Zircon and monazite in ultrahigh temperature (UHT) metamorphic rocks from the Rauer Islands of Prydz Bay in East Antarctica were investigated in terms of U-Th-Pb and rare earth elements (REE) chemistry along with textural context. All five analyzed samples, three from the Mather Paragneiss UHT unit and two from the host orthogneiss unit yield 522–517 Ma concordant zircon ages, with older protolith/inherited zircon ages of 3268 and 2800–2400 Ma along with highly discordant Mesoproterozoic to Neoproterozoic ages. Our data confirm the Archaean protolith age for the host orthogneiss surrounding the UHT Mather Paragneiss. The Archaean and Mesoproterozoic components of the Rauer Islands were not amalgamated in the Rauer Tectonic Event at 1030–990 Ma, and deposition of the Mather Paragneiss was considered at some time after the Rauer Tectonic Event. In contrast to the well-defined 520 Ma ages obtained from the zircons in the UHT rocks, monazite grains measured by electron microprobe show a distinct internal zonation, from 580–560 Ma dark–backscattered electron image (BSE) cores enriched in middle rare earth elements (MREE) and heavy rare earth elements (HREE) to 550–500 Ma bright–BSE rims. From the chemical and textural evidence we infer that the MREE–HREE–rich 580–560 Ma monazite cores may have formed through the decomposition of garnet during decompression just after the UHT event, whereas the MREE–HREE-depleted 550–500 Ma monazite grains/rims formed or recrystallized in reactions associated with subsequent extensive hydration during the upper-amphibolite to granulite–facies main Prydz Tectonic Event, which also caused marked recrystallization of zircon. The above data strongly support the interpretation that the UHT metamorphism occurred prior to 590–580 Ma.

Keywords: Monazite, Rare earth elements (REE), Ultrahigh temperature (UHT) metamorphism, U-Th-Pb geochronology, Zircon

INTRODUCTION

Recent attempts at reconstructing the Neoproterozoic to Cambrian formation of Gondwana from its pre-existing continental fragments have inevitably led to a focus on the amalgamation history of the East Antarctic Shield (Fitzsimons, 2000; Harley, 2003; Harley and Kelly, 2007a; Boger, 2011). With this has come the realization that the Prydz Bay region of East Antarctica is of central importance in establishing where the final suturing of Gondwana took place (e.g., Fitzsimons, 2003), the period of time over which this occurred, and what impacts this may have had on adjoining areas in former Gondwana.

The evidence preserved in high-grade metamorphic gneisses and migmatites for the location of any possible suture is inherently indirect, relying on discriminating terranes on the basis of at best unique or, more generally,
distinctive event sequences and isotopic data recording different geological ages for magmatism, sedimentation and tectonism, and model ages for the ultimate sources of sedimentary detritus in paragneisses or magmatic precursors of orthogneisses. Conversely, the timing of amalgamation, potentially via suturing, can be constrained by identification of the earliest magmatism, sedimentation or tectonothermal events shared by formerly distinct terranes (e.g., Fitzsimons, 2000, 2003; Harley, 2003).

The Prydz Belt of SE Prydz Bay is polymetamorphic (Wang et al., 2008; Liu et al., 2009; Grew et al., 2012, 2013; Harley et al., 2013; Liu et al., 2013). It preserves a complex record of latest Mesoproterozoic to early Neoproterozoic magmatism, sedimentation and granulite facies tectonism (Wang et al., 2008; Liu et al., 2009; Grew et al., 2012) (Table 1) that is broadly comparable to tectonothermal events in the Rayner Complex to the west (Liu et al., 2013). This event sequence is strongly but variably overprinted by a second granulite facies metamorphism in the early to middle Cambrian (545–515 Ma: Hensen and Zhou, 1995; Zhao et al., 1995; Carson et al. 1996; Fitzsimons, 1996; Fitzsimons et al., 1997). Recent structurally-controlled geochronology of the inferred cover sequence, the Brattstrand Paragneiss (Fitzsimons, 1997), in the Larsemann Hills area of SE Prydz Bay (Wang et al., 2008; Grew et al., 2012; Liu et al., 2013) demonstrate a maximum deposition age close to 1000 Ma, and minimum deposition age older than the 960–990 Ma ages of metamorphosed felsic intrusive rocks (the Blundell Orthogneiss of Grew et al., 2012). The basement gneisses (Søstrene Orthogneiss: Fitzsimons, 1997), cover metasediments (Brattstrand Paragneiss) and early intrusive charnockites and enderbites (Blundell Orthogneiss) of the Prydz Belt all experienced a common high-grade metamorphic event broadly constrained from complex zircon age populations to have progressed between 930 and 890 Ma, consistent with 900 Ma ages obtained from pegmatites (Kelsey et al., 2008).

This chronology for SE Prydz Bay contrasts with and supersedes previous interpretations of the detrital zircon and monazite isotopic record in the Brattstrand Paragneiss (Zhao et al., 1995; Carson et al., 2007; Kelsey et al., 2008) that inferred mid- to late-Neoproterozoic maximum deposition ages for their protoliths. These earlier inferences led to the suggestion of a ‘Neoproterozoic Basin’ related to suturing (Kelsey et al., 2008), which was generalized to include paragneisses from the margins of the Prydz Belt in the Rauer Islands.

A complex and poly-metamorphic geologic record has been documented from the Rauer Islands, where pervasive 540–510 Ma metamorphic ages have also been reported (e.g., Kinny et al., 1993; Sims et al., 1994; Harley et al., 1998; Kelsey et al., 2003a, 2007, 2008). Two paragneiss successions have been recognized, the Filla Paragneiss and the Mather Paragneiss (Harley and Fitzsimons, 1991; Harley et al., 1995; Harley, 2003). Zircon and monazite age data on the Filla Paragneiss (Kinny et al., 1993; Kelsey et al., 2007, 2008) indicate it to be polymetamorphic, with a 1030–970 Ma high-temperature metamorphic event (Rauer Tectonic Event; Harley and Kelly, 2007b) overprinted by the Cambrian Prydz event metamorphism at 545–510 Ma (Prydz Tectonic Event; Harley and Kelly, 2007b). The Mather Paragneiss, outstanding for its preservation of evidence for ultrahigh temperature (UHT) metamorphism at 1.0–1.2 GPa and 990–1030 °C (Harley and Fitzsimons, 1991; Harley, 1998; Kelsey et al., 2003b; Harley and Kelly, 2007a), remains enigmatic as the age and regional significance and extent of this UHT event along with the relationship to the pervasive Prydz event (545–510 Ma) is still not well constrained. Harley et al. (2009) recently suggested, on the basis of U–Th–Pb chemical ages of monazite associated with garnet + sapphire + quartz in a Mather UHT paragneiss from Torekler Island, that UHT metamorphism occurred at >580–590 Ma and was associated with an event separate from the major Prydz event at 545–510 Ma.

The revised chronology for Brattstrand Paragneiss and SE Prydz Belt suggesting a correlation with the Rayner Tectonic Event?
ner Complex not only argues against any suturing and terrane amalgamation between these areas but also raises the question of whether the paragneisses of the Rauer Islands to the NE are different in their depositional and metamorphic ages, potentially indicating the Rauer Islands as the focus for Cambrian terrane amalgamation as suggested by Hensen and Zhou (1997). Given the uncertainties surrounding its sedimentary provenance and the age of its UHT metamorphism, this study presents new zircon isotopic and monazite chemical age data on the Mather Paragneiss and its host orthogneisses from the type locality originally documented by Harley (1998) at Mather Peninsula. These data are used to define the ages and sources for the sedimentary precursors to the UHT paragneisses, constrain their maximum ages of deposition and infer the age of UHT metamorphism.

GEOLGY OF RAUER ISLANDS

The Rauer Islands on the eastern coastline of Prydz Bay are underlain by granulite facies orthogneisses and supracrustal sequences, denoted as the Rauer Terrane (e.g., Harley, 2003), located between the Neoproterozoic to Cambrian Prydz Belt to the southwest and the Archaean to earliest Palaeoproterozoic Vestfold Block to the northeast (Fig. 1). The Rauer Terrane contains both Archaean and Proterozoic crustal components (Kinny et al., 1993). These tectonic blocks or crustal domains are now complexly interleaved and infolded as a result of polyphase high-grade deformation events that have cumulatively produced isoclinal, sheath and interference folds with steep SSE-plunging fold axes on all scales, and meter to hundred meter wide arcuate to Anastomosing high strain zones (Harley, 1987; Sims et al., 1994).

The domains have been interleaved and co-deformed in the Cambrian tectonic event at 530–510 Ma, but it is still unclear as to whether they all share a prior history. The Archaean domains are dominated by tonalitic to granodioritic orthogneisses and composite layered mafic–intermediate orthogneisses with protolith and/or intrusive ages from 3450 to 2550 Ma (Kinny et al., 1993; Harley et al., 1998). These orthogneiss units were subjected to high-grade metamorphism prior to 2550 Ma (Harley et al., 1998; S. Harley, unpublished data) and subsequently intruded by several generations of mafic dykes. These mafic dykes are now metamorphosed into pyroxene granulites and variably deformed, being essentially parallel to felsic and composite gneiss fabrics in high strain zones (Harley, 1987; Harley and Fitzsimons, 1991; Sims et al., 1994; Harley et al., 1995). The Archaean domain also contains two groups of layered igneous complexes, the 2840 Ma ferrogabbroic–ferrodioritic Scherbinina Layered
Complex (Snape et al., 1997; Harley et al., 1998; Harley and Kelly, 2007b) and the Mg–rich gabbro–anorthositic Torckler–Tango Complex (Harley et al., 1995).

The Mather Paragneiss, as originally defined (Harley, 1998), includes a varied suite of protoliths hosted or forming boudinaged lenses and stringers within or adjacent to the Archaean tonalitic gneisses described above. The Mather Paragneiss is composed of magnesian and aluminous garnet–orthopyroxene– sillimanite–bearing metapelitic with secondary sapphirine and cordierite, orthopyroxene–sillimanite metaquartzite, magnesian garnet–sillimanite metapelite, orthopyroxene–bearing leucogranite, and garnet–bearing maﬁc granulite (Harley and Fitzsimons, 1991; Harley, 1998). It is also considered to include forsterite–diopside marble and related metasomatic diopsidite rinds, andraditic and Fe–Mn skarn rocks, and garnet–bearing maﬁc granulites (Harley and Fitzsimons, 1991; Buick et al., 1994; Harley et al., 1995). This suite can be traced as thin and laterally discontinuous horizons from Mather Peninsula itself through to Short Point in the eastern Rauer islands (Fig. 1c).

The Archaean basement rocks of the Rauer Islands are interleaved with a Mesoproterozoic to earliest Neoproterozoic domain characterized by the migmatised Felpelites, semipelites and quartzites of the Filla Paragneiss, leucogneisses and leucogranites that occur as sheets, sills and stocks within the Filla Paragneiss, granitic to dioritic orthogneisses and gneissic granitoids, and a varied suite of metabasites with associated metacarbonate horizons that are interpreted to be metavolcanic rocks associated with the Filla Paragneiss (Harley and Fitzsimons, 1991; Harley et al. 1995). Zircon U–Pb age dating of the meta- granitoids, leucogneiss and cross-cutting aplite indicate that these rocks, and the Filla Paragneiss, underwent granulite facies metamorphism and deformation in the interval 1030–990 Ma (Kinny et al., 1993). Metamorphic monazite in these paragneisses usually records two U–Th–Pb age peaks, a younger one at 540–510 Ma and an older one, mainly recorded from monazite cores, that ranges from 1000 to 900 Ma (S. Harley, unpublished data; Kelsey et al. 2007). Hence, the isotopic record of the Filla Paragneiss is consistent with it being polymetamorphic, recording deformation and metamorphism in both the end-Mesoproterozoic to earliest Neoproterozoic Rauer Tectonic Event and the Cambrian Prydz Tectonic Event. This also demonstrates that the Filla Paragneiss was deposited in the Mesoproterozoic, prior to 1030 Ma. A possible minimum age of deposition is provided by a 1058 Ma zircon age obtained by Kinny et al. (1993) from a small–scale partial melt patch in the Filla Metabasite, which occurs in close association with the Filla Paragneiss throughout the Rauer Islands.

**SAMPLE DESCRIPTIONS**

Five samples, three from the main Mg–Al–rich Mather Paragneiss horizon, one from an adjacent tonalitic orthogneiss, and one from another pelitic gneiss horizon within the orthogneiss (Figs. 1c and 2), have been investigated. The Mg–Al–rich gneiss (SH/88/218 and TH/06/30C; both collected from precisely the same sample location) in Mather Peninsula. They preserve mineral assemblages including garnet, high-Al orthopyroxene and/or sillimanite that are constrained to have equilibrated at UHT conditions, from minimum conditions of 0.9–1.0 GPa and 980 °C (Kelsey et al. 2005) up to 1.1–1.2 GPa and 1030 °C
The peak garnet + orthopyroxene + sillimanite assemblages are locally to extensively replaced by fine-grained symplectites composed of combinations of sapphirelne, orthopyroxene, cordierite, spinel and plagioclase (Fig. 3a). For example, former orthopyroxene + sillimanite is generally replaced by fine-grained symplectites of sapphire + cordierite, and garnet by sapphire + orthopyroxene with sillimanite or cordierite (Figs. 3b and 3c), and also extensively hydrated to form biotite (Figs. 3d and 3e). As described and analyzed in detail by Harley and Fitzsimons (1991), Harley (1998) and Kelsey et al. (2003a, 2005), the range of textures formed in different micro-scale bulk compositions are consistent with an initial post-peak evolution involving appreciable decompression of up to 0.4 GPa under granulite-facies conditions. Whilst the precise dP/dT of this post-peak decompressional path is subject to some debate (Kelsey et al., 2005; cf. Harley, 1998, 2003) it is generally agreed that the Mg-Al granulite post-peak P-T path traversed through 0.7–0.8 GPa and 850–900 °C. The UHT gneiss was affected by extensive hydration to form biotite-bearing reaction coronas and biotite-rich reaction zones, some of which are then overprinted by low-Al orthopyroxene + cordierite symplectites. Symplectite coarsening, producing blocky orthopyroxene and sapphire, is associated with this biotite overprint. Late-stage garnet breakdown to cordierite and biotite, and replacement of earlier sapphire + orthopyroxene by these phases, is also observed. Biotites in these textural settings preserves low fluorine (<0.9 wt%) and chlorine (<0.3 wt%) with variable TiO2 (1–3 wt%) contents consistent with their formation on cooling below 800–900 °C.

Sample TH/06/30J was collected from an Opx-bearing leucosome occurring with Mg-Al-rich gneisses. Patchy or vein leucosomes similar to that sampled occur on centimeter to decimeter width scales and are commonly deformed, consistent with the host gneisses. The main leucosome constituents are quartz and orthopyroxene; plagioclase and biotite are minor phases and K-feldspar is generally absent. Orthopyroxene is porphyroblastic with grains up to 2–5 mm across. Biotite is usually anhedral and occurs interstitially around quartz and orthopyroxene crystals. Zircon, rutile and late muscovite are minor. The tonalitic orthogneiss sample (TH/06/33A) is from the orthogneiss units that encloses Mather UHT gneiss layer (SH/88/218, TH/06/30C and TH/06/30J). It is representative of the typical tonalitic orthogneisses of the eastern Rauer Islands and Mather Peninsula area, and consists of quartz, plagioclase, perthite, hornblende, and relatively minor amount of orthopyroxene and clinopyroxene. Zircon, monazite and opaque minerals are also present. The pelitic gneiss sample (TH/06/33B) consists of coarse-grained garnet crystals up to a few centimeters in diameter, which enclose fibrous sillimanite inclusions and are surrounded by coarse-grained (1–2 mm across) prismatic sillimanite that forms the main foliation. Quartz, plagioclase and biotite are minor phases. Biotite is commonly anhedral and interstitial, indicating formation at post-peak. Cordierite occurs interstitially among garnet crystals, and is apparently secondary. Zircon and opaque minerals are present as accessory phases.

ION MICROPROBE ZIRCON CHRONOLOGY

Analytical method
U-Pb and REE data from zircon were obtained using the ion microprobe SHRIMP II at the National Institute of Polar Research, Tokyo. Zircons in the Mg-Al-rich Mather
UHT gneiss samples (SH/88/218 and TH/06/30C) were analyzed in-situ in polished thin section in addition to analyses obtained from mineral separates. Detail of the analytical method is described in Supplementary Documentation (Supplementary Documentation is available online from http://doi.org/10.2465/jmps.150829). The procedures for the Pb and U isotopic analyses of zircon followed those of Compston et al. (1984) and Williams (1998) with U-Pb measurements were calibrated against 204Pb-corrected (Pb/U)/(UO/U)2 values for standard zircon FC1 (1099 Ma, Paces and Miller, 1993). Data reduction and processing were performed using the Excel add-in program SQUID (Ludwig, 2001) and plots were generated using ISOPLOT (Ludwig, 2003). Common Pb contents were corrected using the measured 204Pb and a Stacey and Kramers (1975) model for ages approximating those of standard and unknown zircon ages (see Ludwig, 2001 for details). Errors on single spot ratios and ages are quoted at 1-sigma, whereas pooled ages and concordia intercept ages are quoted at 95% confidence levels. Zircon REE contents for standard reference material 91500 (Wiedenbeck et al., 2004) were within 10% of published values.

Results
The Mg-Al-rich gneiss (TH/06/30C = SH/88/218, the original UHT rock described by Harley and Fitzsimons (1991) and Harley (1998)) includes subhedral to rounded zircon grains, some of which preserve a marked discontinuous internal zonal structure (Fig. 4). U-Pb analyses were made on a total of 129 analytical spots on 107 zircon grains from the separates mounted in the epoxy resin disc (TH/06/30C) and 27 analytical spots on 17 zircon grains from the polished thin section (SH/88/218) (Supplementary Table S1: Supplementary Table S1 is available online from http://doi.org/10.2465/jmps.150829). Both groups of zircon analyses yield consistent results, with a large spread in zircon analyses lying between a main upper intercept at 2600 Ma and lower intercept near 500 Ma. A few zircon cores yielded Archaean ages older than 2600 Ma (>2700–3200 Ma: Figs. 5a and 5b). In detail, the spread of data on Tera–Wasserburg Concordia diagrams (Figs. 5a and 5b) defines a broadly triangular field from near 2600 Ma to lower intercepts ranging from <1000 to 500 Ma, with concordant younger age domains being either near 500 Ma or between 900–710 Ma (206Pb/206Pb ages). The pooled ages of the younger group of in-situ analysis and grain mount analysis yielded concordia ages of 522 ± 13 Ma (decay-constant errors included, MSWD of concordance = 1.7, probability of concordance = 0.19) and 519.8 ± 4.7 Ma (decay-constant errors included, MSWD of concordance = 1.8, probability of concordance = 0.17), respectively. We carefully investi-
The UHT orthopyroxene-bearing leucosome (TH/06/30J) also yields scattered and discordant zircon data with an upper intercept of 2460 Ma and lower intercept of 540 Ma based on 36 analytical spots on 30 zircon grains (Fig. 7a). Notably, this analytical population does not contain any zircon, concordant or discordant, that falls in the age range 1000 ± 100 Ma. Three concordant analyses and one slightly discordant point plot at 540–520 Ma, whilst one analysis occurs near 635 Ma.

Both Mather UHT gneiss (SH/88/218 and TH/06/30C) and Opx–bearing leucosome (TH/06/30J) preserve a similar age spectrum (Figs. 5c, 5d, and 7d). Th/U ratios in zircons are in the range of 0.4–1.0 for 2400–2600 Ma concordant (and near upper intercept) zircon domains and below 0.4 for 520–500 Ma concordant (and near lower intercept) domains.

Thirteen analyses on 12 zircon grains from the tonalitic orthogneiss (TH/06/33A) defined a discordant array with several near-concordant analyses bracketing an upper intercept age of 3268 ± 4 Ma (Fig. 7b). This age is coincident with the 3269 ± 9 Ma age obtained by Sheraton et al. (1984) for an orthogneiss from Short Point, about 1 km south of the Mather Peninsula UHT site (Fig. 1).

In the case of the metapelitic garnet-sillimanite gneiss (TH/06/33B), 49 analytical spots were obtained on 39 zircon grains. The zircons have no inherited magmatic grain cores or textural domains and so are all interpreted to be recrystallized metamorphic grains. The analytical population (n = 49) yielded a precise concordia age of 516.6 ± 2.0 Ma (decay–constant errors included, MSWD of concor-
dance = 4.4, probability of concordance = 0.036) (Fig. 7c).

**ELECTRON MICROPROBE MONAZITE CHRONOLOGY**

Analytical method

Chemical analyses were made on monazite grains in a normal polished thin section from sample SH/88/218 using electron microprobe with a wavelength-dispersive X-ray analytical system (JEOL JXA-8800M) at the National Museum of Nature and Science, Tokyo, Japan. The theoretical basis of electron microprobe dating follows that of the chemical Th–U–total Pb isochron method (CHIME) described by Suzuki et al. (1991). Detail of the analytical method is described in Supplementary Documentation, which essentially follow that described in Hokada et al. (2004). Internal monazite standards with their ages ranging from 3460 to 1 Ma have been routinely monitored to check the reliability of the obtained ages (Santosh et al., 2006).

Results

Despite their varied textural settings (i.e., inclusions in UHT orthopyroxene, grains in syltectites, grains grown with late biotite) almost all monazite grains yield U–Th–Pb electron microprobe chemical ages in the range 580–450 Ma, with weak evidence for 650 Ma inheritance (Figs. 8 and 9) (Supplementary Table S3: Supplementary Tables S3 is available online from http://doi.org/10.2465/jmps.150829). The full group of analyses (total 100 analyses on 69 grains) treated without consideration of texture or chemistry yielded a weighted average age of 521 ± 28 Ma. However, the monazites occasionally showed distinct internal structures, typified by dark–BSE cores, mid–BSE mantles, and bright–BSE rims. These variations in BSE correlate with grain chemistry (see Fig. 6; please note that Y is commonly used as proxy for Ho and Er): the dark–BSE monazite cores (e.g., Mnz–#15, #27, and #14 in Fig. 8) are relatively enriched in M–HREE and Y (depleted in ThO2), whereas the bright–BSE mantles or structureless grains (e.g., Mnz–#15, #9, and #10 in Fig. 8) have lower
The Rauer Islands contain both Archaean and Proterozoic crustal components (e.g., Kinny et al., 1993; Harley and Kelly, 2007a, 2007b), with the Archaean domain dominant at in the Scherbinina Island - Mather Peninsula and Torckler Island areas (Fig. 1). The Archaean/Proterozoic boundary is inferred to run through Mather Peninsula (Fig. 1; Harley and Kelly, 2007a, 2007b) some 500 metres to the west of the UHT locality. The Mather Paragneiss detrital zircon age spectra (dominantly >2800–2400 Ma) and 3267 Ma age for the protolith of the host tonalitic orthogneiss obtained in this study are consistent with the previously reported zircon dates from Archaean orthogneisses of the Rauer Islands (2800 Ma: Kinny et al., 1993; 3279 Ma: Sheraton et al., 1984; 2840 and >3300 Ma: Harley et al., 1998) and confirm that the host orthogneiss surrounding the UHT paragneisses at Mather Peninsula is Archaean in protolith age. The zircon age spectrum for the Mather Paragneiss is also consistent with its highly evolved Nd isotope signature and whole rock model age ($T_{DM} = 2900$–3700 Ma: Hensen and Zhou, 1995, 1997).

As noted above, it is now generally accepted that the Mesoproterozoic lithotectonic units are polymetamorphic, and experienced granulite-grade tectonism at both 1000 Ma (Rauer Tectonic Event) and 530 Ma (Prydz Tectonic Event). However, it remains a matter of debate as to whether the Prydz Tectonic Event was (1) responsible for the high-grade amalgamation of formerly separate Archaean and Mesoproterozoic lithotectonic units, or (2) only responsible for reworking a mixed basement that included Archaean and Mesoproterozoic gneisses. In the first model, proposed initially by Hensen and Zhou (1997), the Archaean and Mesoproterozoic lithotectonic units would have had distinct and unrelated crustal histories up until amalgamation in the Cambrian. In the second model, the Archaean and Proterozoic gneisses may have been assembled in and shared the 1030–990 Ma Rauer Tectonic Event (Kinny et al., 1993; Harley et al., 1998).

This ambiguity arises for two main reasons. Firstly, as recognized by Hensen and Zhou (1997), the Archaean orthogneisses do not record in their zircon U–Pb isotopic signatures the effects of the 1000 Ma Rauer Tectonic Event, but instead preserve a spectrum of Archaean ages disturbed by resetting at 540–505 Ma and new zircon growth at 530 Ma (e.g., Kinny et al., 1993; Harley et al., 1998; Harley and Kelly, 2007b). Secondly, the dominant Mesoproterozoic sedimentary suite, the Filla Paragneiss, is found to lack (Kinny et al., 1993) or have very few (Kelsey et al., 2008) detrital zircons derived from...
Archaean sources and records Nd and Sr isotope signatures consistent with derivation from dominantly Palaeo-Mesoproterozoic basement (Kinny et al., 1993; Hensen and Zhou, 1995).

Given this uncertainty, the presence of Archaean and Mesoproterozoic material in the zircon age spectra from the Mather Paragneiss is of critical importance. This study and two previous isotopic studies of samples of the Mather Paragneiss (Wang et al., 2007; Kelsey et al., 2008) indicate that near-concordant zircons of late-Mesoproterozoic to Neoproterozoic age occur in these rocks. In the present study we have identified 4 high-U (3000–1100 ppm), low Th/U (0.01), near-concordant zircon grains with $^{207}\text{Pb}/^{206}\text{Pb}$ ages in the range 900–710 Ma in the Mg-Al pelite, and none in the Opx-leucosome. Notably, no concordant zircon grains or grain rims have been found with ages in the range corresponding to the 1030–990 Ma Rauer Tectonic Event.

Wang et al. (2007) reported SHRIMP U–Pb data for zircons separated from a UHT Mather Paragneiss sample. Their data were also dominated by highly discordant to concordant Archaean core populations, with weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 2657 ± 17 Ma and 2532 ± 12 Ma, in most cases overgrown by rims with ages consistent the Prydz Tectonic Event (532 ± 7 Ma). That study also identified a texturally distinctive set of near-concordant high-U, low Th/U (<0.02) overgrowths or mantles on some Archaean zircon cores, which yielded a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 995 ± 15 Ma. On the basis of these near-concordant zircons, and a discordia defined by analyses of some of Archaean zircon cores that projects down to a lower intercept near 1000 Ma, Wang et al. (2007) suggested that the Mather Paragneiss is polymetamorphic, affected not only by the Prydz Tectonic Event but also the Rauer Tectonic Event at 1000 Ma. If this was the case, it would uniquely imply that the Archaean and Mesoproterozoic rocks of the Rauer Islands shared their geological evolution from at least 1000 Ma. In the interpretation of Wang et al. (2007) the sedimentary precursors of the Mather Paragneiss would be older than 1000 Ma, like the Filla Supracrustals, but sourced from a basement dominated by the local Archaean gneisses rather than perhaps a more distal Proterozoic source region.

Kelsey et al. (2008) documented the LA–ICP–MS U–Pb age spectra of zircons separated from two Mather Paragneiss samples. Their results were consistent with those of Wang et al. (2008) in defining broad triangular fields of mostly discordant analyses on the Wetherill concordia diagrams, dominated by detrital zircon cores of Archaean to early Palaeoproterozoic age (2800–2300 Ma). Near-concordant zircon grains or rims ranging in apparent age from 980–580 Ma, as well as 550–500 Ma rims, formed the younger age components of their zircon spectra. In contrast to Wang et al. (2007), Kelsey et al. (2008) interpreted their 980–580 Ma analytical group, which also were mainly characterised by low Th/U (<0.1), as detrital grains of metamorphic provenance. Based on this interpretation Kelsey et al. (2008) concluded that the Mather Paragneiss precursors were deposited in the late Neoproterozoic with varied detrital sources that ranged in age to as young as 580 Ma.

Like the Mather Paragneiss zircon data reported here and by Wang et al. (2007), the discordant zircon data of Kelsey et al. (2008) indicate extensive Pb loss from the Archaean zircons at ages older than 800 Ma. The zircon data presented in Kelsey et al. (2008) could therefore be interpreted as reflecting the dominance of originally Archaean detrital zircon grains that have been variably affected and disturbed by the Rauer Tectonic Event at 1000 Ma, as well as by the later Prydz Tectonic Event. Examination of the CL images of Kelsey et al. (2008) suggests that many, if not all, of the Neoproterozoic zircon grain domains have experienced textural changes, such as oscillatory zone ‘blurring’ and ‘bleaching’ and invasion by lobate chemical fronts. These internal textural features are typical of metamorphic modification (e.g., Harley et al., 2007) facilitated by coupled dissolution/reprecipitation (Geisler et al., 2007). The non-uniform spread in the near-concordant Neoproterozoic zircon U–Pb data in Kelsey et al. (2008) is re-interpreted here as reflecting the variable effects of the Prydz Tectonic Event at 530 Ma on pre-existing Mesoproterozoic metamorphic zircon formed during the Rauer Tectonic Event. In this interpretation no exotic sources of mid–Neoproterozoic zircons are required.

The evidence from Wang et al. (2007) and in–situ analyses here which show that some >1000 Ma zircon may have nucleated on 2600–2400 Ma Archaean detrital cores, isotopically disturbed during the Rauer Tectonic Event, and could be interpreted to reflect the juxtaposition or amalgamation of the Archaean and Mesoproterozoic components of the Rauer Islands prior to or during the Rauer Tectonic Event at 1030–990 Ma. However, this is not a necessary conclusion. The detrital zircon spectrum obtained by Kelsey et al. (2008) on a sample of undisputed Proterozoic Filla Paragneiss (11104B, west Mather Peninsula) includes 3 Archaean grains with $^{207}\text{Pb}/^{206}\text{Pb}$ intercept ages of 2950 to 2600 Ma, and a sample from Luny Island contains one 2670 Ma detrital grain. Hence, it is possible that zircons with Archaean cores rimmed by 1000 Ma overgrowths could be derived from the erosion of the Filla Paragneiss or similar rocks, whether the Archaean component of the Rauer Islands was present or not. This observation, coupled with the lack of any 1000 Ma zircon record in the Archaean orthogneisses reported in
Timing of UHT metamorphism and tectonic implications

Placing a strong time constraint on the UHT event in the Mather Paragneiss is critical for models of the development of the Rauer Islands, the Prydz Belt and the amalgamation of East Antarctica (Harley et al., 2013). The first indication that these paragneisses might record an event distinct in age from the Prydz Tectonic Event was reported by Hensen and Zhou (1995, 1997), who obtained a 600 Ma Sm–Nd garnet–whole rock isochron for Mather Paragneiss SH/88/218. This result is unique within their garnet–whole rock Sm–Nd dataset for the eastern Prydz Bay region, as all other paragneiss samples yielded isochrons ages near 510–500 Ma. This would be consistent with the retention of a pre-Prydz Tectonic Event garnet formation episode in the Mg–Al UHT granulites of the Mather Paragneiss.

As noted in the previous section, Wang et al. (2007) ascribed the formation of 1000 Ma age high–U, low Th/U rims or mantles on Archaean zircons in the Mather Paragneiss to the UHT metamorphic event. They further suggested that the anomalously high temperatures were caused by syn–metamorphic enderbitic magmatism, requiring the host orthogneiss to be of that age. The age of 3268 ± 4 Ma obtained in the present study for the host tonalitic orthogneiss means that this cannot be a heat source for UHT metamorphism if that occurred at 1000 Ma, and hence argues strongly against a key facet of the interpretation of Wang et al. (2007).

Based on their interpretation that 980–580 Ma zircons in their Mather Paragneiss sample were detrital grains of varied metamorphic provenance, Kelsey et al. (2008) concluded that the Mather Paragneiss was not older than 580 Ma, citing this as proof that the UHT metamorphism occurred in the Prydz Tectonic Event from 575 through to 510 Ma, in accord with evidence from monazite chemical dating (Kelsey et al. 2003b, 2007). As argued above, the broad range in Neoproterozoic ages could plausibly be the result of variable resetting of early Neoproterozoic detrital grains by the Prydz Tectonic Event, so that the Mather Paragneiss could have been deposited as early as 1000 Ma but after the Rauer Tectonic Event. Hence, the previous zircon data and our new data also allow UHT metamorphism to be as old as 1000 Ma, but do not require it.

All five analyzed samples in this study, three from the Mather UHT unit (TH/06/30C and SH/88/218: Mg–Al-rich UHT gneiss, TH/06/30J: orthopyroxene–bearing leucosome) and two from the host orthogneiss unit (TH/06/33A: felsic orthogneiss, TH/06/33B: Garnet–sillimanite–bearing metapelitic gneiss lens in orthogneiss) yield concordant to near–concordant 530–510 Ma zircons, consistent with previous age data on zircons from the Mather Paragneiss (Wang et al., 2007; Kelsey et al., 2008) and nearby orthogneisses (Kinny et al., 1993; Harley et al., 1998). These clearly only place a lower age limit on UHT metamorphism. The Opx–bearing leucosome TH/06/30J, which is likely to have formed through melting and melt–wall rock interaction syn– or late during the UHT event, preserves one near–concordant zircon with a $^{206}$Pb/$^{238}$U age of 635 Ma, but otherwise there is no clear evidence in the zircon data from the Mather Paragneiss samples to precisely constrain an age for the onset and duration of UHT metamorphism.

The calculated apparent REE distribution coefficients $\text{[D}_{\text{REE}}(\text{Zrn/Grt})]_{\text{app}}$ can be compared with empirical or experimentally derived D values inferred to represent equilibrium (e.g., Kelly and Harley, 2005). Although garnet generally has much less (1/100) REE concentration than zircon as can be seen from Figure 6, the modal proportion of garnet is much greater than that of zircon — probably 1000 times or more especially for the case of the current sample which has >10% modal proportion of garnet (see Figs. 2c and 3a) in the rock. Therefore, even
though garnet has much less REE contents than zircon, garnet still contributes to control theREE pattern of metamorphic zircon if zircon growth/recrystallization took place at the presence of garnet. Although, there still remains several discrepancies among recent experimental results (Rubatto and Hermann, 2007; Taylor et al., 2015), comparison of the $D_{\text{HREE}}(\text{Zrn/Grt})$ values calculated for all zircon types in SH/88/218 with experimentally-constrained values for $D_{\text{HREE}}(\text{Zrn/Grt})$ under UHT conditions of $T > 950 \, ^{\circ}\text{C}$ (Rubatto and Hermann, 2007; Taylor et al., 2015) shows that none of these zircons have equilibrated with the garnet present in the UHT gneiss. As the garnet in the studied UHT sample shows relatively low–Ca and metamorphosed under $T > 900 \, ^{\circ}\text{C}$, the experimental conditions of Taylor et al. (2015) are to be more appropriate. However, the $D_{\text{HREE}}(\text{Zrn/Grt})$ values of the studied sample suggests HREE-enriched D pattern that is far different from the experimental results of Taylor et al. (2015) suggesting flat M–HREE D pattern to be equilibrium partitioning (Fig. 6). Hence, none of the zircon ages obtained in our study provide an age of the peak UHT event in which garnet was stable. These observation implies that the zircon grains, even if they are included in the orthopyroxene or garnet porphyroblasts, were more or less affected by lead loss, partial resorption–reprecipitation and/or recrystallization promoted by pervasive hydration during the upper-amphibolite–granulite–facies main Prydz Tectonic Event at 520–510 Ma.

Monazite chemical dating offers an alternative means of addressing the age of the UHT event in the Mather Paragneiss, especially when considered using in-situ analysis and monazite mineral chemistry. Kelsey et al. (2003b) reported monazite electron microprobe chemical ages for the Mather Paragneiss that ranged from 521 ± 8 to 500 ± 6 Ma. These data were complemented by in-situ results from two further samples that yielded ages of up to 544 ± 11 Ma for monazites hosted in or exhumed from garnet porphyroblasts (Kelsey et al., 2007). Kelsey et al. (2007) also recognized a 574 ± 16 Ma monazite age population, hosted in orthopyroxene, which they ascribed to a prograde, pre-garnet, stage of UHT metamorphism that later peaked at 545 Ma as part of the regionally documented Prydz Tectonic Event.

Monazite grains analyzed in-situ in the present study by electron microprobe show distinct internal zonation: 580–560 Ma dark–BSE cores, 550–520 Ma mid-BSE mantles and 510–500 Ma bright–BSE rims, with minor inheritance of an earlier but poorly defined population of 650 Ma monazite. The 580–560 Ma monazite cores have relatively high M(–H)REE whereas the 550–520 Ma mantle domains and structureless grains preserve lower M(–H)REE contents, suggesting their growth or modification under different conditions (Fig. 6a). The 510–500 Ma outermost rims have the lowest M(–H)REE concentrations, again suggesting an evolution in the REE chemistry of their growth environment that may be related to the formation or consumption of other REE-bearing minerals. A simple interpretation may be the 580–560 Ma monazite to be formed prograde metamorphism pre-dating the pervasive 520 Ma ages obtained from both zircon and monazite. It cannot be ruled out the possibility that the older monazite dates just inherited from the 1000 Ma Rauer Tectonic Event. In order to assess this we need more data and information of the nature of Rauer Tectonic Event, and at moment we could not discuss more on this.

The Mg–Al-rich gneisses in Mather Peninsula preserve UHT mineral assemblages including garnet, orthopyroxene and/or sillimanite that are locally replaced by fine-grained symplectite composed of sapphirine, cordierite, orthopyroxene, spinel or plagioclase along the post-peak decompressional $P$–$T$ path (Harley, 1998). These gneisses have also experienced extensive hydration, manifested in the formation of biotite-bearing reaction coronas and localized biotite-rich zones and reaction selvages. Almost all monazite grains are distributed in the symplectitic reaction zones. From the chemical and textural evidence we infer that the M–HREE-rich 580–560 Ma monazite cores may have formed not prograde but through the decomposition of garnet, for example to orthopyroxene + sapphirine, during decompression just after the UHT event, whereas the M–HREE-depleted 550–500 Ma monazite grains/rims formed or recrystallized in reactions associated with the subsequent extensive hydration, which also caused the marked recrystalization of zircon.

The monazite data support the interpretation proposed by Harley et al. (2009) that the UHT metamorphism occurred prior to 590 Ma, and are consistent with the 600 Ma Sm–Nd garnet isochron obtained for the same rock by Hensen and Zhou (1995, 1997). The observation that this age (600–580 Ma) is only recorded in the UHT Mather Paragneiss and is not present in adjacent or nearby Archaean or Neoproterozoic units within the Rauer Islands, all of which record the 530 Ma Prydz Tectonic Event, supports the speculation of Harley et al. (2009) that the Mather Paragneiss experienced its UHT metamorphism prior to final accretion to and during interleaving with those other units in the Cambrian.

**SUMMARY AND CONCLUSIONS**

Given its present position the evolution of the Rauer Terrane is critical to understanding the amalgamation of East Antarctica, and particularly the relative importance of 1000 and 530–510 Ma tectonothermal events in weld-
ing together the various Archaean and Proterozoic crustal blocks (Zhao et al., 1995; Hensen and Zhou, 1995; Carson et al., 1996; Hensen and Zhou, 1997; Fitzsimons, 2000; Harley, 2003; Carson et al., 2007; Wang et al., 2007; Kelsey et al., 2007, 2008; Boger, 2011; Harley et al., 2013). The Mather Paragneiss detrital zircon age spectra (upper intercepts of 2800±2400 Ma) and the protolith zircon age of the host tonalitic orthogneiss (3268±4 Ma) obtained in this study are consistent with the previously reported zircon dates from Archaean orthogneisses of the Rauer Islands, and confirm that the host orthogneiss surrounding the UHT paragneisses are Archaean in protolith age. Although we have identified a few near-concordant 900–700 Ma zircon grains from the Mg-Al UHT gneiss, no concordant zircon grains or grain rims have been found with ages in the range corresponding to the 1030–990 Ma Rauer Tectonic Event. This observation leads us to conclude that the Archaean and Mesoproterozoic components of the Rauer Islands were not amalgamated in the Rauer Tectonic Event, and that deposition of the Mather Paragneiss was at some time after the Rauer Tectonic Event. The near-concordant early Neoproterozoic (700 Ma) zircons are considered to reflect the variable effects of the Prydz Tectonic Event at 530 Ma on the pre-existing metamorphic zircon, rather than defining a younger maximum age of deposition for the Mather Paragneiss.

Two alternative tectonic scenarios have been proposed previously for the context and development of the UHT metamorphism in the Mather Paragneiss. The first scenario, that of a single tectonic event, proposed that UHT, ITD and subsequent biotite formation all occurred during the age interval >575–510 Ma and hence reflect the Prydz Belt tectonism seen further SW in Prydz Bay (Kelsey et al., 2007, 2008). The second, two tectonic event scenario of Wang et al. (2007), proposed that an older possibly 1000 Ma UHT metamorphism was overprinted by the later high-T hydration event at 580–510 Ma. Neither of these scenarios fully accounts for the data presented in this study, in particular the monazite age-chemistry evidence which suggest that 580–560 HREE-enriched monazite formed in the Mather Paragneiss accompanying the decomposition of high-Mg garnet at or following UHT conditions. The implications of the monazite data are that UHT metamorphism occurred at or just prior to 580 Ma and was followed by extensive decompression and cooling, whereas the development of M-HREE depleted 550–500 Ma monazite grains/rims reflects a distinct overprinting episode associated with the subsequent extensive hydration related to the upper-amphibolite to granulite-facies main Prydz Tectonic Event in the Rauer Islands.

The zircon and monazite data present in this study imply the contrasting behavior of these minerals in response to crystallization/modification during high-T/UHT metamorphism. Zircon is commonly a robust mineral that can retain older protolith/inherited isotopic compositions, but conversely is not always a reliable recorder of HT and UHT metamorphic events (e.g., Kelly and Harley, 2005) as zircon may not grow in the absence of suitable melts, and furthermore may be extensively modified by coupled dissolution–precipitation under relatively lower-T but fluid-rich conditions (e.g., Geisler et al., 2007). In contrast, whilst monazite has less ability to retain older protolith/inherited isotopic compositions, it may have greater potential to record the HT–UHT metamorphic events. The combined or integrated use of isotopic and chemical analysis of zircon and monazite, preferably in-situ and in concert with host silicate and other minerals that may compete for REE, offers greater potential to provide insights on the development of complex and poly-metamorphic terranes than the use of zircon alone.

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SUPPLEMENTARY MATERIALS

Supplementary Documentation, Tables S1-S3, and color version of Figures 1–3, and 6 are available online from http://doi.org/10.2465/jmps.150829.

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