Evolution and modification of lithospheric mantle within deeply continental subduction zone: Insights from two contrasting orogenic garnet peridotites in South Altun–North Qaidam belt

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Abstract: Deciphering the geodynamic evolution and compositions of the Earth's mantle is crucial for understanding the origin and evolution of the Earth, however, the original geodynamic setting and significance of tectonically emplaced mantle in ancient orogens is always ambiguous. Orogenic garnet peridotites can shed light on the understanding of upper mantle petrology and the tectonic processes that operate at convergent plate boundaries. Petrographical evidence and P-T conditions of two contrasting types of orogenic garnet peridotites in the South Altun–North Qaidam (SAT–NQD) HP/UHP metamorphic belt suggest that they experienced a notably different geological history. Geochemical characteristics show that the garnet peridotites in the Bashiwake unit represent ultramafic complexes emplaced into the continental crust before subduction, while those in the Luliangshan unit originate from the mantle wedge above a deep subduction zone. Srsingle bondNd isotopes for the two contrasting ultramafic rocks indicate that both have been modified either by mantle metasomatism or crustal contamination. The distinct petrochemical and isotopic characteristics of these contrasting orogenic garnet peridotite types demonstrate spatio-temporal variation in the tectonothermal-evolution of the SAT–NQD HP/UHP orogen.

Key words: orogenic garnet peridotites; continental lithospheric mantle; crust–mantle interactions; deeply continental subducted zone; South Altun–North Qaidam

1. Introduction

Revealing the geodynamic evolution and compositions of the Earth's mantle is crucial for understanding the origin and evolution of the Earth (Palin and Santosh, 2021; Varas-Reus et al., 2018). Given that the mantle cannot be studied in situ, tectonically emplaced subcontinental, sub-oceanic, and sub-arc mantle rocks in ancient orogens allow direct inspection of lithospheric and asthenospheric materials (Bodinier and Godard, 2014); however, the original geodynamic setting and significance of tectonically emplaced mantle is always ambiguous, owing to syn- and post-emplacement reworking (Bodinier and Godard, 2014; Menzies and Dupuy, 1991). Orogenic garnet peridotites typically occur in dispersed ultramafic bodies within collisional mountain belts, and offer an excellent opportunity to address these issues. These ultramafic rocks within deeply continental subducted zone not only can provide crucial information regarding lithospheric evolution and crust–mantle interactions at convergent boundaries (Brueckner et al., 2010), but also can provide primary constraints on geodynamic models of the orogen's evolution (Van Roermund, 2009a, Van Roermund, 2009b). Based on petrochemistry and tectonic evolution, orogenic garnet peridotites have commonly been classified as ‘crustal’ and ‘mantle’ origin (Brueckner and Medaris, 2000), which originate from distinct tectonic settings: the ‘crustal’ peridotites originated from mafic-ultramafic magmas that underwent magmatic differentiation in the lower continental crust prior to subduction (Brueckner and Medaris, 2000), whereas the ‘mantle’ peridotites are considered to be slices of mantle wedge above the slab or subducted lithospheric mantle trapped by the slab (Beyer et al., 2006; Scambelluri et al., 2006). Comparing these two types of orogenic garnet peridotites within the HP-UHP metamorphic belts can help us better understand the evolutionary history of the lithospheric mantle within deeply continental subduction zone.

The SAT–NQD HP/UHP metamorphic belt hosts a variety of UHP eclogites, HP granulites, and felsic gneisses, which is regarded as the northernmost orogenic collage of the Proto-Tethyan (Zhang et al., 2017). Two contrasting types of garnet peridotite have been identified in the Bashiwake unit and the Luliangshan unit of the SAT–NQD HP/UHP metamorphic belt (Fig. 1). Some research has been conducted on the petrology, geochemistry, and geochronology of these garnet peridotites in the SAT–NQD (e.g. Chen et al., 2017; Li et al., 2013, Li et al., 2015; Liu et al., 2002; Shi et al., 2010; Song et al., 2004, Song et al., 2005a, Song et al., 2005b; Wang et al., 2011; Xiong et al., 2015; Yang and Powell, 2008); however, few studies have considered the relationships between the two contrasting orogenic garnet peridotites as well as the tectonic environment. Moreover, the relationship between the South Altun and North Qaidam terranes also remains controversial. Herein, we present detailed petrological and geochemical data for garnet peridotites in each locality, and 1) explore their petrogenesis and geotectonic environments of formation; 2) outline the genetic relationships between these units and the geodynamic processes of lithospheric evolution and modification. These results will shed light on the geodynamic processes of deeply subducted rocks and their significance for orogenesis.

2. Geological setting

The early Paleozoic Altun–North Qaidam orogenic system extends by the Altun Fault into two parts: the Altun and Qilian–North Qaidam domains (Fig. 1a). From northeast to southwest, the Altun is subdivided into four tectonic units (Fig. 1b): the Archean Milan Complex, the North Altun complex, the Central Altun complex, and the South Altun subduction–collision complex (Zhang et al., 2017). And the North Qaidam (NQD) metamorphic belt also can be divided into four units from east to west (Fig. 1a), including: (1) the Yuka-Luofengpo unit, (2) the Luliangshan unit, (3) the Xitieshan unit, and (4) the Dulan unit (Song et al., 2014; Zhang et al., 2017).

2.1. The Bashiwake garnet peridotite-granulite unit in the South Altun

The Bashiwake unit comprises lenses of mafic granulites, garnet peridotite, and eclogite enclosed in felsic granulites (Fig. 1c, Fig. 2a-f). Conventional mineral thermobarometry indicates that these metamorphic rocks experienced HP conditions of 1.8–2.7 GPa and 870–1050 °C, followed by a medium-high pressure (MP) granulite-facies overprint (0.9–1.2 GPa, 780–820 °C) (Guo et al., 2020; Li et al., 2013; Zhang et al., 2005), although UHP conditions have been obtained for the magnesite-bearing garnet peridotites and associated mafic granulites based on exsolution features, such as clinopyroxene and rutile exsolution in garnet and monazite + (Cu_xFe_{1-x})S in apatite (e.g. Liu et al., 2002, Liu et al., 2009; Wang et al., 2011; Dong et al., 2019). Zircon UPb ages of ca. 900 Ma and ca. 500 Ma interpreted as the metamorphic and protolith ages have been acquired for the (U)HP rocks (e.g. Dong et al., 2019; Guo et al., 2020, 2021a; Li et al., 2015, Li et al., 2020a, Li et al., 2020b; Liu et al., 2009; Wang et al., 2011; Zhang et al., 2005, Zhang et al., 2014), while two age clusters (ca. 500 Ma and ca. 450 Ma) of rutile UPb ages have been acquired for the HP/(U)HT metamorphism and reheating event related to the regional Barrovian-type metamorphism (Zhang et al., 2014). Recent work suggests that eclogite-facies partial melting activity occurred at around 491 ± 2 Ma as recorded by zircon U Pb age from the felsic veins within the mafic granulite from the Bashiwake unit (Guo et al., 2021b).

2.2. The Luliangshan garnet peridotite-gneisses unit in the North Qaidam

The Luliangshan unit mainly comprises kyanite-sillimanite-garnet-bearing paragneiss, granitic gneiss, retrograde eclogite, and orogenic peridotites (Fig. 1d). The garnet peridotite block contains dunite, garnet lherzolite, and garnet pyroxenite (Fig. 2g-l) (Chen et al., 2017; Song et al., 2007; Yang and Powell, 2008). P-T conditions of 4.5–6.5 GPa and ~ 1000 °C have been estimated for the garnet peridotite (Song et al., 2004, Song et al., 2005a, Song et al., 2005b). While an HP granulite-facies stage (1.0–1.4 GPa and 720–830 °C) followed by a medium-pressure (0.6–0.9 GPa and 730–850 °C) overprint was proposed for the retrograde eclogite (Zhang et al., 2008). KAr dating of phlogopite has yielded an age of 490 Ma for the garnet peridotites in the Luliangshan unit (Yang and Deng, 1994), while four clusters of SHRIMP UPb zircon ages have been acquired for the garnet peridotites: 457 ± 22 Ma, 423 ± 5 Ma, 397 ± 6 Ma, and 368–349 Ma (Song et al., 2005b). These ages have previously been interpreted as documenting protolith crystallization, UHP metamorphism (>200 km), and two thermal events post-exhumation during subsequent orogenesis, respectively. However, recent work has suggested that the zircons from the garnet peridotites and pyroxenites are metasomatic in origin (Chen et al., 2017; Xiong et al., 2011), and ages of 426 ± 3 and 417 ± 4 Ma are interpreted to record metasomatic reaction by addition of continental fluids/melts during the early stage of exhumation. Recently, orogenic carbonatite associated with the peridotites was recognized in the Luliangshan unit, which was interpreted as having formed due to the recycling of sedimentary carbonates (Li et al., 2018).

3. Petrography

3.1. Garnet peridotites in the Bashiwake unit

Garnet peridotites in the Bashiwake unit show a porphyroblastic texture, with coarse-grained garnet, clinopyroxene, orthopyroxene, and olivine porphyroblasts set in a matrix of fine-grained olivine, pyroxene, amphibole, and spinel (Fig. 3a, f). Large garnet porphyroblasts contain isolated inclusions of clinopyroxene, amphibole, spinel, olivine, and phlogopite (Fig. 3b, c). Intergrowths of fibrous spinel, clinopyroxene, orthopyroxene, and amphibole occur as kelyphitic rims around the garnet, separating the garnet boundary from the matrix (Fig. 3c, d). The kelyphitic rims grow perpendicular to the garnet rims and coarsen outwards from the edges of the garnet (Fig. 3d, e). Rare garnet has been partially replaced by fibrous spinel with diopside (Fig. 3h). Exsolution lamellae were observed within rare clinopyroxene and orthopyroxene porphyroblasts (Fig. 3f, k, l). Amphibole and euhedral phlogopite occur along the boundary of garnet grain (Fig. 3d, g).

3.2. Garnet peridotites in the Luliangshan unit

Garnet peridotites from the Luliangshan unit have a porphyroblastic texture, and primarily comprise of olivine, garnet, clinopyroxene, and orthopyroxene, with minor spinel-chromite and phlogopite. Large garnet (~12 mm in diameter) and clinopyroxene porphyroblasts are settled in a fine-grained matrix consisting of olivine, clinopyroxene, orthopyroxene, amphibole, and serpentine, some of which exhibit 120° triple junctions (Fig. 4a-d). Garnet porphyroblasts contain various inclusions of orthopyroxene, clinopyroxene, and amphibole with minor quantities of spinel, and are surrounded by symplectic aggregates of orthopyroxene + spinel + amphibole + clinopyroxene (Fig. 4i, k, l). Kelyphitic rims of orthopyroxene + spinel + amphibole + clinopyroxene also grow perpendicular to the garnet rim and coarsen outwards from the garnet rims (Fig. 4e), which separate the garnet from the matrix. Some amphibole and phlogopite were observed at the garnet's margin (Fig. 4f). Few clinopyroxene grains contain exsolved orthopyroxene, amphibole, and chromium spinel (Fig. 4g, h, j).

4. Mineral chemistry

4.1. Major elements for minerals

4.1.1. Garnet

Major element composition profiles of garnet grains from each garnet peridotites type are relatively flat. Grains from the Bashiwake area have 53–55 mol% pyrope, 29–32 mol% almandine, 10–11 mol% grossular (Fig. 5a), whereas grains from garnet peridotite in the Luliangshan area are richer in pyrope (67–70 mol%) but poorer in almandine (20–22 mol%) and grossular (6–8 mol%) (Fig. 5b). Garnet in the Bashiwake garnet peridotite has a lower Cr_2O_3 content (0.04–0.23 wt%) than that of garnet in the Luliangshan garnet peridotite, which is within the range of 1.20–1.45 wt % (Fig. 6a, b, Tables S1, S2).

4.1.2. Clinopyroxene

All clinopyroxene porphyroblast in the studied ultramafic rocks is diopside-rich in composition, with grains from the Bashiwake garnet peridotite having low Al_2O_3 (3.19–4.98 wt%) and Na_2O (0.21–0.54 wt%), corresponding to 1–4 mol% jadeite (Jd) and 1–6 mol% Ca-Tschermaks (CaTs) components (Tables S1, S2). There are no obvious compositional discrepancies between clinopyroxene inclusions, kelyphitic clinopyroxene, and matrix clinopyroxene in the Bashiwake garnet peridotite samples, and $Mg^{\#}$ values (Mg/(Mg + Fe)) range from 0.82 to 0.86 (Fig. 6c, d), with low $Cr^{\#}$ values (Cr/(Cr + Al)) (Fig. 7a).

The composition of clinopyroxene porphyroblast from the Luliangshan garnet peridotites varies according to microstructural position. Clinopyroxene porphyroblasts contain $Mg^{\#}$ values of around 0.90–0.94, corresponding to 3–5 mol% Jd and 5–7 mol % CaTs components, while the clinopyroxene within the kelyphite and matrix have slightly lower $Mg^{\#}$ values (0.89–0.91 and 0.86–0.91, respectively). Furthermore, $Mg^{\#}$ values of the clinopyroxene as inclusions in the garnet range from 88 to 90, and exhibit similar overlapping with some of the matrix type (Fig. 6d).

4.1.3. Orthopyroxene

Orthopyroxene in garnet peridotites from the Bashiwake and Luliangshan units show compositional variations, especially in their Al_2O_3 content (Fig. 6e, f). For the Bashiwake garnet peridotites, orthopyroxene inclusions within garnet porphyroblast have a lower enstatite component (77–79 mol%) than that of orthopyroxene porphyroblasts (80–84 mol%). The orthopyroxene inclusions have higher Al_2O_3 contents (3.41–4.46 wt%) than those of orthopyroxene porphyroblasts (2.77–4.01 wt%). Orthopyroxene in the kelyphitedisplay relatively lower $Mg^\#$ values and has similar overlapping Al_2O_3 (3.94–4.56 wt%), Cr_2O_3 (0.01–0.05 wt%), and CaO (0.24–0.37 wt%) contents to those in the matrix (Fig. 6e, Tables S1, S2).

In general, orthopyroxene in Luliangshan garnet peridotites shows obvious compositional variation in different textural settings: porphyroblasts in the Luliangshan garnet peridotite have 78–84 mol% enstatite component, and contain lower Al_2O_3 (0.36–1.12 wt%) contents and higher Cr_2O_3 contents (0.08–0.19 wt%) than those of orthopyroxene in the Bashiwake peridotite. Orthopyroxene grains in the kelyphite and matrix have relatively higher Al2O3 contents and lower Cr_2O_3 contents than those of orthopyroxene porphyroblasts. Further, the inclusions of orthopyroxene exhibit lower $Mg^\#$ values than that of other types of orthopyroxene grains (Fig. 6f).

4.1.4. Olivine

Olivine porphyroblasts in the Bashiwake garnet peridotite have relatively lower forsterite (Fo 80–85 mol%) component and NiO component (0.09–0.22 wt%) than those of olivine porphyroblasts in the Luliangshan garnet peridotite (Fo: 88–91 mol% and NiO: 0.39–0.59 wt%, Fig. 7b, Tables S1, S2). The olivine grains in each garnet peridotite type exhibit only minor compositional variation in Mg$^{\#}$ values, although olivine in the Luliangshan garnet peridotite shows a relatively higher NiO component (Fig. 7b). Further, olivine inclusions display similar compositions of Mg$^{\#}$ values and NiO component (Fig. 7b).

4.1.5. Spinel

Spinel occurs as inclusions in kelyphite structures and as a matrix mineral. For the Bashiwake garnet peridotites, spinel inclusions in garnet have 3.43–4.36 wt% Cr_2O_3, kelyphitic spinel has 2.47–3.16 wt% Cr_2O_3 (Fig. 7c, d, Tables S1, S2), although matrix grains are more variable (0.28–5.61 wt% Cr_2O_3). Mg$^{\#}$ values of all spinel grains range from 0.56 to 0.69. In contrast, spinel from the Luliangshan garnet peridotites has slightly higher Mg$^{\#}$ values (0.59–0.75) and extremely high Cr_2O_3 contents (5.70–54.62 wt%) compared to those in the Bashiwake garnet peridotites, and matrix grains are richer in Cr_2O_3 (42.24–54.62 wt%) than those of kelyphitic grains (5.70–14.74 wt%) and inclusion in garnet (23.12–48.52 wt%).

4.1.6. Amphibole

Amphibole in Bashiwake garnet peridotites is highly calcic (Tables S1, S2) and mostly pargasite in composition (amphibole classification diagrams in Electronic Appendix Part 4). Amphiboles from Luliangshan garnet peridotites contain calcic amphiboles with high Mg$^{\#}$ values (0.85–0.92), and these amphiboles range in composition from pargasite-hornblende to edenite-hornblende (Fig. S1).

4.1.7. Phlogopite

In both garnet peridotite types, phlogopite occurs as inclusions in garnet porphyroblasts or as a matrix phase. Phlogopite inclusions are often euhedral, and those in the matrix are located adjacent to garnet rims. In Bashiwake units, the phlogopite is intergrown with amphibole around the boundary of garnet porphyroblasts. The $Mg^{\#}$ values of phlogopite inclusions and matrix grains in these samples are 0.88–0.90 and 0.91–0.92, respectively. Phlogopite inclusions have slightly higher MgO and Cr_2O_3 contents than those of phlogopite grains in the matrix. Phlogopite in Luliangshan garnet peridotite has an $Mg^{\#}$ value of 0.91–0.93 (Tables S1, S2).

4.2. Trace elements for minerals

4.2.1. Garnet

The REEs and trace elements of garnet grains in the two contrasting garnet peridotites are shown in Table S3. The garnet from both Bashiwake and Luliangshan units exhibits a steep increase from La to Sm and then a more subdued increase from Sm to Lu (Fig. 8a). As shown in the primitive mantle (PM)-normalized spider diagrams, all of the garnet grains from the two ultramafic complexes exhibit strong negative Ba, Sr, and Li anomalies relative to adjacent elements, and display various extents of enrichment of high field strength elements (HFSEs) (Fig. 8b).

4.2.2. Clinopyroxene and amphibole

Clinopyroxene porphyroblast exhibits REE patterns that become progressively depleted from LREE to HREE (Fig. 8c). Some clinopyroxene porphyroblasts display sinusoidal or humped REE patterns, representing potential evidence for metasomatic alteration of the garnet peridotites. Amphibole from both peridotite units shows a PM-normalized pattern similar to that of clinopyroxene, but has slightly higher total REE abundances (Fig. 8c).

In the PM-normalized diagram, clinopyroxenes in Luliangshan garnet peridotites show strong depletion of HFSE, negative anomalies for Ti, and strong positive anomalies for Pb and Li, while those of Bashiwake garnet peridotite exhibit negative anomalies of Sr and positive anomalies of Li, and they are relatively enriched in highly incompatible elements. Amphibole is strongly enriched in Li and Pb relative to REEs, but has a slight negative anomaly in Sr, Zr, and Ti compared to neighboring elements (Fig. 8d).

4.2.3. Olivine and orthopyroxene

The REEs of olivine and orthopyroxene grains in the two contrasting garnet peridotites are shown in Fig. 8e. Both of them exhibit relatively depleted and flat patterns of REEs. Further, orthopyroxene porphyroblast displays marked positive Ti, Pb, and Li anomalies and significant variations in highly incompatible elements (Fig. 8f). Olivine displays strong positive Li, U, and Pb anomalies relative to neighboring elements. Orthopyroxene and olivine often have 0.1–0.01 times their concentration in lithophile elements, and are significantly depleted compared to PM.

5. Metamorphic evolution and *P-T* estimates

5.1. Metamorphic evolution

Based on micro-textural analyses and mineralogical investigation, four stages have been identified for the two contrasting garnet peridotites. And the idealized equilibrium mineral assemblages considered to have been stable at each of the recognized stages in the metamorphic evolution of the two contrasting garnet peridotites are outlined in Table S4. Although mineral assemblages in each stage of the two contrasting garnet peridotites show a minor difference, both of them have experienced a clockwise P-T path evolution. Herein, a comprehensive description of the metamorphic evolution of the two types of garnet peridotites is performed. And the detailed descriptions of each stage are as follows: (I) crystallization of precursor minerals that now exist as inclusions (e.g. spinel, olivine, clinopyroxene), which record the mineralogy of the primary protolith; (II) peak (U)HP/UHT metamorphism is demonstrated by the mineral assemblage of large porphyroblasts occurring in the fine-grained matrix; (III) granulite-facies retrogression during decompression is manifested by kelyphite development around coarse-grained garnet porphyroblasts or symplectites that formed during decompression and exhumation; and (IV) a final amphibole-greenschist-facies retrogressive stage characterized by recrystallization of amphibole + serpentine + phlogopite + chlorite + magnetite.

5.2. ***P-T*** estimation

5.2.1. Conventional thermobarometer

The measured compositions and observed microstructural relationships for each evolutionary stage in the studied peridotites allow appropriate geothermobarometers to calculate equilibrium *P* and/or *T* conditions for these garnet-bearing ultramafic rocks. The garnet-orthopyroxene barometers (Brey and Köhler, 1990) were applied to estimate the pressure, and garnet-olivine (O'Neill and Wood, 1979), the two-pyroxene (Brey and Köhler, 1990), and garnet-clinopyroxene (Krogh Ravna, 2000; Powell, 1985) thermometers were used for temperature estimation.

Given that inclusions in garnet are likely to have experienced compositional change post-entrapment due to the high temperatures of subsequent metamorphism, quantitive *P-T* conditions were unable to determine for stage I. For stage II, the thermometer/barometer combination gave *P-T* conditions of 1.8–2.5 GPa and 900–1050 °C for the Bashiwake garnet peridotite, and 3.9–5.4 GPa and 890–1020 °C for the Luliangshan garnet peridotite (Table S5).

For stage III, the kelyphitic Cpx–Opx pairs gave temperature conditions of 710–800 °C and 700–840 °C for the Bashiwake and the Luliangshan garnet peridotites, respectively, at a low crustal pressure of 10–12 kbar (the pressure was fixed based on the associated HP granulites, Zhang et al., 2005, Zhang et al., 2008, Table S5).

5.2.2. REE-based thermobarometer

As major elements typically diffuse faster than trace elements and REEs, corroborating evidence for the thermal evolution of the studied samples was obtained using the thermobarometer of REE-in-garnet-clinopyroxene (Sun and Liang, 2015), which should be less sensitive to potential post-crystallization modification of primary compositions. The REE contents of garnet and clinopyroxene porphyroblasts from the two contrasting garnet peridotites were plotted in the inversion diagrams of (lnD-A) vs. B, and a best-fit line was drawn using a robust regression method (Fig. 9). This technique produced stage II *P–T* conditions of 895–920 °C and 2.0–2.9 GPa, and

800–910 °C and 2.8–3.8 GPa for the Bashiwake and Luliangshan garnet peridotite, respectively (Fig. 9).

6. Whole-rock geochemistry

6.1. Major and trace-elements geochemistry

Whole-rock major and trace element data for the two contrasting garnet peridotites from the Bashiwake and Luliangshan units are shown in Table S6. The Bashiwake garnet peridotites have a relatively lower MgO content but higher TiO_2, CaO, and FeO compositions than those of the Luliangshan garnet peridotites.

The trace element and REE contents of the Bashiwake garnet peridotites are slightly higher than the Luliangshan garnet peridotites. For example, the Bashiwake garnet peridotites contain high ΣREE (24.5–49.5 ppm), and exhibit LREE-enriched patterns with high $(La/Yb)_N$ (3.19–4.34) values. In contrast, the Luliangshan garnet peridotites contain lower ΣREE (2.92–6.69 ppm) and have low $(La/Yb)_N$ (0.80–1.62), alongside flat chondrite-normalized REE patterns with no apparent anomalies (Fig. 10a). PM-normalized spider diagrams are given in Fig. 10b. Most Bashiwake garnet peridotites exhibit weak negative Ti and Nb anomalies, and have strong positive U anomalies. The Luliangshan garnet peridotites show general enrichment trends from moderately to highly incompatible elements. They exhibit pronounced positive Li, U, and Pb anomalies, and weak negative Zr, Hf, Nb, and (rare) Ti anomalies relative to their neighboring elements.

6.2. SrNd isotopic composition

Measured SrNd data for representative garnet peridotites samples are given in Table S7. Garnet peridotites in the Bashiwake unit show relatively lower $^{87}Sr/^{86}Sr$ values of 0.7072 to 0.7091 compared to values for representatives from the Luliangshan unit, which are also more dispersed (0.7130–0.7247). Samples from the Bashiwake unit have slightly higher $^{143}Nd/^{144}Nd$ values than the results from the Luliangshan unit, with ranges of 0.5123–0.5127 and 0.5118–0.5122, respectively. The $\varepsilon_{Nd\ (t=779\ Ma)}$ values of the Bashiwake garnet peridotites range from −0.9 to 2.6, and $\varepsilon_{Nd\ (t=500\ Ma)}$ values range from −2.6 to 0.2. These results of the Bashiwake garnet peridotite are consistent with the previous SrNd isotopic data ($^{87}Sr/^{86}Sr$ ratios ranging from 0.707204 to 0.710016 and $^{143}Nd/^{144}Nd$ ratios ranging from 0.512354 to 0.512418, Li et al., 2015). In contrast, the Luliangshan garnet peridotites yield negative $\varepsilon_{Nd\ (t=500\ Ma)}$ values ranging from −8.4 to −4.3.

6.3. Whole-rock PGE characteristics

The whole-rock PGE characteristics of garnet peridotites from both study regions are listed in Table S8. The total PGE contents for both garnet peridotite types are lower than that of PM (28.5 ppb, see Barnes et al., 1988), being 0.55–0.77 ppb in Bashiwake samples and 11.5–19.5 ppb in Luliangshan samples. The Bashiwake garnet peridotites have relatively low and constant PGE contents, with Os contents of 0.03–0.07 ppb, Ir contents of 0.04–0.07 ppb, Ru contents of 0.03–0.06 ppb, Rh contents of 0.02–0.03 ppb, Pt contents of 0.20–0.36 ppb, and Pd contents of 0.20–

0.24 ppb (Table S8). In contrast, the Luliangshan garnet peridotites are relatively enriched in Os (2.24–3.54 ppb), Ir (1.38–2.27 ppb), Ru (2.78–4.68 ppb), Pt (1.29–3.79 ppb), Pd (2.58–4.87 ppb), and Au (0.74–2.20 ppb).

In a Primitive-mantle-normalized PGE diagram (Barnes et al., 1988), the Luliangshan garnet peridotites show nearly flat patterns with strongly negative Pt anomalies (Fig. 11). In contrast, the Bashiwake garnet peridotites deplete PGEs and unusual patterns with a negative slope from Ru to Pd (Fig. 11).

7. Discussion

7.1. Metamorphic evolution of the garnet peridotites

Spinel inclusions in garnet porphyroblasts from the Bashiwake garnet peridotites suggest a spinel peridotite protolith (stage I), which is stable at low-P and HT conditions of <1.5 GPa and 900–1000 °C (Gasparik, 1987; Herzberg et al., 1990). Based on the interpreted peak metamorphic assemblage (stage II), peak *P*–*T* conditions of 900–920 °C and 2.0–2.9 GPa were defined by the REE-based thermobarometer, although this pressure is higher than those of conventional thermobarometry also applied in this study. In addition, while exsolution features of clinopyroxene and rutile exsolution in garnet grains indicate that garnet peridotites in the Bashiwake unit have experienced UHP metamorphism (Liu et al., 2002; Wang et al., 2011), whether or not they reached UHP conditions is controversial (Li et al., 2020b, Li et al., 2021; Zhang et al., 2017). Here, the results calculated by the REE-based thermobarometer in this study indicate that this is a possibility, which in turn suggests that the garnet peridotites must have been transported to great depths within the mantle (>100 km; Palin et al., 2017), most likely during steep subduction associated with convergent plate margin activity. Subsequent decompression was nearly isothermal, as indicated by the granulite-facies coronal texture around garnet porphyroblasts, described by the reaction Grt + Ol = Spl + Cpx + Opx. During this nearly isothermal decompression, peak mineral assemblage became unstable, forming Spl + Opx + Cpx ± Amp symplectic coronas (stage III). The observed kelyphite mineral assemblage matches the stable field of Spl + Cpx + Opx + Amp, with temperatures ranging from 750 °C to 820 °C and pressures lower than ten kbar. Subsequently, the Bashiwake garnet peridotite experienced amphibolite-facies retrogression and serpentinization (stage IV). Similar metamorphism is also documented for the associated felsic and mafic granulites in the region (Zhang et al., 2005), suggesting that garnet peridotites and their surrounding rocks share a similar metamorphic exhumation history.

The Luliangshan garnet peridotites preserve a primary (stage I) mineral assemblage representative of spinel lherzolite, with relic inclusions of Spl + Cpx + Amp + Ilm ± Opx in garnet porphyroblasts, which stabilize at low pressures and high temperatures. Primary Spl, Opx, and Cpx reacted to form garnet during subduction during UHP metamorphism. Calculated *P–T* conditions for stage II metamorphism of 800–910 °C and 2.8–3.8 GPa, constrained here by the REE-based thermobarometer, are slightly lower than those estimated by Song et al., 2005a, Song et al., 2007, although Yang and Powell (2008) acquired *P–T* conditions of >700 °C and 3.0–3.5 GPa using calculated phase equilibria on *P–T* pseudosections, in conjunction with constraints on the dehydration of serpentinites within the stability field of the diamond. Together, these results suggest that the garnet peridotites in the Luliangshan unit very likely experienced UHP metamorphism during peak stage II subduction. During exhumation, the garnet porphyroblast was substituted by a kelyphitic assemblage of Opx + Spl + Amp + Cpx in the garnet peridotite, suggesting a granulite-facies metamorphism overprint (stage III), followed by an amphibolite-chlorite facies retrograde event during residence in the continental crust (stage IV).

The microtextures described here and *P–T* conditions calculated using mineral composition data indicate that both contrasting garnet peridotite types experienced a complex evolutionary history. Combining with our results and previous data, a clockwise *P–T* path can be deduced for the two contrasting garnet-bearing ultramafic rocks, recording subduction to mantle depths, compression, and heating due to collisional orogenesis and metamorphism, and later decompression and cooling (Fig. 12). The decompression sequence from granulite-facies to amphibolite-greenschist-facies reflects uplift and tectonic exhumation through upper crustal levels.

7.2. Provenance of the two contrasting garnet peridotites in SAT–NQD

7.2.1. Neoproterozoic magmatic cumulates for the Bashiwake ultramafic complex

The nature and petrogenesis of orogenic garnet peridotites have long been discussed, and many studies demonstrated that garnet peridotites within orogenic belts are of mantle-derived origin (Brueckner and Medaris, 2000; Zhang et al., 2000). The Bashiwake garnet peridotites have low MgO and Cr contents and very high FeO and TiO_2 contents, and they also have low PGEs and Ni abundances, which are consistent with the features of type B garnet peridotite (metamorphosed mafic–ultramafic complexes, Zhang et al., 2000). Further, the compositions of olivine porphyroblasts do not drop the range of mantle olivine array in the diagram of $Mg^{\#}$ vs. NiO (Fig. 7b). Conversely, they are closer to the area of orogenic cumulative dunites (Fig. 7b). Moreover, inherited zircon's positive Hf isotope value (1.66–3.38; Li et al., 2015) suggests a mantle signature for the protolith, and compared with the inferred composition of the primitive mantle (McDonough and Sun, 1995), which is very different, the Bashiwake garnet peridotite most likely formed as a cumulate (i.e. olivine and pyroxene) within a layered mafic intrusion emplaced at shallow levels of the lithosphere. This is also supported by the trends of some major elements ($Mg^{\#}$ vs. FeO, CaO, and Al_2O_3, Li et al., 2015) and Ir vs. Ir/(Pt + Pd) concentration analysis (Fig. 13), which suggests that the Bashiwake garnet peridotite is related to cumulate peridotites, rather than being a typical lithospheric mantle peridotite.

Several geochemical characteristics of the Bashiwake garnet peridotites suggest that they may have been contaminated by crustal materials, modified by metasomatism, or both. Firstly, these orogenic garnet peridotites in the Bashiwake area show LREE-enriched characteristics, and they are enriched in incompatible trace elements, large ionic lithophile elements (LILE), and high field strength elements (HFSE). Secondly, some metasomatic minerals, such as phlogopite, apatite, and zircon, indicate the extent of metasomatic influence. Similar cases have been reported in the typical orogenic belts (Marocchi et al., 2007; Scambelluri et al., 2006). Lastly, $Cr^{\#}$ vs. $Mg^{\#}$ ratios (Fig. 7a) of clinopyroxene suggested that the garnet peridotites in the Bashiwake area have suffered refertilization. Moreover, Th, U enrichments in the garnet, enrichment of LILEs and HFSEs in orthopyroxene, and humped REE patterns in clinopyroxene also support the refertilization. Clinopyroxene and amphibole in the Bashiwake garnet peridotite show pronounced LILE enrichment (LREEs, Ba, and Sr compositions, Fig. 8), which is similar to those in some other orogenic peridotites has been interpreted as a product of contamination by crustal derived metasomatic agents (Rampone and Morten, 2001). We, therefore, interpret that the Bashiwake garnet peridotites were refertilized by crustal-derived hydrous melts/fluids. Moreover, the garnet peridotites from the Bashiwake unit also show minor variation in $^{143}Nd/^{144}Nd$, but a slightly broad range in $^{87}Sr/^{86}Sr$. The ranges of $\varepsilon_{Nd(t)}$ and $(^{87}Sr/^{86}Sr)_i$ for these samples are beyond or near the zone of ‘mantle array’ (line of depleted mantle evolution). Such a characteristic may be interpreted as the original magma having been derived from the mantle, but was later isotopically and chemically modified via crustal contamination or metasomatism (Chavagnac and Jahn, 1996). And these geochemical features of the garnet peridotites in the Bashiwake unit are consistent with the results of crustal peridotites from other massifs, such as Dabie-Sulu terrane (Zhang et al., 2000) and Bory of Gfohl Nappe (Medaris et al., 2005). In another aspect, zircon UPb ages indicate that the magmatic protolith of the Bashiwake mafic-ultramafic complexes crystallized before 801–779 Ma (Li et al., 2015, Li et al., 2021). The geological activity of this age is common in northern Tibet and shows an affinity with the breakup of the Rodinia supercontinent (Li et al., 2020b, Li et al., 2021; Liu et al., 2012). The extension during the Neoproterozoic Era resulted in the production of the mafic-ultramafic magmas generated from the upwelling asthenosphere. And it formed mafic and ultramafic igneous rocks in the South Altun-North Qaidam orogenic belts. Thus, the nature and protolith of the garnet peridotites in the Bashiwake unit was likely a mafic-ultramafic cumulate sequence that crystallized from mantle-derived magma during Neoproterozoic Era. This magma was probably emplaced into the crust or uppermost mantle, and it was later affected by metasomatism or crustal-derived contamination, and then metamorphosed with the adjacent terrane during the Early Paleozoic.

7.2.2. The Luliangshan garnet peridotite as a fragment of a metasomatic mantle wedge

The Luliangshan garnet peridotites have previously been proposed as (1) residual mantle depleted after melt extraction (Yang and Deng, 1994), (2) a serpentinized seafloor peridotite (Yang and Powell, 2008), (3) an Alaskan-type magmatic cumulate (Song et al., 2007, Song et al., 2009, Song et al., 2014), and (4) refertilized Archean mantle (Chen et al., 2017; Shi et al., 2010; Xiong et al., 2014, Xiong et al., 2015). These origins are mutually exclusive, and this uncertainty is problematic for reconstructing the geological history of the South Altun-North Qaidam orogenic belt. Several characteristics of these units are key to interpreting their origin. Experimental data suggest that lizardite observed in serpentinized units forms at the low temperature (<200 °C) via the reaction olivine (forsterite) + fluid = brucite + lizardite; hence, it cannot remain stable at higher grades during prograde subduction metamorphism (Evans, 2004). Layering in these units may also not necessarily be of cumulate origin, but could form by melt-rock reactions or metamorphic differentiation during migmatization, and differences in LuHf isotope characteristics between the garnet peridotite and pyroxenite suggest the Luliangshan Massif is not a cumulate (Xiong et al., 2014, Xiong et al., 2015). Furthermore, our new data showing PGE abundance and Ir vs. Ir/(Pt + Pd) ratios suggest that the Luliangshan garnet peridotite is a refractory lithospheric mantle (Fig. 11, Fig. 13).

It is well known that identifying the protoliths of mantle-derived garnet peridotites is difficult, owing to intense fluid- and/or melt-driven alteration during subduction (Vrijmoed et al., 2013). However, dunites from orogenic belts can be of more use in exploring the origins of orogenic garnet peridotites and their geodynamic history before subduction, as they can be more resistant to metasomatic change than garnet peridotite (Brueckner et al., 2002). Garnet peridotite from the Luliangshan unit has similar characteristics to that of interlayered dunite being highly refractory, and having very high $Mg^{\#}$ values (Shi et al., 2010; Yang and Deng, 1994). Whole-rock major and trace elements and ReOs geochemistry suggest that the dunites from the Luliangshan unit are slices of Archean mantle, whereas the garnet peridotites generated when the dunites were metasomatized by mafic melts during the Paleoproterozoic Era (Shi et al., 2010). Thus, the protoliths of the

Luliangshan garnet peridotite may be refractory peridotite, akin to the associated dunite, although they have higher CaO and Al_2O_3 contents and lower $Mg^{\#}$ values than those of the dunite. The garnet peridotite may thus record refertilisation by cryptic melt or infiltrated fluid. The REE patterns of the garnet peridotites in the Luliangshan unit are parallel to those of surrounding and interlayered dunites and garnet pyroxenites, and do not similar to those of residual peridotites with typical LREE-depleted patterns (Beyer et al., 2006; Clos et al., 2014). This feature was interpreted as mixing between refractory dunites and percolating melts (Le Roux et al., 2007; Saal et al., 2001), and their higher Al, Ca, and LILE contents, and LREE enrichment compared to refractory dunites likely resulted from refertilization or metasomatism (Scambelluri et al., 2006). Moreover, previous studies suggested that metasomatic minerals of amphibole, phlogopite, zircon, and carbonate minerals around garnet porphyroblasts suggest metasomatism by hydrous fluids and/or water-rich or carbonatitic melts (Beyer et al., 2006). Furthermore, enrichment in Sr and LREE, positive Pb anomalies, and HFSE depletion in clinopyroxene imply metasomatism by either volatile-bearing fluids (Ionov et al., 1997; Stalder et al., 1998), volatile-rich silicate melts (Zangana et al., 1999) or carbonatitic melts (Yaxley and Green, 1998).

Experimental data indicate that the partition coefficients of HREEs, Si, Zr, Al, and Ti between clinopyroxene and melt in the carbonate system are higher than those in the silicate system (Blundy and Dalton, 2000), although the fractionate of REE and HFSE resulted from carbonatite melts is more effective than the results generated by silicate melt or volatile-rich fluid (Blusztajn and Shimizu, 1994). Other partitioning experiments on the trace elements between volatile-rich fluids and minerals (Keppler, 1996) suggest that the melts and fluids have resembled capabilities in transporting LILE elements (e.g., Sr, Ba). Amphibole and phlogopite are the modal metasomatic minerals in orogenic garnet peridotites or mantle xenoliths (Ionov et al., 1997). Both minerals can provide critical constraints on the style and cause of metasomatic processes. Their compositions reflect the nature (fluids or melts) and trace-element engagement of the proxy from which they crystallized (Ionov et al., 1997). In particular, amphiboles crystallized from Si-rich melts are commonly enriched in LILE and HFSE, with no obvious fractionation (Ionov et al., 1997). In contrast, amphiboles enriched in LILE but depleted HFSE occur in orogenic peridotites metasomatized by carbonated materials (Rampone and Morten, 2001). Meanwhile, low Ti/Eu ratios and the LREE enrichment coupled with noticeable HFSE depletion in clinopyroxene have also been significant hints of metasomatism related to carbonatite melts (Coltorti et al., 1999; Klemme et al., 1995). Furthermore, the clinopyroxenes in the Luliangshan garnet peridotite display low Ti/Eu ratios and relatively high Ca/Al ratios (Xiao et al., 2023, Fig. S2) that are suggestive of carbonate metasomatism. Thus, we suggest that the garnet peridotites from the Luliangshan unit experienced metasomatism by carbonatitic melts and/or volatile-rich fluids, with orogenic carbonatites that occur close to the ultramafic bodies (Li et al., 2018) supporting this interpretation. In addition, the geochemical characteristics of strong negative whole-rock $\varepsilon_{Nd(t)}$ and zircon $\varepsilon_{Hf(t)}$ (Xiong et al., 2011), enrichment of LREE and mobile elements, and the exsolution features or inclusions of hydrous minerals (Song et al., 2005a; Yang and Powell, 2008) indicate that the protoliths of the garnet peridotite in the Luliangshan unit are the fragment from metasomatized mantle wedge above a subducting slab.

7.3. Geodynamical evolution of lithospheric mantle in the SAT–NQD

In the South Altun region, zircon UPb ages of 503.3 ± 3.1 Ma and 495.7 ± 2.7 Ma for garnet peridotite (Li et al., 2015) are consistent with zircon metamorphic ages determined for associated eclogite, felsic granulites, and mafic granulites (Guo et al., 2020, Guo et al., 2021a; Li et al., 2015, Li et al., 2020a, Li et al., 2020b, Li et al., 2021; Wang et al., 2011; Zhang et al., 2005). Inclusions of high-Jd clinopyroxenes, garnet, orthopyroxene, and olivine in the zircon grains suggest that these zircons may be formed during HP/(U)HT metamorphism and sourced from fluids crept from the continental crust. Furthermore, SmNd isochron age (493 ± 24 Ma) was also derived from whole-rock compositions and those of separated clinopyroxene and garnet for the garnet pyroxenite (Li et al., 2015). These results are consistent with the zircon UPb ages obtained for the peak metamorphism in UHP eclogites with coesite pseudomorphs in the Jianggelesayi area (Liu et al., 2012) and UHP eclogites with coesite inclusions in the Qingshuiquan area (Gai et al., 2017). We interpret the similarity in age between the garnet peridotites from the Bashiwake unit and the eclogites from the Jianggelesayi and Qingshuiquan units to suggest that they experienced the same UHP metamorphic event from the continental subduction to collision in the South Altun at the Cambrian-Ordovician boundary.

In the North Qaidam, KAr dating of phlogopite has yielded an age of 490 Ma for the garnet peridotites in the Luliangshan unit (Yang and Deng, 1994), while four clusters of SHRIMP UPb zircon ages have been acquired for the garnet peridotites: 457 ± 22 Ma, 423 ± 5 Ma, 397 ± 6 Ma, and 368–349 Ma (Song et al., 2005b). These ages have previously been interpreted as documenting protolith crystallization, UHP metamorphism (>200 km), and two thermal events post-exhumation during subsequent orogenesis, respectively. However, recent work has suggested that the zircons from the garnet peridotites and pyroxenites are metasomatic in origin (Chen et al., 2017; Xiong et al., 2011), and ages of 426 ± 3 and 417 ± 4 Ma are interpreted to record metasomatic reaction by addition of continental fluids/melts during the early stage of exhumation. Moreover, UPb zircon dating integrated with petrology and microstructural analysis suggests that the associated retrograde eclogite and host country gneisses in the Luliangshan area experienced at least three metamorphic stages: eclogite-facies (>450 Ma), high-pressure granulite-facies (450 Ma, zircon grains with inclusions of garnet, clinopyroxene, rutile, and plagioclase) and medium pressure granulite-facies (ca. 425 Ma, zircon domains with inclusions of sillimanite, orthopyroxene, and plagioclase; Zhang et al., 2008, Zhang et al., 2017). In addition, a granite pluton with a similar emplacement age of 428 ± 10 Ma has been identified in the Luliangshan unit (Fig. 1d), and formed due to decompression-related partial melting of (meta)sedimentary rocks that were part of subducted continental crust during the same event related to the MP granulite-facies metamorphism (Zhang et al., 2017).

Garnet peridotites and (U)HP metamorphic rocks from the Bashiwake unit in the South Altun record (U)HP metamorphism at ca. 505–475 Ma, while garnet peridotites and associated (U)HP rocks from the Luliangshan unit in the North Qaidam have experienced the (U)HP metamorphism before ca. 450 Ma. We combine our new data with previous work to produce a tectonic model for the evolution of the two contrasting ultramafic rocks and surrounding rocks in each studied region of the SAT–NQD metamorphic belt.

Following Rodinia breakup, upwelling mafic-ultramafic magmas that formed precursors to the Bashiwake garnet peridotite have been emplaced into the lower continental crust or uppermost subcontinental mantle lithosphere, creating a sequence of mafic-ultramafic cumulate before 801–779 Ma (Li et al., 2020b, Li et al., 2021; Fig. 14a). Subduction of oceanic lithosphere must have taken place before ca. 517 Ma, as shown by the emplacement and crystallization of O-type adakitic plutons in the Huangtuquan unit (Kang, 2014) (Fig. 14b). During the Early Paleozoic era, continent–continent collision (Fig. 14c) transformed spinel (Stage I) in these peridotites to garnet (Stage II), and these intrusive ultramafic bodies, alongside associated mafic and felsic rocks (mafic and felsic granulite origins), were transported to greater depths within the mantle. After HP/(U)HT metamorphism, the buoyant subducted lithologies, consisting of felsic rocks and associated mafic-ultramafic rocks, experienced exhumation and entrainment into the lower crust, and then experienced an ordinary Barrovian metamorphism at ca. 450 Ma (Fig. 14d), which was associated by extensive magmatism (Kang et al., 2013; Li et al., 2020b, Li et al., 2021; Zhang et al., 2017), with rutile UPb ages of felsic and mafic granulites (ca. 450 Ma) considered being the post-peak reheating event, as constrained by Zr-in-rutile thermometry (Zhang et al., 2014). This subduction-exhumation scenario resembles models for the generation of migmatitic domes (Vanderhaeghe, 2009), and has been effectively used to interpret the evolution of the garnet peridotite-granulite association in the Bohemia Massif (Kusbach et al., 2015; Lexa et al., 2011).

The Luliangshan garnet peridotite experienced a notably different geological history. Subduction of the Qilian Ocean lithosphere occurred at ca. 520–460 Ma (Fig. 15a), while closure led to continental collision beginning at 450–440 Ma, when fragments of mantle wedge were incorporated into the subducting slab and were subsequently subducted together with the downgoing plate (Fig. 15b). Due to buoyant and doming processes, the UHP slab was exhumed at ca. 430–400 Ma (Fig. 15c). These ultramafic rocks exhumed to the middle-lower crust experienced the Barrovian metamorphism, and then shared the final retrograde amphibolite to greenschist-facies overprints, as is common in Himalayan-type orogenic environments (e.g. Palin et al., 2014).

8. Conclusions

1) The protoliths of the Bashiwake garnet peridotites in the South Altun were a sequence of mafic-ultramafic cumulates from an asthenosphere-derived magma that emplaced into the continental crust during the Neoproterozoic, which then suffered crustal-derived contamination or metasomatism. This sequence of mafic-ultramafic

rocks and associated country (felsic) rocks were then subducted to mantle depths during the Early Paleozoic.

2) The protolith of the Luliangshan garnet peridotite in the North Qaidam is a slice of an overlying Archean mantle wedge, which follows the deep subduction and continental collision as well as the metasomatism by fluids released from subducted crustal materials, and the garnet peridotite was then exhumed together with this subducted continental crust.

3) Both garnet peridotites from the Bashiwake and Luliangshan units of the SAT–NQD HP/UHP terrane record significantly different metamorphic evolutionary and initial tectonic settings.

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Figure captions:

Fig. 1 Geological sketch map of the Altun–Qilian–Kunlun (AQK) orogenic system in the northern Tibet (a) (after Zhang et al., 2017); Simplified geological map showing tectonic units of the Altun (b) (after Zhang et al., 2005a) and sketch map of garnet peridotite-HP granulite unit in the Bashiwake area, South Altun (c) (after Li et al., 2020b); Geological sketch maps of the Luliangshan peridotite massif in the North Qaidam Orogen (d) (after Li et al., 2018a).

Fig. 2 Photographs showing field characteristics of the studied garnet peridotite in the Bashiwake area (a-f) and the Luliangshan area (g-l), South Altun-North Qaidam orogenic belt.

Fig. 3 Photomicrographs and backscattered electron (BSE) images showing petrographic features and mineral assemblages of the representative garnet peridotite samples in the Bashiwake area, South Altun (some figures are from Li et al., 2013). (a) Porphyroblast of garnet (Grt), olivine (Ol), clinopyroxene (Cpx), and orthopyroxene (Opx) in the garnet peridotite. (b-c) Inclusions of spinel (Spl), clinopyroxene, and phlogopite (Phl) in the garnet porphyroblast. (d-e, j) Detailed texture of kelyphite (Kel) around garnet. (f) Porphyroblast of clinopyroxene, orthopyroxene, and garnet in the fine-grained matrix. (g) Phlogopite (Phl) and amphibole (Amp) around garnet. (h) Fine-grained assemblage of spinel and tremolite

(Tr), resulting from breakdown of garnet grain. (i) Structure of transformation beween spinel and magnetite (Mag). (k) Exsolution lamellae of clinopyroxene in orthopyroxene porphyroblast. (l) Exsolution lamellae of orthopyroxene in clinopyroxene porphyroblast.

Fig. 4 Photomicrographs and backscattered electron (BSE) images showing petrographic features and mineral assemblages of the representative garnet peridotite samples in the Luliangshan area, North Qaidam. (a-c) Porphyroblast of garnet (Grt), olivine (Ol), clinopyroxene (Cpx), and orthopyroxene (Opx) in the garnet peridotite. (d) Clinopyroxene insetted in the matrix mainly consisting of olivine and serpentine (Serp). (e) Inclusion of clinopyroxene in the garnet porphyroblast. (f) Phlogopite (Phl) and amphibole (Amp) with rare carbonate minerals around garnet pseudomorph replaced by the kelyphite. (g-h, j) Exsolution textures in clinopyroxene porphyroblast. (i) Inclusions of spinel and amphibole in the clinopyroxene porphyroblast. (k-l) coronic texture around garnet porphyroblast.

Fig. 5 Compositional profiles of garnet porphyroblasts from the garnet peridotites in the Bashiwake area (a) and the Luliangshan area (b), South Altun-North Qaidam orogenic belt.

Fig. 6 Compositional variation of $Mg^{\#}$ versus Cr_2O_3 (a, garnet), CaO versus Cr_2O_3 (b, garnet), $Mg^{\#}$ versus Al_2O_3 (c) and Na_2O (d, clinopyroxene), $Mg^{\#}$ versus Al_2O_3 (e) and

Cr_2O_3 (f, orthopyroxene) for minerals from the garnet peridotites in the Bashiwake area and Luliangshan area, South Altun-North Qaidam orogenic belt.

Fig. 7 Compositional variation of $Mg^\#$ versus NiO (a, olivine), $Mg^\#$ versus $Cr^\#$ (b, clinopyroxene), $Mg^\#$ versus $Cr^\#$ (d, spinel) and $Mg^\#$ in olivine versus $Cr^\#$ in spinel (d) for minerals from the garnet peridotites in the Bashiwake area and Luliangshan area, South Altun-North Qaidam orogenic belt.

Fig. 8 Chondrite-normalized (McDonough and Sun, 1995) REE patterns of garnet, clinopyroxene, amphibole, olivine, and othopyroxene from the garnet peridotites in the Bashiwake area and Luliangshan area South Altun-North Qaidam.

Fig. 9 T_{REE} inversion diagrams for the garnet peridotites in Bashiwake area and Luliangshan area, South Altun-North Qaidam, using the REE-in-garnet-clinopyroxene thermobarometer (Sun and Liang, 2015). The parameter of *D* is the partition coefficient of REE, while the parameters of *A* and *B* are coefficients that depend on mineral major element compositions.

Fig. 10 Chondrite-normalized (McDonough and Sun, 1995) REE patterns (a) and Primitive-mantle-normalized spider diagram (b) for the garnet peridotites in Bashiwake area and Luliangshan area, South Altun-North Qaidam. Previous data of the dunite and garnet peridotites are from Song et al. (2007), Shi et al. (2010), Wang et al. (2011), Li et al. (2015), Xiong et al. (2015).

Fig. 11 Primitive mantle-normalized (McDonough and Sun, 1995) PGE diagram for the the garnet peridotites in Bashiwake area and Luliangshan area, South Altun-North Qaidam. PEG data source: cumulative peridotites (Hattori and Guillot, 2007; Zheng et al., 2008; Liu et al., 2012; Wang et al., 2012) and mantle-derived peridotites (Chen et al., 2006; Zheng et al., 2008; Xie et al., 2013; Su et al., 2016; Chen et al., 2017b) and mantle xenoliths (Pearson et al., 2004; Zheng et al., 2005b; Zhang et al., 2008; Liu et al., 2010, 2015).

Fig. 12 *P*-*T* paths showing the proposed metamorphic evolution for garnet peridotites in the Bashiwake area and Luliangshan area, South Altun-North Qaidam. Metamorphic facies boundaries are after Vernon and Clarke (2008), and coesite-quartz (Bohlen and Boettcher, 1982) transformations is shown, and the *P*-*T* conditions of previous data were also showed in the figure (Liu et al., 2002; Li et al., 2013; Song et al., 2005; Wang et al., 2011; Xiong et al., 2015; Yang and Powell, 2008; Zhang et al., 2005a).

Fig. 13. Diagram of Ir vs. Ir/(Pt + Pd) for the garnet peridotites in the Bashiwake area and Luliangshan area, South Altun-North Qaidam. Data sources: cumulative peridotites (Hattori and Guillot, 2007; Zheng et al., 2008; Liu et al., 2012; Wang et al., 2012) and mantle-derived peridotites (Chen et al., 2006; Zheng et al., 2008; Lorand et

al., 2013; Xie et al., 2013; Su et al., 2016; Chen et al., 2017b), mantle xenoliths (Pearson et al., 2004; Zheng et al., 2005b; Zhang et al., 2008; Liu et al., 2010, 2015) and primitive mantle (McDonough and Sun, 1995).

Fig. 14 Schematic tectonic model for the evolution of the granulite-peridotite unit in the Bashiwake region, South Altun. (a) The mafic-ultramafic cumulate sequence at 779~802 Ma related to the plume-induced Rodinia rifting; (b) The conjectural collision between oceanic crust and continental crust prior to ~517 Ma; (c) Continental collision prior to 500~482 Ma and subsequent HP/(U)HT metamorphism; (d) Relaminated to the mid-lower crust, and regional-scale Barrovian metamorphism at *ca.* 450 Ma.

Fig. 15 Schematic tectonic model for the evolution of the garnet peridotite in the Luliangshan region, North Qaidam. (a) Oceanic subduction resulted from the closure of South Qilian Ocean (or North Qaidam Ocean?) at 520-460 Ma; (b) Mantle wedge incorporated into the continental crust, and deep continental subduction and collision occurred at 450-440 Ma, the released fluids metasomatised the mantle wedge; (c) After slab breakoff and the HP-UHP rocks exhumated at ca. 430-400 Ma; (d) Mafic-ultramafic rocks exhumed to the middle-lower crust experienced the regional-scale Barrovian metamorphism.

Fig. 16 Summary of dating ages for key events in South Altun-North Qaidam, which are summarized in Tables S1 and Table S2.