Gondwana Research 23 (2013) 617–640

Contents lists available at SciVerse ScienceDirect

Gondwana Research

journal homepage: www.elsevier.com/locate/gr

Evidence for late Paleoproterozoic (ca 1690–1665 Ma) high- to ultrahigh-temperature metamorphism in southern Australia: Implications for Proterozoic supercontinent models

K.A. Cutts [a,b,*], D.E. Kelsey [a], M. Hand [a]

[a] *Centre for Tectonics, Resources and eXploration (TRaX), The University of Adelaide, Adelaide, South Australia, 5005, Australia*
[b] *Centre for Crustal Petrology, Department of Earth Sciences, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa*

ARTICLE INFO

Article history:
Received 29 December 2010
Received in revised form 15 April 2012
Accepted 20 April 2012
Available online 3 May 2012

Handling Editor: M. Santosh

Keywords:
Phase diagram
Granulite
Petrology
In situ monazite geochronology
Supercontinents

ABSTRACT

Oxidised metasediments in the western Gawler Craton southern Australia record late Paleoproterozoic high-temperature (HT) to ultrahigh-temperature (UHT) metamorphism. The HT-UHT rocks are magnetite-rich and come from drill core in an unexposed region of the Gawler Craton. Coarse-grained cordierite-bearing assemblages that potentially contained osumilite are overprinted by orthopyroxene-sillimanite-bearing assemblages, which in turn are overprinted by garnet. This microstructural record indicates a metamorphic evolution involving early high-*T*, low-*P* conditions that were overprinted by lower thermal gradient assemblages. In situ LA–ICP–MS monazite U-Pb age dating yields a range of ages between 1850 and 1530 Ma with large populations at ca 1690–1650 Ma and ca 1600 Ma. Elsewhere in the Gawler Craton HT and UHT metamorphism occurred in the earliest Mesoproterozoic (ca 1580 Ma). The timing of the Australian UHT events coincides with several other documented examples and occurred during the postulated existence of the Columbia supercontinent. If arguments that link the formation of UHT belts to supercontinental amalgamation are valid, then the existence of ca 1700 to 1600 Ma UHT metamorphism may place additional constraints on the timing of Columbian assembly.

1. Introduction

Ultrahigh-temperature (UHT) metamorphism has been documented in orogenic belts that range in age from ca 3200 Ma to 30 Ma, and is likely to be occurring in the contemporary Earth in lower crustal settings (e.g. Basin and Range and Tibet). While UHT metamorphism has occurred throughout much of Earth history, the temporal record of these events appears to fall into distinct groupings: the Neoarchean–earliest Paleoproterozoic (ca 2700–2450 Ma), mid-Paleoproterozoic (ca 2000–1800 Ma), Late Mesoproterozoic to early Neoproterozoic (ca 1300–900 Ma), late Neoproterozoic–Cambrian (ca 650–500 Ma). In general the temporal pattern of UHT events appears to coincide with the postulated assembly intervals of the supercontinents (e.g. Brown, 2006, 2007). The greatest recorded concentration of UHT events is associated with Gondwana (e.g. Brown, 2007), and has been suggested to reflect thickening of thermally extreme continental back arcs during amalgamation. In the case of the Gondwanan UHT belts, the majority show significant high-*T* to UHT decompression, suggesting that exhumation of the belts may have occurred as a consequence of thickening. If this is the case, then the formation of UHT terrains and their subsequent high-*T* exhumation may be a hallmark of inversion of high heat flow settings during collision or accretion.

One region where the documented record of UHT metamorphism is comparatively sparse is Australia, despite the extensively documented record of regional high to very high thermal gradient metamorphism in Proterozoic orogenic belts (Clarke et al., 1987; Collins and Vernon, 1991; Rubenach, 1992; Buick et al., 1998; Rasmussen et al., 2006; Hand et al., 2007). Mineral assemblages suggestive of ultrahigh-temperature (UHT) metamorphism (Harley, 1998; Kelsey, 2008) have only been documented from a limited number of localities throughout Proterozoic Australia (Scrimgeour et al., 2005; Cutts et al., 2011). The timing of these UHT events falls into an interval (ca 1780–1300 Ma) previously considered to be a comparative "gap" in the global UHT temporal record (e.g. Brown, 2007, 2008), and one that coincides with the post amalgamation stages of Columbia (e.g. Rogers and Santosh, 2002; Zhao et al., 2002, 2003, 2004; Hawkesworth et al., 2009; Reddy and Evans, 2009). However there is growing evidence for the existence of UHT events during this interval (e.g. Brandt et al., 2003; Scrimgeour et al., 2005; Bhandari et al., 2011; Cutts et al., 2011; Bose et al., 2012; Korhonen

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* Corresponding author at: Centre for Tectonics, Resources and eXploration (TRaX), The University of Adelaide, Adelaide, South Australia, 5005, Australia.
E-mail address: kathryn.cutts@gmail.com (KA. Cutts).

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doi:10.1016/j.gr.2012.04.009

et al., 2012; Zhang et al., 2012). This suggests that the link between UHT metamorphism and supercontinent amalgamation is either less direct than suggested by Brown (2007, 2008), or that assembly of Columbia was more protracted than generally considered.

Here we present calculated phase equilibria integrated with in situ monazite U-Pb LA-ICP-MS geochronology to constrain the conditions and timing of HT-UHT metamorphism of late Paleoproterozoic to early Mesoproterozoic age from the western Gawler Craton, southern Australia. This represents a second area of the Gawler Craton where HT to UHT metamorphism has been documented (see also Cutts et al., 2011). The Gawler Craton is part of the larger southern Australian Craton, or Mawson Continent (Payne et al., 2008, 2009). Both documented UHT occurrences come from drill core in areas characterised by regional-scale non outcrop. The identification of HT-UHT metamorphism from the extremely limited basement drill core intersections in the Gawler Craton implies that high-temperature, high geothermal gradient metamorphism was probably widespread throughout the late Paleoproterozoic to early Mesoproterozoic of southern Australia. This study is based on limited samples and small sample sizes obtained from exploration drilling, and highlights that in situ geochronological techniques, coupled with mineral equilibria modelling derived from mineral-scale mapping of bulk compositions can provide substantive constraints from poorly to unexposed terrains.

2. Geological setting

The Gawler Craton (Fig. 1) has a protracted geologic history spanning approximately two billion years from the Mesoarchean (ca 3250 Ma) to the mid-Mesoproterozoic (ca 1450 Ma; Fraser and Lyons, 2006; Hand et al., 2007; Fraser et al., 2010). The geological evolution of the Gawler Craton has been discussed in detail by Daly et al. (1998) and Hand et al. (2007). Major periods of Paleoproterozoic and Mesoproterozoic tectonism in the Gawler Craton span the time intervals of ca 1850 Ma (Cornian Orogeny), ca 1740–1690 Ma (Kimban Orogeny) and ca 1600–1580 Ma (Kararan Orogeny; see Hand et al., 2007). The region of interest to this study is the remote far western Gawler Craton, a region where investigations of the geological history are severely hampered by a lack of outcrop (Thomas et al., 2008; Stewart et al., 2009; Howard et al., 2011a). Geological investigations have relied on geophysical imagery complemented by sparse diamond drill core (Thomas et al., 2008; Stewart et al., 2009; Stewart and Betts, 2010). The samples for this study are from diamond drill hole 'Ooldea DDH2' (Figs. 1, 2), drilled by the South Australian Department of Mines and Energy in 1985 after earlier reports from percussion drilling indicated the presence of sapphirine-bearing assemblages in magnetite-rich metasediments (Daly, 1987). Petrology reports for Ooldea DDH2 indicated the presence of sapphirine-quartz and orthopyroxene-sillimanite-quartz bearing assemblages (Oliver and Purvis, 1986; Daly, 1987; Oliver et al., 1988). However, despite the existence of these rocks being known for over twenty years, this study presents the first integrated approach using modern techniques aimed at constraining the pressure–temperature–time (*P*–*T*–*t*) evolution of these mineral assemblages (cf. Teasdale, 1997; Fanning et al., 2007; Payne et al., 2008).

The magnetite-rich lithology that contains the reported orthopyroxene-sillimanite and sapphirine-quartz assemblages has been classified as the Moondrah Gneiss (Teasdale, 1997; Daly et al., 1998). Drill holes 'Ooldea DDH1' and 'Ooldea DDH3' also intersect the Moondrah Gneiss but the magnetite-rich lithology was not intersected by these drill holes. Reconnaissance geochronology on the HT-UHT rocks has produced metamorphic zircon ages between 1690–1660 Ma (Teasdale, 1997; Daly et al., 1998; Fanning et al., 2007) and monazite ages of ca. 1690 (Payne et al., 2008). Payne et al. (2008) attributed ca 1690 Ma ages to a high-grade metamorphic event that effectively dehydrated the rock mass, and the ca 1660 Ma age to high-temperature reworking. U-Pb ages of ca 1690 Ma are widespread elsewhere in the Gawler Craton, corresponding to the tail end of the regionally extensive 1730–1690 Ma Kimban Orogeny (Figs. 1, 2; Hand et al., 2007; Dutch et al., 2008; Payne et al., 2008; Howard et al., 2011a). Ages of ca 1660 Ma occur in upper amphibolite facies metasediments in the western Gawler Craton and appear to form an age continuum with the typically considered duration of the Kimban Orogeny (e.g. Dutch et al., 2010; Howard et al., 2011a).

In the central part of the Gawler Craton HT-UHT metamorphism occurred in the interval 1590–1560 Ma (Cutts et al., 2011). This belt of high-grade metamorphism forms a domain flanking the northern margin of the Archean core of the Gawler Craton and is separated from it by a moderately north-dipping terrain-scale shear system (Korsch et al., 2010). The timing of this high-grade event coincides with voluminous I- to A-type magmatism which is most obviously manifest by the Gawler Range Volcanics and associated Hiltaba magmatic suite in the central and southern Gawler Craton (Daly et al., 1998; Hand et al., 2007; Figs. 1, 2).

The metasediments of the Moondrah Gneiss comprise part of the Nawa Domain of the Gawler Craton (Fig. 1), which is a large non-outcropping region covered by Neoproterozoic to Recent sequences. Rocks of the Nawa Domain have been intersected by a limited number of mineral and petroleum exploration drill holes. Detrital zircon, Nd isotopic and geochemical data coupled with metamorphic monazite data from metasedimentary rocks intersected in drilling indicates that deposition occurred between ca 1750 Ma and 1730 Ma with sequences derived from a crust similar to that presently exposed in central Australia (Payne et al., 2008). These sequences appear to have been deposited on a basement that in part consists of 1780–1750 Ma granites (Howard et al., 2011b). Much of the Nawa Domain records the effects of the 1730–1690 Ma Kimban Orogeny, with upper amphibolite to granulite facies metamorphism (Payne et al., 2006, 2008; Howard et al., 2011b).

The Moondrah Gneiss forms a distinct highly magnetic package in the SW part of the Nawa Domain immediately adjacent to the Karari Shear Zone (Fig. 2), which separates the Proterozoic-aged Nawa rocks from the Neoarchean to early Paleoproterozoic core of the Gawler Craton (Rankin et al., 1989; Fraser and Lyons, 2006). The metasediments intersected in Ooldea DDH2 are believed to be part of the Nawa Domain metasedimentary system, however there is no preservation of detrital zircons that definitively link it to the broader system of Nawa metasediments (Payne et al., 2006).

3. Sample description and petrography

As the high-grade rocks in the Ooldea region do not outcrop, all samples have been obtained from the sub-vertical drill hole Ooldea DDH2 (GDA94 zone 52, E:764644 S:6613064; Fig. 2) which penetrated 169.50 m of high-grade dominantly oxidised metasediments. High-temperature metamorphic assemblages from metapelitic rocks in Ooldea DDH2 preserve a rich microstructural record of mineral reaction and contain monazite, making them useful for conducting an integrated metamorphic-in situ geochronological study. In the following sections petrographic observations are divided into interpreted 'peak' and 'overprinting' (or 'post-peak') assemblages on the basis of grain size as well as microstructural context (e.g. corona, symplectite, porphyroblast). Sample numbers refer to the meterage of the drill core that the sample was obtained from.

3.1. Sample descriptions: general

The drill core in Ooldea DDH2 has several characteristic features. Firstly the rock types are predominantly magnetite-rich, implying that the metapelites are typically iron-rich and oxidised. Secondly, the Moondrah Gneiss sampled in Ooldea DDH2 was derived from a coarse-grained precursor. The drill hole lithologies typically contain a steeply dipping and intense mylonitic ribbon fabric that encloses porphyroclasts of K-feldspar and garnet, and in places, decimetre