Thermo-mechanical evolution of orogeny in the Musgrave Province

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Chapter 6

Abstract

The architecture of orogens, the physical record of deformation and metamorphism, and the duration and rates at which orogeny progresses is intimately linked with thermomechanical state of the lithosphere and it's evolution and modification during orogenesis in polymetamorphic terrains. This thesis presents an integrated study that investigates the structural, metamorphic and geodynamic features of the Musgrave Province to understand the interplay between orogenesis and the temporal and spatial changes in lithospheric rheology.

The metamorphic record in the Musgrave Province is dominated by Grenvillian-aged (1270–1100 Ma) ultra-high-temperature metamorphism which was characterised by > 80 Myr of metamorphic temperatures of approximately 1000 °C. The duration of such extreme conditions resulted in extremely residual crust which had major implications for the style of reworking in the younger Ediacaran–Cambrian intraplate Petermann Orogeny.

Crustal thickening during intraplate orogeny occurred at ~ 600 Ma and resulted in the development of a thick-skinned foreland fold-thrust belt. Loading of the lithosphere caused the development of an extremely deep and narrow flexural foreland basin in which syn-orogenic sequences were buried to depths of ~10 km. The architecture of the foreland implies that intraplate deformation was localised into a region of dramatically weakened lithosphere, which could have developed in response to the initial distribution (and burial) of heat producing layers in the mid-crust.

In the deep-crustal core of the orogen, migmatites from the western part of the orogenic system which record peak metamorphism between 600 and 570 Ma and long-lived pervasive deformation (> 40 Myr), represent a comparatively warm and weak portion of crust. To the east, discrete and brittle deformation occurred in comparatively strong lithosphere and but is accompanied by a similar record of elevated metamorphic temperatures (>600 °C) which span 590 to 530 Ma. Observed variations in deformational response independent of temperature or duration highlights the important role of other factors, such as availability of fluids, might have in facilitating reduction in strength and localise deformation in residual lithosphere. Ultimate re-strengthening of the Petermann Orogen lithosphere was achieved during progressive removal of the orogenic heat production during erosion, enabling the preservation of a puzzling record of intraplate orogeny.

Declaration

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Publications arising from this thesis

Journal articles

Walsh, A. K., T. Raimondo, D. E. Kelsey, M. Hand, H. L. Pfitzner, and C. Clark. 2013. Duration of high-pressure metamorphism and cooling during the intraplate Petermann Orogeny. *Gondwana Research*, Volume 24, Issues 3–4, November 2013, Pages 969-983, ISSN 1342-937X, http://dx.doi.org/10.1016/j.gr.2012.09.006.

Walsh, A. K., D. E. Kelsey, C.L. Kirkland, M Hand, R. Hugh Smithies, C Clark, and H.M. Howard. in press. P−T−t evolution of a large, long-lived, ultrahigh-temperature Grenvillian belt in central Australia. *Gondwana Research*, Available online 27 June 2014, ISSN 1342-937X, http://dx.doi.org/10.1016/j.gr.2014.05.012.

Walsh, A. K., Hand, M. & Kelsey, D. E., in review. A metamorphic perspective on foreland flexure during intraplate orogeny: evidence for the involvement of weak lithosphere. *Terra Nova*.

Walsh, A. K., Kelsey, D. E., Hand, M. & Jourdan, F. in review. Crustal thickening prior to 600 Ma; evidence from 40Ar–39Ar thermochronology and implications for spatial patterns of reworking and exhumation in intraplate orogens. *Journal of the Geological Society of London*.

Conference abstracts

Walsh, A. K., D. E. Kelsey, C.L. Kirkland, M Hand, R. Hugh Smithies, C Clark, and H.M. Howard. A long-lived UHT Grenvillian belt in central Australia. Granulites and Granulites conference 2013.

Walsh, A. K., D. E. Kelsey, C.L. Kirkland, M Hand, R. Hugh Smithies, C Clark, and H.M. Howard. A long-lived UHT Grenvillian belt in central Australia. International Geological Congress, Abstracts 2012

Walsh, A. K., Kelsey, D. E., Hand, M. Duration of high-pressure metamorphism and cooling during the intraplate Petermann Orogeny. Specialist Group for Geochemistry, Mineralogy and Petrology conference, Abstracts 2011

Walsh, A. K., Kelsey, D. E., Hand, M. Constraining the thermal evolution of a large intracontinental orogen. Australian Earth Sciences Convention, Abstracts 2010

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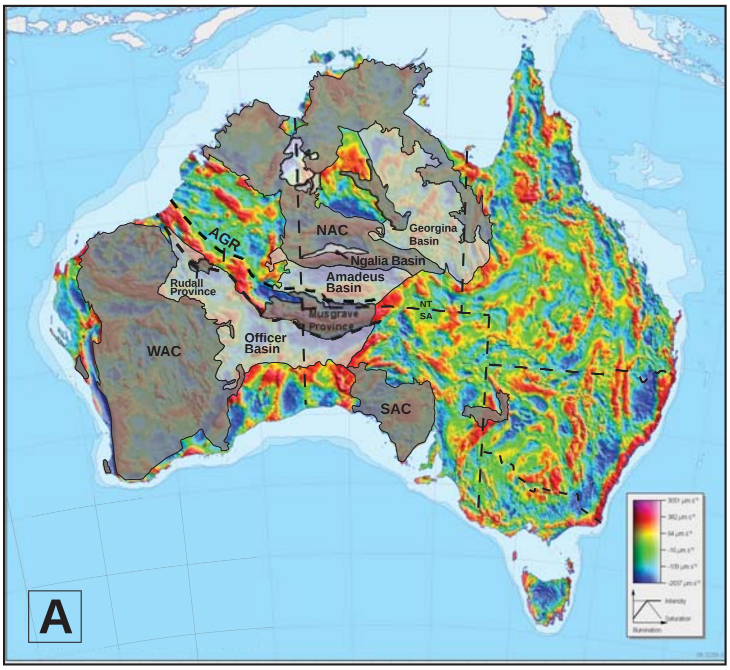
Literature, significance and aims of this thesis

The physical architecture of orogens and the duration and rates at which orogeny progresses is a function of the inherited thermomechanical state of the lithosphere and it's evolution through orogenesis. Furthermore metamorphism and deformation will result in modification of the thermal and mechanical properties of lithosphere and seek to dramatically affect the future reworking of a terrane. It follows then that the investigating the time-integrated record of metamorphism and deformation of a terrane will provide insight into the cause of orogeny and the effect of orogenic processes in modifying the physical properties of lithosphere.

The Musgrave Province in central Australia preserves a polymetamorphic and deformational record which spans at least 1330–520 Ma. Therefore, the Musgrave Province provides an excellent natural laboratory to examine the thermal and mechanical evolution of lithosphere through multiple orogenic cycles.

The metamorphic and deformational record is dominated by the 1220–1150 Ma Musgrave Orogeny predominantly involved the emplacement of voluminous felsic magmatism expressed as the orthopyroxene-bearing (charnockitic, 'A-type') granitic rocks of the Pitjantjatjara Supersuite (Maboko, et al., 1992; White, et al., 1999; Edgoose, et al., 2004; Evins, et al., 2010; Smithies, et al., 2011). These granitic rocks typically have an anhydrous primary mineralogy, are ferroan and enriched in titanium and phosphorus, and had extremely high intrusive temperatures >900ºC (Smithies, et al., 2010; Smithies, et al., 2011). Mafic magmatism was rare and of low volume during the Musgrave Orogeny (Smithies, et al., 2011). Although it is established that temperatures were high (~900 °C) during Grenvillian metamorphism (Clarke & Powell, 1991; Glikson, et al., 1996; White, et al., 1999; White, et al., 2002; Wade, et al., 2008; Smithies, et al., 2011), the duration and footprint of the event are unknown. Therefore, investigating the time-integrated thermal structure of the crust is crucial, as metamorphic rocks provide a primary record of the temporal thermal state of the Earth (Brown, 2007) and such information can provide insight into the tectonic setting of such high-T metamorphism— which is debated, and the mechanisms by which the crust is able to reach high temperatures. The need to characterise and understand high-T events in a polymetamorphic terrane becomes crucial as it has major implications for future crustal reworking.

Reworking of the Musgrave Province occurred during the Ediacaran–Cambrian (600–520 Ma) intraplate Petermann Orogeny (e.g. Scrimgeour & Close, 1999; Scrimgeour, et al., 1999; Camacho & McDougall, 2000; Buick, et al., 2001; Flöttmann, et al., 2004; Wade, et al., 2005; Aitken, et al., 2009; Camacho, et al., 2009; Gregory, et al., 2009; Raimondo, et al., 2009; Raimondo, et al., 2010). The Petermann Orogeny involves magnitudes of crustal thickening, shortening and exhumation comparable to both plate margin orogenic systems, and intraplate systems such as Tien Shan in central Asia (Flöttmann, et al., 2004; Raimondo, et al., 2014). the Petermann Orogen has been the focus of numerous studies to understand the thermal and mechanical evolution of the system by investigating the timing, duration and physical conditions of metamorphism and deformation (Camacho, et al., 1997; e.g. Camacho, et al., 2001; Camacho, et al., 2009; Gregory, et al., 2009; Raimondo, et al., 2009; Raimondo, et al., 2010; Walsh, et al., 2013; Walsh, et al., in review). It is evident from these studies that the orogen preserves a spatially and temporally complex record of the thermal and mechanical evolution. Initial deformation and crustal thickening is argued to have developed in comparatively weak lithosphere, reflecting a regionally elevated thermal regime (Sandiford & Hand, 1998; Hand & Sandiford, 1999; Walsh, et al., in review), potentially caused by sedimentary cover creating thermal blanketing of high-heat-producing granitic crust (approximately 4 μW m-3) that was localised in the mid-upper crust (Sandiford & Hand, 1998; Hand & Sandiford, 1999; Sandiford



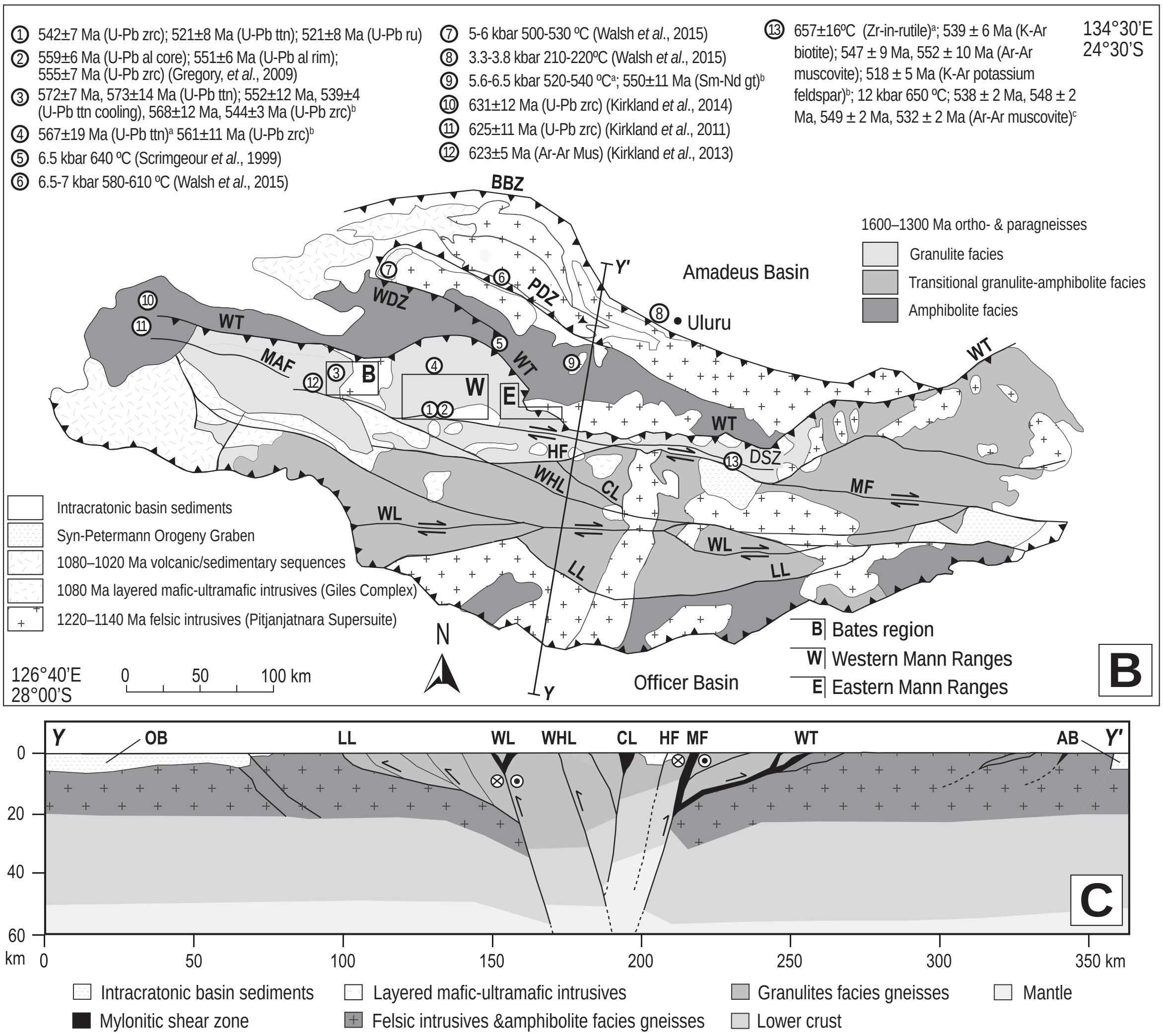


Figure 1. (a) Gravity map of Australia overlain with distribution of Proterozoic and early Phanerozoic basement provinces and sedimentary basins. Interpreted continuity of Ediacaran intraplate orogenic belt outlined in association with the Anketell Gravity Ridge (AGR). (b) Regional solid geology map of the Musgrave Province. The locations of key E-W trending fault structures of the Petermann Orogen and previously collected geochronological and *P–T* data are shown. 1. (Walsh et al., 2013); ; 3.(Raimondo et al., 2009, 2010); 4a. (Walsh et al., 2013); 5. (Scrimgeour et al., 1999); 9. a (Walsh et al., in review) b (Scrimgeour et al., 1999); 13. a (Camacho et al., 2009), b (Camacho et al., 1997), c (Camacho and McDougall, 2000). Figure modified from Edgoose et al. (2004), Raimondo et al. (2010) and Aitken et al. (2009). (c) Schematic cross section (Y-Y′) across the central Musgrave Block. Highlights the overall crustal-scale dextral transpressive shear system, involving significant Moho displacement and deep exhumation along the Woodroffe Thrust/Mann Fault. Modified from Aitken et al. (2009). Abbreviations: AB, Amadeus Basin; BBZ, Bloods Back Thrust Zone; CL, Caroline Lineament; HF, Hinckley Fault; LL, Lindsay Lineament; MAF, Mount Aloysius Fault; MF, Mann Fault; NAC, North Australian Craton OB, Officer Basin; PDZ, Piltardi Detachment Zone; SAC, South Australian Craton; WAC, West Australian Craton WDZ, Wankari Detachment Zone ; WHL, Wintiginna-v Hinckley Lineament; WL, Wintiginna lineament; WT, Woodroffe Thrust.

& McLaren, 2002; McLaren, et al., 2003). The development of a deep (~10 km) and narrow foreland basin, a thick (≥20 km) basement-involved (thick-skinned) foreland fold-thrust belt and the exhumation of the core of the orogen via lateral extrusion (channel flow) reflect continued orogenic evolution in a mechanically weak lithosphere associated with elevated temperatures (Raimondo, et al., 2009; Raimondo, et al., 2010; Walsh, et al., in review).

However, in contrast to this notion of a (hot/warm) weak lithosphere across the Petermann Orogen is the presence of comparatively low geothermal gradient rocks (~9 °C km^{-1}; 350 °C, 12 kbar) in the axial core, in which low temperatures are deduced based on the interpretation that Ar–Ar isotopic systems have failed to reset (Camacho, et al., 1997; Camacho & McDougall, 2000). Within this core, mylonitic shear zones that host transitional-eclogite facies rocks and voluminous pseudotachylites (Lin, et al., 2005) define Petermann-aged metamorphism. Mesoproterozoic granulites to the south of the orogenic core are largely unaffected by Petermann-aged reworking. To explain the presence of 'cold', transitional eclogite facies rocks and pseudotachylites as well as their spatially restricted occurrence, the heat source for Petermann-aged tectonism has been argued to be shear heating (Camacho, et al., 2001). Tectonism (i.e. burial, metamorphism and exhumation) associated with shear heating is argued to be rapid—of the order of 1 Myr—within regionally cold and strong lithosphere (Camacho, et al., 2009). Such an interpretation has been reinforced through using compositional zoning profiles in garnet from the core of the orogen to estimate/constrain cooling rates and the preservation of pre orogenic ages in low-T thermochronometers (Camacho, et al., 2001; Camacho, et al., 2009). Therefore, the Petermann Orogen preserves a seemingly paradoxical record of tectonism in warm, weak lithosphere as well as in cold, strong lithosphere.

The currently established views on the tectonic and metamorphic evolution of the Petermann Orogeny imply opposing views on the thermomechanical state of the central Australian lithosphere. This has significance as it has implications for the initiation and localisation of deformation and the development of orogeny in the interior of the Australian plate.

The general aim of this thesis is to characterise the metamorphic and structural evolution of the Musgrave Province with the aim of understanding how the physical properties of crustal lithosphere change through time in response to the metamorphic processes which occur during orogenesis. This is firstly achieved by investigating the Grenvillian-aged high temperature metamorphic event to understand the effects of high-T crustal processes and establish the lithospheric framework in which to assess younger Ediacaran–Cambrian reworking. Secondly, it focusses on the mechanical response of lithosphere to Ediacaran–Cambrian reworking in an intraplate setting to assess the importance of inherited lithospheric thermal and mechanical properties and more broadly, the thermo-mechanical evolution of intraplate orogeny.

The specific aims of this thesis are:

1. Determine the physical conditions and duration of high-T Grenvillian-aged metamorphism and investigate the crustal and tectonic processes leading to high temperatures in the Musgrave Province
2. To obtain precise geochronological constraints on deformation, metamorphism and exhumation/cooling from both the orogenic foreland and hinterland to evaluate the spatial and temporal patterns of deformation during intraplate reworking.
3. To investigate the mechanical strength of the pre-Petermann Orogeny lithosphere
4. Assess drivers for metamorphism by investigating the duration, timing and spatial footprint of high-grade metamorphism in the core of the orogen.
5. To critically evaluate the thermomechanical state of the lithosphere prior to, during and post Petermann orogeny.

Chapter Outlines

Chapter 1 provides an assessment of the *P–T-t* evolution of Grenvillian-aged high-T metamorphism in the Musgrave Province. It presents an application of modern metamorphic analysis (*P–T* pseudosections) and high-precision U–Pb monazite geochronology to high-grade metamorphic rocks across the orogen in order to constrain the timing, duration, physical conditions and spatial distribution of high-T metamorphism in the Musgrave Province. More broadly, these datasets allow discussion of the ability of the crust to generate and maintain high temperatures, the use of monazite as a geochronometer in high-T terrains, the tectonic setting of the Musgrave Province during the Grenvillian and the spatial footprint of high-T metamorphism. This chapter describes and discusses high-T metamorphic processes which dramatically modify the thermal and mechanical properties of the lithosphere. Therefore the outcomes of this study have major implications for future reworking of the Musgrave Province.

Chapter 2 shifts the focus of the thesis to the younger Ediacaran–Cambrian intraplate Petermann Orogeny. It investigates the timing of high-P metamorphism and the rate of cooling during intraplate reworking in the Mann Ranges region, central Musgrave Province. Titanite, zircon and rutile geochronology is collected from partially migmatised meta-igneous rocks from shear zones. This data allows the temperature–time history of orogeny to be constructed and the applicability of previously suggested models for the thermal evolution of the Petermann Orogeny to be tested. Additionally partially migmatised zones represent volumetrically minor Petermann-aged deformation in an otherwise anhydrous orogenic core and therefore requiring mechanisms additional to elevated temperatures in order to localise metamorphism and deformation during intraplate reworking.

Chapter 3 builds on the previous chapter by assessing the thermomechanical state of the lithosphere during orogeny by examining the large scale architecture of the foreland fold-thrust belt and foreland basin system. The record of deep burial metamorphism of syn-orogenic sediments in the foreland basin and thick-skinned fold-thrust is used to measure the flexural (burial) response of the foreland basin and fold-thrust belt. The architecture of the foreland is a direct function of the mechanical strength of the lithosphere in which the Petermann Orogen developed, therefore this innovative approach allows the lithospheric strength to be measured and the mechanisms by which intraplate orogeny develops to be examined.

Chapter 4 builds on the previous chapter in that it constrains the timing of deep burial of the foreland of the Petermann Orogeny, therefore placing the localisation of deformation in the foreland in an absolute time context in the history of the orogen. $^{40}Ar/^{39}Ar$ muscovite and biotite geochronology is used to constrain the timing of metamorphism in fold-thrust belt sequences and therefore the burial of the foreland of the orogen. Integration of geochronological data from the foreland allows the spatial and temporal patterns of deformation to be assessed and provides insight into the processes by which intraplate orogens develop and how lithosphere evolves rheologically during orogenesis.

Chapter 5 builds on the previous chapters by investigating the record of metamorphism in the lower crust of the Petermann Orogeny. U–Pb geochronology and metamorphic *P–T* pseudosections are used to assess the physical conditions of metamorphism, the duration of elevated temperatures and cooling, and the spatial distribution of metamorphism in lower crustal shear zones and their host country rocks in Amata region of the Musgrave Province. This study specifically seeks to addresses whether metamorphism during intraplate orogeny was pervasively developed or localised in zones of high-strain. The study discusses the drivers for metamorphism of the Petermann Orogeny, the ability of the crust to record multiple cycles of metamorphism and highlights that the inherited composition of the crust plays a fundamental role in the thermal and mechanical evolution of the orogen.

Chapter 6 concludes the thesis by providing a concise discussion of the current views regarding the thermomechanical evolution of the central Australian lithosphere during the intraplate Petermann Orogeny and the significant role Grenvillian-aged metamorphism played in modifying the crust. It assimilates the key results and interpretations of the previous chapters and highlights questions that future research might pursue.