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Intraplate deformation in central Australia, the link between subsidence and fault reactivation

Martin Hand *, Mike Sandiford

Department of Geology and Geophysics, University of Adelaide, Adelaide SA, 5005, Australia

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Abstract

Central Australia has experienced two intraplate orogenic events involving significant north–south shortening: the late Neoproterozoic to Early Cambrian Petermann Orogeny and the Devonian to Carboniferous Alice Springs Orogeny. In each event pre-existing structures inherited from Mesoproterozoic terrain amalgamation were reactivated and basement rocks exhumed from beneath thick sedimentary successions accumulated in the Centralian Superbasin. The pattern of fault reactivation during these events shows a striking similarity to the pattern of subsidence in the overlying basin. Immediately prior to the Petermann Orogeny, the Centralian Superbasin was thickest in the vicinity of the Musgrave Block, the region in which deformation was subsequently localised. At the same time crustal-scale faults elsewhere in central Australia that were covered by a relatively thin sheet of sediment remained inactive despite being favourably oriented to accommodate the north–south shortening. Between the Petermann and Alice Springs Orogenies, subsidence patterns shifted, such that fault systems in the Arunta Block and also those in the southern Musgrave Block were buried by significant thicknesses of sediment, whereas the major structures that were exhumed during the Petermann Orogeny were not significantly buried. During the Alice Springs Orogeny reactivation once again occurred along the most deeply buried faults, even in the instances where those faults had remained inactive during the earlier Petermann Orogeny. Importantly the major Petermann-aged structures that were not buried during renewed subsidence remained inactive during the Alice Springs Orogeny. The record of reactivation implies that the presence of pre-existing crustal-scale faults alone was insufficient to localise deformation. Rather, fault reactivation appears to have required a priming process that modulated the strength of the lithosphere on a regional scale. The correspondence between the distribution of basement fault reactivation and subsidence patterns during both the Petermann and Alice Springs Orogenies implies a link between relatively thick sedimentation and long-term lithospheric weakening. We show that this link is compatible with the thermal effects of a thick sedimentary blanket. In the context of central Australia the mechanical impact of basin formation is likely to be enhanced by the presence of regionally elevated heat production in the Proterozoic basement. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: basement reactivation; intraplate deformation; sedimentation; central Australia

* Corresponding author. Tel.: +61 8 303 58841; Fax: +61 8 303 43447; E-mail: mhand@geology.adelaide.edu.au

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1. Introduction

The factors that control the distribution of intraplate deformation have been the subject of considerable discussion, with many workers articulating the view that intraplate deformation is localised by virtue of suitably oriented structural weaknesses such as faults (e.g. Cooper and Williams, 1989; Daly et al., 1989; Zielger et al., 1995; Thomas and Coward, 1995; Holdsworth et al., 1997). The notion that faults cause long-term lithospheric weakening is supported by the observation that many continental interior faults have experienced numerous episodes of reactivation during their history (e.g. Good and De Wit, 1997; Pinheiro and Holdsworth, 1997; Imber et al., 1997). A large number of studies have shown that faults may cause long-term weakening as a consequence of (1) grain size reduction within the fault fabrics, (2) creation of fracture networks, and/or (3) reaction softening associated with hydration (see reviews by White et al., 1986; Holdsworth et al., 1997). The long-term weakening will be most pronounced where faults cut through the main load-bearing regions of the lithosphere in the upper crust and the upper mantle. In addition to structurally induced weakening, long-term lithospheric weakening may also be promoted by processes such as basin formation that modify the thermal and/or compositional structure of the lithosphere (Sonder and England, 1986; England, 1987; Ord and Hobbs, 1989; Sandiford, 1999).

Although a number of factors promote long-term weakening within fault zones, the actual controls on reactivation are less clear. There are numerous examples where reactivation within a system of roughly parallel faults is highly selective (e.g. Badley et al., 1989; Williams et al., 1989), suggesting that geometry is not always the overriding factor controlling the distribution of reactivation. Selective reactivation may be caused by local effects such as the nature of fault material in a particular fault zone (e.g. Imber et al., 1997), the specific dip of a fault segment (e.g. Hayward and Graham, 1989), thermal weakening associated with magmatism (e.g. D'Lemos et al., 1997) or local fluid overpressuring (Sibson, 1995). Where the pattern of reactivation appears to show systematic variations on a regional scale, or crustal-scale fault systems remain inactive despite a favourable orientation (e.g. Good and De Wit, 1997), the controls on reactivation are likely to be more general. In these cases, reactivation of existing structures should not only be viewed in terms of structural criteria such as geometry, but also, given the importance of temperature on crustal rheology, in terms of the thermal state of the lithosphere at the time of reactivation. The purpose of this paper is to show that the shifting pattern of intraplate deformation in central Australia highlights the importance of regional thermal controls on the distribution of basement reactivation.

Central Australia (Fig. 1) is an excellent place to study the extent to which pre-existing structures control the distribution of intraplate deformation because the region shows a coherent shift in the pattern of fault reactivation associated with two major intraplate compressional events, the late Neoproterozoic to Early Cambrian (570–530 Ma) Petermann Orogeny and the Devonian to Carboniferous (400–300 Ma) Alice Springs Orogeny. Both events involved significant north–south shortening (Forman, 1966; Veevers, 1984; Collins and Teyssier, 1989; Shaw et al., 1991a; Lindsay and Leven, 1996; Camacho et al., 1997; Scrimgeour and Close, 1998), implying that deformation occurred in response to a similarly oriented in-plane regional stress field (Stephenson and Lambeck, 1985; Lambeck, 1986; Shaw et al., 1991a). Within each orogenic belt, crustal-scale faults were reactivated, while similarly oriented structures in the adjoining regions remained inactive. The combined effects of both orogenic events resulted in the emergence of the Musgrave and Arunta Blocks (Fig. 1) from beneath a once continuous Centralian intracratonic basin (the Centralian Superbasin; Walter and Gorter, 1994; Walter et al., 1995) now represented by the Officer, Amadeus, Ngalia and Georgina Basins (Fig. 1). Viewed in this context both events effectively represent extreme examples of basin inversion (Sandiford and Hand, 1998a).

The fact that the locus of deformation shifted with time within a system of essentially parallel crustal-scale faults indicates that the presence of pre-existing structures alone was insufficient to localise deformation. Prior to each orogeny the topography in central Australia appears to have been subdued (Lindsay and Korsch, 1989, 1991; Shaw et al., 1991a; Walter et al., 1995; Walter and Veevers, 1997) suggesting that

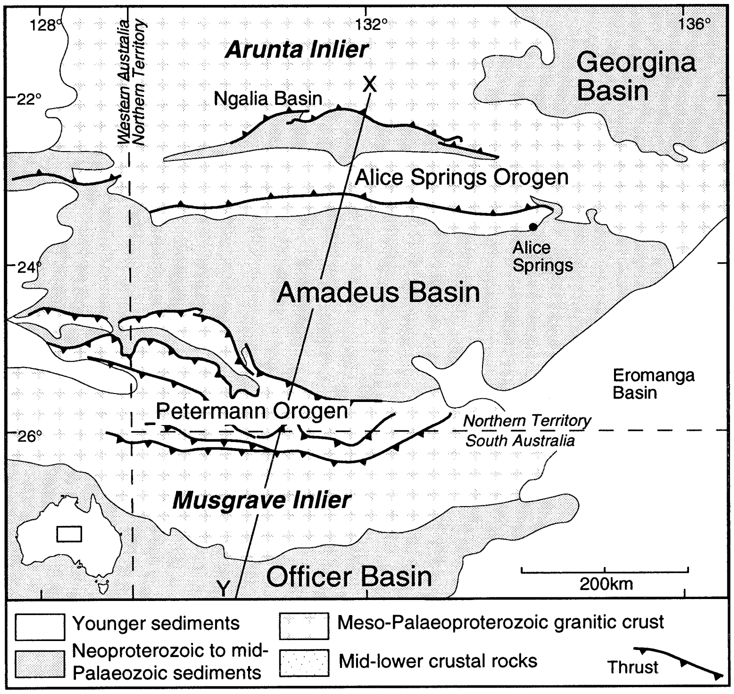


Fig. 1. Map of the central Australian region showing the location of the major crustal blocks and the Neoproterozoic to mid-Palaeozoic sedimentary basins that belonged to the formerly continuous Centralian Superbasin (grey). Thick-skinned deformation during the late Neoproterozoic to Early Cambrian (570–530 Ma) Petermann Orogeny and the mid-Palaeozoic (400–300 Ma) Alice Springs Orogeny resulted in the exhumation of the Musgrave and Arunta Blocks from beneath the sedimentary cover. Section X–Y is shown in Fig. 2.

the change in the locus of deformation is unlikely to reflect regional variations in lithospheric potential energy. In this paper we focus on the relationship between subsidence patterns in the Centralian Superbasin and the distribution of fault reactivation associated with intraplate orogeny. We show that reactivation of existing structures during each event occurred in regions where sediment thicknesses were greatest, implying a link between sediment blanketing and fault reactivation. This work extends that of Sandiford and Hand (1998a) in that it focuses on the interplay between pre-existing structures and the long-term mechanical consequences of basin formation.

2. Crustal structure of central Australia

Central Australia is dominated by two major crustal blocks, the Palaeoproterozoic to Mesoproterozoic Arunta Block and the Mesoproterozoic Musgrave Block which amalgamated sometime in the Mesoproterozoic (by ~1100 Ma; Myers et al., 1994, 1996; Clarke et al., 1995a; Shaw et al., 1996). The blocks separate the intracratonic Officer, Amadeus, Ngalia and Georgina Basins (Fig. 1) which constitute the remnants of the once continuous Centralian Superbasin that covered the entire Central Australian region (e.g. Walter and Gorter, 1994; Walter et al., 1995). In this section we briefly review the deep seismic reflection profiles (Goleby et al., 1988, 1989; Lindsay and Leven, 1996; Korsch et al., 1998) and teleseismic data (Lambeck, 1991; Lambeck and Burgess, 1992) showing that the crustal architecture is dominated by planar north- and south-dipping faults associated with large gradients in the gravity field (Mathur, 1976) (Fig. 2). Although the timing of initiation of these structures varies, there is a general consensus that most of the structures formed during Mesoproterozoic terrain amalgamation (Myers et al., 1994, 1996; Clarke et al., 1995a; Shaw et al., 1996) and therefore pre-date the Petermann and Alice Springs Orogenies. Our discussion focuses on

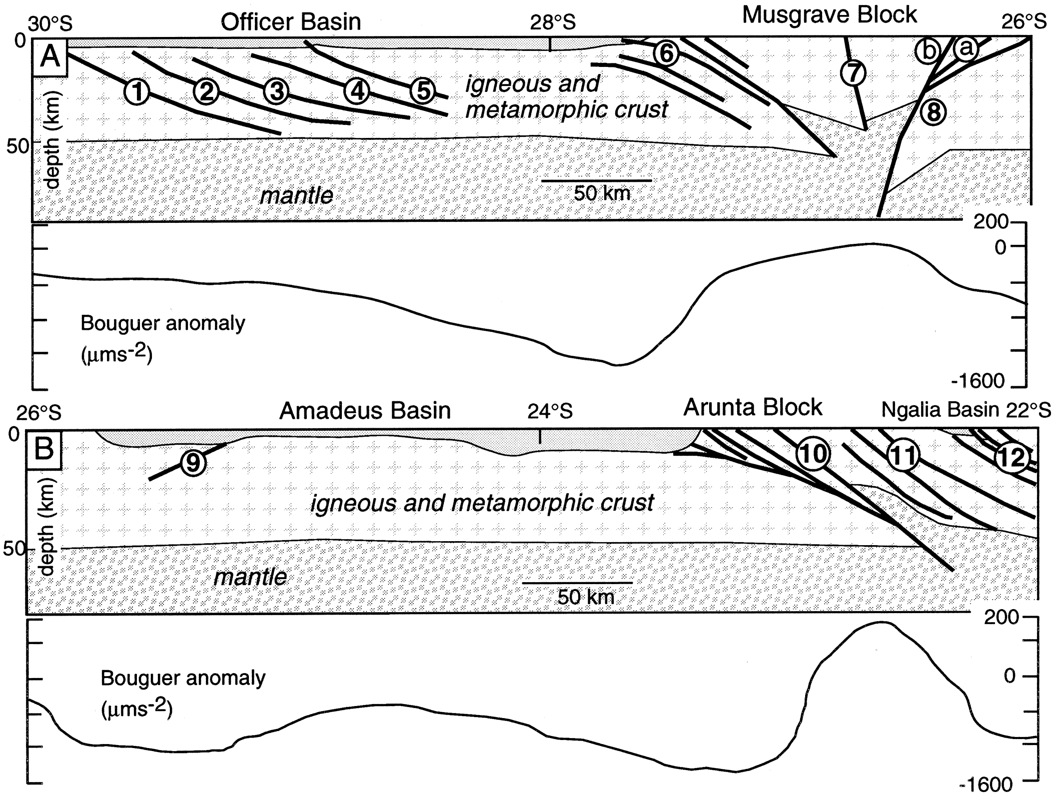


Fig. 2. Transect across the central Australian region showing the location of crustal-scale fault systems thought to have originated during the Mesoproterozoic (after Korsch et al., 1998). Also shown is the Bouguer gravity profile along the transect. Note the large gradients in the gravity field associated with the faults that dissect the Musgrave and Arunta Inliers. (A) Section from the central Officer Basin to the northern edge of the Musgrave Inlier. With one exception (fault *5*), the structures beneath the central Officer Basin do not truncate the Neoproterozoic basal sequences. (B) Section from the southern Amadeus Basin to northern margin of the Ngalia Basin. Faults: *1–5* = unnamed faults beneath the Officer Basin; *6* = Munyarai Thrust; *7* = Hinckley Fault; *8a* = Woodroffe Thrust; *8b* = Mann Fault; *9* = Uluru Fault; *10* = Redbank Shear Zone; *11* = Mt Harris Thrust; *12* = Napperby Thrust.

a region extending from the central Officer Basin in south Australia to the southern Georgina Basin in the Northern Territory (Fig. 1). This region has an area of roughly 600,000 km^2 and constitutes the bulk of the southern central Australian Craton.

2.1. Mesoproterozoic structures

In the southern part of the central Australian craton, seismic refraction data show that the crustal structure consists of a system of north-dipping faults that appear to sole out close to the Moho at a depth of approximately 45 km (Lindsay and Leven, 1996; Korsch et al., 1998). With one exception (see later) the faults terminate against the mid-Neoproterozoic basal sequences of the Officer Basin (Fig. 2A), indicating that they formed prior to basin inception at ~800 Ma (Lindsay and Leven, 1996) and have not been reactivated since. Along the northern margin of the Officer Basin, seismic reflection (Lindsay and Leven, 1996; Korsch et al., 1998) and teleseismic data (Lambeck and Burgess, 1992) indicate the presence of a planar structure that displaces the Moho by as much as 20 km (Fig. 2A). This fault is known as the Munyarai Thrust (Shaw and Black, 1991) and dips north at between 25 and 40° (Milton and Parker, 1973; Lindsay and Leven, 1996; Korsch et al., 1998). The fault has been interpreted as forming the original Mesoproterozoic suture between the largely Palaeoproterozoic Gawler Craton in southern Australia and the Mesoproterozoic Musgrave Province (Shaw et al., 1996; Korsch et al., 1998), but displaces sediments as young as Devonian (Hoskins and Lemon, 1995; Lindsay and Leven, 1996). The northern Musgrave Block is cut by the Woodroffe–Mann fault system which displaces the Moho with an opposite sense of vergence to the Munyarai Thrust (Fig. 2A). Relatively intense deformation along the Woodroffe–Mann fault system during the Petermann Orogeny (see below) has obscured much of its earlier history. However, the observation that the fault system parallels Mesoproterozoic fabrics in the Musgrave Block (Glickson et al., 1995, 1996; Clarke et al., 1995a,b) suggests that its orientation was controlled by the pre-existing crustal fabric.

In the Arunta Block, to the north of the Amadeus Basin, the crustal structure is dominated by the Redbank Shear Zone; a major north-dipping mylonite system initiated around 1450 Ma (Shaw and Black, 1991). The Redbank Shear Zone offsets the Moho by at least 20 km (Fig. 2B) and is one of a number of parallel faults within the Arunta Inlier, including the Napperby Thrust along the northern margin of the Ngalia Basin (Fig. 2B), that have been imaged to lower crustal depths (Fig. 2B). Beneath the Amadeus Basin between the Arunta and Musgrave Inliers, the only major basement fault is a south-dipping structure beneath the southern Amadeus Basin that parallels the exposed northern edge of the Musgrave Block (Fig. 2B), which we term the Uluru Fault. There is insufficient coverage along the central Australian deep seismic traverse to determine whether the Uluru Fault extends into the lower crust ($>$20 km depth). However, the trace of the structure coincides with the northern boundary of the Musgrave magnetic domain (Wellman, 1991; Shaw et al., 1991b) suggesting that it does indeed represent a significant crustal discontinuity. The fact that the Uluru Fault does not truncate the mid-Neoproterozoic basal sequences of the Amadeus Basin (Korsch et al., 1998) indicates that it pre-dates the Petermann and Alice Springs Orogenies and did not undergo significant reactivation during either event.

2.2. Structural reactivation during the Petermann Orogeny

The Petermann Orogeny was a major intraplate orogeny that resulted in the exhumation of the Musgrave Block from beneath the Centralian Superbasin (Forman, 1966; Walter and Gorter, 1994; Walter et al., 1995; Clarke et al., 1995b; Camacho et al., 1997; Close et al., 1998; Scrimgeour and Close, 1998; Fig. 3A). One important consequence of the Petermann Orogeny was that the Centralian Superbasin was fragmented into a southern portion, represented by the Officer Basin, and a northern segment represented by the Amadeus, Georgina and Ngalia Basins (Walter and Gorter, 1994; Walter et al., 1995). Sedimentological and thermochronologic data indicate that shortening began around 570 Ma and continued until about 530 Ma (Maboko et al., 1992; Walter and Gorter, 1994; Walter et al., 1995; Hoskins and Lemon, 1995; Lindsay and Leven, 1996; Camacho et al., 1997). Deformation during the Petermann Orogeny was centred on the northern part of the Musgrave Block in the vicinity of the Woodroffe–Mann fault system. The Woodroffe Thrust is a south-dipping mylonite zone up to 3 km thick (Edgoose et al., 1993; Stewart, 1995; Camacho et al., 1995) which offsets the Moho by $\sim$20 km and is associated with a prominent gradient in the gravity field (Fig. 2). The principal Petermann-aged structures trend roughly east–west (Fig. 3), and as noted previously, are sub-parallel to Mesoproterozoic fabrics (Glickson et al., 1995, 1996; Clarke et al., 1995b). In addition, they locally show a strong spatial association with mafic dykes of c. 800 Ma (Zhao et al., 1994; Camacho et al., 1997) indicating the importance of pre-existing structures on strain localisation during the Petermann Orogeny. A foreland depression containing late Neoproterozoic clastics shed from the Musgrave Block (Preiss and Krieg, 1992; Moussavi-Harami and Gravestock, 1995; Lindsay and Leven, 1996) is located along the northern margin of the Officer Basin, implying that the Munyarai Thrust was reactivated during the Petermann Orogeny (e.g. Drexel et al., 1993; Hoskins and Lemon, 1995; Lindsay and Leven, 1996).

As yet there are no definitive estimates of the amount of crustal shortening during the Petermann Orogeny. The Woodroffe Thrust dips at $\sim$30° and the presence of $\sim$12-kbar structures in the hanging wall (Camacho et al., 1997; Scrimgeour and Close, 1998) implies $\sim$60 km shortening across this structure alone. Given the presence of other major mylonite zones, it appears that total crustal shortening within the Musgrave Block during the Petermann Orogeny was significant (= 100 km; Close et al., 1998). The shortening appears to be restricted to a relatively narrow E–W-trending domain, to the extent that in the Amadeus Basin, pre-existing Mesoproterozoic basement structures within the foreland such as the Uluru Fault (Fig. 2) underwent little or no reactivation. Similarly south of the orogen, all but the most northerly of the crustal-scale faults beneath the Officer Basin remained inactive (Fig. 4).

2.3. Structural reactivation during the Alice Springs Orogeny

The Alice Springs Orogeny was initiated some time around 400–390 Ma (Veevers, 1984; Lindsay and Korsch, 1989; Shaw et al., 1991a) and was marked by the deposition of Early Devonian syn-orogenic sediments marginal to the rising basement regions. The growing topography separated the formerly continuous Amadeus, Ngalia, Georgina and Wiso Basins (Fig. 3B; Walley et al., 1991) into the presently preserved system of isolated, structurally remnant basins. Although shortening associated with the Alice Springs Orogeny was widespread, there are two major regions affected by significant basement involved deformation (Fig. 3B). The most important in terms of both the magnitude of deformation and current level of understanding is in the Arunta Inlier. The second, comparatively poorly known, region occurs along the northern margin of the Officer Basin (Hoskins and Lemon, 1995; Lindsay and Leven, 1996; Morton and Drexel, 1997).

In the Arunta Block, the major structural feature reactivated during the Alice Springs Orogeny is the Redbank Shear Zone (Fig. 3B) which dips north at ∼45° and offsets the upper mantle by ∼20 km (Goleby et al., 1989; Korsch et al., 1998) producing a major gravity anomaly (Fig. 2B). The Redbank Shear Zone consists of an amphibolite to greenschist facies mylonite zone up to 8 km wide (Shaw and Black, 1991; Warren and Shaw, 1995). It forms one of a number of reactivated faults that define an anastomosing network within the Arunta Inlier that accommodated at least 80 km of shortening during the Alice Springs Orogeny (Collins and Teyssier, 1989; Shaw and Black, 1991; Lambeck, 1991; Shaw et al., 1992; Korsch et al., 1998). Early to Middle Devonian syn-orogenic sediments in the northern Amadeus Basin immediately south of the Redbank Shear Zone contain clasts of the underlying sequences including basement (Jones, 1972, 1991) indicating that movement on the Redbank Shear Zone was initiated around 400–390 Ma (see also Shaw and Black, 1991). In the central part of the Arunta Inlier, the Napperby Thrust carries a major basement wedge composed mainly of granite over sediments in the northern Ngalia Basin (Wells and Moss, 1983). The Napperby Thrust was initiated during the Late Devonian to Early Carboniferous (Wells and Moss, 1983), some 40–50 Ma after reactivation began along the Redbank Shear Zone. It accommodated at least 20 km of shortening along an ∼30°-dipping thrust surface (Wells and Moss, 1983; Bradshaw and Evans, 1988). Along the northern and northeastern margins of the Arunta Block, basement has been thrust northward over Neoproterozoic and early Palaeozoic cover sequences belonging to the Georgina and Wiso Basins (Fig. 3B). In places these faults bound deep narrow rifts in the southern Georgina Basin (Fig. 5) locally containing up to 8 km of Neoproterozoic sediment (Harrison, 1979, 1980; Tucker et al., 1979). The suggestion, yet to be confirmed by detailed field studies, is that these thrusts reactivate earlier formed structures that exerted a fundamental control during initiation of the Centralian Basin.

In the northern Officer Basin, the Alice Springs Orogeny caused reactivation of the Munyarai Thrust which had also undergone reactivation during the Petermann Orogeny (Hoskins and Lemon, 1995; Lindsay and Leven, 1996) (Fig. 3B). Shortening resulted in southward thrusting of basement rocks belonging to the Musgrave Block across the northern margin of the basin.

2.4. Summary

The discussion presented above provides an intriguing insight into the temporal and spatial patterns in deformation during the Petermann and Alice Springs Orogenies. During the Petermann Orogeny deformation was mainly confined to the northern part of the Musgrave Block where the major structure was the south-dipping Woodroffe Thrust (Fig. 4A). Importantly, less than 80 km to the north near the central arch of the Amadeus Basin, the Uluru Fault did not undergo reactivation. Further north, the Red-

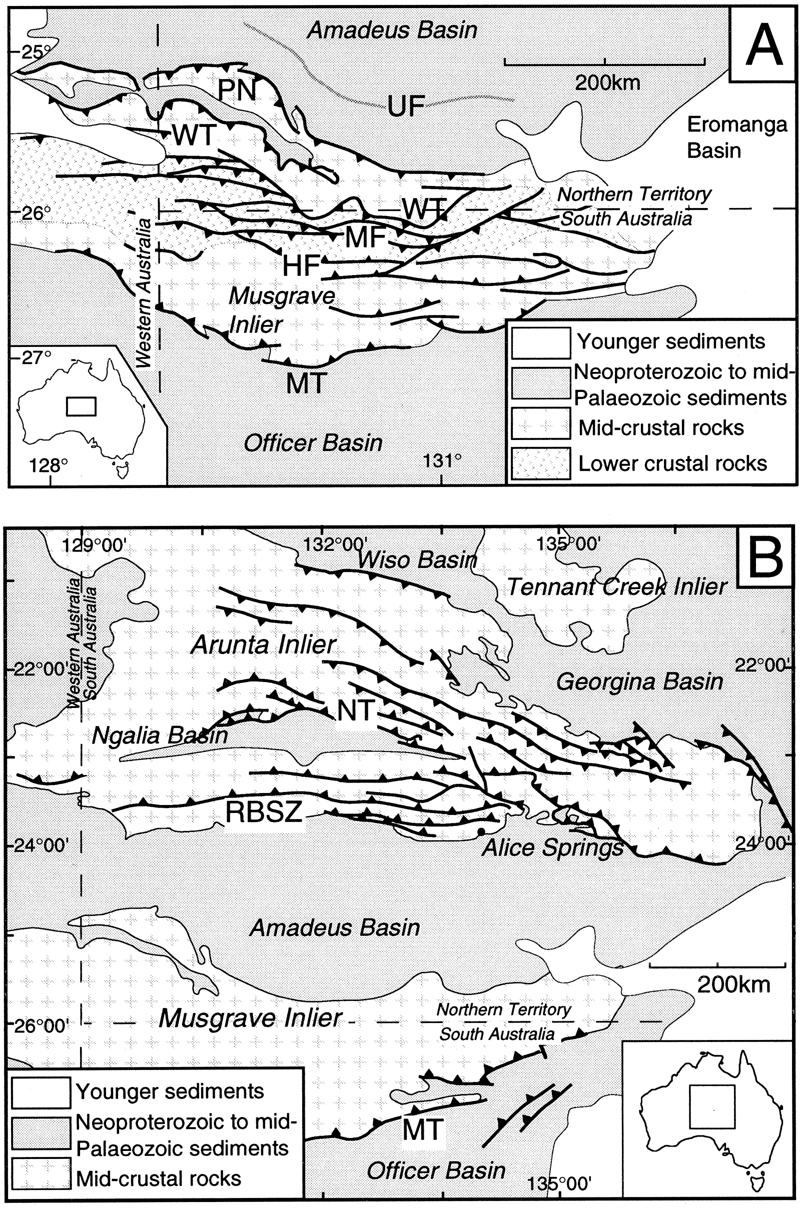


Fig. 3. Distribution of basement-involved deformation during the Petermann Orogeny (A), and the Alice Springs Orogeny (B). Deformation during the Petermann Orogeny was focused in the northern part of the Musgrave Block and resulted in exhumation from depths of >40 km (Camacho et al., 1997; Scrimgeour and Close, 1998) along crustal-scale thrusts. Note that the Uluru Fault (*UF*) beneath the Amadeus Basin immediately north of the Petermann Orogen did not accommodate significant deformation. As with the Petermann Orogeny, deformation during the Alice Springs Orogeny was both north and south vergent. Note that faults in the northern Musgrave Block such as the Woodroffe Thrust which accommodated significant north–south shortening during the Petermann Orogeny remained inactive during the Alice Springs Orogeny (see text for further discussion). Faults: *MT* = Munyarai Thrust; *HF* = Hinckley Fault; *MF* = Mann Fault; *WT* = Woodroffe Thrust; *UF* = Uluru Fault; *RBSZ* = Redbank Shear Zone; *NT* = Napperby Thrust.

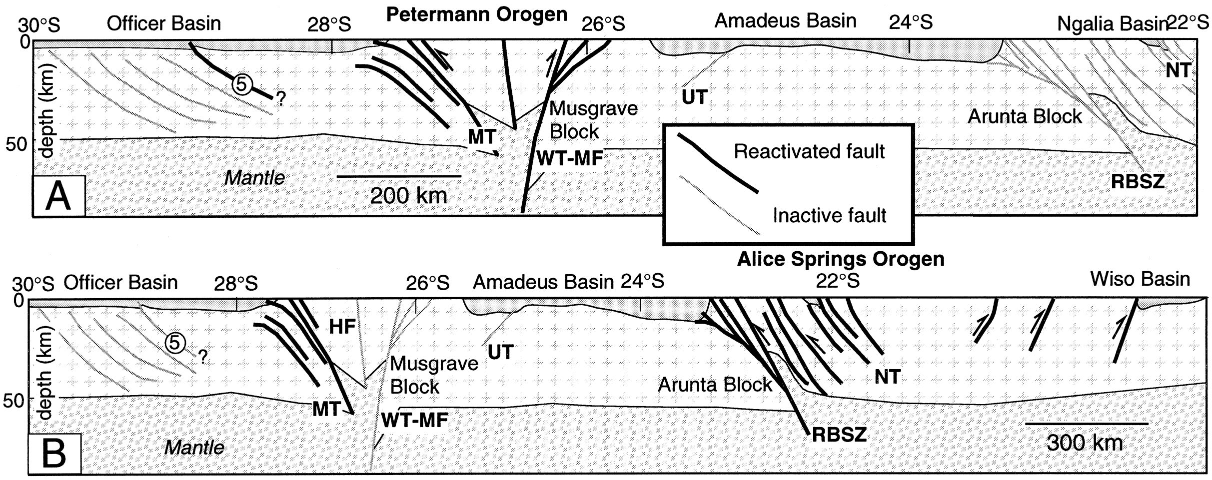


Fig. 4. Crustal transect (after Korsch et al., 1998) showing the locus of reactivation during the Petermann and Alice Springs Orogenies (section line as for Fig. 2). (A) Reactivation during the Petermann Orogeny occurred along both north- and south-dipping structures within the Musgrave Block. However, similarly oriented structures in the Arunta Block (including the Redbank Shear Zone) and faults beneath the Amadeus and Officer Basins were not reactivated. The one exception is fault *5*, which cuts Neoproterozoic sequences in the Officer Basin, but does not cut Cambrian sequences (Korsch et al., 1998). (B) Distribution of reactivation during the Alice Springs Orogeny. Deformation was most strongly concentrated along the northern margin of the Amadeus Basin. The major Petermann-aged structures in the northern Musgrave Block did not undergo reactivation despite a favourable orientation. In contrast, deformation occurred along other Petermann structures such as the Munyarai Thrust along the northern margin of the Officer Basin. Reactivation may have extended as far south as fault *5* (Korsch et al., 1998). See Fig. 3 for fault abbreviations.

bank Shear Zone also remained inactive despite having an orientation clearly conducive to north–south shortening (as evidenced by its behaviour during the Alice Springs Orogeny). To the south of the Mann Fault, only those faults close to the present margin of the Officer Basin, and within the southern Musgrave Block underwent reactivation (Fig. 4A), while the majority of the Mesoproterozoic structures beneath the Officer Basin remained inactive.

During the Alice Springs Orogeny the Mesoproterozoic Redbank Shear Zone and associated structures in the Arunta Block (Fig. 4B) accommodated significant north–south shortening. Reactivation occurred along both north- and south-dipping structures as indicated by the bi-vergent exhumation of the Arunta Block (Fig. 3B and Fig. 4B). However, the Woodroffe Thrust and associated structures in the northern Musgrave Block did not undergo reactivation during the Alice Springs Orogeny, despite having accommodated significant north–south shortening some 150 Ma earlier. In contrast, the Munyarai Thrust was reactivated again during the Alice Springs Orogeny, but most other structures beneath the Officer Basin remained inactive. These observations regarding the shifting locus of reactivation on a regional scale during successive north–south-shortening events raise important questions regarding the factors that influenced the response of various fault systems in central Australia during the Petermann and Alice Springs Orogenies.

3. Subsidence patterns in the Centralian Superbasin

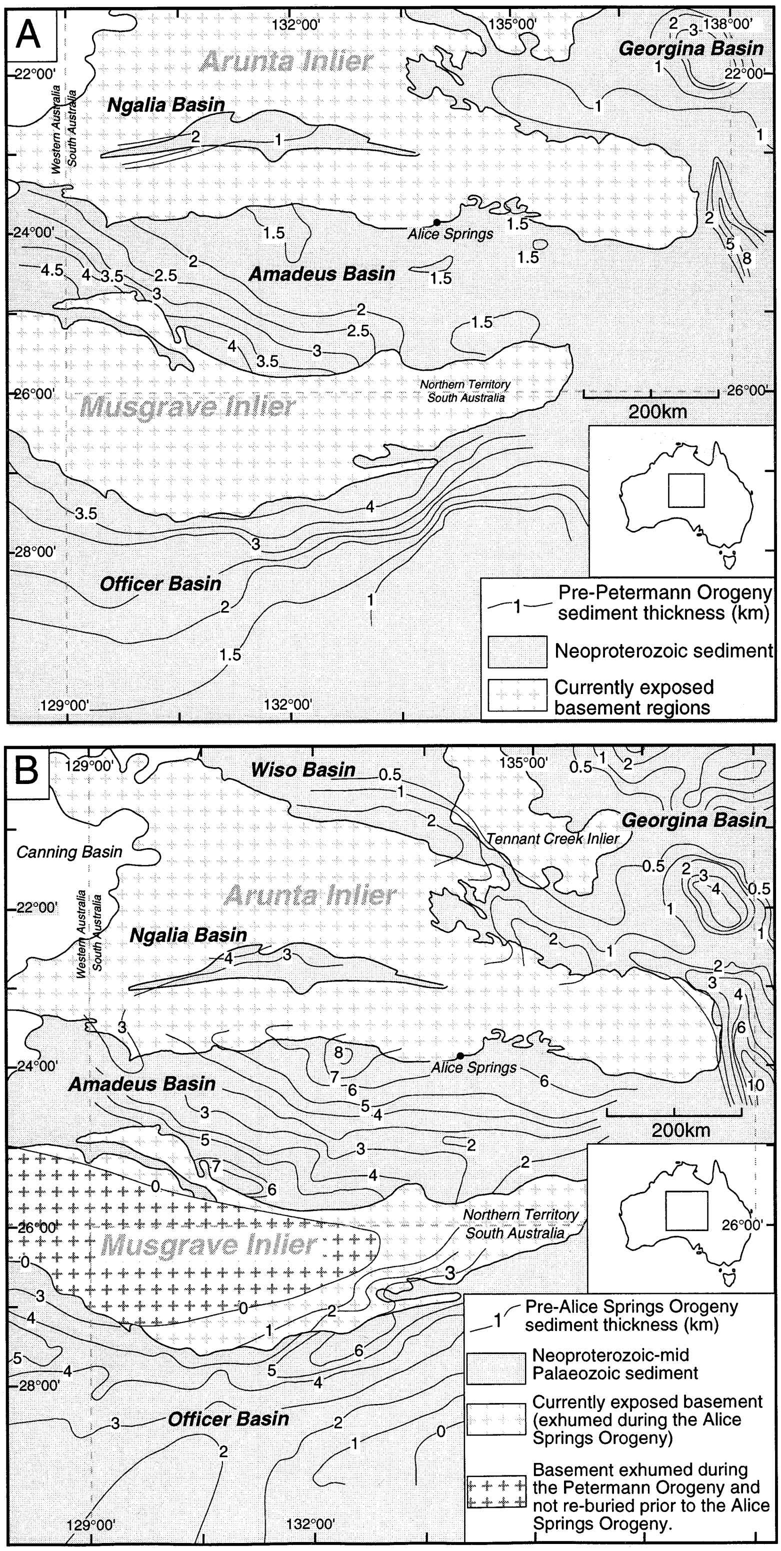
A number of workers have recognised that intraplate deformation in central Australia must be seen in the broader context of the development of the Centralian Superbasin (e.g. Lambeck, 1986; Shaw et al., 1991a; Sandiford and Hand, 1998a). In particular Sandiford and Hand (1998a) have suggested that the subsidence patterns in the Amadeus Basin may have exerted a first-order control on the distribution of intraplate deformation around the basin margins. In this section we briefly review the patterns of subsidence in the broader context of the Centralian Superbasin as a precursor to discussing factors that may have affected the pattern of basement reactivation associated with the Petermann and Alice Springs Orogenies.

The Centralian Superbasin was initiated around 800 Ma as a broad intracratonic sag that covered central Australia (Korsch and Lindsay, 1989; Lindsay and Korsch, 1989, 1991; Shaw et al., 1991a; Walter and Gorter, 1994; Walter et al., 1995; Lindsay and Leven, 1996). The presently preserved basins (Officer, Amadeus, Ngalia and Georgina) are structural remnants and effectively those parts of the basin that underwent little or no basement involved deformation during the Petermann and Alice Springs Orogenies. Regional variations in subsidence within the Centralian Superbasin produced significant thickness variations across the basin (Fig. 5). Prior to the Petermann Orogeny, sediment thickness increased toward the presently exposed Musgrave Inlier (Fig. 5A). Facies data and stratigraphic correlations indicate that the Officer and Amadeus Basins were connected by a continuous sedimentary blanket prior to the Petermann Orogeny (e.g. Walter and Gorter, 1994; Walter et al., 1995; Lindsay and Leven, 1996) with a regional depocenter located in the area now occupied by the exhumed Musgrave Block (Fig. 5A). Immediately prior to the Petermann Orogeny sediment thicknesses in the northern Officer and southwestern Amadeus Basin were in excess of 4 km (Fig. 5A). At the same time, the basin thinned across a broad arch in the central Amadeus Basin to generally less than 2 km, with localised grabens in the southern Georgina Basin approximately 40 km wide containing up to about 8 km of sediment. The dominantly shallow marine nature of the Centralian Superbasin prior to the Petermann Orogeny implies that the entire central Australian craton was characterised by subdued topography (Wells et al., 1970; Lindsay and Korsch, 1989; Shaw et al., 1991a; Walter et al., 1995; Lindsay and Leven, 1996; Walter and Veevers, 1997).

Subsequent to the Petermann Orogeny, the axis of principal deposition shifted northwards such that by the time of the Alice Springs Orogeny, the main depocenter was located along, or beyond, the present-day northern margin of the Amadeus Basin (Fig. 5B). During this interval sedimentation in the Georgina Basin contracted southward (Smith, 1972; Shergold and Druce, 1980) suggesting that a regional depocenter was located between the Georgina Basin and Amadeus Basins (Fig. 5B). The western extension of this depocenter occupied a trough between the Amadeus and Ngalia Basins that contained in excess of 7 km of sediment. In the northern Officer Basin, another depocenter accumulated up to 6 km of sediment prior to the Alice Springs Orogeny. Progressive northward expansion of deposition in the Officer Basin during the Late Cambrian (Moussavi-Harami and Gravestock, 1995; Lindsay and Leven, 1996) indicates that topography associated with the Petermann Orogeny had been largely removed. This notion is also supported by the progressive southward onlap of Early Ordovician siliciclastics in the Amadeus Basin onto the northern margin of the Musgrave Inlier (Wells et al., 1970; Lindsay and Korsch, 1991; Shaw et al., 1991a).

The underlying causes controlling the distribution of the Neoproterozoic depocenters in the Centralian Superbasin are not well understood. There is a general consensus that extension (albeit limited) played a role during the Neoproterozoic (Lindsay and Korsch, 1989, 1991; Shaw et al., 1991a; Lindsay and Leven, 1996). This is consistent with the approximate parallelism of mafic dykes of c. 800 Ma in the Musgrave Inlier and the axis of principal deposition in the southern Amadeus Basin (Zhao et al., 1994), as well as localised deep grabens in the southern Georgina Basin. Importantly, any active rifting and magmatism ceased approximately 200 Ma before the onset of the Petermann Orogeny, indicating that the elevated mantle heat flow would have decayed well before deformation began. The regional controls on subsidence between the Amadeus and Georgina Basins, and also along the northeastern margin of the Officer Basin following the Petermann Orogeny, are less clear. Some workers have argued that subsidence in the northern Amadeus Basin reflects north–south extension coeval with the Petermann Orogeny (Lindsay and Korsch, 1989, 1991; Shaw et al., 1991a). However the evidence of this in the sedimentary record is equivocal (Lindsay and Korsch, 1991; Shaw et al., 1991a). By the Late Cambrian ($\sim$500 Ma) there is good evidence for significant extension located between the Amadeus and Georgina Basins (Hand, 1998), leaving the question of the subsidence mechanism for the $\sim$2.5 km of section deposited in the interval 570–500 Ma (Lindsay, 1993) in the northern Amadeus Basin still unresolved.

Fig. 6A shows the spatial relationship between


A
Arunta Inlier
Ngalia Basin
Georgina Basin
Western Australia
South Australia
Alice Springs
Amadeus Basin
Northern Territory
South Australia
Musgrave Inlier
Officer Basin
200km
132°00'
135°00'
138°00'
22°00'
24°00'
26°00'
28°00'
129°00'
Pre-Petermann Orogeny sediment thickness (km)
Neoproterozoic sediment
Currently exposed basement regions
B
Wiso Basin
Georgina Basin
Tennant Creek Inlier
Canning Basin
Arunta Inlier
Ngalia Basin
Western Australia
South Australia
Alice Springs
Amadeus Basin
Northern Territory
South Australia
Musgrave Inlier
Officer Basin
200km
129°00'
132°00'
135°00'
22°00'
24°00'
26°00'
28°00'
Pre-Alice Springs Orogeny sediment thickness (km)
Neoproterozoic-mid Palaeozoic sediment
Currently exposed basement (exhumed during the Alice Springs Orogeny)
Basement exhumed during the Petermann Orogeny and not re-buried prior to the Alice Springs Orogeny.

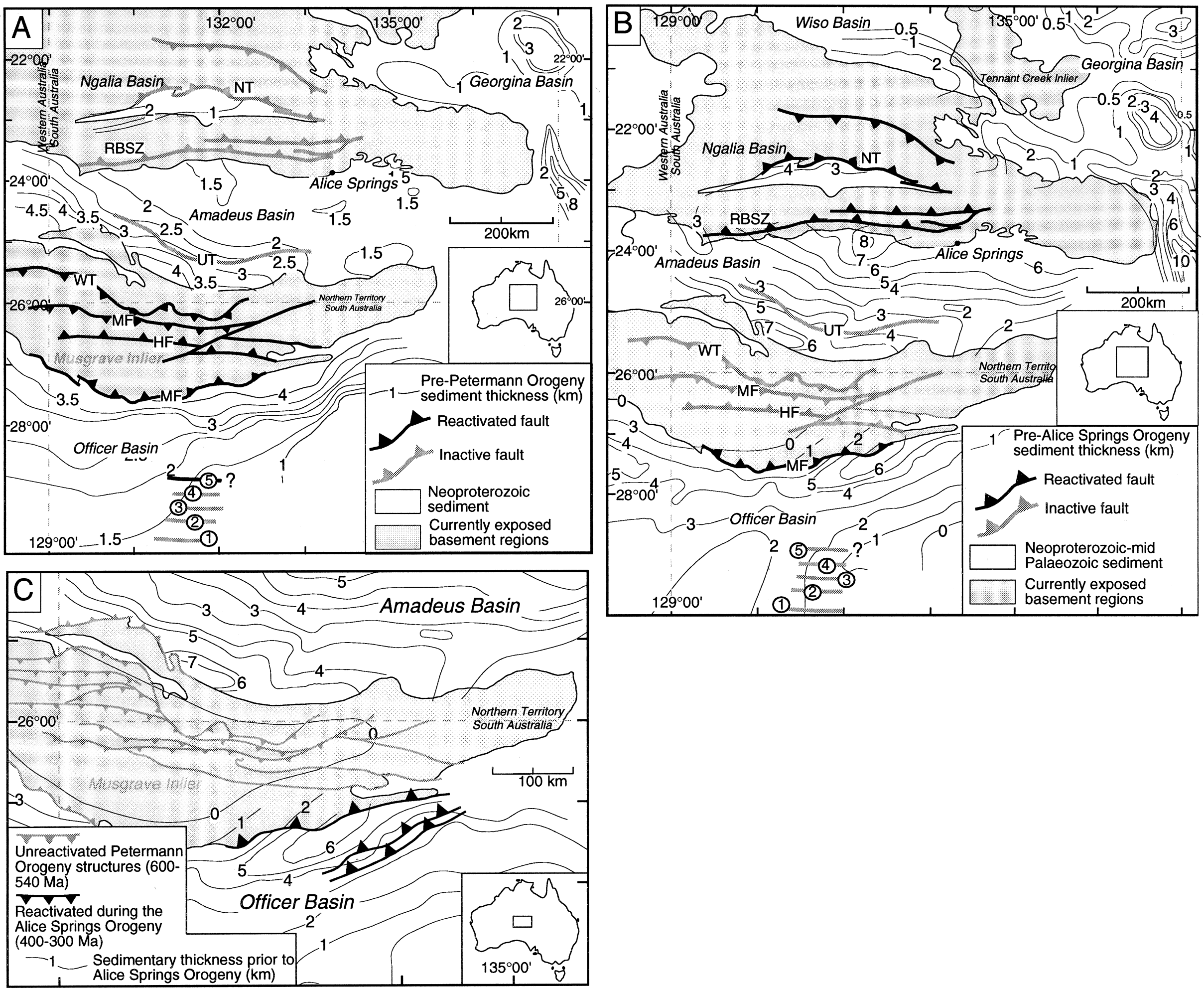


Fig. 6. Spatial relationships between subsidence in the Centralian Superbasin and the locus of reactivation during the Petermann Orogeny (A) and the Alice Springs Orogeny (B and C). Faults abbreviations as for Figs. 2 and 3.

subsidence immediately prior to the Petermann Orogeny and crustal structure associated with the orogeny. It is clear that the locus of reactivation during the Petermann Orogeny coincided with a major depocenter within the Centralian Superbasin. The isopach data show that fault systems that remained inactive during the Petermann Orogeny were covered by much thinner sequences. For example the Redbank Shear Zone in the Arunta Block was probably buried to less than 2 km during the Petermann Orogeny. Similarly the Uluru Fault beneath the southern Amadeus Basin was covered by significantly less sediment than active faults further south within the Musgrave Block. In the central Officer

Fig. 5. Generalised isopach maps for sequences in the Centralian Superbasin prior to the Petermann Orogeny (A) and the Alice Springs Orogeny (B). The discontinuities in sediment thickness around the edges of the Musgrave Inlier in (B) result from the denudation associated with the Petermann Orogeny, and subsequent re-burial prior to the Alice Springs Orogeny. Data for isopachs from Wells et al. (1970); Smith (1972); Tucker et al. (1979); Harrison (1979, 1980); Kennewell and Huleatt (1980); Wells and Moss (1983); Lindsay (1987); Oaks et al. (1991); Wellman (1991); Lindsay (1993); Walter and Gorter (1994); Deckelman and Davidson (1994); Wakelin-King (1994); Moussavi-Harami and Gravestock (1995), Lindsay and Leven (1996); Morton and Drexel (1997).

Basin, the system of north-dipping faults that do not cut the basin sequences were overlain by less than 2 km of Neoproterozoic sediment. A similar pattern emerges immediately prior to the Alice Springs Orogeny (Fig. 6B). In the Arunta Block the reactivated Redbank Shear Zone was located within a depocenter that contained up to 7 km of sediment. Similarly, along the northern edge of the Ngalia Basin the Napperby Thrust and associated structures truncate an east–west-trending depocenter that contained at least 4 km of sediment. Along the northern margin of the Arunta Block, depocenters in the southern Wiso and southwestern Georgina Basins have been truncated by exhumation of the Arunta Block (Fig. 3B and Fig. 5B).

In the Musgrave Block the influence of subsidence patterns on the distribution of deformation during the Alice Springs Orogeny is highlighted by the record of reactivation of major faults that accommodated north–south shortening during the Petermann Orogeny (Fig. 6C). Along the northern margin of the Officer Basin, the Petermann Orogeny was associated with the reactivation of crustal-scale thrusts (Fig. 4A) that exhumed the Musgrave Block (Walter et al., 1995; Hoskins and Lemon, 1995; Lindsay and Leven, 1996). However, subsidence during the Cambrian and Ordovician resulted in burial of the southeastern margin of the Musgrave Block and the northeastern Officer Basin by up to 2 km of early Palaeozoic sediment (Moussavi-Harami and Gravestock, 1995). Although the orientation of Petermann-aged structures within (and bounding) the Musgrave Block were conducive to north–south shortening (as evidenced by their behaviour during the Petermann Orogeny), reactivation during the Alice Springs Orogeny only occurred in the vicinity of the southeastern margin of the Musgrave Inlier, along thrusts that had been buried by a significant thickness of sediment leading up to the Alice Springs Orogeny (Fig. 6C).

The relationship between fault reactivation and subsidence is also highlighted by the behaviour of faults beneath the Officer Basin. In the central Officer Basin seismic reflection data (Lindsay and Leven, 1996; Korsch et al., 1998) show that with one exception the north-dipping faults beneath the basin were not reactivated during either the Petermann or Alice Springs Orogeny (Fig. 4). The one exception comes from the northern end of the seismic line where an increase in sediment thickness reflects the general northward deepening of the basin. The spatial association between basement reactivation during both the Petermann and Alice Springs Orogenies and subsidence patterns in the Centralian Superbasin suggests that the development of sub-basins acted as a primary trigger for strain localisation during subsequent intraplate orogeny.

4. Thermal and mechanical consequences of basin formation in central Australia

Basin formation results in changes in the distribution of heat production and the thermal conductivity structure of the crust as well as the depth to rheologically important compositional boundaries within the lithosphere. Consequently, basin formation is likely to impact on the long-term mechanical stability of the lithosphere (e.g. Karner, 1991; Watts, 1992; Sandiford, 1999). The long-term mechanical consequences of basin formation are likely to be sensitive not only to the nature and thickness of the basin-fill, but also to the basin forming mechanism. Basins formed in the absence of pervasive lithospheric strain will always lead to long-term strength reductions, because they necessarily lead to long-term increases in Moho temperatures. In contrast, extensional basin formation may lead to either long-term strengthening or weakening (e.g. Karner, 1991; van Wees and Stephenson, 1995; Zielger et al., 1995; Sandiford, 1999). The majority of previous studies have concluded that extensional basin formation will lead to long-term lithospheric strengthening as the post-extensional lithosphere cools. However, Sandiford (1999) has shown that under some circumstances extensional basin formation may lead to long-term lithospheric weakening, engendering the possibility that subsequent deformation will be localised beneath the previously formed basin. Such weakening is favoured if the total crustal heat production prior to basin formation exceeds $\sim$30 mW m^{-2} and is concentrated in the upper part of the crust, and the total amount of extension is low. In addition, the character of the basin fill also profoundly affects the potential for weakening. Significant long-term weakening is favoured if the fill is relatively dense, or has elevated heat production or low thermal conductivity. Depending on the interplay between these factors, long-term weakening can be as much as 5% per km of rift-fill, when normalised against the strength of the pre-rift lithosphere (Sandiford, 1999). In this section we briefly outline the factors that suggest that the character of the central Australian lithosphere is appropriate to long-term weakening following basin formation.

The basement complexes in the Musgrave and Arunta Blocks form part of an extensive Proterozoic province that is characterised by a broad north–south band of elevated heat flow (Cull, 1982) (the Central Shield Province of Sass and Lachenbuch, 1979). In this province, heat flows are typically in the range 60–120 mW m^{-2} and average around 75 mW m^{-2} (Cull, 1982; Houseman et al., 1989). The zone of high heat flow includes the eastern Officer Basin and the Georgina Basin and extends as far east as the Mt Isa Inlier in northwestern Queensland. Bottom hole temperatures from exploration wells in the Amadeus, Georgina and Officer Basins indicate thermal gradients in the range 20–30ºC/km with regions locally as high as 40ºC/km (Gorter, 1984; Somerville et al., 1994; Morton and Drexel, 1997), suggesting the existence of a generally elevated thermal regime throughout central Australia. The presence of thick contemporary mantle lithosphere beneath much of the central Australian heat flow province (Zielhuis and van der Hilst, 1996; van der Hilst et al., 1998) suggests low contemporary mantle heat flows (~10–15 mW m^{-2}) and therefore implies that the crustal contribution to the heat flow is typically about 45 mW m^{-2} and may locally exceed 60 mW m^{-2}. This range in crustal contributions to the surface heat flow contrasts markedly with the commonly held view that the crustal component of the continental heat flow must lie in the range 18–48 mW m^{-2} (e.g. McLennan and Taylor, 1996). However, as discussed below, these high heat flow values are consistent with the presence of extensive high heat production granitic gneisses in the basement to the Centralian Superbasin (Sandiford and Hand, 1998b).

Within the Musgrave and Arunta Blocks the differential denudation during the Petermann and Alice Springs Orogenies (e.g. Scrimgeour and Close, 1998; Mawby et al., 1998) provides an insight into the vertical distribution of heat production in the basement beneath the inverted depocenters. In the Arunta Block the regions of maximum denudation (>20 km) are characterised by low to intermediate (typically less than 1.5 μW m^{-3}) average heat production (Fig. 7). In contrast regions that underwent between 8 and 12 km of denudation such as those adjacent to the existing margins (e.g. Shaw et al., 1992; Dunlap et al., 1995) contain extensive granitic

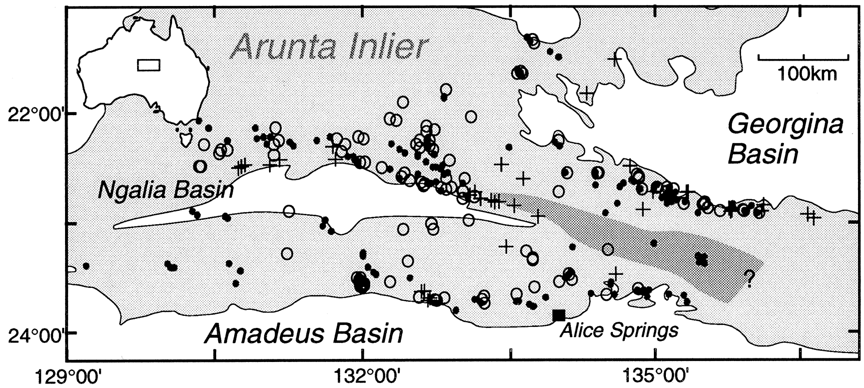


Fig. 7. Distribution of heat production in granitic rocks in the Arunta Inlier. The highest average values are located in granites along the northern margin of the Ngalia and southern edge of the Georgina Basin (average ~6 μW m^{-3}). Open circles show granite with heat production between 5–10 μW m^{-3}, crosses granite with heat production >10 μW m^{-3}. Filled circles represent granite with heat production <5 μW m^{-3}. In general, non-granitic rocks have heat productions <3 μW m^{-3}. The dark shaded area represents >~20 km denudation during the Alice Springs Orogeny. In this region, heat production values are relatively low (= ~2 μW m^{-3}), implying that crustal heat production was concentrated in the mid-upper crust. U–Th–K data from Iyer et al. (1984), Warren (1989), Zhao (1992), McLaren (1996), Hazel et al. (1997) and our own unpublished data.

suites characterised by elevated heat production. For example, along the northern edge of the Ngalia Basin and southern edge of the Georgina Basin, mean heat production in granites is $\sim$6 μW m^{-3}. The values are slightly lower along the northern margin of the Amadeus Basin (around 4 μW m^{-3}), suggesting that significant regional variations in heat production existed at mid and upper crustal levels during the Alice Springs Orogeny. These observations imply that heat production in the Arunta Block was strongly concentrated in the upper 5–10 km of the basement. Similarly in the northern Musgrave Block in the immediate footwall of the Woodroffe Thrust adjacent to the southwestern Amadeus Basin, granitic rocks that were located in the mid-crust during the Petermann Orogeny average 5 μW m^{-3} (I. Scrimgeour, Northern Territory Geological Survey, pers. commun., June 1998) and occupy several thousand km^2 of outcrop (Forman, 1966, 1972; Lewis, 1989). Structural relief within this granitic complex is at least 4 km (Forman, 1972), implying that this body alone could have contributed $\sim$20 mW m^{-2} to the surface heat flow in the northern Musgrave Block. In contrast, south of the Woodroffe Thrust, the exposed lower crustal rocks average less than 2 μW m^{-3} (Hazel et al., 1997; I. Scrimgeour, pers. commun., June 1998), again implying that heat production was strongly stratified.

The basin-fill in the various remnants of the Centralian Superbasin is dominated by sandstones with significant thicknesses of dolomitic carbonates and minor shales. Preliminary studies of the southern Georgina Basin section suggest that the fill is characterised on average by thermal conductivity of about 3.0 W m^{-1} K^{-1}, and an average density of 2650 kg m^{-3} (David Kelsey, pers. commun.). Radiometric survey data indicate abundances of heat producing elements are about half that of the adjacent basement terranes (Young and Shelley, 1977). Following the approach of Sandiford (1999), these values (together with estimates of the basement heat production distribution discussed above) can be used to estimate the long-term thermal and mechanical consequences of basin development as shown in Fig. 8. Fig. 8 shows that, for parameters appropriate to central Australia, basin formation should be expected to lead to significant long-term lithospheric strength reductions. The estimated proportional strength reduction varies between $\sim$3 and $\sim$8% per kilometre of basin-fill depending on the rheological model employed, and the proportion of rift to non-rift related subsidence (see caption of Fig. 8 for further discussion).

5. Discussion

Localised intraplate deformation must reflect either localised reductions in strength in the presence of an in-plane stress or stress amplification due to changes in the density structure at depth (e.g. Jones et al., 1996). Although both the Petermann and Alice Springs Orogeny involved reactivation of existing crustal structures during north–south compression, the different regional distributions of reactivation during each event documented in this paper implies that deformation was not localised solely as a consequence of the interaction between pre-existing structures and an in-plane stress. Rather, the pattern of intraplate deformation in central Australia implies that fault reactivation required a priming process that operated on a regional scale, effectively modulating the strength of the lithosphere at scales greater than $\sim$100 km. The calculations summarised in Fig. 8 (see also Sandiford, 1999, and Sandiford and Hand, 1998a) which indicate that basin formation may result in long-term lithospheric weakening, provide a plausible physical basis for the documented association of reactivated structures with relatively thick sedimentary cover in the Centralian Superbasin during the Petermann and Alice Springs Orogenies. To a large extent, we attribute this weakening to thermal consequences accruing from the burial of an unusually radioactive basement beneath the basin. In this respect, it is worth noting that the mechanical impact of basin formation in central Australia is likely to have been accentuated compared to other regions by this regionally elevated heat production (Sandiford and Hand, 1998a). For more typical heat production values (e.g. McLennan and Taylor, 1996) with associated reductions in prevailing geothermal gradients, we would expect that (1) relatively greater levels of intraplate stress would be required to drive deformation, and (2) basin formation would tend to strengthen, rather than weaken, the lithosphere (Sandiford, 1999).

The long-term weakening resulting from the dif-

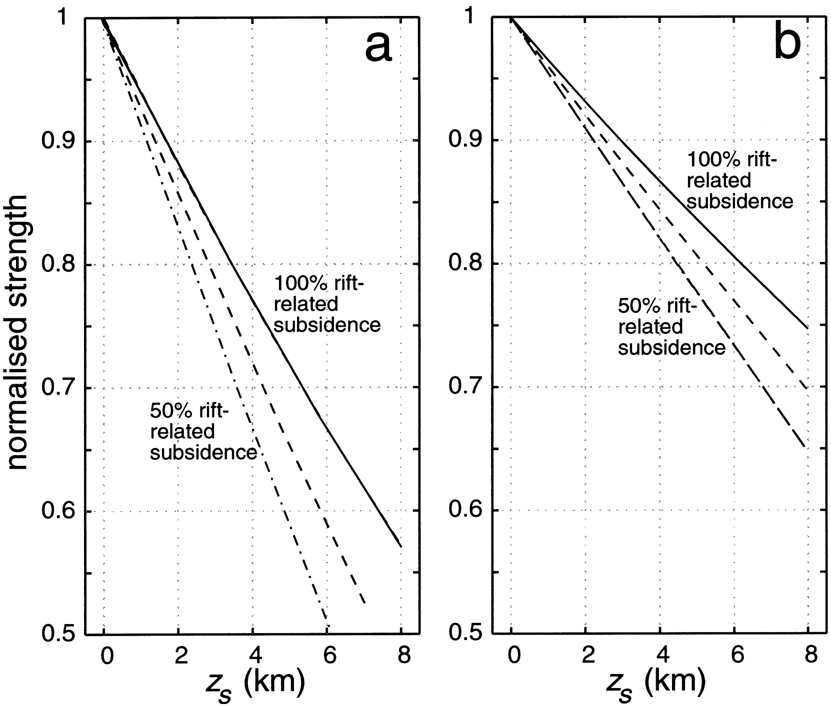


Fig. 8. Estimated long-term mechanical consequences of basin formation relative to the pre-basinal lithosphere for three types of basins that encompass the styles found in central Australia (e.g. see Korsch and Lindsay, 1989; Lindsay and Korsch, 1989, 1991; Shaw et al., 1991a): (1) subsidence (Z_s) is solely the result of rifting followed by thermally driven subsidence (solid line); (2) 75% of subsidence results from rifting and the ensuing sag, with the remaining 25% generated by flexural loading (dashed line); (3) 50% rift-sag related and 50% flexural loading (dot–dash line). (a) Lithospheric configuration consisting of weak crust and weak mantle (see Sandiford, 1999, table 2, for rheological parameter ranges). Note that subsidence due to flexural loading leads to significantly greater long-term weakening compared to rift-related subsidence. (b) Results for a lithospheric configuration consisting of strong crust and strong mantle. Parameters: assumed parameters for the basin fill are based on preliminary estimates for the southern Georgina Basin (David Kelsey, pers. commun., 1998), thermal conductivity of basin and basement = 3 W mK^{-1}, $\rho_{(\mathrm{basin})} = 2650$ kg m^{-3}, $\rho_{(\mathrm{basement})} = 2750$ kg m^{-3}, $\rho_{(\mathrm{mantle\ lithosphere})} = 3350$ kg m^{-3}, heat production in the top 10 km of the basement = 4.5 μW m^{-3}, producing 45 mW m^{-2} of heat flow contribution from the basement which is considered typical for the central Australian heat flow province; heat production in the basin fill = 2.25 μW m^{-3}, pre-rift crustal thickness = 35 km (see Sandiford, 1999 for a complete description of the methodology employed in the calculations).

ferential subsidence (and erosion) in the Centralian Superbasin is highlighted by the structural style of both the Petermann and Alice Springs Orogenies. In both cases, major structures verge both north and south, toward the remnant basins that flank the orogens. This implies that the lithosphere bordering the orogens, which had only a relatively thin sedimentary cover, effectively acted as a 'stress guide' despite being dissected by crustal-scale faults whose orientation was conducive to accommodating north–south shortening (see Fig. 4). The absence of reactivation along the major Petermann structures in the northern Musgrave Block during the Alice Springs Orogeny implies that the lithosphere in that region had become relatively 'strong' by this time. We attribute this strengthening to the deep denudation associated with the Petermann Orogeny which removed the sedimentary cover and the upper crustal high heat producing parts of the basement (Sandiford and Hand, 1998a,b; see also Beekman et al., 1997). The relative strengthening offsets to a large extent the potential weakening caused by the thick wedge of sediment that was located adjacent to the Musgrave Block in the southwestern Amadeus Basin during the Alice Springs Orogeny (Fig. 5) (see Sandiford and Hand, 1998a). The hypothesis that deformation can be localised by relatively thick basins above a radiogenic basement implies that the strength of the lithosphere is very sensitive to the thermal regime (e.g. Neil and Houseman, 1997; Sandiford and Hand, 1998a). Since on the large scale, deformation during both the Alice Springs and Petermann Orogeny was concentrated in relatively narrow mantle-penetrating zones (e.g. Redbank Shear Zone and the Woodroffe Thrust), deformation did not result in widely distributed crustal thickening. Under these circumstances the deformation served primarily to exhume the rocks, with lithospheric cooling and strengthening consequent upon the removal of the basin sediments and the enriched upper parts of the basement. The pattern of fault of reactivation in the Arunta Block during the Alice Springs Orogeny provides some evidence that fault systems may have become progressively 'stronger' as deformation and associated denudation proceeded. Along the southern margin of the Arunta Block, the Redbank Shear Zone was exhumed from beneath as much as 8 km of sediment (see Fig. 4), commencing in the Early Devonian (400–380 Ma; (Lindsay and Korsch, 1989; Shaw et al., 1991a, 1992; Jones, 1991). The presence of basement clasts within early mid-Devonian synorogenic sequences in the northern Amadeus Basin (Jones, 1972) indicates that stripping of the sedimentary overburden accompanied the deformation along the Redbank Zone and associated faults, while thermochronological data indicate that the hanging wall of the Redbank Shear Zone began to cool at 400 Ma (Shaw et al., 1992). Interestingly, as the shortening continued, the locus of deformation did not step toward the foreland as is common in many thrust belts (e.g. Mitra and Fisher, 1992; McClay, 1992), or remained focussed within the active fault system, but apparently shifted some 80 km northward toward the hinterland, in the region of the Napperby Thrust (Figs. 3 and 4). In this region, fault reactivation along the northern edge of the Ngalia Basin began in the Late Devonian to Early Carboniferous ($\sim$350 Ma) (Wells and Moss, 1983; Bradshaw and Evans, 1988), some 50 Ma after reactivation of the Redbank zone, and possibly continued into the Early Permian ($\sim$300 Ma; Bradshaw and Evans, 1988), leading to the inversion of a depocenter in the vicinity of the northern Arunta Block that contained at least 4 km of sediment (Fig. 5B). Thus the pattern of reactivation within a system of parallel faults in the Arunta Block appears to mimic the regional-scale behaviour exhibited during the Petermann and Alice Springs Orogenies. In this respect the shifting patterns of intraplate basement reactivation in central Australia and spatial relationships to subsidence patterns has the potential to yield further insights as to why crustal-scale discontinuities undergo reactivation, and equally interestingly, why reactivation is inhibited on favourably oriented structures with respect to prevailing stress fields.

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