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Low thermal Peclet number intraplate orogeny in central Australia

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Abstract

The late Phanerozoic Alice Springs Orogen in central Australia is an archetypal intraplate orogen characterised by a dense, granulitic core exhumed from beneath a carapace comprising a highly radiogenic granitic mid-upper crust and sediments deposited in a shallow intracratonic basin. Exhumation occurred in large part along a crustal penetrative fault system, the Redbank Shear Zone, producing one of the largest gravity anomalies ($\sim$150 mgal) known from the continental interiors. The lithospheric strength implied by the preservation of this anomaly for more than 300 Myr raises the intriguing conundrum of what localised the intraplate deformation in the first place. Available biostratigraphic and thermochronologic data imply bulk convergence rates of less than 1 mm/yr for the orogen as a whole, several orders of magnitude lower than typical of plate margin orogens. The thermal and mechanical evolution of intraplate orogens deformed at such low thermal Peclet numbers differs in fundamental ways from plate margin orogens. In particular, at such low thermal Peclet numbers the conductive response to exhumation of heat sources cools the mid to deep crust during progressive orogenic activity. This is consistent with the hypothesis that the density structure and associated gravity anomalies may have been *locked-in* by virtue of the strength acquired during the orogenic process provided that the lithospheric strength changes associated with a reduction in average crustal temperature of 20–30°C are of the same order as the forces that drive intraplate deformation.

Keywords: thermal properties; heat sources; intraplate processes; orogenic belts

1. Introduction

Plate margin orogens typically evolve at rates commensurate with the subduction of oceanic lithosphere attached to one of the two interacting plates. Since subduction forms an important component of the natural convective pattern in the Earth's interior it is necessarily characterised by velocities (greater than about 1 cm/yr) that prohibit significant conductive heating of the subducting slab during its descent into the deeper mantle. Indeed, the thermal density defect of the subducting slab provides a principal source of stress driving mantle flow and the motion of surface plates [1]. The connection between plate margin orogens and subduction implies that they also typically evolve at high thermal Peclet numbers

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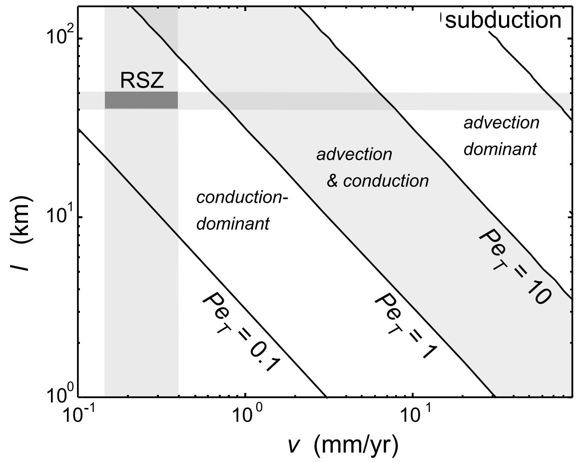

Fig. 1. Estimated values of mean displacement rates, v, and appropriate length scales, l, for the movement on the Redbank Shear Zone (RSZ) during the ASO (see text for discussion). Contours show values of thermal Peclet numbers, Pe_T, and indicate that the Redbank Shear Zone operated in a low-Pe_T regime where conduction was likely to dominate its thermal evolution. Note that typical plate margin orogens associated with subduction of oceanic lithosphere are likely to evolve with $Pe_T \gg 10$.

($Pe_T > 10$, Fig. 1), with their thermal evolution dominated by the advection of material through the orogen [2]. Material advection through orogenic belts tends to cool the deeper parts of the lithosphere, where the flow is dominantly downwards (mantle downwelling), and heat the upper parts of the orogen, where flow is typically towards the surface due to erosion [2]. When flow in the crust stagnates, as happens when the advection of the buoyant crustal material into the orogen exceeds its removal by erosion, significant heating accrues from the accumulation of a thickened radiogenic crust [3]. These factors tend to promote crustal heating and weakening with respect to typical continental lithosphere, making plate margin orogens susceptible to tectonic collapse once the forces driving orogenesis are relaxed [4].

Unlike most plate boundary settings, orogens that form in intraplate settings in response to transmission of stress from distant plate boundaries are not required to deform at rates commensurate with subduction. For very low convergence rates (i.e. low $Pe_T < 1$) the thermal effects of material advection in the crust are subordinate to conductive heat loss (Fig. 1). Moreover, low convergence rates reduce the possibility of material accumulation in the orogen implying limited potential for the development of a thickened radiogenic crust. The thermal evolution of this kind of small, low-Pe_T orogen will be dominated by the conductive response to the redistribution of radiogenic heat sources induced by the material flux through the orogen. In particular, the slow exhumation of radiogenic crust along structures that root beneath the heat producing parts of the crust must lead to crustal-scale cooling, allowing the possibility of progressive orogenic strengthening. Such low-Pe_T orogens have limited potential for collapse once the driving forces for convergence relax and should be capable of preserving non isostatically balanced density structures formed early in orogenic construction.

The Alice Springs Orogen (ASO) in Central Australia (Figs. 2 and 3) is an archetypal intraplate orogen formed in the late Phanerozoic [5,6]. One of the most intriguing aspects of the ASO relates to its gravity signature ([7], Fig. 3a) that includes some of the largest anomalies (~150 mgal) known from the continental interiors. These extraordinary anomalies clearly relate to the orogenic architecture developed during the construction of the orogen [5], and their long-term (> 300 Myr) preservation implies virtually no readjustment of the orogenic architecture since the end of convergence, consistent with an exceptionally strong crust. Curiously, this raises a conundrum of why intraplate deformation was localised in such a strong part of the continent. One possibility is that tectonic stresses were greatly amplified in the central Australian region, compared to surrounding regions, to the extent that they were capable of deforming relatively rigid lithosphere. In this case the principal source of stress must almost certainly relate to a dynamic mantle process directly beneath central Australia, rather than distant plate boundary sources. Arguing against this hypothesis is the fact that Alice Springs aged deformation is now known to have occurred over vast regions of the Australian continent ([8]; Fig. 3). An alternative possibility is that the deformation was localised in a relatively weak re-

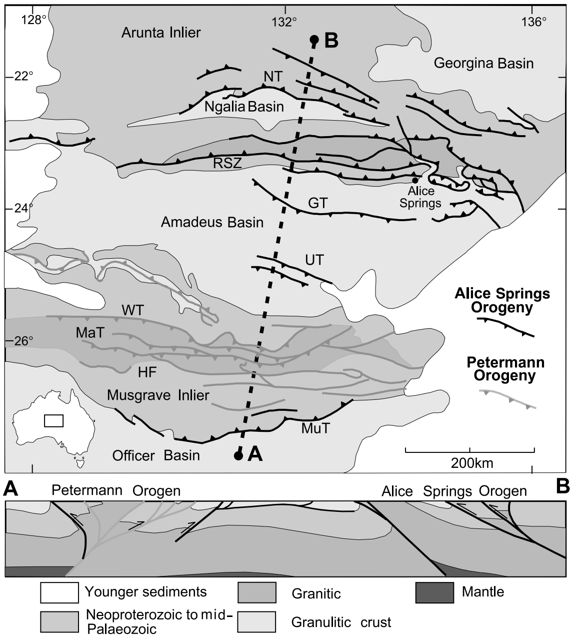

Fig. 2. Geological map of the central Australian region, showing the structurally remnant Neoproterozoic basins (the Officer, Amadeus, Ngalia and Georgina basins), separated by basement inliers (the Musgrave and Arunta inliers). Within the basement inliers we can distinguish two distinct types of terrane: (1) gneissic granite terranes that form the peripheral regions of the inliers and which are unconformably overlain by the sediments in the basins; (2) depleted granulite terranes that define the cores of the inliers and which are tectonically juxtaposed with the gneissic granite terranes. This juxtaposition reflects, in part, the strain associated with intraplate orogeny accumulated during the exhumation of the basement inliers from beneath a formerly more or less continuous intracratonic basin. In the Arunta Inlier this intraplate deformation was principally associated with the 450–300 Ma Alice Springs Orogeny, while in the Musgrave Inlier it was associated with the 550–500 Ma Petermann Orogeny. GT: Gardiner Thrust, HF: Hinckley Fault, MaT: Mann Thrust, MuT: Munyari Thrust, NT: Napperby Thrust; RSZ: Redbank Shear Zone, UT: Uluru Thrust; WT: Woodroofe Thrust.

gion that, by virtue of the orogenic process, has radically changed its mechanical properties [9]. The proposed mechanism relates to the way deformation and associated denudation has redistributed crustal radiogenic heat sources, thereby leading to changes in lithospheric thermal regimes. This mechanism is only likely to provide a viable mechanism for *locking-in* the extraordinary gravity anomalies if the thermal structure of the orogen was able to adapt to the redistribution of heat sources during the deformation [10]; as would apply if it were deformed at a low Pe_T ($Pe_T < 1$). This paper reviews evidence for the time-integrated deformation rates associated with the ASO, suggesting that it did indeed evolve as a low-Pe_T orogen, and briefly explores the implications of this hypothesis for the notions of lithospheric strength.

2. The ASO

The ASO formed part of a widespread zone of intraplate deformation in the central part of the Australian continent in the late Phanerozoic ([8], Figs. 2 and 3b). Deformation was most spectacularly developed in the vicinity of Alice Springs in a region that was, up until this time, covered by an extensive Neoproterozoic to Early Phanerozoic basin termed the Centralian Superbasin [11]. Within the ASO, Paleao-Mesoproterozoic metamorphic and granitic basement complexes have been exhumed from beneath this basin, resulting in the present configuration of basement inliers (e.g. the Arunta Inlier) surrounded by structurally, remnant basins including the Amadeus, Ngalia and Georgina basins (Fig. 3b). The ASO deformation was most intense along the southern part of the Arunta Inlier where it was focussed along a crustal-scale system of south-vergent thrusts forming the Redbank Shear Zone ([5], Figs. 2 and 4). A deep seismic section across the southern third of the inlier indicates this zone dips northwards at ∼45° into the lower crust offsetting the Moho by at least 10 km [12,13]. At least some of the ASO structures have reactivated older Mesoproterozoic thrusts [14], resulting in a somewhat ambiguous picture of the extent of ASO-aged basement deformation. Consequently, the magnitude of crustal shortening during the ASO has proven difficult to quantify precisely. However, estimates based primarily on the extent of cover/basement interleaving imply shortening of at least 80 km [5,6], while the extent of basement denudation inferred from thermo-chronological data limit total shortening to less than 100–125 km [15]. Thermo-chronological data from the eastern Ar-

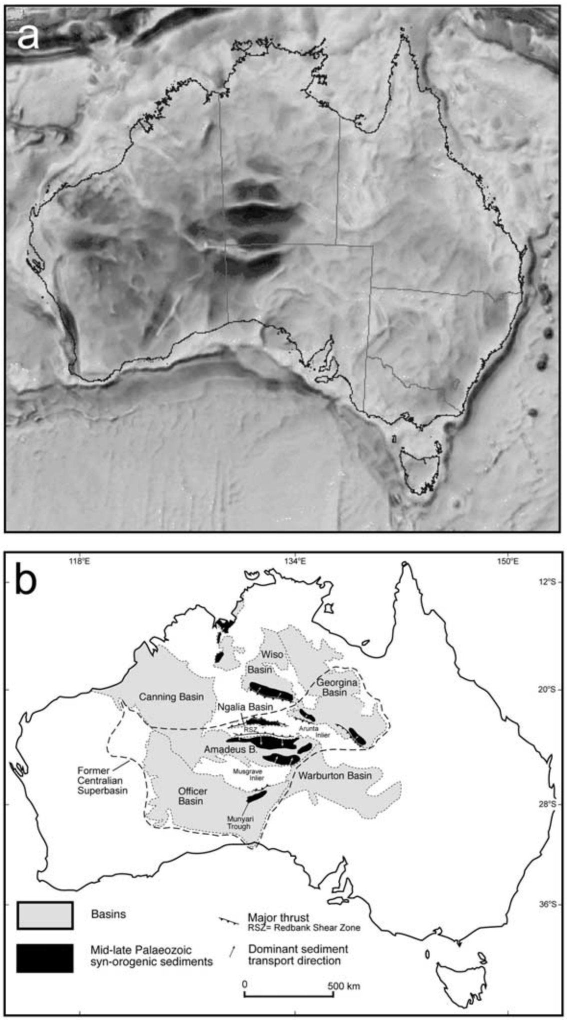

Fig. 3. (a) Bouguer gravity field of Australia based on the Australian Geological Survey Organization gravity database (black low, white high). The extraordinary anomalies in the Central Australian region have amplitudes of ~150 mgal [7] and clearly correlate with the main structures in the Alice Springs and Peterman orogens (e.g. [5,7], Fig. 2). (b) the distribution of Neoproterozoic sedimentary basins and mid-late Phanerozoic sediments in the Australian continent highlighting the widespread record of Alice Springs aged deformation across the Australian continent [8].

unta Inlier show that maximum denudation associated with the ASO was ~20 km [16], although throughout much of the orogen it was closer to 10 km. One consequence of this denudation was the exhumation of an orogenic core comprising older, higher-grade metamorphic rocks. This high-grade core comprises both mafic and felsic granulites that are readily distinguished from mid-crustal granite-dominated terranes that immediately underlie the Centralian Superbasin sediments along the margin of the Arunta Inlier in terms of their radioelement concentrations ([10], Fig. 4). Typical heat production rates for the high-grade core are < 1–$1.5\ \mu W\ m^{-3}$ whereas the marginal granitic terranes have characteristic heat production rates of 3–5 $\mu W\ m^{-3}$, with some individual granites having heat production rates in excess of 10 $\mu W\ m^{-3}$ [10]. This granitic layer has been estimated to contribute approx. 50 $mW\ m^{-2}$ to the surface heat flow [10].

The duration of the ASO is constrained by both stratigraphic and thermochronologic data [6,8] as summarised in Fig. 5. The isotopic record of mineral closure in a diverse range of mineral systems spans an interval of ~150 Myr from the late Ordovician [14,16] to the late Carboniferous [14]. While the data summarised in Fig. 5 show a relatively continuous record of mineral isotope resetting through this interval, discrete pulses of isotopic resetting have been inferred from various parts of the orogen at ~450–430 Ma, ~390–380 Ma, ~365–350 Ma and ~330 Ma by various authors [6,14,16,17,18]. Thus, although there is clear evidence for episodic cooling within given subdomains, it is not yet clear whether the record is episodic at the scale of whole orogen. In the SW Arunta Inlier, in the region near the Redbank Shear Zone (as shown in Fig. 4), Shaw et al. [18] document a mineral isotope resetting over an interval of at least 60 Myr from > 390 to 330 Ma.

The sedimentary record of the Amadeus, Ngalia and Georgina basins provide a subtle record of unroofing of the surrounding basement inliers [8,19]. The first indications of ASO-related tectonic denudation of the Arunta Inlier occurred in the Late Ordovician (~450 Ma) with the deposition of an immature, deltaic sedimentary package (the Carmichael Sandstone) in the central and western Amadeus Basin. This package was derived from the northeast and its depocentre probably extended above the western Arunta Inlier, connecting the Amadeus and Ngalia basins [8,19]. Similar trends in equivalent-aged packages in the Georgi-

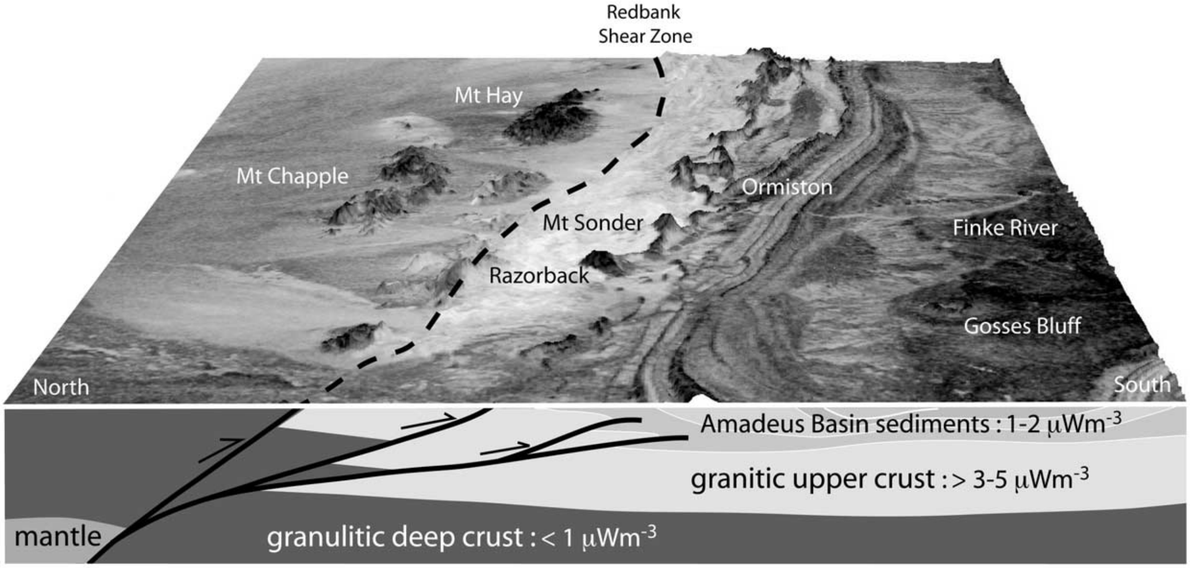

Fig. 4. Airborne radiometric image, data courtesy of Northern Territory Geological Survey, draped over a digital elevation model of the western Macdonnell ranges along the boundary between the Arunta Inlier and the Amadeus basin. In terms of radioelement concentrations, three distinct elements can be identified [10]; (1) the sediments of the Amadeus basin that have heat production rates of 1–2 μW m^{-3}, (2) the granites and gneisses that immediately underlie the Amadeus Basin and have heat production rates of >3 μW m^{-3} (locally up to ~ 10 μW m^{-3}) and (3) the deep crustal mafic granulites that outcrop as isolated monadnocks (e.g. Mount Chapple and Mount Hay) in the desert to the north of the Redbank Shear Zone with heat production rates <1 μW m^{-3}.

na Basin [8] imply that the initiation of ASO deformation occurred along a WNW-axis trending through the eastern Arunta Inlier ([8], Fig. 6). The depocentres of subsequent sedimentary packages comprising the Mereenie Sandstone and Pertnjara Group trend EW reflecting more extensive uplift throughout the Arunta Inlier on structural trends controlled by the Redbank Shear Zone (Fig. 6). Biostratigraphic constraints place the commencement of the syn-orogenic Pertnjara Group in the late Early Devonian (~ 400 Ma), following deposition of the distinctive Aeolian sequence of Mereenie Sandstone in the Silurian or earliest Devonian [19]. The commencement of the Pertnjara Group deposition in the north central Amadeus Basin correlates reasonably well with a distinct episode of cooling at ~ 390 Ma recognised in the SE Arunta Inlier [6]. The Pertnjara Group coarsens upwards, particularly in the Amadeus and Ngalia basins where it culminates in thick fanglomerate succession suggesting a peak in rate of denudation in the latest Devonian, coinciding with the beginning of a second distinct phase of cooling in the SE Arunta Inlier inferred from thermo-chronological data [6]. While deposition in the Pertnjara Group in the Amadeus Basin is restricted to Devonian (Fig. 3), its record in the Ngalia Basin extends into the late Carboniferous, implying that the locus of deformation switched from the southern Arunta Inlier to the northern Arunta Inlier in the late Devonian [8,20].

3. Thermal evolution of the Redbank Shear Zone

As noted above, a significant fraction of the ASO shortening was accommodated on the Redbank Shear Zone which forms a crustal-scale ramp (Figs. 2) offsetting the Moho by ~ 10 km. The horizontal displacement of the Redbank Shear Zone and its associated splays, such as the Ormiston Thrust, during the ASO has been estimated at ~ 20 km [15]. Given this estimate, the time-averaged slip rates on the Redbank

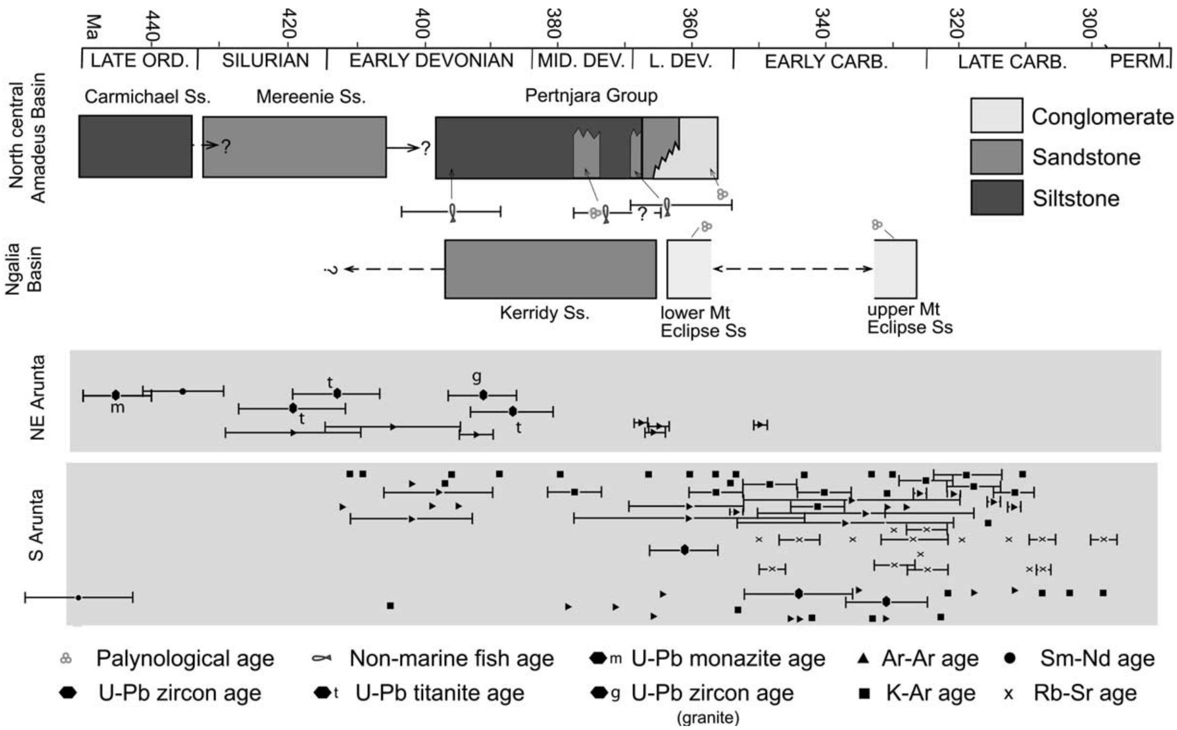

Fig. 5. Summary of stratigraphic can thermochronologic data relevant to the duration of the ASO, adapted from [8]. See text for discussion. Primary thermochronologic sources include [6,14,16,17,18].

Shear Zone lie between ~0.15 and 0.33 mm/yr depending on whether (1) slip accumulated throughout the 150 Myr period of isotopic resetting recorded across the whole of the orogen (Fig. 4) or, as is more likely, (2) slip was restricted to the ~60 Myr period reflected in the mineral isotopic record, and shedding of the Pertnjara Group, from the southern Arunta Inlier in the vicinity of the shear zone [18].

While the history of displacement on the Redbank Shear Zone may well have been intermittent, these bounds provide an insight into the overall thermal response of the system to repeated movement. Moreover, from the point of view of the thermal response to this movement, slip rate fluctuations are of secondary import since the thermal response is always dominated by the principal harmonic. As noted earlier, the qualitative thermal response of a deforming system is encapsulated in the thermal Peclet number, $Pe_T = v\ l/\kappa$, where v is the characteristic velocity, l is the appropriate length scale over which conduction operates, and κ is the thermal diffusivity. The Pe_T provides a measure of the rate of advection of heat to conduction of heat: for $Pe_T > 10$ advection dominates over conduction, while for $Pe_T < 1$ conduction dominates over advection. The bounds on the averaged displacement rates discussed above for the Redbank Shear Zone, where $l \sim 40$ km (the thickness of the crust), $\kappa \sim 10^{-6}$ m^2 s^{-1}, give $Pe_T \sim 0.2$–0.4, imply that the movement must have been accompanied by a conductive response to the redistribution of heat sources attendant with the denudation of the hanging wall sequences (Fig. 1).

The magnitude of the temperature changes during movement on the Redbank Shear Zone can be evaluated using a simple kinematic model as shown in Fig. 7, using constraints on the heat production distributions based on analysis of the various crustal segments shown in Fig. 4 [10]. In this model, the initial configuration is assumed to consist of a laterally homogeneous continental lithospheric section comprising a radiogenic upper

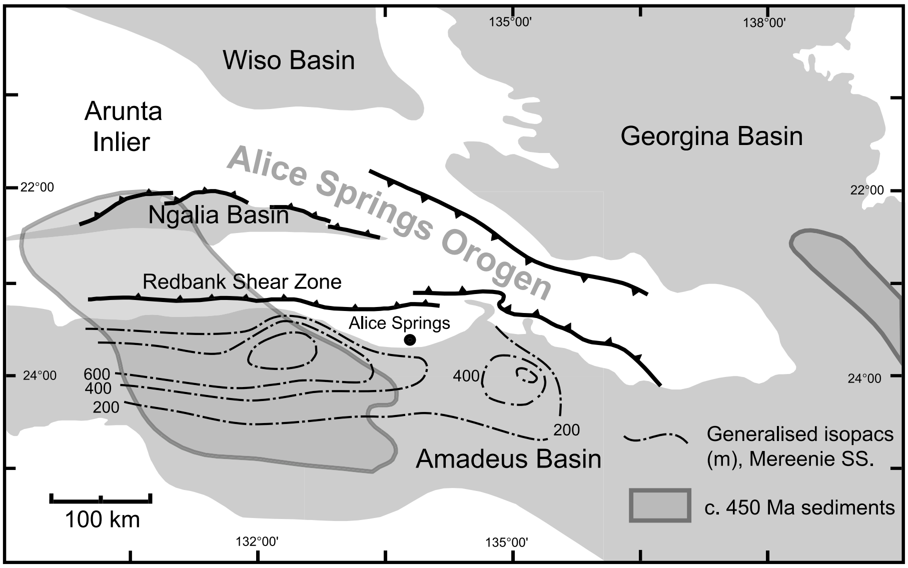

Fig. 6. Outline of the distribution of early syn-orogenic sediments in the Amadeus, Ngalia and Georgina basins (adapted from [8]) suggesting that deformation at ∼450 Ma associated with deposition of Carmichael Sandstones and equivalents initiated in the Eastern Arunta Inlier. By the time of deposition of the Mereenie Sandstone, deformation had been realigned, reflecting initiation of ASO deformation on the Redbank Shear Zone in mid-late Silurian or early Devonian.

crust extending to a depth of 10 km that contributes 50 mW m^{-2} to the surface heat flow [10], above a depleted lower crust. The kinematics of deformation comprises displacement along a crustal-scale ramp dipping at 45° to a depth of 45 km. A constant displacement rate is imposed for sufficient time to allow 20 km of crustal convergence (Fig. 7). Denudation is assumed to balance the

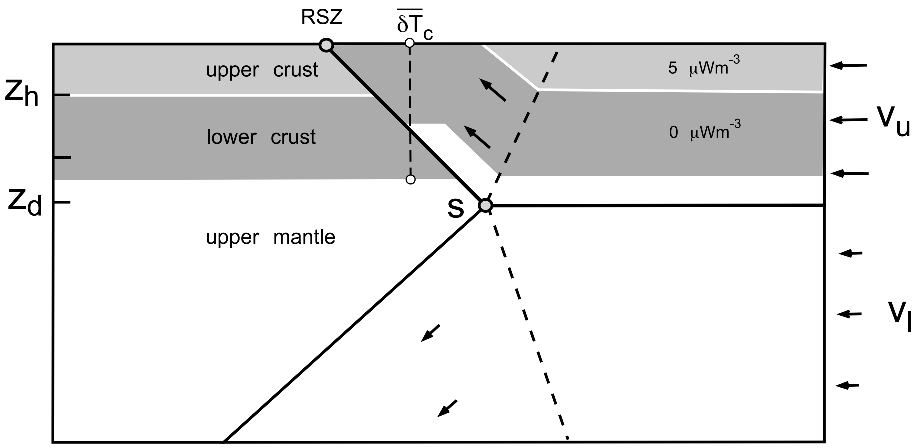

Fig. 7. Outline of kinematic model used to model the thermal consequences of deformation on the Redbank Shear Zone during the ASO, motivated in part the models of Beaumont et al. [2]. In this model the Redbank Shear Zone is assumed to sole at depth z_d slightly below the Moho. Displacement of the upper plate above the detachment occurs at rate v_u while a corresponding flow at rate v_l in the deeper mantle takes material down, inducing a discontinuity in the velocity field at s. Heat production in the upper crustal layer is distributed homogeneously (5 μW m^{-3}), contributing effectively 50 mW m^{-2} to the surface heat flow prior to deformation. The lower crust is considered to have negligible heat production.

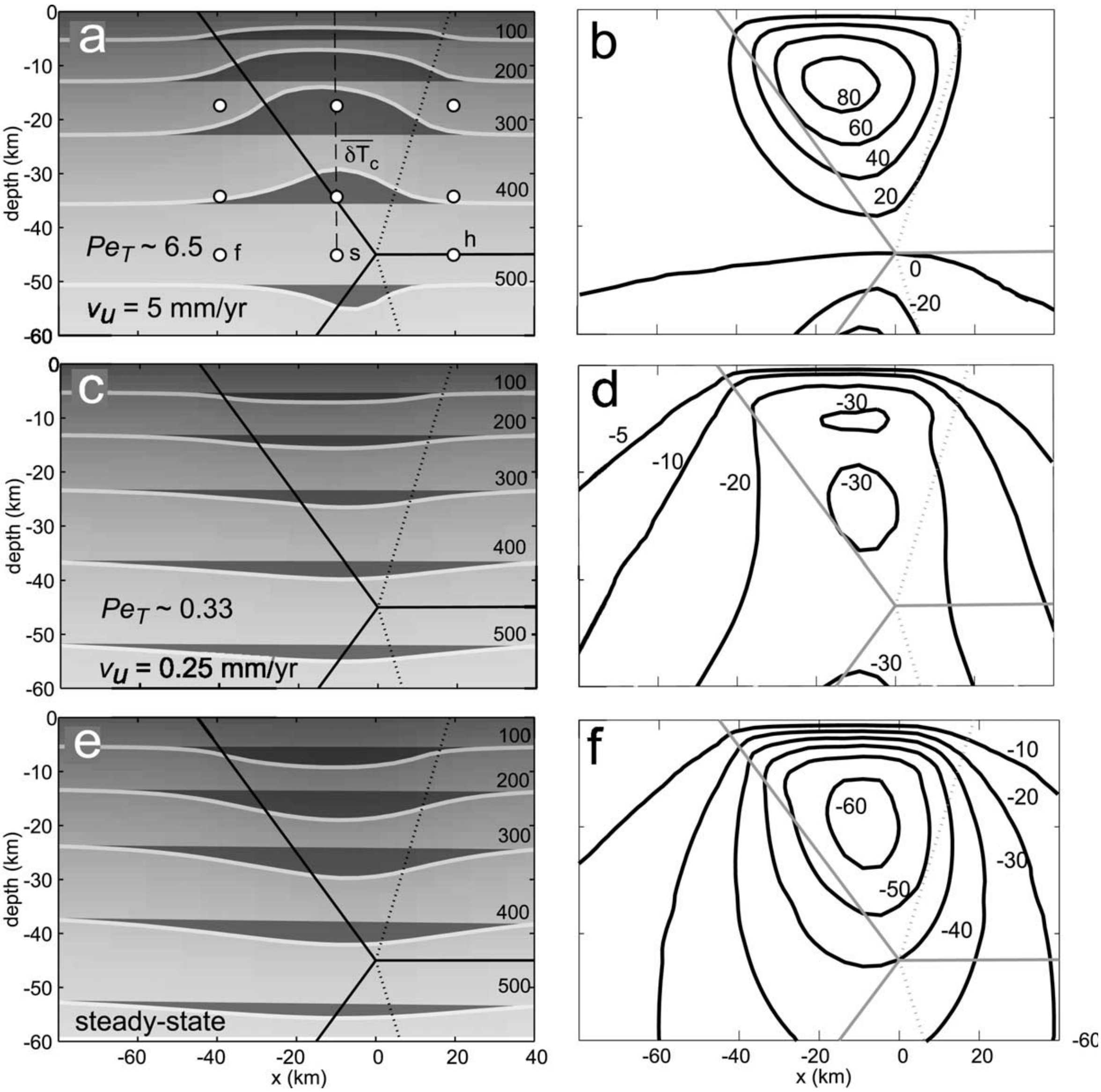

Fig. 8. Calculated temperature fields for the model shown in Fig. 7. (a,b) The temperature field at termination of slip ($v_u = v_l$ = 5 mm/yr). (b–d) The temperature field following slip at ($v_u = v_l$ = 0.25 mm/yr). (e,f) Steady-state conductive temperature field associated with the distribution of heat source induced by 20 km of crustal convergence. (b,d,f) The difference between the computed temperature field and the initial temperature field. Circles in (a) show points at which the temperature–time paths in Fig. 10 have been computed.

mass influx associated with to crustal convergence, consistent with the notion of very low convergence rates. From the point of view of the thermal evolution of the orogen, this kinematic framework leads to the removal of the radiogenic crust from the hanging wall (Fig. 7). The main results are presented in Figs. 8–10.

The temperature field has been computed using a finite element algorithm for a range of convergence velocities (v_u). Two scenarios for the behaviour of the deeper mantle lithosphere have been modelled. In the first (solid lines in Figs. 9 and 10) the mantle lithosphere converges with the same velocity as the crust ($v_l = v_u$), inducing a discontinuity in the velocity field at s (Fig. 7). In the second (dashed lines in Figs. 9 and 10) the deep mantle remains stationary ($v_l = 0$) within the modelled domain, implying a horizontal structure at depth z_s that detatches the crustal displacement from the deeper mantle.

The computed temperature field after 20 km of crustal convergence is shown for the cases $v_l = v_u = 5$ mm/yr and $v_l = v_u = 0.25$ mm/yr in Fig. 8a,c, respectively. Fig. 8e shows the thermal structure appropriate to thermal conductive equilibrium for the post-slip distribution of heat sources as outlined in the Fig. 7 legend. This final configuration is characterised by depressed crustal thermal gradients relative to the initial configuration with the predicted long-term cooling throughout the hanging wall of 40–70°C (Fig. 8f). For the relatively high convergence velocity shown in Fig. 8a ($Pe_T \sim 6.5$), the ramping of the crust along the fault advects sufficient heat to elevate thermal gradients in the mid-upper parts of the hanging wall sequence by 40–100°C (Fig. 8b), with the average crustal temperature increased by ~60°C (Fig. 9). Once slip ceases, significant cooling takes place as thermal structure conductively adapts to the post-slip distribution of heat sources (Fig. 10). For the low velocities appropriate to the long-term average slip rates on the Redbank Shear Zone (Fig. 8c, $Pe_T \sim 0.33$), the crustal ramp cools by up to 35°C relative to its initial configuration as slip proceeds (Fig. 8d), resulting in a mean crustal temperature reduction during deformation of 20–30°C (Fig. 9). Fig. 9 shows the mean crustal temperature changes computed as vertical line integrals through the crust at the time slip ceases, as a function of convergence velocity. This relationship confirms the notion that for $Pe_T < 1$ (i.e. $v_u < 0.8$ mm/yr) conductive cooling in response to the denudation of heat sources from the hanging wall outweighs the advection of heat in the hanging wall. The mean crustal cooling amounts to ~20–30°C for the displacement rates appropriate to the ASO (the shaded zone in Fig. 9), or about 40–60% of the long-term cooling required

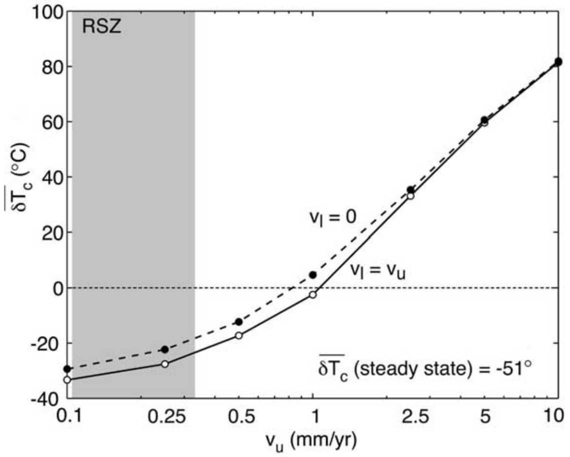

Fig. 9. Mean crustal temperature change (δT_c) at the time deformation finishes plotted as a function of convergence velocity (v_u). δT_c is computed as the line integral of the temperature change over the thickness of the crust at a point 10 km into the footwall sequence from the point s (see Fig. 7).

to balance the post-slip distribution of heat sources. Fig. 10 shows the temperature–time paths for material points during and following deformation, for a variety of convergence velocities. Importantly, for convergence velocities greater than ~2 mm/yr, the deep crust continues to heat for a few million years after slip terminates (Figs. 10e,f), particularly in the footwall of the ramp. This reflects the short wavelength conductive response to the extremely elevated upper crustal thermal regimes generated during slip, and implies that the crust will be at its weakest after deformation terminates. For all models considered here, within 10 Myr of the end of deformation the crust has cooled relative to its initial condition.

The qualitative arguments relating to Pe_T and the numerical calculations summarised in Figs. 8–10 show that the redistribution of heat sources inferred to have accompanied movement on the Redbank Shear Zone during the development of the ASO must have modified the thermal structure of the crust on the time scale of active slip. In particular, the implied low time-averaged slip rates for the Redbank Shear Zone suggest cooling of 20–30°C in much of the hanging wall by the time slip ceased. This represents around 40–60% of the potential long-term conductive cooling ex-

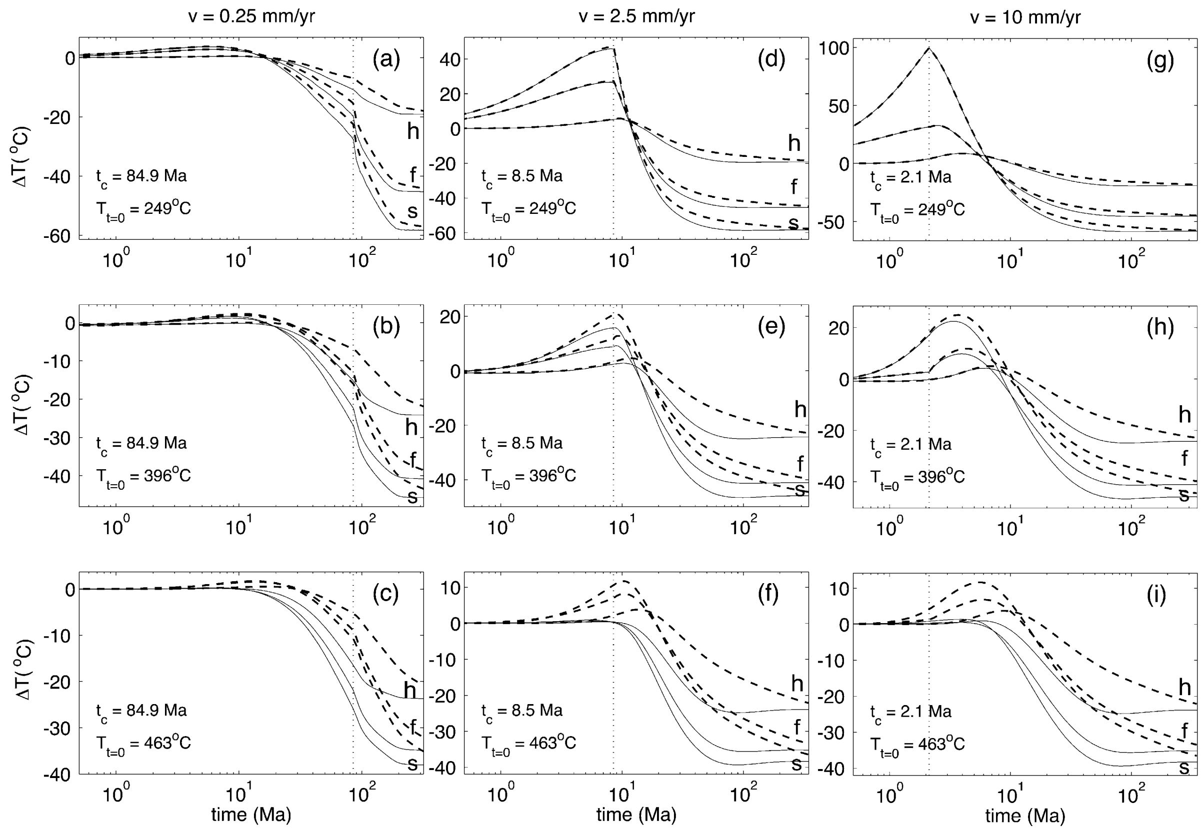

Fig. 10. Temperature–time paths for points at depths 17.5 km (a,d,g), 35 km (b,e,h), and 45 km (c,f,i). Columns are organised by v_u = 0.25 mm/yr (left column), 5 mm/yr (central column), 10 mm/yr (right column). Dashed lines show the case where $v_l = 0$, while solid lines show $v_l = v_u$. In each figure three sets of paths are shown, corresponding to points located 40 km (f) and 10 km (s) to the right of the point *s* (shown in Fig. 7) and 20 km (h) to the left of the point *s* (see Fig. 8a for the location of the points). Vertical dashed lines show the time at which deformation terminates after 20 km of crustal convergence.

pected to result from the redistribution of heat sources due to movement on the Redbank Shear Zone.

4. Discussion

The preservation of the extraordinary Central Australian gravity anomalies implies significant lithospheric strength and seems at odds with the localisation of intraplate deformation in this region. The notion that significant thermal structuring of the crust accompanied the development of these gravity anomalies is supported by the distribution of radiogenic heat sources in the current erosion surface (Fig. 3). The calculations summarised in this paper suggest that the redistribution of heat sources may have induced long-term mean crustal cooling of ~50°C. The low-Pe_T deformation regime implies that ~40–60% of this cooling accrued during deformation. This result contrasts with the thermal evolution of high-Pe_T plate margin orogens, where advective heat transport dominates the thermal evolution during active deformation. For the case of the ASO this has been demonstrated using an idealised kinematic model for the deformation that accords in principle with the available deep seismic profiles. It is important to note however, that the results are likely to be indicative for any plausible flow field arising from low-Pe_T deformation, in which surface denudation depletes the heat producing upper crust during orogeny. Because of the strong temperature dependence of lithospheric rheology, the cooling associated with ongoing deformation in low-Pe_T intraplate orogens such as the ASO is likely to have ramifications for the mechanical response of the orogen, in terms of the processes that lead to the cessation of deformation and the way the locus of deformation shifts with time. For example, it raises the possibility that thermally modulated strength changes may play an important role in limiting the duration of deformation independently of, or in addition to, fluctuations in the forces driving the deformation or the accumulation of gravitational potential energy within the orogen. Available laboratory derived data relative to the rheology of lithospheric materials suggest an extraordinary temperature sensitivity [21], but are highly uncertain [22] and remain to be validated by independent observations of natural tectonic processes. With reference to this temperature sensitivity, Neil and Houseman [23] have shown that for laboratory derived rheological models, Moho temperature variations of as little as 20–30°C are capable of explaining the partitioning of deformation in Central Asia, between essentially undeformed regions such as the Tarim Basin and deformed regions such as the Tien Shan. Given that the potential energy stored in these orogenic systems is similar in magnitude to the forces that drive deformation, the implication is that the change in lithospheric strength accompanying changes in Moho temperature of only a few tens of degrees are also of the same order as the forces that drive intraplate deformation. This is consistent with the notion that the temperature changes associated with low-Pe_T deformation in the ASO may have been sufficient to provide a thermal lock that helped terminate deformation, independently of any consideration of the driving stresses or potential energy stored in the orogenic system.

A further insight bearing on this problem comes from the recognition that the mechanical structuring of the crust and lithosphere during low-Pe_T deformation should lead to relative changes in lithospheric strength at the regional scale. For example, if the thermal structuring of the crust during low-Pe_T deformation leads to significant changes in the mechanical properties of the crust, then deformation should be non-localising on time scales appropriate to thermal conductive response of the crust. In the context of the ASO, the distribution of syn-orogenic sediments (Fig. 6) suggests that the major locus of deformation shifted away from the north-eastern Arunta Inlier to the Redbank Shear Zone in the early Devonian and then, in the late Devonian, from the Redbank Shear Zone to similarly oriented structures some 80–100 km into the interior of the orogen along the northern edge of the Ngalia Basin [8,18,19]. Importantly, the late Devonian shift from the Redbank Shear Zone occurred in spite of the presence of a crustal-scale discontinuity, favourably oriented to localise further deformation, suggesting a local change in strength sufficient to override the localising effect of a profound crustal anisotropy. The apparent change in the locus of deformation during the development of the ASO supports the notion that the extraordinary gravity anomalies of Central Australia provide an important signal of the extreme temperature sensitivity of lithospheric rheology, and its role in the progressive strengthening of low-Pe_T orogens.

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