The architecture and evolution of intracontinental orogens: a structural, metamorphic and geochemical characterisation

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Abstract

Intracontinental orogens are irreconcilable with conventional plate tectonics theory, which confines mountain building to plate-margin settings alone. However, the comparative rarity of such orogenic systems in the geological record means that their architecture and evolution are poorly understood. In order to address this deficiency, this thesis presents an integrated framework that characterises the structural, metamorphic and geochemical features of intracontinental reworking in central and southeastern Australia.

The axial zone of the Ediacaran–Cambrian (600–530 Ma) Petermann Orogen, western Musgrave Province, is characterised by pervasive mylonitic deformation and low geothermal gradient metamorphism that formed at deep crustal levels (P = 10–14 kbar and T = 700–800 °C). Peak metamorphic conditions were attained at *c.* 570 Ma, followed by slow cooling to 600–660 °C by *c.* 540 Ma, at an average rate of 2–6 °C Myr^{-1}. The macroscopic structural, kinematic and metamorphic architecture of this terrane is broadly comparable in style to the Himalayan–Tibetan Orogen, suggesting that both systems are dominantly shaped by the gravitationally-driven flow of deep crustal material. This similarity also extends to their spatial and temporal scales, overall cooling histories, average geothermal gradients, levels of exhumation and extents of crustal thickening, implying that the basic anatomy of intracontinental orogens is analogous to that of typical collisional belts.

The Ordovician–Carboniferous (450–300 Ma) Alice Springs Orogen is characterised by intensely metasomatised ductile shear zones that dissect the eastern Arunta Region. Similar alteration features are also observed in the Cambrian–Ordovician (514–490 Ma) Delamerian Orogen, southern Curnamona Province. In both cases, isotopic datasets confirm that substantial volumes of surface-derived fluids were involved in the rehydration of the deep crust. Calculated $\delta^{18}O$ and δD fluid values are as low as ~2‰ and –60‰ for the former, whereas garnet porphyroblasts from the latter exhibit equilibrium $\delta^{18}O$ fluid values of ~4‰. It is argued these surficial fluid signatures are imposed in the vicinity of the brittle–ductile transition by the burial and dehydration of hydrothermally-altered fault panels, rather than the deep drawdown of a mobile fluid phase via hydraulic forcing. The resultant accumulation of increasing fluid volumes in penetrative fault networks promotes extensive metasomatism and reaction softening at the locus of stress transmission from plate-boundary sources. It is therefore concluded that the interaction of externally-derived fluids with refractory crustal material is a key contributing factor to critical reductions in lithospheric strength, ultimately providing strong impetus for the initiation and advancement of intracontinental orogenesis.

Declaration

I, Thomas Raimondo, certify that this work contains no material which has been accepted for the award of any other degree or diploma 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.

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Publications arising from this thesis

Journal articles

Raimondo, T., Collins, A. S., Hand, M., Walker-Hallam, A., Smithies, R. H., Evins, P. M. & Howard, H. M., 2009. Ediacaran intracontinental channel flow. *Geology*, **37**(4), 291–294, doi: 10.1130/G25452A.1.

Raimondo, T., Collins, A. S., Hand, M., Walker-Hallam, A., Smithies, R. H., Evins, P. M. & Howard, H. M., 2010. The anatomy of a deep intracontinental orogen. *Tectonics*, **29**(4), TC4024, doi: 10.1029/2009tc002504.

Raimondo, T., Clark, C., Hand, M. & Faure, K., 2011. Assessing the geochemical and tectonic impacts of fluid–rock interaction in mid-crustal shear zones: a case study from the intracontinental Alice Springs Orogen, central Australia. *Journal of Metamorphic Geology*, **29**(8), 821–850, doi: 10.1111/j.1525-1314.2011.00944.x.

Raimondo, T., Clark, C., Hand, M., Cliff, J. & Harris, C., 2011. High-resolution geochemical record of fluid–rock interaction in a mid-crustal shear zone: a comparative study of major element and oxygen isotope transport in garnet. *Journal of Metamorphic Geology*, accepted.

Raimondo, T., Clark, C., Hand, M. & Cliff, J., 2011. How do surface-derived fluids infiltrate mid-crustal shear zones? *Geology*, in review.

Conference abstracts

Raimondo, T., & Clark, C., 2011. Fluid–rock interaction in intracontinental shear zones: geochemical and tectonic responses. *Geophysical Research Abstracts, EGU General Assembly 2011*, **13**, EGU2011-5338.

Netting, A., Payne, J., Wade, B., & **Raimondo, T.**, 2011. Trace Element Micro-Analytical Imaging via Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS). *Microscopy and Microanalysis 2011: Proceedings of the 69th Annual Meeting of the Micropscopy Society of America*, **17**, 590.

Raimondo, T., Clark, C., Hand, M., & Cliff, J., 2010. Constraining the timing of deep meteoric fluid flow in reactivated orogenic belts. In: Quinn, C. D. & Daczko, N. R. (eds.) Abstracts of the Specialist Group in Tectonics and Structural Geology Conference, Port Macquarie. *Geological Society of Australia Abstracts*, **97**, 55.

Raimondo, T., Collins, A. S. & Hand, M., 2010. Deep intracontinental channel flow: the anatomy of the Petermann Orogen, central Australia. In: Quinn, C. D. & Daczko, N. R. (eds.) Abstracts of the Specialist Group in Tectonics and Structural Geology Conference, Port Macquarie. *Geological Society of Australia Abstracts*, **97**, 54.

Hand, M., **Raimondo, T.**, Collins, A. S. & Kelsey, D. E., 2009. Intracratonic orogeny in central Australia. In: Timms, N. E., Foden, J., Evans, K. E., & Clark, C. (eds.) Kangaroo Island 2009: Biennial Conference of the Specialist Group for Geochemistry, Mineralogy and Petrology. *Geological Society of Australia Abstracts*, **96**, 24.

Raimondo, T., Clark, C., Hand, M., Faure, K., & Collins, A. S., 2009. Deep intracratonic fluid flow in the Alice Springs Orogen, central Australia. In: Timms, N. E., Foden, J., Evans, K. E., & Clark, C. (eds.) Kangaroo Island 2009: Biennial Conference of the Specialist Group for Geochemistry, Mineralogy and Petrology. *Geological Society of Australia Abstracts*, **96**, 37.

Raimondo, T., Hand, M., Clark, C., Faure, K., & Collins, A. S., 2009. Sources, thermal conditions and mechanisms of fluid ingress during regional rehydration of Alice Springs Orogeny intracratonic shear systems. *Journal of Geochemical Exploration*, **101**, 84, doi:10.1016/j.gexplo.2008.11.008.

Raimondo, T., Collins, A. S., Hand, M., Walker-Hallam, A., Smithies, H., & Evins, P., 2008. A kinematic, metamorphic and geochronological framework for intracratonic reworking in the western Musgrave Block, central Australia: evidence for lower crustal channel flow? *Geological Society of Australia, Australian Earth Sciences Convention (AESC) 2008, Abstracts,* **89**, 206.

Statement of authorship

The research described in this thesis has been published or submitted for publication in scientific journals. The bibliographic details of each journal article are listed at the beginning of each chapter, and include the names of all co-authors involved in their production. The contribution of each author to the conceptualisation, realisation and documentation of these works is described below.

RAIMONDO, T. (Candidate)

Chapters 2–6: Project design; fieldwork; sample selection and preparation; petrology; SHRIMP, EMPA, LA-ICP-MS and SIMS data collection; SIMS methodology development; all calculations and data processing; critical data interpretation; entire manuscript design and composition; creation of all figures.

I certify that the above statement is accurate.

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HAND, M., CLARK, C. and COLLINS, A. S. (Supervisors)

Chapters 2–6: Project design; fieldwork assistance; data interpretation guidance; manuscript review.

I certify that the above statement is accurate and give permission for the relevant manuscripts to be included in this thesis.

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HARRIS, C.

Chapter 5: Stable isotope data collection using prepared mineral separates; manuscript review.

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FAURE, K.

Chapter 4: Stable isotope data collection using prepared mineral separates; manuscript review.

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SMITHIES, R. H., EVINS, P. M., and HOWARD, H. M.

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To anyone else that I've forgotten, I apologise for my absent-mindedness. For all your help, cheers! And to the guy who scheduled the NBA playoffs during the final few months of my PhD, I hold you personally responsible for my (additional) sleep deprivation, and hence any errors that are discovered in the following pages…

Motivation and aims of this thesis

Intracontinental orogens are a conspicuous exception to the plate tectonics paradigm, which assumes that plate interiors are rigid and undeformable, and that mountain-building is restricted to plate margins. In the modern Earth, they are prominently represented by the widespread terranes of central Asia, including the Tien Shan and Altai. In the ancient Earth, arguably the best examples are found in central and southeastern Australia (Fig. 1), where there is a remarkable record of intracontinental deformation spanning the Neoproterozoic and Phanerozoic. The Ediacaran–Cambrian (600–530 Ma) Petermann Orogeny and the Ordovician–Carboniferous (450–300 Ma) Alice Springs Orogeny are major intraplate events affecting the crustal architecture of the Musgrave Region and Arunta Province, respectively. In addition, Palaeoproterozoic crust of the southern Curnamona Province underwent significant reworking inboard of an active plate margin during the Cambrian–Ordovician (514–490 Ma) Delamerian Orogeny.

The existence of these unusual mountain belts requires that active continental deformation is considered using a revised conceptual scheme. However, despite the generally good preservation and exposure of the Australian orogens, the precise details of their tectonic evolution remain poorly understood. This is partly due to conjecture over the driving forces for deformation, with both plate-boundary and intraplate stresses advocated as plausible causes. The dominant factors governing the distribution of intraplate deformation are also somewhat equivocal, with both structural heterogeneities and thermal weakening argued to be primary controls on strain localisation. These uncertainties contribute to a general lack of consensus regarding the mechanical framework for the reworking of continental interiors, and the typical deformational response of the lithosphere to this eventuality. Elucidating the characteristic architecture of intracontinental orogens thus holds the key to unravelling the enigmatic processes behind their formation, and determining the critical factors that influence their structural, kinematic and metamorphic development.

Along with the structural and thermal effects commonly considered to be instrumental in facilitating lithospheric weakening, another potential control on the localisation of intracontinental deformation is deep crustal fluid infiltration and associated reaction softening. However, the role that fluids play in the evolution of intraplate orogens has not been systematically studied. This is despite the evident impact of metasomatic alteration in the Alice Springs and Delamerian Orogens, which feature large shear systems containing intensely rehydrated rocks. In contrast to plate-margin settings, such fluids cannot be derived from conventional sources such as the dehydration of deeply underthrust hydrous slabs. Furthermore, the mechanisms by which they infiltrate into the anhydrous lower crust are not clear, particularly considering the perceived difficulty in transporting fluids beyond the fractured upper crust. There is thus significant motivation to investigate the links between fluid–rock interaction and the large-scale deformation of continental interiors.

The central aim of this thesis is to develop an integrated framework that characterises the structural, metamorphic and geochemical evolution of intracontinental reworking in central and southeastern Australia. Firstly, this involves a consideration of the key architectural features of intracontinental orogens, and their differentiation from plate-boundary equivalents. Secondly, it focuses on the dynamics of fluid–rock interaction in mid-crustal intracontinental shear zones, in order to investigate the impact of deeply penetrative fluids on the mechanical stability of the lithosphere.

The specific aims of this thesis are:

1. To construct an orogenic model that explains the macroscopic structural, kinematic and metamorphic architecture of the Petermann Orogen, and compare it to the basic anatomy of collisional belts;

2. To determine explicit geochronological and metamorphic constraints on the timing of shear zone activity, rate of cooling, pressure–temperature conditions and geothermal gradients in the deeply-exhumed axial zone of this orogenic system;

3. To develop *in situ* techniques for the metamorphic and geochemical characterisation of fluid flow events, including laser-ablation trace element thermobarometry and ion microprobe garnet oxygen isotope analysis;

4. To obtain detailed geochemical constraints on the source of fluids involved in the rehydration of anhydrous crustal volumes in continental interiors, and the mechanisms for isotopic alteration and major element metasomatism;

5. To critically evaluate the available models for fluid ingress into the deep crust, and investigate the significance of fluid–rock interaction in the context of lithospheric processes that moderate the sensitivity of continental interiors to major reworking.

The first two aims involve the integration of structural, metamorphic and geochronological datasets from the Petermann Orogen, central Australia. This system features the greatest range of crustal exposure of any Australian terrane, with exhumation varying from the lower crust (~14 kbar) within the core of the orogen to the uppermost

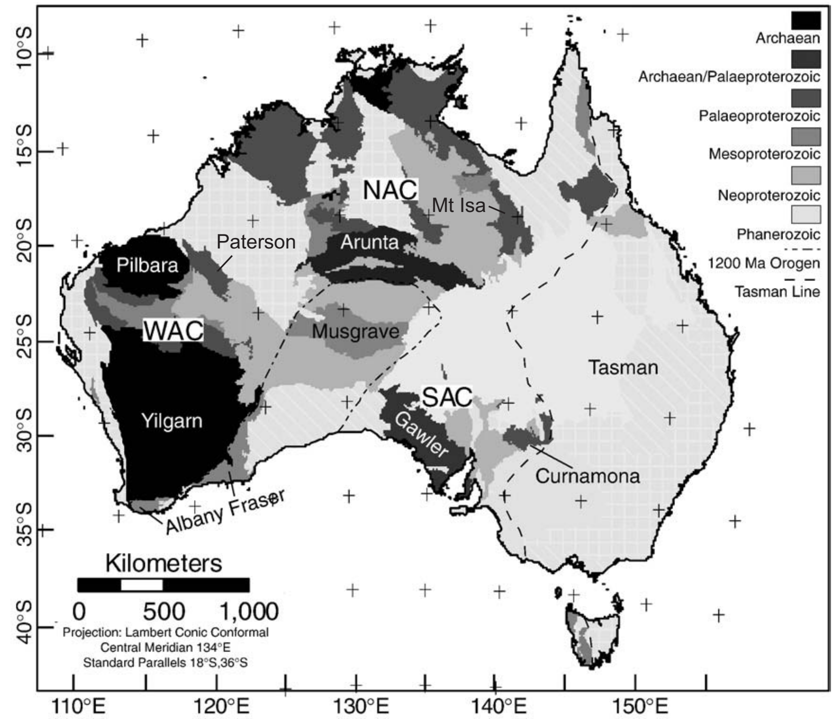

Figure 1. Major geological provinces of continental Australia. The Petermann and Alice Springs Orogenies are primarily recorded in the Musgrave Province and Arunta Region of central Australia, respectively, whereas deformation associated with the Delamerian Orogeny can be observed in the southern Curnamona Province of southeastern Australia. Abbreviations: NAC, North Australian Craton; SAC, South Australian Craton; WAC, West Australian Craton. Figure modified from Aitken & Betts (2009).

crust at its margins. Consequently, it offers a unique opportunity to study both the spatial and temporal distribution of intracontinental deformation across a range of metamorphic grades and crustal levels. The final three aims are addressed by investigating the relationship between fluid–rock interaction and tectonic reworking in the Alice Springs Orogen, central Australia, and the Delamerian Orogen, southeastern Australia. These systems both feature deeply-exhumed crust that has undergone large-scale rehydration subsequent to high-grade metamorphism. They are thus ideal locations to investigate the characteristics of extensive fluid–rock interaction in deep-crustal settings, and its contribution to the initiation and development of intracontinental orogenesis.

Chapter outlines

Chapter 1 introduces the concept of intracontinental orogens and provides an overview of their formation and characteristics. It examines the possible sources of stress in continental interiors, and considers a variety of factors that control the locus of basement reactivation in these settings. It also compares the key features of intracontinental orogens from both the ancient and modern Earth, and examines their differentiation from typical plate-margin systems in terms of their architectural organisation and evolutionary histories. This serves as both a stand-alone reference for the current state of knowledge regarding intracontinental orogens, and a contextual framework for the more detailed discussions of specific issues presented in the following chapters.

Chapter 2 assesses whether the macroscopic structural and metamorphic patterns of the Petermann Orogen satisfy a set of diagnostic criteria for the identification of lower-crustal channel flow. It presents new titanite geochronology from the Bates region, western Musgrave Province, that constrains the timing of pervasive shear activity in the deeply exhumed orogenic core, thus establishing whether opposing kinematic vectors from this area represent a coeval reversal associated with large-scale ductile flow. This comparative approach provides an insight into the similarity between the deformational modes of intracontinental orogens and collisional belts such as the Himalayan–Tibetan system, and tests the applicability of channel flow models to ancient terranes.

Chapter 3 outlines the basic anatomy of the Petermann Orogen, particularly its deep crustal expression in the axial zone between the Mann Fault and the Woodroffe Thrust. It builds on the previous chapter by presenting in more detail the structural, metamorphic and geochronological records of intraplate activity in the western Musgrave Province, primarily including the Bates region and the Mann Ranges. Structural mapping, thermobarometry, zircon geochronology and trace element thermometry are used to document the style of deformation, allowing a multi-faceted appraisal of the dynamics of intracontinental reworking. This enables the development of more comprehensive tests for the suitability of the channel flow hypothesis, and its distinction from alternative orogenic models conventionally applied to collisional systems.

Chapter 4 shifts the focus of this thesis from the intriguing geodynamic aspects of intracontinental orogenesis exemplified by the Petermann Orogen, to the remarkable metasomatic features represented by the Alice Springs Orogen. It investigates the record of fluid–rock interaction in mid-crustal shear zones from the Reynolds–Anmatjira Ranges, northern Arunta Region. Two traverses across deformed and metasomatised basement are used to extract detailed information about the style and characteristics of alteration. Structural mapping, trace element thermobarometry, whole-rock geochemistry and oxygen and hydrogen stable isotope analysis are employed to determine the pressure–temperature (*P–T*) evolution of metasomatism, the mechanisms for geochemical enrichment and depletion, and the sources and pathways of influxing fluids. This facilitates the construction of an integrated and representative overview of fluid–rock interaction across the Alice Springs Orogen, and its potential contribution to the large-scale reworking of previously stable continental interiors.

Chapter 5 introduces a more sophisticated method for investigating the record of fluid–rock interaction that avoids many of the weaknesses and pitfalls of conventional techniques. It builds on the tectonic and metamorphic framework for shear zone reactivation presented in the previous chapter by examining the geochemical evolution of alteration assemblages at high precision and high spatial resolution. An array of garnet textures are presented from both metasomatised shear zone samples and their undeformed and unaltered precursors at Peaked Hill, southeastern Reynolds Range. Their progressive changes in major element and oxygen isotope distribution patterns are explored using electron and ion microprobe techniques, and linked to new age estimates provided by U–Pb monazite and Sm–Nd garnet geochronology. This approach enables the reconstruction of a coupled thermal and temporal history of fluid–rock interaction during the Alice Springs Orogeny, allowing the significance of deep crustal fluid infiltration in initiating and promoting intracontinental reworking to be assessed in more detail.

Chapter 6 applies the high precision and high spatial resolution geochemical techniques outlined in the previous chapter to metasomatic alteration assemblages from an alternative intracratonic terrane. Ion microprobe oxygen isotope analysis and electron microprobe compositional mapping of garnet are combined with existing geochronology and *P–T* estimates to reconstruct the fluid–rock interaction history of the mid-crustal Walter-Outalpa shear zone, southern Curnamona Province. This study specifically addresses the origins and ingress mechanisms of externally-derived fluids in the deep crust, and outlines diagnostic criteria for the identification of meteoric fluid sources. In doing so, it provides a practical set of guidelines for the detailed investigation of fluid–rock interaction and its contribution to critical lithospheric weakening, thus extending the potential influence of metasomatic processes on intracratonic deformation beyond the Alice Springs Orogen alone.

Chapter 7 concludes this thesis by providing a summary of the current state of knowledge regarding the architecture and evolution of intracontinental orogens. It assimilates the key results from each chapter, and highlights the directions that future research should pursue to develop a more complete understanding of the geodynamic framework for intraplate mountain building.

N.B. Chapters 2–6 contain supporting information (such as additional figures, tables and discussion) that complements the main body of text. All supplements are included in a separate section at the end of each chapter. Their general content is described in the text to alert the reader to their existence and provide the necessary context.

REFERENCE

Aitken, A. R. A. & Betts, P. G., 2009. Multi-scale integrated structural and aeromagnetic analysis to guide tectonic models: An example from the eastern Musgrave Province, Central Australia. *Tectonophysics*, **476**(3–4), 418–435.