Neoarchean to Paleoproterozoic high-pressure mafic granulite from the Jiaodong Terrain, North China Craton: Petrology, zircon age determination and geological implications

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1. Introduction

The secular change of the Earth's thermal structure throughout the geological history is a topic of broad interest and is considered to be responsible for the change of metamorphic style and tectonic setting of the continental crust (Brown, 2007a,b; Condie and Kröner, 2013). High P/T (low thermal gradient, ~20 °C/km) metamorphism rarely occurred till the end of Paleoproterozoic. The only known cases include: (1) a garnet-bearing mafic granulites from the Lewisian Complex of northern Scotland (Sajeev et al., 2013), (2) a kyanite–garnet–bearing felsic granulate (2.49 Ga) from the Salem block of southern India (Anderson et al., 2012), (3) a chlorite- and phengite-bearing gneiss (2.2–2.0 Ga) from the Birimian Terrain of the West African Craton (Ganne et al., 2012), (4) the Meso-Neoarchean Belomorian eclogite province in the Kola Peninsula (Mints et al., 2010, 2012), (5) the garnet–albite-bearing para-amphibolites from the Mesoarchean Barberton granitoid–greenstone terrain (Moyen et al., 2006), and (6) the garnet websterites from the early Paleoproterozoic Sharyzhalgai Complex, Siberia Craton (Ota et al., 2004). Ultrahigh-pressure metamorphic (UHP) rocks occur commonly in the Phanerozoic, and the oldest UHP eclogites have only been found in the Neoproterozoic (Jahn et al., 2001). The rare occurrences of UHP–HP metamorphic rocks have provoked the controversy about (1) the tectonic setting(s) in which the rocks were formed (O'Brien and Rötzlzer, 2003; Brown, 2007a; Sizova et al., 2010); (2) the mechanism and mode of exhumation of the rocks (van Hunen and van den Berg, 2008); and (3) the problem of preservation of HP–UHP index minerals (Anderson et al., 2012).

The North China Craton has become a highlight in the study of early Precambrian geology due to the following main research progress in the past decades (Zhai and Santosh, 2011 and references therein): (1) the identification of Eoarchean rocks including the 3.8 Ga TTG gneisses in Anshan, Liaoning Province (Liu et al., 1992; Song et al., 1996; Wan et al., 2001, 2005, 2011c) and ~3.8 Ga detrital zircons in the supracrustal rocks in Caoyuzhong, eastern Hebei Province (Huang et al., 1986; Jahn et
al., 1987; Liu et al., 1992, 2007, 2013; Wu et al., 2005; Wilde et al., 2008); (2) the identification of significant crustal growth at ~2.9, ~2.7 and 2.5 Ga; (3) the still-debated issue on the time of cratonization and its tectonic framework; and (4) the discovery of late-Paleoproterozoic high-pressure granulites and ultrahigh-temperature metapelites (Guo et al., 2006; Santosh et al., 2006; Liu et al., 2007, 2008; Santosh et al., 2007; Tsunogae et al., 2011; Guo et al., 2012; S.J. Liu et al., 2012; Zhang et al., 2012) and the related discussion on the Paleoproterozoic orogenetic belts.

The high-pressure granulites documented so far are mostly produced at the end of Paleoproterozoic; for example, (1) garnet-bearing metabasic dykes in the Hengshan area (Zhao et al., 2001), Sanggan area (Guo et al., 2002, 2005), and Chengde area (Li et al., 1998; Mao et al., 1999), and high-pressure pelitic granulites in the Sanggan area (Ma and Wang, 1995), which are related to the formation of the Central Orogenic Belt (Zhao et al., 2001); (2) kyanite–K-feldspar-bearing high-pressure pelitic granulites in the Qianlishan–Helanshan area (Zhou et al., 2010) during the formation of the Khondalite Belt (Zhao, 2001) or the Inner Mongolia Suture Zone (Santosh, 2010); and (3) high-pressure mafic granulites and high-pressure pelitic granulites in the Jiaobei Massif or Jiaodong Terrain during the formation of Jiao–Liao–Ji belt (Liu et al., 1998; Zhou et al., 2004; J.B. Zhou et al., 2008; X.W. Zhou et al., 2008; Liu et al., 2010; P.H. Liu et al., 2011; Tam et al., 2011; Tam et al., 2012a,b). However, high-pressure granulites of Archean ages are rarely documented in the North China Craton. The only case found is from the Jianping Complex, western Liaoning Province. The metamorphism was characterized by an anti-clockwise P–T path with the peak PT condition at 10.5 ~ 11.7 kbar and 785 ~ 820 °C (Cui et al., 1991; Wei et al., 2001).

In this study, we report the discovery and result of study of a mafic granulite from the Jiaodong Terrain. The mafic granulate occurs as enclaves in a TTG gneiss in the Hexikuang Reservoir of Qixia City. The metamorphic evolution is traced based on the mineral assemblages and reaction textures. The metamorphic P–T condition is calculated using the conventional geothermobarometry and the pseudosection modeling. The timing of the metamorphism will be constrained by a detailed zircon dating using the SHRIMP analytical technique, and the geological implications will be discussed.

2. General geology in Jiaodong Terrain

The Jiaodong Terrain is an important part of the North China Craton (Fig. 1A). It is composed of early Precambrian rocks, covered by sedimentary sequences and intruded by Mesozoic granitoids. The terrain is bounded by the Yantai–Wulian Fault to the southeast against the Sulu UHP metamorphic belt (Fig. 1B). The early Precambrian rocks comprise (1) the Paleoproterozoic Fenzishan “Group” composed of pelitic–psammitic metasediments and marble with subordinate greenstones; (2) the Paleoproterozoic Jinshan “Group” composed of sillimanite–biotite–quartz schist, biotite lepiite and gneiss, and marble with minor amphibolite; and (3) Archean basement made up of TTG gneisses, granitoids and related plutonic rocks with minor supracrustal rocks. A zircon geochronological study established three major tectonothermal events at ~2.9, ~2.7 and ~2.5 Ga (Jahn et al., 2008).

Fig. 1. A. Contour of the North China Craton (after Zhao, 2001) and locality of Eastern Shandong Province. B. The simplified geological map of Eastern Shandong Province and locality of the study area.
The Archean TTG gneisses and associated rocks were emplaced in two stages at ~2.9 and ~2.7 Ga (Jahn et al., 2008; J.H. Liu et al., 2011; Xie et al., under review). The TTG gneisses of the two stages are similar regarding the field occurrence, petrography, whole-rock chemistry, metamorphism, deformation, and local anatectic feature (Jahn et al., 2008; J.H. Liu et al., 2011; Xie et al., under review). Note that they have been subjected to the same 2.5 Ga metamorphic event. The two stages of TTG gneisses are so similar that they can only be distinguished by geochronology (Xie et al., under review). Aside from TTG gneisses, granitoids of 2.5 Ga of age, which occur mainly as high-Si trondhjemitic rocks (Tanggezhuang suite), have also been identified within this area and they are probably produced by partial melting of older TTG sources (J.H. Liu et al., 2011, 2012). In general, the deformation of the 2.5 Ga granitoids is not as strong as the older counterparts with few exceptions. Consequently, it is difficult to distinguish them in the field. Furthermore, some of the 2.5 Ga granitoids underwent metamorphism at the end of the late Paleoproterozoic (Wan et al., 2011a).

The ~2.9 Ga TTG gneisses from the Huangyandi locality are found to contain metamorphosed supracrustal rocks. These rocks occur as small enclaves of varied rock types from amphibolite to leptite. Zircon age study revealed that these rocks formed at ~2.9 Ga and underwent metamorphism at 2.5 Ga (Jahn et al., 2008; J.H. Liu et al., 2011). Another suite of supracrustal rocks, named the “Jiaodong Group”, was probably formed during the Neoarchean, but no zircon U–Pb ages have been obtained for confirmation (J.H. Liu et al., 2011; Wan et al., 2012a). Note that their lithological characteristics are similar to that of the older (~2.9 Ga) supracrustal rocks.

3. Local geology and sampling

In a recent field study around the Qixia City, mafic granulites were discovered at a locality near the southern part of the Hexikuang water reservoir (Fig. 2). The rocks occur as enclaves within Neoarchean TTG gneisses. In fact, this region is dominated by TTG gneisses of Mesoproterozoic to Neoarchean ages. The supracrustal rocks in this area are mainly biotite–plagioclase gneisses and leptite with minor interlayers of amphibolite of Jiaodong “Group”. In addition to the Archean rocks, Proterozoic mafic rocks are also found to intrude into the TTG gneisses. The terminal magmatic activities are represented by the

![Figure 2](http://dx.doi.org/10.1016/j.gr.2014.07.006)
minor intrusions of Mesozoic granite and eruption of Tertiary basalt in some areas.

At the Hexikuang reservoir, the building of the dam has provided fresh outcrops. To the north of the dam, a gneissic quartz diorite and a tonalite of 2.9 Ga have been identified (Xie et al., under review). To the south of the dam, TTG gneisses of 2.5 Ga with enclaves of Grt-bearing mafic granulites are the dominant rock types. The Grt-bearing mafic granulites have a regional NW-trending foliation, which is similar to that of the surrounding TTG gneisses (Fig. 3A). The size of the mafic granulite enclaves ranges from several to more than 10 m. Thus, they are giant enclaves.

The mineral assemblages and grain size show a gradual change in the outcrop. The fine-grained domain is mainly composed of garnet, clinopyroxene, hornblende, orthopyroxene and plagioclase with minor quartz (Fig. 3B) whereas garnet, clinopyroxene and orthopyroxene become less abundant in the coarser domains. In some domains, tiny grains of garnet are surrounded by very thin light-colored rims which are further identified as the symplectite of plagioclase + clinopyroxene or plagioclase + hornblende (“white eye”). A complete retrogression of garnet into plagioclase and hornblende is also observed as shown by white dots of garnet pseudomorphs (Fig. 3C and D).

We collected eight samples with different grain sizes numbered from QX12118-1 to QX12118-8. All the samples are garnet–clinopyroxene–orthopyroxene–hornblende gneisses. The only difference between them is the grain size and phase proportion. The mineral assemblages and reaction textures are best presented in sample QX12118-6, which was subject to the most detailed study in petrography, mineral chemistry and petrology. Two large samples, S1205 and S1207, were collected from the same outcrop for zircon age determination. Sample S1205 is gneissic garnet-bearing amphibolite whereas sample S1207 is gneissic amphibolite with garnet pseudomorph. A host gneissic trondhjemite sample, QX12117 was also collected for age determination. Leucosome veins are avoided when collecting the samples.

4. Analytical methods

4.1. Mineral chemistry

Mineral chemistry of sample QX12118-6 was analyzed using a JXA-8230 electron microprobe analyzer (EPMA) at the Institute of Mineral Resources, Chinese Academy of Geological Sciences. Mineral structural formulae were calculated for fixed oxygen. Fe3+ was calculated by stoichiometric charge balance. Typical mineral assemblages and textures were also documented by backscattered electron (BSE) imaging.

4.2. Whole rock chemistry

The major element composition of sample QX12118-6 was analyzed using an X Ray Fluorescence spectrometer (XRF, PW4400), whereas FeO and Fe2O3 contents were determined by the wet chemical method at the National Research Center of Geoanalysis, Chinese Academy of Geological Science following the standard procedures (Zhang and Ye, 1987).

4.3. Zircon geochronology

Zircon grains were extracted from samples S1205, S1207 and QX12117 following the standard procedures at the Beijing SHRIMP Center, Chinese Academy of Geological Sciences. Zircon grains were mounted on a double-sided adhesive tape and enclosed in epoxy resin disks together with reference zircon standards TEMORA1 (206Pb/238U age = 417 Ma) and M257 (U = 840 ppm) (Black et al., 2003; Nasdala et al., 2008). The disks were then polished and gold coated for the following cathodoluminescence (CL) imaging and U-Th-Pb isotope analyses.

The morphology, internal texture and structure of zircon grains were examined by a joint imaging process using a transmitted and reflected light microscope and a HITACHI S3000-N Scanning
Electron Microscope (SEM) equipped with a ROBINSON back scatter probe and a Gatan Chroma CL probe at the Beijing SHRIMP Center.

Zircon U–Th–Pb isotope analyses were performed using SHRIMP II following the standard procedures (Williams, 1998). The primary ion beam of O²⁻ at the intensity of 6 nA was used to impinge zircon grains with spot size of 25 μm. Following 150 s of rastering for each analytical spot, 5 scans were made through the nine mass stations including 186Zr, 204Pb, background, 206Pb, 207Pb, 208Pb, 238U, 248Th and 254UO. Reference zircon M257 was analyzed for elemental abundance calibration and TEMORA1 was analyzed for calibration of 206Pb/238U after every 3–4 analyses on unknowns. The measured 206Pb abundances were used for common lead correction. Data reduction was done using the SQUIF and ISOPLOT software (Ludwig, 2001, 2003). Errors on individual analysis are based on counting statistics and at 1σ (one standard deviation), whereas the pooled analyses are quoted at 2σ or 95% confidence level.

5. General petrography

Sample QX12118-6 is a fine-medium grained mafic granulate consists of hornblende (25–30%), plagioclase (18–20%), garnet (13–15%), clinopyroxene (13–15%), orthopyroxene (8–10%), quartz (3–5%), opaque minerals (3–5%, mainly magnetite and ilmenite) with accessory minerals including rutile, zircon, chlorite and epidote. The other samples have the same mineral assemblages, only with different phase proportions. According to the inclusion relationship and reaction textures of mineral phases, we have recognized three stages of metamorphism, as described below.

5.1. Pre-peak stage (M1)

The pre-peak metamorphism (Fig. 4A and B) is indicated by the core of porphyroblast of garnet and its mineral inclusions, which comprise rutile (Rt), clinopyroxene (Cpx), plagioclase (Pl), quartz (Qtz), ilmenite (Ilm) with or without epidote (Ep). The inclusion minerals are usually tiny with length smaller than 50 μm. Rutile is sometimes associated with ilmenite (Fig. 4A). The composite inclusion of clinopyroxene and plagioclase is also observed (Fig. 4B). The core of garnet is regarded as growing in equilibrium with these inclusion minerals.

5.2. Peak stage (M2)

The fine- to medium-grained matrix minerals represent the peak stage metamorphism, including rim or mantle of garnet porphyroblast, matrix plagioclase (Plm), clinopyroxene (Cpxm) and quartz (Qtzm). Minor fine-grained rutile (Rtm) is also observed in association with these minerals. The rim or mantle of garnet porphyroblast is inclusion-free (Fig. 4B) and the boundary of garnet grains are always embayed indicating later modification of the grain. Anhedral matrix plagioclase and clinopyroxene grains have sizes from ca. 100 to 1000 μm, whereas anhedral quartz grains are smaller. The peak mineral assemblage is the same as other typical high-pressure mafic granulites (Green and Ringwood, 1967; O'Brien and Rötzer, 2003; O'Brien, 2008; Liu et al., 2010; Tam et al., 2012b).

5.3. Post-peak stage (M3)

The post-peak metamorphism is indicated by the reaction or breakdown of the peak metamorphic minerals. The typical reaction during retrograde metamorphism is the breakdown of garnet in the presence of quartz with or without matrix clinopyroxene and O₂ into symplectite of plagioclase and clinopyroxene or orthopyroxene through the following reactions (Harley, 1989; Carswell and O'Brien, 1993; Zhao et al., 2001; Guo et al., 2002; O'Brien, 2008):

\[
\text{garnet + clinopyroxene} + \text{quartz} + \text{O}_2 \rightarrow \text{orthopyroxene} + \text{plagioclase} + \text{magnetite}
\]  

\[
\text{garnet + quartz} + \text{O}_2 \rightarrow \text{orthopyroxene} + \text{plagioclase} + \text{magnetite}
\]  

\[
\text{garnet + orthopyroxene} + \text{plagioclase}
\]

In the case of the Hexikouan mafic granulate in this study, the symplectites of clinopyroxene (Cpxm) + plagioclase (Plm) and clinopyroxene (Cpxm) + orthopyroxene (Opxm) + plagioclase (Plm) surround garnet grain, forming a typical “white eye” texture (Fig. 4C and D). This reaction texture was regarded as the record of the post-peak metamorphism with an isothermal decompression. Matrix orthopyroxene (Opxm) also occurs as anhedral grains but their sizes are smaller than Cpxm. The Opxm grains are closely associated with the symplectite or corona surrounding the relic garnet grains and are regarded as post-peak stage mineral. Aside from the Cpxm + Opxm + Plm, the symplectite of hornblende (Hbm) and plagioclase (Plm) also surrounds some garnet grains. The Hbm + Plm symplectite may directly touch the garnet grain (Fig. 4D, E and F, left grain) or together with Cpxm + Plm (Fig. 4D, C). Some garnet grains are surrounded by plagioclase corona (Plm) with small grains of hornblende inside (Fig. 4E and F, middle and right grain). Hornblende also occurs as anhedral to subhedral matrix grains (Hbm) in pyroxene-free domain. Furthermore, exsolution of plagioclase lamella (Plm) is also very common in the matrix clinopyroxene (Fig. 4C), probably resulting from breakdown of Al-rich clinopyroxene after the peak metamorphism.

It is noticed that, in certain domains of the same thin section, clinopyroxene and orthopyroxene are absent (Fig. 4C); only matrix garnet, hornblende and plagioclase with minor quartz are present. Minor chlorite (Chl) is also found to intercept hornblende grains. This mineral assemblage is the same as the examined portion of sample S1205 (Fig. 4H). However, this sample is slightly weathered, and garnet is surrounded by dirty rims of clay minerals, suggesting a breakdown of garnet to symplectite or corona (Fig. 4H).

6. Mineral chemistry

In response to the well represented mineral assemblages and reaction textures, we examined the mineral chemistry using the same thin section of sample QX12118-6.

6.1. Garnet (Table 1)

Based on the textural characteristics, garnet could be divided into an inclusion-bearing core domain and an inclusion-free mantle domain. The chemical compositions of three garnet grains are shown in Table 1. In some grains, rim shows a composition different from the mantle (Table 1, grain A). All the examined garnet grains are dominated by the almandine component (XAlm = 0.50–0.62) with minor grossular (XGrs = 0.14–0.28) and pyrope (XPrp = 0.16–0.2). The contents of andradite (XAdr = 0.0–0.06) and spessartine (XSp = 0.004–0.01) are rather low. Most garnet grains are characterized by weak compositional zoning which indicates that the grains have been homogenized during the peak metamorphism. However, some grains show a significant compositional change from core through mantle to rim. For example, the core of grain A in Table 1 is characterized by an increase in the content of grossular and pyrope and a decrease in almandine from core to mantle. This indicates that the composition of the mantle domain corresponds to the peak metamorphism, whereas the core survived and maintained its composition of the pre-peak stage. Furthermore, this grain also
Fig. 4. Representative microphotos and backscattered electron (BSE) images of samples QX12118-6 (A–G) and S1205 (H). A. BSE image showing rutile inclusion inside a garnet porphyroblast which is surrounded by symplectite of clinopyroxene and plagioclase. B. BSE image showing inclusions of quartz and clinopyroxene inside a garnet grain which is surrounded by corona of plagioclase; bar a–b marks the analytical line for the chemical composition of garnet grain with the results showing in Fig. 5; red dashed line marks the core-mantle boundary of the garnet grain. C. Polarized image showing the typical mineral assemblages and the symplectite surrounding garnet (“white eye”). D. Polarized image showing the detail of the symplectite surrounding garnet from Fig. 4C. E. Polarized image showing garnet grains surrounded by corona of plagioclase; one relic garnet almost retrograded into plagioclase and hornblende (garnet pseudomorph). F. Same as Fig. 4E, cross nicols. G. Polarized image showing pyroxene-free domain which is consists of matrix garnet, hornblende and plagioclase. H. Microphoto showing similar mineral assemblages of the sample S1205 to the pyroxene-free domain of sample QX12118-6; possible corona surrounding the garnet is present; cross nicols. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Table 1
Chemical composition of representative garnet in association with texture by EPMA. The calculation of garnet end members and composition are: XAdr = Fe$^{3+}$/2; XGrs = (Ca − 3 × XAdr)/(Fe$^{3+}$ + Mn + Mg + Ca); XAlm = Fe$^{2+}$/(Fe$^{2+}$ + Mn + Mg + Ca); XPrp = Mg/(Fe$^{3+}$ + Mn + Mg + Ca); XSps = Mn/(Fe$^{3+}$ + Mn + Mg + Ca); XFe = Fe$^{2+}$/ (Fe$^{2+}$/Mg).

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<td>1.623</td>
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<tr>
<td>Mg</td>
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<td>0.804</td>
<td>0.595</td>
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<td>0.003</td>
<td>0.003</td>
<td>0.003</td>
<td>0.003</td>
<td>0.003</td>
<td>0.003</td>
<td>0.003</td>
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<tr>
<td>Zn</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
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<td>8.000</td>
<td>8.001</td>
<td>8.001</td>
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<td>XAdr</td>
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<td>0.045</td>
<td>0.038</td>
<td>0.058</td>
<td>0.061</td>
<td>0.05</td>
<td>0.003</td>
<td>0.009</td>
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<tr>
<td>XGrs</td>
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<td>0.244</td>
<td>0.234</td>
<td>0.143</td>
<td>0.222</td>
<td>0.282</td>
<td>0.277</td>
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<td>XAlm</td>
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<td>0.506</td>
<td>0.528</td>
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<td>0.515</td>
<td>0.535</td>
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<tr>
<td>XPrp</td>
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<td>0.197</td>
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<td>XFe</td>
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<td>0.728</td>
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</table>

Fig. 5. Compositional zoning of the garnet grain on Fig. 4B. Calculation formula of the garnet end members is given in Table 1.

Table 2
Chemical composition of representative plagioclase in association with texture by EPMA. The calculation of plagioclase end members and composition are: An = (Ca / (Ca + Na + K)) × 100; Ab = (Na / (Ca + Na + K)) × 100; Or = (K / (Ca + Na + K)) × 100.

<table>
<thead>
<tr>
<th>Texture</th>
<th>I</th>
<th>M-rim</th>
<th>M-core</th>
<th>S-Hb</th>
<th>S-Cpx</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>52.85</td>
<td>54.85</td>
<td>57.93</td>
<td>58.03</td>
<td>49.18</td>
</tr>
<tr>
<td>TiO$_2$</td>
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<td>0.03</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
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<td>28.75</td>
<td>25.88</td>
<td>25.73</td>
<td>31.04</td>
</tr>
<tr>
<td>Cr$_2$O$_3$</td>
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<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>0.02</td>
</tr>
<tr>
<td>FeO</td>
<td>0.13</td>
<td>0.30</td>
<td>0.40</td>
<td>0.39</td>
<td>0.18</td>
</tr>
<tr>
<td>MnO</td>
<td>0.00</td>
<td>0.00</td>
<td>0.06</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>MgO</td>
<td>0.01</td>
<td>0.02</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>CaO</td>
<td>12.37</td>
<td>10.68</td>
<td>8.34</td>
<td>8.60</td>
<td>15.76</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>4.45</td>
<td>5.32</td>
<td>6.85</td>
<td>6.67</td>
<td>4.99</td>
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<tr>
<td>K$_2$O</td>
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<td>0.04</td>
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<tr>
<td>ZnO</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total cation</td>
<td>99.73</td>
<td>99.99</td>
<td>99.57</td>
<td>99.53</td>
<td>98.66</td>
</tr>
<tr>
<td>An</td>
<td>61</td>
<td>53</td>
<td>40</td>
<td>41</td>
<td>78</td>
</tr>
<tr>
<td>Ab</td>
<td>39</td>
<td>47</td>
<td>60</td>
<td>58</td>
<td>22</td>
</tr>
<tr>
<td>Or</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Note: S and M mean symplectite and matrix in texture respectively.
shows outward decrease in grossular and pyrope and increase in almandine, suggesting the composition is in association with the production of the neighboring symplectite of clinopyroxene and plagioclase. A cross-section EPMA analysis was performed on the garnet grain B (Fig. 4B). The result shows a similar trend as in garnet grain A (Fig. 5).

6.2. Plagioclase (Table 2)

The plagioclase could be divided into four groups as: (1) inclusion inside the garnet core (Pl i), (2) matrix grain (Pl m), (3) symplectite plagioclase with clinopyroxene (Pls), and (4) plagioclase lamella inside the clinopyroxene (Pl L). The inclusion plagioclase shows a medium An content (61). The core of matrix plagioclase has the lowest content of An (40) and its rim is slightly rich in An (53). The symplectite plagioclase has the highest content of An and that associated with hornblende has even higher An (78) content than that with clinopyroxene (66).

6.3. Clinopyroxene (Table 3)

Similar to garnet and plagioclase, the clinopyroxene could also be divided into three groups according to their textures: (1) inclusion inside the core of garnet (Cpx i), (2) matrix grain (Cpxm), and (3) symplectite clinopyroxene with plagioclase (Cpxs). Note that clinopyroxene is known to be more Al-rich with increasing metatmagraphic pressure (Anovitz, 1991; Liu et al., 2010; Tam et al., 2012b). The core of matrix clinopyroxene has the highest Al content, up to 2.38 wt.%, whereas the rim has 1.32 wt.%. The symplectite clinopyroxene of this study also shows a strong textural relevance with different textures (Liu et al., 2010; Tam et al., 2012a,b). The clinopyroxene of this study also shows a strong textural relevance (Table 3). They have FeO contents ranging from 8.97 to 12.88 wt.% and XMg from 0.594 to 0.725.

6.4. Orthopyroxene (Table 4)

Orthopyroxene occurs as matrix mineral (Opx m) in association with hornblende and clinopyroxene, and as symplectite (Opx s) with plagioclase and clinopyroxene. In both cases, it is a product of garnet breakdown during the post-peak metamorphism. No significant compositional difference between the two types of orthopyroxene has

---

Table 3

<table>
<thead>
<tr>
<th>Cpx</th>
<th>I</th>
<th>M-core</th>
<th>M-core</th>
<th>M-rim</th>
<th>M-rim</th>
<th>S</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>52.70</td>
<td>51.66</td>
<td>51.96</td>
<td>53.37</td>
<td>51.90</td>
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<td>53.95</td>
</tr>
<tr>
<td>TiO2</td>
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<td>0.24</td>
<td>0.20</td>
<td>0.12</td>
<td>0.19</td>
<td>0.14</td>
<td>0.03</td>
</tr>
<tr>
<td>Al2O3</td>
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<td>2.39</td>
<td>1.82</td>
<td>1.32</td>
<td>1.62</td>
<td>1.73</td>
<td>0.83</td>
</tr>
<tr>
<td>Cr2O3</td>
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<td>0.00</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.06</td>
<td>0.03</td>
</tr>
<tr>
<td>FeO</td>
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<td>11.10</td>
<td>10.86</td>
<td>8.97</td>
<td>12.88</td>
<td>10.63</td>
<td>9.79</td>
</tr>
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<td>MnO</td>
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<td>0.12</td>
<td>0.10</td>
<td>0.10</td>
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<td>MgO</td>
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<td>22.32</td>
<td>22.34</td>
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<td>0.36</td>
<td>0.32</td>
<td>0.36</td>
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<tr>
<td>K2O</td>
<td>0.00</td>
<td>0.06</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>ZnO</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
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<td>98.41</td>
<td>99.95</td>
<td>99.72</td>
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<table>
<thead>
<tr>
<th>Texture</th>
<th>M</th>
<th>M</th>
<th>S</th>
<th>S</th>
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<tbody>
<tr>
<td>Total cation</td>
<td>5.16</td>
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<td>5.58</td>
<td>5.77</td>
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<tr>
<td>XMg</td>
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<td>0.49</td>
<td>0.46</td>
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Note: I, S and M mean inclusion, symplectite and matrix in texture respectively.

---

Table 4

<table>
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<th>Texture</th>
<th>M</th>
<th>M</th>
<th>S</th>
<th>S</th>
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<tbody>
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<td>51.58</td>
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<td>Na2O</td>
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<td>0.00</td>
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<td>100.47</td>
<td>101.34</td>
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</table>

Note: S and M mean symplectite and matrix in texture respectively.
been discerned (Table 4). All analyzed orthopyroxene grains have the X_{Mg} values from 0.494 to 0.537 and X_{Fe} values from 0.463 to 0.506.

6.5. Hornblende (Table 5)

Similar to orthopyroxene, hornblende could also be divided into two types: (1) symplectite hornblende (Hb_s) in association with plagioclase and clinopyroxene, and (2) matrix grains (Hb_m). The two types do not show a significant difference in composition. However, a single symplectite hornblende with plagioclase shows a drop in Ti content similar to orthopyroxene, hornblende shows a drop in Ti content

<table>
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<tr>
<th>Amp</th>
<th>S–Pl–Cpx</th>
<th>M</th>
<th>S–Pl–M</th>
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</thead>
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<td>SiO_2</td>
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<tr>
<td>TiO_2</td>
<td>1.37</td>
<td>1.69</td>
<td>1.37</td>
</tr>
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<td>Al_2O_3</td>
<td>11.88</td>
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</tr>
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<td>11.46</td>
</tr>
<tr>
<td>Na_2O</td>
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<td>K_2O</td>
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<td>0.54</td>
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<td>ZnO</td>
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<td>0.00</td>
</tr>
<tr>
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<td>97.37</td>
<td>96.81</td>
</tr>
<tr>
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<td>23</td>
<td>23</td>
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</tr>
<tr>
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<td>1.533</td>
</tr>
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</tr>
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<td>0.000</td>
<td>0.002</td>
</tr>
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<tr>
<td>Mg</td>
<td>2.167</td>
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</tr>
<tr>
<td>Ca</td>
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<td>1.841</td>
</tr>
<tr>
<td>Na</td>
<td>0.644</td>
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</tr>
<tr>
<td>K</td>
<td>0.105</td>
<td>0.122</td>
<td>0.103</td>
</tr>
<tr>
<td>Zn</td>
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<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Total cation</td>
<td>95.36</td>
<td>97.37</td>
<td>96.81</td>
</tr>
<tr>
<td>X_{Mg}</td>
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<td>0.563</td>
</tr>
<tr>
<td>X_{Fe}</td>
<td>0.470</td>
<td>0.448</td>
<td>0.437</td>
</tr>
</tbody>
</table>

Note: S and M mean symplectite and matrix in texture respectively.

have shown that the clinopyroxene + plagioclase symplectite surrounding the garnet rim has recorded a P–T condition of ~8.7 kbar and ~760 °C. The application of the Grt–Cpx–Pl–Q thermobarometry of Bhattacharya et al. (1991) yielded a result of ~8.7 kbar and ~690 °C whereas the Grt–Hb–Pl–Q thermobarometry of Dale et al. (2000) and Holland and Blundy (1994) gave a result of ~7.8 kbar and ~780 °C.

7.2. Pseudosection modeling

Unlike the conventional geothermobarometry, P–T pseudosection modeling is employed to construct the stable mineral assemblages at a certain P–T condition with a given bulk-rock composition (Holland and Powell, 1998; Powell and Holland, 1998; White et al., 2001, 2003; Clark and Hand, 2010). Here we chose the same sample, QX12118-6, for the pseudosection modeling because its mineral assemblages and reaction textures are well presented. The bulk chemical composition of the sample QX12118-6 is shown below.

The fluid phase was regarded as pure water and set to be in excess. The bulk composition in wt.% was then recalculated to mol% as SiO_2 = 45.06, Al_2O_3 = 16.11, CaO = 11.23, MgO = 6.35, FeO = 3.12, FeO = 12.38, Na_2O = 2.07, TiO_2 = 1.65, K_2O = 0.35, MnO = 0.26 (total = 98.75). The system NCFMASHTO (Na_2O–CaO–FeO–MgO–Al_2O_3–SiO_2–H_2O–TiO_2–O) was chosen because K_2O and MnO are very minor components. Melt is also ignored due to the presence of hornblende (Poli and Schmidt, 2002).

The pseudosection modeling was carried out using THERMOCALC 3.33 (Powell et al., 1998) with the internal thermodynamic data set, tcds55.txt (Holland and Powell, 1998). The phases considered in the calculation included: garnet (G), plagioclase (Pl), clinopyroxene (shown as diopside; Di), hornblende (Db), ilmenite (Ilm), rutile (Rut), magnete (Mt), epidote (Ep), quartz (Q) and pure water (H_2O). Among these phases, rutile, quartz and pure water are considered as pure end-member phases. The activity–composition (a–x) models for garnet are from White et al. (2007), plagioclase from Holland and Powell (2003), clinopyroxene from Green et al. (2007), orthopyroxene from White et al. (2002), hornblende from Diener et al. (2007), ilmenite and magnetite from White et al. (2000), and epidote from Holland and Powell (1998).

The calculated P–T pseudosection of the sample within the P–T range of 6–18 kbar and 650–950 °C is shown in Fig. 6, in which the results of conventional geothermobarometry for the pre-peak, peak and post-peak metamorphic conditions are also shown. The pseudosection is dominated by fields with variance of 3 to 5; only two fields with variance of 2 are shown. The clinopyroxene (as di) and pure water are stable in all the fields. The garnet-out line is nearly horizontal at
The peak metamorphic mineral assemblages correspond to the stability field of HB–Di–Pl–Ep–Ru–G–Q–H₂O or Hb–Di–Pl–Ru–G–Q–H₂O. The Grt–Cpx–Pl–Q thermobarometry gave the conditions below the rutile-out line. This is controversial to the fact that rutile does occur as an inclusion phase of garnet. Therefore, we suggest that the recorded P–T conditions for the peak metamorphism is near the rutile-out line within the two fields mentioned above, even though they have relatively large P–T ranges.

The peak metamorphic mineral assemblages correspond to the stability field of Di–Pl–Ru–G–Q–H₂O at pressure of ~14.5 kbar and temperatures of ~800 °C. The P–T conditions for the stable peak assemblages in the pseucosection are broadly consistent with that calculated by the conventional geothermobarometry of Grt–Cpx–Pl–Q–H₂O. The post peak metamorphism is marked by (1) the breakdown of garnet into symplectite of clinopyroxene (Cpx₁) + plagioclase (Pl₁) ± orthopyroxene (Opx₁) ± hornblende (Hb), (2) the presence of matrix hornblende, ilmenite, magnetite and (3) the absence of rutile. Although it is not easy to identify the production of the symplectite of Cpx₁ + Pl₁ on the P–T pseudosection, the presence and absence of mineral phases indicate that the P–T conditions shifted toward lower pressure conditions crossing the ilmenite-in, hornblende-in, rutile-out, magnetite-in and orthopyroxene-in lines. The presence of quartz peaks indicate that the P–T conditions did not shift to the quartz-out line. The P–T path is also controlled by the results from the conventional geothermometry calculation (Grt–Cpx–Pl–Q and Grt–Hb–Pl–Q thermobarometry) although the calculated temperature is lower than indicated by the P–T pseudosection. However, the calculated P–T condition by using Grt–Opx–Pl–Q is not in agreement with the phase diagram in which the condition lies in the Opx-absent field. The complete breakdown of garnet into plagioclase + quartz indicates that the P–T path shifted into the garnet-absent fields when the metamorphic pressure and temperature further decreased.

7.3. P–T evolution

Integrating the results from the conventional geothermobarometry and pseudosection modeling, a clock-wise P–T path could be constructed (Fig. 6). The recorded P–T condition for the pre-peak mineral assemblages was ca. 10 kbar and 730 °C. With increasing pressure and temperature, the P–T path shifted into the stability field of G–Di–Pl–Q–Ru–H₂O, corresponding to the peak metamorphism at ~17 kbar and 880 °C. Subsequently, the P–T condition dropped along a near isothermal decompression path into the stability field of Q–Hb–Mt–Opx–Ilm–Pl–Di–G–H₂O at ca. 7.5 kbar and 800 °C. Finally, the P–T path crossed the garnet-out line with further decreasing pressure and temperature during the retrograde metamorphism.

8. Zircon geochronology

Zircon dating was performed on two samples (S1205 and S1207). The zircon grains show similar morphology (Fig. 7) and yielded identical ages (Fig. 8). A host gneissic trondhjemite sample (QX12117) was also dated. The “magmatic” zircon grains separated from the two samples have sizes from 80 to 250 μm, and length/width ratios of 4 to 1. Most grains display blurred planar zoning, suggesting partial to strong recrystallization during the high grade metamorphism (sample S1205, grain b and c). Some grains show light gray homogeneous overgrowth rims (sample S1205, grain a; sample S1207 grain c), but some individual grains have dark gray overgrowth rims (sample S1207, grain a). In addition, a few grains with core show oscillatory zoning (sample S1207, grain b), which is not common for zircon from mafic rocks. We suggest that these grains have probably been captured from TTG gneisses when the mafic rock intruded. Sample QX12117 has similar zircon grain sizes but different internal structure. Blurred oscillatory zoning with overgrowth are the main characteristics, indicating reworking of the magmatic zircon.

Seven spots were analyzed on six zircon grains for sample S1205. Four spots were made on the light gray recrystallized magmatic domains and two spots on the light gray overgrowth rims (Table 6). The zircon grains show low U content (27 to 61 ppm) and intermediate Th/U ratios (0.11–0.74). The four spots on the recrystallized magmatic domains, including 1.1RC, 2.1RC, 3.1RC and 4.1RC, yielded a mean 207Pb/206Pb age of 2531 ± 15 Ma (0.11MSWD). The four spots on the overgrowth rims, including 1.1RC, 2.1RC, 3.1RC and 4.1RC, yielded a mean 207Pb/206Pb age of 2488 ± 17 Ma (2.5MSWD). This is considered as the minimum age of the mafic intrusion. The other two spots on the overgrowth rims yielded similar ages of 2488 ± 17 Ma (1.2K and 2450 ± 26 Ma (6.1R). They are interpreted as the time of metamorphism.

For sample S1207, ten spots were analyzed on eight zircon grains; among them, six were on light gray magmatic domains and four on the light to dark gray overgrowth rims. The results are similar to sample S1205. The five spots on the “magmatic” cores (1.1RC, 2.1RC, 4.1RC, 5.1RC and 6.2RC) yielded a mean 207Pb/206Pb age of 2531 ± 15 Ma (MSWD = 1.7). The four analyses on the overgrowth rims (2.2K, 3.1R, 6.1R and 7.1K) yielded a mean 207Pb/206Pb age of 2474 ± 6 Ma (MSWD = 0.75).

Twenty two spots were analyzed on twenty one zircon grains of sample QX12117. The ten spots on “magmatic” cores (2.1RC, 5.1MA, 6.1MA, 7.1RC, 8.1MA, 9.1RC, 11.1RC, 15.1RC, 16.1RC and 21.1RC) yielded...
a mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2540 ± 8.3 Ma (MSWD = 1.7). The five spots on strongly recrystallized domain or overgrowth (1.1RC, 4.1R, 12.1RC, 19.1, 20.1R) gave metamorphic age of 2480 ± 11 Ma (MSWD = 2.1).

If the data of the two mafic granulites samples (S1205 and S1207) are combined (Fig. 8D), the nine spots on “magmatic” core yielded the mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2527 ± 19 Ma (MSWD = 1.9), which is interpreted as the lower limit of the mafic intrusive age. All the spots on the strongly recrystallized domain or overgrowth rim from the three samples yielded the mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2477 ± 5.5 Ma (MSWD = 1.6), which is regarded as the metamorphic age.

9. Discussion

9.1. P–T evolution of the high-pressure mafic granulites

The typical indicator of high-pressure granulite metamorphism in mafic rocks is the mineral assemblages of garnet + clinopyroxene + plagioclase and the reaction texture “white eye” produced by breakdown of garnet into the symplectite of clinopyroxene + plagioclase + orthopyroxene ± hornblende (Green and Ringwood, 1967; Guo et al., 1993; Zhao et al., 2001; O’Brien and Rötzl, 2003; O’Brien, 2008; Liu et al., 2010; Tam et al., 2012a,b). The mineral assemblages and reaction textures of the studied samples are the same as other high-pressure mafic granulites worldwide, so we assume that they have undergone high-pressure granulite facies metamorphism. In fact, this assumption has been confirmed by the mineral chemistry, conventional geothermobarometry and pseudosection modeling.

It has been noticed that in high-pressure mafic granulites, garnet becomes Ca-rich, plagioclase Na-rich and clinopyroxene Al-rich under high pressure conditions (Liu et al., 2010; Tam et al., 2012b). Earlier studies on mafic granulites from Jiaodong have shown that the grossular content in garnet at peak metamorphism is generally higher than 0.30 and reaching 0.38 (Liu et al., 2010; Tam et al., 2012b). In the present study, the grossular content is found to be slightly lower (up to 0.28; Table 1). Note also that the garnet compositions in different samples at peak metamorphism vary significantly, indicating that the mineral chemistry is also controlled by whole-rock composition (Liu et al., 2010). Since sample QX12118-6 has a bulk-rock CaO content lower than the sample studied by Tam et al. (2012b), the lower grossular content in our garnet may be explained by this bulk-rock effect. Similarly, the clinopyroxene of our samples has Al content up to 2.8 wt.% whereas that from late Paleoproterozoic samples has Al content up to 4.2 wt%. Likewise, the plagioclase of this study has Na content similar to that of Liu et al. (2010), which showed an Ab content of ~60, about 10 higher than the examples of Tam et al. (2012b). All the above shows the bulk-rock effect on mineral chemistry.

The application of the conventional geothermobarometry and pseudosection modeling further confirmed the high-pressure granulite metamorphism. Applying the Grt–Cpx thermometry (Ellis and Green, 1979) and Grt–Cpx–Pl–Q thermobarometry (Eckert et al., 1991), the highest P–T condition of ~17 Kbar and ~880 °C was calculated using the compositions from the mantle domain of a garnet grain and the core domains of a nearby plagioclase and clinopyroxene grain. However, the same mineral assemblage (Gt–Plag–Cpx) was also used to obtain the P–T condition using the Newton and Perkins’ (1982)
Grt–Cpx–Pl–Q thermobarometry. It yielded a similar temperature but a lower pressure at ~13 kbar. We chose the former because it was generally consistent with the results from the pseudosection modeling. This P–T condition reaches the eclogite facies metamorphism. However, as indicated by the mineral assemblages and pseudosection modeling, plagioclase is stable at the peak metamorphism.

A significant discrepancy between the results from the conventional geothermobarometry and pseudosection for pre-peak and post-peak metamorphism is also noticed. Especially, the results by the Grt–Opx–Pl–Qt thermobarometry (Bhattacharya et al., 1991) shifted away from the Opx-in fields toward lower temperatures in the pseudosection. This could be explained as follows. (1) the orthopyroxene selected for calculation might have not been in equilibrium with garnet and plagioclase, leading to an uncertainty in the result of the geothermobarometry; (2) the error of the results from the conventional geothermobarometry is large but not shown on the diagram (Liu et al., 2010); (3) although the MnO content is rather low in bulk chemistry, it could affect the stability of garnet; and (4) the “melt” phase was not considered during the construction of the P–T pseudosection due to the presence of hornblende (Poli and Schmidt, 2002). Besides, no mixing model is available for melt-bearing mafic rocks in the pseudosection (Tam et al., 2012b). However, this may lead to an error.

9.2. Timing of the high-pressure granulite metamorphism

The two mafic granulite samples used for zircon SHRIMP geochronology study are collected from exactly the same outcrop as the samples for the petrological study. Although the samples for the age study contain less clinopyroxene and orthopyroxene, they have both recorded the same metamorphism. It is also noticed that garnet grains are surrounded by a dirty rim in the slightly weathered sample S1205 (Fig. 4H), indicating the post-peak metamorphism was recorded. Thus, the results from zircon SHRIMP study might be the age of post-peak metamorphism.

Furthermore, both the high-pressure mafic granulite and surrounding TTG gneisses were not affected by the late-Paleoproterozoic metamorphism, which is broadly recorded in other areas of the Jiaodong Terrain. In another recent work, a ~2.9 Ga TTG gneiss was reported (Xie et al., under review) at the northern dam of the Hexikuang reservoir, about 100 m from the present study locality. The ~2.50 Ga metamorphic event was also recorded but the rock shows no evidence of the late Paleoproterozoic reworking. These authors discussed that
The dry metamorphic condition during late-Paleoproterozoic disfavored the recrystallization or re-growth of the zircon grains (Xie et al., under review). However, hydrous minerals, such as hornblende and chlorite, would be unstable in high-pressure granulite metamorphism. The breakdown of such minerals would result in hydrous fluids which would favor the re-growth of zircon grains. On the other hand, if these minerals were formed during late-Paleoproterozoic, the retrograde metamorphism would be related to fluid-rich conditions. This would also facilitate the zircon growth. Thus, the late-Paleoproterozoic metamorphic event should be well recorded in the zircon grains. In this case, we suggest that the proto-continent represented by the ~2.9 Ga rocks intruded into the TTG and then eclogite, a captured tectonic fragment, was probably a collisional process (Harley, 1989; Brown, 1993, 2001, 2007). However, it is alsoprobable that the mafic rocks and TTG formed contemporaneously because their similar magmatic ages.

9.3. Implications for the crustal evolution of the North China Craton at the end of Neoarchean

The tectono-thermal event at ~2.5 Ga of the North China Craton was characterized by the amalgamation of several micro-continental blocks and large scale crustal growth (Zhai and Santosh, 2011; Wan et al., 2012b). The Neoarchean greenstone belt records the remnants of the supposed sutures (Zhai et al., 2011).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Location</th>
<th>Grade</th>
<th>U content (ppm)</th>
<th>Th content (ppm)</th>
<th>Pb content (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1205-1.RC</td>
<td>0.32</td>
<td>73</td>
<td>0.12</td>
<td>31</td>
<td>0.1632</td>
</tr>
<tr>
<td>S1205-2.RC</td>
<td>0.77</td>
<td>51</td>
<td>0.11</td>
<td>21</td>
<td>0.1583</td>
</tr>
<tr>
<td>S1205-2.1RC</td>
<td>0.42</td>
<td>43</td>
<td>0.14</td>
<td>20</td>
<td>0.1609</td>
</tr>
<tr>
<td>S1205-3.RC</td>
<td>0.12</td>
<td>30</td>
<td>0.70</td>
<td>12</td>
<td>0.1669</td>
</tr>
<tr>
<td>S1205-4.1RC</td>
<td>0.01</td>
<td>72</td>
<td>0.11</td>
<td>17</td>
<td>0.1564</td>
</tr>
<tr>
<td>S1205-5.1R</td>
<td>0.31</td>
<td>64</td>
<td>0.03</td>
<td>3</td>
<td>0.1402</td>
</tr>
<tr>
<td>S1205-6.1R</td>
<td>0.51</td>
<td>61</td>
<td>0.10</td>
<td>24</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Note: (1) R, RC and MA refer to rim, recrystallization and magmatic domain of the zircon grains respectively. (2) Measured 204Pb was used for the common lead correction.
9.4. General implications for the crustal evolution

The high-pressure mafic granulites at the southern dam of the Heixiaowan reservoir might have been formed in an over-thickened continental crust (ca. 50 km) with a relatively low thermal gradient of ca. 19 °C/km; but this condition is known to be rare in the Archean. However, the difference between Archean and post-Archean crust has been noticed due to the dominating rock and metamorphic types (Brown, 2007a,b and references therein). The dominant TGT suite and metamorphism with uniformly high apparent thermal gradients indicate a higher thermal regime, whereas the appearance of paired HP rocks (eclogite to high-pressure granulite) and HT/HTU granulites in the Mesoarchean–Neoarchean time might signify the transition from double-sided to one-sided subduction (Sizova et al., 2010; Brown et al., 2013; Sizova et al., 2014). Numerical modeling also suggested a higher mantle heat flow and a greater radiogenic crustal heat production during the Archean, which is responsible for a weaker continental lithosphere and double-sided subduction (Sizova et al., 2010; 2014). The discovery of the high-pressure mafic granulites with peak P–T conditions up to ~17 kbar and 880 °C in the Jiaodong Terrain, may serve as an indicator of a global transition toward a cooler thermal regime and a thicker continental crust. In any case, the present study provides a new and rare case of subduction–collision tectonic setting at the boundary of Archean and Proterozoic.

10. Conclusion

(1) An unusual late Archean high-pressure mafic granulite was discovered in the Qixia area of the Jiaodong Terrain. The diagnostic mineral assemblage is garnet + clinopyroxene + plagioclase + quartz ± rutile. Application of the conventional geothermo-barometry and pseudosection modeling revealed a clockwise P–T path with the peak metamorphic condition at $P = 17$ kbar and $T = 880$ °C. (2) SHRIMP U–Pb analyses on the overgrowth rim of the zircon grains yielded a metamorphic age of ca. 2.47 Ga. Analyses on recrystallized magmatic cores gave a minimum magmatic age of ~2.53 Ga. (3) The high-pressure mafic granulites have probably recorded a highly significant collisional event at the end of Archean. The occurrence of the granulites may serve as an indicator of a global transition toward a cooler thermal regime and a thicker continental crust.

Acknowledgment

We thank Prof. Shuwen Liu and M. Santosh for constructive comments. Guangshen Ni, Baoying Zheng, and Siyu Zheng performed zircon separation, Chun Yang and Weilin Gan made the zircon mounts, and Guangshen Ni, Baoying Zheng, and Siyu Zheng performed zircon analyses on the overgrowth rim of the zircon.

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Please cite this article as: Liu, S., et al., Neoproterozoic high-pressure mafic granulite from the Jiaodong Terrain, North China Craton: Petrology, zircon age determination and geological implications, Gondwana Research (2014), http://dx.doi.org/10.1016/j.gr.2014.07.006.