Partial melting mechanisms of peraluminous felsic magmatism in a collisional orogen: an example from the Khondalite Belt, North China Craton

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Sedimentary-derived (S-type) granites are an important product of orogenic metamorphism, and a range of subtypes can be recognized by differences in field occurrence, mineralogy, and geochemistry. These subtypes can reflect variations of initial protolith composition, partial melting reactions, pressure and temperature of anatexis, or magmatic processes that occur during ascent through the crust (e.g. mineral fractional crystallization or crustal assimilation). Together, these diverse factors complicate geological interpretation of the partial melting history of peraluminous felsic melt fractions in orogenic settings. To assess the influence of these factors, we performed integrated field investigation, petrology, geochemistry, geochronology, and phase equilibria modeling on a series of leucosomes within migmatite associated with different S-type granites within the Khondalite belt, North China Craton, which is an archetypal collisional orogen. Three types of leucosomes are recognized in the east Khonldalite belt: leucogranitic leucosome, K-feldspar (Kfs)-rich granitic leucosome, and garnet (Grt)-rich granitic leucosome. Phase equilibria modeling of partial melting, with calibration of melt compositions calculated at low temperature, and fractional crystallization processes indicate that leucogranitic leucosomes are most readily produced through fluid-present melting, Kfs-rich granitic leucosomes are produced through muscovite dehydration melting with 3 vol. % of garnet fractional crystallization,

and Grt-rich granitic leucosomes are produced through biotite dehydration melting with 20–40 vol. % of K-feldspar fractional crystallization and up to 20 vol. % of peritectic garnet entrainment. Mineral fractional crystallization and peritectic mineral entrainment occur at the very beginning of granite formation, and play equally important roles with partial melting mechanism in affecting the geochemical compositions of the granitic melts. Thus, we suggest that peraluminous felsic magmas preserved in collisional orogens are dominantly produced by fluid-absent melting conditions in the middle to deep continental crust, although extraction of low-volume melt fractions from an anatectic source region at shallower depths during fluid-present melting can also generate small amounts of S-type granites that subsequently crystallize at high structural levels in the crust.

Keywords: migmatite; partial melting mechanism; peraluminous felsic magma; collisional orogen

1 INTRODUCTION

Water has historically been considered necessary to generate granitic magma (Campbell & Taylor, 1983); however, 'where' the water exists in rocks and how it becomes involved in the partial melting process are matters of great debate (e.g. Clemens & Droop, 1998; Brown *et al*., 2013; Weinberg & Hasalová, 2015; Collins *et al*., 2020). A key issue is whether fluid-present melting could generate large amounts of granitic magmas, given the prevalence of voluminous granite batholiths in orogenic terranes. To date, fluid-present melting has overwhelmingly been suggested to only generate migmatite, while fluid-absent melting has been regarded as the main partial melting mechanism to generate larger granitic bodies (e.g. Sawyer, 1998, 2010; Sawyer *et al*., 2011; Brown, 2013; Carvalho *et al*., 2017; Clemens *et al*., 2020; Schwindinger *et al*., 2020). However, natural granitic batholiths often have identical compositions to melts generated during fluid-present melting (Collins *et al*., 2020; Pourteau *et al*., 2020); especially those from Pacific-type orogens where free water is abundant. By contrast with Pacific-type orogens, most granites in collisional-type orogens show S-type geochemical characteristics (Moyen *et al*., 2021), and form via partial melting of sedimentary rocks in the mid- to lower-crust (Chappell & White, 1974); however, there is little known about the geological mechanism that would allow the introduction of large volumes of free water to the mid- to lower-crust in the absence of subduction.

The Khondalite belt, North China Craton (NCC), is a typical Precambrian collisional orogen, dominated by aluminous granulites associated with migmatite and S-type granite (Zhao *et al*., 2005, Guo *et al*., 2012). Given differences in field occurrence, mineralogy, and geochemistry, these S-type granites have previously been subdivided into leucogranite, Grt-rich granite/ charnockite varieties (Peng *et al*., 2012; Wang *et al*., 2017, 2018, 2023a, 2023b). Geochemical analyses indicate that the Grt-rich granites/charnockites formed via mixing of peraluminous melt, residue (up to 20–40 vol. %), and significant amounts of mafic magma (Wang *et al*., 2018). Further, all batholiths have been overprinted by a more recent episode of ultrahigh temperature (UHT) metamorphism (*c*. 1.92 Ga, Huang *et al*., 2019), making petrogenetic investigation of these bodies complex. Three types of leucosomes have been recognized in nearby migmatite—leucogranitic leucosome, Kfs-rich granitic leucosome and Grt-rich granitic leucosome—which show consistent differences in volume proportion, mineralogy, and geochemistry. By contrast with the granite batholiths (Wang et al., 2018), magma mixing and crustal assimilation in the migmatitic leucosomes has been limited, providing opportunities to explore their partial melting mechanism. In this study, we report the results of petrography, geochemistry, geochronology, and phase equilibria modeling that discriminate the various petrogenetic processes that formed each type of leucosome within migmatite units. We then compare these leucosomes to the nearby S-type granites and show that the batholiths may have formed from hybridization/mixing of multiple melt fractions generated during migmatization. The results might have some implications for partial melting mechanism of S-type granite batholiths in collisional orogenic settings.

2 GEOLOGICAL SETTING

The North China Craton (NCC) formed during the Late Archean (*c*. 2.5 Ga), although subsequent decratonization during the Mesozoic led to progressive destruction of the continental lithosphere, and has complicated detailed investigation of its geological evolution (Kusky & Li, 2003; Kröner *et al*., 2005; Zhai *et al*., 2005; Zhao *et al*., 2005, 2007; Kusky *et al*., 2007, Li & Kusky, 2007; Yang *et al*., 2008; Zhang *et al*., 2009; Wang *et al*., 2010; Kusky, 2011; Trap *et al*., 2012; Zheng *et al*., 2012; Zhai, 2014; Kusky *et al*., 2016). Commonly, the NCC is subdivided into several Archean basement blocks separated by Paleoproterozoic orogens, which may be identified by the presence of high-pressure granulites and retrogressed eclogites (e.g. Zhai *et al*., 1993, 1996; Zhao *et al*., 2001; Guo *et al*., 2002; Yin *et al*., 2014, 2015; Huang *et al*., 2018, 2022). One commonly accepted tectonic model sub-divides the NCC into the Eastern and Western Blocks separated by the Trans-North China Orogen (TNCO). The Western Block could be further divided into the Yinshan Block and Ordos Blocks, separated by the Khondalite Belt (Zhao *et al*., 2003, 2005) (Figure 1a).

The Khondalite Belt is an E–W oriented Paleoproterozoic orogen in the western NCC, which separates the Yinshan Block to the north and the Ordos Block to the south. Based on its lithology, structures, and metamorphism, the

Khondalite Belt is divided into three terranes from west to east: the Helanshan-Qianlishan terrane, the Wulashan-Daqingshan terrane, and the Jining-Liangcheng terrane (Zhao *et al*., 1999). It is mainly composed of Paleoproterozoic upper amphibolite- to granulite-facies metasedimentary rocks (i.e. quartzo-feldspathic gneisses, garnet- and sillimanite-bearing plagioclase gneisses, feldspathic quartzites, marble and calc-silicate rocks) as well as garnet-bearing granites (e.g. Lu *et al*., 1992; Lu & Jin, 1993) that record clockwise pressure–temperature (*P*–*T*) paths. Ages documenting various stages of metamorphism lie in the range *c*. 1.95–1.80 Ga (Santosh *et al*., 2006, 2007; Dong *et al*., 2012; Guo *et al*., 2012; Wan *et al*., 2012; Huang *et al*., 2016, 2019). Among these, *c*. 1.95 Ga high-pressure granulites have been reported from the Helanshan-Qianlishan terrane and the Wulashan-Daqingshan terrane, which may represent an ancient collision zone between the Yinshan Block and the Ordos Block (Yin *et al*., 2009; Zhou *et al*., 2010; Yin *et al*., 2011; Cai, 2014; Yin *et al*., 2014, 2015). Two generations of UHT granulite (*c*. 1.92 Ga and *c*. 1.86 Ga) are reported from the Jining-Liangcheng terrane and the Wulashan-Daqingshan terrane, which may have formed due to advected heat derived from post-collisional mafic magmatism (e.g. Peng *et al*., 2010; Guo *et al*., 2012; Santosh *et al*., 2012; Jiao *et al*., 2017; Li & Wei, 2018; Huang *et al*., 2019). Syn-collisional granite (*c*. 1.95 Ga) and post-collisional granite (*c*. 1.92–1.90 Ga) widely occur in the Khondalite Belt (Dan *et al*., 2012, 2014; Wang *et al*., 2017, 2018; Zhang *et al*., 2017; Li *et al*., 2022).

The Jining-Liangcheng terrane is located at the easternmost part of the Khondalite Belt, near to its boundary with the TNCO (Figure 1b). It is dominated by aluminous gneiss associated with migmatite, S-type granite, and minor gabbro and norite. Pelitic granulites in the Tuguiwula area record the highest-grade metamorphic conditions in this terrane of 0.8–0.9 GPa and 950–1150 °C (Santosh *et al*., 2012; Li & Wei, 2018; Wang *et al*., 2020; Huang *et al*., 2022). Regional-scale mapping of Zr-in-rutile and Ti-in-quartz equilibration temperatures shows that peak metamorphism in the Liangcheng-Tuguiwula area reached UHT conditions (>900 °C), although the metamorphic grade transitions to amphibolite-facies conditions further south (i.e. the Youyu area) (Qi *et al*., 2022; Zheng *et al*., 2022). As described above, S-type granite batholiths mostly occur in northern part of the region and are either leucogranite or Grt-rich granite/charnockite. Leucogranite only occurs in the Anzishan and Wusumu areas (~20 km^2) (Wang *et al*., 2017), while Grt-rich granite/charnockites contain up to 25 vol. % garnet and are ubiquitous in the Jining-Liangcheng terrane, making up 40 vol. % of all lithologies (Wang *et al*., 2018; Wang *et al*., 2023a, 2023b). Compared with leucogranite, Grt-rich granite/charnockite have wide-ranging K_2O/Na_2O ratios, lower SiO_2 contents, higher Al_2O_3, FeO+MgO, Rb/Sr, Nb/Ta and REE contents, and strongly negative Eu/Eu*(Peng *et al*., 2012; Wang *et al*., 2018). Major-element modeling indicates that the Grt-rich granite/charnockite formed by mixing between restite-rich anatectic melt and mafic magma (Wang *et al*., 2018). However, more recent studies suggested that Grt-rich granite/charnockite are produced at temperature > 1050 °C, close to the crustal dry solidus. Varied amount (15–40 vol.%) of peritectic solid phases (e.g. garnet and orthopyroxene) are entrained from the protolith before granite emplacement (Wang *et al*., 2023a, 2023b). However, magma mixing process between granitic and mafic magma is not necessary. They proposed that these Grt-rich granite/charonockite are ultrahigh temperature granitoids, and a new subcategory of S-type granitoids. Both leucogranite and Grt-rich granite/charnockite record an igneous crystallization age of *c*. 1.95 Ga and experienced subsequent metamorphism at *c*. 1.92 Ga (Wang *et al*., 2017; Wang *et al*., 2018; Huang *et al*., 2019). Gabbronorites in the region are tholeiitic in composition, originated from a mantle region with a high potential temperature (~1550 °C), and subsequently experienced strong magmatic differentiation (Peng *et al*., 2010).

3 FIELD OCCURRENCE AND PETROGRAPHY

The study area described in this work, situated at the southern part of Jining-Liangcheng terrane, is dominated by khondalite associated with migmatite (Figure 2). The protoliths of these metasedimentary rocks were likely interbedded clastic rocks (Figure 3a), comprised of ~70 vol. % greywacke and ~30 vol. % pelite at the regional scale (Lu *et al*., 1992; Lu & Jin, 1993). The greywackic gneiss contains fine-grained garnet, biotite, quartz, K-feldspar, plagioclase, and minor rutile (Figure 3b, 4a). The metapelite occurs as biotite schist, with a mineralogy dominated by garnet, biotite, sillimanite and quartz, indicating metamorphic conditions of the upper amphibolite facies (Winkler, 1979; Waters, 1988; Johnson *et al*., 2021) (Figure 4b). Three types of leucosome, leucograntic leucosome, Kfs-rich granitic leucosomes and Grt-rich granitic leucosomes, are identified based on differences in their field volume proportion, mineralogy, and structure (Table S1). The first type of leucosomes, leucogranitic leucosomes, is rare, being present only in the area around Maojiayao (Figure 2). These migmatites occur as stromatic-structured metatexites (migmatite terminology after Sawyer, 2008), in which paleosomes foliations have not been modified, and leucosome occurs as leucocratic sills and dykes within the migmatite (Figure 3c). Fine-grained garnet (1–2 mm in diameter) is randomly distributed through the leucosomes (Figure 3d). The leucogranitic leucosomes contain quartz, K-feldspar, plagioclase, garnet, sillimanite, biotite and minor accessory minerals (ilmenite, apatite and zircon) (Figure 4c). The second type of leucosomes is referred to as Kfs-rich granitic leucosomes, and is pervasive within migmatite in the study area (Figure 2). These migmatites are diatexitic and dominated by schollen structures (Figure 3e). Paleosomes are usually disrupted with a schollen structure, and the foliations of the paleosomes are rotated into different orientations. The Kfs-rich granitic leucosomes are characterized by having large K-feldspar porphyroblasts and relatively scarce garnet (Figure 3f, 4d). These Kfs-rich granitic leucosomes otherwise contain quartz, K-feldspar, plagioclase, garnet, sillimanite, biotite and minor accessory minerals (ilmenite, apatite and zircon) (Figure 4d). The third type of leucosomes is Grt-rich granitic leucosomes and is ubiquitous in the Youyu area (Figure 2). These migmatites occur as schlieren-structured diatexites (Figure 3g). Compositional banding defined by alternating leucosome and schlieren can be identified within these diatexites, and may have formed by suprasolidus flow. The schollens are both rarer and smaller in these units than in the Kfs-rich granitic migmatites, and garnet is much more abundant, making up ~10–15 vol. % of the rock (Figure 3h, 4e). K-feldspar porphyroblasts also occur in Grt-rich granitic leucosomes, but are usually cumulates and less abundant than in the Kfs-rich granitic leucosomes (Figure 3h). The Grt-rich granitic leucosomes contain quartz, K-feldspar, plagioclase, garnet, biotite and minor accessory minerals (ilmenite, apatite and zircon) (Figure 4e). Six leucogranitic leucosome samples, seven Kfs-rich granitic leucosome samples, and six Grt-rich granitic leucosome samples were collected for detailed geochemical work. All of the studied samples were at least 15 cm × 10 cm × 10 cm and comprised enough mass to confidently examine individual leucosome and melanosome/mesosome domains. The sample locations are labeled on Figure 2.

4 GEOCHRONOLOGICAL RESULTS

Leucogranitic leucosome sample 21LH043, Kfs-rich granitic leucosome sample 21LH018, and Grt-rich granitic leucosome sample 21LH061 were selected for zircon U–Pb dating (Table S2). Zircon in sample 21LH043 mostly has a prismatic morphology, with sizes ranging from 100 to 200 μm and length-to-width ratios up to 3:1 (Figure 5a). CL images show that zircon has bright responses and clear oscillatory zoning, indicating an igneous origin. Fifteen analyses were conducted on 15 zircon grains, and the results yielded a discordia with an upper intercept age of 1983 ± 19 Ma (MSWD = 0.85) (Figure 6a). They have U, Th contents and Th/U ratios of 91–1368 ppm, 30–335 ppm, and 0.05–1.09, respectively.

Two types of zircon were identified in sample 21LH018: a subhedral prismatic to subrounded (150–200 μm in size and 2:1 in length:width) population and a rounded (100–200 μm in size and ~1:1 in length:width) population (Figure 5b). The CL images show that the prismatic to subrounded zircon usually have core-rim textures, with brighter CL responses in cores and weaker CL responses in rims. The cores usually show clear oscillatory zoning, which likely record an igneous origin, while those with very bright CL responses are likely xenocrystic. The rims form homogenous domains surrounding the cores, indicating that they formed via recrystallization, dissolution-reprecipitation, or overgrowth during metamorphism (Figure 5b). The rounded zircon grain population exhibits a weak luminescence, with homogenous interiors or sector zoning, and is suggested to represent new growths during metamorphism. Fourteen analyses were conducted on the zircon cores. One analysis yielded a concordia age of 2068 ± 17 Ma, which is intepreted to be xenocrystic in origin. Other data yield a discordia with an upper intercept age of 1976 ± 44 Ma (MSWD = 5.7) (Figure 6b), which is intepreted to be the age of leucosome crystallization. Xenocrystic zircon cores have U and Th contents and Th/U ratios of 101 ppm, 37 ppm and 0.38, respectively, whereas igneous grains have U and Th contents and Th/U ratios of 113–1789 ppm, 27–681 ppm, and 0.03–0.67, respectively. Seven analyses were conducted on seven metamorphic zircon grains, and the data yield an upper intercept age of 1920 ± 10 Ma (MSWD = 0.64) (Figure 6c). These metamorphic zircon grains have U contents of 185–1306 ppm, Th contents of 44–591 ppm, and Th/U ratios of 0.17–1.08.

Zircon in sample 21LH061 was subdivided into three types based on morphology and internal texture. The first two populations are equivalent to zircon in sample 21LH018, with core-rim and homogenous textures, respectively. The third type in this sample showed a prismatic morphology (150–200 μm in size and 2:1 in length:width), which implies an igneous origin; however, CL images showed weak responses and homogenous internal textures (Figure 5c). These zircon grains are therefore suggested to have crystallized during magmatism, but recrystallized during later-stage metamorphism (i.e. they are metamorphic zircon) (Taylor *et al.*, 2016; Rubatto, 2017). Ten analyses were conducted on zircon grains with oscillatory zoning, and the data also yielded a discordia with an upper intercept age of 1966 ± 28 Ma (MSWD = 4.0) (Figure 6d). Eight analyses were performed on the second and third zircon populations with a metamorphic origin, which together yielded a weighted mean age of 1920 ± 9 Ma (MSWD = 1.7) (Figure 6e). Measured U and Th contents and Th/U ratios of igneous zircons were 48–1067 ppm, 14–392 ppm, 0.09–0.90, respectively, and those of metamorphic zircons were 197–518 ppm, 5–156 ppm, and 0.01–0.47, respectively.

5 GEOCHEMICAL RESULTS

5.1 Bulk rock major elements

Even though leucogranitic leucosome samples were all collected from the Maojiayao area, the bulk-rock compositions of each sample varied, given the differences in their mineral modal proportions. These samples have SiO_2 contents of 72.59–79.31 wt. % and Al_2O_3 contents of 12.23–16.53 wt. %. Compared with other two types of leucosomes, these samples generally have higher Na_2O (2.72–4.82 wt. %) and CaO (0.69–2.04 wt. %), intermediate FeO_{total} (0.34–2.76 wt. %) and MgO (0.16–0.36 wt. %), but lower K_2O (1.67–5.53 wt. %) (Figure 7) (Table S3). They are all peraluminous, with ASI values in the range of 1.15–1.31 (Figure 8a). The six leucogranite leucosomes show a wide spread from trondhjemite to granite fields in the Ab-An-Or diagram (Figure 8b), and they exhibit lower

K_2O/Na_2O ratios (0.35–2.03) and intermediate FeO_{total}+MgO contents (0.50–3.12 wt. %) compared with other two types of leucosomes (Figure 8c).

Kfs-rich granitic leucosomes samples have narrow range of SiO_2 (71.94–74.70 wt. %) and Al_2O_3 (14.20–15.34 wt. %) contents. Compared with other two types of leucosomes, Kfs-rich granitic leucosomes samples have higher K_2O (6.01–7.34 wt. %) contents, intermediate Na_2O (2.38–3.09 wt. %), but lower FeO_{total} (0.07–0.85 wt. %), MgO (0.04–0.23 wt. %) and CaO (0.83–1.17 wt. %) contents (Figure 7). The ASI values are in the range of 1.08–1.10, considerably lower than leucogranite samples, but are still peraluminous (Figure 8a). The Kfs-leucosomes form a tight cluster within the granite field on the Ab-An-Or normative plot and lie closer to the Or end-member than any other leucosomes (Figure 8b). In a K_2O/Na_2O-FeO_{total} +MgO diagram, these samples have the highest K_2O/Na_2O (1.95–3.05) values, but lowest FeO_{total}+MgO (0.10–1.08 wt. %) values among the three types of leucosomes (Figure 8c).

Grt-rich granitic leucosomes samples have the largest range in SiO_2 (66.12–80.61 wt. %) and Al_2O_3 (9.79–18.00 wt. %) contents. They are rich in ferromagnesian elements (FeO_{total} = 2.68–6.29 wt. %, MgO = 0.72–3.32 wt. %), but poor in alkaline elements (K_2O = 2.01–4.13 wt. %, Na_2O=1.12–2.46 wt. %) (Figure 7). These granite samples are strongly peraluminous, with ASI values ranging from 1.24 to 1.48 (Figure 8a), and almost all plot in the granite field in an Ab-An-Or normative diagram, with Or content lower than Kfs-leucosomes and highest normative An of all the leucosomes (Figure 8b). In a K_2O/Na_2O-FeO_{total}+MgO diagram, they record the highest FeO_{total}+MgO (3.42–9.61 wt. %) values and intermediate K_2O/Na_2O (1.05–2.53) ratios of all types of leucosomes (Figure 8c).

5.2 Bulk-rock trace elements

Figure 8d, 9 and 10 show bulk-rock trace elements of three types of leucosomes. Leucogranitic leucosome samples have the lowest ΣREE (17.49–81.90 ppm) contents among the three types of leucosome, and the REE patterns show various degrees of HREE enrichment (Gd_N/Yb_N = 0.16–2.22) (Figure 9a). These samples have clear and strong positive Eu anomalies (Eu/Eu* = 1.08–5.66). In the primitive mantle (PM)-normalized trace element spidergram (Figure 9b), the leucogranitic samples are characterized by enrichment of LILE (e.g. Rb, Sr, Ba), but depletion in HFSE (e.g. Nb, Ta, Ti, P). Specifically, Rb, Sr, Ba contents lie in the ranges 29.7–144 ppm, 231–333 ppm and 115–643 ppm, respectively, with Rb/Sr of 0.09–0.59 (Figure 8d). Nb, Ta, Th, U contents are in the ranges 0.08–0.41 ppm, 0.05–0.23 ppm, 0.12–3.89 ppm and 0.34–1.13 ppm, respectively, with Nb/Ta of 0.33–6.85 and Th/U of 0.18–3.45 (Figure 10, Table S4). In the PM-normalized trace element spidergram (Figure 9b), the leucogranitic leucosomes show depletions of Th relative to U, and Nb relative to Ta.

Kfs-rich granitic leucosome samples have intermediate ΣREE (80.43–185.11 ppm) contents, with REE patterns characterized by HREE depletion (Gd_N/Yb_N = 2.1–19.32) and positive Eu anomalies (Eu/Eu* = 1.63–6.50) (Figure 9a). In Figure 9b, these samples are enriched in LILE and depleted in HFSE. They have Rb contents of 174–224 ppm, Sr contents of 285–331 ppm (Rb/Sr of 0.55–0.77), Ba contents of 1063–1771 ppm (Figure 8d), Nb contents of 0.05–3.06 ppm, Ta contents of 0.003–0.16 ppm (Nb/Ta of 1.06–25.57) (Figure 10), Th contents of 0.65–6.85 ppm and U contents of 0.20–0.98 ppm (Th/U of 2.59–7.01). In contrast with leucogranitic leucosomes, the Kfs-rich granitic leucosomes have higher Th/U and Nb/Ta values (Figure 10, Table S4).

Grt-rich granitic leucosomes have the highest ΣREE (134.42–216.66 ppm) contents among all three types of leucosomes. Their REE patterns are consistent and show enrichment in HREE (Gd_N/Yb_N = 1.10–2.02), but with negative to slightly positive Eu anomalies (Eu/Eu* = 0.59–1.53) (Figure 9a). LILE are also enriched and HFSE, except Zr, are depleted in these samples, as shown in Figure 9b. Rb, Sr, Ba contents have ranges of 49–110 ppm, 134–247 ppm and 452–1122 ppm, respectively, with Rb/Sr of 0.31–0.53 (Figure 8d). Nb, Ta, Th, U contents have ranges of 1.11–19.1 ppm, 0.05–0.75 ppm, 1.99–11.7 ppm and 0.52–1.06 ppm, respectively, with Nb/Ta of 21.05–25.58 and Th/U of 2.82–11.60 (Figure 10, Table S4).

5.3 Bulk-rock Sr–Nd isotopes

The five studied leucograntic leucosome samples have εNd (1950 Ma) values of –1.00 to 0.04, seven Kfs-rich granitic leucosome samples have εNd (1950 Ma) values ranging from –1.24 to 0.72, and four Grt-rich granitic leucosome samples exhibit εNd (1950 Ma) values of –0.80 to 0.16 (Figure 11a). In comparison with these relatively consistent Nd isotope values, Sr isotope compositions between samples show notable differences: leucogranitic leucosome samples have low $(^{87}Sr/^{86}Sr)_{1950\ Ma}$ values of 0.702−0.706, Kfs-rich granitic leucosome samples have high and variable $(^{87}Sr/^{86}Sr)_{1950\ Ma}$ values of 0.706−0.712, while Grt-rich granitic leucosome samples have intermediate and similar $(^{87}Sr/^{86}Sr)_{1950\ Ma}$ values of 0.706−0.707 (Figure 11a, Table S5).

5.4 Zircon oxygen isotopes

Oxygen isotope analyses were conducted on 20, 17, and 13 igneous zircons extracted from leucograntic leucosome sample 21LH043, Kfs-rich granitic leucosome sample 21LH018, and Grt-rich granitic leucosome sample 21LH061, respectively. Measured $\delta^{18}O$ values of sample 21LH043 range from 8.80 ± 0.18‰ to 11.70 ± 0.17‰ (mean value = 10.25 ± 0.17‰), 21LH018 range from 7.93 ± 0.17‰ to 10.74 ± 0.17‰ (mean value = 9.13 ± 0.17‰), and 21LH061 range from 6.84 ± 0.11‰ to 9.45 ± 0.11‰ (mean value = 8.15 ± 0.11‰) (Figure 11b, Table S6).

6 PHASE EQUILIBRIA MODELING

Phase equilibria modeling was conducted on metasedimentary rocks in the study area in order to (1) examine the partial melting processes that generate various types of leucosome and (2) constrain how the major and trace element compositions of melts evolve during collisional orogenesis.

Phase equilibria modeling was conducted using THERMOCALC v. 3.40 (Powell & Holland, 1998) with internally consistent dataset (ds62) of Holland & Powell (2011). The modeling employed the Na_2O–CaO–K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O–TiO_2–Fe_2O_3 chemical system using activity–composition (*a*–*x*) models from White *et al*. (2014). The most updated melt model of Holland et al. (2018) is not used since a large divergence between calculated melt compositions and experimental melt compositions (Bartoli & Carvalho, 2021). Quartz, rutile, aluminosilicate (Al_2SiO_5), and H_2O were considered as pure phases. Given the modeled melt compositions calculated in closed and conditional open-system (i.e. melt drained system) display simaliar trends (Bartoli & Carvalho, 2021; Pavan et al., 2021), only closed system is explored in this study. However, we have to note that melt compositions produced in conditional open-system will have lower water contents than those produced in closed system.

Melt compositions predicted via phase equilibria modeling are then calibrated, given their differences from experimental compositions noted by Bartoli & Carvalho (2021). Fully discussions on these uncertainties could be seen in Supplementary files. Our calculated FeO and MgO concentrations of partial melts produced at temperatures <750 °C were doubled before renormalization, and those produced at temperatures between 750 °C and 800 °C were adjusted to be 1.33 times higher than the initial calculations. Those calculated at temperatures >800 °C were not adjusted. We then adjusted CaO contents to be two times higher than the initial calculated melt compositions and Na_2O contents to be 0.8 times the concentrations predicted by our initial calculations.

The concentrations of Rb, Sr, and Ba were calculated using the batch melting equation $C_{melt}/C_{source} = 1/[D + F \times (1-D)]$ (Shaw, 1970), where C_{source} and C_{melt} represent concentrations of a trace element in the source rock and the resultant melt, respectively; $D(=\sum Kd \times X)$ is the bulk partition coefficient, where Kd is the mineral/melt partition coefficient, and X is the proportion in mol. % of the mineral; and F is the degree of melting. The proportions of accessory minerals in the residue were calculated using the refined zircon solubility model from Boehnke et al. (2013), the monazite solubity model from Stepanov et al. (2012), and the apatite solubility model from Harrison & Watson (1984). The Kd values used in the modeling are mean values taken from the literature, which are tabulated in Table S7.

6.1 Determination of bulk rock composition

Given that melt compositions are a function of both $P-T$ conditions and protolith composition, we first determined the likely source rock for each leucosome type before examining the effects of thermobarometric conditions. Three main factors were considered for this task: (1) the protolith source for the leucosome should be as similar as possible to typical rocks in the nearby region, as low-volume melts are not expected to travel long distances from their source; (2) the source rock should be a major component of the study area, rather than being a rare or unusual lithology; and (3) the source rock should not have experienced significant melt extraction. With these factors in mind, we considered an amphibolite-facies metamorphosed greywacke paleosome associated with leucogranitic leucosomes as the precursor composition (sample 21LH030, Table S8). A $T-M_{(H2O)}$ diagram shows that the H_2O content in the source rock has a major influence on both the topology of stable phase equilibria and volume of melt produced during fluid-absent melting (Figure 12a). For sample 21LH030, a volatile content of less than 1.7 wt. % H_2O does not permit fluid-present melting, whereas a fluid content higher than 5 wt. % will allow fluid-present melting up to 800 °C. We used the average water content of a greywacke (2.94 wt. % from Yakymchuk & Brown, 2014, Table S8) as an upper limit, since the total H_2O content in rocks typically decreases during prograde metamorphism at subsolidus conditions (Yardley, 2009), and it must be high enough to ensure that melt generates at the wet solidus via fluid-present melting (Figure 12a). A plot of $T-Fe^{3+}/Fe_{total}$ shows that changing the Fe^{3+}/Fe_{total} of the rock only affects the stability of the ferrotitanium mineral assemblage and has little influence on melt modal proportions (Figure 12b); thus, XFe^{3+} was selected as 0.01 mol. % to ensure that rutile would occur.

6.2 Phase relations

Figure 13 shows the calculated phase relations of metagreywacke sample 21LH030. The wet solidus of the modeled composition is broadly temperature dependent, with the lowest temperature of 670 °C at 0.93 GPa and the highest temperature no more than 700 °C. For an initial water content of 2.94 wt. % in the modeled composition, the fluid-out line is almost parallel to the wet solidus, which lies between 740 °C to 760 °C. The slope of the muscovite-out line above the solidus is positive, and steeper than sillimanite-kyanite polymorphic transition. Muscovite is stable on the high-pressure and low-temperature side of muscovite-out line, and mostly overlaps with the fluid-present field, except at temperatures higher than 750 °C. Muscovite should be totally consumed at temperatures higher than 800 °C. The biotite stability field above the solidus is both temperature and pressure dependent, ranging from 670 °C to 800 °C and 0.5 GPa to 1.3 GPa. Plagioclase is only stable at <0.93 GPa and <730 °C, and cordierite is only stable at <0.7 GPa and >700

°C.

6.3 Melt compositions

Given that the peak pressure of the high-pressure granulites (metamorphosed at *c*. 1.95 Ga) recorded in the Khondalite Belt is 1.1–1.2 GPa (Yin et al., 2014, 2015), melts produced at pressure <1.2 GPa (0.6 GPa, 0.8 GPa, 1.0 GPa and 1.2 GPa) were calculated at 700–875 °C for temperature intervals of 25 °C. Calculated melt compositions were then adjusted based on the scheme described above (Table S9). Figures 14 and 15a−c illustrate the adjusted major compositions of the melt produced at different *P*–*T* conditions. Melts produced at 0.6 GPa, 0.8 GPa, 1.0 GPa and 1.2 GPa are shown as circles, triangles, squares and diamonds, respectively. Melts produced through fluid-present melting, muscovite dehydration melting, biotite dehydration melting and anhydrous mineral melting are shown as blue, orange, red and purple symbols, respectively.

Melts generated through fluid-present melting (blue symbols) have SiO_2 and Al_2O_3 contents of 74.00–76.36 wt. % and 14.09–15.57 wt. %, respectively (Figure 14). The FeO and MgO contents of melts produced during fluid-present melting show a strong temperature dependence, being low at 700°C (FeO+MgO = 0.95−1.37 wt. %) and high at 750°C (FeO+MgO = 2.01−2.02 wt. %), but are not pressure dependent (Figure 14, 15c). CaO contents of the melts produced at higher pressure (1.2 GPa) are lower (0.49−0.79 wt. %) than those produced at lower pressure (1.12−1.43 wt. % at 0.6 GPa) (Figure 14). Fluid-present melting produces melts with wide range of Na_2O and K_2O contents (Na_2O = 1.98−5.95 wt. %, K_2O =2.05−5.41 wt. %), and the K_2O/Na_2O of melts were 0.34−0.99 at 700°C and 1.72−2.73 at 750°C (Figure 14, 15c), similar with the results from Pavan et al. (2021). The ASI values of the melts range from 1.14 to 1.22 (Figure 15a). In the Ab-An-Or normative diagram (Figure 15b), melts produced through fluid-present melting show a wide spread within the trondhjemite and granite fields, but always have higher Ab contents than other melts (Figure 15b). Melts produced through muscovite dehydration melting (orange symbols) have a smaller range of SiO_2 (73.82−75.19 wt. %) and Al_2O_3 (14.10−14.38 wt. %) contents than those produced by fluid-present melting (Figure 14). CaO contents are in the range of 0.80−1.00 wt. %, and also showed similar pressure-dependent features to fluid-present melting. FeO and MgO contents of the melts produced by muscovite dehydration melting (FeO+MgO = 0.97−1.63 wt. %) are within the range of those by fluid-present melting, however, the K_2O/Na_2O ratios of melts generated by muscovite dehydration melting (3.15−5.42) were higher than those generated by fluid-present melting (Figure 14, 15c). The ASI values of the melts produced by muscovite dehydration melting are low, ranging from 1.09 to 1.13 (Figure 15a). In Figure 15b, all melts produced through muscovite dehydration melting plot in the granite field.

Biotite dehydration melting (red symbols) produced melts with SiO_2 contents of 74.51−76.22 wt. % and Al_2O_3 contents of 13.89−14.32 wt. %, of which Al_2O_3 contents are also slightly lower than those melts produced by fluid-present melting (Figure 14). The FeO and MgO contents of these melts are temperature dependent, with higher contents at 750°C (FeO = 1.43 wt. %, MgO = 0.35 wt. %, FeO+MgO = 1.78 wt. %) and lower contents at 800°C (FeO = 0.79−0.97 wt. %, MgO = 0.22−0.27 wt. %, FeO+MgO = 1.00−1.24 wt. %) (Figure 14, 15c). The CaO content of melts produced through biotite dehydration melting are also slightly pressure dependent and in the range of 0.90−1.14 wt. % (Figure 14). K_2O and Na_2O contents are also temperature dependent, with higher Na_2O (1.91 wt. %) and lower K_2O (6.11 wt. %) at 750°C and lower Na_2O (1.30−1.41 wt. %) and higher K_2O (7.22−7.96 wt. %) at 800°C. The K_2O/Na_2O of the melts generated by biotite dehydration melting (K_2O/Na_2O = 3.20−5.66) were higher than those generated by fluid-present melting (Figure 15c). The melts produced by biotite dehydration melting have ASI values of 1.13−1.24 (Figure 15a), and all plot in granite field in the Ab-An-Or normative diagram (Figure 15b). Anhydrous mineral melting occured at temperature > 800°C. SiO_2 contents of the melts are in the range of 73.84−75.78 wt. %, and Al_2O_3 contents of 14.00−14.46 wt. % (Figure 14). FeO and MgO contents are in the ranges 0.88−2.49 wt. % and 0.24−0.50 wt. %, respectively (FeO+MgO = 1.12−2.94 wt. %) (Figure 14, 15c). Calculated CaO contents of the melts also show a pressure dependency, with a range of 0.83−1.02 wt. % at 1.2 GPa, and 1.05−1.20 wt. % at 0.6 GPa (Figure 14). K_2O and Na_2O contents of the melts are pressure dependent, with higher contents at 1.2 GPa (K_2O = 7.82−8.54 wt. %, Na_2O = 1.26−1.38 wt. %) and lower contents at 0.6 GPa (K_2O = 5.82−6.92 wt. %, Na_2O = 0.94−1.12 wt. %), but with a constant K_2O/Na_2O ratio of 6.20 (Figure 14, 15c). These melts produced by anhydrous mineral congruent melting have ASI values from 1.10 to 1.44, and have the highest Or contents in the Ab-An-Or normative diagram (Figure 15a and 15b).

Figure 15d and Table S9 show the modeled Rb/Sr and Ba trace element evolution during partial melting at different pressures and temperatures. These trace element ratios and contents vary with temperature and pressure. For example, at 1.2 GPa, melts produced at lower temperatures (700−750°C) usually have higher Sr contents (374−1016 ppm) and lower Rb and Ba contents (204−207 ppm and 476−585 ppm) than those produced at 825−875°C (Sr = 176−188 ppm, Rb = 230−246 ppm, and Ba = 1383−1477 ppm). While during isothermal decompression at 700°C, melts produced at higher pressure (1.2 GPa) usually have higher Rb, Sr and Ba contents (Sr = 1016 ppm, Rb = 206 ppm, and Ba = 476 ppm) than those produced at lower pressure (0.6 GPa) (Sr = 526 ppm, Rb = 163 ppm, and Ba = 421 ppm). These variations are not consistent for all changes in temperature or pressure; for example, Sr contents of melts produced at 700°C, 0.8 GPa are lower than those produced at 700°C, 0.6 GPa. Fluid-present melting always produces melts with low Rb, Ba contents and Rb/Sr (163−207 ppm, 421−585 ppm and 0.20−0.66, respectively) but high Sr contents (256−1016 ppm). Muscovite dehydration melting produces melts with higher Rb, Ba contents and Rb/Sr (179−231 ppm, 599−1107 ppm and 0.71−1.12, respectively) and lower Sr contents (206−274 ppm) than those produced by fluid-present melting. Melts produced through biotite dehydration melting show similar range of Rb, Sr, and Ba contents and Rb/Sr (173−224 ppm, 179−236 ppm, 590−1142 ppm and 0.73−1.17, respectively) to those generated via muscovite dehydration melting. Anhydrous mineral congruent melting produced melts with the highest Rb, Ba contents and Rb/Sr (182−246 ppm, 1112−1477 ppm and 1.30−1.31, respectively) and lowest Sr contents (138−188 ppm).

7 DISCUSSION

7.1 Petrogenesis of the three types of leucosome

7.1.1 Consanguinity between three types of leucosomes

Alongside examining the melting reactions that form different types of granitic leucosomes, it is pertinent to consider their consanguinity during metamorphism. Field relations show that leucogranitic leucosomes occasionally occur as sills and dykes in stromatic metatexite migmatite in the Maojiayao area, Kfs-rich granitic leucosomes pervasively occur as dykes in schollen-structured diatexite migmatite, and Grt-rich granitic leucosomes ubiquitously occur as felsic bands in schlieren-bearing diatexite migmatite in the study area. The abundance of each leucosome type increases in this order (Figure 2). All leucosomes are associated with metasedimentary rocks, which occur as paleosome and residue in various structured migmatite. Mantle-derived gabbro and norite occur within the north Jining-Liangcheng terrane (Peng *et al*., 2010), but are not associated with these migmatites. Therefore, field occurrences support all leucosomes having been produced by partial melting of metasedimentary rocks.

Only igneous zircon grains were identified in leucogranitic leucosomes, recording an upper intercept age of 1983 ± 19 Ma. Both igneous and metamorphic zircon grains occur in Kfs-rich granitic leucosome and Grt-rich granitic leucosome. The igneous zircons in these samples recorded upper intercept ages of 1976 ± 44 Ma and 1966 ± 28 Ma, respectively. Although various degrees of Pb loss impart large uncertainties on these igneous ages, they are still consistent with each other, indicating these leucosomes were generated during the same metamorphic event. We interpret the igneous ages, especially from leucogranitic leucosomes and Kfs-rich leucosomes, being slightly older than the *c*. 1.95 Ga high-pressure metamorphism due to significant degrees of zircon inheritance. This is also supported wide ranges of zircon saturation temperature discussed below. Metamorphic zircon grains from Kfs-rich leucosomes and Grt-rich leucosomes recorded ages of 1920 ± 10 Ma and 1920 ± 9 Ma, respectively. The ages are the same as for ultra-high temperature metamorphism in the north Jining-Liangcheng terrane (e.g. Santosh et al., 2007; Huang et al., 2019), indicating that this metamorphic event also influenced our study area, although the peak temperature was lower than in the north.

Previous model-focused partial melting studies have been conducted on average metapelitic rocks (e.g. Yakymchuk *et al*., 2017, 2018; Huang *et al*., 2021, 2022). These works suggest that for a specific source composition, melt compositions would show monotonous increases in Nb/Ta and LREE contents during heating (Yakymchuk *et al*., 2017; Huang *et al*., 2022). In this study, increases of Nb/Ta ratios and LREE contents were recognized in the direction from leucogranite leucosomes, through Kfs-rich granitic leucosomes, to Grt-rich granitic leucosomes. Among these two proxies, LREE contents of the melts would largely depend on the dissolution/precipitation of apatite and monazite during partial melting, and not by major-rock forming mineral fractional crystallization (Yakymchuk *et al*., 2017), although major-rock forming minerals might host some accessory phase inclusions to prevent interaction between accessory minerals and the melt. Comparatively, Nb/Ta would be influenced by the fractional crystallization and entrainment of biotite and rutile/ilmenite when melt was extracted from the migmatite (Huang *et al*., 2022). The consistency of the increase of these proxies in three types of leucosomes may provide evidence for similar source compositions and magnitudes of temperature increase. We calculated zircon saturation temperatures (T_{Zr}) for all three types of leucosomes (Watson & Harrison, 1983; Miller *et al*., 2003), which produced ranges of 629−813°C for leucogranitic leucosomes, 618−799 °C for Kfs-rich leucosomes, and 845−890 °C for Grt-rich leucosomes (Table S3). Leucogranitic leucosomes and Kfs-rich leucosomes show a wider range of zircon saturation temperatures than Grt-rich leucosomes, as the former contain more inherited zircon. Miller *et al*. (2003) suggested that ‘cold’ granites are more susceptible for zircon inheritance, and calculated T_{Zr} values should be maxima for magmas that carry inherited zircon crystals. In contrast, T_{Zr} values for Grt-leucosomes are relatively high and consistent, indicating that they were relatively hot and contain little or no zircon inheritence.

The three types of leucosomes have consistent εNd values at 1950 Ma within the range –1.24 to 0.45, although εNd for the Kfs-rich granitic leucosomes covers the entire range that for the leucogranite and Grt-rich granitic leucosomes. In contrast, ^{87}Sr/^{86}Sr of the different types of leucosomes vary. As described above, leucogranitic leucosomes have low but relatively restricted ^{87}Sr/^{86}Sr values, indicating these leucosomes should be derived from the same sedimentary protolith. Kfs-rich granitic leucosomes show scattered ^{87}Sr/^{86}Sr values. We suggest that two possible reasons for these scattered $^{87}Sr/^{86}Sr$ values. The first reason is late-stage (post-crystallization) alteration, given that Rb is an incompatible and highly mobile element (Polat *et al*., 2002; Rollinson & Gravestock, 2012), and these leucosomes have high Rb/Sr ratios ($^{87}Rb/^{86}Sr$ up to 2.204). The second reason might be the limited homogenization, since these leucosomes occur within schollen-structured diatexite migmatite, and lack evidence of flow. The $^{87}Sr/^{86}Sr$ of the leucosomes would then largely inherit the initial $^{87}Rb/^{86}Sr$ of the specific sedimentary layer they formed from, which might have a different $^{87}Rb/^{86}Sr$ value. Grt-rich granitic leucosomes exhibit intermediate and restricted $^{87}Sr/^{86}Sr$ values, which mostly indicate efficient homogenization during magmatic flow. Zircon oxygen isotope compositions show a slight decrease from leucogranitic leucosomes, to Kfs-rich granitic leucosomes, and then Grt-rich granitic leucosomes. The mean value of $\delta^{18}O$ of the zircon in leucogranitic leucosomes is 2‰ higher than that of zircon within Grt-rich granitic leucosomes. The difference of the $\delta^{18}O$ value might be caused by several factors. Firstly, under equilibrium conditions, $\delta^{18}O$ enrichment of minerals would differ and follow the sequence feldspar > muscovite > biotite proposed by Zheng (1993a, b, 2011). In such cases, melt generated by consumption of quartz and feldspar would have higher $\delta^{18}O$ values than melt generated by muscovite breakdown, although small amount of pore water with low $\delta^{18}O$ values would slightly decrease the $\delta^{18}O$ value of melts produced by fluid-present melting. Melt generated through biotite breakdown would have the lowest $\delta^{18}O$ values. The second possibility is that garnet entrainment. As $\delta^{18}O$ values of garnet are lower than those of biotite (Zheng et al., 2013), the $\delta^{18}O$ of zircon crystallized in melts with sufficient garnet entrainment would be be lower than initial melt compositions. Thirdly, fractional crystallization of high-$\delta^{18}O$ minerals could also explain the different $\delta^{18}O$ values. For example, if zircon crystallized after the removal of feldspar, the $\delta^{18}O$ of zircon would be lower than the initial melt composition. Finally, assimilation of mafic magma could also account for this varied $\delta^{18}O$ values. The $\delta^{18}O$ values of mafic magmatic rocks derived from mantle have a narrow range of 5.4 to 5.9 ‰ close to the mantle value (5.3±0.6‰) (Eiler, 2001; Valley, 2005); thus, assimilation of mafic magma would cause the $\delta^{18}O$ values of the crustal-derived peraluminous magma to decrease. However, the scarcity of mafic rocks in the study area, as well as little CaO enrichment of Grt-rich granitic leucosomes then rule out the major influence of mafic magma assimilation.

By combining observations of field occurrences, and analyses of igneous zircon ages, bulk-rock trace element compositions, Nd–Sr isotope compositions, and zircon O isotope compositions for the three types of leucosomes, we suggest that all of them were generated from partial melting of a similar source rocks during the same geological event. Their consanguinity thus provides opportunities to decipher the petrogenesis of felsic peraluminous magma in a collisional orogen.

7.1.2 Comparison between compositions of leucosomes and calculated melts

Given that Nb/Ta and LREE trace element contents show a broad increase from leucogranitic leucosomes, through Kfs-rich granitic leucosomes, to Grt-rich granitic leucosomes (Figure 10), the temperature at which these leucosomes formed should also increase comensurately based on the discussion above. We have compared the measured compositions of leucosomes with modeling results to decipher the petrogenesis of these leucosomes. Leucogranitic leucosomes form at the lowest temperature. Their bulk-compositions show low K_2O/Na_2O ratios, FeO_{total}+MgO contents, Rb/Sr and Ba contents (Figure 7 and 8). In our modeling, the measured compositions of leucogranitic leucosomes are identical to the melt generated through fluid-present melting (Figure 14 and 15).

At higher modeled partial melting temperatures, the compositions of Kfs-rich granitic leucosomes are comparable with modeled melt compositions generated through fluid-absent melting. The Kfs-rich granitic leucosomes are weakly peraluminous and show high concentrations of SiO_2, high K_2O/Na_2O ratios, low FeO_{total}+MgO contents, high Rb/Sr ratios, and high Ba contents (Figure 7 and 8). High K_2O/Na_2O ratios and low FeO_{total}+MgO contents are characteristics of melt generated through muscovite-dehydration melting (Figure 14 and 15). However, muscovite-dehydration should still produce even higher FeO_{total}+MgO contents in melts than those from fluid-present melting, which conflicts with our observations for the compositions of natural leucosomes.

Based on field occurrence relationships, volume proportions, and trace element compositions, Grt-rich granitic leucosomes are interpreted to have formed at the highest temperatures among the three types of leucosomes. Their compositions can be compared with modeled melt compositions generated through fluid-absent melting. The leucosomes are strongly peraluminous and have scattered SiO_2 and Al_2O_3 concentrations (Figure 7, 8a), which is likely a result of the uneven spatial distribution of peritectic minerals (e.g. garnet, K-feldspar) in the leucosomes. Measured K_2O/Na_2O ratios of Grt-rich leucosomes are higher than leucogranitic leucosomes, but lower than Kfs-rich granitic leucosomes (Figure 8c). FeO_{total}+MgO contents of Grt-rich leucosomes are notably higher than leucogranitic leucosomes and Kfs-rich granitic leucosomes, which is consistent with widespread garnet occurrence (Figure 8c). In terms of trace elements, Rb/Sr ratios and Ba contents of Grt-rich leucosomes are higher than leucogranitic leucosomes, but lower than Kfs-rich granitic leucosomes (Figure 8d). The possible reason for the high FeO_{total}+MgO contents of the Grt-rich leucosomes might be produced through biotite-dehydration melting. However, the compositions of Grt-rich leucosomes are incomparable to any modeled compositions proposed for partial melting of greywacke or pelite in orogenic settings (cf. Huang *et al*., 2021). The main difference between observed and modeled compositions in this case is the former having very high FeO_{total}+MgO contents (Figure 15c).

7.1.3 Possible reasons for the differences between leucosome compositions and calculated melts

The comparison discussed above shows similarities between the compositions of leucogranitic leucosomes and the calculated melts produced through fluid-present melting. The leucogranitic leucosomes show various degrees of HREE enrichment, which is resulted from heterogeneously distributed and small garnet grains within leucogranitic domains. Strongly positive Eu/Eu* anomalies indicate that plagioclase might play a significant role as a reactant during partial melting, which is consistent with formation via fluid-present melting reactions (Figure 13), Plagioclase accumulation might also lead to positive Eu/Eu* anomalies. However, positive relationship between $(La/Yb)_N$ and Eu/Eu* or Sr and Eu/Eu* cannot be recognized, ruling out the possibility of plagioclase accumulation. We therefore conclude that leucogranitic leucosomes were produced solely by fluid-present melting.

Kfs-rich granitic leucosomes have the highest K_2O/Na_2O ratios and very low FeO_{total}+MgO contents, consistent with the limited volume proportion of ferromagnesian minerals in the leucosomes. The high K_2O/Na_2O ratios of granitic leucosomes are consistent with calculated melt compositions produced through muscovite dehydration melting at temperatures lower than 775 °C (Figure 15c). We consider that garnet fractional crystallization is the reason for the consistency between analyses and calculation, based on: (1) limited garnet being present in the samples; (2) various degree of depletion of HREE. Fractional crystallization calculations show that 3 vol. % of garnet fractional crystallization would be necessary for producing low-FeO_{total}+MgO leucosomes (Figure 15c). We interpret the enhanced K_2O/Na_2O ratio as a primary characteristic of the produced melt. In addition to the temperature profiles discussed above, Kfs-rich granitic leucosomes are likely produced by muscovite-dehydration melting.

Grt-rich granitic leucosomes are interpreted as biotite-dehydration melting products, given their high volume proportions of ferromagnesian minerals. However, they have intermediate K_2O/Na_2O, Rb/Sr, and Ba characteristics between all three types of leucosomes, which conflicts with them having the highest temperatures of formation. In addition, all samples have very high FeO_{total}+MgO contents that are inconsistent with our calculations. The high SiO_2 contents up to 80 wt.% and reduced K_2O/Na_2O, Rb/Sr, and Ba contents are interpreted to be related to fractional crystallization of K-feldspar (Figure 14 and 15). Additionally, schlieren-structured diatexite migmatites are characterized by compositional banding related to magmatic flow, and K-feldspar porphyroblasts would likely have experienced fractional crystallization during magma flow, as indicated by K-feldspar cumulates associated with residues (Figure 3h). However, plagioclase fractional crystallization would lead to an increase of Rb/Sr, ruling out the possibility of plagioclase removal. Fractional crystallization calculations showed that nearly 20–30 vol. % of K-feldspar must be removed to produce Grt-rich granitic leucosomes (Figure 14 and 15). We account for the enhanced FeO_{total}+MgO contents by either: (1) partial melting of metapelite portions that were enriched in FeO_{total}+MgO, rather than greywacke; (2) fractional crystallization of felsic minerals; (3) assimilation of mafic magma; or (4) entrainment of ferromagnesian minerals (e.g. garnet, ilmenite) (Stevens et al., 2007; Taylor & Stevens, 2010; Taylor et al., 2014). These possibilities can be tested to determine which are most significant.

The partial melting behaviour of metapelite is well known, and previous workers have shown that an average amphibolite-facies metapelite would generate biotite dehydration melts with FeO_{total}+MgO contents below 2.5 wt. %, whereas muscovite dehydration melting would produce melts that are even more FeO_{total}+MgO poor (Patiño Douce & Harris, 1998; Huang *et al*., 2021). Fractional crystallization of K-feldspar may explain the reduction of K_2O/Na_2O, Rb/Sr, and Ba contents discussed above; however, mass-balance calculations show that 40 vol. % of Kfs fractional crystallization could lead to up to 1.19 wt. % of the FeO_{total}+MgO content increase. Nonetheless, this explanation is not applicable here, since the leucosomes still contain significant K_2O, so fractional crystallization cannot be the main reason for the enhancement of FeO_{total}+MgO contents. As described above, mafic rocks have not been discovered in the study area, and are restricted to the north Jining-Liangcheng terrane. While mafic rocks in Jining-Liangcheng terrane are usually rich in CaO contents, no enrichment of CaO has been recognized in Grt-rich leucosomes. The SiO_2 contents of the Grt-rich granitic leucosomes are all higher than 68 wt. %, with some up to 80 wt. %, and their Nd isotope compositions are identical to those of other leucosomes, which rules out the assimilation of mafic magma (Korhonen *et al*., 2015). Zircon $\delta^{18}O$ compositions in Grt-rich granitic leucosomes are slightly lower than those of Kfs-rich granitic leucosomes, which might be related to low-$\delta^{18}O$ biotite dehydration melting, and garnet entrainment of fractional crystallization of K-feldspar before zircon crystallized. Garnet is abundant in these leucosomes, which is consistent with the Grt-rich leucosomes having high HREE contents. Leucosomes with the highest FeO_{total}+MgO contents usually have high Al_2O_3 contents, which support garnet entrainment being responsible for the high concentration of ferromagnesian elements. Mass balance calculation show that up to 20 vol. % entrainment of peritectic garnet could produce the high FeO_{total}+MgO contents in Grt-rich leucosomes (Figure 14 and 15). In addition, garnet entrainment would also decrease the Ba contents in the melts. K-feldspar removal and peritectic garnet entrainment would be the reason for the intermediate Rb/Sr and Ba contents of Grt-rich granitic leucosomes (Figure 15d). Sample 21LH062 recording high Nb, Ta, TiO_2 and Ni contents is also likely the result of ilmenite entrainment.

Our combined observations and calculations suggest that leucogranitic leucosomes are generated through fluid-present melting of greywacke, Kfs-rich granitic leucosomes form through muscovite-dehydration melting followed by up to 3 vol. % of garnet fractional crystallization, and Grt-rich granitic leucosomes form through biotite dehydration melting followed by 20–40 vol. % K-feldspar fractional crystallization and up to 20 vol. % garnet entrainment. The crystal-melt segregation in magmatic systems is driven by gravitation settling, flow differentiation, thermal diffusion, and convective fractionation (Wager & Brown, 1968; Bhattacharji & Smith, 1964; McBirbey & Noyes, 1979; Sparks *et al*., 1984). The viscosity of the magma, magma flow rate and the density difference between crystals and their host melt therefore represent key controls on mineral fractional crystallization. The density of garnet is about 3800 kg/m^3, obviously higher than K-feldspar (2700 kg/m^3) and granitic magma (2400–2500 kg/m^3), making garnet fractional crystallization much easier than K-feldspar. We believe that both Kfs-rich leucosomes and Grt-rich leucosomes must fractionate garnet, but Grt-rich leucosome contain large amount of peritectic garnet, leaving difficulty to identify garnet fractional crystallization in Grt-rich leucosomes. Kfs-rich leucosomes are crystallized from lower temperature granitic magmas (with a higher viscosity) than Grt-rich leucosomes (with a lower viscosity). Besides, magma flow structure could be recognized in Grt-rich leucosome. These factors make K-feldspar fractional crystallization easier in Grt-rich leucosomes than Kfs-rich leucomes.

In our calculations, concentrations of the trace elements Rb, Sr, and Ba show distinct trends that match those from Harris & Inger (1992) and Inger & Harris (1993), which have long been used as a guide to decipher the petrogenesis of S-type granite. Bartoli (2021) also pointed out this distinction, and suggested that Rb/Sr and Ba characteristics of a melt might not be representative of the role of water in the source. The main reactants during fluid-present melting are quartz and feldspar (plagioclase and K-feldspar both of which can incorporate Sr), therefore melts generated through this process would show a decreasing Rb/Sr ratio. Further, K-feldspar incorporates Ba, thus fluid-present melting would also cause Ba contents to increase. The main reactants during muscovite and biotite dehydraton melting would be muscovite and biotite, respectively, both of which incorporate Rb and Ba. Thus, Rb/Sr and Ba should continuously increase during muscovite and then biotite dehydration melting at constant pressure, as shown in Figure 15d.

7.2 Implications for partial melting and granite formation in a collisional orogen

Field observations and the results of petrological modeling allow exploration of the partial melting mechanisms that generate granites in a collisional orogen. When free water is not introduced into a melting zone, fluid in the protolith would be limited. The H_2O content of an average amphibolite-facies metagreywacke (2.94 wt. %) used in this study should be viewed as an upper limit for fluid-present melting, since fluid could be lost during prograde metamorphism at subsolidus conditions. Fluid-present melting only generates occasional leucogranitic leucosomes within a stromatic metatexite. By contrast, fluid-absent melting, including muscovite and biotite dehydration melting, generate pervasive and ubiquitous K-rich granitic leucosomes within schollen and schlieren diatexites. Previous studies show that the recognized mineral assemblages in leucosomes are a function of magmatic water contents (e.g. Clemens & Wall, 1981; Wang *et al*., 2023a). In our calculation, fluid-present melting, mainly consuming feldspar, quartz and H_2O, could produce melts with water contents up to 17 wt.%, while fluid-absent melting, containing muscovite and biotite dehydration melting, could produce melts with water content in the range of 6–13 wt.%. Garnet tend to be consumed by magmatic reabsorption to form biotite at near solidus when sufficient water contents are provided (Wang et al., 2023a). In such case, significant amount of fluids have to expel from the system before melt final crystallization (Figure S1).

In the east Jining-Liangcheng terrane, leucogranite is locally recognized in the Anzishan and Wusumu areas, where it is spatially restricted to an area of 20 km^2. These leucogranite have consistent bulk-rock compositions, with major compositions identical to leucogranitic leucosomes in this study, although there are differences in Eu/Eu* and Ba contents. Leucogranites in the Jining-Liangcheng terrane have Eu/Eu* of 0.88–1.20. The reason for the lack of Eu/Eu* might be plagioclase fractional crystallization. The Ba contents of leucogranites in the Jining-Liangcheng terrane are in the range 789–1341 ppm, notably higher than the leucogranitic leucosomes in this study (Figure 8d). We suggest that the reason for this distinction was a higher Ba content in the protolith. Liangcheng granite/charnockite, which is the dominant form of granite in the east Jining-Liangcheng terrane (comprising up to 40 vol. %), contains K-feldspar porphyroblasts and up to 25 vol. % of garnet (Peng *et al*., 2012; Wang *et al*., 2017; 2018). The compositions of these granites mostly plot on the garnet entrainment line, except for the CaO contents (Figure 14). The high CaO contents in the Liangcheng charnockite were interpreted to be due to mafic magma assimilation (Wang et al., 2018). Our modeling results show that the amount of melt generated through fluid-present melting largely depends on the amount of free fluid (H_2O) in the rock at the point of anatexis.

Given that external fluid was difficult to introduce into the lower crust of a collisional system, fluid-present melting might generate some leucogranite, but not more than that generated through fluid-absent melting. Similar leucogranite in the Khondalite belt can also be found in the Himalaya orogen, Caledonian orogen and Trans-Hudson orogen (Gao *et al*., 2017; Kalsbeek *et al*., 2001; St Onge *et al*., 1992, 2006). Based on these results, we suggest the main partial melting mechanism of granite within the collisional orogeny was fluid-absent melting, although fluid-present melting likely made some contributions.

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SUPPLEMENTARY FILES

Analytical methods and uncertainties on phase equlibira modeling could be found in the Supplementary files. The data underlying this article are available onine.

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FIGURE CAPTIONS

Figure 1 (a) Tectonic subdivision of the North China craton showing

Precambrian units (Zhao *et al.*, 2005). (b) Geological map of Jining-Liangcheng terrane (modified after Guo *et al.*, 2001). The red square represents location of Figure 2.

Figure 2 Geological map of the study area to show distribution of three types of leucosomes (modified after 1:200000 regional map). Leucograntic leucosomes are labeled as blue circles, Kfs-rich granitic leucosomes are labeled as orange circle and Grt-rich granitic leucosomes are labeled as red circle. Samples used for geochemical analysis are labeled with abbreviations (e.g. 31: 21LH031).

Figure 3 Field photographs of metasedimentary rocks and associated migmatite from the study area. (a) interbeded metapelite and metagreywacke; (b) representative metagreywacke used for petrological modeling (21LH030); (c) stromatic metatexite migmatite showing leucogranitic leucosome and paleosome. (d) representative leucogranitic leucosome (21LH043), showing unequally distribute minerals (e.g. fine-grained garnet); (e) schollen-structured diatexite migmaite, containing Kfs-rich granitic leucosomes and paleosome; (f) representative Kfs-rich granitic leucosome (21LH018), containing Kfs porphyroblast; (g) schlieren-bearing diatexite migmatite, containing composition banding of leucosome, paleosome and residue; and (h) representative Grt-rich granitic leucosome (21LH061).

Figure 4 Photomicrographs of metagreywacke, metapelite and three types of leucosomes. (a) metagreywacke sample used for petrological modeling; (b) metapelite sample containing biotite and sillimanite, indicating up to upper amphibolite facies metamorphism; (c) leucogranitic leucosome sample containing fine-grained garnet; (d) Kfs-rich granitic leucosome sample containing K-feldspar porphyroblast; (e) Grt-rich granitic leucosome sample containing coarse-grained garnet. Phase abbreviations follow Whitney & Evans (2010).

Figure 5 Representative CL images of zircon from three types of leucosome samples. (a) leucogranitic sample 21LH043; (b) Kfs-rich granitic leucosome sample 21LH018; (c) Grt-rich granitic leucosome sample 21LH061.

Figure 6 Concordia plots of zircon analyses from three types of leucosomes. (a) igneous zircon analyses from leucogranitic sample 21LH043; (b) igneous zircon analyses from Kfs-rich granitic leucosome sample 21LH018; (c) metamorphic zircon analyses from Kfs-rich granitic leucosome sample 21LH018; (d) igneous zircon analyses from Grt-rich granitic leucosome sample 21LH061; (e) metamorphic zircon analyses from Grt-rich granitic leucosome sample 21LH061.

Figure 7 Harker diagram plots for major elements of three types of leucosomes and Anzishan leucogranite and Liangcheng charnockite. Leucogranitic leucosomes are shown as blue circles, Kfs-rich granitic leucosomes are shown as orange circles, and Grt-rich granitic leucosomes are shown as red circles. Anzishan leucogranites are shown as light grey circles, and Liangcheng charnockite are shown as dark grey circles with bold outlines.

Figure 8 (a) A/NK vs. A/CNK classification diagram (Maniar & Piccoli, 1989) for three types of leucosomes, Anzishan leucogranite and Liangcheng charnockite; (b) Ab-An-Or classification diagram (O'Connor, 1965) for three types of leucosomes, Anzishan leucogranite and Liangcheng charnockite; (c) K_2O/Na_2O vs. $FeO_{total}+MgO$ diagram of three types of leucosomes, Anzishan leucogranite and Liangcheng charnockite; (d) Rb/Sr vs. Ba diagram for three types of leucosomes, Anzishan leucogranite and Liangcheng charnockite.

Figure 9 (a) Chondrite-normalized rare earth element (REE) patterns and (b) primitive mantle (PM) normalized element patterns for three types of leucosomes, Anzishan leucogranite and Liangcheng charnockite. Normalization constants are after Sun & McDonough (1989).

Figure 10 ΣLREE vs. Nb/Ta diagram of three types of leucosomes, Anzishan leucogranite and Liangcheng charnockite.

Figure 11 (a) Bulk rock Sr-Nd isotope composition plots of three types of leucosomes; (b) zircon $\delta^{18}O$ value plots of three types of leucosomes.

Figure 12 (a) $T-H_2O$ diagram contoured with melt proportions for metagreywacke sample; (b) $T\text{-}Fe^{3+}/Fe_{total}$ diagram contoured with melt proportions for metagreywacke sample.

Figure 13 $P-T$ pseudosection of metagreywacke sample 21LH030. Calculated melts produced through fluid-present melting, muscovite dehydration melting, biotite dehydration melting and anhydrous mineral melting are shown as blue, orange, red, and purple symbols, respectively.

Figure 14 Harker diagram plots for major elements of modeled melt compositions. Melts produced through fluid-present melting, muscovite dehydration melting, biotite dehydration melting and anhydrous mineral melting are shown as blue, orange, red, and purple symbols, respectively. Melts produced at 1.2 GPa, 1.0 GPa, 0.8 GPa and 0.6 GPa are shown by diamonds, cubes, triangles and circles, respectively. Red triangle outlined in black lines represent garnet entrainment in 10% increments, and red triangle outlined in green lines represent K-feldspar fractional crystallization in 10%

increment.

Figure 15 (a) A/NK vs. A/CNK classification diagram for modeled melt compositions; (b) Ab-An-Or classification diagram for modeled melt compositions. (c) K_2O/Na_2O vs. $FeO_{total}+MgO$ diagram of calculated melts. (d) Rb/Sr vs. Ba diagram for calculated melts.