Petrogenesis and geological significance of charnockite in the Yinshan Block of North China Craton

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ABSTRACT
A comparative study was performed on the petrography, geochemistry and geochronology of charnockite and granulite in the Xiwulanbulang (XWLBL) area, northern margin of the North China Craton, NW China. Inclusions within garnet in the charnockite are used to identify the mineral assemblage in the granulite during peak metamorphism. The formation of charnockite is attributed to the anatectic of the protolith, as a result of granulite-facies metamorphism during the same tectono-thermal event. Anatexis occurred mainly during the post-peak iso thermal depressurization stage (granulite and charnockite yield peak P-T conditions of 800–850°C and 1.0–1.2 GPa, and 750°C and 0.9–1.0 GPa, respectively), as inferred from the metamorphic evolution and P–T conditions derived from analyses of metamorphic minerals by electron microprobe (EMP). The garnets in the charnockite were a residual or peritectic mineral facies during anatexis, and the charnockite was the product of crystallization from melt with abundant residual minerals. Charnockite has similar geochemical characteristics to felsic granulate, although it differs in having 1) an uneven distribution of major and trace elements; 2) strong depletions in the large-ion lithophile element Cs, the heat producing elements U and Th, and the high-field-strength elements Nb, Ta, P and Ti; and 3) both Eu-enriched and Eu-depleted patterns that are characteristic of granite formed by largely in situ anatectic. The geochemical data indicate that the XWLBL charnockite formed in a subduction-related volcanic arc setting. On the basis of our results, combined with geological data on the Neoarchean structural evolution of the Yinshan Block and εHf(t) values of 1.60–7.81, we propose that the anatectic of charnockite was related to slab break-off during mid-ocean-ridge subduction, which resulted in the ascent of mantle magma through the slab window.

1. Introduction
High-temperature and high-pressure (HTHP) melting experiments that simulate phase equilibria show that charnockite is a granitic rock containing orthopyroxene that formed under anhydrous (or low water activity) conditions. Mainly occurring in Precambrian high-grade metamorphic rocks. It is also an important part of the middle and lower continental crust (Holland 1900; Brown 1994, 2004, 2007; Kriegsman 2001; Le, Maitre 2002; Cheng et al. 2004). The geochemical characteristics of charnockite are complex, ranging from magnesia to iron and calc-alkaline to alkaline (Mikhalsky 2006; Rajesh 2007; Frost and Frost 2008; Rajesh and Santosh 2012). The origin of the charnockite at the northern margin of the North China Craton (NCC) remains debated. The following models have been proposed to explain the origin of charnockite in the western part of Wuchuan, and eastern Hebei, Yishui, and Shandong provinces, China: (1) The product of mixed rock formed by the anatectic of surrounding rock (Sun 1984; Wang et al. 1984; Qian et al. 1985; Zhang et al. 1986); (2) The formation of tonalite–granodiorite protolith that experienced granulite-facies metamorphism involving CO2-rich fluids (Geng et al. 1990); (3) The product of crystallization differentiation (Wang 1992); and (4) The result of partial melting of mafic crustal rocks (Ma et al. 2013; Bai et al. 2015). Zhang et al. (2014) proposed that charnockite in the Xiwulanbulang (XWLBL) area (located north of Gonghudong and Tanyao; Figures 1 and 2) formed by the remelting of mafic granulate, whereas other studies suggest that it is more closely related to felsic granite rock (Institute of Geological Survey of Jilin University, China). Our study aims to further constrain the petrogenesis of the XWLBL charnockite.

The XWLBL area is located at the southern margin of the Yinshan Block, western NCC. Granulate and charnockite are closely spatially and compositionally related, and both experienced granulite-facies metamorphism. Previous studies have shown that the
granulite is widely distributed in high-grade metamorphic complex, with the east–west trending, metamorphic grade reach to middle pressure and high temperature granulite facies, partial retrogression to high amphibolite facies. Petrological studies from various parts of the Yinshan Block point to a multistage metamorphic evolution along anticlockwise P-T path. The protolith age of the rocks are 2560 to 2540 Ma and the metamorphic age are 2519 to 2480 Ma, although the ages vary spatially (Figures 1 and 2; Jin et al. 1991, Jin and Li 1994, Jin and Li 1996; Zhang et al. 2005; Meng 2007; Dong et al. 2012a, Dong et al. 2012b; Jian et al. 2012a; Liu et al. 2016). This metamorphic event is attributed to magma underplating and the intrusion of mantle-derived magma into the continental block. The charnockite
in the Yinshan Block occurs mainly in Shiguai-Baotou (Liu et al. 2017), Gonghudong-Guyang (Dong et al. 2012a; Ma et al. 2013), XWLBL (Zhang et al. 2014), Jining (Shi et al., Unpublished) in Northern margin of NCC, and together with granulites, it forms a significant component of the early Precambrian metamorphic complex that makes up the basement (Figure 1). The petrogenesis of the XWLBL charnockite is likely to have been closely related to the evolution of granulite metamorphism. However, lacking the comparative study of metamorphism between them, we further compare the typical mineral assemblages of metamorphism and the calculation between temperature and pressure, and discussing the genetic connection of them.

Previous studies have shown that charnockite petrogenesis is key to understanding deep crustal processes, crustal growth and tectonic evolution (Janardhan et al. 1982; Santosh and Yoshida 1992; Frost et al. 2000; Kar et al. 2003; Rajesh 2012; Rajesh and Santosh 2012; Yang et al. 2014; Zhang et al. 2014). The ferroan charnockite likely formed in an extensional tectonic setting (Frost and Frost 2008; Rajesh 2012; Rajesh and Santosh 2012), whereas the magnesium charnockite likely formed in a magmatic arc environment (Rajesh 2007). Previous studies have investigated the greenstone belt, TTG gneiss, and charnockite in the Guyang–XWLBL – Wuchuan area of the Yinshan Block (Figures 1 and 2; Zhang et al. 2005; Meng 2007; Dong et al. 2012a; Dong et al. 2012b; Jian et al. 2012a; Liu et al. 2016). These studies suggested that subduction of a mid-oceanic ridge was followed by a collisional orogeny in the Yinshan Block at ~ 2.5 Ga, resulting in a series of subduction–collision–extension -related orogenic events. XWLBL charnockites are spatially and temporally related to the orogenic belt; however, their origin and tectonic background remain debated.

In this paper, we have focused on the origin of anatectic charnockite in Xiulanbulang, and further considered that the anatexis of charnockite occurred during the post-peak cooling and pressure-reduction stage of granulite-facies metamorphism. We summed up U-Pb zircon dating on samples of metamorphic and anatectic rocks with different protolith origins and ages based on a field study, to determine the spatial distribution and timing of the 2.5 Ga event. And its relationship with the anatectic charnockite was related to slab break-off during mid-ocean-ridge subduction, which resulted in the ascent of mantle magma through the slab window. We further discuss the geodynamic significance of this event for Yinshan Block and the NCC.

### 2. Geological background

The NCC is separated into the Eastern Block and the Western Block by a NS-trending Paleoproterozoic belt called the Trans-North China Orogen (Zhao et al. 1998, 2005). The Eastern Block (Figure 1) is composed of two major blocks—the Yinshan Block, the Ordos Block and Khondalite series, all of which were incorporated into a coherent cratonic framework at the end of the Paleoproterozoic. The Yinshan Block (Zhao et al., 1999a, Zhao et al. 2001b, 2003, 2005) is the largest and most complete area of Archean basement in the Western Block, located on the northern margin of the NCC, with the south side bounded by the east–west-trending Xia-Shihao–Jiu-Guan ductile shear zone. The northern side of the ductile shear zone consists mainly of early Precambrian basement that can be divided into granitic rock and greenstone belts. The basement experienced green schist to lower-amphibolite facies metamorphism, and the high-grade metamorphic complex experienced amphibolite to granulite facies metamorphism. A khondalite belt is distributed along the southern side of the ductile shear zone (Figure 2). The supracrustal greenstone belt sequence comprises metakomatite and volcano-sedimentary rocks (Chen 2007; Jian et al. 2012a), and the granitic rock consists of calcalkaline TTG gneiss (Jian et al. 2005, 2012b; Ren 2010) and sanukite (Jian et al. 2012a; Ma et al. 2013). The high-

| Geochemical characteristics | Eu depletion type | Eu enrichment type |
|----------------------------|------------------|-------------------|
| Eu/Eu*                     | 0.67–0.94        | 1.28–4.39         |
| SiO₂                       | 59.56–62.36%     | 62.32–72.75%      |
| CaO                        | 5.28–5.89%       | 3.48–5.11%        |
| CaO+Na₂O                   | 9.24–10.39%      | 7.62–9.33%        |
| Fe₂O₃                      | 2.12–3.2%        | 0.85–3.73%        |
| MgO                        | 3.24–3.66%       | 1.21–3.74%        |
| ∑REE                       | 112.2 × 10⁻⁶ to 160.58 × 10⁻⁶ | 69.6 × 10⁻⁶ to 119.36 × 10⁻⁶ |
| (La/Yb)₆₈                  | 12.88–19.48      | 14.78–27.23       |
| Ba/Sr                      | 0.61–1.31        | 1.53–2.45         |
| High field strength elements| High, U and Th   | Low, U and Th     |
| Large ion lithophile element| Low, K; High, Sr | High, K; Low, Sr  |
Table 2. Zircon U-Pb age and Hf-Nd isotope statistics in Yinshan Block.

| Rock                | Location                  | Age (Ma) | Metamorphic AgeD(Ma) | εHf  | TDM (Ma) | Method       | Data from                  |
|---------------------|---------------------------|----------|-----------------------|------|----------|--------------|-----------------------------|
| Metamorphic Complex | Charnockite E 110°42’00” N 40°57’00” | 2533 ± 15 | 2490 ± 11             | +5.5 to ± 2.3 | LA-ICP-MS Ma et al. 2013 |
|                     | Charnockite E 110°42’00” N 40°57’00” | 2524 ± 17 | 2498 ± 3              | +4.9 to ± 1.4 | LA-ICP-MS Ma et al. 2013 |
|                     | Charnockite E 110°55’25” N 41°04’19” | 2548 ± 24 | 2496 ± 36             | -4.21 to ± 7.36 | SHRIMP Ma et al. 2013 |
|                     | Charnockite E 110°45’43” N 40°55’47” | 2506 ± 9  | 2499 ± 22 2479 ± 12   | -1.6 to ± 8.09 | SHRIMP Ma et al. 2013 |
|                     | Charnockite E 110°55’30” N 41°07’36” | 2502 ± 14 | 2502 ± 14             | +1.40 to ± 3.20 | Cameca Wang et al. 2015 |
|                     | Charnockite E 110°54’06” N 41°03’12” | 2525 ± 8  | 2503 ± 10             | -2.30 to ± 6.49 | SHRIMP Dong et al. 2012b; Ma et al. 2013 |
|                     | Granulite E 110°45’43” N 40°55’47” | 2545 ± 10 | 2503 ± 10             | -2.30 to ± 6.49 | SHRIMP Dong et al. 2012b; Ma et al. 2013 |
|                     | Granulite E 110°56’24” N 40°06’02” | 2561 ± 18 2539 ± 9 | 2511 ± 5             | +1.60 to ± 8.09 | SHRIMP Dong et al. 2012a |
|                     | Granulite E 110°34’12” N 41°10’07” | 2511 ± 5  | 2511 ± 5              | +1.60 to ± 8.09 | SHRIMP Dong et al. 2012a |
|                     | Granulite E 110°35’05” N 40°57’59” | 2512 ± 16 | 2512 ± 16             | +1.60 to ± 8.09 | SHRIMP Dong et al. 2012a |
|                     | Granulite E 110°35’05” N 40°57’59” | 2517 ± 6  | 2517 ± 6              | +1.60 to ± 8.09 | SHRIMP Dong et al. 2012a |
|                     | Granulite E 110°51’03” N 41°05’24” | 2544 ± 5  | 2503 ± 12             | -0.66 to ± 4.44 | SHRIMP Xu et al. Unpublished; Ma et al. 2013 |
|                     | Diorite E 110°39’41” N 41°17’23” | 2503 ± 7  | 2503 ± 7              | -0.66 to ± 4.44 | SHRIMP Xu et al. Unpublished; Ma et al. 2013 |
| Grantoid            | Sanukitoid E 110°45’43” N 40°57’28” | 2523 ± 7  | 2523 ± 7              | +6.3 to ± 1.5 | LA-ICP-MS Ma et al. 2013 |
|                     | Sanukitoid E 110°09’48” N 41°06’05” | 2520 ± 9  | 2520 ± 9              | +6.3 to ± 1.5 | LA-ICP-MS Ma et al. 2013 |
|                     | TTG E 110°06’14” N 41°31’34” | 2534 ± 7  | 2534 ± 7              | +6.3 to ± 1.5 | LA-ICP-MS Ma et al. 2013 |
|                     | TTG E 110°06’14” N 41°31’34” | 2534 ± 7  | 2534 ± 7              | +6.3 to ± 1.5 | LA-ICP-MS Ma et al. 2013 |
| Greenstone Belt     | Trondhjemite E 110°55’23” N 41°07’50” | 2528 ± 16 | 2528 ± 16             | +1.06 to ± 8.83 | SHRIMP Jan et al. 2012a |
|                     | Andesite E 110°35’50” N 41°02’02” | 2510 ± 7  | 2510 ± 7              | +1.06 to ± 8.83 | SHRIMP Jan et al. 2012a |
|                     | Basalt E 110°34’09” N 41°02’02” | 2516 ± 10 | 2516 ± 10             | +1.06 to ± 8.83 | SHRIMP Jan et al. 2012a |
|                     | High-Mg Basalt E 110°35’50” N 41°02’02” | 2533 ± 5  | 2533 ± 5              | +1.06 to ± 8.83 | SHRIMP Jan et al. 2012a |
|                     | Andesit E 110°32’13” N 40°57’57” | 2556 ± 6  | 2556 ± 6              | +1.06 to ± 8.83 | SHRIMP Jan et al. 2012a |
|                     | Basalt E 110°33’58” N 41°08’59” | 2562 ± 14 | 2562 ± 14             | +1.06 to ± 8.83 | SHRIMP Jan et al. 2012a |
grade metamorphic complex is characterized by a dome structure comprising charnockite and granulite, and is exposed mainly in the XWLBL area (Zhang et al. 2005; Ma et al. 2013; Liu et al. 2016). Zircon dating of the rocks of the Yinzhan Block (including in the XWLBL–Wu-Chuan–Gu-Yang area) has confirmed that the metamorphosed intrusive rocks were formed during the Neoarchean (Xu et al. 2011; Dong et al. 2012a; Jian et al. 2012a, 2012b; Ma et al. 2013, 2016; Liu et al. 2016). The dating of metamorphic zircon from the greenstone belt, TTG gneiss, metamorphic–sedimentary rocks, and high-grade metamorphic complex yields ages of 2.55–2.50 Ga (Table 2; Jin et al. 1991; Jin and Li 1994; Jin and Li 1996; Wang et al. 2015; Liu et al. 2016).

The early Precambrian metamorphic basement in the XWLBL area composes primarily of a Neoarchean high-grade metamorphic complex and garnet–kyanite gneisises (Figure 3). The high-grade metamorphic complex consists mainly of the Xinghe Group and charnockite, with minor Neoarchean tonalite–granodiorite gneiss. The Xinghe Group consists of mafic granulite, felsic granulite and garnet quartzite (Xu et al. 2011; Dong et al. 2012a). The mafic granulite is a metamorphosed gabbro (Zhang et al. 2014) that includes the garnet–plagioclase pyroxenite, garnet–diopside–plagioclase amphibolite, garnet–amphibolite–pyroxene granulite and magnetite quartzite. The felsic granulite contains the rock of biotite-two pyroxene-plagioclase granulite, garnet-two pyroxene-plagioclase granulite, amphibolite-two pyroxene-plagioclase granulite, and also comprises felsic gneiss. The garnet quartzite is interbedded with layers of two-pyroxene granulite and (amphibole) two-pyroxene granulite of variable thickness.

The charnockite is characterized by a gneissosity that is attributed to late-stage tectonic movements. It can be subdivided, based on feldspar and quartz contents, into hypersthene–quartz diorite gneiss, hypersthene–plagioclase granitic gneiss, and hypersthenite granodioritic gneiss, which are collectively called charnockite. The charnockite is located mainly in the XWLBL, shows a gradual transition into felsic granulite and contains variably sized inclusions of felsic granulite (Figure 4(a–c)). Garnet–kyanite gneiss, located in the southern XWLBL, occur sporadically as small tectonic fragments in the high-grade metamorphic complex. Most of these rocks in the region were affected by upper amphibolite to granulite facies metamorphism at ~ 2.5 Ga (Figure 3; Dong 2009; Dong et al. 2012a; Jian et al. 2012a, Jian et al. 2012b; Ma et al., 2013; Zhang et al. 2014; Wang et al. 2015). Wang and Guo (2017) performed phase

Figure 3. Detailed geological map of the Xiwulanbulang area and Sampling locations (Modified after Dong et al. 2012a).
equilibria modelling of garnet–kyanite gneisses, yielding peak metamorphic temperatures and pressures of 840°C–870°C and > 14–11 kbar, respectively.

3. Petrography

The rocks surrounding the charnockite consist of felsic granulite s and mafic granulites that are closely related to each other, both spatially and in terms of their petrogenesis. The charnockite also contains numerous xenoliths of granulite of variable size, which Zhang et al. (2014) classified as basic granulite and metamorphosed gabbronorite. The granulite xenoliths in charnockite are garnet two-pyroxene granulite containing minor leucosome, which the felsic granulite also has charnockite xenoliths (Figure 4(a–c)). The proportion of mafic minerals decreases with increasing intensity of anatexis, and remnant felsic leucosomes are interlayered with dark layers of hypersthene and hornblende (Figure 4(d–f)). The XWBL charnockite is composed of hypersthene + garnet + plagioclase + microcline + quartz (Figure 4(g–k)). Garnet (<5%) is xenomorphic and typically mantled by hypersthene and irregular quartz. Hypersthene (~10%) is irregular granular in shape and occurs with irregular granular quartz, both of them are surrounding the garnet (Figure 4(g–l)). Plagioclase (35–40%) is irregular granular in shape with polysynthetic twins, and is interstitial to garnet and hypersthene. Microcline (10–15%) surrounds hypersthene. Quartz (15–20%) shows a granular texture with irregular serrated and resorbed grain boundaries, and encircling hypersthene and feldspar (Figure 4(g–k)). The felsic granulite xenoliths have a typical mineral assemblage of plagioclase (60–65%), hypersthene (10%), diopside (5–10%), biotite (~5%), garnet (~5%), quartz (~5%), and microcline (~5%). Hypersthene and diopside occur as subhedral short columns, with plagioclase displaying polycrystalline twins (Figure 4(l)). The edges of hypersthene, diopside, quartz and plagioclase inclusions in garnet are linear, showing no significant reaction-rim texture.
4. Sample descriptions and analytical methods

Unaltered samples of charnockite and felsic granulite were collected from the XWLBL area (Figure 3). Charnockite (samples 2p5b17-1, 2p6b43-1, B0017-1, and B0029-2) and felsic granulite (2p5b43-1) were collected from the Gonghudong–Tanyao area, together with charnockite (b7158-2, b7165-1, b7167-2, B7174-1, b7174-2, B9008, b7170-2, and b7193-3) and granulite (b7173-6, B9007, and b7164-1) from the Hou-Saihudong–Hao-Laishan area.

Mineral compositions for the charnockite and granulite xenoliths were analyzed by Electron Microprobe at the Key Laboratory of Orogen and Crustal Evolution at the Ministry of Education, Peking University, Beijing, China, using operating conditions of 5 kV accelerating voltage, $1 \times 10^{-8}$ A beam current, and 1 μm spot diameter. Well-defined natural mineral standards were used for calibration (using standard samples of 53 minerals from SPI Supplies, USA). The results are presented in Supplementary Table 1.

Major-element compositions of minerals were measured on an Axios X-ray fluorescence spectrometer at the China National Research Center for Geoanalysis, Beijing, China, and trace-element analyses were conducted using a Elan 9000 inductively coupled plasma–mass spectrometer (ICP–MS, made in the PerkinElmer company of United States in USA), and the accuracy of analysis is better than 10%. Major and trace element compositions and analytical precisions for each element are given in Supplementary Table 2.

5. Analytical results

5.1. Major-element compositions

The major-element compositions of charnockite are similar to those of felsic granulite, with high Al$_2$O$_3$ (13.76–17.64 wt. %), MgO (0.6–3.74 wt.%), CaO (3.37–5.89 wt.%), and Na$_2$O (3.5–4.64 wt.%) contents, and low Fe$_2$O$_3$ (0.07–2.62 wt.%) and MnO (0.01–0.09 wt.%) contents (Supplementary Table 2). Harker diagrams (Figure 4) show that the charnockite samples have moderate-to-high silica contents (59.44–72.75 wt.%), and the contents of Al$_2$O$_3$, Fe$_2$O$_3$, MgO, CaO, MnO and TiO$_2$ decrease with increasing SiO$_2$ content. The results indicate that the charnockite is closely related to the felsic granulite, which is consistent with the close relationship observed in the field.

5.2. Trace-element compositions

The trace-element compositions of the charnockite (Data from Supplementary Table 2) are similar to those of the granulite inclusions, and the charnockite can be divided into intermediate and silicic types (Figure 7(a,b); Ma et al. 2013; Zhang et al. 2014). In the chondrite-normalized rare earth element (REE) diagram (Figure 7(a)), most of the silicic charnockite samples show high trace-element contents, with relative enrichment in elements such as K, Rb, Ba, Zr, and Hf, and depletion in Th, U, Ta, Nb, P, and Yb. A comparison of the charnockite and granulite indicates that the trace-element compositions are close to felsic granulite, with silicic charnockite having a closer affinity to felsic granulite. The samples show enrichment in large-ion lithophile elements (LILEs; e.g. K, Rb, Ba, Sr, La and Ce) and depletion in high-field-strength elements (HFSes; e.g. Nd, P, Zr, Hf, Sm, Yb, Y, Lu and Sc). The geochemical data of the charnockite show features of inheritance as well as unique characteristics; e.g. the total trace-element content is less than that of the granulite, and the samples are relatively enriched in K, Rb, and Ba, and depleted in Th, U, Ta, Nb, P, and Ti.

6. Discussion

6.1. Timing of metamorphism and anatexis

Petrographic analysis shows that the garnet enclaves (plagioclase (Pl) + clinopyroxene (Cpx) + hornblende (Hb) + quartz (Qtz)) in granulites have large grain sizes and linear grain boundaries. The matrix minerals may have continued to recrystallize during the period of peak metamorphism; however, the inclusions in garnet record the initial stage of the period of peak metamorphism (Guo et al. 1994, 1997; Zhang et al. 1997). In the following melting reaction: Gt + Cpx + Qtz → Opx + Pl, This mineral assemblage may represent the cooling and decompression stage of post-peak metamorphism (Guo et al. 1993, 1996; Zhai et al. 1993, 1995, 1996, Jin and Li 1994; Liu 1994; Geng and Liu 1997). These petrographic features are consistent with the anatectic origin of the charnockite, and the heterogeneous distribution of garnet and hypersthene indicate that the residual mineral
phase and the relict crystals were not completely separated. The abundant granulite xenoliths also reflect the partial separation of the initial residual mineral phase and the subsequent melting, indicating that the melt migrated over a short distance. These observations, combined with the close spatial relationship between charnockite and granulite in the XWLBL, indicate that formation of the charnockite was related to the anatexis of the granulite.

The garnet in the granulite has a ‘red eye socket’ structure around the Cpx + Hb + Pl ± Qtz (Figure 4(i)) assemblage (Liu 1995); the significance of this structure remains debated. Previous studies proposed that such a structure indicates the reaction process during isobaric cooling (Jin and Li 1994; Liu 1994; Geng and Liu 1997). However, other studies considered it to indicate an initial increase in temperature and pressure (Guo et al. 1993, 1996, Zhai et al. 1993, 1995, 1996). In contrast, the ‘white eye socket’ metamorphic reaction structure is associated with decompression and provides evidence for high-pressure granulite facies metamorphism. Liu (1995) proposed that the ‘red eye socket’ structure forms under granulite facies conditions during peak metamorphism, with preservation of the initial inclusion morphology due to rapid garnet growth. Here we consider that the ‘red eye socket’ structure in granulite is related to increasing temperature and pressure, and may have formed during peak metamorphism, based on the following evidence. (1) The internal boundaries between garnet and its mineral inclusions are straight, and the garnet forms either a completely closed ‘red eye socket’ structure or a semi-closed ‘C-type red eye structure’ that shows no transitional relationship between garnet and the inclusion minerals (Liu et al. 2017). We consider that the matrix minerals were recrystallized during the peak metamorphism, whereas the garnet-hosted inclusions retained their original form, reflecting the peak primary stage. There is no evidence of reaction between garnet and the mineral inclusions, indicating that the minerals were included in the growing garnet under equilibrium conditions. The ‘red eye socket’ structure is attributed to the different growth rates of minerals and space limitations (Liu 1995; Lu et al. 1996). (2) The crystal sizes of garnet inclusions (Cpx + Hb + Pl + Qtz) are smaller than those of the ‘red eye socket’ rim. Calculations yield temperatures of 800–850°C and pressures of 1.0–1.2 GPa (Data from Supplementary Table 1). These P–T conditions are consistent with the simulated phase equilibria of Liu et al. (2016) for the mafic granulites in the Wuchuan area (peak conditions of 800–850°C and 1.1–1.2 GPa) and of Wang and Guo (2017) for the XWLBL garnet–kyanite gneisses (peak conditions of 840–870°C and 1.1–1.4 GPa). The Gt + Py + Qtz + Pl mineral assemblage in charnockite represents the peak period of granulite metamorphism and is consistent with the ‘white eye socket’ structure mentioned above (Figure 4(g–k)). Geothermometer and geobarometer calculations manifest that the temperature and pressure ranges for the Gt + Py + Qtz + Pl mineral assemblage are ~ 750°C and 0.7–0.9 GPa (Data from Supplementary Table 1).

The garnet in charnockite contains inclusions of Cpx + Qtz + Pl (Figure 4(j, k)), which are indicative of the peak metamorphism stage. They differ from typical garnet-hosted mineral inclusions in granulite, as most inclusions have embayed and serrated shapes. The garnet and its mineral inclusions in charnockite are interpreted as the residual mineral phases from anatectic rocks, and the corresponding melting reactions occur at the same time as the anatexis. It is considered that the anatexis of charnockite occurred during the post-peak cooling and pressure-reduction stage of granulite-facies metamorphism.

Geochronological data further support the relationship between anatexis and metamorphism. Dong et al. (2012a, 2012b) presented an age of 2.5 Ga for the formation of the felsic granulite and metamorphic plutonic rocks in the XWLBL area (e.g. zircon U–Pb dating by SIMS), and reported that the zircons display a core–mantle–rim structure. Ma et al. (2013) considered that zircon cores from the granulite reported by Dong et al. (2012a, 2012b) reflect acidic magmatism, which differ from zircons of mafic rocks, and their ages (~ 2.5 Ga) therefore do not represent the formation of the granulite, but rather the formation of the original metamorphic–plutonic rock. However, the granulite in the present study area is mostly felsic granulite (57.87–67.11 wt.% SiO₂). We agree with the view of Dong et al. (2012a, 2012b) that the characteristics of zircon in mafic rock cannot be used to measure and discriminate on the zircon in the XWLBL felsic granulite. Zircon with an anatetic origin is typically characterized by Th/U < 0.37, with narrow rims and more gradual zoning patterns in cathodoluminescence (CL) images compared with the oscillatory zoning of magmatic zircon (Wan et al., 2009; Wan et al. 2013). Charnockite forms in a nearly anhydrous environment and contains anatectic zircons with narrower rims, which contrasts with fluid-rich areas that are characterized by anatectic zircon with wider rims (Wan et al., 2009; Wan et al. 2013; Dong et al., 2017). Zircon U–Pb dating of the B9008 geochemical sample (collected from the same location as the sample analyzed by Dong et al. (2012a)) yields Th/U ratios of 0.1–0.3 (mantle) and 0.5–0.7 (rims). These features, in conjunction with the narrow zircon rims and
lack of pronounced oscillatory zoning in CL images, indicate an anatectic origin (Wan et al., 2009; Dong et al., 2017). Nine analyses of zircon mantle domains are concordant and yield a weighted-mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2498 ± 22 Ma (MSWD = 2.7), and four analyses from zircon rims yield a weighted-mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2478 ± 12 Ma (MSWD = 10.1) (Figure 8(a)). The younger zircon ages from mantle domains are possibly the result of a later anatexis event. Zircon U–Pb analyses of sample B9008 yield ages of 2498 ± 22 Ma (MSWD = 2.7) to 2478 ± 12 Ma (MSWD = 10.1) that may represent a stage of metamorphic and anatexis (Dong et al. 2012a). Ma et al. (2013) measured in situ Hf isotopes of sample B9008 from the same zircon targets as those analyzed by Dong et al. (2012a) (Figure 8(b)). They proposed that the charnockite is the product of recycling of crustal substance in late Neoarchean, which further supports the anatetic origin of the charnockite.

### 6.2. Geochemical characteristics

The charnockite can be divided into two types based on Eu anomalies (Eu/Eu*), with some samples having significant positive Eu anomalies (Eu/Eu* = 1.14–4.39) and others having negative anomalies (Eu/Eu* = 0.61–0.74). In the chondrite-normalized REE diagram (Figure 7(a,b)), the total REE content is relatively low (49.89 to 119.36 ppm) for samples with significant positive Eu/Eu* values. The charnockite is also characterized by enrichment in LREEs and depletions in HREEs ((La/Yb)$_N$ = 14.48–30.55), consistent with the results of previous studies (Figure 7(a, b); Zhang et al. 2005, Zhang et al. 2014; Ma et al. 2013). The total REE content is relatively high (145.44 to 365.18 ppm) in samples with low Eu/Eu* values, although it is much lower than for the granulite. These samples also have strong REE fractionation patterns (La/Yb)$_N$ = 12.88–22.22), with LREE enrichment and HREE depletion. The samples with significant Eu/Eu* anomalies have similar trace-element compositions to felsic granulite s (Figure 6(c, d)), although are relatively enriched in K, Rb, Ba, Zr, and Ti and depleted in Th, U and P. Our results are consistent with those of previous geochemical studies of the charnockite in the XWLBL (Zhang et al. 2005, 2014; Ma et al. 2013), which indicate higher total trace-element contents in the Eu-depleted charnockite relative to the Eu-enriched type, with similar trace element characteristics to those of felsic granulite (Figure 6(d)).

Although the XWLBL charnockite inherited some geochemical characteristics of the granulites, it retains the following unique characteristics (In Table 1). (1) The charnockites have SiO$_2$ contents of 61.3–69.6 wt.%, similar to felsic granulite s in the region. The contents of Al$_2$O$_3$ FeO$^T$, CaO, MgO, Na$_2$O, P$_2$O$_5$ and TiO$_2$ decrease with increasing SiO$_2$ content. The felsic granulite s are enriched in Al$_2$O$_3$, CaO, MgO, and Na$_2$O, whereas the mafic granulites are relatively rich in Al$_2$O$_3$ and Na$_2$O, and depleted in MgO and K$_2$O, and both are relatively depleted in FeO$^T$ and MnO. The P$_2$O$_5$ and TiO$_2$ contents of the charnockites are similar to those of the felsic granulite, but are lower than those of the mafic granulite (Figure 5). These differences in major-element compositions partly reflect the redistribution of chemical components during anatexis, and indicate that the source rock was dominantly felsic granulite with a minor component of mafic granulite. (2) In the primitive mantle (PM)-normalized trace-element diagram (Figure 7(b)), the partition curve of charnockites is similar to that of granulite. However, the charnockites differ in terms of lower trace element contents, comparing with granulite, enrichment in partial LILEs (e.g. Ba and K), and significant depletion in heat-producing element elements (e.g. U and Th). The charnockites REE curve show that are relatively enriched in LILEs (e.g. K, Rb, and Ba), indicating that they preferentially entered the melt phase during anatexis, and are more depleted in HFSEs (e.g. Nb and Ta). These differences in trace-element compositions reflect the redistribution of chemical components during anatexis. The depletion in radiogenic elements further supports an anatetic origin. (3) The REE pattern of the charnockite is similar to that of the adjacent granulites, with average total REE contents of 99.80 ppm and 142.15 ppm, respectively. The average total REE content of the charnockite is 30% less than that of the granulite, with some samples having significant positive Eu anomalies (Eu/Eu* = 1.14–4.39) and others having negative anomalies (Eu/Eu* = 0.61–0.74). In the chondrite-normalized REE diagram (Figure 7(a, b)), the total REE content is relatively low (49.89 to 119.36 ppm) for samples with significant positive Eu/Eu* values. The charnockite is also characterized by enrichment in LREEs and depletions in HREEs ((La/Yb)$_N$ = 14.48–30.55), consistent with the results of previous studies (Figure 7(a, b); Zhang et al. 2005, Zhang et al. 2014; Ma et al. 2013). The total REE content is relatively high (145.44 to 365.18 ppm) in samples with low Eu/Eu* values, although it is much lower than for the granulite. These samples also have strong REE fractionation patterns (La/Yb)$_N$ = 12.88–22.22), with LREE enrichment and HREE depletion. The samples with significant Eu/Eu* anomalies have similar trace-element compositions to felsic granulite s (Figure 6(c, d)), although are relatively enriched in K, Rb, Ba, Zr, and Ti and depleted in Th, U and P. Our results are consistent with those of previous geochemical studies of the charnockite in the XWLBL (Zhang et al. 2005, 2014; Ma et al. 2013), which indicate higher total trace-element contents in the Eu-depleted charnockite relative to the Eu-enriched type,
with similar trace element characteristics to those of felsic granulite (Figure 6(d)). The partition curve and total REE content are more consistent with felsic granulite, which indicates that anatectic involved mainly this rock type.

The major and trace element contents of the charnockite are heterogeneous, and the charnockite can be separated into intermediate and silicic charnockite based on SiO$_2$ content. Compared with felsic granulite, the charnockite has higher contents of Al$_2$O$_3$, K$_2$O and LILEs (e.g. Rb and Ba) that readily partition into the melt, and are typical characteristics of anatexis. The charnockite is also significantly depleted in part of LILEs (e.g. Cs), radiogenic elements (U and Th), and HFSEs (e.g. Nb, Ta, P, and Ti), and is relatively rich in Sr. The total REE content is much lower than that of the granulite. Prosessing a partition curve of Eu enrichment type and Eu depletion type obviously, in which not only the mainly characteristic of charnockite in region. And the charnockite shows similar characteristics in the Xiashihao area (southern XWLBL), Huai’an in Hebei Province, and Yi-Shui in Shandong Province (Wang et al. 1984; Geng et al. 1990; Geng and Liu 1997; Zhao and He 1991; Zhao 1992; Ma et al. 2013; Han et al. 2016). The coexistence of Eu-enriched and Eu-depleted charnockite types is considered to be a typical feature of anatetic granite (Song et al. 2005; Ma et al. 2015; Shi et al., 2018), further supporting the anatetic origin of the charnockite. The geochemical characteristics of the charnockite show some inheritance and variability; the former may be related to the source rock and the latter to the subsequent convergence and migration of anatetic melting.

6.3. Tectonic setting

Charnockites form in the following tectonic settings, as inferred from their geochemical characteristics (Frost and Frost 2008). (1) Rift-related charnockite plutons occur as a component of the AMCG (anorthosite–man- gerite–charnockite–granite) suite (Emslie 1991), with ferroan alkali-calcic to alkalic metaluminous characteristics. (2) Delamination-related granites occur as low-volume, magnesian, alkali-calcic to alkalic plutons that form during the delamination of thickened continental crust after a collisional orogeny. (3) Deep crustal melting related to granulate facies metamorphism or the emplacement of hot ferroan magmas generates charnockite with whole-rock and isotopic compositions indicating the involvement of a crustal component (Young et al. 1997; Bhattacharya and Sen 2000; Kar et al. 2003; Percival et al., 2003). This charnockite type is transitional between ferroan and magnesian charnockites, and is weakly to moderately peraluminous. (4) Deeply eroded magnesian alkali-calcic to alkalic plutons have
a metaluminous granitoid chemistry, representing a deeply eroded magmatic arc.

The XWLBL charnockites have a calc-alkaline geochemistry, as indicated by the K–Na–Ca diagram (Figure 9(a)). The samples plot mainly in the tonalite field (with a few in the granodiorite field) in the An–Ab–Or diagram (Figure 9(b)), which is consistent with petrographic and geochemical characteristics. The charnockite samples also have relatively low FeO^T/(FeO^T + MgO) ratios of 0.53–0.71, showing typical magnesian charnockite characteristics (Figure 11(b)). They have modified alkali–lime index (MALI) values of −4% to 4%, and alumina saturation index (ASI) values of 0.86–1.05, consistent with a calc-alkaline and metaluminous to slightly peraluminous geochemistry (Figures 10(a,b) and 11(a)), respectively. Therefore, the magnesite and the calcic to calc-alkaline charnockites were formed in an island arc setting.

Figure 6. The primitive mantle-normalized trace element spidergrams (Normalization values after Sun and McDough 1989) in charnockite and granulite (Data in this work, quote from Ma et al., 2013; Zhang et al. 2014).

Figure 7. The Chondrite-normalized REE patterns (Normalization values after Sun and McDough 1989) Eu enrichment type (a), Eu depletion type (b) in charnockite and granulite (Data in this work, quote from Ma et al., 2013; Zhang et al. 2014).
Almost all the genetic mechanisms proposed for the formation of high Ba–Sr charnockite require the addition of a lithospheric mantle component (Figure 12; Ma et al., 2013), as they may be (1) derived from the melting of subcontinental lithospheric mantle (Qian et al. 2003); (2) the products of crustal fractionation of associated shoshonitic magma derived from melting of an enriched lithospheric mantle (Fowler et al. 2001); (3) related to underplating by Sr- and Ba-rich mafic magma; or (4) the products of partial melting of thickened lower crust with a minor involvement of enriched mantle-derived appinitic magma (Ye et al. 2008). The melting of continental lithospheric mantle generally forms potassic magmas (Qian et al. 2003). Crystal fractionation of the associated shoshonitic magma generates magma that is more alkaline (K₂O + Na₂O > 5%)
and rich in K$_2$O (K$_2$O/Na$_2$O > 0.7), which is inconsistent with the K$_2$O content of the XWLBL charnockite. Ma et al. (2013) analyzed sample B9008 of the XWLBL charnockite, yielding $\varepsilon$Hf(t) values of 1.60–7.81 and single-stage model ages (TDM) of 2529–3089 Ma (Figure 8(b), significantly older than the zircon U–Pb age of Dong et al. (2012a)), and proposed that the original rock was juvenile crust. Compared with charnockite in region, $\varepsilon$Hf(t) values range from −4.21 to + 8.09, while most of them are $\varepsilon$Hf(t) > 0, and TDM ages also more older than the zircon U–Pb age (In Table 2). These results, together with our data, we hold a sceptical attitude on the mafic lower-crustal partial melting origin for the charnockite. Petrological, lithofacies, and geochemical data show that the charnockite in this region has more likely characteristics of the mainly semi-in-situ anatectic granite. Zhang et al. (2014) considered that the XWLBL charnockite was formed by the anatexis of mafic granulite, although their geochemical data are more consistent with felsic granulite s. Combined with the abundant felsic granulite xenoliths in the charnockite, we consider the source rock of the charnockite to be felsic granite that was influenced by the underplating of Sr-and Ba-rich mafic magma during anatexis (Figure 12).

Previous studies have shown that anatexis occurs mainly in continental arcs and collision zones (Rajesh and Santosh 2004, 2012; Frost and Frost 2008; Rajesh 2012), and reflects changes in temperature and pressure associated with high-grade metamorphism. Two different tectonic settings have been proposed for the charnockite in the Huain–Qianxi area (eastern NCC, Hebei Province): (1) continental magmatic arc subduction (Bai et al. 2015; Yang et al. 2016), and (2) a mantle plume environment (Zhao et al., 2001a, Zhao et al. 2005; Han et al. 2016). The geochemical data of charnockite from previous studies indicate that it formed in an extensional magmatic arc environment. This is consistent with the origin of contemporaneous gneisschist, sanukite and TTG gneiss, which involved the subduction of a mid-ocean ridge (Jian et al. 2005, 2012a, 2012b; Chen 2007; Ren 2010; Ma et al. 2013), underplating of mantle-derived magmas and partial melting of a sub-ducted slab in the western Wuchuan and Guyang areas of the eastern XWLBL.

U–Pb dating of metamorphic zircon from the Archean basement of the Yinshan Block yielded an age of 2.5 Ga (Figure 13; Xu et al. 2011; Dong et al., 2012a; Jian et al. 2005, 2012a; Ma et al. 2013; Wang and Guo 2017). The analyzed zircons from the metamorphosed plutonic rock yield ages of 2.55–2.50 Ga (Data from Table 2), indicating a continuous period of magmatic activity in the NCC. The trondhjemite granites from the northern side of the XWLBL also yield a metamorphic age of 2.5 Ga (Dong et al. 2012a). Metamorphic ages of 2.5 Ga were obtained for felsic granulite s and charnockite in Housaiduhong, southern...
XWLBL (Dong et al. 2012b). Dating of magmatic zircon cores from the charnockite yield ages of 2683–2645 Ma, whereas the magmatic zircon cores from the granulite yield ages of 2680–2600 Ma (Zhang et al. 2005; Dong et al. 2012a; Jian et al. 2012a; Ma et al. 2013; Zhang et al. 2014). The Archean high-grade metamorphic rocks in the Yinshan Block (northern margin of the NCC) record granulite-facies metamorphism at ~ 2.5 Ga (T = 760°C–880°C, P = 1.30–1.2 GPa; Jin et al. 1991; Jin and Li 1996; Meng 2007), and the felsic granulite has a close relationship to the charnockite. Our geothermobarometry results for the charnockite and the felsic granulite, combined with the results of previous studies, indicate that the XWLBL charnockite formed during the stage of post-peak temperature reduction and decompression of the metamorphic event at 2.5 Ga (Figures 13 and 14).

With recent developments in NCC research, tectonic evolution characteristics of Yinshan Block are also favoured by more and more researchers (Figures 1 and 2), a consensus on the Neoarchean tectonic evolution characteristics of the Yinshan Block is also favoured by more and more researchers (Figures 13 and 14).
evolution characteristics of ridge subduction to extensional environment in Yinshan Block, and carried out a series of more detailed divisions. The neoarchean tectonic evolution of the metamorphosed plutonic rocks in NNC involved subduction–collision–extension processes (e.g. Komatiite–greenschist–TTG gneiss–metamorphosed gabbro–charnockite) (Figures 2, 3 and 15), and these rocks yield magmatic zircon ages of 2.55–2.50 Ga. These rock have similar rock assemblages to orogenic belts in the Alps (e.g. Central and southern Europe) (Davies and Blanckenburg 1995), the Dabie–Sulu (e.g. EN China) Orogen (Zhao et al. 2007, 2011, 2012; Xia et al. 2008; Zhang et al., 2010a), gneiss in Norway (e.g. Northern Europe) (Labrousse et al. 2011), and the northern margin of the Qaidam Basin (e.g. EN China) (Chen et al. 2012; Song et al. 2014; Wang et al. 2014; Wu et al. 2014; Yu et al. 2014), thus indicating the evolution of an orogenic belt in the XWLBL region. Previous studies have reported the anatectic rocks in the Dabie–Sulu orogenic belt, the northern margin of Qaidam, a gneiss unit in western Norway, the Kokchetav orogenic belt in Kazakhstan, and the Caledonian orogenic belt in Greenland (Korsakov and Hermann 2006; Lang and Gilotti 2007; Liu et al. 2010, 2012a; Labrousse et al. 2011; Chen et al. 2012; Yu et al. 2014). It is considered that anatexis occurs during late-stage subduction and is associated with related tectono-thermal events. Abundant metamorphosed mafic volcanic rocks have been identified in the present study region, which are considered to be the result of late-stage subduction and mantle magma upwelling through a slab window (Jian et al. 2012a; Ma et al. 2016). Combined with the above data, we suggest that the charnockite is related to mantle-derived magmatic underplating (and crustal thickening) at 2.5 Ga. The formation of charnockite was also controlled by high metamorphic temperatures, increased pressure, a deep CO₂-rich fluid phase, intra-crustal recirculation of Neoarchaean neo-continental crust (reformed by anatexis), and the addition of mantle-derived materials (Figure 14).

7. Conclusions

Based on zircon U–Pb ages, EMP, geochemical data and regional geological results, we draw the following conclusions.

(1) Metamorphic mineral assemblages were identified in charnockite from the XWLBL area. The metamorphism of granulites and the formation of charnockite occurred during the same tectono-thermal event. Our data on the metamorphic evolution of granulites are consistent with temperature and pressure calculations based on metamorphic minerals. These data indicate that anatexis occurred mainly during the post-peak cooling and pressure-reduction stage of granulite-facies metamorphism.

(2) The in situ anatectic charnockite has distinct petrological and geochemical characteristics, as follows: (1) residual and crystalline mineral phases coexist in charnockite, with variable mineral compositions and contents; (2) the major- and trace-element compositions are heterogeneous, and the trace-element content is generally lower than that of the original rock; (3) significant depletion of LILEs (e.g. Cs) and radiogenic elements (U and Th), and enrichment in Sr; and (4) the charnockite can be divided into Eu-enriched and Eu-depleted types, which further supports an anatectic origin.

(3) Geochronological and isotopic data indicate that anatexis occurred mainly during the post-peak cooling and pressure-reduction stage of granulite-facies metamorphism. We conclude that the anatectic charnockite was related to subduction and underplating by mantle-derived magma.

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