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Short Communication

Petrologic indicators of prograde metamorphism in Paleoproterozoic garnet mafic granulites from the Huai'an complex, North China Craton

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Reconstruction of pressure-temperature-time (*P-T-t*) paths and thermal regimes are essential for inferring tectono-metamorphic processes involved in the formation of metamorphic terranes. However, the *P-T* information, especially the prograde evolution is generally preserved incompletely due to the fast intra- or inter-grains diffusion under high-temperatures. It may result in different *P-T* path styles (e.g., clockwise or counter-clockwise), consequently leading to variable interpretations on the related petrogenetic processes.

Precambrain high-pressure (H*P*) granulites play a critical role in understanding the tectonic processes involved in the lower crust and reconstruction of plate tectonics during early earth history. As such, the Paleoproterozoic garnet mafic granulites (also named mafic H*P* granulites in some literature [1]) from the Huai'an complex offer important constraints on tectonic evolution of the North China Craton (NCC) [2–6]. For their *P-T* evolution history, a consensus has been reached that they experience a near isothermal decompression (ITD) *P-T* path since peak metamorphic stage [1–4]. However, it is still an open issue whether or not they undergo a prograde metamorphism due to lack of robust petrologic evidence [2]. In this study, petrogenetic indicators from microstructure, variations of mineral composition, and phase equilibrium constraints suggest that the garnet mafic granulites from the Huai'an complex have suffered a prograde metamorphism.

The Huai'an complex in north-central part of the NCC, mainly comprises of the Neoarchean tronhjemitic, tonalitic, granitic (TTG) and dioritic gneisses with subordinate supracrustal volcanic-sedimentary rocks, Paleoproterozoic granitic gneiss, garnet mafic granulites, and khondalite series, etc. [4,5] (Fig. 1a, b). Zircon ages indicate that the TTG gneisses were mainly formed during ~2550–2450 Ma ago, and invaded by the Paleoproterozoic granitic gneisses at ~2350 Ma, ~2150–2200, ~2050 Ma, respectively [5,6]. The garnet mafic granulites are widely outcropped as lenses or dismembered dykes in the TTG gneisses or khondalite series, such as in Manjinggou, Liugou, Xiwangshan, Huangtuyao, Gushan and Sifangdun (Fig. 1b). The mineral assemblages of these mafic granulites are mainly of garnet – clinopyroxene – plagioclase – quartz ± rutile, with *P-T* conditions of 10–15 kbar/750–900 °C [1–4]. Some khondalite series rocks occurred as survival rafts in the Huai'an TTG gniesses (Fig. 1b), are dominated by pelitic granulites, with minor semi-pelitic gneisses, quartzites, marbles and graphite-bearing gneisses. The garnet mafic granulites and the khondalite series are spatially associated in places, and were considered to be different tectonic slabs juxtaposed together by tectonic mélange or nappes with the assumption that these rocks had distinct metamorphic histories [5,6,8,9]. By contrast, recent studies revealed that the pelitic granulites record comparable peak metamorphic conditions with the associated garnet mafic granulites [7,10]. The metamorphic zircon ages of various granulite-facies lithologies from the Huai'an complex were dated with wide range of ~1970–1790 Ma, which can be divided into at least two periods of ~1970–1900 Ma and ~1880–1790 Ma, although the formation ages and tectonic affinities of their protoliths are different [2,11,12] (unpublished data). In combination with recent structural analysis, metamorphism and geochronology, it suggests the various Paleoproterozoic granulites from the Huai'an complex have common metamorphic histories since peak metamorphic stage

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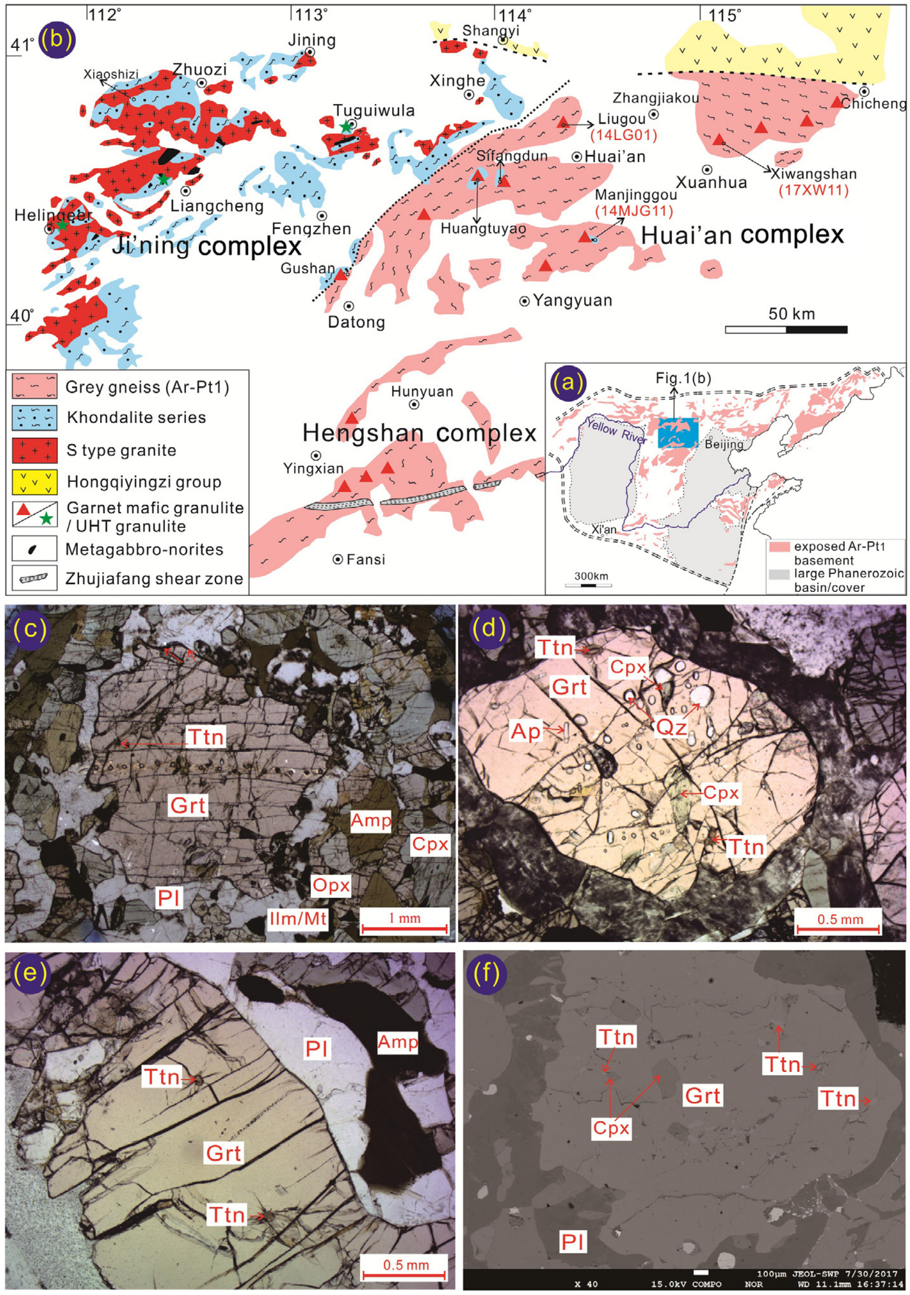

Fig. 1. Geological map of the north-central NCC and representative microphotographs of the investigated samples. (a) Distribution of Early Precambrain rocks in the NCC (modified after [7]), (b) Regional geological sketch map of the Huai'an complex and adjacent area (modifed after [4]), (c–f) Microphotographs of the garnet mafic granulites from the Huai'an complex: sample 14MJG11 (c), sample 14LG01 (d), sample 17XW11(e) and sample 14MJG11(f). Amp, amphibole; Ap, apitite; Cpx, clinopyroxene;Grt, garnet; Ilm, ilmenite; Mt, magnetite; Opx, orthopyroxene; Pl, plagioclase; Qz, quartz; Ttn, titanite.

[2,7,10–12]. Previous studies suggest that the garnet mafic granulites documented a *HP* granulite-facies stage, followed by medium-pressure to low-pressure granulite-facies and then amphibolite-facies retrogression, defined a near isothermal decompression (I*T*D) and a near isobaric cooling (IBC) *P-T* segment, though it is still argued for a prograde metamorphism [1–4,13].

Three representative samples as lenses or dismmebered dykes in the TTG gneisses were collected from the Huai'an complex. Sample 14MJG11 from Manjinggou area, 17XW11 from Xiwangshan, and 14LG01 from Liugou area in the Huai'an complex were selected (Fig. 1b). The mineral assemblages of all samples mainly consist of garnet (25%–40%), clinopyroxene (20%–35%), plagioclase (15%–25%), orthopyroxene (5%–8%), amphibole (~5%), with minor quartz, rutile, titanite, ilmenite and magnetite. The garnets developed well corona of plagioclase, orthopyroxene/amphibole and ilmenite/magnetite (Fig. 1c–f). If a spherical morphology of garnet is assumed, ~20 vol%–60 vol% of garnet grains are consumed. Quartz, clinopyroxene, plagioclase, rutile, apitite, titanite are observed as inclusions in garnet. Orthopyroxene is separated from garnet by plagioclase moat, and is adjacent to clinopyroxene porphyroblast. Amphibole often occurs as symplectite together with plagioclase, sometimes as flake in clinopyroxene. In local domains, garnet grains have two corona/symplectite layers, with an inner amphibole-plagioclase layer separating an orthopyroxene-plagioclase layer from embayed garnets. It suggests that the *P-T* vector witnessed by the mafic granulites have sequentially crossed the

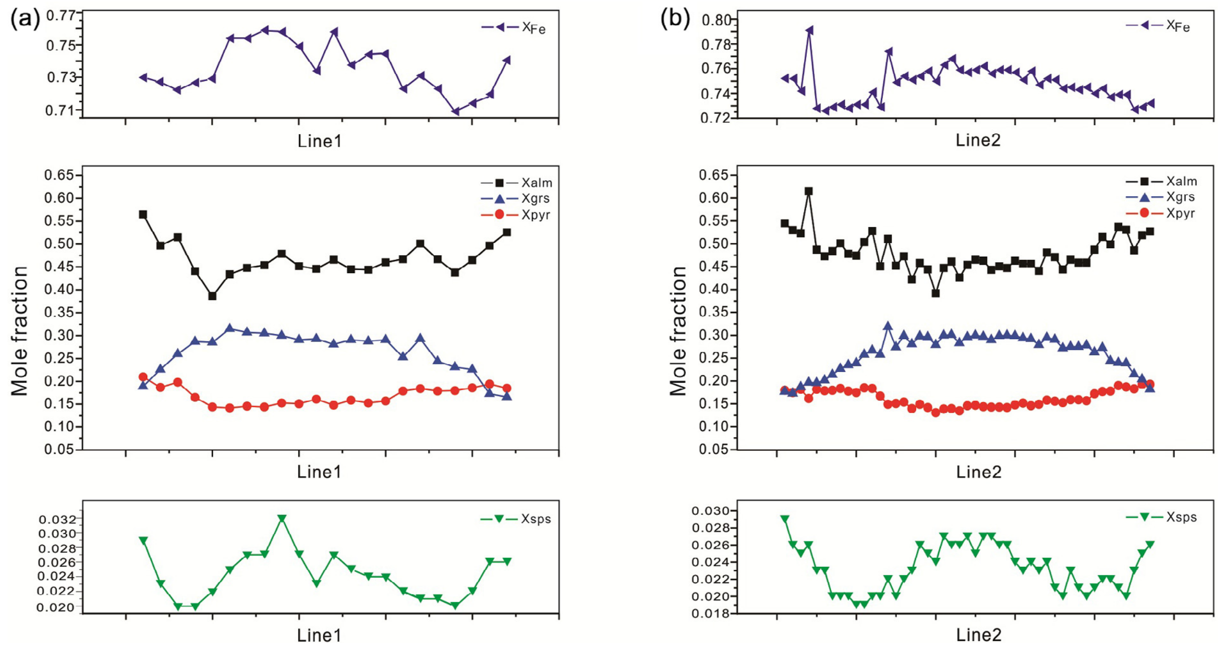

Fig. 2. Two representative composition profiles of garnet from sample 14MJG11 (a–b).

reaction lines of garnet breakdown into orthopyroxene-plagioclase and then to amphibole-plagioclase in *P-T* space.

It is known that porphyroblastic garnets often protect some earlier generation minerals from subsequently metamorphic overprint. Many mineral inclusions are observed in some garnet porphrobalsts from our samples, including quartz, clinopyroxene, apitite, rutile, ilmenite and titanite. Among them, the titanite and high-Al_2O_3 clinopyroxene probably can be used as *P-T* indicators, which mainly occur as inclusion-type minerals within the garnet grains, and few titanite grains in the coronary textures, but none of them can be observed in the matrix. It suggests that the inclusion-type minerals present here are probably other (earlier) generation minerals different from those in the matrix. To test this speculation, mineral chemistry is combined for discussions as follow.

Representative mineral compositions of sample 14MJG11 are listed in Table S1. Garnets exhibit obvious composition zoning, and two representative composition profiles were shown in Fig. 2a and b. The compositions of garnet are dominated by $X_{alm} = Fe^{2+}/(Ca + Fe^{2+} + Mg + Mn)$, $X_{grs} = Ca/(Ca + Fe^{2+} + Mg + Mn)$, and $X_{pyr} = Mg/(Ca + Fe^{2+} + Mg + Mn)$, with minor $X_{sps} = Mn/(Ca + Fe^{2+} + Mg + Mn)$. The X_{sps} displays well-preserved 'bell-shaped' from the core (~0.032–0.027) to mantle (~0.019–0.022), with a rimward resportion (~0.026–0.029) in the rim. The X_{grs} exhibits rimward decreasing trend (X_{grs}=0.30 → 0.17), while the X_{alm} (0.45 → 0.57) and X_{pyr} (0.15 → 0.21) display rimward increasing trend. The Fe# index [$=Fe^{2+}/(Fe^{2+}+Mg)$] exhibits similar trend with X_{sps}, accompanying with Fe# decreased from core (~0.76) to mantle (~0.71), and increased towards the rim (~0.73–0.75). The 'bell-shaped' X_{sps} profiles from garnet core to mantle suggest that these domains should represent original growth zoning with relatively insignificant diffusion relaxation; correspondingly, the symmetric, increasing X_{pyr}, X_{alm} and complementary decreasing Fe# profiles probably suggest these garnet domains grow continuously with increasing temperature. While the composition patterns near the garnet reaction rims are interpreted as reworked zoning by strong resorption.

The Al_2O_3 content of clinopyroxene could be useful *P-T* indicator during metamorphic evolution for granulite terranes due to its sluggish diffusion rate [14]. Here, the two occurrences of clinopyroxene exhibit contrasting Al_2O_3 concentrations. The clinopyroxene inclusions have relatively high Al_2O_3 (5.41 wt%–6.45 wt%), TiO_2 (1.20 wt%–1.34 wt%) and X_{Mg} (0.71–0.73), in contrast, the clinopyroxene porphyroblasts in matrix display low Al_2O_3 (2.95 wt%–3.58 wt%), TiO_2 (<0.4 wt%) and X_{Mg} (0.57–0.66). The latter is considered to be formed at peak metamorphic stage, and hence the former is probably the earlier clinopyroxenes before peak metamorphism or relic igneous precursor (discussion in another paper). This speculation can be confirmed by another two lines of evidence: (1) some clinopyroxene inclusions directly contact with titanite within garnet core and mantle, (2) the estimated temperatures are approximately of ~700 ± 50 °C (if *P* is assumed at ~10 kbar) using Fe-Mg exchange thermometer between inclusion-type clinopyroxene and the adjacent garnet, which are lower than the calculated peak metamorphic conditions (~10–15 kbar/750–900 °C) [1–4]. Titanite composition is relatively homogenous. A preliminary phase equilibrium modelling for sample 14MJG11 suggests that titanite appears in the *P-T* range of T < 820 °C, P = ~8–14 kbar (Fig. S1).

Based on above microstructures and mineral compositions of the investigated samples, four metamorphic generations (M_1–M_4) are inferred. M_1 is featured by inclusion-type mineral assemblage in garnet, which is absent in matrix, indicative of an early generation, namely garnet core-titanite-clinopyroxene-quartz ± plagioclase ± amphibole ± ilmenite ± rutile. M_2 is characterized of porphyroblastic minerals in matrix, such as garnet-clinopyroxene-plagioclase ± rutile ± quartz ± amphibole ± ilmenite. M_3 is represented by corona/symplectite-type orthopyroxene-plagioclase-amphibole ± ilmenite ± magnetite, and M_4 is composed of amphibole-plagioclase symplectite around embayed garnet. The defined M_2 to M_4 can correspond well to the mineral assemblages of peak metamorphism (H*P* granulite-facies), retrograde moderate- to low-pressure granulite-facies and amphibolite-facies stages in previous studies, respectively [1–4]. The four generation assemblages together define a clockwise *P-T* loop (Fig. S1).

This study suggests that the Paleoproterozoic garnet mafic granulites probably experienced a prograde metamorphism, characterized by slightly increased pressure, and prominently elevated temperature, which is comparable to the prograde *P-T* vectors from the associated pelitic granulites from Datong-Huai'an area [7,10]. The estimated apparent thermal gradients vary in the range of ~16–25 °C/km for these granulite-facies rocks from the study area [2,7,10]. Taken together with the peak metamorphic conditions, we propose that the Paleoproterozoic granulites from the Huai'an complex are probably formed within a crustal-scale tectonic regime, instead of cold and deep subduction regime involved in the Phanerozoic H*P*-UH*P* metamorphic terranes [2,7,10].

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.scib.2017.12.017.

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