospheric source

Although commonly found in mid-ocean ridges or ophiolite sequences (Puchelt & Emmermann 1977), LREE-depleted basalts rarely occur in terrestrial regions. There are a few cases of LREE-depleted basalts erupted on the continental crust, but these rocks were generally attributed either to a plume-related large igneous province (e.g. Barrat *et al.* 2003), or to hydrous partial melting of upper mantle in a subduction-related environment (Duggen *et al.* 2004), or to decompressional melting of upwelling asthenosphere during ridge–trench collision (Maeda &

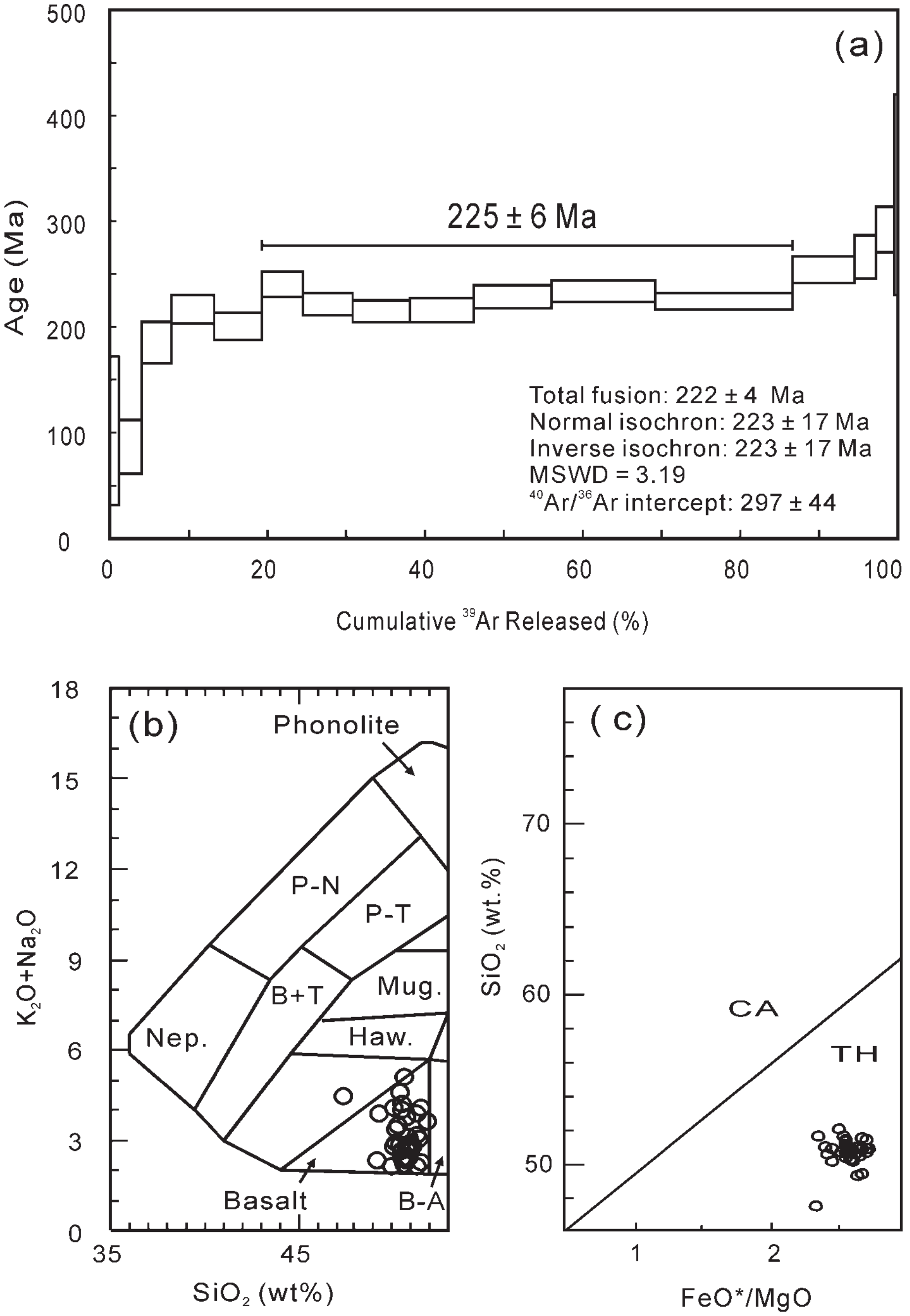

Fig. 2. Age and classification of the Ashele basalt of the Chinese Altai. (**a**) Whole-rock Ar/Ar release spectra. (**b**) Chemical classification diagram (after Cox *et al.* 1979). (**c**) FeO*/MgO v. SiO_2 diagram (after Miyashiro 1974). CA, calc-alkaline; P–N, phonolitic nephelinites; Nep., nephelinites; P–T, phonolitic tephrites; B + T, basanites and tephrites; Mug., mugearites; Haw., hawaites; B–A, basaltic andesites; TH, tholeiitic.

Kagami 1996). These dynamic scenarios are not applicable to the Late Triassic Ashele basalt, because after the closure of the Palaeo-Asian Ocean in the Late Permian there was no active subduction in the Chinese Altai and no evidence for Late Triassic plume magma in the area has been found (Xiao *et al.* 2004; Windley *et al.* 2007). Although the relatively low Mg-number (45–49) indicates that the Ashele basalt may not represent the primary magma, the low K_2O contents and coherent trace element and Nd–Sr isotope compositions of the samples imply that contamination of crustal materials during their ascent to the surface was at a negligible level. The basaltic rocks contain Cr and Ni much lower, and V higher than those of N-MORB. Cr, Ni and V behave differently in magma, where oxygen fugacity exerts a primary control on multivalent elements. With the increase of oxygen fugacity, partition coefficients of Cr for orthopyroxene and clinopyroxene and that of Ni for olivine increase remarkably, whereas V becomes more incompatible (Ehlers *et al.* 1992; Lee *et al.* 2003; Mallmann & O'Neill 2009). The low Cr and Ni and high V levels of the rocks may therefore reflect crystallization of pyroxene and olivine under high oxygen fugacity. Sr and Eu excess are commonly attributed to plagioclase accumulation or alteration. However, the rocks are generally undeformed and fresh, and their low LOI (mostly $<4\%$) suggests an insignificant influence of alteration (Polat & Hofmann 2003). Moreover, no textural evidence of plagioclase accumulation has been found. Therefore, the positive Sr and Eu anomalies of the samples were probably inherited from their mantle source. Sr excess has been widely observed in oceanic

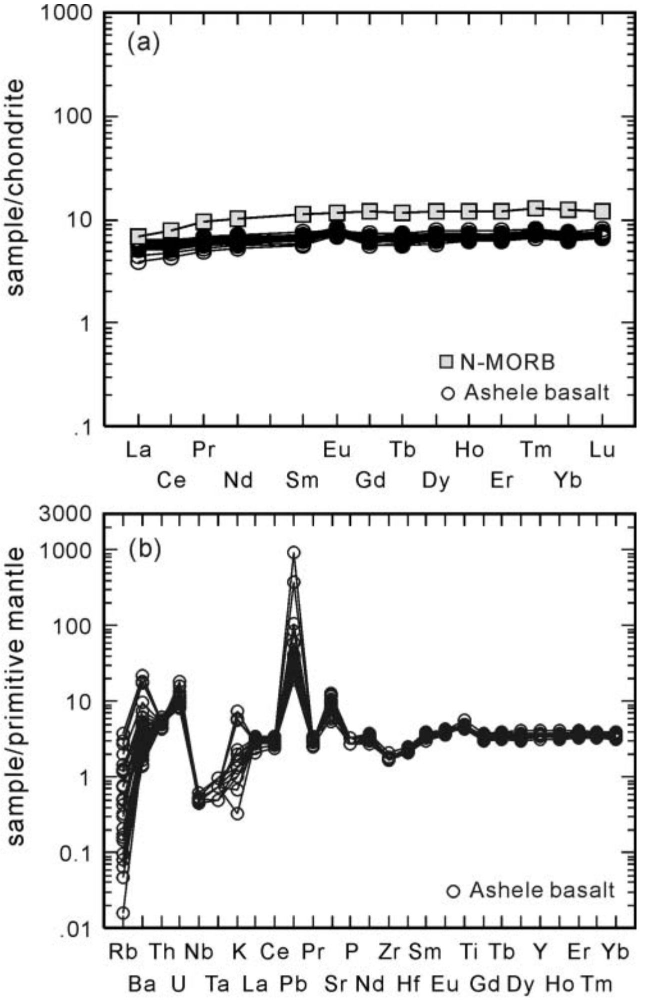

Fig. 3. Trace element diagrams of the Ashele basalt. (**a**) Chondrite-normalized REE distribution diagram (chondrite data from Taylor & McLennan 1985; N-MORB data from Sun & McDonough, 1989); (**b**) primitive mantle normalized multi-element diagram (primitive mantle data from Sun & McDonough 1989).

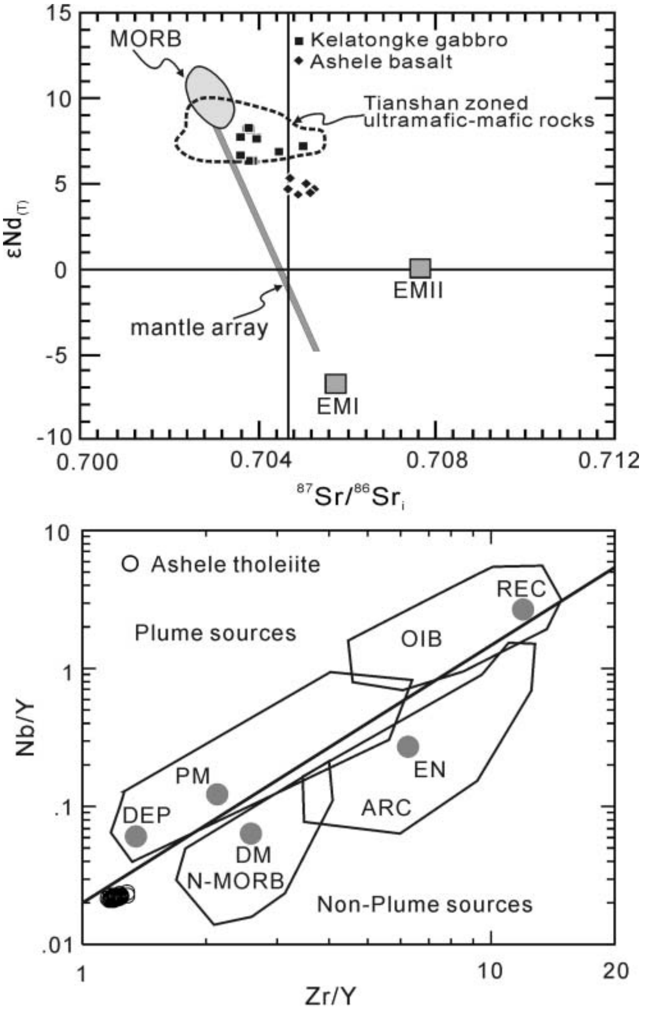

Fig. 4. Discrimination for mantle source of the Ashele basalt. (**a**) Nd–Sr isotope correlation diagram (data for the Tianshan zoned ultramafic–mafic rocks from Zhou *et al.* 2004; data for the Kelatongke gabbro from Zhang *et al.* 2009). (**b**) Nb/Y v. Zr/Y diagram for the major mantle domains (after Condie 2005). PM, primitive mantle; DM, shallow depleted mantle; ARC, arc-related basalts; N-MORB, normal mid-ocean ridge basalt; OIB, ocean island basalt; DEP, deep depleted mantle; EN, enriched component; REC, recycled component.

and plume-related basalts and usually considered as either an intrinsic feature of the depleted MORB mantle (DMM) source (Niu & O'Hara 2009), or a signature of recycled plagioclase-rich oceanic crustal cumulates (Sobolev *et al.* 2000). The low HFSE contents and Zr/Y and Nb/Y ratios make the Ashele basalt remarkably different from any of the major mantle domains in the asthenosphere (Condie 2005; Fig. 4b). Moreover, both the Sr-enriched melt inclusions trapped in primitive olivine phenocrysts from plume-derived picrites and high-pressure experimental melts of gabbro all exhibit normalized Th/Nb ratios lower than unity (Sobolev *et al.* 2000; Yaxley & Sobolev 2007). This is considerably different from those of the Ashele basalts (normalized Th/Nb ~ 6, Fig. 3b), and hence does not support recycled oceanic crust as the source of the Ashele basalt. The low Ce/Pb ratios (0.1–3.9), striking Nb–Ta depletion and the high V/Sc ratios collectively reflect a subduction-related environment (Pearce & Peate 1995; Kelley & Cottrell 2009). This is consistent with the geological observation that the Abagong Unit is an accreted Silurian–early Devonian island arc (Xiao *et al.* 2004).

The Ashele samples exhibit unfractionated HREE patterns indicative of an origin from a spinel peridotite mantle, which raises a question of whether the Ashele basalt could be generated by the partial melting of the newly accreted oceanic lithospheric mantle. Oceanic peridotite usually contains plagioclase precipitated during the passage of melt through the lithosphere, and thus it is a potential lithospheric mantle source for basalts with Sr excess (Niu & O'Hara 2009). The unusually depleted composition of the basalt suggests that the mantle source underwent significant melt extraction, probably in an oceanic spreading centre. The relatively old but highly variable Nd model ages do not imply a continental lithospheric mantle. Instead, they may reflect the existence of an old oceanic mantle stranded within the subduction zone (Parkinson *et al.* 1998). With the accretion of the island arc, the mantle source was incorporated into the lithospheric mantle of the juvenile continent. Lithospheric mantle is normally considered to be infusible because of its relatively low geothermal gradient (Niu & O'Hara 2009), which may be one of the reasons for the rarity of MORB-type basalt in post-Archaean orogens. However, in some circumstances, lithospheric mantle can melt to generate magma. For example, upwelling of hot asthenosphere may cause basal heating and partial melting of lithospheric mantle (e.g. Anderson 1994), and local shear deformation of lithosphere could also induce small degrees of partial melting and generate melt passing through the lithosphere (Asmerom *et al.* 2000). Although we cannot preclude the possibility of the first case, the small volume (<0.1 km^2) of the Ashele basalt and synchronous shear deformation in the Chinese Altai (Briggs *et al.* 2009) make the second scenario more possible. We therefore suggest that partial melting of the plagioclase peridotite of the accreted oceanic lithospheric mantle, probably induced by large-scale transpressional movement, may have led to the N-MORB-like Ashele basalt.

Implications for continental lithosphere

The Ashele basalt formed after the closure of the Palaeo-Asian Ocean and is, to our knowledge, the first case of LREE-depleted terrestrial basalt irrelevant to mantle plume or active subduction. It provides important insights into the geological evolution of the Altai orogen and formation of the continental lithospheric mantle. The striking subduction signatures of the Ashele basalt, as indicated by relative enrichment of large ion lithophile elements (LILE) and the noted depletions in Nb–Ta–Ti, are consistent with the arc nature of the Abagong Unit (Xiao *et al.* 2004). The low incompatible element concentrations of the Ashele basalt reveal the existence of a depleted lithosphere beneath the Chinese Altai, which verifies previous inferences that oceanic, MORB-type mantle can be incorporated into the continental lithosphere during accretion of arcs or back-arc basins (James & Fouch 2002; Horodyskyj *et al.* 2007; Wittig *et al.* 2008), suggesting that subduction–accretion processes can be an important mechanism in making continental lithosphere. The presence of the LREE-depleted basalt in the Altaids shows that the newly accreted oceanic mantle, despite its much depleted composition, has potential to melt and generate lithospheric mantle-derived melts. This is consistent with previous geophysical and geochemical observations that lithospheres beneath Phanerozoic mobile belts are thinner and less depleted than those of ancient cratons (Poudjom Djomani *et al.* 2001; Griffin *et al.* 2009). Melt extraction from the newly accreted lithosphere may be essential for the lithospheric mantle to become refractory and thus more buoyant and stable.

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