Long-lived (>100 Myr) post-collision exhumation and cooling in the Paleoproterozoic Trans-North China Orogen: Evidence from phase equilibria modeling and monazite petrochronology of granulite-facies metapelites in the Fuping Complex

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ABSTRACT

Long-lived collisional orogens that formed over tens to hundreds of millions of years are common in the geological record. The Trans-North China Orogen (TNCO) marks the collision between the Eastern and Western Blocks of the North China Craton, and preserves metamorphic rocks with ages between 1.98 Ga and 1.80 Ga. These units allow detailed assessment of the timescale and duration of crustal thickening, exhumation and cooling associated with a major Proterozoic orogeny. In this study, we present integrated petrography, mineral chemistry, phase equilibria modeling and texturally controlled in situ LA-ICP-MS monazite U-Th-Pb and trace element analyses performed on a suite of orthopyroxene-bearing pelitic granulites and garnet-biotite gneisses from the Fuping Complex within the TNCO. These rocks record clockwise pressure-temperature (P-T) paths involving granulite-facies peak conditions of 9.9-11.0 kbar and 850-880 °C for pelitic granulites, and 10.9-11.6 kbar and 860-880 °C for garnet-biotite gneisses, followed by post-peak decompression to ca. 8-9 kbar and later cooling, with final solidification of melt at <840 °C. Four monazite populations are identified in these samples. Group I grains are irregular and elongated, and occur in contact with or embay garnet. They have high REE and Y contents and metamorphic ages of 1.90-1.86 Ga, which correspond to the breakdown of garnet during post-peak decompression. Most monazite grains crystallized from melt are represented by Groups II+III+IV, and are associated with orthopyroxene, biotite, plagioclase and quartz in the matrix. They have crystallization ages between 1.86 Ga and 1.76 Ga, and have relatively low REE and Y concentrations. These data imply a long-lived (>100 Myr) post-collisional exhumation and cooling involving decompression from 10-12 kbar to ca. 9 kbar during 1.90-1.86 Ga, followed by retrograde cooling from 1.86 to 1.76 Ga under prolonged residence in the middle to lower crust. Initial collision and peak metamorphism occurred before 1.90 Ga, ultimately leading to the final cratonization of the North China Craton and its incorporation into the Columbia supercontinent.

Key words: Monazite petrochronology; Phase equilibria modeling; Long-lived metamorphism; Pelitic granulite; Trans-North China Orogen

INTRODUCTION

High-grade metamorphic rocks involved in orogenesis generally experience multiple metamorphic episodes, which together can last for tens of million years or more (e.g., >100 Myr; Zhang et al., 2015; Clark et al., 2018). Determining the timing and duration of metamorphism and their connections with polyphase pressure-temperature (P-T) histories is a major challenge in petrology (Hermann and Rubatto, 2003; Taylor et al., 2015). Accessory minerals used for U-Th-Pb dating, such as monazite and zircon, can grow episodically throughout prograde, peak, and retrograde metamorphism. Both monazite and zircon can form during subsolidus burial and heating (Rubatto et al., 2001; Wing et al., 2003; Waller et al., 2016; Jiao et al., 2020), partial melting (Harley and Nandakumar, 2014; Dumond et al., 2015; Wang et al., 2015) and retrograde cooling accompanied with melt crystallization (Fitzsimons et al., 1997; Kelsey et al., 2008; Ding et al., 2021). In addition, complex internal textures in these accessory minerals that may result from dissolution, recrystallization and multistage growth make the ages and their relation to metamorphic conditions more obscure. Attempts to relate monazite and zircon growth to specific metamorphic reactions or particular metamorphic minerals (e.g. garnet and plagioclase) on the basis of systematic microstructural location, internal texture and composition zoning, as well as mineral trace element data (especially HREE, Y and Eu) provide an important tool to gain a better understanding of the metamorphic ages (e.g. Rubatto et al., 2001, 2013; Harley and Nandakumar, 2014; Johnson et al., 2015; Jiao et al., 2020).

The North China Craton (NCC) is the largest and oldest craton in eastern Eurasia, and contains several Archean continental blocks and three Paleoproterozoic orogenic belts, including the Trans-North China Orogen (TNCO), the Inner Mongolia Suture Zone and the Jiao-Liao-Ji Belt (Fig. 1A). The collisional events in these three belts occurred at 2.0-1.8 Ga, leading to final cratonization of the NCC and its incorporation into the Columbia supercontinent during the Paleoproterozoic (e.g. Rogers and Santosh, 2002; Zhao et al., 2002a; Santosh, 2010; Meert, 2012; Tang and Santosh, 2018a). Zhao et al. (2000a, 2005) proposed a three-fold subdivision for the tectonic framework of the NCC which includes the Eastern Block, the Western Block and the intervening TNCO. Several competing models have been proposed for Paleoproterozoic collision along the TNCO, including i) the metamorphism and collisional event occurred at ~1.85 Ga (Zhao et al., 2005, 2012; Zhang et al., 2006; Zhao and Zhai, 2013); ii) prograde and peak metamorphism associated with crustal thickening occurred at ~1.95 Ga, with post-collision exhumation and retrograde cooling between 1.92 Ga and 1.80 Ga, and therefore indicate that the final collisional event initiated at ~1.95 Ga (Wei et al., 2014; Qian et al., 2017; Tang et al., 2017); iii) peak metamorphism correlated with the collisional event at 1.95-1.83 Ga (Chen et al., 2020); iv) two stages of collisional events at ~2.1 Ga and 1.9-1.8 Ga (Trap et al., 2012); and v) multistage amalgamation and arc-continent collision proposed to happen at 2.5-2.3 Ga (Kusky et al., 2016; Wang et al., 2017a). These discrepancies mainly stem from diverse interpretations of the prolonged record of metamorphic ages in the period 1.98-1.80 Ga (e.g. Liu et al., 2006, 2020a; Qian and Wei, 2016; Tang and Santosh, 2018a).

The Fuping Complex, central TNCO, exposes granulite- to lower amphibolite-facies metapelitic rocks in the Wanzi supracrustal sequence, including pelitic granulite, sillimanite-bearing gneiss, garnet-biotite gneiss and garnet-bearing schist (Cheng et al., 2004; Xia et al., 2006; Tang et al., 2015; Liu et al., 2021a, 2021c). Garnet-bearing pelitic granulites and gneisses represent ideal lithologies to unravel Paleoproterozoic metamorphism and long-lived collisional processes in TNCO, as they commonly contain multiple generations of monazite and zircon. In this study, we present integrated phase equilibria modeling and texturally controlled in situ LA-ICP-MS monazite U-Th-Pb and trace element analyses on a suite of pelitic granulite and garnet-biotite gneiss samples from the Fuping Complex. The combination of TESCAN Integrated Mineral Analyser (TIMA) scanning, back-scattered electron (BSE) imaging, X-ray chemical mapping, trace element analysis, and U-Th-Pb dating was used to perform detailed petrochronology and closely integrate monazite crystallization behavior and absolute age data with metamorphic P-T conditions. The results provide quantitative information on the metamorphic history, tectonic evolution, and rates of burial and exhumation during the prolonged Paleoproterozoic collisional orogeny in the TNCO.

REGIONAL GEOLOGY

The Chinese mainland is mainly composed of three Precambrian cratons: the NCC, the South China Craton, and the Tarim Craton (Fig. 1; Zhao et al., 2005). The NCC is the largest and oldest of the three, and is bordered by the Central Asian Orogenic Belt to the north, the Qilian-Qinling-Dabie Orogenic Belt to the west and south, and the Sulu Belt to the east. The tectonic evolution of the NCC has been described by two main models that include both Archean and Paleoproterozoic events. The first model proposes that the NCC is mainly composed of several Archean nuclei (or microblocks) that were welded together along granite-greenstone belts at 2.75-2.6 Ga and ~2.5 Ga (Wu et al., 1998; Zhai and Santosh, 2011; Santosh et al., 2016; Tang and Santosh, 2018b). The second model sub-divides the NCC into the Eastern Block, the Western Block and the intervening TNCO (Fig. 1a). In this scenario, the TNCO represents a Paleoproterozoic collisional orogen that experienced either prolonged subduction during 2560–1880 Ma (Zhao et al., 2005, 2012) or multiple stages of subduction-accretion-collision between the Eastern and Western Blocks (Faure et al., 2007; Wang et al., 2010; Trap et al., 2012; Santosh et al., 2015; Kusky et al., 2016). Recently, Tang and Santosh (2018a) proposed that the TNCO recorded two stages of subduction-rift systems during Paleoproterozoic terrane assembly before the final collision occurred at 1.96–1.90 Ga.

The TNCO contains several metamorphosed basement terranes (e.g. Fuping, Wutai, Hengshan, Fig. 1), which expose Neoarchean to Paleoproterozoic tonalite–

trondhjemite–granodiorite (TTG) gneisses, metamorphosed mafic boudins (mafic granulite and amphibolite), meta-supracrustal rocks, gneissic and un-metamorphosed granitoids, and mafic dykes (Zhao and Zhai, 2013; Wei et al., 2014). The mafic and pelitic granulites are mainly exposed in the Fuping, Xuanhua-Huai'an, Hengshan, Chengde and Lüliang Complexes (Fig. 1a; Zhao et al., 2000a; Guo et al., 2005; Zhang et al., 2006; Xiao et al., 2017).

The Fuping Complex is composed of four major rock units, including the Fuping TTG gneiss, Longquanguan augen gneiss, Nanying granite and Wanzi supracrustal sequence (Fig. 2). The protoliths of the Fuping TTG gneiss and Longquanguan augen gneiss were emplaced at 2.54–2.48 Ga, as shown by magmatic zircon U–Pb ages (Guan et al., 2002; Zhao et al., 2002b; Wilde et al., 2005; Tang et al., 2016a). Nanying gneissic granite bodies intruding the TTG gneiss record emplacement ages of 2.10–2.02 Ga and formed in an arc (Liu et al., 2005; Tang et al., 2015) or rift setting (Wang et al., 2020). The Wanzi supracrustal sequence mainly includes pelitic gneiss and schist, calc-silicate rock, marble, and minor amphibolite and pelitic granulites (Liu and Liang, 1997; Xia et al., 2006; Ren et al., 2013; Tang et al., 2016b; Liu et al., 2021c). The mafic and pelitic granulites occur as boudins, layers and sheets in the Fuping TTG gneiss and the Wanzi supracrustal sequence (Zhao et al., 2000; Cheng et al., 2004; Liu et al., 2021a). Zircon and monazite in metapelite, amphibolite, mafic granulite and TTG gneiss in the Fuping complex record consistent metamorphic ages of 1924-1802 Ma (Guan et al., 2002; Zhao et al., 2002b; Cheng et al., 2004; Trap et al., 2008; Tang et al., 2015, 2016, 2017; Meng et al., 2017; Qian et al., 2018; Liu et al., 2019, 2021a, 2021b, 2021c), corresponding to the final collision and post-collision process between the Eastern and Western Blocks along the TNCO. Geothermobarometry and pseudosection modeling show that these metamorphosed mafic and pelitic rocks yield clockwise P–T paths involving near isothermal decompression, which is typical of granulite-facies metamorphic rocks in collisional orogenic belts (Liu et al., 1996; Zhao et al., 2000; Meng et al., 2017; Tang et al., 2017; Qian et al., 2018; Liu et al., 2019, 2021a). However, the interpretations of the metamorphic ages remain equivocal with several debates including the following. (i) Cheng et al. (2004) proposed that the pelitic granulite experienced peak granulite-facies metamorphism at ~2.54 Ga and was overprinted by an amphibolite-facies metamorphic event at ~1.83 Ga. (ii) Tang et al. (2017) suggested that the 1.93–1.92 Ga ages from the mafic granulites represent the peak granulite-facies metamorphism and the 1.86–1.83 Ga ages were correlated with the retrograde event. (iii) Qian et al. (2018) considered that the cooling stage of metamorphism occurred at 1.89–1.85 Ga. (iv) Liu et al. (2021c) proposed that the Wanzi supracrustal sequence had undergone middle to high pressure metamorphism during 1.84–1.82 Ga.

SAMPLES AND PETROGRAPHY

The granulite- to amphibolite-facies metapelitic rocks in the Fuping Complex mainly include garnet-biotite gneiss in the Wanzi supracrustal sequence, and pelitic granulite and garnet-biotite gneiss occurring as stratigraphic layers in the northern part of the complex (Fig. 2). The studied garnet-biotite gneisses (20FP-16, 38°28′41″N, 113°53′00″E) were collected from Zhaigou, ~1 km west of the Xiazhuang village. Pelitic granulite samples 20FP-26 (38°52′58″N, 114°09′37″E) and 20FP-27 (38°52′46″N, 114°09′28″E) and garnet-biotite gneiss sample 20FP-28 (38°52′43″N, 114°09′37″E) were collected from Sanlinghui village. The petrographic features of these rocks are summarized below.

Pelitic granulite

Pelitic granulite samples (20FP-26 and 20FP-27) from both localities have similar features and are dominantly composed of garnet (10-12 vol.%), orthopyroxene (10-12 vol.%), biotite (12-15 vol.%), quartz (25-28 vol.%), plagioclase (35-38 vol.%), with minor ilmenite, magnetite, monazite and zircon (Figs. 3, 4, S1A). In some locations, the rocks show patches and discontinuous layers of quartzo-feldspathic domains, which are sub-parallel and define a weak foliation (Fig. 3A, 3B). The prograde assemblage is preserved as mineral inclusions of quartz, plagioclase, biotite and ilmenite inclusions in garnet porphyroblasts (Fig. 4B-D). The peak mineral assemblage is defined by the coarse- to medium-grained porphyroblastic garnet (0.2-2 mm), orthopyroxene (0.5-1.5 mm), biotite (0.6-1.2 mm), plagioclase (0.5-2 mm), quartz (0.6-1.5 mm) and ilmenite (Figs. 4, S1A). The coarse-grained orthopyroxene displays near-equigranular granoblastic texture, and is inferred to have equilibrated with garnet at peak metamorphism (Fig. 4A-C). Flaky biotite grains are euhedral and parallel to the weak foliation. Retrograde assemblage is recognized in the following textural associations, (i) moats of biotite + quartz + plagioclase aggregates embay the garnet porphyroblast (Fig. 4B, 4C), indicative of retrogression assemblage; (ii) thin quartz films representing pseudomorphs of melt-filled pores with low dihedral angles in contact with garnet and orthopyroxene (Fig. 4B); (iii) fine-grained xenoblastic orthopyroxenes form intergrowths with fine-grained biotite and quartz in the matrix (Fig. 4D); and (iv) quartzo-feldspathic aggregates intergrowth with biotite in the leucosome layers. The thin quartz films and quartzo-feldspathic layers indicate the product of melt crystallization during the retrograde cooling process.

Monazites in the two pelitic granulite samples occur mainly in four textural domains (Figs. 4, S1A): (i) monazite grains embay garnet porphyroblasts in sample 20FP-27; (ii) in contact with medium- to fine-grained xenoblastic orthopyroxenes in the matrix; (iii) in contact or intergrowth with medium- to fine-grained biotite in the matrix; and (iv) in close association with quartz and plagioclase in the matrix and quartzo-feldspathic aggregates.

Garnet-biotite gneiss

Garnet-biotite gneiss sample 20FP-16 shows discontinuous quartzo-feldspathic layers, which are parallel to the NE-trending foliation (Figs. 3C, 5A). Sample 20FP-28 contains patches and discontinuous layers of quartzo-feldspathic aggregates that wrap around garnet and occur throughout the matrix (Figs. 3D, S1B). Both samples show gneissose structure and have similar metamorphic assemblages, which are mainly composed of garnet (10-12 vol.%), biotite (20-22 vol.%), quartz (28-30 vol. %), plagioclase (30-32 vol.%), K-feldspar (2-3 vol.%), and accessory ilmenite, magnetite, zircon and monazite (Figs. 5, S1B). The prograde assemblage is defined by mineral inclusions of quartz, plagioclase, biotite and ilmenite in garnet porphyroblasts (Fig. 5C-D). The peak assemblage is dominant, and comprises porphyroblastic garnet that grew in equilibrium with the matrix mineral assemblage of biotite, quartz, plagioclase, K-feldspar and ilmenite. Garnet porphyroblasts vary in size of 0.1-1.5 mm and display corroded morphology, indicating late garnet consumption (Fig. 5A). Biotite in the matrix is aligned parallel to the foliation, and is both coarse-grained (idioblastic) and fine-grained (sub-idioblastic), and reddish to dark brown in color. Fine-grained biotite (0.1-0.4 mm) also occurs in the quartz-feldspathic layer (Fig. 5A). Quartz films wrap around garnet and occur throughout in the matrix (Fig. 5B, 5C). The presence of quartz film and layers of quartz + plagioclase + biotite assemblage represents the product of melt crystallization in the retrograde cooling stage.

Monazites in the two garnet-biotite gneiss samples have the same textural features with those of the pelitic granulites, and occurs in four principal textural associations (Figs. 4, 5, S1, S3): i) Group I comprises irregular and elongated grains that embay garnet; ii) Group II comprises inclusions and intergrowths with xenoblastic orthopyroxene; iii) Group III comprises inclusions and intergrowths with biotite in the matrix; and iv) Group IV comprises grains in close association with quartz and plagioclase in the matrix and quartzo-feldspathic aggregates. Monazite inclusion in garnet is not observed in our samples.

ANALYTICAL METHODS

Whole-rock geochemistry

Whole-rock major oxides were measured at the Analytical Laboratory of Beijing Research Institute of Uranium Geology using an Axios-mAX X-ray fluorescence spectrometer (XRF). Hand specimens containing both garnet-bearing portions and layers/patches of quartzo-feldspathic aggregates were trimmed to remove surface weathering and alteration. The fresh hand specimens were used for thin-section preparation, and all remaining parts were crushed and powdered to approximately 200 mesh by using a tungsten carbide ball mill. Precision and accuracy for MnO and P_2O_5 are 5%, and those for other oxides are better than 2%. The FeO contents were measured by titration. All whole-rock geochemical data are provided in Table S1.

Petrographic and EPMA study

Petrographic observations on thin sections were performed using an optical microscope at China University of Geosciences Beijing, and TESCAN Integrated Mineral Analyser (TIMA) scanning at Peking University. TIMA scanning of whole polished thin sections was performed with a beam energy of 25 kV, bean current of 5.8 nA, spot size of ~110 nm and working distance of 15 mm. Mineral identification was processed offline by dedicated TIMA software. Monazite grains in thin sections were identified by TIMA scanning.

Backscattered electron (BSE) image, X-ray intensity mapping and electron microprobe analysis (EMPA) were conducted at the Institute of Geology and Geophysics, China Academy of Sciences (IGGCAS). BSE images were obtained on a scanning electron microscope (SEM) with an accelerating voltage of 15 kV to examine the texture of minerals and internal structure of monazite grains. Compositional zoning of monazite was assessed by X-ray intensity mapping of Y (Lα, PET or TAP) and Ce (Lα, LLIF) at the IGGCAS. Working conditions for the X-ray mapping comprised an accelerating voltage of 15 kV, beam current of 100 nA, and focused beam dwell time of 50–100 ms. Mineral compositions for garnet, plagioclase, biotite, orthopyroxene and K-feldspar were acquired via EPMA on a JEOL-JXA-8100 electron microprobe, with an acceleration voltage of 15 kV, beam current of 24 nA and beam diameter of 10 µm.

Monazite U-Th-Pb isotopic analysis

Monazite U-Th-Pb dating was conducted in situ on an Agilent 7700e inductively coupled plasma mass spectrometer (ICP-MS) equipped with a COMPexPro 102 ArF excimer laser ablation (LA) system housed at the Wuhan SampleSolution Analytical Technology Co., Ltd., Wuhan, China. The spot size of the laser was 16 µm. Helium was used as a carrier gas, and argon was applied as the make-up gas. The laser ablation system included a "wire" signal smoothing device, which produces smooth signals at very low laser repetition rates below 1 Hz (Hu et al., 2015). Monazite 44069 and glass NIST610 were analyzed repeatedly as external standards for U-Th-Pb dating and trace element calibration, respectively. Each spot analysis incorporated a 20-30 s background acquisition followed by 50 s of sample acquisition. The 12 analyses of monazite standard yielded average $^{206}Pb/^{238}U$ age of 275.4 ± 1.2 Ma (MSWD = 1.1) and concordia age of 275.3 ± 0.6 Ma (MSWD = 0.01). The software ICPMSDataCal was used for the integration of analytical signals, time-drift correction, and quantitative calibration of U-Th-Pb age and trace elements (Liu et al., 2008).

MINERAL CHEMISTRY

Garnet

Garnet porphyroblasts in pelitic granulite and garnet-biotite gneiss samples are mainly almandine + pyrope + grossular solid solutions, with minor spessartine (X_{Sps} = Mn/(Fe^{2+}+Mg+Ca+Mn) = 0.02-0.05) (Table S2; Fig. 6). In pelitic granulite sample 20FP-26, garnet has a relatively small core domain with higher grossular (X_{Grs} = Ca/(Fe^{2+}+Mg+Ca+Mn) = 0.15-0.16) and slightly lower almandine (X_{Alm} = Fe^{2+}/(Fe^{2+} +Mg+Ca+Mn) = 0.59-0.61) and pyrope (X_{Pyr} = Mg/(Fe^{2+}+Mg+Ca+Mn) = 0.21-0.23) contents than those in the rim ($Alm_{60-63}Pyr_{22-25}Grs_{11-14}Sps_{2-3}$). Garnet in pelitic granulite sample 20FP-27 shows distinct compositional zoning from core ($Alm_{59-61}Pyr_{23-25}Grs_{13-15}Sps_{2-3}$) to rim ($Alm_{61-70}Pyr_{20-28}Grs_{6-12}Sps_{2-3}$). Porphyroblasts in garnet-biotite gneiss samples 20FP-16 and 20FP-28 show relatively homogeneous cores but compositionally variable rims (Fig. 6). The cores have higher grossular (20FP-16, X_{Grs} = 0.07-0.09; 20FP-28, X_{Grs} = 0.09-0.10) and lower almandine (20FP-16, X_{Alm} = 0.64-0.65; 20FP-28, X_{Alm} = 0.62-0.65) contents than rims (20FP-16, X_{Grs} = 0.05-0.07, X_{Alm} = 0.65-0.69; 20FP-28, X_{Grs} = 0.07-0.08, X_{Alm} = 0.64-0.69).

Orthopyroxene

Orthopyroxene compositions in pelitic granulite samples vary according to textural location. In sample 20FP-26, the cores of coarse-grained orthopyroxenes have higher Al contents (0.12-0.13 p.f.u.) than rims and finer grains in the matrix (0.11-0.12 p.f.u., Fig. 7A). The coarse-grained sub-idioblastic orthopyroxene in sample 20FP-27 also contains higher Al values (0.12-0.13 p.f.u.), whereas the fine-grained orthopyroxene in the matrix contains lower Al values (0.10-0.12 p.f.u.). The different Al values and texture features define two orthopyroxene generations that we interpret formed at peak conditions and during the post-peak stages, and also at different pressures and temperatures.

Biotite

Coarse-grained biotite in pelitic granulite sample 20FP-26 has a Ti content of 0.29-0.31 p.f.u., whereas the finer grains in the matrix and around garnet rims have a lower Ti content (0.25-0.28 p.f.u., Fig. 7B). In sample 20FP-27, coarse biotite grains in the matrix and grains intergrown with coarse orthopyroxene have relatively higher Ti contents (0.26-0.29 p.f.u.) than fine grains in matrix and those around garnet rims (Ti = 0.22-0.27 p.f.u.). In garnet-biotite gneiss sample 20FP-16, the coarse-grained idioblastic biotites have higher Ti contents (0.25-0.26 p.f.u.) than those of inclusions in garnet (Ti = 0.16-0.20 p.f.u.) and fine grained biotite in the matrix (Ti = 0.20-0.22 p.f.u.). In sample 20FP-28, biotite inclusions and coarse-grained biotite in the matrix have consistent Ti contents of 0.24-0.26 p.f.u, which are higher than those of fine grains in matrix (Ti = 0.18-0.22 p.f.u.). Textural observations and EPMA data therefore define three generations of biotite: prograde inclusions in garnet, coarse idioblastic grains in the matrix or intergrowths with coarse-grained orthopyroxene in the peak assemblage, and retrograde fine grains in the matrix and around garnet rims. Most X_{Mg} values are indistinguishable between biotite generations (Fig. 7B).

Plagioclase

Three generations of plagioclase occur in the studied samples: early (prograde) inclusions in garnet and orthopyroxene, coarse grains in the matrix (peak), and finer grains in the matrix and as moats around garnet (retrograde). In sample 20FP-26, all three generations have a similar composition of anorthite (An_{29-32}) and albite (Ab_{65-69}), with no significant K-feldspar component. In sample 20FP-27, prograde inclusions have variable anorthite values (An_{30-41}), but are generally higher than the other two plagioclase types in the matrix (An_{29-31}). In sample 20FP-16, the three plagioclase types show a decreasing trend of anorthite from prograde to peak and then retrograde populations (An_{40-47}, An_{28-40}, An_{27-31}, respectively). Plagioclase inclusions in sample 20FP-28 have variable anorthite (An_{30-41}) and albite (Ab_{58-68}) contents, whereas the coarse- and fine-grained phases in matrix have relatively constant compositions (An_{29-31} and Ab_{67-69}).

PSEUDOSECTION MODELING

Thermobarometry was performed on the studied samples by constructing $P–M_{H2O}$ and P–T pseudosections, which constrain changes in the depths and thermal regimes of metamorphism through time. These diagrams were constructed using Theriak-Domino (de Capitani and Brown, 1987; de Capitani and Petrakakis, 2010) and the internally consistent thermodynamic database ds-62 (Holland and Powell, 2011). The following activity-composition (a-x) relations were considered in these models: garnet, plagioclase, K-feldspar, biotite, orthopyroxene, cordierite, staurolite, spinel-magnetite, ilmenite-hematite, and melt (White et al., 2014a, 2014b). Quartz, kyanite, sillimanite, rutile and aqueous fluid (H_2O) were treated as pure phases. The system MnNCKFMASHTO ($MnO–Na_2O–CaO–K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O–TiO_2–O$) was used for all models, and bulk-rock compositions (Table S1) were obtained from the same portions of samples that thin sections were cut from. Due to extensive devolatilisation that accompanies prograde metamorphism, exhumed granulite-facies rocks are typically drier than they were during initial burial and heating, especially if they have also experienced partial melting (e.g. Palin et al., 2016a, 2016b). While hydration of metamorphic rocks may also occur during retrograde metamorphism and/or exhumation, this is often evidenced by particular microstructures, such as pseudomorphic replacement of anhydrous porphyroblasts by hydrous, lower-temperature minerals. As these features are absent from the studied samples, modeled H_2O contents for the prograde-to-peak stages were constrained using $P–M_{H2O}$ diagrams. The $P–M_{H2O}$ diagrams are constructed at the temperature of 850 °C which is an appropriate value based on the garnet-orthopyroxene geothermobarometer (830-895 °C; Bhattacharya et al., 1991) and is within the temperature range of 690-880 °C of metapelitic rocks from the Fuping Complex (Liu and Liang, 1997; Liu et al., 2021a, 2021c). The H_2O contents are fixed by the fields of the peak phase assemblages which are just above the solidus (Fig. S2). The pelitic granulite and garnet-biotite gneiss samples are fresh, therefore we use the FeO/Fe_2O_3 ratios analyzed by conventional titration for the calculations. Finally, absolute uncertainty on the positions of calculated phase boundaries are estimated to be in the region of ±50 °C and ±1 kbar at 1 S.D. (Powell and Holland, 2008); however, as the same thermodynamic dataset and a-x relations are employed for all diagrams, the relative uncertainty on calculated P-T conditions for each stage of metamorphism is reduced to ±20 °C and ±0.1–0.2 kbar (Palin et al., 2016c).

Pelitic granulite

In the calculated $P–M_{H2O}$ diagram for sample 20FP-26, a H_2O content of 1.6 mol. % was chosen for subsequent P–T diagram construction based on the stable field of the peak assemblage (garnet + orthopyroxene + biotite + plagioclase + quartz + ilmenite + melt) which is just above the solidus (Fig. S2A). In the P–T pseudosection, the solidus falls in the temperature range of 810-850 °C between 5 kbar and 14 kbar. The peak assemblage is stable at 8.5-12.6 kbar and 840-896 °C, as defined by the melt-out, orthopyroxene-out, K-feldspar-in and magnetite-in assemblage field boundaries (Fig. 8A). Contours showing isopleths of X_{Grs} and X_{Pyr} in garnet and Ti (cpfu) in biotite are superimposed onto these phase equilibria. The intersections of X_{Grs} and X_{Pyr} isopleths for garnet core compositions further constrain the peak conditions to 10.1-10.8 kbar and 850-870 °C. Compositional variation from core to rim of garnet and intersections of X_{Grs} and X_{Pyr} define an episode of retrograde decompression to 8.8 kbar. Notably, some of the X_{Grs} and X_{Pyr} intersections of garnet rims fall in the field with K-feldspar, and these intersections show a P–T range of 8.6-9.5 kbar and 860-875 °C (Fig. 8A). However, K-feldspar is absent in the pelitic granulite sample (Fig. 4), thus the decompression trajectory is constrained to along the univariant line of K-feldspar. The P–T ranges and intersections of garnet rims in the field with K-feldspar are within the calculated uncertainty of ±50 °C and ±1 kbar.A P–T pseudosection for sample 20FP-27 was constructed using a H_2O content of 1.7 mol. % which is obtained from the stability field of peak mineral assemblage (garnet + orthopyroxene + biotite + plagioclase + quartz + ilmenite + melt) above the solidus and represents the highest water content calculated from the LOI value (Fig. S2B; Table S1). In the pressure range 5-14 kbar, the temperature of the solidus varies between ~810 °C and ~855 °C. The stability field of the peak assemblage is defined by the melt-out, orthopyroxene-out, K-feldspar-in and magnetite-in curves, and correlates with P–T conditions of 9.1-12.0 kbar and 850-890 °C. Isopleths representing the garnet core compositions further constrain peak conditions to a narrow range of 9.9-11.0 kbar and 870-880 °C (Fig. 8B). Intersections of X_{Grs} and X_{Pyr} in garnet rims and Ti in biotite (0.19-0.20 p.f.u.) define a retrograde decompression and cooling path to conditions of 8-9 kbar and <840 °C (Fig. 8B). The mineral assemblage and pseudosection topology of sample 20FP-27 are similar to sample 20FP-26, and thus the retrograde decompression trajectory is also constrained to be along the K-feldspar univariant line and the X_{Grs} and X_{Pyr} intersections of garnet rims fall within the uncertainty.

Garnet-biotite gneiss

For sample 20FP-16, the H_2O content was fixed at 1.6 mol. % based on the peak phase assemblage (garnet + biotite + plagioclase + quartz + K-feldspar + ilmenite + melt) is just above the solidus in the P–M_{H2O} diagram constructed at 850 °C (Fig. S2C). At these conditions, the solidus is located at 825-850 °C from 5 to 14 kbar. The peak phase assemblage lies within a stable field that spans a wide pressure range of 6.6-12.3 kbar and temperature range between 845 °C and 905 °C. The stable conditions for peak metamorphism were constrained by the melt-out, sillimanite-in, kyanite-in, rutile-in and orthopyroxene-in assemblage field boundaries (Fig. 8C). The pseudosection was further contoured with isopleths of X_{Grs} and X_{Pyr} in garnet, and Ti (cpfu) in biotite. However, the X_{Grs} and X_{Pyr} isopleths matching garnet core compositions do not intersect in the examined region of P-T space, which is interpreted to be a result of modification of the garnet composition due to substantial Fe–Mg exchange during retrograde cooling and exhumation (Fitzsimons and Harley, 1994). As Ca diffuses in garnet at a significantly slower rate than Mg (Carlson, 2006), X_{Grs} contours are considered more reliable, and values of 0.07-0.08 (garnet core) and Ti (cpfu) of 0.25-0.26 in coarse-grained idioblastic biotite define a peak condition of 11.6-12.1 kbar and 865-878 °C. It is noteworthy that X_{Grs} value of some garnet cores reach 0.085 which fall in the field with rutile (Fig. 8C). Rutile is absent in the garnet-biotite gneiss sample 20FP-16, and therefore the upper pressure limit is constrained by the rutile-in line, and the P-T condition (12.5 kbar, 880 °C) of these garnet core compositions is within the uncertainty of ±50 °C and ±1 kbar. The lowest X_{Grs} value of 0.05 in garnet rim and Ti (cpfu) of 0.20 in fine-grained matrix biotite predict retrograde conditions of ~10 kbar and ~845 °C.

For sample 20FP-28, a P–M_{H2O} pseudosection constructed at 850 °C was used to constrain a H_2O content of 1.5 mol. % which corresponds to the field of peak assemblage (garnet + biotite + plagioclase + quartz + K-feldspar + ilmenite + melt) just above the solidus (Fig. S2D). The solidus in the P–T pseudosection for this bulk composition is located at 805-850 °C in the pressure range 5-14 kbar. The melt-out, kyanite-in, rutile-in, biotite-out, orthopyroxene-in curves provide limits on the peak P–T conditions of 7.5-12.6 kbar and 820-895 °C. The highest grossular composition (X_{Grs} = 0.102) measured in garnet cores yields a peak pressure at 11.5 kbar, and the highest Ti value (0.258 p.f.u.) of coarse-grained biotite suggests a temperature of 872 °C (Fig. 8D). Furthermore, the lowest grossular values of the garnet core and Ti in coarse biotite provide a lower limit to the peak condition at 10.9 kbar and 860 °C. Isopleths of X_{Grs} in garnet rims and Ti cpfu in fine-grained matrix biotite define a post-peak decompression and retrograde cooling path to ~9 kbar and <840 °C (Fig. 8D).

MONAZITE COMPOSITION AND U-Th-Pb AGE

Backscattered electron (BSE) imaging and X-ray maps (Y and Ce) show that the all groups of monazite have relatively homogeneous internal textures, lacking obvious zoning or nucleation features in individual grains (Fig. S3). The results show that the ages are consistent within single grains based on 3-6 analyses of each monazite (Table S3), and therefore the crystallization ages of monazite are mainly related to their textural associations. In pelitic granulite sample 20FP-26, twenty in situ analyses were obtained from six monazite grains, including one grain from Group II, four grains from Group III, and one grain from Group IV. The ^{207}Pb/^{206}Pb ages lie in the range 1842-1783 Ma and form a population that is scattered along concordia, without systematic differences between the three groups. The 20 spots yield a weighted mean ^{207}Pb/^{206}Pb age of 1807 ± 11 Ma (MSWD = 0.56), and have Y, HREE and Eu/Eu* values of 352-2766 ppm, 4.4-142 ppm and 0.16-0.34, respectively (Table S3).

Twenty in situ analyses were obtained from six monazite grains in pelitic granulite sample 20FP-27, including one grain from Group I, one grain from Group II, and four grains from Group IV. The two dates from the Group I monazite grain that is in direct contact with garnet record ^{207}Pb/^{206}Pb ages of 1872 ± 28 Ma and 1863 ± 32 Ma (Fig. 9). The remaining 18 data points from the Group II+IV monazites show ^{207}Pb/^{206}Pb ages in the range from 1852 ± 24 Ma to 1772 ± 23 Ma, yielding a weighted mean age of 1803 ± 11 Ma (MSWD = 1.0). Group I monazite has a relatively higher Y (2053-3401 ppm), HREE (176-242 ppm, Fig. 10) and lower Eu/Eu* (0.17-0.18) content than those in Group II+IV monazite, and the latter grains have values of 235-2250 ppm, 13-110 ppm and 0.18-0.29, respectively (Figs. 10-11).

In garnet-biotite gneiss sample 20FP-16, 30 analyses were obtained from Group III+IV monazite that is associated with biotite, quartz and plagioclase in the matrix.

The results form a scattered group with $^{207}Pb/^{206}Pb$ ages range between 1861 ± 26 Ma and 1776 ± 32 Ma, yielding a weighted mean age of 1815 ± 9 Ma (MSWD = 0.76). The Group III monazite grains associated with matrix biotite have relatively lower Y (527-681 ppm) and HREE (25-37 ppm) than those in Group IV monazite (Y = 559-2226 ppm, HREE = 24-140 ppm), whereas they have constant Eu/Eu* values (0.13-0.16; Fig. 11; Table S3).

In garnet-biotite gneiss sample 20FP-28, 33 in situ analyses were performed on seven grains, including two grains from Group I, one grain from Group III, and four grains from Group IV. Eight spot ages from the Group I monazites show older $^{207}Pb/^{206}Pb$ ages ranging from 1900 ± 26 Ma to 1876 ± 24 Ma and define a weighted mean age of 1886 ± 18 Ma (MSWD = 0.13). The Group I monazites have relatively high Y contents of 1726-3691 ppm, HREE contents of 124-194 ppm (Fig. 10) and Eu/Eu* values of 0.15-0.20, except for one spot (Y = 655 ppm, HREE = 37 ppm, Eu/Eu* = 0.13; Table S3). Twenty-five data points from Group III+IV monazite form a second population showing a wide spread of $^{207}Pb/^{206}Pb$ ages from 1859 ± 31 Ma to 1761 ± 28 Ma, with a weighted mean age of 1823 ± 11 Ma (MSWD = 0.91). In comparison, these monazite analyses have relatively low Y, HREE and Eu/Eu* values of 516-1385 ppm, 21-81 ppm and 0.13-0.16, respectively.

DISCUSSION

Metamorphic evolution and the role of melt

Metapelitic rocks from the Fuping Complex record a three-stage tectonothermal evolution defined by a clockwise P-T path involving a prograde heating and burial stage, peak metamorphic stage, and a retrograde decompression and cooling stage. The metamorphic conditions of the prograde stage cannot be precisely constrained, as garnet from the pelitic granulite and garnet-biotite gneiss only contains inclusions of quartz, plagioclase, biotite and ilmenite (Figs. 4-5, S1), which represent parts of the prograde paragenesis. Unfortunately, these minerals are stable over a wide range of subsolidus and suprasolidus P-T space in metapelitic lithologies (e.g. White et al., 2014a; Palin and Dyck, 2021), and so the pre-peak evolution was instead inferred on the basis of the Ti content of biotite and the topology of isopleths on the calculated P-T pseudosection (Fig. 8). For both pelitic granulite and garnet-biotite gneiss samples, the biotite inclusions in garnet contain relatively lower Ti contents than those of coarse-grained idioblastic peak biotite grains in the matrix (Fig. 7B), supporting the interpretation of multiple generations of growth and recrystallization. The heating process and dehydration melting of hydrous prograde minerals is the main mechanism that drives partial melting of metapelitic rocks in the continental crust (White et al., 2004; Kelsey and Hand, 2015; Zhang et al., 2015). The rounded shape of the inclusion phases in garnet indicates that biotite, quartz and plagioclase were consumed to generate melt, which is then preserved as patches and discontinuous layers of quartzo-feldspathic aggregates, and thin films of quartz around garnet and orthopyroxene in the matrix (Figs. 3-5).

The metamorphic peak phase assemblages of the pelitic granulite and garnet-biotite gneiss from the Fuping Complex are calculated to be stable just above the solidus, and so reflect the metamorphic conditions where the matrix minerals equilibrated with remnant melt (Fig. S2; White et al., 2004; Korhonen et al., 2011, 2013). Peak *P–T* conditions for the pelitic granulite samples 20FP-26 and 20FP-27 have been constrained at 10.1-10.8 kbar and 850-872 °C, and 9.9-11.0 kbar and 870-880 °C, respectively, based on the stability of the interpreted peak assemblage (garnet + orthopyroxene + biotite + plagioclase + quartz + ilmenite + melt) and intersections of X_{Grs} and X_{Pyr} isopleths of garnet cores (Fig. 8A, 8B). Notably, peak biotite in pelitic granulite samples has a Ti content of 0.22-0.28 p.f.u., which is partly consistent with the extended stable field of peak phase assemblage. Small discrepancies between measured Ti contents and some calculated Ti contents arise from the preferential ordering of cations on the M1 site in the biotite a-x model, which does not always replicate natural cation distributions (Tajčmanová et al., 2009; Liu and Wei, 2020). The peak phase assemblage of garnet + biotite + plagioclase + quartz + K-feldspar + ilmenite + melt in the garnet-biotite gneiss samples is stable over a wide range of P-T conditions. Measured X_{Grs} and X_{Pyr} values in garnet do not show intersecting isopleths, although we interpret that X_{Grs} isopleths are more reliable, because the diffusion of Ca is several orders of magnitude slower than Fe and Mg between garnet and matrix minerals (Ellis and Green, 1979; Schwandt et al., 1996). The peak conditions for the garnet-biotite gneiss samples are thus constrained by the isopleths of X_{Grs} in garnet core and Ti content in peak biotite, producing results of 11.6-12.1 kbar and 865-878 °C for sample 20FP-16 and 10.9-11.5 kbar and 860-872 °C for sample 20FP-28 (Fig. 8).

Retrograde decompression and exhumation processes are constrained by X_{Grs} and X_{Pyr} isopleths for garnet rims, and the cooling process is constrained by isopleths for garnet rim compositions, Ti contents in biotite, and the crystallization of melt. Both pelitic granulite samples record slightly different retrograde P-T paths. The intersections of X_{Grs} and X_{Pyr} isopleths from garnet core to rim in sample 20FP-26 yield a clear isothermal decompression process, whereas those in sample 20FP-27 display a post-peak decompression and cooling path (Fig. 8A, 8B). Notably, isopleth intersections for garnet rim compositions in sample 20FP-27 are scattered, with some spots shifted to atypically lower temperature due to Fe-Mg exchange and a decrease in X_{Pyr} content. The decrease of pressure to ca. 8-9 kbar in the post-peak stage is demonstrated by a second generation of orthopyroxene occurring as fine grains in the matrix, and having rims with lower Al contents (0.10-0.12 p.f.u.) than those in peak orthopyroxene (Al = 0.12-0.13 p.f.u.; Fig. 7A). The subsequent final cooling process was accompanied by the crystallization of melt, as revealed by patches or layers of quartzo-feldspathic aggregates and thin films of quartz in both pelitic granulite and garnet-biotite gneiss. The fine-grained biotites in quartzo-feldspathic aggregates have Ti values similar to those of post-peak biotite in the matrix or around garnet, suggesting new biotite growth during exhumation at temperatures <840 °C.

Monazite constraints on the timing and duration of Paleoproterozoic deformation and metamorphism

Monazite is a common accessory mineral in metapelitic rocks and can grow at a wide range of P-T conditions, including in the subsolidus regime during prograde metamorphism (Rubatto et al., 2001; Wing et al., 2003; Jiao et al., 2020), partial melting close to or at the peak stage (Harley and Nandakumar, 2014; Dumond et al., 2015; Wang et al., 2015), and due to decompression and melt crystallization during retrograde metamorphism and exhumation (Fitzsimons et al., 1997; Yakymchuk and Brown, 2014; Ding et al., 2021). At suprasolidus conditions, phase equilibria modeling results suggest that prograde and inherited monazite will be completely consumed at several tens of degrees above the solidus in rocks that have a low initial LREE concentration (~50 ppm), or above 750 °C in rocks that have a moderate initial LREE concentration (~150 ppm) (Kelsey et al., 2008; Yakymchuk and Brown, 2014). In this study, all four samples record suprasolidus peak temperatures between 850 °C and 880 °C (Fig. 8), and therefore no pre-existing prograde or inherited monazite is expected to survive during partial melting. This is supported by the absence of monazite inclusions in garnet and the lack of relict cores in monazite in the studied samples.

During retrograde decompression and cooling at suprasolidus conditions, new monazite can form by incorporating REEs from the breakdown of garnet (e.g. Rubatto et al., 2013; Wang et al., 2017b) and grow as the remaining melt fraction solidifies (e.g. Rubatto et al., 2001; Charette et al., 2021). Group I monazite grains that are in contact with or embaying garnet display $^{207}Pb/^{206}Pb$ ages of 1872-1863 Ma (20FP-27) and 1900-1876 Ma (20FP-28), and have high Y and HREE contents (Figs. 9, 10, S3). These geochemical characteristics in monazite are primarily controlled by garnet and xenotime growth in the reactive bulk composition. Xenotime is absent in pelitic granulite and garnet-biotite gneiss samples from the Fuping Complex; therefore, we suggest that the variations in monazite Y and HREE reflect the behavior of garnet, such that low Y and HREE values represent grains that formed when garnet was abundant or growing simultaneously, whereas the opposite is true for monazite grains that formed during the breakdown of garnet (Fig. 10; Foster et al., 2002; Rubatto et al., 2013; Wang et al., 2017b). Therefore, the ages of 1.90-1.86 Ga recorded by Group I monazites are interpreted to define the timing of garnet breakdown during post-peak decompression.

Group II+III+IV monazites associated with fine-grained orthopyroxene, biotite, quartz and plagioclase in the matrix show a large age range from 1861 ± 26 Ma to 1761 ± 28 Ma. Compared with Group I monazites, grains in these three groups have relatively lower Y and HREE concentrations (Figs. 10-11). The ages and geochemical compositions among grains in Groups II+III+IV are indistinguishable, and so we therefore interpret the 1.86-1.76 Ga ages to represent protracted monazite growth during melt crystallization along retrograde cooling paths. The overall negative Eu anomalies (Eu/Eu* = 0.1-0.4) in monazite REE patterns indicate that feldspar also grew during the decompression and cooling process. Notably, in garnet-biotite gneiss sample 20FP-28, the Group III+IV monazites (1859-1761 Ma) have lower Eu/Eu* values (0.13-0.16) than Group I monazites (0.16-0.20). K-feldspar has a markedly more prominent Eu anomaly than plagioclase, resulting in more negative Eu anomalies in matrix monazite that co-crystallized from melt with K-feldspar, whereas monazite associated with plagioclase formed from the breakdown of garnet has a relatively weak Eu anomaly (Figs. 10-11).

Taken together, monazite occurrence, internal texture, U-Th-Pb geochronology and compositions all indicate that post-peak decompression occurred at 1.90-1.86 Ga, and that further crystallization of monazite in the presence of melt during the cooling process occurred at 1.86-1.76 Ga. A minimum duration of ~100 Myr for retrograde exhumation and cooling is therefore estimated from the weighted mean ages (Fig. 9).

Implication for prolonged collisional processes in the Trans-North China Orogen

Many collisional orogens on Earth formed at ca. 2.0-1.8 Ga, and this has been considered as a global scale event that led to the development of supercontinent Columbia (Rogers and Santosh, 2002; Zhao et al., 2002a, 2011; Meert, 2012; Meert and Santosh, 2017, 2022). The TNCO is regarded as a major Paleoproterozoic collisional orogen along which the Western and Eastern Blocks assembled, in combination with the collision along the northern margin of the craton, marking the incorporation of the NCC into the Columbia supercontinent (Zhao et al., 2001, 2002b, 2005, 2012; Santosh, 2010; Trap et al., 2012; Wan et al., 2015; Kusky et al., 2016; Tang and Santosh, 2018a). Basement rocks in the TNCO generally record clockwise P–T paths involving crustal thickening from the prograde to the peak stages, followed by nearly isothermal decompression (ITD) and progressive retrograde cooling events that are typical of continent-continent collisional environments (England and Thompson, 1984; Brown, 1993). In this study, the pelitic granulite and garnet-biotite gneiss samples from the Fuping Complex show granulite-facies peak metamorphism, post-peak ITD and retrograde cooling process, defining clockwise P–T paths that are comparable to other documented high-grade metamorphic rocks in the TNCO (e.g. Zhao et al., 2000; Tang et al., 2017; Qian et al., 2017; Xiao et al., 2019; Liu et al., 2021a).

Constructing P-T-t paths and determining the timing and duration of polyphase metamorphism is important to understand the evolution of Precambrian terranes. The basement rocks in the TNCO record prolonged metamorphism at 1.98-1.80 Ga (Tang and Santosh, 2018a, and references therein), whereas the peak of this collisional event is variably considered to have occurred at ~1.95 Ga, ~1.85 Ga or 1.95-1.83 Ga by different studies (e.g. Wei et al., 2014; Qian et al., 2017; Tang et al., 2017; Chen et al., 2020). Recently, Tang et al. (2017) compiled published metamorphic ages from various basement terranes in the TNCO and showed two major age peaks at 1.94-1.92 Ga and 1.85-1.84 Ga, which they interpreted to represent peak and retrograde metamorphic events, respectively. In the Fuping Complex, the zircon and monazite from metamorphosed pelitic, mafic and granitic rocks record metamorphic ages of 1924-1802 Ma (Fig. 12; Guan et al., 2002; Zhao et al., 2002b; Cheng et al., 2004; Trap et al., 2008; Tang et al., 2015, 2016a, 2017; Meng et al., 2017; Qian et al., 2018; Liu et al., 2019, 2021a, 2021b, 2021c). Except for two metamorphic ages of 1924 ± 21 Ma and 1923 ± 19 Ma from mafic granulites that were proposed to represent the age of peak granulite-facies metamorphism (Tang et al., 2017), the remaining ages of 1891-1802 Ma from available data are consistent with the monazite ages (1900-1760 Ma) in this study (Fig. 12).

The results of petrochronology and phase equilibria modeling of the pelitic granulite and garnet-biotite gneiss from the Fuping Complex can therefore be employed to construct P-T-t paths involving post-peak decompression at 1.90-1.86 Ga and then retrograde cooling at 1.86-1.76 Ga. The metamorphic ages of 1.98-1.90 Ga have been reported in most basement terranes in the TNCO, including Taihua (1.97-1.91 Ga; Huang et al., 2013; Lu et al., 2020), Lüliang (1.96-1.91 Ga; Zhao et al., 2017; Xiao et al., 2019), Fuping (1.93-1.92 Ga; Tang et al., 2017), Wutai (1.97-1.93 Ga; Qian et al., 2013; Qian and Wei, 2016), Hengshan (1.96-1.92 Ga; Qian and Wei, 2016; Qian et al., 2017) and Huai'an-Xuanhua (1.95-1.90 Ga; Su et al., 2014; Liao and Wei, 2019). Therefore, widespread crustal thickening and peak metamorphism associated with collisional orogenesis is interpreted to have occurred at 1.98-1.90 Ga. In addition, post-peak decompression from 10-12 kbar to ca. 9 kbar during 1.90-1.86 Ga indicates a slow uplift and exhumation from the lower crust. This evolution is supported by the absence of reaction textures (e.g. symplectite) around garnet, which usually forms during rapid exhumation, particularly in rocks that have a strong density contrast with their surroundings (e.g. Palin et al., 2014). The final stage of cooling suggests a prolonged residence (1.86-1.76 Ga) of the high-grade metamorphic rocks in the middle- to lower-crustal level (Wei et al., 2014), suggesting that the duration of orogenesis in Paleoproterozoic terranes may be typically longer than those in Phanerozoic terranes.

CONCLUSION

Integrated petrography, mineral chemistry, phase equilibria modeling and monazite petrochronology of pelitic granulite and garnet-biotite gneiss from the Fuping Complex has allowed construction of P-T-t paths that provide new insight into the occurrence of prolonged Paleoproterozoic metamorphism in the TNCO.

(1) Pelitic granulite and garnet-biotite gneiss samples record clockwise P-T paths, yielding peak conditions of 10.1-10.8 kbar / 850-872 °C (20FP-26), 9.9-11.0 kbar / 870-880 °C (20FP-27), 11.6-12.1 kbar / 865-878 °C (20FP-16) and 10.9-11.5 kbar / 860-872 °C (20FP-28), followed by post-peak decompression and cooling to ca. 8-9 kbar and <840 °C that led to melt solidification.

(2) Monazite populations can be divided into: i) Group I, irregular and elongated grains that have high HREE and Y contents, are in direct contact with or embay into garnet, and record post-peak decompression at 1.90-1.86 Ga and ii) Group II+III+IV grains that are associated with orthopyroxene, biotite, plagioclase and quartz in the matrix, which have consistently low HREE and Y contents, and have $^{207}Pb/^{206}Pb$ ages of 1.86-1.76 Ga that record the duration of the prolonged cooling process.

(3) The P-T-t paths of the pelitic granulite and garnet-biotite gneiss from the Fuping Complex are characterized by post-peak decompression from 10-12 kbar to ca. 9 kbar during 1.90-1.86 Ga, and then retrograde cooling during the prolonged stay from 1.86 to 1.76 Ga in the middle-lower crust. Paleoproterozoic long-lived collisional processes along the TNCO resulted in the final cratonization of the North China Craton and its incorporation into the Columbia supercontinent.

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Figure Captions

Fig. 1 (A) Simplified geological map of the North China Craton, showing the tectonic framework and exposures of basement rocks (modified after Zhao et al., 2005; Santosh, 2010). (B) Geological sketch map of the Fuping-Wutai-Hengshan Complexes. Abbreviations: FP, Fuping; WT, Wutai; HS, Hengshan; LL, Lüliang; ZH, Zanhuang; HA, Huai'an; XH, Xuanhua; NH, Northern Heibei; CD, Chengde; TH, Taihua; DF, Dengfeng; ZT, Zhongtiao; EB, Eastern Block; WB, Western Block.

Fig. 2 Geological map of the Fuping Complex, showing major lithologies and sample locations (modified after Zhao et al., 2000).

Fig. 3 Field photographs of pelitic granulite and garnet-biotite gneiss from the Fuping Complex. (A) Field exposure of pelitic granulite sample 20FP-26, quartz + feldspar aggregates occur as discontinuous layers. (B) Pelitic granulite sample 20FP-27, showing an assemblage of garnet + orthopyroxene + biotite + quartz + plagioclase and patches of quartzo-feldspathic aggregates. (C) Field exposure of garnet-biotite gneiss sample 20FP-16, showing discontinuous layers of quartzo-feldspathic aggregates parallel to the gneissosity. (D) Garnet-biotite gneiss sample 20FP-16 contains patches of quartzo-feldspathic aggregates around coarse-grained garnet or in the matrix.

Fig. 4 (A) TIMA scanning map of pelitic granulite sample 20FP-26, showing the distribution and number of monazite grains. (B) The garnet porphyroblast hosts inclusions of biotite + plagioclase + ilmenite, and ribbon quartz distributes around coarse-grained sub-idioblastic orthopyroxene (transmitted light). (C) The porous garnet contains numerous quartz + plagioclase inclusions and is surrounded by fine-grained retrograde assemblage of biotite + quartz + plagioclase (BSE image). (D) Intergrowth of fine-grained orthopyroxene + biotite + quartz + plagioclase in the matrix (transmitted light).

Fig. 5 (A) The TIMA scanning map of garnet-biotite gneiss sample 20FP-16, showing the distribution and number of monazite grains. (B) Representative photomicrograph shows porphyroblastic garnet, monazite inclusion in idioblastic biotite and ribbon quartz (transmitted light). (C) Fine-grained biotite and ribbon quartz around garnet which host quartz inclusions (BSE image). (D) Porphyroblastic garnet hosts inclusions of biotite + quartz (BSE image).

Fig. 6 Compositional profiles of garnet porphyroblasts from samples 20FP-26 (A), 20FP-27 (B), 20FP-16 (C) and 20FP-28 (D). The locations of profiles are shown in Figs. 4, 5, S1.

Fig. 7 (A) Mg/(Mg + Fe^{2+}) v. Al (p.f.u.) plot for orthopyroxene from pelitic granulite samples. (B) Mg/(Mg + Fe^{2+}) v. Ti (p.f.u.) plot for biotite from pelitic granulite and garnet-biotite gneiss samples from the Fuping Complex. PG, prograde inclusions in garnet and orthopyroxene; PK, peak assemblage, which occurs as coarse-grained phases in the matrix; RG, retrograde assemblage, which occurs as fine-grained phases in the matrix and around garnet.

Fig. 8 P–T pseudosection for pelitic granulite (A, B) and garnet-biotite gneiss (C, D) samples calculated in the system MnNCKFMASHTO. The circles represent the intersects of X_{Grs} and X_{Pyr} of garnet (white circle for garnet core and grey circles for garnet rim). Mineral abbreviations are as follows: g, garnet; opx, orthopyroxene; bi, biotite; q, quartz; pl, plagioclase; ksp, K-feldspar; ilm, ilmenite; mt, magnetite; ky, kyanite; sill, sillimanite; crd, cordierite; ru, rutile; liq, liquid (melt).

Fig. 9 Results of monazite U-Th-Pb dating by LA-ICP-MS for samples (A) 20FP-26, (B) 20FP-27, (C) 20FP-16 and (D) 20FP-28.

Fig. 10 Chondrite-normalized REE patterns of dated monazite from the Fuping Complex. Abbreviations: Mnz, monazite; Grt, garnet; Opx, orthopyroxene; Qz, quartz; Bi, biotite; Pl, plagioclase.

Fig. 11 Binary plots of individual monazite ^{207}Pb/^{206}Pb ages versus (A) Y, (B) HREE and (C) Eu/Eu*. Abbreviations: Grt, garnet; Opx, orthopyroxene; Qz, quartz; Bi, biotite; Pl, plagioclase.

Fig. 12 Compilation of metamorphic ages recorded by meta-mafic, metapelitic and meta-granitic rocks from the Fuping Complex. Data sources: Guan et al., 2002; Zhao et al., 2002a; Cheng et al., 2004; Trap et al., 2008; Tang et al., 2015, 2016a, 2017; Meng et al., 2017; Qian et al., 2018; Liu et al., 2019, 2021a, 2021b, 2021c.

Supplementary Materials

Fig. S1 TIMA scanning maps of pelitic granulite sample 20FP-27 (A) and garnet-biotite gneiss sample 20FP-16 (B).

Fig. S2 P–M_{H2O} diagram for pelitic granulite samples 20FP-26 (A) and 20FP-27 (B), and garnet-biotite gneiss samples 20FP-16 (C) and 20FP-28 (D) constructed at 850 °C. The red line is the solidus, the blue dashed line represent the location of appropriate H_2O content.

Fig. S3 Representative BSE image and X-ray map of monazite in samples 20FP-26 (A-B), 20FP-27 (C-D), 20FP-16 (E-F) and 20FP-28 (G-H).

Table S1 Whole-rock geochemical data of pelitic granulite and garnet-biotite gneiss samples from the Fuping Complex.

Table S2 Electron microprobe data of garnet, orthopyroxene, biotite and plagioclase in pelitic granulite and garnet-biotite gneiss samples from the Fuping Complex.

Table S3 Monazite U-Th-Pb ages and trace elements of pelitic granulite and garnet-biotite gneiss samples from the Fuping Complex.