

# P–T–t Path of Unusual Garnet–Kyanite–Staurolite–Amphibole Schists, Ellesmere Island, Canada—Quartz Inclusion in Garnet Barometry and Monazite Petrochronology

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## Abstract

Garnet–kyanite–staurolite assemblages with large, late porphyroblasts of amphibole form garbenschists in Ordovician volcanoclastic rocks lying immediately south of the Pearya terrane on northernmost Ellesmere Island, Canada. The schist, which together with carbonate olistoliths makes up the Petersen Bay Assemblage (PBA), displays a series of parallel isograds that mark an increase in metamorphic grade over a distance of 10 km towards the contact with Pearya; however, a steep, brittle Cenozoic strike-slip fault with an unknown amount displacement disturbs the earlier accretionary relationship. The late amphibole growth, probably due to fluid ingress, is clear evidence of disequilibrium conditions in the garbenschist. In order to recover the P–T history of the schists, we construct isochemical phase equilibrium models for a nearby garnet–mica schist that escaped the fluid event and compare the results to quartz inclusion in garnet (QuiG) barometry for a garbenschist and the metapelitic garnet schist. Quartz inclusions are confined to garnet cores and the QuiG results, combined with Ti-in-biotite and garnet–biotite thermometry, delineate a prograde path from 480 to 600°C and 0.7 to 0.9 GPa. This path agrees with growth zoning in garnet deduced from X-ray maps of the spessartine component in garnet. The peak conditions obtained from pseudosection modelling using effective bulk composition and the intersection of garnet rim with matrix biotite and white mica isopleths in the metapelite are 665°C at ≤0.85 GPa. Three generations of monazite (I, II and III) were identified by textural characterization, geochemical composition (REE and Y concentrations) and U–Pb ages measured by ion microprobe. Monazite I occurs in the matrix and as inclusions in garnet rims and grew at peak P–T conditions at 397 ± 2 Ma (2σ) from the breakdown of allanite. Monazite II forms overgrowths on matrix Monazite I grains that are oriented parallel to the main schistosity and yield ages of 385 ± 2 Ma. Monazite III, found only in the garbenschist, is 374 ± 6 Ma, which is interpreted as the time of amphibole growth during fluid infiltration at lower temperature and pressure on a clockwise P–T path that remained in the kyanite stability field. These results point to a relatively short (~12 Myr) Barrovian metamorphic event that affected the schists of the PBA. An obvious heat source is lacking in the adjacent Pearya terrane, but we speculate it was large Devonian plutons—similar to the 390 ± 10 Ma Cape Woods granite located 40 km across strike from the fault—that have been excised by strike-slip. Arc fragments that are correlative to the PBA are low grade; they never saw the heat and were not directly involved in Pearya accretion.

**Keywords:** U–Pb geochronology, QuiG, Pearya, P–T pseudosection, monazite, garbenschist

## INTRODUCTION

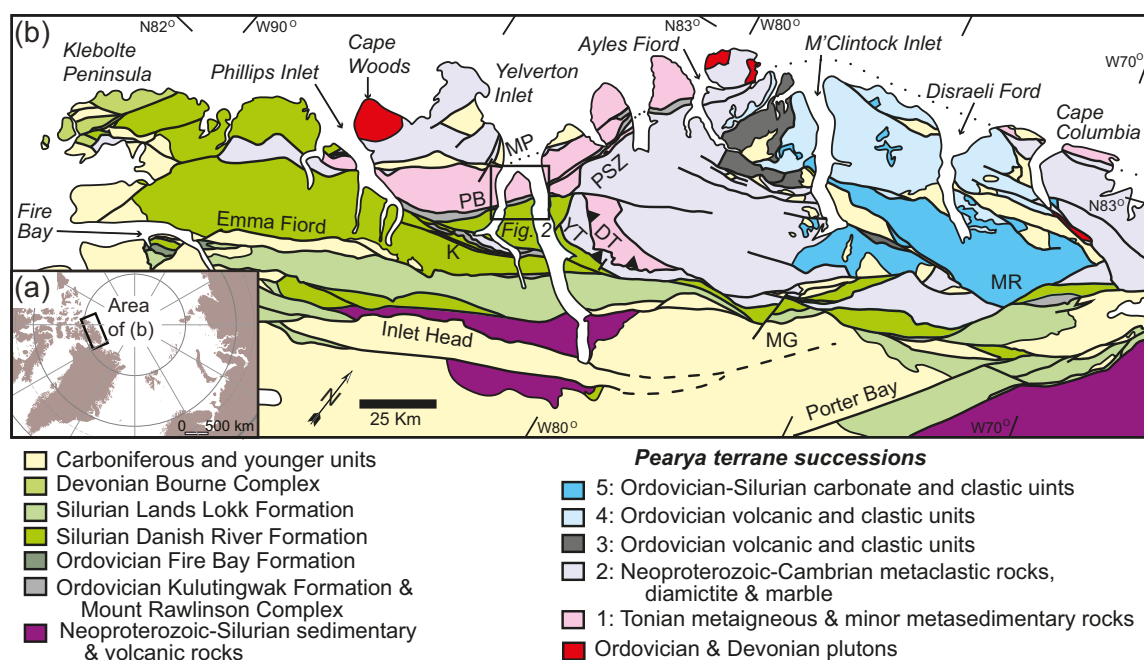
The Petersen Bay Assemblage (PBA) on northernmost Ellesmere Island (Fig. 1) contains volcanoclastic schists with the unusual assemblage garnet + kyanite + staurolite + amphibole (Klaper & Ohta, 1993). The amphibole commonly forms late, feathery porphyroblasts up to 10 cm long that are characteristic of garbenschist. Similar schists have been described from the Tauern Window in the Austrian Alps (Selverstone *et al.*, 1984), the Sierra de Pie de Palo, Argentina (Casquet *et al.*, 2001;

Mulcahy *et al.*, 2011) and adjacent to the Coast Mountains batholith in southeastern Alaska (McClelland *et al.*, 1991). Subsets of this assemblage have also been reported from amphibolites with igneous origins (e.g. Helms *et al.*, 1987; Kuyumjian, 1998; Tsujimori & Liou, 2004; Faryad & Hoinkes, 2006; Scott *et al.*, 2009). Establishing the metamorphic evolution of garbenschist is challenging, in part because the unoriented amphibole neoblasts clearly grow late in the history and deciphering equilibrium assemblages can be difficult (Steffen & Selverstone,

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**Fig. 1.** (a) Polar projection of the Arctic region. (b) Simplified geologic map of northern Ellesmere Island after Trettin (1998). The following fault zones are abbreviated as: DT, Deuchars thrust; K, Kulutingwak fault; MG, M'Clintock Glacier fault; MP, Mitchell Point fault; MR, Mount Rawlinson fault; PB, Petersen Bay fault zone; PSZ, Pearya shear zone; YT, Yelverson thrust.

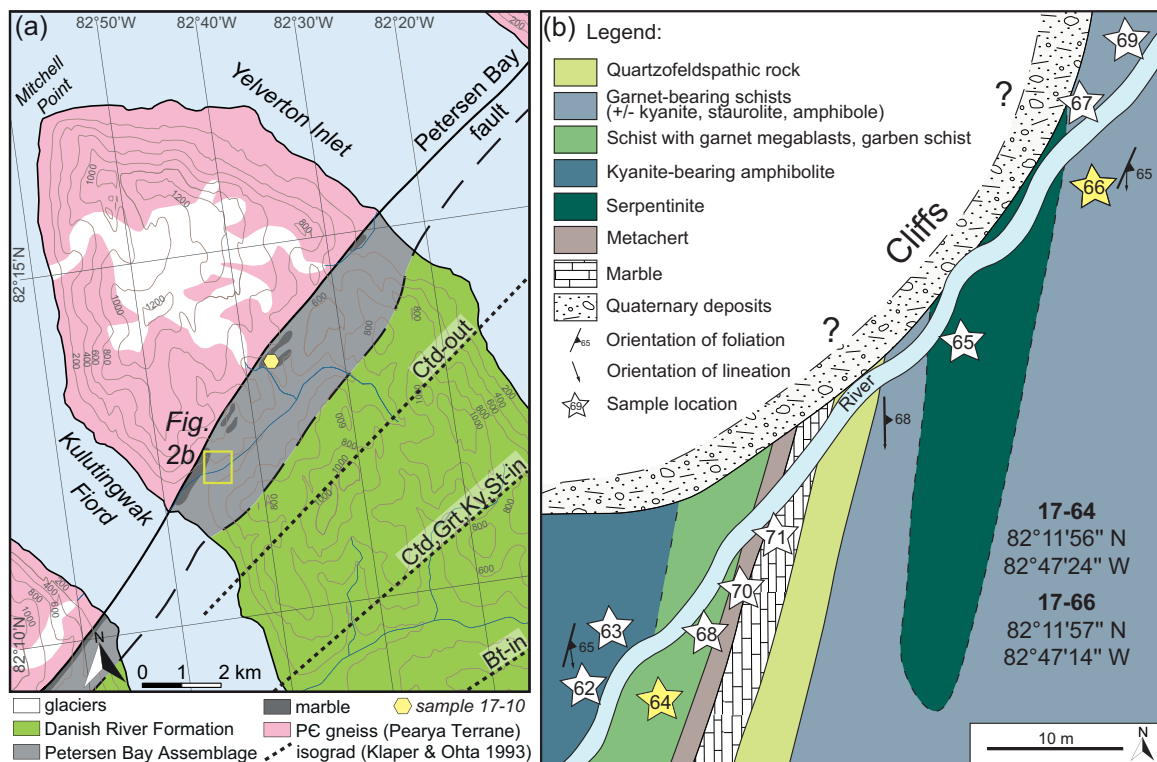
2006). With the obvious disequilibrium texture and growth of amphibole associated with late fluid influx, thermodynamic modeling to obtain metamorphic conditions is not applicable to the garbenschist (Lanari & Duesterhoeft, 2019). Fatehi et al. (2017) propose that hornblende in some garbenschist may even precipitate from hydrothermal fluids, which further complicates peak pressure ( $P$ ) – temperature ( $T$ ) estimates.

The PBA displays the highest grade of metamorphism seen along the entire accretionary contact with the composite, exotic Pearya terrane to the northwest. Steep, evenly spaced isograds in the volcanoclastic schists and adjacent turbidites require a local heat source in Pearya to cause the metamorphism (Fig. 2a). Despite truncation of the Tonian granitic gneiss of Pearya against the PBA due to late, Cenozoic brittle displacement, metamorphism in the PBA is the best target for understanding the timing and physical conditions of accretion. Speculation on the age of accretion ranges from Late Silurian from stratigraphic arguments (Trettin, 1987) to Early Carboniferous (Piepjohn et al., 2013; Piepjohn & von Gosen, 2018). The latter authors view the emplacement of the Pearya terrane as causing the sizeable fold-and-thrust belt of the Ellesmerian orogeny on the Laurentian margin. There are, however, no direct dates for this accretionary event.

The low variance volcanoclastic schists of the PBA are good candidates for geothermobarometry. Pressure is an important variable in the formation of the unusual garbenschist assemblage (Arnold et al., 2000), with typical estimates ranging from Barrovian conditions at  $\approx 1$  GPa (Selverstone et al., 1984) to near eclogite facies (up to 1.9 GPa; Tsujimori & Liou, 2004). Determining  $P$  is fraught with difficulty, especially when applying conventional

thermobarometry, which requires choosing the correct, equilibrium mineral compositions to match the proposed metamorphic evolution. Quartz-in-garnet (QuiG) elastic thermobarometry provides a relatively simple way to estimate pressure independent of mineral equilibrium (Angel et al., 2014; Kohn, 2014; Spear et al., 2014; Thomas & Spear, 2018; Gonzalez et al., 2019; Alvaro et al., 2020) and is widely applicable because quartz inclusions are very common in garnet porphyroblasts. The QuiG technique is especially practical for situations with complex metamorphic growth histories that can be gleaned from garnet zoning (e.g. Košmińska et al., 2020; Wolfe & Spear, 2020; Wolfe et al., 2021). QuiG is also useful in evaluating  $P$ - $T$  estimates derived from compositional zoning in terms of equilibrium versus metastable reaction overstepping (Castro & Spear, 2017; Spear & Wolfe, 2020).

Establishing the timing of metamorphism requires dating radiometric accessory minerals that can be linked to the  $P$ - $T$  path in a process referred to as petrochronology (Engi et al., 2017). Monazite is a common accessory mineral in a variety of metamorphic rocks including medium  $P$  schists (e.g. Spear, 2010; Engi, 2017) and one of the main hosts of U and Th. Different generations of monazite can be recognized based on textural and compositional characteristics (Kohn et al., 2005; Dumond et al., 2015); they can record multiple events and a complex history. *In-situ* monazite dating allows for preservation of textural context while targeting different growth zones (Catlos et al., 2002; Williams & Jercinovic, 2012; Kylander-Clark et al., 2013; Hallett & Spear, 2015). Thus, monazite has proven to be a useful mineral for constraining time ( $t$ ) on the  $P$ - $T$  path of complex metamorphic rocks (e.g. Štípská et al., 2015; Engi, 2017).



**Fig. 2.** (a) Geological map of the Mitchell Point peninsula modified from Trettin & Frisch (1996); metamorphic isograds are from Klaper & Ohta (1993). (b) Detailed geological map of the studied outcrop showing small-scale variation in lithology. Stars indicate sample locations. Yellow stars are samples chosen for petrochronological studies.

Textural relationships and trace element patterns help link the growth of monazite to the formation of other major and accessory minerals such as garnet (Foster et al., 2000; Pyle & Spear, 2003; Kohn et al., 2005; Rubatto et al., 2013; Dumond et al., 2015; Mottram et al., 2014; Petrák et al., 2019).

This study focuses on two monazite-bearing samples to establish a  $P$ - $T$ - $t$  path for the unit that includes the unusual garbenschists of the PBA. Phase equilibrium thermodynamic modeling of a garnet-bearing and amphibole-absent metapelite is used to establish a partial  $P$ - $T$  path because the garnet-kyanite-staurolite garbenschist, with its post-tectonic, fluid-facilitated overgrowths of large amphibole, is not suitable for modeling. We apply the QuiG technique to both the metapelite and the garbenschist to further establish the  $P$  of garnet growth during a Barrovian metamorphic event. Monazite with three different textures and compositions can be tied to the petrology and is dated with *in-situ* secondary ion mass spectrometry techniques. The timing of the peak Barrovian metamorphism most likely reflects the accretion of the Pearya terrane simultaneous with subduction-related(?) magmatism in the Middle Devonian.

## GEOLOGICAL SETTING

The composite Pearya Terrane (Trettin, 1987, 1998) constitutes northernmost Ellesmere Island in the Canadian Arctic archipelago (Fig. 1). Pearya is an amalgamation of

a Tonian crystalline arc, a low-grade package of Neoproterozoic to Paleozoic metasedimentary rocks, an Ordovician sub-arc igneous complex and volcanoclastic units that are unconformably overlain by middle Ordovician to Silurian sedimentary rocks (Trettin, 1998; Malone et al., 2014, 2017, 2019; Estrada et al., 2018). Pearya is the only exotic element recognized along the Arctic margin of Laurentia, and its accretionary history is enigmatic (McClelland et al., 2022). The Pearya terrane is separated from the Laurentian margin deep-water deposits and platform sedimentary rocks of the Neoproterozoic to early Paleozoic Franklinian basin (Dewing et al., 2019 and references therein) by a belt of rocks dominated by Silurian flysch, but also containing puzzling Ordovician-Silurian volcanic rocks and metamorphic rocks of uncertain age and affinity (Trettin, 1998). The flysch, known as the Danish River and Lands Lokk formations (Trettin, 1998), comprises turbiditic deposits that blanket the underlying Franklinian basin. Isolated sedimentary and volcanic sections with possible arc affinities, such as the Ordovician Kulutingwak formation (Bjørnerud & Bradley, 1992; Trettin, 1998) and the Fire Bay volcanic assemblage (Koch et al., 2022), lie adjacent to prominent strike-slip faults (Fig. 1b). The sedimentary rocks of the Franklinian basin, Kulutingwak formation and flysch are folded together above a proposed decollement lying above Paleoproterozoic Laurentian basement (Piepjohn & von Gosen, 2018).

The steep Petersen Bay fault zone marks the southern boundary of Pearya west of Yelverton Inlet (Fig. 1b). The

older, ductile shear zone has been interpreted as either a SE-directed overturned thrust (Klaper, 1992) or a significant translational zone formed in transpression (Trettin, 1987; McClelland *et al.*, 2021, 2022). The current Petersen Bay fault is a Cenozoic, brittle structure with both dextral and sinistral strike-slip shear sense (Piepjohn *et al.*, 2013; Piepjohn & von Gosen, 2018). Cataclasites, locally up to a few hundred meters thick, suggest substantial brittle translation, although the amount of Cenozoic displacement is unknown (McClelland *et al.*, 2022). Northwest of the fault, the Pearya terrane is characterized by medium-grade, polydeformed, Tonian orthogneiss and associated paragneiss (Trettin, 1998; Malone *et al.*, 2017; Estrada *et al.*, 2018). The unusual schists of this study (Fig. 2) are part of the PBA (Klaper, 1992), which forms a 22 km long and 1–3 km wide layer lying immediately southeast of the fault zone (Trettin & Frisch, 1996). The PBA is assumed to be in depositional contact with the younger Danish River formation to the southeast (Klaper, 1992).

The PBA consists of marble, amphibole ± garnet schist, amphibolite, serpentinite and minor psammitic and pelitic schists. The PBA has been correlated with the lower-grade Ordovician Kulutingwak Formation (Trettin & Frisch, 1996; Trettin, 1998), which has been interpreted as a carbonate-volcanic association with arc affinity (Bjørnerud, 1991; Bjørnerud & Bradley, 1992). We retain the original name here (i.e. PBA) to distinguish the higher-grade metamorphic rocks of the study area from lower grade sections along other faults. The rocks of the PBA have a steep schistosity that is approximately parallel to the strike of the Petersen Bay fault; stretching lineations are uncommon in the schists (Klaper, 1992). Klaper & Ohta (1993) estimated peak metamorphic conditions up to 600°C and 0.6 GPa for garnet-kyanite schist from the PBA. They also defined a series of isograds extending southeastward over a distance of 10 km from amphibolite to greenschist facies (Fig. 2a). The age of metamorphism has not been directly determined; however,  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau ages of  $433 \pm 3$  Ma on hornblende from a PBA schist and  $322 \pm 2$  Ma from muscovite in a cross-cutting pegmatite (Trettin *et al.*, 1992) put some limits on the timing.

Our study focuses on an outcrop of exceptionally well-preserved PBA lithologies located in a stream that was accessible during low meltwater conditions (Fig. 2b). In contrast, much of the PBA along the fault zone (Fig. 2a) is considerably altered by pervasive, late  $\text{CO}_2$ -rich fluids. The studied locality is a mixture of at least seven lithologies suggestive of a deformed *mélange* in an arc environment (Figs 2b and 3; Table 1). Massive amphibolite with visible kyanite but no garnet occurs in the SE part of the outcrop (samples 17-62, 17-63; Fig. 3a, b) and serpentinite forms prominent lenses (sample 17-65, Fig. 3c). Quartzofeldspathic psammite, metachert and marble constitute a package of cm-thick layers (samples 17-71, 17-70; Fig. 3d). A variety of garnet-bearing schists (samples 17-66, 17-67 and 17-69, Fig. 3f–h), locally with garnet megablasts up to 5 cm (sample 17-68, Fig. 3e), are

common. In some places, the schistosity is overprinted by amphibole sheaves forming garbenschist (sample 17-64, Fig. 3f); these are typically the rocks with the lowest variance assemblage. Two samples, metapelite 17-66 and garbenschist 17-64, contain monazite and were thus suitable for petrochronological analysis.

## METHODS

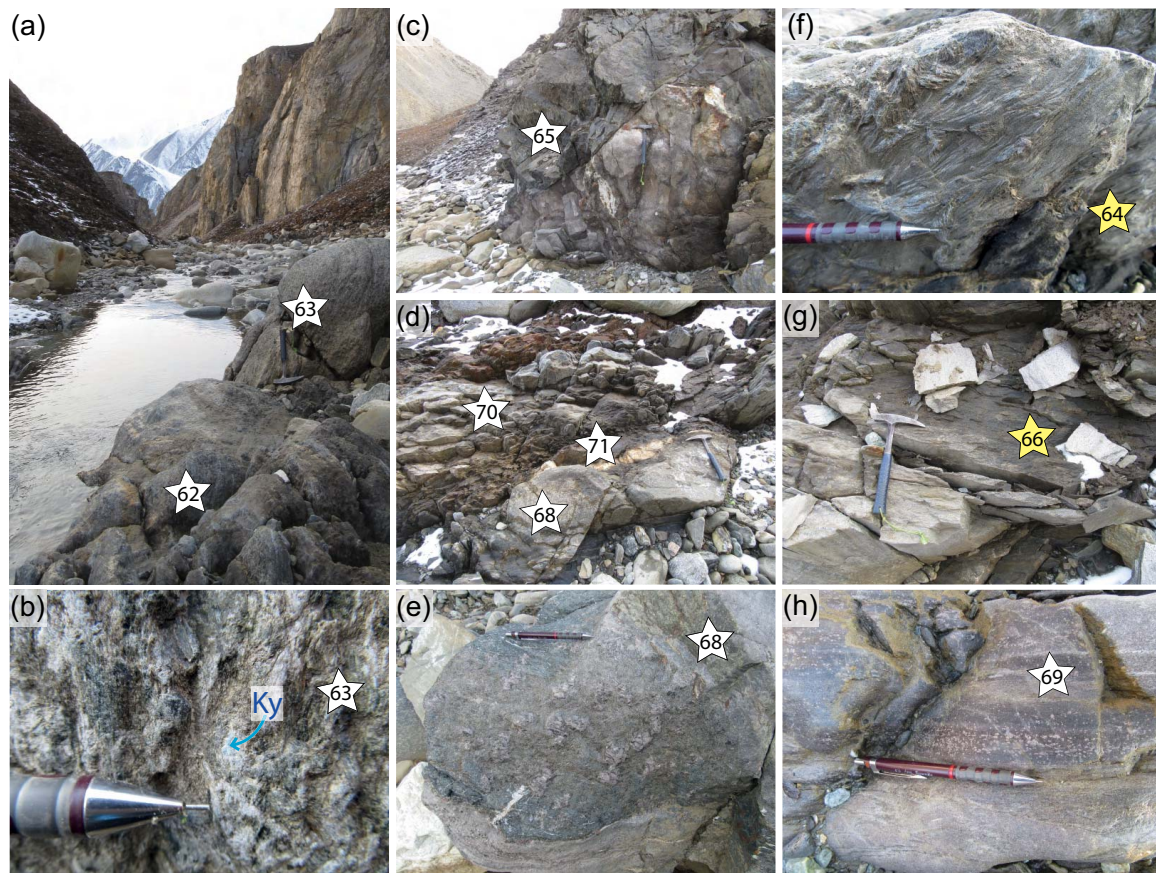
### Mineral and whole rock chemistry

The mineral chemistry and X-ray concentration maps were determined by wavelength dispersive spectrometry using a JEOL JXA-8230 Superprobe Electron Probe Microanalyser (EPMA) at the University of Iowa, Iowa City, IA. The operating conditions for the spot analyses were 20 nA beam current, 15 kV accelerating voltage and counting times of 10 s on peaks and 5 s on background. The beam size varies from 1  $\mu\text{m}$  to 10  $\mu\text{m}$  depending on the mineral. Natural mineral standards were used for calibration. Representative analyses are reported in Tables 2–4. Garnet X-ray mapping of major and trace element composition was performed with 15 kV accelerating voltage, 100 nA beam current and 100 ms dwell time. Mapping of monazite used a similar routine, with a shorter dwell time of 50 ms. The pixel size for X-ray maps varied depending on the size of the individual grains or porphyroblasts. X-ray maps were processed using the software ImageJ (Schneider *et al.*, 2012). Mineral abbreviations are after Whitney & Evans (2010).

The bulk rock composition of five samples was determined by X-ray fluorescence at the Bureau Veritas Mineral Laboratories in Canada (Table S1). Samples were fused with  $\text{LiBO}_2/\text{Li}_2\text{B}_4\text{O}_7$ .

### Phase equilibrium modelling

Isochemical phase equilibrium modelling to produce *P*–*T* pseudosections was performed using Perple\_X software version 6.8.4 (Connolly, 1990, 2005) with the internally consistent thermodynamic database by Holland & Powell (2011) in the  $\text{MnO}$ – $\text{Na}_2\text{O}$ – $\text{K}_2\text{O}$ – $\text{CaO}$ – $\text{FeO}$ – $\text{MgO}$ – $\text{Al}_2\text{O}_3$ – $\text{SiO}_2$ – $\text{H}_2\text{O}$ – $\text{TiO}_2$ – $\text{O}_2$  (MnNCKFMASHTO) system. The amount of  $\text{Fe}^{3+}$  was set as 5% of total Fe based on the pelitic character of the sample and presence of ilmenite (e.g. Palin *et al.*, 2016; Manzotti *et al.*, 2018; Forshaw & Pattison, 2021). A pseudosection with no  $\text{Fe}^{3+}$  is presented for comparison as the Supplementary Figure S1. Calculations in the range of 0–10%  $\text{Fe}^{3+}$  show limited effect on phase assemblage fields.  $\text{H}_2\text{O}$  was assumed to be present in excess, which is supported by the abundance of hydrous phases, particularly white mica and biotite. *P*–*T* pseudosections were calculated for the range of 0.5–1.0 GPa and 550–700°C. The following solution models were used in the calculations: garnet (White *et al.*, 2007), biotite (White *et al.*, 2014), white mica (White *et al.*, 2014), plagioclase (Holland & Powell, 2003), ilmenite (White *et al.*, 2000) and chlorite (White *et al.*, 2014).



**Fig. 3.** Outcrop photographs of the Petersen Bay Assemblage; stars mark sample locations, yellow stars are samples studied in detail. (a) Amphibolite with kyanite viewed to the SW, (b) kyanite-bearing amphibolite, (c) lens of serpentinite, (d–e) garnet-bearing schist with megablasts (sample 17-68), metachert (17-70) and marble (17-61), (f) garbenschist, (g–h) garnet-bearing schists.

**Table 1:** Samples, locations and mineral assemblages

| Sample ID | IGSN*     | Lithology        | Lat           | Long          | Grt | Amp | Ms | Bt | Pl | Qz | Ilm | Rt | Ky | St | Cal | Ser |
|-----------|-----------|------------------|---------------|---------------|-----|-----|----|----|----|----|-----|----|----|----|-----|-----|
| 17-10     | IEMCC001C | Leucocratic dike | 82° 13' 25.7" | 82° 37' 50.9" |     |     | x  |    | x  | x  |     |    |    |    |     |     |
| 17-62     | IEMCC002J | Amphibolite      | 82° 11' 56.1" | 82° 47' 26.1" |     | x   |    | x  | x  | x  |     | x  | x  |    |     |     |
| 17-63     | IEMCC002K | Amphibolite      | 82° 11' 56.3" | 82° 47' 25.4" |     | x   |    | x  | x  | x  |     | x  | x  |    | x   |     |
| 17-64     | IEMCC002L | Schist           | 82° 11' 56.1" | 82° 47' 24.2" | x   | x   |    | x  | x  | x  | x   | x  | x  | x  |     |     |
| 17-65     | IEMCC002M | Serpentinite     | 82° 11' 57.0" | 82° 47' 16.8" |     |     |    |    |    |    |     |    |    |    |     | x   |
| 17-66     | IEMCC002N | Schist           | 82° 11' 57.4" | 82° 47' 13.6" | x   |     | x  | x  | x  | x  | x   | x  | x  |    |     |     |
| 17-67     | IEMCC002O | Schist           | 82° 11' 57.6" | 82° 47' 13.9" |     |     |    |    |    |    |     |    |    |    |     |     |
| 17-68     | IEMCC002P | Schist           | 82° 11' 56.3" | 82° 47' 23.1" | x   |     | x  | x  | x  | x  | x   | x  |    |    | x   |     |
| 17-69     | IEMCC002Q | Schist           | 82° 11' 57.8" | 82° 47' 12.7" | x   |     | x  | x  | x  | x  | x   |    |    |    |     |     |
| 17-70     | IEMCC002R | Chert            | 82° 11' 56.4" | 82° 47' 22.3" |     |     |    |    |    | x  |     |    |    |    |     |     |
| 17-71     | IEMCC002S | Limestone        | 82° 11' 56.5" | 82° 47' 21.4" |     |     |    |    |    |    |     |    |    |    | x   |     |

\* IGSN - International Generic Sample Number

### Raman spectroscopy and elastic thermobarometry

Minerals commonly contain inclusions with significantly different elastic properties that can be used for elastic thermobarometry (Rosenfeld & Chase, 1961; Rosenfeld, 1969; Van der Molen & Van Roermund, 1986; Enami et al., 2007; Angel et al., 2014; Ashley et al., 2014; Kohn, 2014; Angel et al., 2015; Thomas & Spear, 2018; Murri et al., 2018). Elastic property differences between host and mineral inclusions can cause strain in the inclusion/host

system that produces inclusions with remnant pressures. The remnant pressure in an inclusion can be related to its entrapment  $P$ - $T$  conditions using equations of state and a physical model that describes volumetric changes to the inclusion-host mineral system. We calculated inclusion pressures ( $P_{inc}$ ) from room temperature measurements of the 128, 206 and 464  $\text{cm}^{-1}$  Raman bands of strained quartz inclusions in garnet.  $P_{inc}$  was calculated using an elastic tensor approach, which is discussed in detail by Bonazzi et al. (2019) and Gonzalez et al. (2019). The

**Table 2:** Representative analyses of garnet

| Sample ID                      | 17-64  | 17-64  | 17-64  | 17-64  | 17-66  | 17-66  | 17-66  | 17-66  |
|--------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| Text.type                      | Rim    | Rim    | Core   | Core   | Rim    | Rim    | Core   | Core   |
| Analysis                       | 5      | 141    | 83     | 92     | 1      | 86     | 47     | 48     |
| SiO <sub>2</sub>               | 38.63  | 38.65  | 38.31  | 38.44  | 37.26  | 37.64  | 36.97  | 37.55  |
| TiO <sub>2</sub>               | 0.03   | 0.04   | 0.05   | 0.02   | 0.03   | 0.02   | 0.01   | 0.02   |
| Al <sub>2</sub> O <sub>3</sub> | 21.81  | 21.70  | 21.61  | 21.54  | 21.01  | 21.23  | 20.82  | 20.77  |
| Cr <sub>2</sub> O <sub>3</sub> | 0.01   | 0.05   | 0.06   | 0.06   | 0.01   | 0.02   | 0.00   | 0.00   |
| FeO                            | 27.38  | 27.40  | 24.62  | 24.71  | 36.13  | 34.32  | 32.06  | 32.09  |
| MnO                            | 2.40   | 2.19   | 6.03   | 5.87   | 1.01   | 0.81   | 4.77   | 4.75   |
| MgO                            | 7.29   | 6.80   | 6.20   | 6.44   | 2.78   | 3.55   | 2.34   | 2.35   |
| CaO                            | 2.96   | 3.27   | 3.43   | 3.20   | 2.49   | 3.26   | 3.11   | 2.86   |
| Total                          | 100.51 | 100.10 | 100.31 | 100.27 | 100.72 | 100.84 | 100.17 | 100.15 |
| O                              | 12     | 12     | 12     | 12     | 12     | 12     | 12     | 12     |
| Si                             | 2.994  | 3.008  | 2.993  | 3.001  | 2.988  | 2.990  | 2.989  | 3.018  |
| Ti                             | 0.002  | 0.002  | 0.003  | 0.001  | 0.002  | 0.001  | 0.001  | 0.001  |
| Al                             | 1.992  | 1.991  | 1.990  | 1.982  | 1.987  | 1.989  | 1.984  | 1.968  |
| Cr                             | 0.001  | 0.003  | 0.004  | 0.003  | 0.001  | 0.001  | 0.000  | 0.000  |
| Fe                             | 1.775  | 1.784  | 1.609  | 1.613  | 2.423  | 2.280  | 2.167  | 2.157  |
| Mn                             | 0.158  | 0.144  | 0.399  | 0.388  | 0.069  | 0.055  | 0.327  | 0.324  |
| Mg                             | 0.841  | 0.788  | 0.722  | 0.749  | 0.333  | 0.420  | 0.282  | 0.282  |
| Ca                             | 0.246  | 0.273  | 0.287  | 0.267  | 0.214  | 0.278  | 0.269  | 0.247  |
| Cation total                   | 8.010  | 7.993  | 8.007  | 8.005  | 8.016  | 8.014  | 7.994  | 8.016  |
| X <sub>Alm</sub>               | 0.59   | 0.60   | 0.53   | 0.53   | 0.80   | 0.75   | 0.71   | 0.72   |
| X <sub>Sps</sub>               | 0.05   | 0.05   | 0.13   | 0.13   | 0.02   | 0.02   | 0.11   | 0.11   |
| X <sub>Prp</sub>               | 0.28   | 0.26   | 0.24   | 0.25   | 0.11   | 0.14   | 0.09   | 0.09   |
| X <sub>Grs</sub>               | 0.08   | 0.09   | 0.10   | 0.09   | 0.07   | 0.09   | 0.09   | 0.08   |
| X <sub>Fe</sub>                | 0.68   | 0.69   | 0.69   | 0.68   | 0.88   | 0.84   | 0.88   | 0.88   |

X<sub>Alm</sub> = Fe<sup>2+</sup>/(Fe<sup>2+</sup> + Mg + Ca + Mn); X<sub>Sps</sub> = Mn/(Fe<sup>2+</sup> + Mg + Ca + Mn); X<sub>Prp</sub> = Mg/(Fe<sup>2+</sup> + Mg + Ca + Mn); X<sub>Grs</sub> = Ca/(Fe<sup>2+</sup> + Mg + Ca + Mn); X<sub>Fe</sub> = Fe<sup>2+</sup>/(Fe<sup>2+</sup> + Mg)

difference between the calculated shift of Raman bands and unstrained quartz ( $\Delta\omega$ ) was used for strain ( $\epsilon$ ) calculations in *stRAINMAN* software (Angel et al., 2019). We calculated stress ( $\sigma$ ) using the elastic tensor of quartz (Wang et al., 2015). The  $P_{inc}$  was derived from the stresses following the equation:  $P_{inc} = -\frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$ . We used software EoSFit-Pinc (Angel et al., 2017) to create entrapment isomekes.

We used ~150  $\mu\text{m}$ -thick doubly polished rock sections for Raman spectroscopic measurements at Syracuse University, Syracuse, NY, and 30  $\mu\text{m}$ -thick thin sections at Rensselaer Polytechnic Institute, Troy, NY. All inclusions measured were free of cracks, spherical and > 3 radii from any other interfaces (e.g. inclusions, polished surface, etc.). Raman spectra were measured on Bruker Senterra (Rensselaer Polytechnic Institute) and Renishaw inVia (Syracuse University) Raman microprobe spectrometers at room conditions of 1 bar (0.1 MPa) and 23°C. The spectrometers were calibrated against the Rayleigh scattered light from the 532 nm lasers, Ne lines and the 520.5  $\text{cm}^{-1}$  Raman band of a silicon standard. Throughout analytical sessions, we also measured the 128, 206 and 464  $\text{cm}^{-1}$  Raman bands of synthetic quartz crystals cut parallel to the c axis as reference materials. The laser was focused on the center of inclusions using 100 $\times$  objectives (N.A. = 0.9) to perform confocal measurements. The Raman shifted light (180° backscattering geometry) was dispersed with 1200 line/mm (Bruker) or 1800 line/mm (Renishaw) gratings onto charged-couple devices for 20 to

30 second analyses. We determined changes to the Raman band positions of quartz inclusions ( $\Delta\omega_{128}$ ,  $\Delta\omega_{206}$  and  $\Delta\omega_{464}$ ) by measuring band positions in inclusions and subtracting the position of the same bands of a free quartz crystal (e.g. a piece of quartz reference material sitting on the Raman microscope stage).

### Monazite U-Pb geochronology and trace elements

Monazite U-Pb and trace element analysis was performed *in-situ* on polished thin sections using the Sensitive High-Resolution Ion Microprobe with Reverse Geometry (SHRIMP-RG) at the Stanford-USGS Micro-Analysis Center at Stanford University, CA. Back scattered electron (BSE) images of thin sections were collected using a Hitachi S-3400 N at the University of Iowa and a JEOL 5600 SEM at Stanford University. The thin sections were then cut and mounted together with natural reference materials in epoxy megamounts (37.5 mm diameter). The primary O<sub>2</sub><sup>-</sup> ion beam was accelerated at 10 kV to achieve an intensity of 2.5–3.0 nA and focused to an 18  $\times$  20  $\mu\text{m}$  diameter spot. Pit depth was approximately ~2–3  $\mu\text{m}$ . The SHRIMP-RG was tuned for a mass resolution of ~8500 (10% peak height), with the energy selection window set to accept high-energy ions into the collector in order to minimize transmission of low-energy, complex isobaric interferences (e.g. <sup>232</sup>Th + REE + <sup>16</sup>O<sup>++</sup> or <sup>232</sup>Th + REE + <sup>31</sup>P<sup>++</sup>) and minimize the background at the Pb peak positions.

**Table 3:** Representative analyses of biotite, muscovite and amphibole

|                                | 17-64   | 17-64  | 17-66  | 17-66  | 17-66  | 17-66     | 17-66  | 17-64     | 17-64  | 17-64  |
|--------------------------------|---------|--------|--------|--------|--------|-----------|--------|-----------|--------|--------|
| Mineral                        | Biotite |        |        |        |        | Muscovite |        | Amphibole |        |        |
| Text.type                      | Matrix  | Matrix | Matrix | Matrix | Matrix | Matrix    | Matrix | Core      | Mantle | Rim    |
| Analysis                       | 49      | 51     | 12     | 7      | 18     | 11        | 25     | 17        | 26     | 37     |
| SiO <sub>2</sub>               | 38.55   | 38.89  | 35.90  | 35.96  | 35.82  | 45.85     | 45.94  | 47.82     | 48.76  | 48.61  |
| TiO <sub>2</sub>               | 1.23    | 0.97   | 2.09   | 2.23   | 1.59   | 0.67      | 0.76   | 0.14      | 0.08   | 0.12   |
| Al <sub>2</sub> O <sub>3</sub> | 18.26   | 17.98  | 18.90  | 18.78  | 19.01  | 36.78     | 35.91  | 13.79     | 12.05  | 12.29  |
| Cr <sub>2</sub> O <sub>3</sub> | 0.00    | 0.00   | 0.00   | 0.04   | 0.03   | 0.01      | 0.00   | 0.09      | 0.03   | 0.03   |
| FeO                            | 8.71    | 8.62   | 17.04  | 17.21  | 17.36  | 0.97      | 1.25   | 14.82     | 15.40  | 16.23  |
| MnO                            | 0.03    | 0.03   | 0.02   | 0.00   | 0.00   | 0.01      | 0.00   | 0.29      | 0.36   | 0.46   |
| MgO                            | 18.76   | 19.05  | 10.91  | 11.31  | 11.83  | 0.82      | 0.85   | 19.25     | 19.50  | 18.75  |
| CaO                            | 0.01    | 0.01   | 0.00   | 0.00   | 0.00   | 0.00      | 0.00   | 0.49      | 0.39   | 0.32   |
| Na <sub>2</sub> O              | 0.59    | 0.50   | 0.38   | 0.38   | 0.37   | 1.55      | 1.36   | 1.30      | 1.30   | 1.18   |
| K <sub>2</sub> O               | 8.46    | 8.29   | 9.26   | 9.40   | 8.69   | 9.54      | 9.54   | 0.01      | 0.00   | 0.02   |
| BaO                            | 0.10    | 0.16   | 0.05   | 0.00   | 0.10   | 0.21      | 0.15   | n.a.      | n.a.   | n.a.   |
| F                              | 0.06    | 0.19   | 0.17   | 0.23   | 0.31   | 0.01      | 0.04   | 0.00      | 0.00   | 0.00   |
| Cl                             | 0.01    | 0.02   | 0.00   | 0.01   | 0.00   | 0.00      | 0.00   | 0.00      | 0.00   | 0.00   |
| Total                          | 94.77   | 94.71  | 94.73  | 95.55  | 95.12  | 96.43     | 95.80  | 98.00     | 97.87  | 97.99  |
| O                              | 11      | 11     | 11     | 11     | 11     | 11        | 11     | 22        | 22     | 22     |
| Si                             | 2.778   | 2.804  | 2.720  | 2.707  | 2.703  | 3.012     | 3.039  | 6.665     | 6.821  | 6.822  |
| Ti                             | 0.067   | 0.053  | 0.119  | 0.126  | 0.090  | 0.033     | 0.038  | 0.015     | 0.008  | 0.014  |
| Al <sup>IV</sup>               | 1.222   | 1.196  | 1.280  | 1.293  | 1.297  | 0.988     | 0.961  | 1.335     | 1.179  | 1.178  |
| Al <sup>VI</sup>               | 0.329   | 0.331  | 0.407  | 0.372  | 0.393  | 1.859     | 1.839  | 0.931     | 0.807  | 0.855  |
| Cr                             | 0.000   | 0.000  | 0.000  | 0.002  | 0.002  | 0.001     | 0.000  | 0.009     | 0.004  | 0.003  |
| Fe <sup>3+</sup>               | 0.000   | 0.000  | 0.000  | 0.000  | 0.000  | 0.000     | 0.000  | 0.430     | 0.423  | 0.367  |
| Fe <sup>2+</sup>               | 0.525   | 0.519  | 1.080  | 1.084  | 1.096  | 0.053     | 0.069  | 1.298     | 1.379  | 1.538  |
| Mn                             | 0.002   | 0.002  | 0.002  | 0.000  | 0.000  | 0.000     | 0.000  | 0.035     | 0.042  | 0.054  |
| Mg                             | 2.015   | 2.047  | 1.232  | 1.269  | 1.331  | 0.080     | 0.084  | 4.000     | 4.067  | 3.923  |
| Ca                             | 0.001   | 0.001  | 0.000  | 0.000  | 0.000  | 0.000     | 0.000  | 0.074     | 0.058  | 0.048  |
| Na                             | 0.082   | 0.070  | 0.056  | 0.056  | 0.055  | 0.197     | 0.175  | 0.353     | 0.351  | 0.320  |
| K                              | 0.777   | 0.762  | 0.895  | 0.903  | 0.837  | 0.799     | 0.805  | 0.000     | 0.000  | 0.000  |
| Ba                             | 0.003   | 0.004  | 0.002  | 0.000  | 0.003  | 0.005     | 0.004  | n.a.      | n.a.   | n.a.   |
| Total                          | 7.800   | 7.789  | 7.793  | 7.812  | 7.806  | 7.029     | 7.014  | 15.145    | 15.139 | 15.122 |
| X <sub>Fe</sub>                | 0.21    | 0.20   | 0.47   | 0.46   | 0.45   |           |        | 0.24      | 0.25   | 0.28   |

X<sub>Fe</sub> = Fe<sup>2+</sup>/(Fe<sup>2+</sup> + Mg)

Repeated analysis of reference material 44 069 monazite (Concordia age = 424.9 ± 0.5 Ma; Aleinikoff *et al.*, 2006) was used to calculate ages of unknowns. Trace element concentrations (Y, REE, U, Th) were calibrated using 44 069 values established through comparison with trace element concentrations of reference material NAM monazite (Aleinikoff *et al.*, 2012). The estimated uncertainty (1 $\sigma$  SD) for monazite trace element concentrations is 3 to 6% for U, Th, Y, La, Pr, Nd, Sm, Eu, Gd, and Dy and ~10% for Er and Yb based on repeated analysis of 44 069 and reported reproducibility of NAM (Aleinikoff *et al.*, 2012).

Data processing and plotting was performed using Squid 2.51 and Isoplot 4.15 (Ludwig, 2009, 2012). Corrections for common Pb using compositional estimates from Stacey & Kramers (1975) were based on <sup>207</sup>Pb for <sup>206</sup>Pb/<sup>238</sup>U ages and the measured <sup>204</sup>Pb for <sup>207</sup>Pb/<sup>206</sup>Pb ages. Isotopic ratios and dates are reported with analytical uncertainties (2 $\sigma$ ). The <sup>206</sup>Pb/<sup>238</sup>U and <sup>207</sup>Pb/<sup>206</sup>Pb model ages are reported with 2 $\sigma$  uncertainties that include error in external reproducibility (1 $\sigma$  SD) of reference material 44 069 during the individual analytical session summed in quadrature.

## RESULTS

### Petrography and chemistry

Thirty thin sections of the PBA were carefully examined and the mineral assemblages for samples from the studied outcrop are given in Table 1. Bulk and trace element chemistry for selected samples is presented in Table S1. Amphibolite containing kyanite and staurolite has been classified as high-Al metabasite in the literature (e.g. Helms *et al.*, 1987). The kyanite-amphibolite in the PBA falls short of the criteria for high-Al basalts given by Crawford *et al.* (1987), i.e. SiO<sub>2</sub> < 54 wt % and Al<sub>2</sub>O<sub>3</sub> > 16.5 wt %, although sample 17-62 is close with SiO<sub>2</sub> = 55.16 wt % and Al<sub>2</sub>O<sub>3</sub> = 16.37%. Garbenschist sample 17-64 has a very similar bulk composition as garbenschist 88E1118 studied by Klaper & Ohta (1993). Garbenschist samples 17-64 and 17-62 are characterized by SiO<sub>2</sub> of 57.70 and 59.09 wt %, Al<sub>2</sub>O<sub>3</sub> of 13.97 and 15.05 wt %. The two garnet-bearing schists (17-64 and 17-66) that contain monazite, and are thus suitable for petrochronology, are described below. Tables 2–4 present representative analyses of their mineral chemistry.

Garbenschist 17-64 is composed of garnet, biotite, amphibole, staurolite, kyanite, plagioclase and quartz

**Table 4:** Representative analyses of plagioclase and staurolite

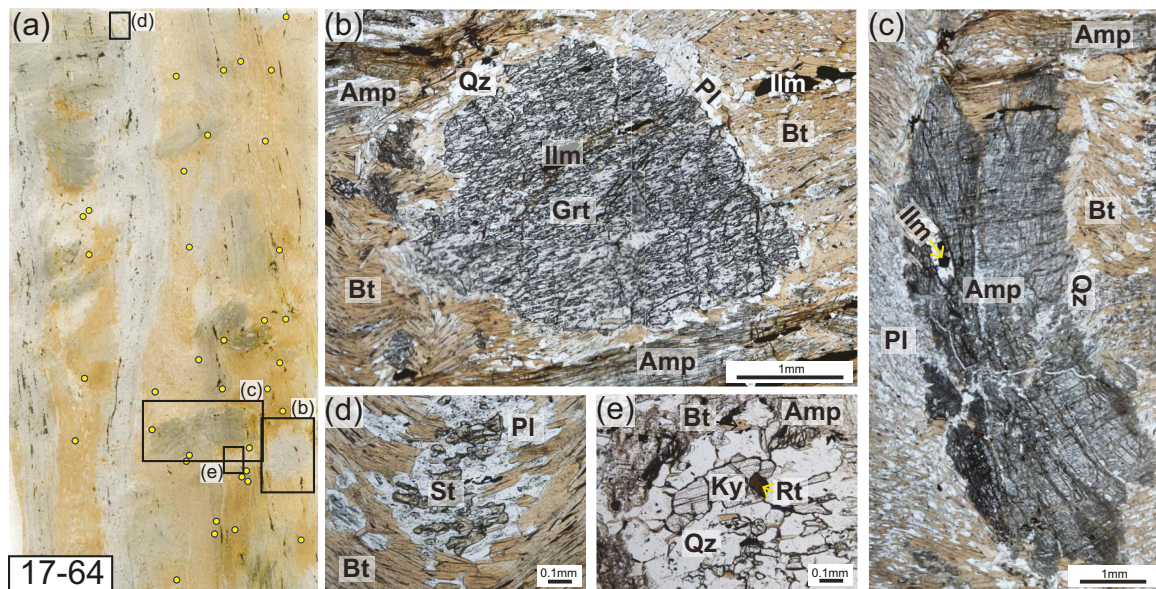
| Sample ID                      | 17-64       | 17-64  | 17-66 | 17-66  | 17-66 | 17-64      | 17-64  |
|--------------------------------|-------------|--------|-------|--------|-------|------------|--------|
| Mineral                        | Plagioclase |        |       |        |       | Staurolite |        |
| Text.type                      | Matrix      | Matrix | Core  | Rim    | Rim   | Core       | Rim    |
| Analysis                       | 38          | 48     | 7     | 17     | 18    | 11         | 13     |
| SiO <sub>2</sub>               | 60.70       | 61.42  | 61.60 | 64.04  | 63.07 | 28.52      | 28.27  |
| TiO <sub>2</sub>               | 0.00        | 0.04   | 0.00  | 0.00   | 0.02  | 0.69       | 0.50   |
| Al <sub>2</sub> O <sub>3</sub> | 25.24       | 25.06  | 24.14 | 23.55  | 23.84 | 53.96      | 53.77  |
| Cr <sub>2</sub> O <sub>3</sub> | n.a.        | n.a.   | n.a.  | n.a.   | n.a.  | 0.31       | 0.30   |
| FeO                            | 0.10        | 0.50   | 0.07  | 0.04   | 0.01  | 9.82       | 10.48  |
| MnO                            | 0.00        | 0.00   | 0.00  | 0.00   | 0.00  | 0.13       | 0.13   |
| MgO                            | 0.00        | 0.02   | 0.00  | 0.00   | 0.00  | 3.31       | 2.96   |
| CaO                            | 6.79        | 5.74   | 5.46  | 3.94   | 4.76  | 0.00       | 0.01   |
| Na <sub>2</sub> O              | 7.21        | 7.46   | 7.74  | 8.45   | 8.12  | 0.07       | 0.07   |
| K <sub>2</sub> O               | 0.02        | 0.16   | 0.51  | 0.10   | 0.04  | 0.01       | 0.01   |
| ZnO                            | n.a.        | n.a.   | n.a.  | n.a.   | n.a.  | 1.43       | 1.46   |
| Total                          | 100.05      | 100.39 | 99.53 | 100.13 | 99.86 | 98.25      | 97.96  |
| O                              | 8           | 8      | 8     | 8      | 8     | 23         | 23     |
| Si                             | 2.692       | 2.713  | 2.743 | 2.811  | 2.782 | 3.899      | 3.890  |
| Ti                             | 0.000       | 0.001  | 0.000 | 0.000  | 0.001 | 0.071      | 0.052  |
| Al                             | 1.320       | 1.305  | 1.267 | 1.219  | 1.240 | 8.695      | 8.720  |
| Cr                             | 0.000       | 0.000  | n.a.  | n.a.   | n.a.  | 0.033      | 0.032  |
| Fe                             | 0.004       | 0.019  | 0.003 | 0.002  | 0.001 | 1.123      | 1.206  |
| Mn                             | 0.000       | 0.000  | 0.000 | 0.000  | 0.000 | 0.015      | 0.015  |
| Mg                             | 0.000       | 0.001  | 0.000 | 0.000  | 0.000 | 0.675      | 0.607  |
| Ca                             | 0.323       | 0.272  | 0.260 | 0.185  | 0.225 | 0.000      | 0.001  |
| Na                             | 0.620       | 0.639  | 0.669 | 0.719  | 0.695 | 0.019      | 0.019  |
| K                              | 0.001       | 0.009  | 0.029 | 0.005  | 0.002 | 0.002      | 0.001  |
| Zn                             | 0.000       | 0.000  | n.a.  | n.a.   | n.a.  | 0.144      | 0.148  |
| Cation total                   | 4.959       | 4.957  | 4.972 | 4.942  | 4.946 | 14.676     | 14.692 |
| X <sub>Ab</sub>                | 0.66        | 0.69   | 0.70  | 0.79   | 0.75  |            |        |
| X <sub>An</sub>                | 0.34        | 0.30   | 0.27  | 0.20   | 0.24  |            |        |
| X <sub>Or</sub>                | 0.00        | 0.01   | 0.03  | 0.01   | 0.00  |            |        |
| X <sub>Fe</sub>                |             |        |       |        |       | 0.57       | 0.61   |

$X_{Fe} = Fe^{2+}/(Fe + Mg)$ ;  $X_{Ab} = Na/(Na + Ca + K)$ ;  $X_{An} = Ca/(Na + Ca + K)$ ;  $X_{Or} = K/(Na + Ca + K)$ .

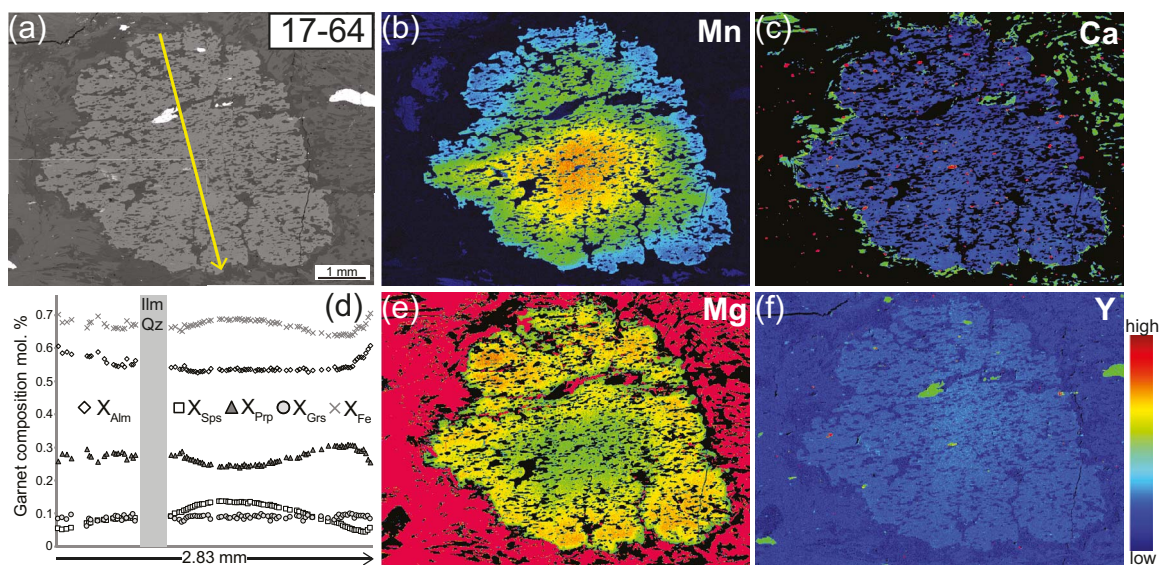
(Fig. 4). The accessory phases are zircon, monazite, allanite, xenotime, apatite, tourmaline, pyrite, ilmenite and rutile. Garnet forms anhedral porphyroblasts up to 5 mm in diameter and is not abundant (i.e. 1–2 porphyroblasts at the thin section scale; Fig. 4a and b). The porphyroblasts have abundant inclusions of quartz, ilmenite, pyrite and allanite. Garnet rims are partly replaced by plagioclase and biotite. Garnet exhibits prograde zoning, which is demonstrated by bell-shaped spessartine component, varying from 0.14 in the core to 0.05 mol % in the rim (Fig. 5).  $X_{Fe} = Fe^{2+}/Fe^{2+} + Mg$  decreases from core to rim. Grossular is rather constant at ~0.09 mol % throughout the garnet porphyroblast. Back diffusion is observed in the garnet rim (Fig. 5), which results in an increase of  $X_{Sps}$  and  $X_{Fe}$  in the outer rim. The preferred shape orientation of biotite defines the main schistosity. Biotite has  $X_{Fe} = Fe^{2+}/Fe^{2+} + Mg$  ranging from 0.20 to 0.21 and low Ti between 0.05–0.07 a.p.f.u (atoms per formula unit). Plagioclase is mostly sodic and characterized by Ab = 66–70%, An = 30–34% and Or = 0–1%. Amphibole grew over the foliation and developed typical garben texture (Fig. 4c), forming randomly oriented, feather-like neoblasts up to 5 cm long. Amphibole is gedrite according to the classification of Hawthorne et al. (2012), with Si = 6.42–7.02 a.p.f.u. and moderate to

low Na = 0.27–0.36 a.p.f.u.  $X_{Fe} = Fe^{2+}/Fe^{2+} + Mg$  is slightly zoned and varies from 0.24 to 0.26. Amphibole is partly replaced by chlorite and biotite, and cut by veins that formed during late fluid influx (Fig. 4c). Staurolite remnants in the matrix (Fig. 4d) are ferrous ( $X_{Fe} = 0.63–0.67$ ) and characterized by Zn ranging from 0.14–0.17 a.p.f.u.; Zn is higher near the rims. Kyanite is found in the matrix, often showing resorbed rims (Fig. 4e) or helicitic texture. Ilmenite, partially replaced by rutile, is abundant in the matrix and as inclusions in garnet.

Metapelite 17-66 has a well-developed foliation marked by biotite and white mica (Fig. 6a), and consists of garnet, biotite, muscovite, plagioclase, quartz and kyanite. Accessory minerals are zircon, monazite, allanite, xenotime, apatite, tourmaline, ilmenite and rutile. The sample contains almost no sign of retrogression. Garnet is ~1–2 mm in diameter and forms subhedral porphyroblasts surrounded by matrix minerals (Fig. 6a, b and c). Garnet cores are inclusion-rich, while rims are rather inclusion free. The inclusions are mostly quartz, ilmenite, zircon, apatite and allanite; no kyanite was observed in the garnet. Garnet shows prograde growth zoning and is generally almandine rich (Fig. 7). Spessartine has a bell-shaped profile with a decrease of  $X_{Sps}$  from 0.11 to 0.02 mol % towards the rim. A



**Fig. 4.** Photomicrographs from garbenschist sample 17-64 in plane-polarized light (PPL). (a) Thin section scan; brown areas are biotite rich, dots are monazite locations, (b) garnet porphyroblast overgrowing schistosity, (c) amphibole overgrowing the crenulated foliation, (d) relict of staurolite, (e) kyanite in the matrix.



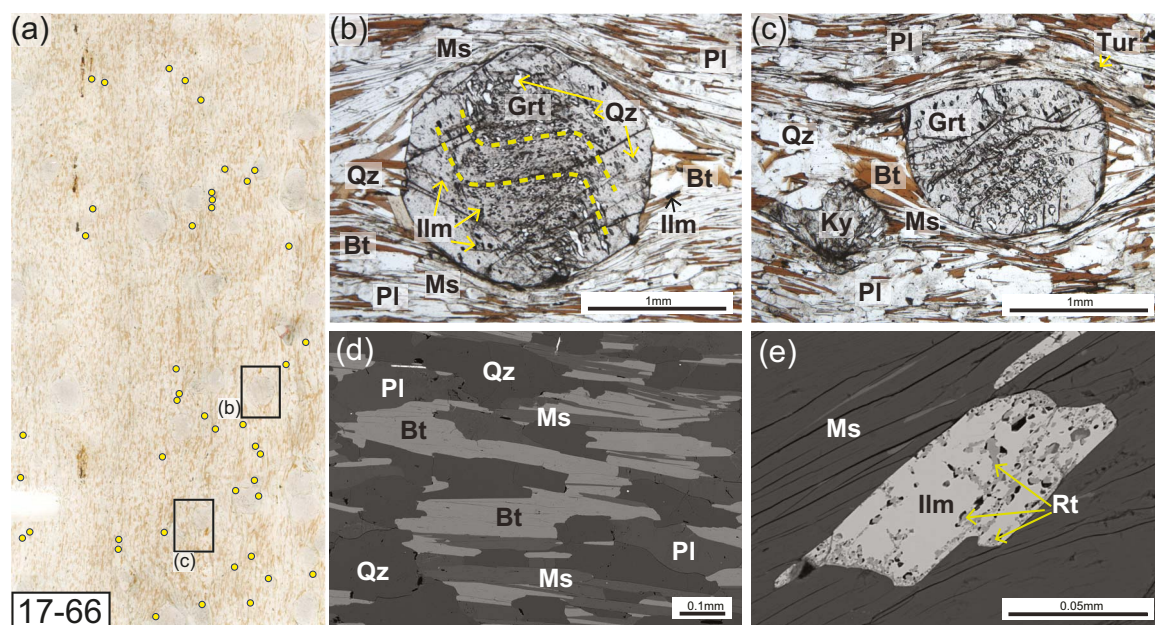
**Fig. 5.** Chemistry of a garnet in sample 17-64. (a) Back-scattered electron (BSE) image, (d) compositional profile along the transect marked on the BSE image, (b,c,e,f) Mn, Mg, Ca and Y compositional maps of garnet.

small increase of  $X_{\text{Sps}}$  ( $<0.01$  mol %) is observed in the outer rim.  $X_{\text{Fe}}$  varies from 0.88 in the core to 0.84; it increases slightly in the outer rim (up to 0.88). Grossular is characterized by higher values in the core (up to 0.09) and depletion in the rim ( $\sim 0.06$ ). The grossular X-ray map demonstrates calcium diffusion along the bigger quartz inclusions (Fig. 7). Up to 0.26 mol % Y is concentrated in the garnet core and decreases below the detection limit in the mantle and rim. Very thin,  $\sim 1\text{--}2\ \mu\text{m}$ , Y-rich annuli occur in the garnet rims (Fig. 7). Biotite defines the foliation, commonly forming intergrowths with white mica (Fig. 6d). Biotite is compositionally homogenous with  $X_{\text{Fe}} = 0.45\text{--}0.47$  and  $\text{Ti} = 0.09\text{--}0.13$  a.p.f.u. White mica is muscovite with  $\text{Si} = 3.01\text{--}3.04$  a.p.f.u. and Na varying

from 0.17–0.20 a.p.f.u. Plagioclase, mostly sodic, is slightly zoned with a composition of  $\text{Ab}_{70\text{--}79}\text{An}_{17\text{--}30}\text{Or}_{0\text{--}5}$ . Kyanite forms grains up to 0.5 mm long that lie parallel or slightly oblique to the foliation (Fig. 6c). Kyanite rims are rarely replaced by sericite. Ilmenite is a common phase in the garnet and matrix. Ilmenite in the garnet rim and in the matrix is partly replaced by rutile (Fig. 6e).

### Thermodynamic modeling

Phase equilibria modeling (i.e. pseudosections) could not be applied to most of the PBA samples. Garnet-bearing schists typically contain late calcite and amphibole overgrowing the metamorphic fabrics, making it impossible to define the bulk composition representing



**Fig. 6.** PPL photomicrographs and BSE images from metapelite 17-66. (a) Thin section scan, dots are monazite locations, (b) garnet porphyroblast with inclusion trails marked in yellow, (c) kyanite and garnet porphyroblasts are oblique to the main foliation, (d) shape preferred orientation of biotite and muscovite define the foliation, (e) rutile replacing matrix ilmenite.

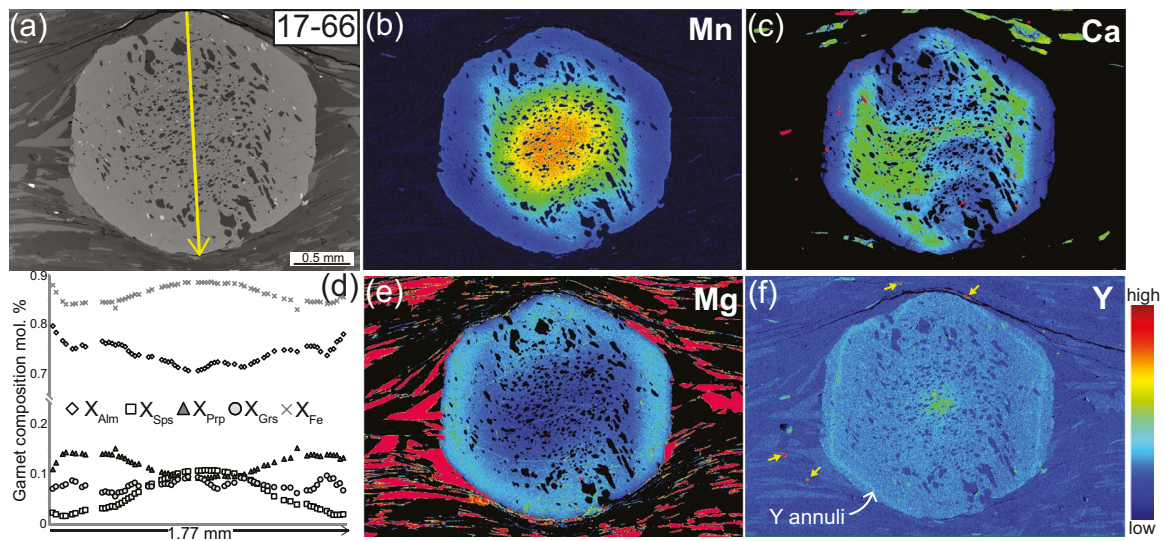
the conditions of equilibrium. Only garnet–mica schist 17-66, a typical metapelite, is suitable for pseudosection modeling because it contains the least altered mineral assemblage and shows no direct evidence of late fluid influx. The  $P$ – $T$  conditions of growth of the garnet core were estimated using compositional isopleths. The intersecting isopleths plot in the stability field of biotite + garnet + plagioclase + white mica + ilmenite + chlorite + quartz at c. 0.76–0.82 GPa and 585–600°C (Fig. 8a). A second pseudosection was calculated based on the effective bulk composition obtained by subtracting the garnet core composition from the whole rock chemistry (e.g. Evans, 2004; Lanari & Engi, 2017). The modal proportion of garnet core (2.5%) was estimated using image analysis in ImageJ software. The isopleths of grossular from the garnet rim were compared with isopleths of  $X_{\text{Fe}}$  in biotite and Si number in white mica. The modelled isopleths intersect at ~0.79–0.85 GPa and 650–665°C in the stability field of biotite + garnet + plagioclase + white mica + kyanite + rutile + quartz  $\pm$  ilmenite (Fig. 8b). These peak  $P$ – $T$  conditions represent garnet rim formation and the mineral assemblage is in agreement with petrographic observations.

### QuiG thermobarometry

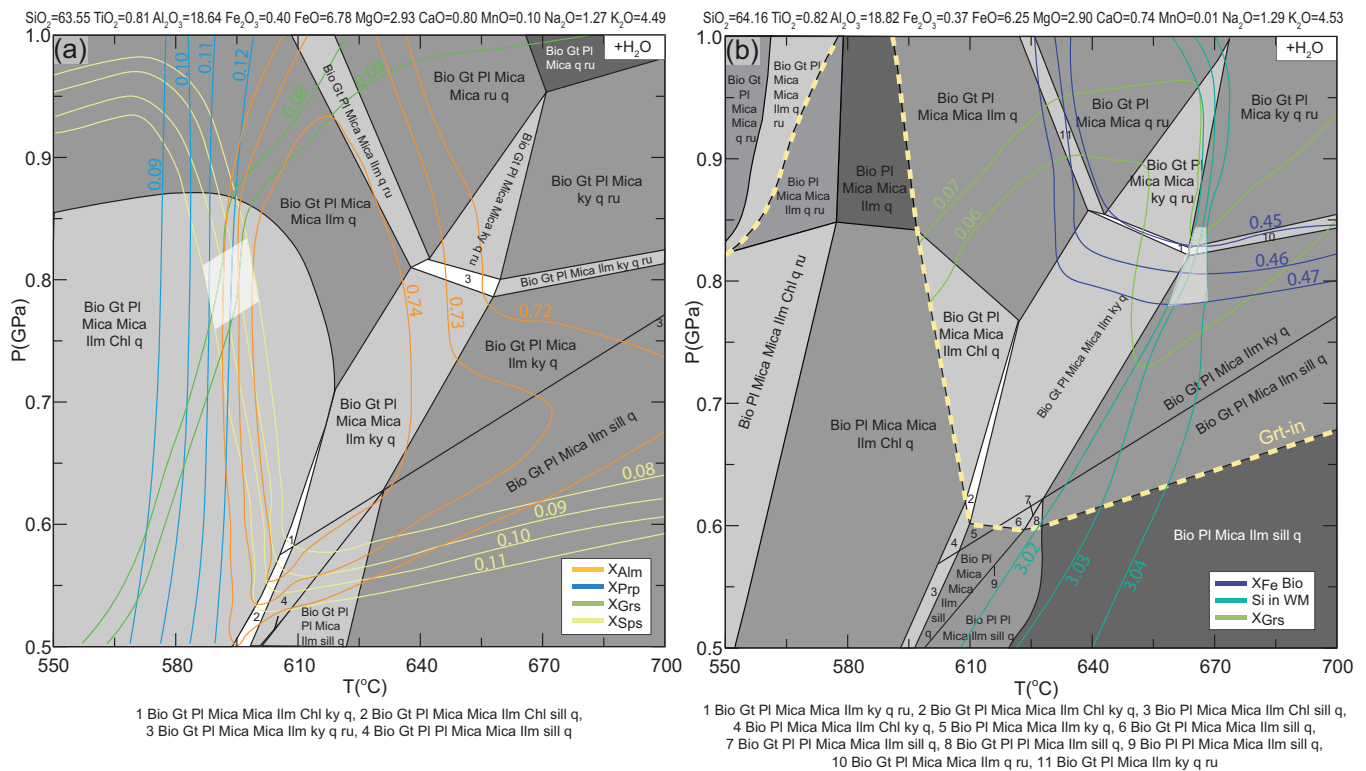
Garnet in both samples contains abundant quartz inclusions. The inclusions are mostly concentrated in the cores of garnet crystals (Fig. 6b–c, 7). All inclusions chosen for Raman measurements were spherical, 5–30  $\mu\text{m}$  in diameter (Fig. 9b–c) and isolated from any interfaces (see Methods). Inclusions with visible cracks or defects were avoided. Forty-four quartz inclusions in garnet were measured in metapelite 17-66 (Table S2). The repeatable

measurements of reference quartz give stable errors on the 128, 206 and 464  $\text{cm}^{-1}$  Raman bands. Quartz inclusions from sample 17-66 give an average  $P_{\text{inc}}$  of  $0.24 \pm 0.08$  GPa (Table S2, Fig. 9). The anisotropy ( $A$ ) varies from  $-0.002$  to  $-0.045$ , but calculated isomekes give consistent pressures of entrapment.

A number of authors have combined QuiG thermobarometry with inclusion trace element thermometry (e.g. Zirconium-in-rutile: Castro & Spear, 2017; Wolfe & Spear, 2018; Harvey et al., 2021; Titanium-in-quartz: Gonzalez et al., 2019); however, the PBA rocks are not suitable for this approach. Rutile forms thin (<2  $\mu\text{m}$ ) intergrowths with ilmenite (Fig. 6e) that are too small for microprobe analysis. The chemical equilibrium between rutile intergrowths and zircon, and between quartz and rutile, and their associations with garnet collectively complicate using the crossing points of QuiG isomekes with Ti-in-quartz and/or Zr-in-rutile isopleths for thermobarometry. Thus, the QuiG data have been combined with conventional thermobarometry to estimate the  $P$ – $T$  conditions. Ti-in-biotite thermometry (Henry et al., 2005) gives reliable estimates for amphibolite facies rocks (e.g. Palin et al., 2012). The Ti-in-biotite thermometry for sample 17-66 intersects with the average QuiG isomeke at 0.7–0.9 GPa and 540–600°C (Fig. 9a). Results from the geothermometer garnet–biotite (GB, Hodges & Spear, 1982) and geobarometer GASP (Hodges & Spear, 1982) are shown for comparison (Fig. 9a), since they are commonly used in metapelites. The lowest  $X_{\text{Fe}}$  in biotite was paired with the highest  $X_{\text{Fe}}$  in garnet and the highest  $X_{\text{Fe}}$  in biotite was combined with the lowest  $X_{\text{Fe}}$  in garnet to provide the possible range of temperatures. GASP was applied to the garnet rim, matrix biotite and plagioclase because kyanite occurs



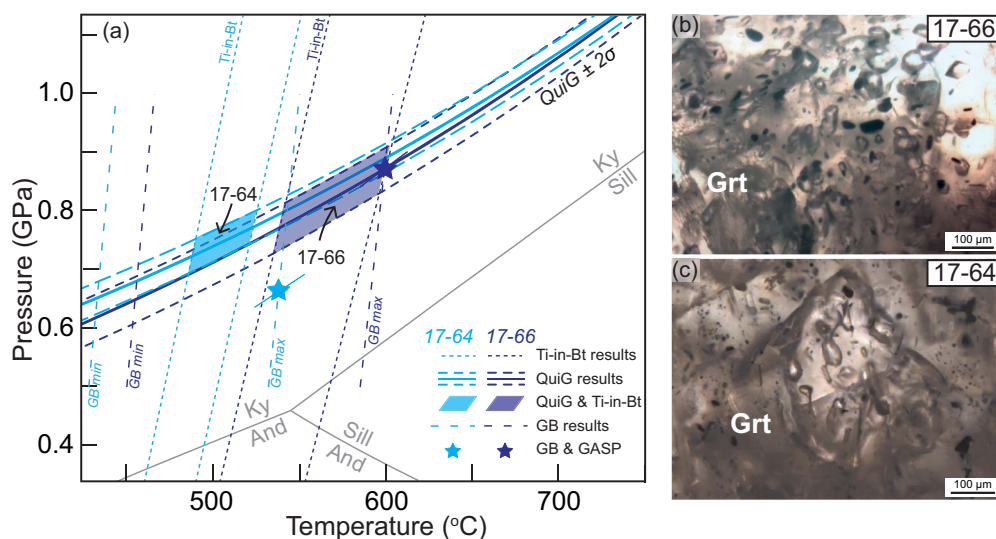
**Fig. 7.** Chemical zoning of a garnet in metapelite 17-66. (a) BSE image, (d) compositional profile shown on the BSE image, (b,c,e,f) X-ray maps of garnet for Mn, Mg, Ca and Y. Yellow arrows on Y map indicate monazite grains.



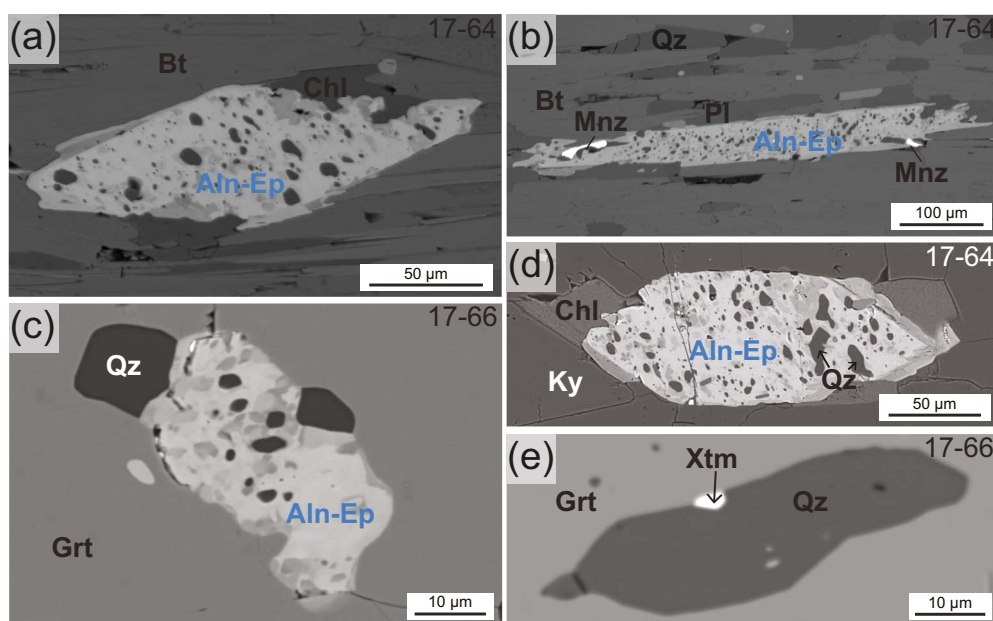
**Fig. 8.** P–T pseudosections for metapelite 17-66. (a) garnet cores (b) garnet rims (based on the effective bulk composition). Colored lines show constant composition for indicated mineral components. Light gray rhombs are the estimated conditions of core and rim growth.

only in the matrix (Fig. 6c) and there is no textural evidence for kyanite growth together with the garnet core. GB is consistent with Ti-in-biotite results, but yields a wider spread of temperature ranging from 450° to 600°C. The GB thermometer coupled with the GASP barometer gives the results of ~600°C at 0.85 GPa. Representative biotite composition and QuiG data used for calculations are given in Tables 3 and S2, respectively.

We applied a similar procedure to garbenschist 17-64. Quartz inclusions ( $n=30$ ) were measured in two garnets.  $P_{\text{inc}}$  calculated for the measured inclusions gives an average  $P_{\text{inc}}$  of  $0.17 \pm 0.02$  GPa ( $A = -0.022-0.003$ ). The Ti-in-biotite thermometry together with the average QuiG isomekes estimates P–T conditions at 0.7–0.8 GPa and 480–520°C (Fig. 9a). GB yields a wide temperature range of 440° to 530°C. GB coupled with GASP barometry displays lower P–T conditions of ~540°C at 0.66 GPa.



**Fig. 9.** (a) P–T diagram with QuiG, Ti-in-biotite (Ti-in-Bt), garnet–biotite (GB) and GASP results shown for sample 17-66 and 17-64, (b) and (c) representative PPL photomicrographs showing abundant quartz inclusions in garnet.



**Fig. 10.** BSE images showing relationships among REE-bearing phases allanite, epidote, monazite and xenotime.

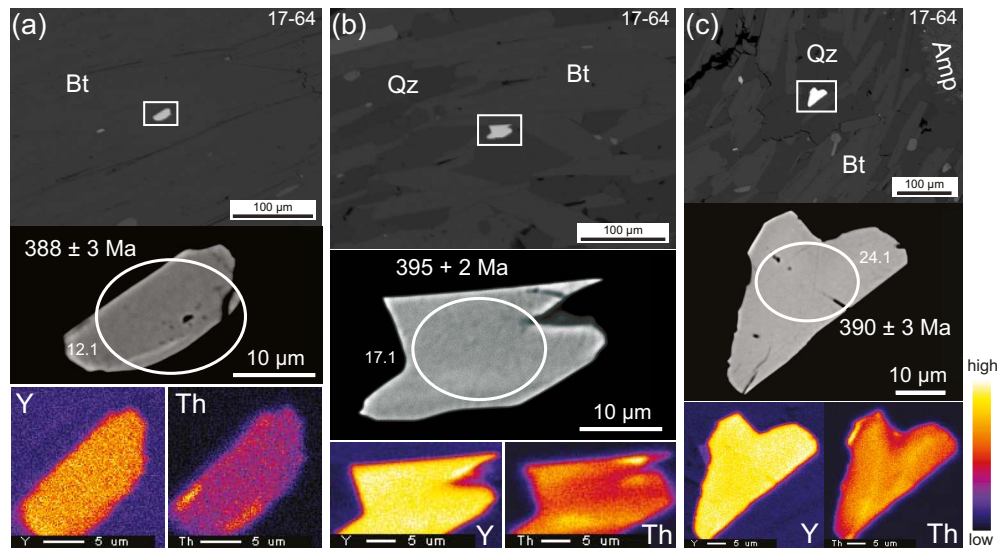
### REE phase relationships and monazite petrochronology

Sample 17-64 contains the REE bearing minerals xenotime, allanite and monazite. Xenotime occurs as small grains (<5  $\mu\text{m}$ ) in the garnet and in the matrix. Allanite forms inclusion-rich grains up to 500  $\mu\text{m}$  long in the matrix (Fig. 10a and b). The inclusions are mostly quartz. Allanite is typically replaced by epidote (Fig. 10a and b) with rare overgrowths of microcrystalline monazite (Fig. 10b). Allanite also occurs as inclusions within garnet and kyanite (Fig. 10d). Monazite forms small (<30  $\mu\text{m}$ ) grains that occur only in the matrix (Fig. 11). Apatite is a common accessory mineral both in the matrix and in the garnet.

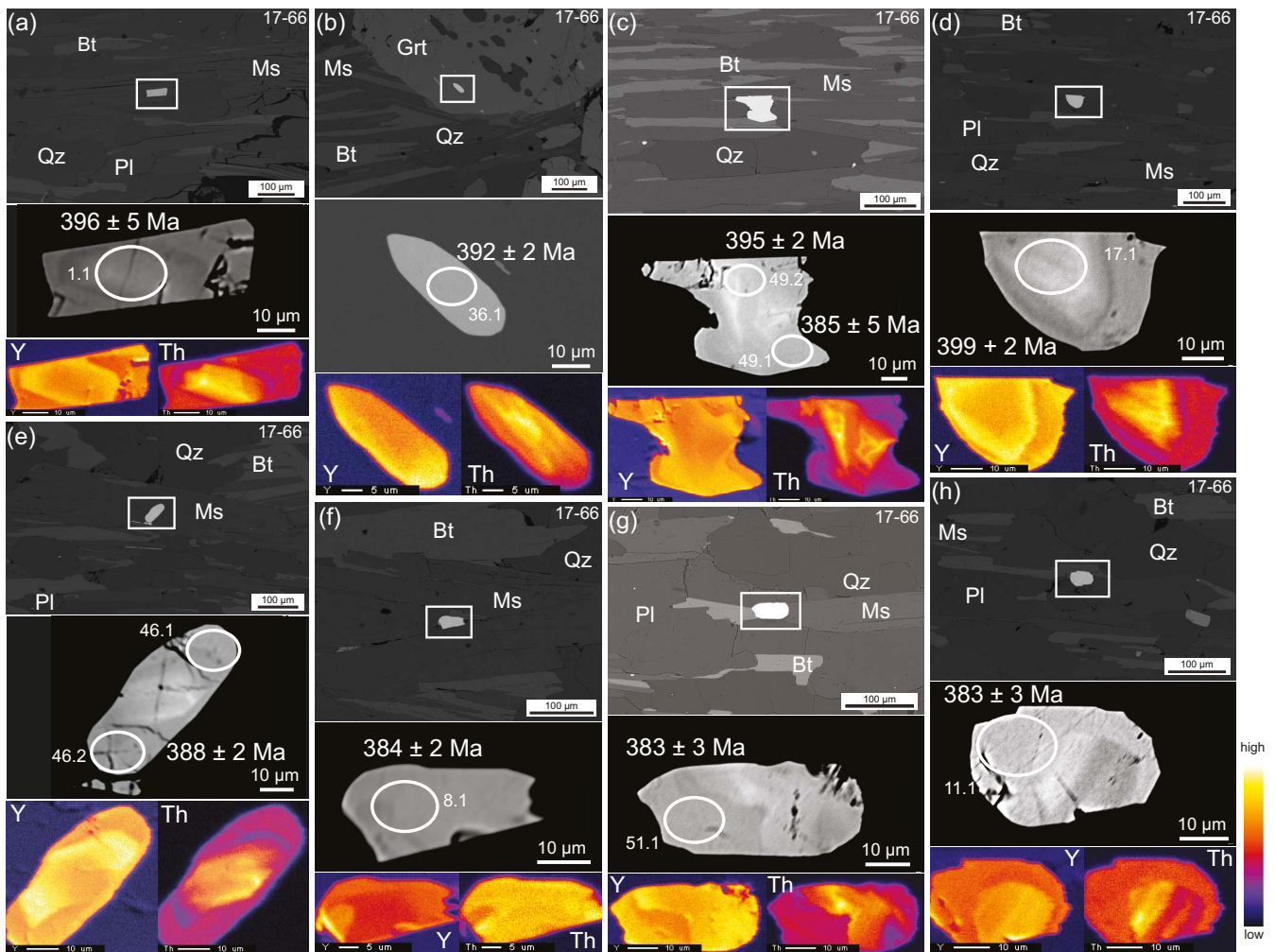
Xenotime, monazite and allanite are the REE bearing phases in sample 17-66. Xenotime occurs as inclusions

<5  $\mu\text{m}$  in diameter within high-Y garnet cores (Figs 7 and 10e). Allanite forms aggregates breaking down to REE-enriched epidote and apatite, occurring as metastable matrix grains or as inclusions in the garnet core (Fig. 10c). Monazite occurs as inclusions in garnet rims (<30  $\mu\text{m}$ ) or as grains in the matrix (<50  $\mu\text{m}$ ). Representative monazite grains are shown in Fig. 12.

Monazite in garbenschist 17-64 is chemically zoned with three recognizable domains. The dominant trend shows Th and Y decreasing between populations I–III (Fig. 13). Thorium concentration varies between 15 480 and 53 772 ppm, whereas Y ranges from 10 780–17 150 ppm (Fig. 13b, Table 5). The trace element signature is consistent within monazite domains and shows enrichment in LREE, slight depletion in HREE and a moderate negative Eu anomaly ( $\text{Eu}^* = 0.19$  to 0.31;



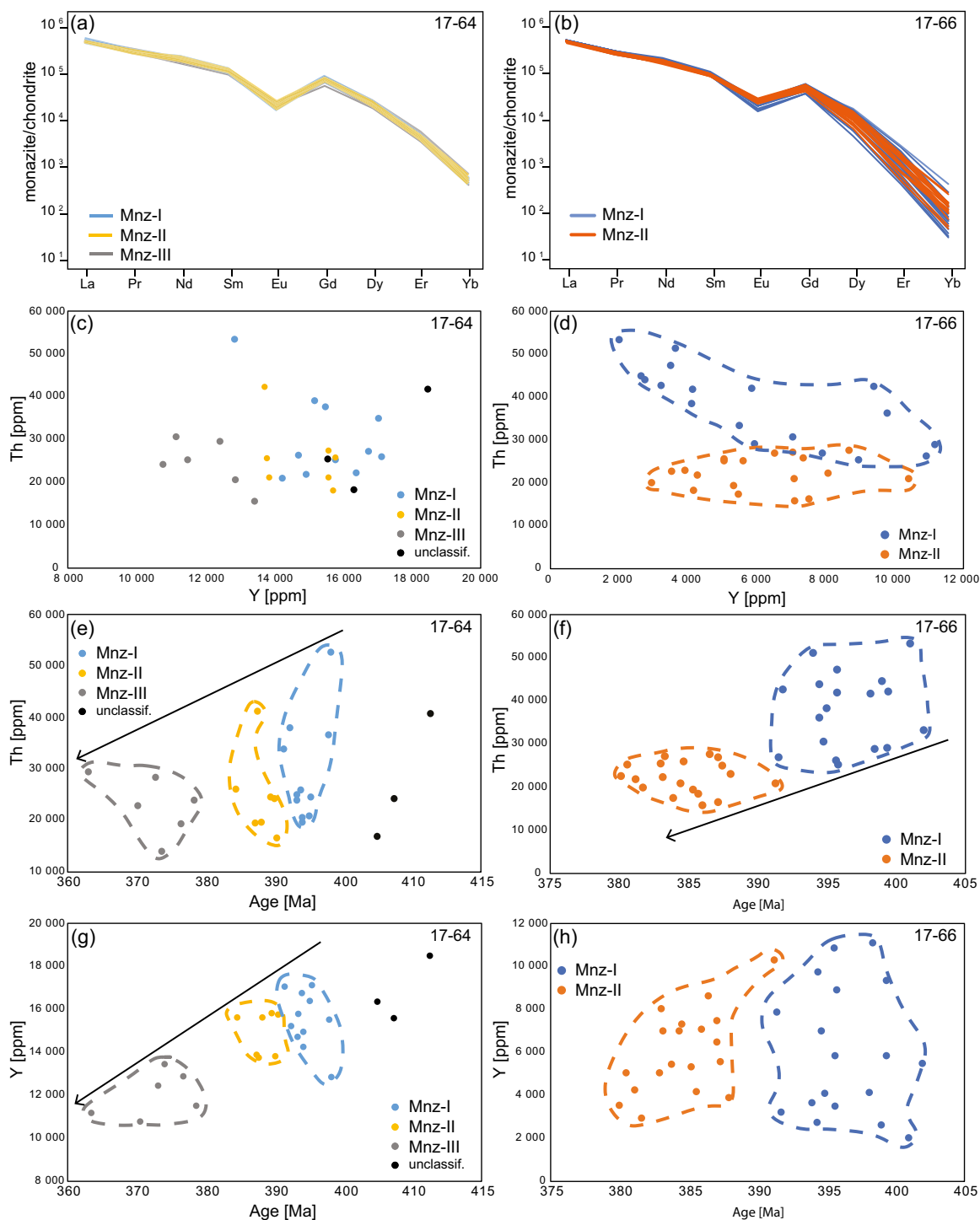
**Fig. 11.** BSE images, Th and Y X-ray chemical maps of selected monazite grains from garbenschist 17-64. Ellipses indicate analytical spots for U/Pb and trace elements collected with SHRIMP-RG.



**Fig. 12.** BSE images, Th and Y compositional maps of representative monazite grains from metapelite 17-66. Ellipses indicate analytical spots for U/Pb and trace elements.

Fig. 13a, Table 5). Monazite-I defines a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $394 \pm 2$  Ma ( $n=11$ , MSWD=0.6, Fig. 14a, Table 6) and is characterized by high/moderate Th

(21 025–53 773) and Y (12 863–17 150) contents. Monazite-II yields the age of  $388 \pm 2$  Ma ( $n=7$ , MSWD=0.8, Fig. 14a). Monazite-II gives moderate Th (18 073–42 397)



**Fig. 13.** Chemistry of monazite from samples 17-64 and 17-66. (a), (b) Chondrite-normalized REE patterns (Sun & McDonough, 1989); (c), (d) Y vs Th binary diagram; (e), (f) age vs Th binary diagram; (g), (h) age vs Y binary diagram. Points excluded from age calculations are not included on Fig. 13: sample 17-64: 7.1, 13.1, 14.1, 18.1, 25.1; sample 17-66: 10.1, 46.1, 54.1 Black dots are unclassified analyses which are most probably mixed analyses.

and Y (13 775–15 833). A younger age of  $374 \pm 6$  Ma is recorded by a more scattered Monazite-III population ( $n=6$ , MSWD=3.1, Fig. 14a). Monazite-III yields lower Th (15 480–30 698) and Y (10 782–13 457) compared to other populations. Three older ( $> 400$  Ma) monazite dates are reported and are interpreted as a mixed age between the detrital monazite core and the metamorphic rim.

Monazite in metapelite 17-66 is chemically zoned with distinct cores and rims. Two domains were defined based on high-contrast BSE images and X-ray maps (Fig. 12). Domain I (Monazite-I) corresponds to high Th (25 077–53 285 ppm) and moderate Y (2 029–11 191 ppm) (Fig. 12f, Table 5). Monazite-I occurs within garnet rims (Fig. 12b) or forms cores of matrix monazite (Fig. 12a, c, d, e and g). Monazite-II is characterized by

Table 5: Monazite TE

| Population                 | Spot name | Grain location | Spot location | U (ppm) | Th (ppm) | Y (ppm) | La (ppm)  | Pr (ppm) | Nd (ppm) | Sm (ppm) | Eu (ppm) | Gd (ppm) | Dy (ppm) | Er (ppm) | Yb (ppm) |
|----------------------------|-----------|----------------|---------------|---------|----------|---------|-----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Sample 17-66<br>Monazite-I | 1766-01.1 | Matrix         | Core          | 2974    | 41 770   | 5878    | 114 050   | 27 227   | 86 324   | 14 694   | 1143     | 10 234   | 2710     | 186      | 12       |
|                            | 1766-03.1 | Matrix         | Rim           | 2256    | 29 010   | 5898    | 118 191   | 25 424   | 82 778   | 13 881   | 1429     | 9776     | 2718     | 193      | 16       |
|                            | 1766-13.1 | Matrix         | Core          | 2774    | 36 069   | 9823    | 115 148   | 26 741   | 81 261   | 14 245   | 1492     | 11 539   | 4011     | 432      | 45       |
|                            | 1766-17.1 | Matrix         | Core          | 3038    | 44 653   | 2642    | 121 549   | 26 771   | 86 582   | 14 035   | 1130     | 8163     | 1435     | 87       | 6        |
|                            | 1766-18.1 | Matrix         | Core          | 2675    | 33 120   | 5517    | 120 315   | 26 904   | 87 854   | 14 606   | 1442     | 10 179   | 2567     | 162      | 12       |
|                            | 1766-19.1 | Matrix         | Core          | 3297    | 47 236   | 3518    | 118 732   | 27 717   | 88 107   | 14 625   | 1273     | 9440     | 1896     | 108      | 8        |
|                            | 1766-20.1 | In garnet      | Core          | 1792    | 25 077   | 8968    | 120 416   | 26 303   | 85 270   | 14 234   | 1612     | 10 632   | 3755     | 286      | 21       |
|                            | 1766-21.1 | Matrix         | Core          | 2901    | 43 820   | 2776    | 120 525   | 27 293   | 81 373   | 12 772   | 1006     | 7539     | 1485     | 78       | 5        |
|                            | 1766-30.1 | Matrix         | Core          | 2052    | 26 812   | 7914    | 121 885   | 26 603   | 88 456   | 14 533   | 1605     | 10 364   | 3407     | 219      | 16       |
|                            | 1766-31.1 | Matrix         | Core          | 3311    | 42 209   | 9413    | 117 340   | 27 407   | 96 420   | 16 263   | 1466     | 11 584   | 3804     | 339      | 26       |
|                            | 1766-36.1 | In garnet      | Core          | 3159    | 42 563   | 3244    | 121 346   | 27 226   | 84 959   | 13 218   | 927      | 7260     | 1494     | 98       | 8        |
|                            | 1766-39.1 | Matrix         | Core          | 3416    | 51 138   | 3660    | 120 346   | 27 952   | 88 784   | 14 250   | 1093     | 8300     | 1853     | 135      | 11       |
|                            | 1766-41.1 | Matrix         | Core          | 2524    | 30 390   | 7052    | 118 583   | 27 656   | 86 204   | 14 422   | 1389     | 10 327   | 3069     | 202      | 14       |
|                            | 1766-42.1 | In garnet      | Core          | 2102    | 28 672   | 11 191  | 111 615   | 26 224   | 81 597   | 13 818   | 1403     | 9525     | 4163     | 447      | 69       |
|                            | 1766-45.1 | Matrix         | Core          | 1932    | 25 936   | 10 954  | 116 391   | 26 407   | 82 529   | 14 116   | 1576     | 10 736   | 3907     | 315      | 23       |
|                            | 1766-48.1 | Matrix         | Core          | 3188    | 53 285   | 2029    | 119 082   | 27 479   | 82 999   | 12 994   | 837      | 7176     | 1112     | 67       | 5        |
|                            | 1766-49.2 | Matrix         | Core          | 2764    | 38 284   | 4132    | 116 014   | 25 453   | 90 273   | 14 789   | 1333     | 9309     | 2088     | 133      | 10       |
|                            | 1766-50.1 | Matrix         | Core          | 3052    | 41 573   | 4141    | 120 176   | 26 913   | 87 033   | 14 261   | 1128     | 8974     | 2067     | 152      | 11       |
|                            | 1766-02.1 | Matrix         | Core          | 1849    | 20 714   | 10 376  | 116 244   | 25 241   | 83 415   | 14 123   | 1484     | 10 841   | 4049     | 338      | 28       |
|                            | 1766-07.1 | Matrix         | Core          | 1974    | 15 587   | 7121    | 118 777   | 25 243   | 83 695   | 13 952   | 1607     | 10 513   | 3113     | 238      | 24       |
| Monazite-II                | 1766-08.1 | Matrix         | Core          | 1787    | 17 102   | 5480    | 120 409   | 25 977   | 76 170   | 12 619   | 1306     | 9084     | 2445     | 179      | 17       |
|                            | 1766-11.1 | Matrix         | Rim           | 2381    | 26 939   | 7053    | 117 667   | 26 763   | 82 969   | 14 329   | 1462     | 11 379   | 3241     | 284      | 44       |
|                            | 1766-14.1 | Matrix         | Rim           | 2422    | 20 723   | 7052    | 114 905   | 25 645   | 83 311   | 14 171   | 1458     | 10 366   | 3113     | 307      | 46       |
|                            | 1766-22.1 | Matrix         | Core          | 1481    | 16 146   | 7541    | 121 459   | 25 452   | 87 059   | 14 391   | 1616     | 10 752   | 3520     | 207      | 13       |
|                            | 1766-23.1 | Matrix         | Core          | 2069    | 24 837   | 5621    | 121 064   | 26 738   | 85 731   | 14 372   | 1506     | 10 516   | 2810     | 189      | 18       |
|                            | 1766-26.1 | Matrix         | Core          | 2192    | 22 430   | 3553    | 121 215   | 25 494   | 87 481   | 14 390   | 1397     | 9979     | 2013     | 126      | 20       |
|                            | 1766-27.1 | Matrix         | Core          | 2317    | 26 609   | 6536    | 118 088   | 26 888   | 88 934   | 15 258   | 1619     | 11 474   | 3135     | 245      | 28       |
|                            | 1766-28.1 | Matrix         | Core          | 1824    | 19 134   | 5348    | 120 759   | 26 293   | 84 307   | 13 678   | 1419     | 9669     | 2495     | 175      | 18       |
|                            | 1766-34.1 | Matrix         | Core          | 1815    | 18 085   | 4190    | 118 034   | 25 707   | 81 686   | 13 522   | 1509     | 9273     | 2188     | 105      | 9        |
|                            | 1766-35.1 | Matrix         | Core          | 2415    | 27 439   | 8695    | 119 101   | 26 605   | 83 827   | 14 115   | 1527     | 10 517   | 3536     | 278      | 25       |
|                            | 1766-37.1 | Matrix         | Rim           | 1989    | 21 518   | 4282    | 118 251   | 26 355   | 85 220   | 14 231   | 1454     | 10 323   | 2241     | 137      | 21       |
|                            | 1766-40.1 | Matrix         | Core          | 1709    | 19 776   | 2951    | 118 649   | 25 024   | 81 535   | 13 106   | 1396     | 8581     | 1662     | 83       | 8        |
|                            | 1766-46.2 | Matrix         | Rim           | 2160    | 22 819   | 3922    | 116 700   | 25 807   | 85 588   | 14 200   | 1463     | 9391     | 1933     | 122      | 17       |
|                            | 1766-49.1 | Matrix         | Rim           | 2210    | 25 690   | 7376    | 116 754   | 26 436   | 90 013   | 15 361   | 1645     | 11 747   | 3419     | 245      | 27       |
|                            | 1766-51.1 | Matrix         | Rim           | 2191    | 25 384   | 5074    | 119 218   | 26 484   | 87 310   | 14 750   | 1475     | 10 778   | 2544     | 186      | 29       |
|                            | 1766-52.1 | Matrix         | Core          | 1843    | 22 030   | 8097    | 117 527   | 26 186   | 84 383   | 14 225   | 1611     | 10 623   | 3507     | 270      | 23       |
|                            | 1766-53.1 | Matrix         | Core          | 2317    | 24 919   | 5067    | 119 799   | 26 446   | 88 796   | 15 020   | 1573     | 11 068   | 2692     | 178      | 24       |
|                            | 1766-10.1 | Matrix         | Core          | 1604    | 18 254   | 9804    | 116 944.4 | 25 317   | 81 680   | 13 386   | 1503     | 10 029   | 3816     | 477      | 65       |
|                            | 1766-46.1 | Matrix         | Rim           | 3028    | 30 728   | 3122    | 121 206   | 26 321   | 96 471   | 16 230   | 1650     | 11 286   | 1811     | 92       | 15       |
|                            | 1766-54.1 | Matrix         |               | 5354    | 77 559   | 4240    | 128 767.4 | 30 228   | 95 230   | 15 589   | 1411     | 9251     | 2247     | 161      | 14       |

Continues

Table 5: Continued

| Population                   | Spot name | Grain location | Spot location | U (ppm) | Th (ppm) | Y (ppm) | La (ppm) | Pr (ppm) | Nd (ppm) | Sm (ppm) | Eu (ppm) | Gd (ppm) | Dy (ppm) | Er (ppm) | Yb (ppm) |
|------------------------------|-----------|----------------|---------------|---------|----------|---------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Sample 17-64<br>unclassified | 1764-9.1  | Matrix         | Core          | 6481    | 41 996   | 18 504  | 121 186  | 30 204   | 96 411   | 17 510   | 1170     | 16348    | 6597     | 877      | 107      |
|                              | 1764-20.1 | Matrix         | Core          | 3611    | 18 302   | 16 354  | 117 341  | 27 046   | 88 881   | 16 034   | 1356     | 15210    | 6066     | 736      | 76       |
|                              | 1764-35.1 | Matrix         | Core          | 4598    | 25 605   | 15 586  | 124 083  | 27 702   | 104 767  | 17 691   | 1056     | 15931    | 5558     | 691      | 74       |
|                              | 1764-11.1 | Matrix         | Core          | 8665    | 53 772   | 12 863  | 129 896  | 30 195   | 92 473   | 16 187   | 1055     | 13697    | 5102     | 633      | 68       |
|                              | 1764-16.1 | Matrix         | Core          | 3581    | 25 338   | 15 807  | 115 518  | 26 716   | 87 935   | 15 948   | 1156     | 14750    | 5858     | 754      | 84       |
| Monazite-I                   | 1764-17.1 | Matrix         | Core          | 3562    | 22 282   | 16 419  | 112 262  | 26 802   | 88 693   | 16 123   | 1065     | 14873    | 5912     | 758      | 83       |
|                              | 1764-19.1 | Matrix         | Core          | 3574    | 21 966   | 14 960  | 110 085  | 27 560   | 89 490   | 16 134   | 1214     | 14905    | 5571     | 688      | 74       |
|                              | 1764-22.1 | Matrix         | Core          | 4201    | 25 973   | 17 150  | 116 893  | 26 618   | 94 378   | 18 581   | 1245     | 16940    | 6305     | 764      | 81       |
|                              | 1764-23.1 | Matrix         | Core          | 4068    | 27 331   | 16 781  | 111 652  | 27 253   | 94 178   | 17 312   | 1169     | 16207    | 6052     | 751      | 80       |
|                              | 1764-26.1 | Matrix         | Core          | 4537    | 35 129   | 17 068  | 115 565  | 28 591   | 94 642   | 17 224   | 1216     | 15418    | 6052     | 764      | 86       |
|                              | 1764-28.1 | Matrix         | Core          | 5736    | 39 268   | 15 217  | 122 212  | 29 171   | 93 758   | 16 968   | 1279     | 14974    | 5936     | 739      | 80       |
|                              | 1764-29.1 | Matrix         | Core          | 4919    | 37 869   | 15 524  | 116 690  | 28 806   | 96 688   | 17 105   | 1078     | 14867    | 5643     | 729      | 83       |
|                              | 1764-32.1 | Matrix         | Core          | 4038    | 26 359   | 14 738  | 111 654  | 27 422   | 87 558   | 15 616   | 1042     | 13595    | 5235     | 662      | 73       |
|                              | 1764-36.1 | Matrix         | Core          | 3911    | 21 025   | 14 263  | 112 557  | 26 156   | 89 562   | 15 634   | 968      | 14258    | 5247     | 679      | 75       |
|                              | 1764-2.1  | Matrix         | Core          | 3977    | 25 862   | 15 833  | 117 230  | 28 497   | 95 370   | 17 602   | 1366     | 15801    | 5874     | 692      | 84       |
| Monazite-II                  | 1764-3.1  | Matrix         | Core          | 3160    | 18 073   | 15 766  | 114 665  | 26 676   | 88 069   | 15 924   | 1327     | 14481    | 5954     | 676      | 76       |
|                              | 1764-10.1 | Matrix         | Core          | 3979    | 20 991   | 13 884  | 115 419  | 26 982   | 89 184   | 15 901   | 1110     | 13929    | 5473     | 699      | 79       |
|                              | 1764-12.1 | Matrix         | Core          | 3300    | 21 039   | 15 619  | 114 579  | 27 349   | 88 537   | 16 052   | 1348     | 15097    | 5957     | 675      | 79       |
|                              | 1764-21.1 | Matrix         | Core          | 6265    | 42 397   | 13 755  | 117 105  | 27 884   | 103 075  | 17 927   | 1008     | 14915    | 5245     | 664      | 73       |
|                              | 1764-37.1 | Matrix         | Core          | 3757    | 25 635   | 13 830  | 113 773  | 26 215   | 90 323   | 16 013   | 988      | 14367    | 5141     | 638      | 69       |
| Monazite-III                 | 1764-4.1  | Matrix         | Core          | 4448    | 27 453   | 15 628  | 112 809  | 27 572   | 90 490   | 16 175   | 1240     | 14515    | 5777     | 754      | 101      |
|                              | 1764-5.1  | Matrix         | Core          | 4136    | 25 380   | 11 505  | 113 685  | 26 123   | 86 511   | 15 228   | 1094     | 12628    | 4812     | 586      | 64       |
|                              | 1764-8.1  | Matrix         | Core          | 3560    | 20 695   | 12 892  | 111 910  | 26 965   | 81 081   | 14 563   | 1050     | 12756    | 5091     | 644      | 71       |
|                              | 1764-27.1 | Matrix         | Core          | 3461    | 24 189   | 10 782  | 114 053  | 27 534   | 78 226   | 13 823   | 1152     | 11 095   | 4428     | 538      | 63       |
|                              | 1764-27.1 | Matrix         | Core          | 4264    | 30 698   | 11 161  | 111 338  | 26 713   | 91 581   | 16 166   | 1441     | 12 640   | 4906     | 581      | 65       |
| Not included                 | 1764-30.1 | Matrix         | Core          | 3804    | 29 694   | 12 434  | 111 650  | 28 325   | 89 297   | 16 327   | 1390     | 13 629   | 4989     | 599      | 65       |
|                              | 1764-34.1 | Matrix         | Core          | 2743    | 15 480   | 13 457  | 115 036  | 26 033   | 82 526   | 14 552   | 1212     | 12 768   | 4931     | 596      | 64       |
|                              | 1764-14.1 | Matrix         | Core          | 6301    | 54 126   | 10 028  | 117 717  | 29 461   | 122 930  | 22 192   | 1822     | 17 274   | 6714     | 751      | 73       |
|                              | 1764-13.1 | Matrix         | Core          | 8565    | 87 272   | 10 364  | 112 089  | 26 153   | 121 122  | 21 492   | 1734     | 14 247   | 5441     | 663      | 74       |
|                              | 1764-25.1 | Matrix         | Core          | 5060    | 32 996   | 13 270  | 113 374  | 26 608   | 92 249   | 16 590   | 1399     | 13 814   | 5571     | 689      | 76       |
|                              | 1764-18.1 | Matrix         | Core          | 6586    | 29 926   | 12 357  | 117 061  | 26 426   | 103 091  | 17 559   | 1494     | 12 272   | 5187     | 730      | 97       |
|                              | 1764-7.1  | Matrix         | Core          | 3125    | 17 955   | 13 755  | 114 724  | 27 088   | 80 522   | 14 440   | 1104     | 13 065   | 5361     | 676      | 80       |

Table 6: Monazite U–Pb

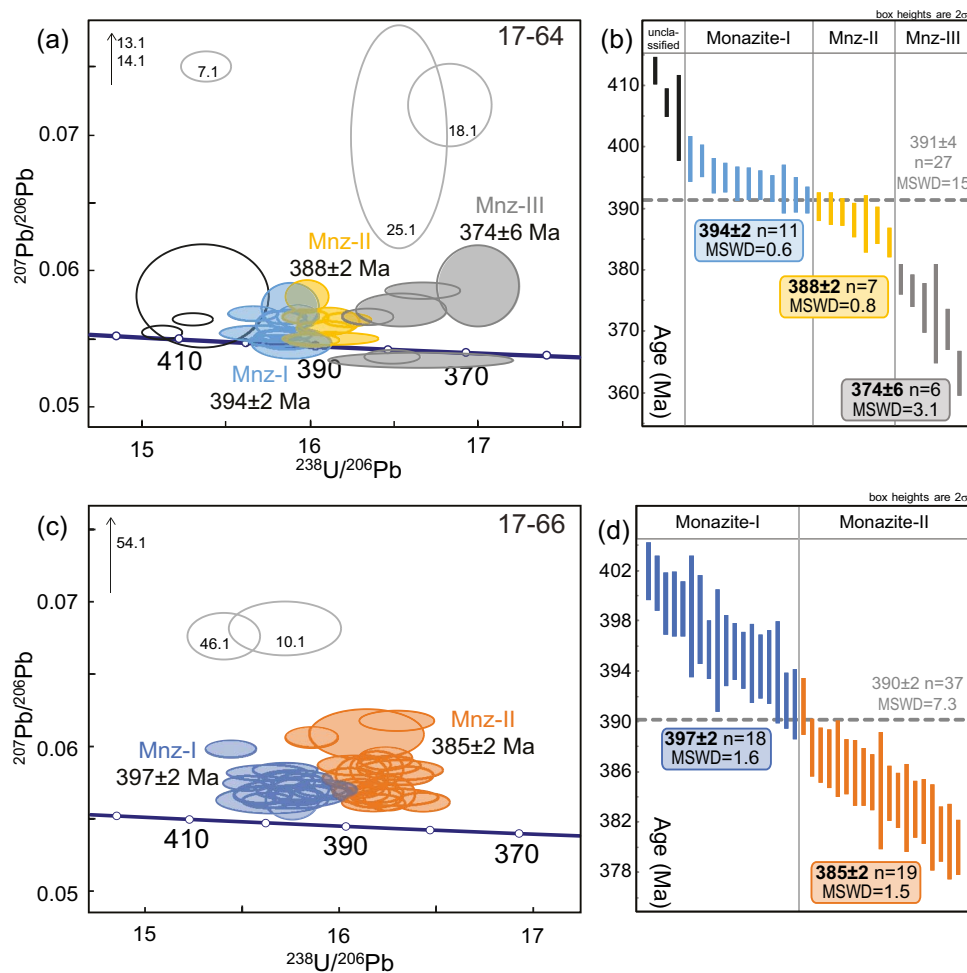
| Population                 | Analysis <sup>a</sup> | Grain location | Spot location | U (ppm) | Concentrations <sup>b</sup> |      |                          | Isotopic Ratios (uncorrected) <sup>c</sup> |                                     |             |                                      | Isotopic ratios ( <sup>204</sup> Pb-corrected) <sup>d</sup> |                                     |             |                                      | Date ( <sup>207</sup> Pb-corrected) <sup>e</sup> |                                          |               |
|----------------------------|-----------------------|----------------|---------------|---------|-----------------------------|------|--------------------------|--------------------------------------------|-------------------------------------|-------------|--------------------------------------|-------------------------------------------------------------|-------------------------------------|-------------|--------------------------------------|--------------------------------------------------|------------------------------------------|---------------|
|                            |                       |                |               |         | Th (ppm)                    | Th/U | <sup>206</sup> Pb* (ppm) | f <sup>206</sup> Pb <sub>c</sub> (%)       | <sup>238</sup> U/ <sup>206</sup> Pb | % err (1 s) | <sup>207</sup> Pb/ <sup>206</sup> Pb | % err (1 s)                                                 | <sup>238</sup> U/ <sup>206</sup> Pb | % err (1 s) | <sup>207</sup> Pb/ <sup>206</sup> Pb | % err (1 s)                                      | <sup>206</sup> Pb/ <sup>238</sup> U (Ma) | err abs (1 s) |
| Sample 17-66<br>Monazite-I | 1766-01.1             | Matrix         | Core          | 2974    | 41 770                      | 14.5 | 162                      | 0.26                                       | 15.755                              | 1.2         | 0.0567                               | 1.1                                                         | 15.818                              | 1.2         | 0.0535                               | 2.2                                              | 396                                      | 5             |
|                            | 1766-03.1             | Matrix         | Rim           | 2256    | 29 010                      | 13.3 | 124                      | 0.24                                       | 15.609                              | 0.6         | 0.0566                               | 0.7                                                         | 15.654                              | 0.6         | 0.0543                               | 1.1                                              | 399                                      | 2             |
|                            | 1766-13.1             | Matrix         | Core          | 2774    | 36 069                      | 13.4 | 150                      | 0.31                                       | 15.798                              | 0.6         | 0.0571                               | 1.2                                                         | 15.875                              | 0.6         | 0.0532                               | 1.6                                              | 394                                      | 2             |
|                            | 1766-17.1             | Matrix         | Core          | 3038    | 44 653                      | 15.2 | 167                      | 0.19                                       | 15.631                              | 0.5         | 0.0563                               | 0.6                                                         | 15.672                              | 0.5         | 0.0542                               | 1.0                                              | 399                                      | 2             |
|                            | 1766-18.1             | Matrix         | Core          | 2675    | 33 120                      | 12.8 | 148                      | 0.62                                       | 15.443                              | 0.6         | 0.0598                               | 0.7                                                         | 15.529                              | 0.6         | 0.0554                               | 1.4                                              | 402                                      | 2             |
|                            | 1766-19.1             | Matrix         | Core          | 3297    | 47 236                      | 14.8 | 179                      | 0.46                                       | 15.724                              | 0.7         | 0.0584                               | 0.6                                                         | 15.781                              | 0.7         | 0.0554                               | 1.0                                              | 396                                      | 3             |
|                            | 1766-20.1             | In grt         | Core          | 1792    | 25 077                      | 14.5 | 97                       | 0.21                                       | 15.759                              | 0.6         | 0.0563                               | 1.6                                                         | 15.799                              | 0.6         | 0.0543                               | 1.9                                              | 396                                      | 2             |
|                            | 1766-21.1             | Matrix         | Core          | 2901    | 43 820                      | 15.6 | 157                      | 0.27                                       | 15.806                              | 0.7         | 0.0568                               | 0.6                                                         | 15.852                              | 0.7         | 0.0545                               | 1.0                                              | 394                                      | 3             |
|                            | 1766-30.1             | Matrix         | Core          | 2052    | 26 812                      | 13.5 | 110                      | 0.31                                       | 15.924                              | 0.7         | 0.0570                               | 0.8                                                         | 16.034                              | 0.7         | 0.0514                               | 1.8                                              | 391                                      | 3             |
|                            | 1766-31.1             | Matrix         | Core          | 3311    | 42 209                      | 13.2 | 182                      | 0.24                                       | 15.607                              | 0.6         | 0.0567                               | 0.6                                                         | 15.708                              | 0.6         | 0.0514                               | 2.8                                              | 399                                      | 2             |
|                            | 1766-36.1             | In grt         | Core          | 3159    | 42 563                      | 13.9 | 170                      | 0.32                                       | 15.909                              | 0.6         | 0.0571                               | 0.6                                                         | 15.962                              | 0.6         | 0.0544                               | 1.1                                              | 392                                      | 2             |
|                            | 1766-39.1             | Matrix         | Core          | 3416    | 51 138                      | 15.5 | 185                      | 0.28                                       | 15.823                              | 1.0         | 0.0568                               | 0.6                                                         | 15.869                              | 1.0         | 0.0545                               | 1.0                                              | 394                                      | 4             |
|                            | 1766-41.1             | Matrix         | Core          | 2524    | 30 390                      | 12.4 | 137                      | 0.39                                       | 15.775                              | 0.8         | 0.0577                               | 0.7                                                         | 15.840                              | 0.8         | 0.0544                               | 1.3                                              | 395                                      | 3             |
|                            | 1766-42.1             | In grt         | Core          | 2102    | 28 672                      | 14.1 | 115                      | 0.20                                       | 15.654                              | 1.2         | 0.0563                               | 1.1                                                         | 15.758                              | 1.2         | 0.0509                               | 2.3                                              | 398                                      | 5             |
|                            | 1766-45.1             | Matrix         | Core          | 1932    | 25 936                      | 13.9 | 105                      | 0.36                                       | 15.742                              | 0.6         | 0.0575                               | 0.7                                                         | 15.854                              | 0.6         | 0.0518                               | 1.8                                              | 396                                      | 2             |
| Monazite-II                | 1766-48.1             | Matrix         | Core          | 3188    | 53 285                      | 17.3 | 176                      | 0.33                                       | 15.527                              | 0.5         | 0.0574                               | 0.6                                                         | 15.578                              | 0.5         | 0.0548                               | 1.0                                              | 401                                      | 2             |
|                            | 1766-49.2             | Matrix         | Core          | 2764    | 38 284                      | 14.3 | 150                      | 0.24                                       | 15.790                              | 0.6         | 0.0565                               | 0.7                                                         | 15.859                              | 0.6         | 0.0530                               | 1.4                                              | 395                                      | 2             |
|                            | 1766-50.1             | Matrix         | Core          | 3052    | 41 573                      | 14.1 | 167                      | 0.43                                       | 15.628                              | 0.9         | 0.0582                               | 0.6                                                         | 15.687                              | 0.9         | 0.0551                               | 1.1                                              | 398                                      | 3             |
|                            | 1766-02.1             | Matrix         | Core          | 1849    | 20 714                      | 11.6 | 99                       | 0.76                                       | 15.859                              | 0.6         | 0.0606                               | 0.8                                                         | 15.967                              | 0.6         | 0.0552                               | 1.8                                              | 391                                      | 2             |
|                            | 1766-07.1             | Matrix         | Core          | 1974    | 15 587                      | 8.2  | 105                      | 0.21                                       | 16.173                              | 0.7         | 0.0560                               | 0.7                                                         | 16.208                              | 0.7         | 0.0543                               | 1.0                                              | 386                                      | 3             |
|                            | 1766-08.1             | Matrix         | Core          | 1787    | 17 102                      | 9.9  | 94                       | 0.29                                       | 16.252                              | 0.5         | 0.0567                               | 1.4                                                         | 16.304                              | 0.6         | 0.0541                               | 1.7                                              | 384                                      | 2             |
|                            | 1766-11.1             | Matrix         | Rim           | 2381    | 26 939                      | 11.7 | 125                      | 0.26                                       | 16.283                              | 0.9         | 0.0564                               | 0.7                                                         | 16.337                              | 0.9         | 0.0538                               | 1.2                                              | 383                                      | 3             |
|                            | 1766-14.1             | Matrix         | Rim           | 2422    | 20 723                      | 8.8  | 128                      | 0.51                                       | 16.194                              | 0.6         | 0.0584                               | 1.4                                                         | 16.309                              | 0.6         | 0.0527                               | 2.2                                              | 384                                      | 2             |
|                            | 1766-22.1             | Matrix         | Core          | 1481    | 16 146                      | 11.3 | 79                       | 0.29                                       | 16.111                              | 0.6         | 0.0567                               | 0.8                                                         | 16.148                              | 0.6         | 0.0549                               | 1.2                                              | 387                                      | 2             |
|                            | 1766-23.1             | Matrix         | Core          | 2069    | 24 837                      | 12.4 | 110                      | 0.32                                       | 16.093                              | 0.6         | 0.0570                               | 0.8                                                         | 16.174                              | 0.6         | 0.0530                               | 1.6                                              | 387                                      | 2             |
|                            | 1766-26.1             | Matrix         | Core          | 2192    | 22 430                      | 10.6 | 114                      | 0.23                                       | 16.428                              | 0.6         | 0.0561                               | 0.8                                                         | 16.501                              | 0.6         | 0.0525                               | 1.6                                              | 380                                      | 2             |
|                            | 1766-27.1             | Matrix         | Core          | 2317    | 26 609                      | 11.9 | 123                      | 0.52                                       | 16.074                              | 0.8         | 0.0586                               | 0.8                                                         | 16.157                              | 0.8         | 0.0545                               | 1.5                                              | 387                                      | 3             |
|                            | 1766-28.1             | Matrix         | Core          | 1824    | 19 134                      | 10.8 | 96                       | 0.29                                       | 16.190                              | 0.6         | 0.0567                               | 0.8                                                         | 16.275                              | 0.6         | 0.0525                               | 1.6                                              | 385                                      | 2             |
|                            | 1766-34.1             | Matrix         | Core          | 1815    | 18 085                      | 10.3 | 96                       | 0.25                                       | 16.179                              | 0.6         | 0.0564                               | 0.8                                                         | 16.223                              | 0.6         | 0.0542                               | 1.3                                              | 386                                      | 2             |
|                            | 1766-35.1             | Matrix         | Core          | 2415    | 27 439                      | 11.7 | 128                      | 0.44                                       | 16.114                              | 0.5         | 0.0579                               | 1.4                                                         | 16.172                              | 0.6         | 0.0551                               | 1.8                                              | 386                                      | 2             |
| Not included               | 1766-37.1             | Matrix         | Rim           | 1989    | 21 518                      | 11.2 | 104                      | 0.45                                       | 16.344                              | 0.6         | 0.0579                               | 0.7                                                         | 16.413                              | 0.6         | 0.0545                               | 1.4                                              | 381                                      | 2             |
|                            | 1766-40.1             | Matrix         | Core          | 1709    | 19 776                      | 12.0 | 90                       | 0.50                                       | 16.314                              | 0.9         | 0.0583                               | 0.8                                                         | 16.409                              | 0.9         | 0.0537                               | 1.6                                              | 382                                      | 3             |
|                            | 1766-46.2             | Matrix         | Rim           | 2160    | 22 819                      | 10.9 | 115                      | 0.41                                       | 16.054                              | 0.6         | 0.0577                               | 0.8                                                         | 16.149                              | 0.6         | 0.0530                               | 1.7                                              | 388                                      | 2             |
|                            | 1766-49.1             | Matrix         | Rim           | 2210    | 25 690                      | 12.0 | 117                      | 0.80                                       | 16.138                              | 1.2         | 0.0608                               | 1.9                                                         | 16.251                              | 1.2         | 0.0552                               | 2.7                                              | 385                                      | 5             |
|                            | 1766-51.1             | Matrix         | Rim           | 2191    | 25 384                      | 12.0 | 115                      | 0.53                                       | 16.252                              | 0.7         | 0.0586                               | 0.7                                                         | 16.354                              | 0.7         | 0.0536                               | 1.6                                              | 383                                      | 3             |
|                            | 1766-52.1             | Matrix         | Core          | 1843    | 22 030                      | 12.4 | 97                       | 0.59                                       | 16.235                              | 0.6         | 0.0591                               | 0.9                                                         | 16.347                              | 0.6         | 0.0535                               | 1.9                                              | 383                                      | 2             |
|                            | 1766-53.1             | Matrix         | Core          | 2317    | 24 919                      | 11.1 | 121                      | 0.92                                       | 16.294                              | 0.8         | 0.0617                               | 0.8                                                         | 16.500                              | 0.8         | 0.0516                               | 2.3                                              | 381                                      | 3             |
|                            | 1766-10.1             | Matrix         | Core          | 1604    | 18 254                      | 11.8 | 86                       | 1.69                                       | 15.721                              | 1.2         | 0.0682                               | 1.8                                                         | 15.997                              | 1.2         | 0.0542                               | 3.7                                              | 391                                      | 5             |
|                            | 1766-46.1             | Matrix         | Rim           | 3028    | 30 728                      | 10.5 | 166                      | 1.60                                       | 15.406                              | 0.8         | 0.0676                               | 1.6                                                         | 15.619                              | 0.8         | 0.0566                               | 3.0                                              | 399                                      | 3             |
|                            | 1766-54.1             | Matrix         |               | 5354    | 77 559                      | 15.0 | 314                      | 2.38                                       | 14.316                              | 0.6         | 0.0746                               | 5.7                                                         | 14.713                              | 0.9         | 0.0527                               | 13.0                                             | 425                                      | 3             |
| Continues                  |                       |                |               |         |                             |      |                          |                                            |                                     |             |                                      |                                                             |                                     |             |                                      |                                                  |                                          |               |

Continues

Table 6: Continued

| Population                | Analysis <sup>a</sup> | Grain location | Spot location | U (ppm) | Concentrations <sup>b</sup> |      |                          | Isotopic Ratios (uncorrected) <sup>c</sup>           |             |                                      |             | Isotopic ratios ( <sup>204</sup> Pb-corrected) <sup>d</sup> |             |                                      |             | Date ( <sup>207</sup> Pb-corrected) <sup>e</sup>  |     |   |
|---------------------------|-----------------------|----------------|---------------|---------|-----------------------------|------|--------------------------|------------------------------------------------------|-------------|--------------------------------------|-------------|-------------------------------------------------------------|-------------|--------------------------------------|-------------|---------------------------------------------------|-----|---|
|                           |                       |                |               |         | Th (ppm)                    | Th/U | <sup>206</sup> Pb* (ppm) | <sup>238</sup> U/ <sup>206</sup> Pb <sub>c</sub> (%) | % err (1 s) | <sup>207</sup> Pb/ <sup>206</sup> Pb | % err (1 s) | <sup>238</sup> U/ <sup>206</sup> Pb                         | % err (1 s) | <sup>207</sup> Pb/ <sup>206</sup> Pb | % err (1 s) | <sup>206</sup> Pb/ <sup>238</sup> U err abs (1 s) |     |   |
|                           |                       |                |               |         |                             |      |                          |                                                      |             |                                      |             |                                                             |             |                                      |             |                                                   |     |   |
| Sample 17-64 unclassified | 1764-9.1              | Matrix         | Core          | 6481    | 41996                       | 6.7  | 368                      | 0.06                                                 | 15.121      | 0.5                                  | 0.0555      | 0.6                                                         | 15.152      | 0.5                                  | 0.0539      | 0.8                                               | 413 | 2 |
|                           | 1764-20.1             | Matrix         | Core          | 4598    | 25605                       | 5.2  | 201                      | 0.19                                                 | 15.302      | 0.5                                  | 0.0564      | 0.5                                                         | 15.415      | 1.7                                  | 0.0554      | 5.2                                               | 407 | 2 |
|                           | 1764-35.1             | Matrix         | Core          | 3611    | 18302                       | 5.8  | 258                      | 0.41                                                 | 15.363      | 1.7                                  | 0.0581      | 4.3                                                         | 15.357      | 0.5                                  | 0.0535      | 0.9                                               | 405 | 7 |
|                           | 1764-11.1             | Matrix         | Core          | 8665    | 53772                       | 6.4  | 474                      | 0.10                                                 | 15.678      | 0.9                                  | 0.0555      | 0.7                                                         | 15.709      | 0.9                                  | 0.0538      | 1.0                                               | 398 | 4 |
|                           | 1764-16.1             | Matrix         | Core          | 4919    | 37869                       | 7.3  | 194                      | 0.27                                                 | 15.663      | 0.6                                  | 0.0569      | 0.6                                                         | 15.942      | 0.5                                  | 0.0520      | 1.2                                               | 398 | 2 |
|                           | 1764-17.1             | Matrix         | Core          | 4201    | 25973                       | 6.5  | 193                      | 0.03                                                 | 15.803      | 0.7                                  | 0.0549      | 0.5                                                         | 15.851      | 0.6                                  | 0.0530      | 0.8                                               | 395 | 3 |
|                           | 1764-19.1             | Matrix         | Core          | 3562    | 22282                       | 6.4  | 194                      | 0.07                                                 | 15.809      | 0.6                                  | 0.0552      | 0.5                                                         | 15.895      | 0.6                                  | 0.0528      | 1.5                                               | 395 | 2 |
|                           | 1764-22.1             | Matrix         | Core          | 3911    | 21025                       | 6.4  | 228                      | 0.09                                                 | 15.845      | 0.7                                  | 0.0553      | 0.5                                                         | 15.829      | 0.7                                  | 0.0536      | 0.7                                               | 394 | 3 |
|                           | 1764-23.1             | Matrix         | Core          | 3574    | 21966                       | 6.9  | 220                      | 0.18                                                 | 15.832      | 0.6                                  | 0.0560      | 1.1                                                         | 15.898      | 0.6                                  | 0.0530      | 0.8                                               | 394 | 3 |
|                           | 1764-26.1             | Matrix         | Core          | 4068    | 27331                       | 8.0  | 244                      | 0.01                                                 | 15.866      | 0.6                                  | 0.0547      | 0.5                                                         | 16.002      | 0.5                                  | 0.0530      | 1.5                                               | 394 | 2 |
| Monazite-I                | 1764-28.1             | Matrix         | Core          | 3581    | 25338                       | 7.1  | 309                      | 0.25                                                 | 15.851      | 0.5                                  | 0.0566      | 0.5                                                         | 15.944      | 0.7                                  | 0.0541      | 2.4                                               | 393 | 2 |
|                           | 1764-29.1             | Matrix         | Core          | 4038    | 26359                       | 8.0  | 269                      | 0.01                                                 | 15.893      | 1.0                                  | 0.0547      | 1.3                                                         | 15.747      | 0.6                                  | 0.0526      | 1.4                                               | 393 | 4 |
|                           | 1764-32.1             | Matrix         | Core          | 5736    | 39268                       | 6.7  | 218                      | 0.35                                                 | 15.879      | 0.7                                  | 0.0574      | 2.0                                                         | 15.929      | 1.0                                  | 0.0528      | 1.5                                               | 392 | 3 |
|                           | 1764-36.1             | Matrix         | Core          | 4537    | 35129                       | 5.6  | 212                      | 0.27                                                 | 15.929      | 0.5                                  | 0.0567      | 1.0                                                         | 15.876      | 0.7                                  | 0.0537      | 0.7                                               | 391 | 2 |
|                           | 1764-2.1              | Matrix         | Core          | 3160    | 18073                       | 6.7  | 213                      | 0.26                                                 | 15.973      | 0.6                                  | 0.0566      | 0.6                                                         | 16.051      | 0.5                                  | 0.0545      | 1.8                                               | 390 | 2 |
|                           | 1764-3.1              | Matrix         | Core          | 3757    | 25635                       | 5.9  | 170                      | 0.06                                                 | 16.020      | 0.7                                  | 0.0549      | 0.5                                                         | 16.014      | 0.6                                  | 0.0545      | 0.9                                               | 390 | 3 |
|                           | 1764-10.1             | Matrix         | Core          | 3977    | 25862                       | 5.5  | 212                      | 0.45                                                 | 15.981      | 0.5                                  | 0.0581      | 1.4                                                         | 16.148      | 0.8                                  | 0.0543      | 1.4                                               | 390 | 2 |
|                           | 1764-12.1             | Matrix         | Core          | 3300    | 21039                       | 6.6  | 176                      | 0.17                                                 | 16.082      | 0.7                                  | 0.0558      | 0.6                                                         | 16.118      | 0.7                                  | 0.0540      | 0.9                                               | 388 | 3 |
|                           | 1764-21.1             | Matrix         | Core          | 6265    | 42397                       | 7.0  | 334                      | 0.08                                                 | 16.121      | 1.2                                  | 0.0551      | 0.6                                                         | 16.153      | 1.2                                  | 0.0534      | 0.8                                               | 388 | 4 |
|                           | 1764-24.1             | Matrix         | Core          | 3979    | 20991                       | 7.0  | 201                      | 0.23                                                 | 16.107      | 0.7                                  | 0.0563      | 1.2                                                         | 16.056      | 0.7                                  | 0.0532      | 0.7                                               | 387 | 3 |
| Monazite-III              | 1764-37.1             | Matrix         | Core          | 4448    | 27453                       | 6.4  | 235                      | 0.26                                                 | 16.225      | 0.6                                  | 0.0564      | 0.6                                                         | 16.281      | 0.6                                  | 0.0536      | 1.0                                               | 385 | 2 |
|                           | 1764-4.1              | Matrix         | Core          | 4136    | 25380                       | 6.3  | 215                      | 0.52                                                 | 16.446      | 0.6                                  | 0.0584      | 0.7                                                         | 16.532      | 0.6                                  | 0.0542      | 1.3                                               | 379 | 2 |
|                           | 1764-5.1              | Matrix         | Core          | 3560    | 20695                       | 6.0  | 184                      | 0.15                                                 | 16.591      | 0.7                                  | 0.0554      | 0.6                                                         | 16.632      | 0.7                                  | 0.0534      | 1.0                                               | 377 | 3 |
|                           | 1764-8.1              | Matrix         | Core          | 2743    | 15480                       | 7.2  | 176                      | 0.58                                                 | 16.645      | 1.1                                  | 0.0588      | 1.4                                                         | 16.904      | 0.9                                  | 0.0541      | 1.5                                               | 374 | 4 |
|                           | 1764-27.1             | Matrix         | Core          | 3804    | 29694                       | 7.4  | 212                      | 0.13                                                 | 16.763      | 2.2                                  | 0.0551      | 0.7                                                         | 17.227      | 1.0                                  | 0.0547      | 5.9                                               | 373 | 8 |
|                           | 1764-30.1             | Matrix         | Core          | 3461    | 24189                       | 8.1  | 195                      | 0.77                                                 | 16.776      | 0.9                                  | 0.0602      | 0.6                                                         | 16.827      | 2.2                                  | 0.0521      | 1.2                                               | 370 | 3 |
|                           | 1764-34.1             | Matrix         | Core          | 4264    | 30698                       | 5.8  | 141                      | 0.84                                                 | 17.101      | 1.0                                  | 0.0606      | 3.2                                                         | 16.733      | 1.1                                  | 0.0546      | 1.8                                               | 363 | 4 |
|                           | 1764-7.1              | Matrix         | Core          | 5060    | 32936                       | 5.9  | 170                      | 1.97                                                 | 16.526      | 1.1                                  | 0.0699      | 7.7                                                         | 15.821      | 0.7                                  | 0.0527      | 2.8                                               | 372 | 5 |
|                           | 1764-13.1             | Matrix         | Core          | 8565    | 87272                       | 10.5 | 415                      | 12.33                                                | 15.542      | 1.7                                  | 0.1530      | 5.7                                                         | 17.040      | 2.0                                  | 0.0849      | 14.9                                              | 354 | 7 |
|                           | 1764-14.1             | Matrix         | Core          | 3125    | 17955                       | 8.9  | 326                      | 2.53                                                 | 15.384      | 0.6                                  | 0.0751      | 1.0                                                         | 15.197      | 1.9                                  | 0.1215      | 6.4                                               | 396 | 3 |
| Not included              | 1764-18.1             | Matrix         | Core          | 6586    | 29926                       | 4.7  | 328                      | 2.28                                                 | 16.832      | 1.0                                  | 0.0722      | 2.8                                                         | 17.197      | 1.0                                  | 0.0551      | 5.4                                               | 364 | 4 |
|                           | 1764-25.1             | Matrix         | Core          | 6301    | 54126                       | 6.7  | 258                      | 10.97                                                | 14.762      | 1.8                                  | 0.1427      | 4.2                                                         | 16.839      | 1.3                                  | 0.0549      | 12.6                                              | 378 | 7 |

Note: All analyses were performed on the SHRIMP-RG ion microprobe at the United States Geological Survey-Stanford Microanalytical Center at Stanford University. The analytical routine followed Barth & Wooden (2006, 2010). Data reduction utilized the Squid 2.51 program of Ludwig (2009). <sup>a</sup>Analyses in bold were used in age calculation. <sup>b</sup>Pb\* denotes radiogenic Pb; Pb<sub>c</sub> denotes common Pb; f<sup>206</sup>Pb<sub>c</sub> = 100 × (206Pb<sub>c</sub>/206Pb<sub>total</sub>). <sup>c</sup>Calibration concentrations and isotopic compositions were based on replicate analyses of monazite reference material 44069 (424.9 ± 0.5 Ma; Aleinikoff et al., 2006, 2012). Reported ratios are not corrected for common Pb. <sup>d</sup>Ratios are corrected for common Pb. Initial common Pb isotopic composition approximated from Stacey & Kramers (1975). Uncertainties reported as 1σ. <sup>e</sup>Ages were calculated from 206Pb/238U ratio corrected for common Pb using the 207Pb method (see Williams, 1998). <sup>f</sup>Calculated ages are reported at 95% confidence level and include systematic errors added in quadrature.



**Fig. 14.** Tera-Wasserburg plots of U/Pb data with  $2\sigma$  error ellipses: (a) garbenschist 17-64 and (c) metapelite 17-66. Colored ellipses represent different monazite-populations and unfilled ellipses are not used in the date calculation. (b), (d) Plots of age distribution also delineate textural groups. MSWD is the mean square of weighted deviates. Analyses marked in black for sample 17-64 are interpreted as a mixed date between the detrital monazite core and the metamorphic rim.

lower Th (15 587–27 439 ppm) and moderate Y (2951–10 376 ppm) (Fig. 13f and h). It forms rims on Monazite-I (Fig. 12a, c, d, e and g) or occurs as separate grains in the matrix (Fig. 12f). Trace element patterns of dated monazite are the same for both chemical domains (Fig. 13b), with LREE enrichment and HREE depletion. A moderately negative Eu anomaly ( $\text{Eu}^* = 0.26\text{--}0.41$ ) is observed. Monazite-I from sample 17-66 defines a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $397 \pm 2$  Ma ( $n=18$ , MSWD=1.6, Fig. 14c and d, Table 6), whereas Monazite-II gives an age of  $385 \pm 2$  Ma ( $n=19$ , MSWD=1.5, Fig. 14c and d).

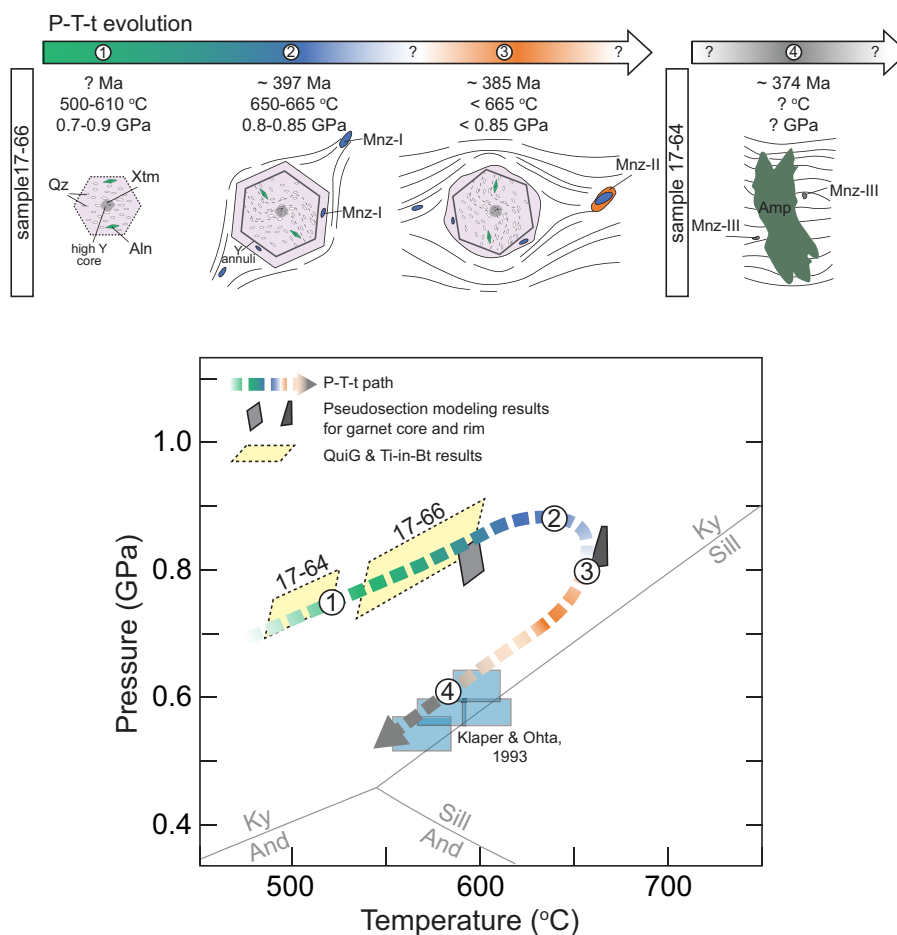
## DISCUSSION

Phase equilibrium modeling together with conventional and QuiG thermobarometry applied to the schists of the PBA reveal that this complex was metamorphosed at conditions of 480–650°C at pressures between 0.6 GPa and 0.9 GPa. The geochronological results demonstrate that the rocks have experienced several episodes of monazite growth in Middle to Late Devonian. The detailed

petrological studies together with *in-situ* monazite U–Pb dating establish a *P–T–t* path for the study area, which is summarized in Fig. 15. These results provide an important frame of reference for understanding the metamorphic evolution of the PBA in relation to the accretionary history of the Pearya terrane.

## *P–T–t* path and monazite reaction history

The textural observations, mineral chemistry, X-ray maps and trace element geochemistry reveal typical features of a prograde metamorphic evolution. The high-Y garnet core and few xenotime grains within this chemical domain are evidence for xenotime breakdown parallel to the garnet-in reaction. The rapid decrease of Y from the core to the mantle suggests xenotime consumption with garnet growth (cf., Pyle *et al.*, 2001; Spear & Pyle, 2002). QuiG isomekes together with Ti-in-biotite thermometry indicate garnet cores grew at 0.7–0.9 GPa and 540–600°C for garnet schist 17-66 and 0.7–0.8 GPa and 480–520°C for garbenschist 17-64 (Fig. 15, stage 1). The pseudosection model of 17-66 gives slightly different *P–T* conditions for garnet core formation of



**Fig. 15.** Summary of metamorphic evolution based on phase equilibrium modeling, QuiG thermobarometry, Ti-in-biotite thermometry and monazite petrochronology. *P-T-t* evolution: step 1—garnet core formation at 0.7–0.9 GPa and 500–610°C; step 2—prograde growth of Monazite-I at the expense of allanite to reach peak *P* conditions of ~0.8–0.85 GPa and 650–665°C in the Middle Devonian; step 3—Monazite-II formation after peak-*P* condition (<0.85 GPa and <665°C) in middle Devonian; step 4—Monazite-III growth in the garbenschist during a late stage of retrogression. Aluminosilicate stability fields from Pattison (1992).

0.76–0.82 GPa and 585–600°C (Fig. 15, stage 2). The effective bulk composition and intersecting isopleths indicate garnet rim growth under peak conditions at ~0.79–0.85 GPa and 650–665°C. The garnet rims are inclusion-poor, thus QuiG thermobarometry could not be used for estimating *P-T* conditions of rim growth. Our estimates of peak conditions are marginally hotter and significantly higher pressure than previous work (600°C and 0.6 GPa; Klaper & Ohta, 1993).

Allanite and monazite occur together and their textural relationships are in agreement with literature examples from garnet-bearing schists (e.g. Yang & Pattison, 2006; Spear & Pyle, 2002; Skrzypek et al., 2018). Allanite occurs as inclusions in the garnet core, whereas monazite is present in the rim, thus providing additional evidence for a temperature increase during garnet growth. The monazite forming reaction most likely involved allanite and a *P*-bearing phase like apatite. X-ray maps of Y in garnet show enrichment at the rims, suggesting Y-bearing phase breakdown (e.g. Yang & Pattison, 2006)—in this case allanite. The monazite inclusions in garnet (outside the Y annuli) as well as cores of matrix monazite, Monazite-I, yield a weighted average

U-Pb age of  $397 \pm 2$  Ma ( $n=18$ , MSWD=1.6, Fig. 14b) for sample 17-66 and  $394 \pm 2$  Ma ( $n=11$ , MSWD=0.6, Fig. 14a) for the garbenschist 17-64. Based on the textural observations, this age is interpreted as prograde monazite crystallization at the expense of allanite at peak *P* conditions (~0.79–0.85 GPa and 650–665°C, stage 2 on Fig. 15) in the Middle Devonian. Monazite-I was rotated and followed by growth of Monazite-II parallel to the foliation (Fig. 15). Monazite-II forms single grains or overgrowths on rotated matrix Monazite-I cores. The textural observations suggest that Monazite-II grew after peak-*P* (<0.85 GPa and <665°C, stage 3 on Fig. 15) in the Middle Devonian; however, it is challenging to pinpoint the exact *P-T* conditions. Monazite-II yields the age of  $388 \pm 2$  Ma ( $n=7$ , MSWD=0.8, Fig. 14a) for sample 17-64 and  $385 \pm 2$  Ma ( $n=19$ , MSWD=1.5, Fig. 14b) for sample 17-66. The reaction responsible for the formation of Monazite-II was most likely an allanite, apatite and/or Monazite-I consuming reaction, since allanite is still present in the matrix as a metastable phase. The reason for the Monazite-II growth is unclear, but it is probably a fluid driven reaction during deformation. Monazite-III is present only in the garbenschist sample

and defines the age of  $374 \pm 6$  Ma ( $n=6$ ,  $\text{MSWD}=3.1$ , Fig. 14a). This domain could have grown during a late stage of retrogression due to fluid–rock interaction, which is demonstrated by the growth of amphibole. Fluid availability during retrogression is consistent with emplacement of leucocratic dikes that crosscut the amphibolite-facies schistosity in the PBA at  $369 \pm 6$  Ma (see [Supplementary Appendix 1](#) and [Fig. S2](#)). The lack of Monazite-III in sample 17-66 may be evidence for heterogeneous deformation and fluid activity.

### Application of quartz-in-garnet barometer to garbenschist

The PBA apparently experienced heterogeneous fluid flow after the peak of metamorphism. Sample 17-66 does not show any retrograde features, whereas 17-64 contains abundant, randomly oriented amphibole, thus suggesting garben growth under post-peak metamorphic conditions. This study acts as a natural laboratory and testing area for further application of QuiG thermobarometry. QuiG thermobarometry applied to the garbenschist provides  $P$  estimates of metamorphic conditions in a lithology for which conventional, equilibrium-based techniques have limited use (i.e. the equilibrium state is not assured). Garbenschists commonly occur in metamorphic terranes, but most studies do not use them for thermobarometry because of the difficulties in obtaining  $P$ – $T$  conditions of their formation. This study shows that QuiG thermobarometry can be used to estimate the early metamorphic conditions of porphyroblast growth in garbenschists (Figs. 9 and 15). A recent study of [Cesare et al. \(2021\)](#) shows that post-entrapment shape modifications can affect elastic thermobarometry. However, quartz in the studied garbenschist does not show evidence of post-entrapment adjustment (e.g. negative crystal shapes). Additionally, the temperatures recorded by the PBA are below  $700^\circ\text{C}$  (Fig. 15). The peak  $P$  obtained by QuiG thermobarometry for the metapelite sample, 17-66, is slightly higher than the results of the pseudosection modelling for the garnet core. QuiG commonly returns crystallization pressures that are higher than those obtained from phase equilibrium modelling (e.g. [Spear & Wolfe, 2020](#)) that may result from errors related to the thermodynamic modelling and/or overstepping of the garnet-in reaction (e.g. [Castro & Spear, 2017](#); [Wolfe & Spear, 2018](#); [Nagurney et al., 2021](#)). Garnet overstepping is a plausible explanation for PBA rocks, but requires further, extensive studies which are beyond the scope of this contribution.

### Implications for the tectonic history

The Ordovician volcanoclastic schists of the PBA, including the unusual garnet–kyanite–staurolite garbenschist, are characteristic of an arc environment. Fragments of Ordovician arcs, (e.g. the Kulutingwak formation; [Bjørnerud, 1991](#)), the Fire Bay formation ([Koch et al., 2022](#)) and the Mount Rawlinson complex ([Trettin, 1998](#)) are strung out along a series of east-striking strike-slip faults

south of the Pearya terrane (Fig. 1). The PBA displays the highest grade of metamorphism seen along the southern margin of Pearya. When taken together with the isograd pattern, the age of the metamorphism gives the best indication of the time of accretion of the Pearya terrane to the Ordovician arcs and Danish River flysch, as well as the deep water part of the Franklinian margin. The high-grade rocks of the PBA are metamorphic equivalents of the sub-greenschist facies Kulutingwak formation (Fig. 1; [Klaper & Ohta, 1993](#); [Trettin, 1998](#)), which is found along the Kulutingwak and the Emma Fiord fault zones. Serpentine blocks and carbonate olistoliths mixed with a variety of schist and amphibolite in the PBA suggest deposition in a subduction environment. [Selverstone et al. \(1984\)](#) argued for subduction zone metamorphism to explain a similar garbenschist assemblage in the Tauern window, Austrian Alps, but the peak temperature was  $100^\circ\text{C}$  lower and the pressure was marginally higher (1.0 GPa) than the PBA. An Eclogite Zone structurally beneath the garbenschist unit with  $P=0.9$ – $1.3$  GPa points to subduction in the Tauern window as well; however, [Smye et al. \(2011\)](#) consider the possibility of a Barrovian overprint due to later overthrusting of Austroalpine units. Nevertheless, the peak conditions of  $665^\circ\text{C}$  at 0.78–0.85 GPa for the PBA are too hot and marginally too low pressure for metamorphism in a subduction zone. The Devonian monazite in the PBA, which grew on the prograde and retrograde clockwise  $P$ – $T$  path, is also incompatible with Ordovician subduction.

The medium temperature/medium pressure (MT/MP) conditions of the PBA, i.e.  $650^\circ\text{C}$  at  $\leq 0.9$  GPa, are more characteristic of a Barrovian metamorphic history. Our monazite dating shows that garnet grew on a prograde path over a period of  $\approx 12$  Myr from 397–385 Ma. This period falls outside [Viete & Lister's \(2017\)](#) 10 Myr threshold for short duration regional metamorphism, but still requires a localized heat source in a time frame much less than that required for conductive heating in a continent–continent collision (e.g. [England & Thompson, 1984](#); [Dewey, 2005](#)). The closely spaced, steep, parallel isograd surfaces (Fig. 2b) indicate a heat source to the northwest that was applied after the main fabric-forming event ([Klaper & Ohta, 1993](#); Figs 4 and 6). The localized nature of the Barrovian metamorphism of the PBA indicates either a heat source from nearby magma emplacement or a ‘hot iron’ of obducted arc and thin ophiolitic forearc ([Ryan & Dewey, 2019](#)). Shear heating along the emplacement structure is unlikely to increase the temperature much beyond  $20^\circ\text{C}$  (e.g. [Platt, 2015](#)). The lack of ophiolite and the age difference between metamorphism and the arc fragments in the PBA argue against a hot iron mechanism associated with the Ordovician arc system.

The crystalline basement of the composite Pearya terrane lies directly northwest of the PBA and its proximity suggests a causal relationship between accretion and Barrovian metamorphism ([Klaper & Ohta, 1993](#); [Trettin, 1998](#)). For example, granulite facies crust forming a

hot orogenic root was thrust over the Moravian zone of the Bohemian massif to produce peak Barrovian conditions (Štípská *et al.*, 2015) similar to those observed in the PBA. The 485–440 Ma magmatic rocks and Ordovician metamorphism associated with the M'Clintock collisional event within the Pearya terrane (McClelland *et al.*, 2012; Estrada *et al.*, 2018; Majka *et al.*, 2021) are too old to be considered a viable heat source for the PBA metamorphism. On the other hand, evidence for metamorphism and granitic magmatism in the Pearya basement at 365–340 Ma (Trettin, 1998; Estrada *et al.*, 2018) is too young to be directly related to the PBA metamorphism. The P–T conditions of the adjacent quartzofeldspathic gneisses of Pearya have not been determined, but they do not appear to exceed amphibolite facies and were probably not hot enough to produce the metamorphic isograds observed in the PBA. Another possible heat source may be Devonian magmas intruded into the Pearya terrane or other Ordovician arc fragments and brought into contact with a fragment of an Ordovician arc containing the PBA. The Cape Woods pluton (Fig. 1) is a plausible example of such a magma: it has a U–Pb titanite intrusive age of  $390 \pm 10$  Ma (Trettin *et al.*, 1987) and a contact aureole with scattered kyanite and staurolite adjacent to the pluton (Frisch, 1974). No intrusion similar to the Cape Woods pluton is seen directly northwest of the PBA today, but it could have been excised by later brittle faults in the Cenozoic. The Bourne Complex exposed on the Kleybolte Peninsula (Fig. 1) includes calc-alkaline intermediate volcanic rocks with an average age of  $380 \pm 14$  Ma based on  $^{40}\text{Ar}/^{39}\text{Ar}$  data (Henry, 1981; Trettin, 1998). This section may represent remnants of a Devonian arc system, the roots of which could result in Barrovian metamorphism if emplaced next to the PBA. The Bourne Complex is juxtaposed along the steep Kleybolte fault with serpentinized ultramafic rocks of unknown age, the Danish River Formation and Carboniferous units in a setting similar to the PBA. In either scenario—magma emplacement or hot iron-like juxtaposition with the deeper levels of a Devonian magmatic complex—it is clear that the present day juxtaposition of the Pearya terrane against the PBA does not reflect the primary relationship at the time of Barrovian metamorphism. The Petersen Bay Fault Zone experienced intense Cenozoic brittle faulting with an unknown amount of displacement (Piepjohn *et al.*, 2013; Piepjohn & von Gosen, 2018). An approximately 250–300 m thick package of cataclasite, derived primarily from the quartzofeldspathic gneiss of Pearya and observed just 1 km SW of the studied outcrop, indicates significant late displacement. Thus, the causal relationship between Pearya terrane accretion and Barrovian metamorphism of the PBA (Klaper & Ohta, 1993) requires significant post-accretion modification to establish the present day relationships.

Metamorphism associated with the development of the kyanite–staurolite–garnet garbenschist appears to be a common occurrence in collisional to accretionary settings that involve magmatic rocks that can form a

Barrovian heat source and bulk compositions appropriate for the unusual low-variance assemblage. The Tauern window garbenschist formed in response to subduction of volcanic protoliths to 1 GPa and 530°C, followed by exhumation and continued heating to 0.7 GPa and 550°C (Selverstone *et al.*, 1984; Selverstone, 1985, 1993). Preservation of the relatively cool system can be attributed to the absence of arc magmatism and short duration of the subduction to exhumation cycle (Smye *et al.*, 2011). The kyanite–staurolite–garnet–amphibole assemblage observed in the Pie de Palo complex, Argentina formed at conditions ranging from 0.9–1.3 GPa and 600–638°C within a fore arc setting during collision of the Precordillera terrane (Casquet *et al.*, 2001; Mulcahy *et al.*, 2011). Structurally higher units that experienced deformation at 1.2–1.3 GPa and 735–800°C in the presence of melt represent deeper portions of the long-lived arc–continent collision prior to the onset of strike-slip terrane displacement (Mulcahy *et al.*, 2011; Tholt *et al.*, 2021). Similarly, garbenschist formed at 0.87 GPa and 545°C during underthrusting of the Alexander terrane in an intra-arc setting (McClelland *et al.*, 1991) was followed by margin parallel displacement on an intra-arc dextral shear zone (McClelland & Mattinson, 2000). Metamorphism in the PBA appears to represent burial to 0.8–0.9 GPa and Barrovian metamorphism associated with the final arc-related magmatic event within the Pearya terrane. The timing of PBA metamorphism suggests that underthrusting of Ordovician arc fragments inboard of the Pearya terrane within a transpressional setting (McClelland *et al.*, 2022) occurred after its accretion to and before contraction of the Ellesmerian orogeny initiated at  $\approx 360$  Ma (Latest Famennian to Tourmasian; Piepjohn *et al.*, 2013). In all of these settings, units that experienced burial-related Barrovian metamorphism are rapidly exhumed and variably overprinted by post collisional deformation at shallower crustal levels.

## CONCLUSIONS

This study shows that garbenschist-type rocks that commonly have textural evidence indicating chemical and microstructural disequilibrium can be used for interpreting metamorphic evolution by combining QuiG with other thermobarometric and geochronological approaches. Quartz in garnet Raman thermobarometry and Ti-in-biotite thermometry produced peak MT/MP conditions of 650°C and  $\leq 0.9$  GPa that are consistent with results of phase equilibrium modelling of nearby well-equilibrated and unaltered garnet–mica schists. The QuiG results help define the prograde path leading up to the peak temperatures recorded by the pseudosection models from adjacent garnet–mica schists. The original P estimates from the PBA (Klaper & Ohta, 1993) were based on conventional thermobarometry and are considerably lower than those provided by QuiG. We suggest that the lower pressures were realized during exhumation, which still took place in the kyanite stability field. QuiG has

the potential to improve the  $P$  estimates and  $P$ – $T$  paths for garbenschist in general because the method is not based on assumptions of chemical equilibrium inherent in conventional thermobarometry or thermodynamic modeling.

Tying geochronologic information to the  $P$ – $T$  path remains challenging, but garnet-bearing assemblages containing monazite are useful because of inclusion-matrix relationships and partitioning of REE elements such as Y. Three different monazite domains were identified and dated in this study. Monazite I grew at  $397 \pm 2$  Ma (sample 17-66) and  $394 \pm 2$  Ma (sample 17-64) from allanite after the garnet core formed; this age is the best approximation of the timing of accretion of Pearya to the Ordovician arcs and Siluro-Devonian flysch. Further allanite reaction produced Monazite II at  $388 \pm 2$  Ma (sample 17-66) and  $385 \pm 2$  Ma (sample 17-66) with lower Th that overgrew Monazite I and formed elongate matrix grains parallel to the dominant schistosity. A late phase of lower Y Monazite III grew at  $374 \pm 6$  Ma in the matrix of the garbenschist probably due to fluid influx during exhumation. The *in-situ* dating and analysis of monazite chemistry is essential for relating the textural position to other important phases like garnet to establish the  $P$ – $T$ – $t$  path.

Closely spaced isograds show that temperature and pressure increased to the northwest, requiring a heat source in the direction of the adjacent Pearya terrane. The amphibolite facies gneiss of Pearya was probably not hot enough to produce the prograde metamorphism seen in the PBA over a relatively short (12 Myr) time frame. We speculate that Devonian magmas in the Pearya terrane caused the metamorphism and were later excised by the Cenozoic strike-slip fault that separates the two areas. Although there is no *a priori* reason to expect the tectonic settings of the unusual garbenschist assemblages to be the same, there are some striking similarities among these occurrences. The garnet–kyanite–staurolite garbenschists from Ellesmere Island, Austria, Argentina and Alaska all record complicated MT/MP metamorphic histories associated with burial and exhumation in collisional and accretionary settings. All but the Tauern example were fragments formed in a transpressional regime that was modified by significant later translation.

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## SUPPLEMENTARY DATA

Supplementary data are available at *Journal of Petrology* online.

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