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Controls on the locus of intraplate deformation in central Australia

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Abstract

The locus of intraplate deformation in central Australia changed from the presently preserved southern margin of the Amadeus Basin during the late Neoproterozoic to early Phanerozoic Petermann Orogeny to the northern margin in the late Phanerozoic Alice Springs Orogeny. Immediately prior to each event the thickness of the Amadeus basin sediments varied from as little as 1.5 km in the central parts of the basin to as much as 7 km in the vicinity of the presently preserved margins of the basin with the locus of deformation mimicking the locus of maximum sedimentary thicknesses at the onset of each orogenic event. As such these orogenies represent extreme examples of basin inversion; a process observed in many intracratonic basins worldwide. We show that differential burial of the central Australian Proterozoic basement complexes beneath the Amadeus basin is capable of producing variations in Moho temperature of up to 30ºC prior to the Petermann Orogeny and up to 110ºC prior to the Alice Springs Orogeny. For a 'Brace–Goetze' model of lithospheric rheology, the variations in Moho temperature equate to variations in effective lithospheric strain rate of 1–4 orders of magnitude, implying that variations in thickness of the sedimentary blanket may have played a primary role in localising Phanerozoic intraplate deformation in central Australia. An appealing aspect of this model lies in its corollary: that the removal of the sedimentary blanket during denudation of the orogen will be accompanied by dramatic cooling and strengthening of the lithosphere. This may provide a plausible explanation for the long-term persistence of the extraordinary gravity anomalies (~150 mGal) developed during these central Australian intraplate orogenies.

Keywords: Amadeus Basin; intraplate processes; orogeny

1. Introduction

Central Australia preserves an intriguing record of Neoproterozoic to Phanerozoic intraplate deformation associated with the formation of the Petermann and Alice Springs Orogens [1–4]. Both orogens involve Palaeoproterozoic and Mesoproterozoic metamorphic basement complexes and Neoproterozoic to early Phanerozoic sedimentary successions of the Amadeus Basin (Fig. 1). The Petermann Orogen involved northward-directed, early Cambrian-aged thrusting of Musgrave Inlier over the southern margin of the basin, while the Alice Springs Orogen involved southward-directed, Carboniferous-aged thrusting of the Arunta Inlier over the northern margin of the Amadeus Basin (Fig. 1). It is important to realise that the Amadeus Basin is a structural remnant of a formerly more extensive intracratonic basin, termed the Centralian Superbasin, that covered the bounding basement complexes to the north and

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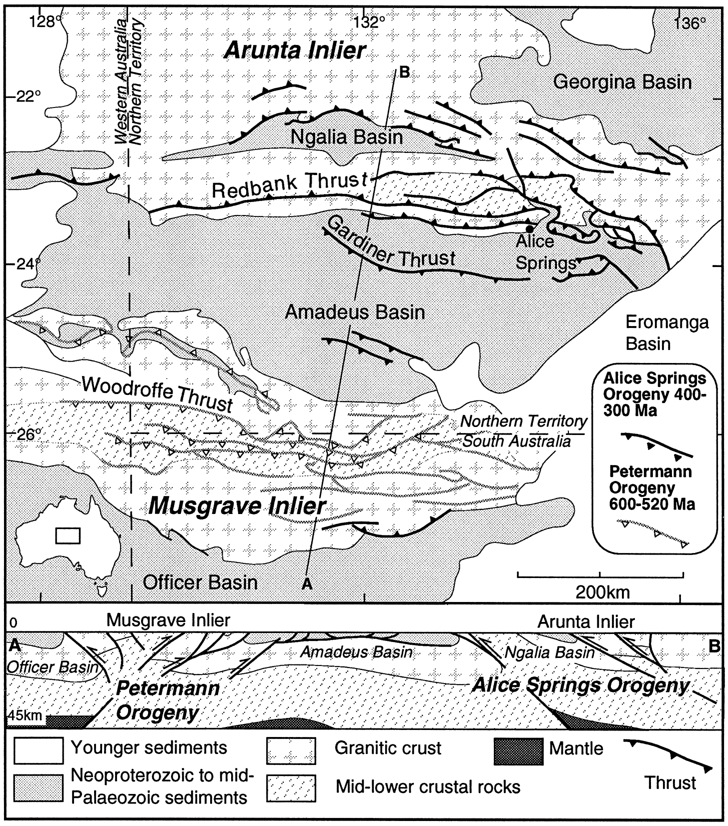

Fig. 1. Geological map of the Central Australian region, showing distribution of Phanerozoic deformation in the Amadeus Basin and Musgrave and Arunta Inliers (modified from Ref. [1]). Deformation within the Amadeus Basin is characterised by thin-skinned structures in contrast to the thick skinned processes that resulted in the exhumation of both the Musgrave and Arunta Inliers.

south, with the preservation of the basin restricted to those regions which suffered little Phanerozoic deformation. The sequences within the Amadeus basin thicken towards depocentres located at or beyond the present margins of the basins (Figs. 2 and 3).

The fact that these orogens have apparently formed far from active plate margins has received considerable attention largely focused on the structural architecture (e.g. [2,4–7]) and on the controls on the long wavelength expression of the deformation (e.g. [8,9]). In contrast, there has been little attempt to understand the factors responsible for the change in locus of deformation from the presently preserved southern margin of the basin in the early Phanerozoic to the northern margin in the late Phanerozoic. Prior to each orogeny, the central Australian region appears to have been characterised by very subdued topography (see further discussion below), and consequently the distribution of deformation is unlikely to reflect regional variations in lithospheric potential energy. Intriguingly, immediately prior to the Petermann Orogeny the greatest thickness of sediment was located along (or beyond) the preserved southern margin of the basin where the Petermann orogenic structures subsequently developed, while prior to the Alice Springs Orogeny the greatest thickness of sediment was located along (or beyond) the northern margin in the region where the Alice Springs orogenic structures were developed. These observations suggest that these central Australian orogens represent extreme examples of basin inversion.

In this paper we explore the connection between the thickness of the sedimentary blanket and the location of intraplate deformation by modelling the thermal and mechanical consequences of the burial

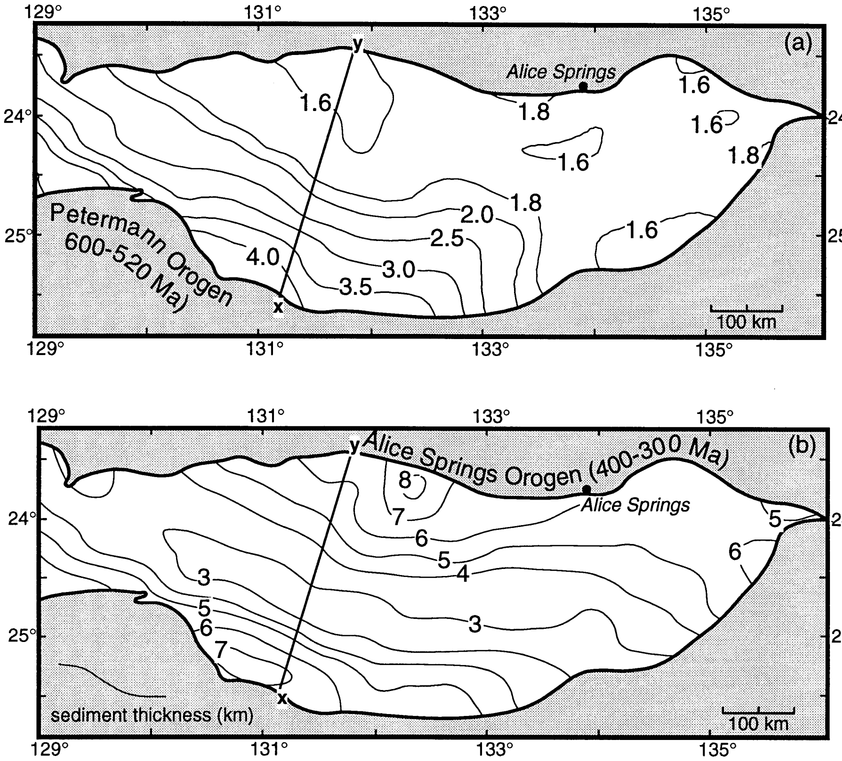

Fig. 2. Generalised isopach maps within the Amadeus Basin prior to the onset of the Petermann Orogeny (a) and the Alice Springs Orogeny (b) (data from Refs. [1,3,50,51]. The NE trending line shows the section used to model the thermal and mechanical responses to variations in sedimentary thickness (see Fig. 3).

of high heat-production (HHP) basement beneath a variable thickness sedimentary cover sequence. The logic for addressing this problem in terms of a burial of a HHP basement sequence comes from the recognition of the relatively high modern-day heat flows associated with Australian Proterozoic provinces [10,11]. In particular, we are motivated by the observation made by Cull and Conley [12] that burial of this central Australian heat flow province beneath insulating sedimentary blankets may increase the Moho temperature by as much as 40°C per kilometre of additional sediment. In view of the probable controlling influence of upper mantle thermal structure on the strength of the continental lithosphere (e.g. [13]), changes in the thickness of the sedimentary blanket should have significant impact on the distribution and magnitude of intraplate deformation.

2. Phanerozoic deformation in central Australia

The Amadeus Basin forms one of a number of Neoproterozoic–Phanerozoic intracratonic basins preserved in the central Australian region, along with the Officer, Ngalia and Georgina basins [5,14]. These formerly contiguous basins are now separated by Palaeoproterozoic and Mesoproterozoic basement complexes exposing generally high-grade metamorphic rocks of the Arunta and Musgrave Inliers (Fig. 1). The sedimentary record of these basins reflects widespread subsidence commencing at around ~800 Ma [4,15] with the deposition of the Heavitree Quartzite and its equivalents. Along the southern margin of the Amadeus Basin localised, pre-Heavitree Quartzite rifting, prior to regional subsidence, is reflected in the deposition of the Bloods Range Beds and Mt Harris Basalt [3]. Regional variations in subsidence produced significant thickness variations across the basin (Figs. 2 and 3). Prior to the

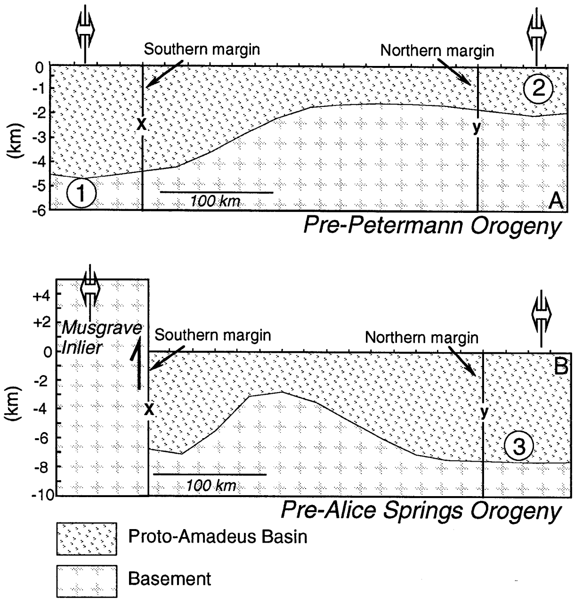

Fig. 3. Sketch showing the model basin shape used in the calculations. The existing isopach data is extrapolated to 50 km beyond the presently preserved margin where a depocentre is 'created' by mirror imaging the basin shape (double headed arrows). (a) Pre-Petermann Orogeny basin shape with a model (1) located beyond the present southern margin, and a secondary depocentre located beyond the present northern margin. (b) Pre-Alice Springs Orogeny basin shape.

Petermann Orogeny, the depocentre was located beyond the presently preserved southern margin of the basin, where the total sedimentary blanket (including the Bloods Range Beds) must have exceeded 4 km in thickness (Fig. 2a). At this time the basin thinned towards the central arch, north of which the total stratigraphic thickness was ~1.5 km. The shallow-marine nature of the latest Neoproterozoic sediments throughout the Centralian Superbasin (e.g. [3]) implies that prior to the onset of the Petermann Orogeny the continental interior was characterised by extremely subdued, mostly submerged, relief.

Following the Petermann Orogen the depositional axis in the Amadeus Basin shifted to the north (Fig. 2b and Fig. 3) such that by the onset of the late Palaeozoic Alice Springs the maximum stratigraphic thickness (~7.5 km) occurred along the northern preserved margin of the basin. During this time, sedimentation in the Georgina Basin (Fig. 1) was progressively localised in the southwest [16,17] suggesting the regional depocentre may have been located between the Amadeus and Georgina Basins, above what was to become the eastern Alice Springs orogen (Fig. 4). Sedimentation during this time is interpreted to have initially occurred in an extensional environment, however by the mid-Ordovician subsidence rates were minimal [4,5] suggesting any sag phase subsidence had largely ceased. A narrow basin (preserved width of ~20 km) containing coarse clastics (the Mount Currie Conglomerate) shed from the Petermann Orogen defines a subsidiary depositional axis along the southern margin of the Amadeus Basin (Fig. 2b) and records the stripping of the sedimentary blanket from the Musgrave Inlier during to the Petermann Orogen. Two lines of evidence suggest that the topography associated with the Petermann Orogen was denuded by Cambrian times. Firstly, mineral cooling ages from the orogen cluster tightly at 540–530 Ma [20], implying active denudation was mainly Cambrian in age. Secondly, fine-grained clastics of the Stokes Siltstone shows widespread onlap onto the Musgrave Inlier [3], implying that by the early Ordovician this region was characterised by generally subdued topography.

The underlying causes controlling the distribution of Neoproterozoic depocentres in the Amadeus Basin are not well understood, although in the broader central Australian context there general consensus that deposition occurred in mainly extensional environments [5]. The main rifting associated with basin-initiation stage is >800 Ma, and thus any enhanced mantle heat flow associated with such rifting must have decayed by the time of onset of the Petermann Orogeny. Subsidiary rifting, prior to the Ordovician in vicinity of the north eastern Arunta Inlier, is at least partly responsible for the shift in depocentres from south to north following the Petermann Orogeny. Again, the thermal effects of this rifting must have largely decayed by the onset of the Alice Springs orogeny by the early Devonian (~390 Ma).

2.1. The Petermann Orogeny

The crustal architecture in central Australia is largely the result of two major intracratonic orogenic events that resulted in the emergence of the Musgrave and Arunta Inliers from beneath a formerly more-or-less continuous intracratonic basin, now represented by the Officer, Amadeus, Georgina and Ngalia Basins (e.g. [14]). The latest Proterozoic to early Cambrian Petermann Orogen [18–20] is a dextral transpressional belt with strong north-vergent component (Fig. 1) that can be grossly divided into two domains. North of the Woodroffe Thrust, structures associated with the Petermann Orogeny are characterised by large scale (>2000 km^2) mid-crustal nappes and thrusts (including the Petermann Nappe) that incorporate the lower units of the Amadeus Basin [1,18,21]. The metamorphism in the cover rocks reaches kyanite–muscovite grade, implying significant burial (>15 km) of the basin sediments. South of the Woodroffe thrust, transitional eclogite facies (>1000 MPa) reworking of Mesoproterozoic granulite facies rocks [20,22] was associated with dextral strike-slip and dip-slip movement along crustal scale mylonite zones. This reworking is most pronounced in the northern Musgrave Inlier, and the affects appear to decline to the south (Fig. 1). The lower crustal rocks were exhumed along the Woodroffe thrust; a major south-dipping mylonite zone traceable to the present Moho [7].

As yet there are no definitive estimates of the amount of crustal shortening associated with the Petermann Orogeny. The Woodroffe thrust dips at ∼30º [7] and the presence of ≥1000 MPa rocks in the hanging wall, implies ∼60 km shortening across this structure alone, and Forman [18] suggested ≥60 km of shortening accompanied the formation of the Petermann Nappe. Given the presence of other major mylonite zones, it appears total crustal shortening with in the Musgrave Inlier during the Petermann Orogeny was significant (≥120 km). The shortening appears to be restricted to a relatively narrow E–W trending do-

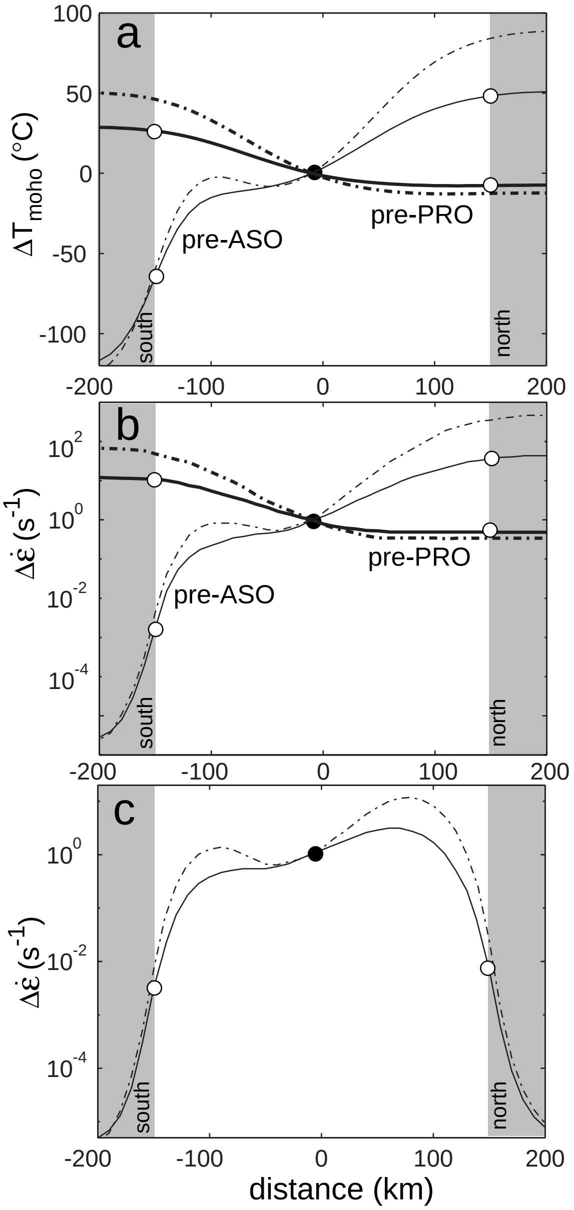

Fig. 4. Calculated variations in Moho temperature (a) and mechanical strength (b) across the Amadeus basin due to variations in thickness of the Amadeus Basin prior to the Petermann (thick lines) and Alice Springs Orogenies (thin lines). The mechanical response is represented by the vertically averaged strain rate $\Delta\dot{\epsilon}_{zz}$ (normalised against the centre of the basin) due to an imposed in plane force of 5×10^{12} N m^{-1}, while the thermal response is represented by the Moho temperature ΔT_{moho} (expressed as a difference with the centre of the basin. The horizontal axis shows distance across the basin measured relative to centre of the basin, with sediment thickness characteristics taken from Fig. 2, as shown in Fig. 3. The solid lines show the calculated responses assuming that subsidence is rift related, and that rifting differentially attenuates the heat production in the basement. The dashed lines show, for comparison, the response where basement heat production parameters remains constant across the basin. The thermal and mechanical parameters used in the calculations are listed in Table 1. (c) Shows the calculated variation in $\Delta\dot{\epsilon}_{zz}$ across the basin following denudation of the Alice Springs Orogen (see Fig. 4b caption for details). Basement denudation is assumed to have been sufficient to remove ∼33% of the basement heat production.

main, to the extent that in the central Amadeus Basin, Petermann-aged deformation was restricted to gentle folding of the cover sequences [4].

2.2. The Alice Springs Orogeny

The Devonian–Carboniferous Alice Springs Orogeny was a major orogenic event that exhumed the Arunta Inlier during mainly south-directed thrusting and resulted in deposition of thick foreland sediments in northern Amadeus and Ngalia Basins as they became isolated by the emerging basement topography. As noted above, there appears to have been little residual topography associated with the Petermann Orogen by the onset of the Alice Springs Orogen. As with the Petermann Orogeny, there is a marked division in the style of deformation within the orogen. Alice Spings structures in the southern Arunta Inlier define a crustal-scale system of south-vergent thrusts (Fig. 1). A deep seismic section across the southern third of the inlier indicates these faults dip at ~45° into the lower crust, and in the case of the Redbank Thrust appear to offset the Moho by ~10 km [6,23]. At least some of these faults have reactivated north-dipping Mesoproterozoic thrusts [24], resulting in a somewhat ambiguous picture of the extent of basement deformation during the Alice Springs Orogeny. However, recent geochronological data from the eastern Arunta Inlier [25] show that up to 20 km of exhumation was accommodated along the shear zone system during the Alice Springs Orogeny. In contrast with the basement-controlled deformation in the Arunta Inlier, deformation within the Amadeus Basin was largely thin-skinned in nature (Fig. 1), producing typical foreland fold-thrust structures [26–28]. This thin-skinned deformation was facilitated by salt-bearing horizons near the base of the Amadeus Basin succession.

The magnitude of crustal shortening during the Alice Springs Orogeny is difficult to estimate due to the existence of Mesoproterozoic faults in the basement, but increases to the east, where cover/basement interleaving implies shortening of in excess of 80 km [2,29]. Deformation during the Alice Springs Orogeny extended as far south as the southern third of the Amadeus Basin, causing tightening of gentle Petermann-aged folds within the basin, and the formation of discrete thrust faults (Fig. 1). Importantly, there is little evidence of reactivation of any of the large-scale Petermann-aged structures further south [4].

Although the Petermann and Alice Springs Orogenies are separated by at least 150 Ma there are remarkable similarities between the two, and in many ways the orogens appear to be mirror images of each other. In both belts, older amphibolite–granulite facies terrains have been reworked along crustal scale shear zones that juxtapose crustal blocks of differing character. The structures that separate these crustal blocks generally trend E–W and dip toward the hinterland in both orogens. In both cases the transport is dominantly toward the Amadeus Basin suggesting increased crustal strength in that region. The remarkable feature of the central Australian crustal architecture is the relatively restricted locus of basement deformation during each orogeny despite the existence of crustal scale faults throughout the central Australian Craton with geometries conducive to localising deformation during N–S compression. This observation poses an important question regarding the factors that helped localise intracratonic deformation in central Australia in different regions at different times.

3. The Central Australian heat flow province

A prominent feature of the Australian heat flow field is a broad, N–S trending band of elevated heat through the central part of the continent [8,11]. In this 'central' Australian province (the 'Central Shield Province' of Sass and Lachenbruch [8]) heat flow is typically in the range 60–120 mW m^{-2}, and averages about 85 mW m^{-2}. Geologically, this province correlates with the distribution of Proterozoic metamorphic terranes, and can be clearly distinguished from the much lower heat flow (40–50 mW m^{-2}) associated with the older Archaean terranes of the western Gawler Craton and Western Australia. The band of elevated heat flow includes the eastern part of the Gawler craton (and the adjacent Stuart Shelf) and the Willyama and Mount Painter Inliers in the south, the Mount Isa Inlier in western Queensland, and the Tennant Creek Block in the Northern Territory. Only two heat flow measurements exist for the

Arunta Inlier (there are no records from the Musgrave Inlier). In the context of the Central Australian heat flow province, these measurements are anomalously low (58 and 62 mW m^{-2}) probably reflecting relatively low crustal radiogenic contributions ($q_c \sim 45$ mW m^{-2}) due to the relatively deep level exposures through much of the Arunta Inlier (see below). Bottom-hole temperatures from exploration wells in the northern half of the Amadeus Basin suggest modern-day thermal gradients mostly in the range 20–25ºC/km and locally as high as 35ºC/km [30]. These data show no systematic variation in thermal gradient with proximity to the present-day northern margin of the basin, implying that the formation of the Alice Springs Orogen is unlikely to have resulted simply from the mechanical response to spatial variations in heat flow.

The presence of a relatively thick (~250 km) lithosphere throughout this ‘Central Australian heat flow province’ [31,32] suggests low to moderate contemporary mantle heat flows (~10–15 mW/m^2). Such mantle heat flows imply an average crustal contribution to the surface heat flow (q_c) of ~70 mW m^{-2} in areas of the ‘Central Australian heat flow province’ that have not undergone significant denudation, and ~45 mW m^{-2} in the Arunta Inlier. Such high crustal contributions are supported by generally high surface heat production rates in basement rocks [8,11]. In particular, high heat production rates are associated with granitic gneisses that form sill-like sheets that locally comprise up to 70% of the surface exposure of individual Proterozoic terranes (e.g. [33]). In the Arunta Inlier, the best examples of this kind of HHP granite are in the relatively low-*P* (4–5 kbar) Reynolds–Anmatjira Range region where granite averaging 6.5 μW m^{-3} is exposed over some 3000 km^2. Such high heat production in outcrop implies much of the total crustal heat production is now concentrated at shallow crustal levels and probably relates to the pervasive development of sill-like granitic bodies, originally emplaced at mid-crustal levels during the processes of crustal growth and differentiation during the Palaeo-Mesoproterozoic tectonism (e.g. [34]). We note that the implied range of crustal radiogenic contributions to surface heat flow contrasts markedly with the more commonly held view as expressed, for example, by McLennan and Taylor [35] who state “the crustal radiogenic component of continental heat flow must lie in the range 18–48 mW m^{-2}”.

In the central Arunta Inlier, to the north of the Redbank Shear Zone, denudation associated with the Alice Springs Orogeny has resulted in the exposure of low heat production deep-crustal granulite terranes [36–38] such as the Strangways Metamorphic Complex, implying that: (1) any HHP mid-upper crustal granite terrane (of the type responsible for elevated heat flow elsewhere in the ‘Central Australian heat flow province’) has been removed from most of the central Arunta Inlier as a consequence of the Alice Springs Orogeny; and (2) prior to the Alice Springs Orogeny, the contribution of the Arunta Inlier to the crustal heat flow was likely to have been significantly greater than the ~45 mW m^{-2} inferred from the analysis of the present-day surface heat flow data presented above.

4. Thermal and mechanical effects of burial of radioactive basement

In this section we explore the thermal and mechanical effects of burial of a typical HHP Australian Proterozoic basement sequence beneath a sedimentary cover succession simulating the Amadeus Basin. We use heat production parameters as discussed in the previous section (explicitly $q_c = 45$ mW m^{-2}) and investigate the thermal and mechanical response associated with the Amadeus Basin configuration immediately prior to the Petermann and Alice Springs Orogenies as shown in Fig. 3. For each orogenic event we have extrapolated the thicknesses of the basin sequences (Fig. 3) to a point of reflection located 50 km beyond the present margin of the basin (Fig. 3). We assume that the basin formation was due to rifting, and that the initially laterally uniform distribution of heat production in the basement prior to rifting has been attenuated in proportion to the rifting needed to generate the observed subsidence. As noted earlier, the main rifting associated with basin formation is >800 Ma, and thus any enhanced mantle heat flow associated with such rifting must have decayed by the onset of the Petermann Orogeny. Similarly, the thermal effects of the early Palaeozoic rifting event in the vicinity of the Arunta Inlier, would have almost completely

Table 1
Values of parameters used in calculations

z_c	crustal thickness	40 km
q_m	mantle or reduced heat flow (applied at 150 km depth)	15 mW m^{-2}
k	thermal conductivity of crust and mantle	2.5 W m^{-1} K^{-1}
H_s	heat production in sediment pile	2.0 μW m^{-3}
H_{uc}	heat production in upper 10 km of basement*	4.5 μW m^{-3}
H_{mc}	heat production in middle 10 km of basement*	1.5 μW m^{-3}
H_{lc}	heat production in lower 20 km crust*	0 μW m^{-3}
H_m	heat production in mantle	0 μW m^{-3}
μ	coefficient of friction	0.85
A_c	power-law creep, pre-exponential constant (cover)	5×10^{-6} s^{-1} MPa^{-3}
A_b	power-law creep, pre exponential constant (basement)	5×10^{-2} s^{-1} MPa^{-3}
A_m	power-law creep, pre exponential constant (mantle)	7×10^{4} s^{-1} MPa^{-3}
Q_c	power-law creep, activation energy (cover)	1.9×10^{5} J mol^{-1}
Q_b	power-law creep, activation energy (basement)	2.8×10^{5} J mol^{-1}
Q_m	power-law creep, activation energy (mantle)	5.2×10^{5} J mol^{-1}
σ_m	Dorn-law creep, threshold stress (mantle)	5.7×10^{5} MPa
Q_d	Dorn-law creep, activation energy (mantle)	5.4×10^{4} J mol^{-1}

Note that the quoted thicknesses of the basement heat production layers (*) apply to the reference crust, prior to rifting. The details of the mechanical modelling follow the outline given by Sandiford et al. [52].

decayed by the onset of the Alice Springs Orogeny some 100 Ma later.

The thermal structure of the lithosphere is solved using a finite element algorithm with parameter values listed in Table 1. In order to quantify the potential rheological effects accompanying burial of a radiogenic basement we adopt the 'Brace–Goetze' model in which lithospheric deformation is assumed to be controlled by a combination of frictional-sliding, power-law creep and Dorn-law creep (e.g. [39]). In this 'Brace–Goetze' model, the integrated lithospheric strength (F_l) is defined once the compositional structure, thermal regime and vertically averaged strain rate ($\dot{\epsilon}_{zz}$) are defined (e.g. [40]). Alternatively, the model can be used to approximate $\dot{\epsilon}_{zz}$ for a lithospheric column subject to a prescribed 'tectonic' force. We assume a simple lithospheric compositional model dominated by quartz in the sedimentary cover, feldspar in the metamorphic basement and olivine in the mantle, and explore the variations in lithospheric strength (and strain rate) associated with the thermal response (e.g. [13]).

It should be noted that very large uncertainties are attached to estimating absolute lithospheric strengths (or $\dot{\epsilon}_{zz}$) using the 'Brace–Goetze' model (or, for that matter, any other model) because: (1) an inadequate knowledge of the thermal conductivity structure of the lithosphere introduces uncertainties in the thermal structure of the deep crust and upper mantle, (2) lithospheric strength is sensitive to the precise depth of the Moho, and (3) basic uncertainty in the material constants defining the various flow laws governing deformation of lithospheric materials. However, since we are seeking only plausible controls on spatial variations in deformation intensity, we need only consider relative variations in strength. Because systematic errors both in the thermal conductivity and in material constants will cancel, the uncertainty in estimating relative changes in strength (or $\dot{\epsilon}_{zz}$) accompanying changes in thermal regime due to variation in the thickness of the Amadeus Basin sequences is much less than that associated with estimates of absolute strength. The primary question we seek to answer is this: do spatial and temporal variations in the thickness of the Amadeus basin produce significant variations in the strength of the lithosphere, all other factors being equal? Since we are primarily interested in the thermal and mechanical consequences of variations in depth to the HHP basement caused by development of a variable thickness basin, we neglect the possible role of thermal conductivity contrasts across the basement-cover interface. However, we note that because the basin-filling sediments are likely to have a lower conductivity than basement rocks, our estimates of the thermal response will be minimal estimates. Incorporation of a more realistic thermal conductivity structure would produce even more substantial variations but would obscure the relative contributions. Finally, we note that our primary motivation here is in understanding the factors responsible for the primary localisation of the intraplate deformation in the central Australian region. Once deformation starts and an orogen begins to build, many other factors come into play, such as the evolving thermal and density structure of the orogen, which will change the distribution of strength and stress. These factors are fundamental to the long-term evolution of the orogen (and we return to them in the discussion where we consider the remarkable gravity anomalies associated with the central Australian orogens), but they are not relevant to the question of the initial localisation of the deformation. Importantly, because stratigraphic observations (outlined above) imply that prior to each orogeny the central Australian region was characterised by subdued relief, its seems unlikely that variations in lithospheric gravitational potential energy can have played a significant role in localising deformation.

Fig. 4a shows the calculated variations in Moho temperatures (relative to the centre of the basin) induced solely by variations in the thickness of the cover, immediately prior to the Petermann and Alice Springs Orogeny's. Prior to the Petermann Orogeny, the ~3 km variation in thickness of the sedimentary blanket results in an estimated variation in T_{Moho} of ~30ºC, with a strong gradient in T_{Moho} predicted across the present day southern margin of the basin. The coolest thermal regimes are associated with the shallowest central part of the basin where the sedimentary sequence at this time was 1.5 km thick. Prior to the Alice Springs Orogeny, the predicted Moho temperatures varied by up to ~110ºC, with the maximum temperatures along the northern margin of the basin where the thickness of the sedimentary column attained 7.5 km. The coolest crustal thermal regimes occurred in the south where the cover had been completely removed from the Musgrave Inlier following the Petermann Orogeny. Note that the calculations summarised in Fig. 4a are based on the assumption that erosional denudation of the Petermann Orogen removed sufficient quantities of the basement to reduce q_{c} by 33% (consistent with current heat flow measurements from the Arunta Inlier and also the very low heat production in the presently exposed Musgrave Block, [37]). Of course, varying the amount of basement removed (or more strictly the reduction of heat production) from the Musgrave Inlier following the Petermann Orogen would influence the calculated thermal regime. However, it does not alter the fact that the Moho beneath the southern margin of the Amadeus Basin must have been appreciably cooler than beneath the northern margin at the time of onset of the Alice Springs Orogeny by virtue of the removal sedimentary cover from the former region.

In order to assess variations in strength across the basin we calculate $\dot{\epsilon}_{zz}$ associated with the deformation of a lithospheric column subject to an in-plane tectonic force of 5×10^{12} N m^{-1} (Fig. 4a,b). Two factors lead to variations in strength across the basin. The most important is due to the sensitivity of the 'Brace–Goetze' lithosphere to upper mantle temperatures (e.g. [13,40]), which implies that the predicted variations in T_{Moho} equate to dramatic variations in $\dot{\epsilon}_{zz}$. A second-order effect relates to the assumed mineralogical changes at the basement-cover transition which imply the cover may be appreciably weaker than the basement providing temperatures at the interface are sufficient to cause failure by power-law creep in the cover. Variations in the depth to this interface may therefore contribute to small variations in calculated strength.

Our calculations show an across-basin variation in $\dot{\epsilon}_{zz}$ of about one order of magnitude at the initiation of the Petermann Orogen. The maximum values occur along and beyond the (preserved) southern margin of the Amadeus Basin, and are directly associated with the thickest sediment accumulation occurred. During the initiation of the Alice Springs Orogen the predicted variation in $\dot{\epsilon}_{zz}$ is greater than 4 orders of magnitude, with the maximum values located beyond the northern margin of the preserved basin. Fig. 4a,b show that an increase in the thickness of a sedimentary cover succession by 3 km over a horizontal length scale of around 100 km or more causes a corresponding increase in the vertically averaged strain rate by a factor of 10 in a Brace–Goetze lithosphere.

The potential significance of these calculations is highlighted with the realisation that the spectrum from geologically insignificant strain rates (of the order 10–16 s^{-1}) to the fastest rates of distributed deformation in the modern earth (of the order 10–13 s^{-1}) is about 3 orders of magnitude. Therefore, the calculations summarised in Fig. 4 illustrate a potentially profound role for the variable thickness sedimentary blanket in localising deformation of the lithosphere subject to an in-plane tectonic force. The predicted variations in $\dot{\epsilon}_{zz}$ associated with variations in stratigraphic thickness are more than sufficient to allow for the regional variations in strain implied by the localised nature of deformation during both the Petermann and Alice Springs Orogens. Note that since T_{Moho} provides the dominant control on lithospheric strength, the length-scale of the sedimentary thickness variations is important. Due to the dissipating effect of lateral heat flow at small wavelengths ($\ll$100 km), variations in the thickness of the sedimentary pile associated with individual half-grabens, and other small-scale features, will not significantly affect Moho temperatures and thus will not lead to significant variations in strength. In the context of the Amadeus Basin, this has a bearing on the mechanical consequences of stratigraphic thickness variations associated with the Mount Currie Conglomerate, which occupies a deep narrow trough in the southern Amadeus Basin (Fig. 2b).

5. Discussion and conclusions

Spatially restricted intraplate deformation, of the type affecting central Australia during the latest Proterozoic and Phanerozoic, must reflect either the localised reduction in strength in the presence of an in-plane stress field, or the local amplification of regional stresses due to variations in the density structure at depth (e.g. [42]) (or possibly some combination of the two). The possibility that localised deformation in central Australia is caused by crustal shortening induced by intraplate mantle lithosphere subduction has been investigated by Braun and Shaw [43]. The analysis in the preceding sections shows that variations of order of 5 km or so in the depth to a HHP basement, of the type characterising the ‘central Australian heat flow province’, may be sufficient to provide the weakening needed to localise deformation in the presence of an ‘in-plane’ tectonic stress field. The predicted variations in strength are robust to significant lateral variations in basement heat production parameters. For example, our calculations show that in order to annihilate the regional variations in strength immediately prior to the Alice Springs Orogen, heat production beneath the northern margin of the basin needs to be reduced by $>$50% relative to the centre of the basin. Importantly, our calculations show that regional variations in strength inferred from the observed geological record of strain accumulation during the Petermann and Alice Springs Orogenies may reflect the variations in the thickness of sedimentary successions, resulting from spatial variations in deposition and erosion in the proto-Amadeus Basin (i.e., the Centralian Superbasin).

The relative distribution of lithospheric strength implied by our calculations is consistent with several important features of the Phanerozoic orogens in central Australia, namely: (1) the major structures in both the Petermann and Alice Springs Orogenies verge toward the Amadeus Basin, implying the basin effectively acted as an indenter, and (2) within the basin, shortening associated with both orogens was characterised by thin-skinned deformation with detachments occurring along several thick salt-bearing horizons (Bitter Springs Formation, Pinyinna beds; Chandler Formation) [4,26,28]. In contrast, high strain belts along the footwall margins of both inliers show a strong degree of coupling between cover and basement [2,18,44–46], despite the presence of the evaporitic horizons. This provides an alternative line of evidence suggesting that differential burial of radiogenic basement by only a few kilometres can decrease lithospheric strength to the point where mechanical contrasts between adjacent layers are effectively annihilated.

Although the above calculations show that sedimentary thickness can provide a first-order control on the localisation of deformation in central Australia and a plausible explanation for partitioning of thin-skinned and thick-skinned deformation, it is less clear why the style of deformation during the Alice Springs Orogeny changes along the orogen over a length scale of approximately 100 km. In the basement, this change is manifest by the transition from discrete fault zone deformation with dominantly steep displacements west of Alice Springs [6,24,47,48] to sub-horizontal transport in the eastern part of the inlier [29,47]. This change in style of deformation is accompanied by an increase in orogenic strain and by the degree of Palaeozoic exhumation along the orogen (from ∼≤10 km in the west to ≥20 km in the east [21,29,48]). In the eastern inlier, mid- to upper-amphibolite facies metamorphism (600–650ºC, 500–700 MPa) during the Palaeozoic appears was characterised by negligible vertical temperature gradients (<5ºC/km) over depth ranges of at least ∼5 km (our own unpublished data). Moreover, temperatures in this region appear to have remained above 500ºC for ∼70 Ma during the later stages of the Alice Springs Orogeny [49]. One way this type of thermal structure can be maintained for such long time scales, is if the exceptionally high heat production is concentrated at shallower crustal levels. The observed metamorphic structure can be approximated with upper crustal sources contributing ∼75 mW m^{-2}. While such a high contribution is certainly unusual, it is consistent with the elevated heat flow elsewhere in the Australian Proterozoic [11]. Moreover, in the Arunta Complex, it is supported by the presence of voluminous HHP granites in marginal parts of inlier that have escaped significant Palaeozoic denudation [38]. Regional variations in crustal heat production of ∼15 mW m^{-2} would result in corresponding variations in Moho temperatures of up to ∼50ºC. Thus, in addition to the effects due to variations in the thickness of the pre-orogenic sedimentary carapace, variations in crustal heat production may have exerted a further important control on the style of deformation (see also [43]).

Any discussion of the formation of the central Australian orogens must inevitably encounter the problem of the extraordinary modern-day gravity anomalies (∼150 mGal) associated with these orogens, which are amongst the largest anomalies preserved in continental lithosphere [8]. It is now well understood that these anomalies reflect the structural architecture developed during the Petermann and Alice Springs Orogenies [6]. It is less clear what has sustained the anomalies, and associated structures, over the past several 100 Ma (e.g. [8,41]), which are clearly out of isostatic equilibrium. The implication of a relatively strong lithosphere, sufficient to sustain large gravity anomalies over long geological timescales, seems at odds with the localised nature of intraplate deformation in the earlier Palaeozoic. The notion that deformation can be localised by the thermal impact of the development of a thick basin above a relatively radiogenic basement sequence, im-

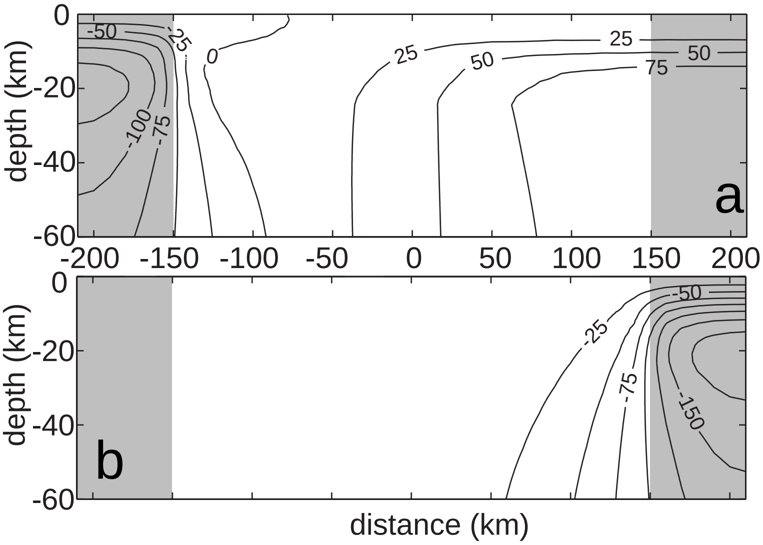

Fig. 5. Calculated temperature changes in crust and upper mantle in the interval (a) pre-Petermann Orogeny to pre-Alice Springs Orogeny and (b) pre-Alice Springs Orogeny to post-Alice Springs Orogeny. The vertical axis is the depth from the surface while the horizontal axis is the distance across the basin measured relative to the centre of the basin. The predicted cooling (150–200ºC) of the lower crust and upper mantle is based on the assumption that denudation of the orogens has removed the entire sedimentary carapace as well as ∼33% of the basement heat sources.

plies that the strength of the lithosphere is very sensitive to the thermal regime. An important corollary of this notion is that significant lithospheric cooling, and associated strengthening, will be expected to accompany the removal of the basin sediments (and upper, HHP parts of the basement) during denudation. Fig. 4c and Fig. 5 show the mechanical and thermal effects of the localised denudation using the same assumptions employed earlier to calculate the thermal weakening induced by basin formation. The very significant strength increases associated with removal of the sedimentary carapace (and upper 5 km of basement) equate to a decrease in Moho temperatures of up to 200ºC (Fig. 5) and a reduction in the effective strain rate of 2–5 orders of magnitude. Such profound mechanical changes potentially allow (1) orogeny to be self-limiting, and (2) significant orogenic-scale geophysical anomalies to be ‘frozen-in’ during the terminal stages of the orogeny.

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