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Multi-stage metamorphism in the Rayner–Eastern Ghats Terrane: *P*–*T*–*t* constraints from the northern Prince Charles Mountains, east Antarctica

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ABSTRACT

Metapelitic rocks from the northern Prince Charles Mountains in the Rayner Complex in east Antarctica record evidence for a protracted metamorphic history during the late Mesoproterozoic to early Neoproterozoic. In situ LA–ICP–MS U–Pb monazite geochronology yields ages in the interval 1030–880 Ma. There is a spread in U–Pb ages both between and within individual samples. Two samples record monazite populations at c. 1020 Ma, which have been variably reset. The remaining samples contain single monazite populations with $^{206}Pb/^{238}U$ weighted mean ages of 940–900 Ma. Calculated metamorphic phase diagrams for a sample preserving a defined late Mesoproterozoic monazite population suggest this early part of the metamorphic history may reflect a higher-pressure phase of metamorphism. This stage was overprinted by a cordierite-bearing assemblage, texturally accompanied by monazite growth at 950–900 Ma. The conditions of the second event are consistent between samples, and suggest that it involved lower pressures of 6–7 kbar and temperatures of 850–880 °C. The geochronology and metamorphic conditions for the Neoproterozoic metamorphism obtained in this study are consistent with the evolution proposed for elsewhere in the Rayner Complex and also the contemporaneous and formerly contiguous UHT metamorphism in the Eastern Ghats Province in India. This is the first study to integrate metamorphic constraints from the now separate terranes, and it suggests that that Rayner–Eastern Ghats terrane as a whole records prolonged high temperatures over a spatially large (>500,000 km^2) area. This has implications for the timescales and footprint of geodynamic processes involving the mid-to-deep crust.

1. Introduction

Metamorphism along high thermal gradients (>100 °C/kbar), particularly if it reaches ultrahigh temperature (UHT) conditions, has been the focus of much attention as it has implications for lithospheric rheology, crust–mantle interaction and the geodynamic settings in which high thermal gradients can be developed and maintained (e.g. Brown, 2007; Clark et al., 2011; Harley, 2004; Kelsey, 2008; Kelsey and Hand, 2015; Sizova et al., 2014). It is increasingly appreciated that many regional greenschist and amphibolite-facies high thermal gradient terranes may simply be the upper crustal levels of granulite to ultrahigh-*T* (G–UHT) terranes, and therefore G–UHT metamorphism may be relatively common in the crust (e.g. Brown, 2007, 2014; Clark et al., 2011; Kelsey and Hand, 2015; Morrissey et al., 2014; Sandiford and Powell, 1986; Stüwe, 2007). However, the requirements and mechanisms for the regional generation of these high temperatures remain uncertain (e.g. Brown, 2007; Brown and Korhonen, 2009; Clark et al., 2011; Gorczyk et al., 2015; Jamieson and Beaumont, 2013; Kelsey and Hand, 2015; Santosh and Kusky, 2010; Sizova et al., 2010, 2014; Vielzeuf et al., 1990). Large terranes that preserve long-lived (many tens of millions of years), high thermal gradients are of particular interest, as they provide direct evidence that the crust is capable of sustaining extreme thermal conditions for very long timescales. An investigation of the timescale of metamorphism and the *P*–*T* evolution of these terranes provide a guide to the possible geodynamic setting of G–UHT terranes (e.g. Brown, 2007; Kelsey and Hand, 2015). Moreover, detailed geological and metamorphic constraints from terranes recording high thermal gradients are required to underpin geodynamic forward models that are used to propose geodynamic settings for the formation of G–UHT conditions.

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The once contiguous Rayner–Eastern Ghats (R–EG) terrane formed a vast Meso-Neoproterozoic (c. 1140–900 Ma) orogenic belt, the fragments of which now reside in eastern India and east Antarctica (Fig. 1a and b). The R–EG terrane records voluminous charnockitic and granitic magmatism and high thermal gradient metamorphism, with the exposure of UHT rocks in the Eastern Ghats Province (Dharma Rao et al., 2012; Korhonen et al., 2013a,b; 2014; Mezger and Cosca, 1999; Simmat and Raith, 2008). *P–T* evolutions in both regions appear to be anticlockwise, dominated by isobaric cooling and associated with magmatism (Boger and White, 2003; Clarke et al., 1989; Dasgupta et al., 1995; Halpin et al., 2007a; Kamineni and Rao, 1988; Korhonen et al., 2013a; Mukhopadhyay and Bhattachrya, 1997; Sengupta et al., 1990). Geochronology from both the Rayner Complex and Eastern Ghats Province suggests that high temperatures may have persisted for >100 Ma (Boger et al., 2000; Bose et al., 2011; Halpin et al., 2012; Korhonen et al., 2013b; Simmat and Raith, 2008).

Detailed *P–T–t* studies have been undertaken on rocks from the Eastern Ghats Province, providing important information for geodynamic forward models (e.g. Korhonen et al., 2011, 2013a,b, 2014; Sizova et al., 2014). In contrast, studies from the Rayner Complex that have combined in situ geochronology with modern metamorphic phase equilibria have been largely limited to the MacRobertson and Kemp Land coasts (Fig. 1; Halpin et al., 2007a,b). Therefore, detailed *P–T–t* constraints required as critical input for geodynamic forward models are limited for much of the Rayner Complex.

The northern Prince Charles Mountains (nPCM) are a large region of inland outcrop in the Rayner Complex (Fig. 1), and therefore provide an opportunity to further investigate the thermobarometric architecture of the orogen. Previous attempts to temporally constrain the deformation and metamorphism have relied on geochronology from structurally controlled samples and predominantly conventional thermobarometry (e.g. Boger et al., 2000; Boger and White, 2003; Fitzsimons and Harley, 1992; Nichols, 1995; Stephenson and Cook, 1997; Thost and Hensen, 1992). There have been no studies that combine in situ U–Pb geochronology with modern metamorphic analysis to constrain the temporal evolution of the major silicate mineral assemblages in the region.

This study uses samples of metapelite from across the nPCM to better constrain the metamorphic and temporal evolution of Grenvillian-aged metamorphism. The results from this study will then be discussed in the context of previous work elsewhere in the Rayner Complex and the Eastern Ghats. This provides a clear metamorphic framework with which to evaluate the geodynamic models for the R–EG terrane.

2. Geological setting

The Prince Charles Mountains (PCM) outcrop as a series of steep sided massifs and nunataks that stretch for 600 km inland from the Mawson Coast in MacRobertson Land, east Antarctica (Fig. 1c). They have been divided into four distinct geological terranes (e.g. Boger et al., 2008; Mikhalsky et al., 2001, 2006a; Phillips et al., 2006; Tingey, 1991). The southern Prince Charles Mountains (sPCM) are composed of the Ruker Terrane, which has an Archaean history, and the Lambert Terrane, which has an Archaean–Paleoproterozoic history and makes up much of the Mawson Escarpment (Fig. 1c; Boger et al., 2008; Corvino et al., 2008; Mikhalsky et al., 2001, 2006b; Phillips et al., 2006). The Fisher Complex is located between the sPCM and nPCM and is composed of 1300–1200 Ma calc-alkaline volcanics that have been metamorphosed to amphibolite facies, with late granitoids emplaced at 1050–1020 Ma (Fig. 1c; Beliatsky et al., 1994; Kinny et al., 1997; Mikhalsky et al., 1996, 2001). The nPCM form part of the Proterozoic Rayner Complex. The Rayner Complex is interpreted to extend west from Enderby Land to Princess Elizabeth Land in the east, and south from the coastline of Kemp and MacRobertson Lands to the Fisher Terrane and sPCM (Fig. 1c; e.g. Boger, 2011; Kamenev, 1972; Kelly et al., 2002; Liu et al., 2009a; Phillips et al., 2009; Tingey, 1991). Outcrop in the Rayner Complex is sparse and occurs mainly along the MacRobertson and Kemp Land coasts and within the nPCM (Fig. 1c).

The Rayner Complex is dominantly composed of granulite facies felsic and mafic gneisses, with comparatively minor interleaved metasedimentary units (e.g. Boger et al., 2000; Fitzsimons and Thost, 1992; Hand et al., 1994b; Thost and Hensen, 1992; Tingey, 1991). The emplacement of orthogneiss protoliths in the nPCM has been dated at 1070–1020 Ma (Boger et al., 2000; Mikhalsky and Sheraton, 2011).

The Rayner Complex was deformed and metamorphosed during the Grenvillian-aged Rayner Orogeny at c. 1000–900 Ma (e.g. Boger et al., 2000; Carson et al., 2000; Halpin et al., 2007a, 2013, 2012; Hensen et al., 1997; Kelly et al., 2002; Kinny et al., 1997). This event was accompanied by voluminous charnockitic and granitic magmatism (e.g. Carson et al., 2000; Kinny et al., 1997; Manton et al., 1992; Munksgaard et al., 1992; Tingey, 1991; Zhao et al., 1997). However, detailed geochronology along the Mawson Coast appears to record evidence of discrete charnockite 'events' at 1145–1140 Ma, 1080–1050 Ma and 985–960 Ma (Halpin et al., 2012). This suggests that the high temperature evolution in the Rayner Complex may have begun as early as 1145 Ma, and proceeded either continuously or as a punctuated thermal system for c. 250 Myr.

The structural evolution of the Rayner Orogeny appears to be consistent throughout the nPCM, although the events have been assigned different nomenclature by various workers (e.g. Boger et al., 2000; Fitzsimons and Thost, 1992; Hand et al., 1994b; McKelvey and Stephenson, 1990; Nichols, 1995; Scrimgeour and Hand, 1997; Thost and Hensen, 1992). The structural studies have been summarised by Boger et al. (2000). D_1 involved the formation of a layer-parallel foliation, which forms the dominant fabric throughout the nPCM. This foliation was folded into recumbent, isoclinal, layer-parallel folds during D_2. The evolution from D_1 to D_2 has been interpreted to have been progressive, and to have occurred at c. 990 Ma (Boger et al., 2000; Fitzsimons and Thost, 1992; Hand et al., 1994b; Thost and Hensen, 1992). The layer-parallel foliation and isoclinal folds were reoriented about upright E–W trending folds during D_3 at c. 940 Ma. Intensification of strain on the limbs of these folds led to the development of E–W trending, steeply dipping shear zones late in D_3 (Boger et al., 2000; Fitzsimons and Thost, 1992; Hand et al., 1994b; Nichols, 1995; Thost and Hensen, 1992). Discrete mylonites and pseudotachylites are the final stage of deformation (D_4), and have been dated at c. 500–475 Ma (Boger et al., 2000, 2002; Nichols, 1995).

The Rayner Orogeny is typically considered to have involved an anticlockwise *P–T* evolution, dominated by isobaric cooling (Fig. 2; e.g. Boger and White, 2003; Clarke et al., 1989; Fitzsimons and Harley, 1992; Halpin et al., 2007a; Stephenson and Cook, 1997; Thost and Hensen, 1992). Along the Mawson Coast, metamorphism occurred at 990–970 Ma and involved high thermal gradients (~140–175 °C/kbar), with peak temperatures of 850 °C and pressures of 5.6–6.2 kbar at Cape Bruce, and 900 °C and 5.4–6.2 kbar at Forbes Glacier (Fig. 2). The rocks record an anticlockwise *P–T* evolution, with peak temperatures followed by crustal thickening to 6–7 kbar, synchronous with repeated pluton emplacement (Fig. 2; Halpin et al., 2007a). However, further west in Kemp Land, metamorphism occurred later at c. 940–900 Ma (Kelly et al., 2002), and involved a clockwise *P–T* evolution from peak pressures of 7.4–10 kbar and peak temperatures of 870–990 °C. Peak pressures have been interpreted to increase westwards, towards the margin of the Napier Craton (Halpin et al., 2007b). The terrane then