Characterising the *P–T–t* histories and effects of melt loss in high thermal gradient terranes.

LAURA J. MORRISSEY

Geology and Geophysics
School of Physical Sciences
University of Adelaide

This thesis is submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

May 2016

TABLE OF CONTENTS

TABLE OF CONTENTS

ABSTRACT

Zircon U–Pb and Lu–Hf isotopes, in situ U–Pb monazite geochronology and calculated metamorphic phase diagrams are used to explore the tectonic settings of regional high thermal gradient metamorphism as well as the consequences of melt loss on the bulk composition and reactivity of residual rock packages. Case studies are presented from four high thermal gradient terranes: the Windmill Islands in Wilkes Land, east Antarctica; the central Aileron Province in central Australia, the Rayner Complex in east Antarctica and the southern Gawler Craton in South Australia.

The Windmill Islands region records two stages of high thermal gradient metamorphism between c. 1320–1300 Ma and c. 1240–1170 Ma. The first stage of metamorphism occurred at conditions of 3.5–4 kbar and 700–730 °C and was associated with the formation of a horizontal fabric. The second stage of metamorphism is most strongly recorded in the southern Windmill Islands where it reached conditions of ~4 kbar and 850 °C, coincident with the emplacement of voluminous isotopically juvenile granitic and charnockitic magmas. The metasedimentary rocks of the Windmill Islands contain both arc- and craton-derived detrital zircon grains, suggesting that they formed in a back-arc setting. An extensional setting is consistent with the high thermal gradients and the formation of a regional horizontal fabric during the first stage of metamorphism. The intrusion of juvenile charnockite further suggests that the overall tectonic regime was extensional and that the crust beneath the Windmill Islands contained little evolved material.

The central Aileron Province records long-lived high thermal gradient anatectic conditions between c. 1590 and 1520 Ma. Peak temperatures were in excess of 850 °C with pressures of 6.5–7.5 kbar, corresponding to a thermal gradient of >130–140 °C/kbar. The retrograde evolution involved minor decompression and then slow cooling, culminating with the development of andalusite. The absence of any syn-metamorphic magmatism and the development of contractional structures during metamorphism suggest that long-lived high thermal gradient metamorphism was likely to have been driven to a significant extent by the burial of high heat producing pre-metamorphic granitic rocks that volumetrically dominate the terrane.

The Rayner Complex in east Antarctica was extensively deformed and metamorphosed during the Rayner Orogeny between c. 1020 and 900 Ma. Metamorphism was associated with voluminous granitic and charnockitic magmatism. The earliest phase of metamorphism is recorded in the southern Rayner Complex and involved pressures of >7.5 kbar. Pervasive metamorphism at 950–900 Ma affected the whole Rayner Complex and involved temperatures of 850–880 °C and lower pressures of 6–7 kbar. The Rayner Complex is interpreted to be a back-arc basin that was closed during two-stage collision between the Archean Antarctic cratons to the south and the arc, followed by collision with the Indian Craton.

High thermal gradient metamorphism can occur in both collisional and extensional regimes and in both plate margins and intracontinental settings. The primary thermal driver in the Windmill Islands and the Rayner Complex was likely to have been the thinned lithosphere resulting from back-arc extension, whereas in the central Aileron Province, the primary thermal driver was likely to be anomalously high heat producing crust. However, in all three terranes, the attainment of regional high temperatures was facilitated by the preconditioning (dehydration) of the crust by prior melt loss events and slow erosion rates.

In all four studied terranes, high thermal gradient metamorphism resulted in melt loss that significantly altered the compositions and reactivity of the residual rocks. One implication of melt loss during regional high temperature metamorphism is that it creates a terrane comprising anhydrous, residual rock compositions that are relatively resistant to reworking during subsequent metamorphic events. As demonstration of this, the Rayner Complex records a metamorphic event at c. 540–500 Ma that reached peak conditions of 800–870 °C and 5.5–6.5 kbar. However, high-*T* mineral growth at 540–500 Ma is only recorded in some locations. The spatial distribution of this mineralogical reworking was controlled by localised rock reactivity that may reflect domains that had undergone hydrous retrogression at the end of the Rayner Orogeny, locally enhancing the responsiveness of the rock mass during the Cambrian.

In the southern Gawler Craton, forward modelling of an Fe-rich phyllite sequence shows that melt loss can also have economic implications by increasing the concentration of iron in the residual rock package, leading to enrichment in Fe-oxide minerals (magnetite and hematite). Muscovite-rich rocks with lower iron content are more fertile, produce more melt and therefore show a more significant increase (up to 35%) in the Fe-oxide content in the residual (melt depleted) rock package. Rocks with primary Fe-rich compositions are less fertile, lose less melt and therefore do not experience the same relative increase in the amount of Fe-oxides in the residuum. The economic implications of the modelling are that the more fertile horizons with lower primary iron contents may be significantly upgraded as a result of melt loss, thereby improving the overall grade of the ore system. In the case of southern Gawler Craton, melt loss-driven Fe enrichment has contributed to the formation of one of Australia's largest known magnetite resource systems.

DECLARATION

I, Laura Morrissey, certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

I give consent to this copy of my thesis when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

The author acknowledges that copyright of published works contained within this thesis resides with the copyright holder(s) of those works.

I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

LAURA MORRISSEY DATE

PUBLICATIONS DURING THE COURSE OF THIS THESIS

Peer reviewed journal articles:

Morrissey, L.J., Payne, J.L., Hand, M., Clark, C., Taylor, R., Kylander-Clark, A., Kirkland, C.L. Linking the Windmill Islands, east Antarctica and the Albany–Fraser Orogen: insights from U–Pb zircon geochronology and Hf isotopes. *Precambrian Research*, under review.

Morrissey, L.J., Hand, M, Lane, K., Kelsey, D.E., Dutch, R.A., 2016. Upgrading iron-rich sequences to economic grade iron-ore deposits by melt loss during granulite-facies metamorphism. *Ore Geology Reviews*, 74, 101–121.

Morrissey, L.J., Hand, M., Kelsey, D.E., Wade, B.P., 2016. Cambrian high-temperature reworking of the Rayner-Eastern Ghats terrane: constraints from the northern Prince Charles Mountains region, east Antarctica. *Journal of Petrology*, 57, 53–92.

Wong, B., **Morrissey, L.J.,** Hand, M., Fields, C., Kelsey, D.E., 2015. Grenvillian-aged reworking of late Paleoproterozoic crust of the southern North Australian Craton, central Australia: implications for the assembly of Mesoproterozoic Australia. *Precambrian Research*, 270, 100–123.

Morrissey, L.J., Hand, M, Kelsey, D.E., 2015. Multi-stage metamorphism in the Rayner–Eastern Ghats terrane: *P–T–t* constraints from the northern Prince Charles Mountains, east Antarctica. *Precambrian Research*, 267, 137–163.

Morrissey, L.J., Hand, M., Raimondo, T., Kelsey, D.E., 2014. Long-lived high-temperature, low-pressure granulite facies metamorphism in the Arunta Region, central Australia. *Journal of Metamorphic Geology*, 32, 25–47.

Morrissey, L.J., Hand, M., Wade, B.P., Szpunar, M., 2013. Early Mesoproterozoic metamorphism in the Barossa Complex, South Australia: links with the eastern margin of Proterozoic Australia. *Australian Journal of Earth Sciences*, 60, 769–795.

Conference presentations:

Morrissey, L., Hand, M., Lane, K., Kelsey, D.E., Dutch, R., 2015. Melt loss and magnetite: improving ore grades during granulite facies metamorphism. Granulites and Granulites 2015, Windhoek, Nambia, July 2015, p. 29.

Morrissey, L., Hand, M., Kelsey, D., Payne, J., 2013. Temporal constraints on the metamorphic evolution of the northern Prince Charles Mountains, east Antarctica. Granulites and Granulites 2013, Hyderabad, January 2013, p. 46.

Morrissey, L., Wong, B., Hand, M., Payne, J., Kelsey, D., Collins, W. J., 2012. Grenvillian-aged reworking in the southern North Australia Craton, central Australia. Proceedings of the 24th International Geological Congress 2012, Brisbane, August 2012.

ACKNOWLEDGEMENTS

Firstly, thank you to my supervisors Martin and Dave who have both provided excellent support and guidance along the way. Both of you have been very generous with your time and knowledge and I have been lucky to have you as supervisors. I would like to thank Martin especially for the chance to pursue opportunities outside my thesis and allowing me to travel to so many interesting locations. I would also like to thank Dave for his unfailing patience and for always being approachable.

I have been very lucky with the places I have visited for fieldwork and for conferences and I have learnt a lot from both. I am indebted to the people who have helped out with fieldwork, in particular the Australian Antarctic Division and the personnel at Casey Station in the 2013–2014 season. The people I met at conferences and the reviewers of various chapters of this thesis also deserve thanks for providing alternative scientific perspectives and ideas, as their comments and suggestions have doubtlessly improved both the manuscripts they reviewed and the subsequent chapters.

Thank you to the staff at Adelaide Microscopy who have been an enormous help with analytical work. Especially thank you to Ben, Aiofe and Angus who have had to repair the laser and the probe many times throughout the course of this PhD, and thank you as well to Ken who has carbon coated many thin sections on short notice.

Thanks to all the other PhD students (and honorary PhDs), including Katherine, Morgan, Naomi, Kat, Bel, Alec, Jade, Bonnie, Dan, Kieran, Lachy and Vicky, as well as old PhDs Katie, Dee and Russell and more recent PhD students Kam, Kiara and Meg, whose friendship has made my PhD and the Mawson Building significantly more enjoyable. Thanks as well to the honours students throughout the last few years who have taught me an awful lot about troubleshooting thermocalc.

Thanks to the coffee shops of Adelaide, without which this thesis may never have been written.

Thank you to my non-geology friends and family for their support and encouragement over the last few years and for never actually voicing the fact that this PhD seemed to take a really long time. Thanks to Kate for listening whenever required and for being my outdoor consultant. A special thank you to my parents for the late night pickups from Adelaide Microscopy and early drop offs at airports, for their assurance that I won't have to pay rent until I'm finished and for their love, patience and encouragement in everything I do. Finally, thank you to Justin, who has alternately provided supervision, moral support, tough love, chocolate and wine as required.