Anatexis of late Neoarchean-Early Paleoproterozoic and late Paleoproterozoic garnet-bearing leucogranite from the North China Craton

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ABSTRACT

Two episodes of late Neoarchean-early Paleoproterozoic and late Paleoproterozoic garnet-bearing leucogranite, named the Baotou and Jining–Liangcheng garnet-bearing leucogranite are recognized from the Khondalite Belt in the North China Craton. Geochemical studies show that garnet-bearing leucogranite has high Al₂O₃ content and FeO/MgO ratio, with a large variation in the CaO content and K₂O/Na₂O ratio. Additionally, the garnet-bearing leucogranite is enriched in light rare earth elements and large ion lithophile elements and depleted in Nb, Ta, P, and Ti. However, there are some variations in Eu anomalies, as indicated by the Eu-enriched and Eu-depleted patterns. The sensitive high-resolution ion microprobe (SHRIMP) zircon U-Pb dating of the Baotou garnet-bearing leucogranite and Jining–Liangcheng garnet-bearing leucogranite show that their anatexis ages were 2.35–2.43 Ga and 1.90–1.92 Ga, respectively, with zircon εHf (t) values of −0.01–3.93 and −4.36–1.99, and two-stage model ages (TDM2) of 2.76–3.02 Ga and 2.57–2.83 Ga, respectively. U-Th-Pb SHRIMP analyses on zircon reveal ages of ca. 2.35–2.47 Ga for the Baotou metapelitic gneiss and ca. 1.90–1.91 Ga for the Jining–Liangcheng metapelitic gneiss, which represent the ages of tectonic-metamorphic events related to the anatexis. Our results, combined with geological and petrographical observations, geochemistry, and geochronology, suggest that (1) Garnet-bearing leucogranites formed as a result of anatexis of metapelitic gneisses; (2) They are mixtures of leucosomes, residual minerals and mantle-derived materials; (3) Two episodes of garnet-bearing leucogranites have been identified; and (4) Both two episodes of garnet-bearing leucogranites corresponded to late Neoarchean-early Paleoproterozoic and late Palaeoproterozoic tectono-thermal events, respectively.
1. Introduction

Anatexis is achieved through partial melting of the mid to lower crust, segregation of an incompatible element-enriched felsic magma from a more mafic residuum, and magma migration out of the source and intrusion at significantly higher levels in the crust (Sederholm 1967; Sawyer 1996, 2001; Vanderhaeghe 2009; Kisters et al. 2009; Bons et al. 2010; Brown 2010, 2013; Brown et al. 2011; Sawyer et al. 2011; Soesoo and Bons 2015; Taylor et al. 2014; Nicoli et al. 2017). The chemical relationships between source, leucosomes and the granites, which are likely to be derived from such sources, are not straightforward (Sawyer et al. 2011; Taylor et al. 2014; Nicoli et al. 2017). Thus, more and more researchers pay their attention on the relationship of the residuum segregation from partial melting, leucosomes in the source rock, and the leucogranite (Taylor et al. 2014; Nicoli et al. 2017). Recently studies showed that anatexis is commonly associated with high-grade metamorphism (Sawyer 2001; Vanderhaeghe 2009; Brown et al. 2011), metamorphic rocks in the deep crust are generally considered to melt partially under temperature rise, decompression, fluid flux, or tectonic deformation during the evolution of regional geological events (Kisters et al. 2009; Taylor and Stevens 2010; Bons et al. 2010; Brown 2010, 2013; Sawyer et al. 2011; Soesoo and Bons 2015; Nicoli et al. 2017). There have been many reports of anatectic granitoid rocks in the Sulu Dabie Orogenic Belt (Li et al. 2019; Zhou et al. 2019), Limpopo Belt of South Africa (Kriegsman 2001; Taylor et al. 2014; Nicoli et al. 2017) and the Khondalite Belt of the North China Craton (Cai et al. 2017; Shi et al. 2018, 2021a, 2021b; Xu et al. 2018). Because of melting initiated by major mantle heat addition to the crust is considered to be one of the main mechanisms by which voluminous granitic magmas arise (Taylor and Stevens 2010). To accomplish the differentiation of the continental crust, anatetic melt must migrate from the grain boundaries where it was formed and become progressively concentrated into a more focused flow pattern (Brown et al. 2011). Melt can move from one set of dilatant structures to the next as the crust progressively deforms, crystallizing partially in each and creating a complex network of leucosomes in source rocks. The processes recorded by the metapelitic gneiss of Khondalite Belt may be considerably more relevant to the production of such magmas than those which occur in migmatites that underwent slower, and more protracted heating. It is from sources such as these that more mafic, but also hot, water-undersaturated and highly mobile S-type granitic melts may be derived (Sawyer et al. 2011).

In particular, the field exposure and relationships between garnet-bearing leucogranite and metapelite gneisses in the Khondalite Belt can provide more direct evidence for the process and mechanism of anatexis. The garnet-bearing leucogranites in the Khondalite Belt were formed in the late Neoarchean and Paleoproterozoic eras (Dong et al. 2013, 2014; Cai et al. 2014, 2017; Li and Wei 2016, 2018; Wang et al. 2017; Shi et al. 2018, 2021a, 2021b), and affected by the later metamorphism and deformation events, which complicated former analyses of their composition. Nevertheless, garnet-bearing leucogranites can still provide a ‘natural laboratory’ for studying the characteristics of anatexis. At present, most studies on these garnet-bearing leucogranite focused on petrography, geochemistry, and geochronology, concluding that the products of anatexis can be regarded as magmatic intrusions (Lackey et al. 2011, 2012; Wei 2016). However, such large-scale garnet-bearing leucogranites in the Baotou–Jining–Liangcheng area in the Khondalite Belt of the NCC have not been considered as intrusion (Shi et al. 2018, 2021a, 2021b; Wang et al. 2021). Previous studies on the anatexis mechanism in this region are incomplete and have not reported the detailed characterization of the anatexis rocks. In this study, we further explore the field contact relationships between garnet-bearing leucogranite and source rocks (e.g. metapelite gneisses), as well as mineral assemblages, geochemistry, and geochronology of the rocks from the Khondalite Belt. The results of this study provide important insights into understanding the anatexis mechanism that formed the garnet-bearing leucogranite.

2. Geological background

The NCC is among the oldest cratons worldwide, having a geological evolution of more than 3.8 Ga and spanning almost across the east to the west of China (Wan et al. 2015, 2018). In the past two decades, researchers have carried out extensive lithological, geochemical, structural, metamorphic, and geochronological investigations on the NCC, and have reached a broad agreement that the craton formed by amalgamation of several micro-blocks as a results of a completed cratoni- zation (Zhai et al. 2000; Zhao et al. 2001, 2020; Kusky and Li 2003; Santosh et al. 2009). Most scholars consider that
the NCC can be divided into the Eastern Block, Trans-North China Orogen, and Western Block (Figure 1(a), Zhao et al. 2001; Xia et al. 2006; Li et al. 2011; Wang et al., 2020a). The Western Block is further divided into the Yinshan Block in the north and the Ordos Block in the south, separated by the Paleoproterozoic Khondalite Belt, which is considered to have formed by amalgamation of the Yinshan and Ordos blocks (Figure 1(b), Zhao et al. 2001; Li et al. 2011; Wang et al. 2022a).

2.1 Daqingshan high-grade metamorphic terrane

The Daqingshan high-grade metamorphic terrane is located in the central segment of the Khondalite Belt (Figure 2), and the Precambrian basement was originally divided into the granulite series (Sanggan group), biotite hornblende gneiss series (Lower Wulashan ‘Subgroup’), and Khondalite series (Upper Wulashan ‘Subgroup’). The other metamorphosed magmatic units in the region are divided into metamorphic plutonic intrusive rocks and anatexis granites (Wang et al. 2021a, 2021b). This subgroup also contains late Neoarchean metasedimentary formation with metamorphic age of ~2.45 Ga, revealed by sensitive high-resolution ion microprobe (SHRIMP) U-Pb dating of zircon sampled from the Upper Wulashan subgroup (Wan et al. 2009; Dong et al. 2014). These rock types are garnet-biotite gneiss, sillimanite-cordierite-
garnet-biotite gneiss, sillimanite garnet-felsic gneiss, and magnetite quartzite are referred to as the Daqingshan supracrystal rocks, of which garnet-biotite gneisses are similar to the aluminum-rich gneisses in terms of rock types, mineral assemblages and metamorphic evolution characteristics. In addition to different metamorphic ages, main differences between the Upper Wulashan subgroup and the Daqingshan supracrustals are summarized as follows: (1) the aluminum-rich gneisses of the Upper Wulashan subgroup are closely associated with the diopside gneiss and marble formations in space, while the sillimanite-cordierite-biotite garnet gneiss of the Daqingshan supracrustals is not in contact with the diopside gneiss and marble formation; (2) the Khondalite series of the Upper Wulashan subgroup contains graphite ores particularly in the aluminum-rich gneisses whereas the Daqingshan supracrustal rocks contains the banded iron formation, with little graphite (Dong et al. 2014).

2.2 Jining–Liangcheng high-grade metamorphic terrane

The Jining–Liangcheng high-grade metamorphic terrane is also located in the eastern section of the Khondalite Belt (Figure 3). The early Precambrian basement of the terrane consists mainly of Khondalite series,
granulites, and metamorphosed intrusive rocks. The Khondalite series consists of aluminum-rich gneisses (mainly sillimanite-cordierite-garnet gneisses) and marbles, which formed at approximately 1.95 Ga during the collision between the Yinshan Block to the north and the Ordos Block to the south (Zhao et al. 1999, 2001, 2005, 2010, 2012; Zhao 2009; Wang et al. 2020b, 2021c, 2022b). The aluminum-rich gneisses are a set of metapelite gneisses with metamorphic zircon U-Pb ages of 1.91–1.93 Ga (Shi et al. 2018), whereas the marbles are a set of magnesium-rich carbonate formations with sedimentary ages of 1.95–2.0 Ga (Santosh et al. 2007a, 2007b; Guo et al. 2012; Cai et al. 2014). The basement of the early Precambrian in the Liangcheng area is mainly composed of Khondalite series and plutonic intrusive rocks. The Sanchakou gabbro dyke in Jining was emplaced at some time between 1.92 Ga and 1.96 Ga (Peng et al. 2010, 2012, 2014).

3. Occurrences

The peraluminous ‘S-type’ granite mainly exposed in the middle-eastern part of the Khondalite Belt, is divided into the Baotou garnet-bearing leucogranite in the Daqingshan high-grade metamorphic terrane and the Jining–Liangcheng garnet-bearing leucogranite in Jining–Liangcheng high-grade metamorphic terrane.

### 3.1 Baotou garnet-bearing leucogranite

This Baotou garnet-bearing leucogranite is located in the Daqingshan high-grade metamorphic terrane in the Hademengou, Baotou area (Figure 2). The Baotou garnet-bearing leucogranite and the Daqingshan supracrustal rocks are spatially and compositionally related (Dong et al. 2013, 2014; Shi et al. 2021a, 2021b). They appear in a lenticular shape on the surface of the Daqingshan supracrustal rocks from nearly east to west in the Hademengou part of the Baotou area. In the Kunduigou part of the Baotou area, small-scale garnet-bearing leucogranite occurs as lens in the Daqingshan supracrustals.

The Baotou garnet-bearing leucogranite is composed of leucosome (felsic minerals) and dark stripes (mafic minerals). The boundaries between the stripes are unclear and characterized by gradual transition (Figure 3(a)); the leucosome stripes are mainly composed of quartz and feldspar, while the dark stripes...
consist of garnet, biotite, and small amounts of sillimanite. With increasing melting point, the grain sizes of minerals in the leucosomes increase significantly, and even approach porphyritic structure. The leucosomes are characterized by irregular lumps or leucosome stripes parallel to the gneisses in the matrix (Figure 3(d–g)). The thickness of the leucosome stripes is generally in the order of millimeters to centimeters, occasionally meters, forming garnet-bearing leucogranite with the gradual increase in the content of leucosomes (Figure 3(a–g)). An increasing degree of anatexis melting can be observed in the same section after in situ, near in situ, and semi in situ migration, which forms different rock types under sufficient melting and strong hot spot heat supply. For example, Daqingshan supracrustal rocks, leucosome, and garnet-bearing leucogranite can be observed in a section of Baotou area (Figure 3(a)).

3.2 Jining–Liangcheng garnet-bearing leucogranite

Jining–Liangcheng garnet-bearing leucogranite is located in the Jining–Liangcheng area (Figure 4), having a similar mineral composition to garnet-biotite gneiss, as they are composed of quartz, biotite, and garnet. Specifically, medium-to-fine-grained garnet-bearing leucogranite contains many hook-like,
lenticular, and irregular metapelite gneiss enclaves, residual bodies, and residual mineral facies, and it is closely spatially associated with the metapelite gneiss of the Khondalite series. The main lithologies of the mantle-derived magmatic rocks are gabbro and norite, which are distributed in Xigou, Sanchakou, Tuguwula, Dayushu, and Jining, and have undergone retrograde metamorphism to perilla pyroxene plagioclase granulite.

According to studies on garnet-bearing leucogranite in the Jining–Liangcheng area, anatexic granite can be traced back to its anatexic source rocks (Figure 5(a–g)). Jining–Liangcheng garnet-bearing leucogranite and aluminum-rich gneiss are gradually transitional and closely coexisting. Furthermore, the metamorphic age of the aluminum-rich gneiss closely matches that of garnet-bearing leucogranite (Shi et al. 2018). Numerous results of previous studies show that anatexis often occurs after the peak stage of metamorphic evolution of a high-grade metamorphic complex, near the stage of constant temperature and decompression (Shi et al. 2018, 2021a, 2021b). In addition, the composition of the garnet-bearing leucogranite is heterogeneous because the source rock enclaves, residual bodies, and melted material have not been completely separated (Figure 5(b–d)). For instance, aggregates of garnet and quartz can be observed as lenses (Figure 5(a,b)).

4. Analytical methods

4.1 Electron probe microanalysis of minerals

Mineral composition data for the source rocks and the garnet-bearing leucogranite were collected using an electron microprobe at the Key Laboratory of Orogen and Crustal Evolution of the Ministry of Education, Peking University, Beijing, China, with a 5 kV accelerating voltage, $1 \times 10^{-8}$ A beam current, and 1 μm spot diameter. Fifty-three standard samples of well-defined natural minerals (SPI Supplies, West Chester, Pennsylvania, USA) were used for calibration. The results are presented in Supplementary Tables 1 to 6.

4.2 Bulk-rock major and trace element analysis

The major element compositions of the minerals were determined using an Axios X-ray fluorescence spectrometer at the China National Research Center for Geoanalysis, Beijing, China, while the trace element analyses were conducted using an Elan 9000 inductively coupled plasma mass spectrometer (PerkinElmer, Waltham, Massachusetts); the accuracy of the analyses was better than 10% and the results and analytical precisions for each element are reported in Supplementary Table 7.

4.3 Zircon U-Pb dating

Zircon crystals were obtained via standard crushing and separation techniques. The U-Pb dating was carried out using a SHRIMP II instrument at the Beijing SHRIMP Centre, Chinese Academy of Geological Sciences. The hand-picked crystals, together with the TEMORA zircon standard (with a conventionally determined $^{206}\text{Pb}/^{238}\text{U}$ age of 417 Ma; Black et al. 2003), were cast in epoxy resin disks and polished. All grains were photographed in both transmitted and reflected light and then imaged using cathodoluminescence (CL) to reveal the internal structure and identify preferred locations for in situ SHRIMP analyses. The U-Pb dating parameters are reported in Supplementary Table 8, and the instrument operation parameters in Supplementary Table 10.

4.4 Zircon Lu-Hf isotopes

Zircon Lu-Hf isotope analyses were performed on the same spots measured for the SHRIMP U-Pb isotopes. Hf isotope analyses were performed using a Neptune Plus MC-ICP-MS (Thermo Fisher Scientific, Dreieich, Germany) at Wuhan Sample Solution Analytical Technology Co., Ltd., Hubei, China. The laser beam size was set to 44 μm with a frequency of 8 Hz and an energy density of ~8 J/cm$^2$ using helium as the carrier gas. The exponential law, which was initially developed for TIMS measurement and remains the most widely accepted and utilized law with MC-ICP-MS, was used to assess the instrumental mass discrimination in this study. Mass discrimination correction was carried out via internal normalization to an $^{179}\text{Hf}/^{177}\text{Hf}$ ratio of 0.7325 (Lin et al. 2016). The interference elements Yb and Lu were completely separated by the exchange resin process. The remaining interferences of $^{176}\text{Yb}^+$ and $^{176}\text{Lu}^+$ were corrected based on the method described by Lin et al. (2016). One Alfa Hf standard was measured for every 10 samples analysed. Analyses of the JMC 475 standard yielded an $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.212861 ± 13 (2SD, n = 12), which is identical within error to the published value (0.282163 ± 21). When all solutions yielded $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of ~0.28216, the instrument settings were considered optimized for laser ablation analyses and seven standard zircons (91500, TEMORA [TEM], GJ and Plesovice) were analysed. In addition, the USGS reference materials BCR-2 (basalt) yielded 0.282865 ± 10 (2SD, n = 4) for $^{176}\text{Hf}/^{177}\text{Hf}$, which is
identical within error to the published value. Details of the analytical procedures, results, and isotope ratios used for calculating the single-stage Hf-depleted mantle ages ($T_{DM1}$) and two-stage Hf crustal model ages ($T_{DM2}$) from the Hf-model age values are presented in Supplementary Table 9, and the instrument operation parameters in Supplementary Table 10.

5. Petrography and microstructures

The Daqingshan supracrustal rocks (sillimanite-cordierite-biotite gneiss) are composed mainly of garnet (10–15 vol. %), biotite (10–15 vol. %), quartz (15–20 vol. %), feldspar (45–50 vol. %), sillimanite (<5 vol. %), cordierite (<5 vol. %), and ilmenite (<1 vol. %; Figure 6(a)). The gneisses contain strong foliations defined by oriented sillimanite and biotite in the matrix (Figure 6(a–e)). Inclusions of sillimanite, biotite, quartz, plagioclase, and ilmenite occur in garnet porphyroblasts (Figure 6(c–f)), and their sizes increase gradually from the cores to the rims of the host grains. Biotite and quartz show irregular or granular shapes and occur with irregular granular feldspar, all of which surround the garnet in the matrix (Figure 6(e–h)). Biotite occurs either as inclusions in porphyroblasts or as irregular/granular grains in the matrix, which are reddish-brown and brown in colour, respectively (Figure 6(e–g)). Feldspar is mainly microcline and plagioclase and has irregular or granular shapes (Figure 6(g,h)).
Sillimanite occurs as irregular slab or columnar grains surrounded by cordierite, quartz, feldspar, and ilmenite (Figure 6(h)).

Baotou garnet-bearing leucogranite samples are relatively uniform in composition and are composed mainly of garnet (10–15 vol. %), biotite (5–10 vol. %), quartz (20–25 vol. %), feldspar (50–55 vol. %), and sillimanite (<1 vol. %). Inclusions of biotite, quartz, plagioclase, and ilmenite are present in the garnet porphyroblasts (Figure 6(g,h)), and the sizes of these inclusions gradually increase from garnet cores to garnet rims. Biotite, quartz, and feldspar are all irregular and granular in shape, and all surround garnet in the matrix (Figure 6(g,h)). The biotite can be divided into inclusion and matrix types, both of which are irregular or granular in shape, although matrix-type biotite often overgrows the outer rim of garnet (Figure 6(g,h)). The feldspar is mainly plagioclase and occurs as both inclusions and in the matrix (Figure 6(g,h)). The sillimanite content of all lithologies is low and it occurs as a fibrous domain adjacent to garnet rims (Figure 6(g,h)).

Jining–Liangcheng garnet-bearing leucogranite has a weak gneissic texture or medium- to fine-grained granite texture and a massive structure. Based on the composition and content of the minerals, the garnet-bearing leucogranite is mainly subdivided into medium- to fine-grained garnet monzogranite (Figure 7(a,b)). Furthermore, garnet-bearing leucogranite are mainly

Figure 5. Geological sections of the Jining–Liangcheng area (a), northern margin of the NCC, highlighting local characteristics. (b, c) Jining–Liangcheng garnet-bearing leucogranite contains a large number of garnet grains, dark and leucosome stripes. Their sizes increase gradually from the dark to leucosome stripes. (d, e) The coexistence of dark and leucosome stripes in metapelite gneiss in the Jining–Liangcheng area sample.
Figure 6. Photomicrographs of Daqingshan supracrustal rocks and garnet-bearing leucogranite from the Khondalite Belt of the NCC, and the characteristics of minerals that occur as inclusions and in the matrix: showing the garnet surrounded by an assemblage of Crd + Q + Sil + Pl in Daqingshan supracrustal rocks (a), and garnet-bearing leucogranite (b). (c) and (d) show the mineral assemblage of Pl + Q + Sil as inclusions in garnet in the Daqingshan supracrustal rocks, with elongated garnet grains including oriented sillimanite; (e) show biotite in the matrix; (f) show garnet surrounded by an assemblage of Crd + Q + Sil + Pl; (g) show plagioclase in the matrix; (h) show mineral inclusions in cordierite and sillimanite as irregular slabs and columns in the Daqingshan supracrustal rocks and garnet-bearing leucogranite.
Figure 7. Photomicrographs of Jining–Laicheng garnet-bearing leucogranite, metapelitic gneiss of the NCC. (a, b) The irregular serrated and resorbed grain boundaries of quartz and feldspar in Jining–Laicheng garnet-bearing leucogranite, with mineral assemblage of Gt + Bt + Pl + Kfs + Q. (c, d) Biotite and sillimanite in the metapelitic gneiss from the Jining–Liaocheng area is precipitated with iron, and the edge of biotite is darkened. (e, f) Characteristics of plagioclase in MG18-1 sample of Jining–Laicheng garnet-bearing leucogranite. (g, h) Metapelitic gneiss samples of DYS18-1 in Jining–Liaocheng area, composed of hairy sillimanite distributed on the surface of garnet and plate columnar sillimanite in the matrix. Gt: garnet; Bt: Biotite; Q: Quartz; Pl: plagioclase; Kfs: K-feldspar; Sil: sillimanite; Crd: Cordierite.
6. Mineral chemistry

Representative minerals from the Daqingshan supracrustal rocks, Baotou garnet-bearing leucogranite, Jining–Liancgheng metapelitic gneiss and garnet-bearing leucogranite were analysed using an electron microprobe to obtain their chemical compositions. These data are listed in.

6.1 Garnet

The garnet generally occurs as xenomorphic porphyroblasts with embayed rims (Figures 5, 7). Inclusions of quartz, biotite, and plagioclase are common. In the Daqingshan supracrustal rocks and Jining–Liancgheng metapelitic gneiss, garnet has clear zoning with the following end-member mol. % proportions: 0.57–0.68 almandine [Fe²⁺/(Fe²⁺ + Mg + Ca + Mn)], 0.26–0.36 pyrope [Mg/(Fe²⁺ + Mg + Ca + Mn)], 0.02–0.07 grossular [Ca/(Fe²⁺ + Mg + Ca + Mn)], and 0.01–0.04 spessartine [Mn/(Fe²⁺ + Mg + Ca + Mn)]. Similarly, garnet in the Baotou and Jining–Liancgheng garnet-bearing leucogranite contains inclusions of quartz, biotite, and plagioclase. The garnet porphyroblasts are usually >1.5 mm in diameter and have compositions of 0.62–0.69 almandine, 0.26–0.33 pyrope, 0.03–0.05 grossular, and 0.01–0.02 spessartine (mol. %), with clear zoning akin to the Daqingshan supracrustal rocks and Jining–Liancgheng metapelitic gneiss. In the Daqingshan supracrustal rocks and Jining–Liancgheng metapelitic gneiss, garnet rims in direct contact with plagioclase show a lower MgO (6.84–9.17) and higher FeO⁴⁺ (26.82–31.17) compared with the cores (7.72–9.76 and 27.60–30.10, respectively).

The compositional zoning of the garnet in the Baotou and Jining–Liancgheng garnet-bearing leucogranite resembles that of the core regions of garnet in the Daqingshan supracrustal rocks and Jining–Liancgheng metapelitic gneiss. Similarly, in the garnet-bearing leucogranite samples, garnet rims in direct contact with plagioclase and quartz also show lower MgO (6.80–7.28) and higher FeO⁴⁺ (29.6–32.0) contents compared to the core regions (7.9–8.5 and 28.9–30.7, respectively). The rimward increase in Fe records the effects of cation diffusion zoning from cores to rims that occurred during retrograde metamorphism (Dallmeyer and Dodd 1971). The XMg[Gt] [Mg/(Mg + Fe²⁺)] and XFe[Gt] [Fe/(Mg + Fe²⁺)] values of Daqingshan supracrustal rocks and Jining–Liancgheng metapelitic gneiss are 0.27–0.36, 0.59–0.70, and 0.02–0.07, respectively, while the Baotou and Jining–Liancgheng garnet-bearing leucogranite samples have ratios of 0.27–0.34, 0.57–0.70, and 0.03–0.05, respectively.

6.2 Biotite

Biotite inclusions in Daqingshan supracrustal rocks and Jining–Liancgheng metapelitic gneiss (Figures 5, 7) have XMg(Bt) ranging from 0.57 to 0.82 and are characterized by a moderate to high TiO₂ content (1.30–3.64 wt. %) in the garnet core (Supplementary Tables 3 and 4); however, biotite in the matrix in direct contact with plagioclase and quartz shows a lower XMg(Bt) of 0.42 to 0.78 and is characterized by a moderate to higher TiO₂ content (2.88–4.88 wt. %). Similarly, biotite in Baotou and Jining–Liancgheng garnet-bearing leucogranite sample shows a XMg(Bt) ratio that increases from 0.51 to 0.72 from the core to rim of garnet, whereas biotite in the matrix of other samples has a lower XMg(Bt) of 0.59–0.66. Aydin et al. (2003) showed a linear negative correlation between Fe and Mg in biotite, as one element replaces the other during metamorphism. Further, the Ti content and XMg(Bt) value of biotite is dependent on the chemical composition of the rock, the equilibrium mineral assemblage, the extent of retrograde reaction, and diffusion of Fe–Mg, among other factors (Spear and Florence 1992). Spear et al. (1999) showed that the Ti content of biotite increases alongside the degree of metamorphism (Supplementary Tables 3 and 4).

6.3 Feldspar

Feldspar in the analysed samples is mostly plagioclase (Figures 5, 7), and feldspar inclusions in the Daqingshan supracrustal rocks and Jining–Liancgheng metapelitic gneiss are dominated by albite (XAb = 0.51–0.74) and anorthite (XAn = 0.25–0.48), with minor orthoclase (XOr <0.02; Supplementary Table 5). Similarly, feldspar in the Baotou and Jining–Liancgheng garnet-bearing leucogranite is dominated by albite (XAb = 0.48–0.73) and anorthite (XAn = 0.27–0.50) with some orthoclase (XOr <0.02). Feldspar in Daqingshan supracrustal rocks shows an increasing XAn ratio from core to rim in
garnet (0.50–0.59), which increases to 0.70–0.74 in the matrix. The XAn of the plagioclase inclusions in the garnet-bearing leucogranite resemble those in the Daqingshan supracrustal rocks and Jining–Liangcheng metapelite gneiss, with $X_{ab}$ values of 0.51–0.68 from core to rim in garnet and 0.69–0.74 in the matrix. All grains are rich in albite and are chemically classified as oligoclase or andesine. The plagioclase inclusions in coronitic garnet are slightly more Ca-rich, with $X_{an} = 0.29–0.48$. The $X_{Ca}(pl)$ [Ca/(Ca + K + Na)] values of Daqingshan supracrustal rocks and Jining–Liangcheng metapelite gneiss are 0.25–0.48, and those for garnet-bearing leucogranite are 0.26–0.51 (Supplementary Tables S5 and S6).

7. Bulk chemistry

Bulk-rock major and trace element compositions of representative Daqingshan supracrustal rocks, garnet-bearing leucogranite and metapelite gneiss rocks from the Baotou and Jining–Liangcheng area are presented in Supplementary Table 7.

7.1 Major element analysis

The lithology of the Baotou–Jining–Liangcheng garnet-bearing leucogranite varies greatly, and the content of SiO$_2$ is 56.63–78.85 wt. %, generally concentrated in the 66.81–72.32 wt. % range, which is equivalent to the silicic end-members of metapelite gneisses. However, the Al$_2$O$_3$, FeO$^T$, and MgO contents are relatively enriched, and Na$_2$O and P$_2$O$_5$ are relatively depleted, and the content of MnO is lower than that of the intermediate end-members. K$_2$O contents can be divided into enriched and depleted types, and the content of TiO$_2$ is similar to that of the silicic end-members of metapelite gneisses (Figure 8). In general, the garnet-bearing leucogranite is characterized by a relatively high K$_2$O and Na$_2$O contents and low CaO contents, as well as relatively higher Al$_2$O$_3$, FeO, MgO, and MnO contents than the metapelite gneiss (Figure 8). With the increase in the SiO$_2$ content, the contents of Na$_2$O and K$_2$O increase, whereas the contents of Al$_2$O$_3$, FeO, CaO, MgO, and MnO decrease (Figure 8).

7.2 Trace element analysis

In the primitive mantle-normalized trace element diagram (Figure 9(a)), the partition curve of Baotou and Jining–Liangcheng garnet-bearing leucogranite is similar to that of Daqingshan supracrustal rocks and Jining–Liangcheng metapelite gneiss. However, the garnet-bearing leucogranite has lower trace element contents, depleted partial LILEs (e.g. Cs) and heat-producing elements (e.g. U and Th), and significant enrichment in Sr contents compared to metapelite gneiss. Based on the normalized trace element diagram of garnet-bearing leucogranite, the relative enrichment of LILEs (e.g. K, Rb, and Ba) indicates that those elements preferentially entered the melt phase during anatexis, possibly promoted by a small amount of fluid in the system. While the HFSEs (e.g. Nb, Ta, P, and Ti) are more depleted (Figure 9(a)). Baotou and Jining–Liangcheng garnet-bearing leucogranite can be divided into two types based on the Eu anomalies (Eu/Eu$^*$). The Baotou garnet-bearing leucogranite samples showed significant positive Eu anomalies (Eu/Eu$^* = 1.00–5.36$) while other samples showed negative anomalies (Eu/Eu$^* = 0.45–0.99$); the Jining–Liangcheng garnet-bearing leucogranite samples showed significant positive Eu anomalies (Eu/Eu$^* = 1.05–7.72$) and other samples showed negative anomalies (Eu/Eu$^* = 0.3–0.92$) (Table 1). In the chondrite-normalized REE diagram (Figure 9(b)), the REE pattern and total REEs of the garnet-bearing leucogranite samples, which were consistent with a petrographic study showing that the content of garnet is similar to that of the metapelite gneiss.

Data from: (Wu et al. 2013; Ma et al. 2015; Shi et al. 2018, 2021a, 2021b); This paper.

8. Zircon U-Pb ages and Lu-Hf isotopes

8.1 SHRIMP zircon U-Pb dating

Supplementary Fig 1 shows representative CL images of zircon grains from Liangcheng sillimanite-garnet- felsic gneiss DYS18-1 samples, which were transparent, colorless, oblong, and with prismatic shapes. Zircon grains from this sample were 50–150 μm in length with aspect ratios of 1:1 to 2:1 and were dominantly euheudal, elongate, or prismatic. Most zircons were incomplete and broken, and the internal cracks were very well developed. The core-mantle-rim structures within zircon grains were distinguished based on the CL images; a clear magmatic oscillatory zoning in core of zircon grains indicated a detrital origin (Koschek 1993). Three U-Pb analyses of oscillatory-zoned zircons produced apparent $^{207}$Pb/$^{206}$Pb ages of 1889–2014 Ma with U and Th contents of 62–105 ppm and 189–526 ppm, respectively, and relatively large Th/U ratios (mostly 0.13–0.34). The rims of zircon are mostly dark gray to gray and have a metamorphic origin; they surround and nibble the residual detrital cores of zircons. The rims of metamorphic zircons are 25–45 μm in length with a relatively large variation in the Th/U ratios (mostly 0.02–0.50) and U and Th contents of 189–727 ppm and
Eight U-Pb analyses of oscillatory-zoned zircons produced a weighted mean of apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1885 ± 10 Ma, with the mean squared weighted deviation (MSWD) of 0.68 (Figure 10(e)).

Representative CL images of zircon from the garnet-bearing leucogranite MG18-1 samples are displayed in Supplementary Fig 1. Zircon grains from this sample are 100–250 μm in length with aspect ratios of 1:1 to 1:2 and are dominantly euhedral, elongate, or prismatic. Six U-Pb analyses of oscillatory-zoned zircons produced apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1980–2079 Ma with U and Th contents of 147–393 ppm and 61–187 ppm, and relatively large Th/U ratios of 0.40–0.62. This may represent the lower limit of the formation ages of the anatetic source rocks. Core zircons are mostly dark gray to gray with a metamorphic origin, and they surround and nibble the core residual zircons. The mantle metamorphic zircons are 25–45 μm in length with a relatively large variation in the Th/U ratios (mostly 0.05–1.15), and the U and Th contents are in ranges of 177–494 ppm and 18–197 ppm, respectively. Seven U-Pb analyses of mantle zircons produced a weighted mean of apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1885–1947 Ma. The rims of metamorphic zircons are 10–40 μm in length and show relatively large variations in the Th/U ratios (mostly 0.05–0.96); the U and Th contents are 101–494 ppm and 23–157 ppm, respectively. Seven U-Pb analyses of mantle zircons produced a weighted mean of apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1885–1947 Ma, and the fuzzy mantle oscillatory-zoned zircons revealed the origin of metamorphic anatexis zircon. Eleven U-Pb analyses of mantle and rim zircons produced a weighted mean of apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1905 ± 8 Ma (MSWD = 1.3) (Figure 10(f)), representing the anatexis age of garnet-bearing leucogranite.


8.2 Zircon Lu-Hf isotopes

Lu-Hf isotope analyses were performed on two zircon grains from garnet-bearing leucogranites, consisting of Baotou garnet-bearing leucogranite (Sample WL18-1), Jining garnet-bearing leucogranite (Samples MG18-1). The results are shown in Figure 11 and Supplementary Table 9.

8.2.1 Baotou garnet-bearing leucogranite

Eleven Lu-Hf isotope analyses were performed for the zircons from Sample WL18-1. Their $^{176}$Hf/$^{177}$Hf ratios range from 0.281263 to 0.281364, and their calculated εHf(t) values range from −0.01 to 3.93 (Supplementary Table 9, Figure 11), corresponding to (TDM1) and (TDM2) ages varying from ca. 2.63 to 2.81 Ga and from ca. 2.76 to 3.02 Ga, respectively. In the εHf(t) vs. $^{207}$Pb/$^{206}$Pb age plot in Figure 11, most of the grains fall into the field above the chondrite line, indicating that the parental source involved crustal components.

8.2.2 Jining garnet-bearing leucogranite

Thirteen Lu-Hf isotope analyses were performed for the zircons from Sample MG18-1. Their $^{176}$Hf/$^{177}$Hf ratios range from 0.281484 to 0.281562, and their calculated εHf(t) values range from −4.36 to 1.99 (Supplementary Table 9, Figure 11), corresponding to (TDM1) and (TDM2) ages varying from ca. 2.31 to 2.46 Ga and from ca. 2.57 to 2.83 Ga, respectively. In the εHf(t) vs. $^{207}$Pb/$^{206}$Pb age plot in Figure 11, most of the grains fall into the field below the chondrite line, indicating that the parental source involved crustal and mantle components.
9. Discussion

9.1 Timing of magmatism and metamorphism

Zircon SHRIMP U-Pb ages obtained from the garnet-bearing leucogranite samples from metapelite gneiss of the sources rock can be divided into four main categories: 1) ~2.6–2.5 Ga, 2) ~2.43–2.35, 3) 2.3–2.0 Ga. Recent studies indicate that the zircon ages of 2.37–2.0 Ga obtained in the Daqingshan area may be the result of the influence of late Paleoproterozoic metamorphism events (Zhang et al. 2016a). These ages are considered to represent at least partial resetting of the isotopic system (Wan et al. 2020), as well as indicate that the limit of the metamorphic anatexis ages of garnet-bearing leucogranite is before ~2.43 Ga and probably formed in the late Neoarchean (Wan et al. 2009; Dong et al. 2014; Shi et al. 2021a, 2021b). Wan et al. (2021) discussed this issue in more detail. Although some Neoarchean rocks contain metamorphic zircon yielding a relatively small range of U-Pb
dates, the analyses from the Daqingshan area (the Baotou area) as a whole are distributed along concordia from ~2.50 to 1.82 Ga, with most clustered between 2.5 and 2.2 Ga, and 2.0 and 1.82 Ga, respectively. There were two episodes of high-grade metamorphism that affected the area, the first in the late Neoarchean and the second in the mid to late Paleoproterozoic. Jining garnet-bearing leucogranite and metapelite gneiss (silimanite-garnet-felsic gneiss) revealed metamorphic zircon ages of 1911 ± 10 Ma and recrystallized zircon ages of 1919 ± 17 Ma (Figure 10(c,d)). Liangcheng garnet-bearing leucogranite and metapelite gneiss (silimanite-garnet-biotite gneiss) showed metamorphic ages of 1885 ± 10 Ma and metamorphic anatexis origin zircon ages of 1905 ± 8 Ma. The formation of Jining–Liangcheng garnet-bearing leucogranite may have happened in the late Paleoproterozoic (Chen et al. 2016; Zhang et al. 2016b; Wang et al. 2017; Shi et al. 2018). In general, there are at least two types of metamorphic anatectic granites in the Khondalite Belt of the northern margin of the NCC.

Simultaneously, metapelite gneiss in the source rock of the Baotou and Jining–Liangcheng garnet-bearing leucogranite have different chronological characteristics; specifically, the metamorphic zircon ages concentrate at 2.45–2.37 Ga (Figure 10(a)), Shi et al. 2021a) and 1.92–1.90 Ga, respectively (Figure 10(c-e)), (Shi et al. 2018; this paper). The metamorphic ages represent two different tectonometamorphic thermal events in the Baotou–Jining–Liangcheng area in the late Neoarchean and late Paleoproterozoic (Wan et al. 2009; Santosh et al. 2013; Cai et al. 2014, 2017; Dong et al. 2014; Peng et al. 2014; Wang et al. 2015). The isotopic geochronology of the surrounding metapelite gneiss is consistent with the age obtained from the metamorphic anatectic zircon in the corresponding garnet-bearing leucogranite. Petrographical and field observations of the anatexis, combined with the geochemical characteristics of the sampled rocks, allowed us to determine the origin of the metamorphic anatexis of the garnet-bearing leucogranite.

### 9.2. Origin and petrogenesis of the rocks

In this study, garnet-bearing leucogranite samples were peraluminous to strongly peraluminous, which are typical features of S-type granites. And these samples have high Al$_2$O$_3$ content and FeO$^T$/MgO ratio, with a large variation in the CaO content and K$_2$O/Na$_2$O ratio. Additionally, garnet-bearing leucogranite is enriched in light rare earth elements and large ion lithophile elements and depleted in Nb, Ta, P, and Ti. However, there are some variations in Eu anomalies, as indicated by the Eu-enriched and Eu-depleted patterns. Previous studies have shown that characteristics of the Eu anomaly are usually closely related to the contents of plagioclase and garnet in samples (Hidaka et al. 2002). The content of CaO and Ca$_2$O + Na$_2$O was much lower and that of FeO$^T$, MgO, and Nb was much higher in the samples with positive Eu anomalies than in the samples with negative Eu anomalies (Figure 12, Table 1). This indicated that the samples with the negative Eu anomalies contained more garnet and less plagioclase than those with the positive Eu anomalies.

The garnet-bearing leucogranite samples showing REE pattern curves with positive and negative Eu anomalies were also found in the Damara Central Orogenic Belt, Namibia, and Turku area in southern Finland. Jung et al. (2000a) showed that samples with positive Eu anomalies are the products of further fractional crystallization of
samples with negative Eu anomalies, representing the accumulation of residual and felsic melting. However, the difference is that the contents of SiO\(_2\) in the Baotou and Jining–Liangcheng garnet-bearing leucogranite samples are 55.63–72.32 wt. %, which is not completely consistent with those samples from Namibia and Finland. Therefore, we considered the gradual separation of melting, residual body, and residual mineral phase of the Baotou and Jining–Liangcheng garnet-bearing leucogranite samples with the specific evidence as follows: 1) Petrology, petrography, and geochemistry further support that garnet-bearing leucogranite is the product of the gradual separation of anatectic melts, residual body, and mineral phases. 2) Experimental petrological studies have shown that the solubilities of MgO and FeO in peraluminous granite are 0.22–0.90 wt. % and 1.27–3.01 wt. %, respectively (Jung et al. 2000b). The MgO and FeO contents in the Baotou garnet-bearing leucogranite are 2.17–9.23 and 0.70–10.14 wt. %, and those in the Jining–Liangcheng garnet-bearing leucogranite are 3.97–11.35 and 0.6–3.73 wt. %. All these values are much higher than the solubilities determined in experimental petrological studies, indicating that a part of the mafic minerals is in anatectic residual minerals. 3) With the gradual increase in the content of SiO\(_2\), the residual mineral phases gradually decrease (diablastic texture of garnet, brown ablative biotite, and enclave formation), which indicates that the anatexis melt is gradually separated from the residual enclaves and minerals.

From the viewpoint of magmatic rocks, peraluminous and strongly peraluminous granites are products of partial melting of terrigenous materials in the deep crust. During emplacement, the melt separated from the residual body, intruded the shallow crust, formed intrusive rocks, and erupted to the surface to form volcanic rocks. Almost all intrusive rocks have been formed following this process; however, there are different understandings of the mineral and chemical composition of the residue: Campbell et al. (1984) suggested that many granites and related volcanic rocks contain a certain amount of unmelted or incompletely melted residual crystals in the source area. These residual mineral bodies/phases are separated from the granitic magma in varying degrees during granite magma accumulation, migration, and ascending emplacement, altering the granite composition. Residual minerals can be found in most granites, and the most common mineral is residual zircon, which is often affected by the melt temperature and pressure, the distance of melt migration, and other factors; garnet, biotite, and some accessory minerals can also remain in the residue.

The occurrence and melting point of anatexis are not only related to temperature, pressure, and fluid, but also depend on melting ability of the metamorphic protolith (Kriegsman 2001; Yang et al. 2003). The protoliths of different metamorphic rocks have distinct melting degrees under similar conditions. The metapelite gneisses in the source rocks of garnet-bearing leucogranites are mainly garnet-biotite and sillimanite-cordierite-garnet-biotite gneisses in the Daqingshan area; the lithology of the Jining–Liangcheng garnet-bearing leucogranite is mainly sillimanite-cordierite–garnet gneiss sillimanite-cordierite-garnet-felsic gneiss (Figure 13(a,b)). However, the anatexis degrees of magnetite quartzite, neutral granulite, and garnet quartzite show relatively lower content in Baotou garnet-bearing leucogranite; garnet-felsic gneiss, garnet quartzite, and graphite gneiss also exist in Jining–Liangcheng garnet-bearing leucogranite, where selectivity of anatectic source rocks is observed. A comparison of the geochemical characteristics showed that the garnet-biotite gneiss is the anatectic source rock of the Baotou garnet-bearing leucogranite, and the source rock metapelite gneiss may be the anatectic source

![Figure 12](image_url). The diagram of Eu/Eu* vs. (CaO+Na\(_2\)O)/(FeO\(^{2+}\)+MgO) and Eu/Eu* vs. Nb in the Baotou, Jining–Liangcheng garnet-bearing leucogranite of the NCC.
rock of the Jining–Liangcheng garnet-bearing leucogranite (Figure 13(c,d)), (Chen et al. 2016; Zhang et al. ; Shi et al. 2018).

A comparison between the geochemical characteristics of garnet-bearing leucogranite, metapelite gneisses, and mafic magmatic rocks suggests that the petrogenesis of garnet-bearing leucogranite may be related to the basic magmatism (Figures 8 and 9). The results of Lu-Hf isotopic analysis further support this view; the εHf(t) values of the Baotou and Liangcheng garnet-bearing leucogranite (from −8.0–6.9, −2.0–5.9) are partly similar to those of the metamorphic gabbro (εHf(t) values: −6.2–7.4, −1.70–3.90) in the region (Figure 11(a,b)); (Peng et al. 2010, 2012, 2014; Wang et al. 2011, 2018; Dong et al. 2013, 2014; Ma et al. 2015). Wang et al. (2018) suggested that the values of granitic rocks in the Jining–Liangcheng area can be summed up in two aspects: (1) The similarity between granitic and mafic magma is formed by complete hybridization or extensive isotope diffusion under high temperature for a long time (Lesher 1990); (2) The metapelite gneisses of the source rock originated from the young and reconstructed crust and rapidly returned to the surface (Xia et al. 2008; Wang et al. 2015).

9.3 Mineral behaviour during anatexis

Previous work has shown that garnet is one of the minerals most resistant to intercrystalline diffusion during metamorphism (Florence and Spear 1991; Wu 2019. However, Powell and Holland (2008) recently reported that ion diffusion becomes notably faster at granulite-facies metamorphic conditions; thus, using the compositions of Fe–Mg minerals, such as garnet and biotite, to constrain peak metamorphism must be performed with care show that garnet from Daqingshan supracrustal rocks, Baotou garnet-bearing leucogranite, Jining–Liangcheng metapelite gneiss and garnet-bearing leucogranite show slight zoning from core to rim, recording cation diffusion that occurred during retrograde metamorphism (Dallmeyer and Dodd 1971).

Biotite compositions are also easily modified during cooling due to Fe–Mg exchange reactions among minerals in granulites (Spear et al. 1999; Powell and Holland 2008). Li and Wei (2018) showed that higher X_{Mg}(Bt) values can form due to rapid diffusion under subsolidus conditions and can yield higher temperature estimates close to the peak results in suprasolidus fields. However, stable isopleths of X_{Mg}(Bt) calculated during phase

![Figure 13](image-url)

**Figure 13.** The diagram of Rb/Sr- Rb/Ba (a) (Simonen 1953), CaO/((MgO+FeO\(^\text{Tot}\))/2)/Al\(_2\)O\(_3\)/(MgO+FeO\(^\text{Tot}\)) (b), Rb/Ba-Rb/Sr (c), CaO/Na\(_2\)O-Al\(_2\)O\(_3\)/TiO\(_2\)(d) in the Baotou, Jining–Liangcheng garnet-bearing leucogranite and metapelite gneiss of the NCC.
equilibria modelling occur in the peak mineral assemblages and have near-vertical slopes with respect to the pressure axis, which indicates strong sensitivity to temperature changes. A comparison of the $X_{	ext{Mg}}$(Bt) values of the biotite from these samples in the core of the garnet, the matrix, and the matrix in contact with other minerals showed a consistent trend, indicating the operation of Fe–Mg exchange reactions. For example, higher $X_{	ext{Mg}}$(Bt) values for biotite inclusions in the garnet than in the matrix could be a result of cation exchange with the host garnet. Therefore, $X_{	ext{Mg}}$(Bt) may be used as the best variable for determining peak temperature conditions.

Plagioclase is stable at all P–T conditions considered for pseudosection construction. Spear and Florence (1992) reported that the NaSi ↔ CaAl intracrystalline diffusion rate in plagioclase is much lower than the Fe–Mg exchange rate in garnet and biotite (Li and Wei 2016). Thus, plagioclase prefers to recrystallize rather than forming a new composition when equilibrating with other minerals (Spear and Florence 1992), and its composition in granulite facies rocks might not change as easily as Fe–Mg minerals during retrogression. Therefore, $X_{	ext{Ca}}$(Pl) should be used to record the peak P–T conditions. Analyses of albite plagioclase inclusions in the core of garnet and grains in the matrix in contact with other minerals revealed that the $X_{	ext{Ca}}$(Pl) value decreased from the inclusions to the matrix. The higher content of albite in the matrix in contact with other minerals (plagioclase, quartz, biotite) in the Baotou and Jining–Liangcheng garnet-bearing leucogranite than that in the Daqingshan supracrystalline rocks and Jining–Liangcheng metapelitic gneiss indicates that the $X_{	ext{Ab}}$(Pl) decreased during anatexis.

9.4 Melting reaction and P–T evolution

Wei (2016) showed that anatexis can occur under various temperature and pressure conditions of amphibolite and granulite facies, and that corresponding melting reactions occur. For example, the biotite melting reaction often occurs in metamorphic argillaceous rocks during isobaric heating and melting, whereas K-rich feldspar and biotite melting often occur in granulite facies metamorphism during almost constant temperature and decompression. The melt composition is controlled by the pressure and temperature conditions, as well as the melting reaction. Biotite and K-feldspar melt to form strong peraluminous monzonitic granite under granulite facies metamorphism. Garnet-bearing leucogranite rocks can be formed by a strong peraluminous monzonitic (K-feldspar) granite melt of the K-feldspar, garnet, and mafic mineral under medium pressure and ultrahigh temperature. Garnet-bearing leucogranite is strongly peraluminous in this area, with a garnet content of more than 10 vol. % and occasionally reaching 30 vol. %. Similar to the garnet characteristics of the source rock, garnet-bearing leucogranite also has a sieve-like meta-crystalline structure and generally contains metamorphic mineral inclusions such as quartz, plagioclase, biotite, and sillimanite. The electron probe microanalysis results showed that garnet from garnet-bearing leucogranite (compositional zoning: almandine: 0.57–0.68, pyrope: 0.26–0.35, grossular: 0.02–0.07, spessartine: 0.01–0.02) and from garnet-biotite gneiss (compositional zoning: almandine: 0.62–0.69, pyrope: 0.26–0.33, grossular: 0.03–0.04, spessartine: 0.01–0.02) have similar mineral composition and compositional zoning characteristics.

Previous studies have suggested that garnet in granitic rocks can be divided into three types: metasomatic, metamorphic, and magmatic minerals (Lackey et al. 2011, 2012; Jiao et al. 2013; Liu et al. 2014; Xia et al. 2016). The garnet in garnet-bearing leucogranite is similar to that in the source rock: both have a palisade meta-crystalline structure and contain numerous inclusion minerals, which are similar to those in the metapelitic gneiss of the source rock (Shi et al. 2018). The garnet of relict mineral facies may be the product of assimilation and contamination of metamorphic relict minerals inherited from the source rock area or directly captured from source rock by magma, or even formed by the reaction between the source rock and magma. Many researchers suggested that the remelting reaction and anatexis are mainly related to dehydration and melting of biotite in metapelitic gneisses (Villaros et al. 2009; Taylor and Stevens 2010; Lackey et al. 2012); the formation of peraluminous melt is an important reason for the compositional difference of S-type granite. This is highly consistent with the fact that the garnet-bearing leucogranite and source rock have more bands of felsic minerals and garnet. With the increase in the content of felsic melt, the garnet content increases, which is supported by the fact that the largest part of garnet is distributed in felsic bands. Transformed fused garnet has been previously observed in garnet-bearing leucogranite; the main reaction is as follows: $\text{Sil} + \text{Bt} + \text{Qz} \pm \text{Pl} \rightarrow \text{Grt} + \text{Kfs} + \text{Melt}$ (Patiño, Douce and Johnston 1991) or $\text{Bt} + \text{Qz} + \text{Pl} \rightarrow \text{Grt} + \text{Kfs} + \text{Melt}$ (Vielzeuf and Montel 1994).

The preservation of garnet-derived from residual/metamorphic mineral facies in the magma has remained a point of debate. The preservation of garnetb derived from residual/metamorphic mineral facies – in the magma has remained a point of debate. The preservation of garnet derived from residual/metamorphic mineral facies – in the magma has remained a point of debate. The preservation of garnet derived from residual/metamorphic mineral facies – in the magma has
remained a point of debate. Metasomatic garnet comes from the partial melting of metapelitic gneiss and then enters the magma. It may be mixed with magma in different periods and finally be preserved in the process of magmatism, whereas magmatic garnet proliferates at the edge of the garnet (Lackey et al. 2011, 2012). This feature is confirmed by a large amount of radial biotite distributed around the garnet, which is called a reverse reaction structure (Cai et al. 2014, 2017; Wei 2016), formed by the main reactions follows: Grt + Sill + Melt → Crd + Bt + Fe-oxide or Grt + Melt → Bt + Qz ± Pl. A large amount of biotite and orthoclase in the source rock indicates that the possible melting reactions are the dehydration melting of K-feldspar and biotite during the process of isothermal decompression. In addition, the peak period columnar sillimanite and cordierite are developed in the wall rock, whereas only columnar sillimanite is developed in the garnet-bearing leucogranite, and it is surrounded by garnet. This phenomenon indicates that the melting occurred in the peak period with a clockwise P-T trajectory, the K-feldspar and biotite melting occurred during the peak period, while isothermal depressurization occurred after the peak period (Figure 14; Santosh et al. 2007a; Yin 2010; Wang et al. 2011; Guo et al. 2012; Jiao et al. 2013; Cai et al. 2014; Li and Wei 2018; Shi et al. 2021b). The garnet also has a sieve meta-crystalline structure in the Jining–Liangcheng garnet-bearing leucogranite, containing fine-grained reddish-brown biotite, plagioclase, K-rich feldspar, and hairy sillimanite inclusions (Figures 5, 7). There is less biotite in the source rock, and sillimanite and cordierite occur more often. The possible melting reaction is still the melting of K-feldspar and biotite during the peak period and the isothermal depressurization process after the peak stage with a clockwise P-T path.

9.5 Tectonic setting and geological significance

Brown and Korhonen (2009) study showed that partial melting mostly occurs by prograde heating in HT-UHT granulite terranes, along the evolution from peak pressure to peak temperature in high-pressure granulite terranes, and during decompression in ultrahigh-pressure metamorphic terranes. Recent studies revealed that multiple episodes of crustal melting occurred in some orogenic belts, such as Himalayan orogen, Dabieshan orogen and Limpopo Belt of South Africa (Taylor et al. 2014; Nicoli et al. 2017; Li et al. 2019; Zhou et al. 2019). It is well accepted that Khondalite Belt is a continental collisional orogenic belt as the result of the convergence between Yinshan and Ordos Block (Zhao et al. 2001). Multiple crustal melting events have been identified in the Khondalite Belt, mostly producing voluminous garnet-bearing leucogranite generated by biotite-dehydrated melting or higher degree melting of metasedimentary rocks under HT-UHT granulite facies metamorphism (Figure 15; Peng et al. 2012). This extensive crustal melting was promoted by the contemporaneous underplated mantle-derived magma (Peng et al. 2010, 2012, 2014).

Zircon U-Pb ages obtained from garnet granite samples from the Daqingshan supracrustal rocks can be divided into four main episodes (Table 2): (1) detrital zircon at 2.6–2.5 Ga (Cai et al. 2014, Wan et al. 2009; Dong et al. 2013, 2014; Cai et al. 2017) and metamorphic zircon with ages of (2) 2.45–2.37 Ga (Wan et al. 2009, 2013; Ma et al. 2015), (3) 2.3–2.0 Ga (Wan et al. 2009; Xia et al. 2016), and (4) 1.95–1.8 Ga (Wan et al. 2009; Liu et al. 2014; Cai et al. 2014; Cai et al. 2017). Recently studies indicate that the zircon ages of 2.37–2.0 Ga obtained in Daqingshan area may be the result of the influence of Late Paleoproterozoic metamorphism event. The metamorphic anatectic zircon ages of ~2.46 Ga, ~2.45 Ga, and ~2.39 Ga were obtained from the garnet-bearing leucogranite in Baotou Hademengou area, whereas the ~2.45 Ga, ~2.44 Ga, ~2.40 Ga, and ~2.37 Ga metamorphic ages were obtained from its source rocks (Figure 16, Supplementary Fig. 2, (Table 2), (Wan et al. 2009; Dong et al. 2013, 2014; Shi et al. 2021a, 2021b).

Shi et al. (2021a) studies shown that the Daqingshan supracrustal rocks (Sample KDG1912, mainly garnet-biotite gneisses) obtained the metamorphic zircon U-Pb ages of 2367 ± 8 Ma and Baotou garnet-bearing leucogranite (Sample WL18-1) obtained the anatectic zircon U-Pb ages of 2434 ± 6 Ma (Figure 10(a,b)). The anatexis of Baotou garnet-bearing leucogranite likely occurred at ~2.43–2.40 Ga (Shi et al. 2021a). However, numerous studies have shown that the ages of these metamorphic zircons are generally influenced by Paleoproterozoic tectono-thermal events (Zhang et al. 2016a). SHRIMP zircon geochronology results indicated that this metamorphic anatexis event occurred in the late Neoarchean, while there was an activity event of mantle-derived magma in the same period (Wan et al. 2013). This was consistent with the age of late Neoarchean tectono-thermal events reported by predecessors for the northern margin of the NCC (Wan et al. 2020). Dong et al. (2014) reported that high-grade supracrustal rocks of the Daqingshan Complex underwent two tectono-thermal events in the Early Paleoproterozoic (2.45–2.40 Ga) and Late Paleoproterozoic (1.95–1.90 Ga), while Wan et al. (2020) study shown the ca.2.45–2.40 Ga tectono-thermal event related to Late Neoarchean event. This is consistent with the view that part metamorphic ages of ~2.45–2.40 Ga
and ~1.95 Ga for pelitic granulites of the Daqingshan–Wulashan high-grade complex, which corresponds to tectono-thermal event, and a continent-continent collisional event between the Yinshan and Ordos block. A comparative study was performed on charnockite and garnetite from the Xiwulanbulang area, Yinshan Block in northern Baotou area, shown a subduction related volcanic arc setting in late Neoarchean (Jian et al. 2012b; Ma et al. 2013; Shi et al. 2019). Wan et al. (2013) reported that mafic magmatism occurred at ~2.45 Ga in
| Order | Location | Lithology | Detrital zircon (Ga) | Metamorphic anatexis (Ga) | Method | Data from |
|-------|----------|-----------|----------------------|---------------------------|--------|-----------|
| 1     | Baotou Area | 109°30′ 25″ E, 40°41′ 15″ N | Garnet-bearing leucogranite | -2.37 | SHRIMP | Shi et al. 2021a |
| 2     | 110°15′ 33″ E, 40°48′ 44″ N | Garnet biotite gneiss | -2.43 | SHRIMP | Shi et al. 2021a |
| 3     | N40°42′ 30″ E, 109°38′ 31″ N | Garnet-bearing leucogranite | 2.53–2.47 | SHRIMP | Wang et al. 2009 |
| 4     | N40°48′ 32″ E, 109°38′ 31″ N | Sil-Gt-Bt gneiss | 2.56–2.48 | SHRIMP | Wang et al. 2009 |
| 5     | N40°48′ 39″ E, 110°15′ 29″ N | Garnet biotite gneiss | 2.52–2.47 | SHRIMP | Dong et al. 2014 |
| 6     | N40°41′ 52″ E, 109°48′ 19″ N | Garnet biotite gneiss | 2.54–2.45 | SHRIMP | Dong et al. 2014 |
| 7     | N40°41′ 52″ E, 109°48′ 19″ N | Garnet biotite gneiss | 2.54–2.44 | SHRIMP | Dong et al. 2014 |
| 8     | N40°41′ 52″ E, 109°48′ 19″ N | Garnet biotite gneiss | 2.50–2.34 | SHRIMP | Dong et al. 2014 |
| 9     | N40°41′ 38″ E, 109°38′ 28″ N | Garnet-bearing leucogranite | 2.50–2.33 | SHRIMP | Dong et al. 2014 |
| 10    | N40°48′ 38″ E, 110°15′ 27″ N | Garnet biotite gneiss | 2.50 | SHRIMP | Dong et al. 2013 |
| 11    | N40°41′ 37″ E, 110°15′ 27″ N | Garnet biotite gneiss | 2.54–2.45 | SHRIMP | Dong et al. 2014 |
| 12    | Jining–Liangcheng Area | 113°48′ 14″ E, 41°03′ 44″ N | Garnet-bearing leucogranite | -1.91 | LA-ICP-MS | Cai et al. 2014 |
| 13    | 112°43′ 12″ E, 41°11′ 38″ N | Sil-Gt-Bt gneiss | -1.91 | LA-ICP-MS | Cai et al. 2017 |
| 14    | N40°32′ 33″ E, 112°31′ 50″ | Leucosome granite | -1.93 | SIMS | Wang et al. 2017 |
| 15    | N40°32′ 33″ E, 112°31′ 50″ | Leucosome granite | -1.93 | SIMS | Wang et al. 2017 |
| 16    | N40°32′ 33″ E, 112°31′ 50″ | Stilimanite Garnet granite | -1.92 | SIMS | Peng et al. 2014 |
| 17    | N40°44′ 18″ E, 113°15′ 35″ | Sil-Gt-Bt gneiss | -1.92 | LA-ICP-MS | Li et al. 2018 |
| 18    | 112°12′ 35″ E, 40°45′ 49″ N | Garnet-bearing leucogranite | -1.91 | SHRIMP | Shi et al. 2018 |
| 19    | 112°22′ 34″ E, 40°45′ 30″ N | Sil-Gt-Bt gneiss | -1.89 | SHRIMP | This paper |
| 20    | 112°59′ 43″ E, 40°47′ 16″ N | Sil-Gt-Bt gneiss | -1.90 | SHRIMP | Shi 2020 |
| 21    | 112°22′ 31″ E, 40°32′ 30″ N | Garnet-bearing leucogranite | -1.91 | SHRIMP | Shi 2020 |
| 22    | 112°20′ 42″ E, 40°37′ 48″ N | Porphyritic garnet granite | -1.92 | SHRIMP | Shi 2020 |
| 23    | 112°10′ 03″ E, 40°29′ 28″ N | Sil-Gt-Bt gneiss | -1.93 | SHRIMP | Shi 2020 |
| 24    | 112°10′ 04″ E, 40°29′ 28″ N | fine-grained garnet granite | -1.91 | SHRIMP | Shi 2020 |
| 25    | 112°10′ 04″ E, 40°29′ 28″ N | fine-grained garnet granite | -1.91 | SHRIMP | Shi 2020 |
the Daqingshan area, NCC, which was accompanied by HT–UHT metamorphism due to underplating of the mantle-derived magma. Therefore, ~2.45–2.40 Ga Baotou garnet-bearing leucogranite may be related to the late Neoarchean volcanic arc setting.

The zircon U-Pb ages of 1905 ± 8 Ma and 1885 ± 10 Ma were obtained for the garnet-bearing leucogranite in the Miaogoumen village of the Jining–Liangcheng County, and the metageneric zircon U-Pb ages of 1885 ± 10 Ma were obtained for the metapelite gneisses of the Khondalite Belt in Dayushu of Liangcheng; these are considered to be related to the tectonothermal event of the Khondalite Belt formed by the collision orogeny between the Yinshan and Ordos blocks. Most metamorphic ages from west to east are ~1.95 Ga (Figure 16, Guo et al. 2001; Wang et al. 2005; Zhou and Geng 2009; Zhou et al. 2010; Xu et al. 2011; Dong et al. 2013); However, the 1.91–1.93 Ga metamorphic ages are widespread in the Khondalite Belt of the Jining area (Santosh et al. 2007a, 2007b; Zhou and Geng 2009; Cai et al. 2014; Ma et al. 2015), which is considered to be a result of the strong later tectono-thermal event (Zhou and Geng 2009). The ~1.95 Ga, ~1.92 Ga, and ~1.90 Ga metamorphic anatetic zircon ages were obtained for the Jining–Liangcheng garnet-bearing leucogranite and source rocks (Figure 16, Supplementary Fig.2, Cai et al. 2017; Wang et al. 2017; Li and Wei 2018; Shi et al. 2018), which are closely related to the underplating event of regionally upper-mantle-derived magmatic rocks (Figure 15, Peng et al. 2010, Peng et al. 2012, Peng et al. 2014; Wang et al. 2017).

Mantle-derived mafic magmatic rocks are widely distributed in the region (Figure 16). The Baotou area is mainly characterized by metamorphic basic metagabbro, amphibolite, and norite (Wan et al. 2009, 2016), which are considered as a late Neoarchean basic magmatism event (Wan et al. 2013, 2016). Simultaneously, the late Neoarchean charnockite was exposed, for which the SHRIMP zircon U-Pb age of 2463 ± 11 Ma was obtained. Mafic dykes are also widely distributed in the Jining–Liangcheng area (Zhang et al. 1992; Hu et al. 2007). They are caused by the intrusion of basic magma from the mantle under the background of crustal extension, and they are important indicators of lithosphere (or crust) extension (Liu et al. 2014). Mantle-derived mafic magmatic rocks underpass the lower crust at a high temperature; metapelite gneiss occurred during anatexis, forming many continuously forming and gathering anatetic melts.

**Figure 16.** Histogram of Zircon U-Pb Data provided from this study for associated with the Baotou–Jining–Liangcheng garnet-bearing leucogranite, metapelite gneiss and gabbroarites at the northern margin of the NCC.
When the leucosome stripes reach a certain proportion, the whole system (magma + residual body) can migrate in the presence of stress (Liu et al. 2008; Labrouse et al. 2011). The migration of melting can lead to the separation between magma and residuals and the mixing of different magma. Previous studies have shown that underplating of basic mantle-derived magma provides not only a hot spot but also exchange of materials through crust and mantle interaction (Figure 15, Bonin 2004; Kemp et al. 2007; Federico et al. 2012; Peng et al. 2012; Donnelly et al. 2019).

The late Neoarchean and late Paleoproterozoic garnet-bearing leucogranites were formed as per the following process (Table 2, Figure 15): 1) The late Neoarchean and Paleoproterozoic tectonic movements resulted in the thickening of the crust, burial of metamorphic sedimentary rocks into the lower crust, occurrence of granulite facies metamorphism, and partial melting. 2) Based on the previous data, there were at least two metamorphic anatectic events at ~2.45–2.40 Ga and ~1.95–1.90 Ga (Table 2, Supplementary Fig.2) in the Khondalite Belt on the northern margin of the NCC, which correspond to the late Neoarchean and Paleoproterozoic tectonic events, respectively, which formed the garnet-bearing leucogranite that is closely associated with anatexis protoliths.

10. Conclusion

1) The garnet-bearing leucogranite formed as a result of anatexis of metapelitic gneisses, during the peak period and the isothermal depressurization process after the peak stage with a clockwise P-T path.
2) The melt of garnet-bearing leucogranite is formed by the mixing of the leucosomes, residual minerals and mantle-derived materials.
3) Garnet-bearing leucogranite has high Al2O3 content and FeO/MgO ratio, with the characteristics of enrichment in light rare earth elements, large ion lithophile elements and depletion in Nb, Ta, P, and Ti.
4) SHRIMP U-Th-Pb zircon dating obtained anatectic ages were 2.35–2.43 Ga and 1.90–1.92 Ga, in which identified the two episodes of garnet-bearing leucogranites.
5) The Baotou–Jining–Liangcheng garnet-bearing leucogranite is the product of at least two episodes anatectic events in Inner Mongolia, corresponding to two tectonic events of late Neoarchean-early Paleoproterozoic and late Paleoproterozoic tectonothermal events in NCC.

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Highlights

1) Garnet-bearing leucogranites formed as a result of anatexis of metapelitic gneisses.
2) They are mixtures of leucosomes, residual minerals and mantle-derived materials.
3) Two episodes of garnet-bearing leucogranites have been identified.
4) Both corresponded to late Neoarchean-early Paleoproterozoic and late Paleoproterozoic tectonothermal events, respectively.

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No potential conflict of interest was reported by the author(s).

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