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# Folded basement-cored tectonic wedges along the northern edge of the Amadeus Basin, Central Australia: evaluation of orogenic shortening

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## Abstract

Intracontinental deformation at the northern margin of the Amadeus Basin, Central Australia, is characterised by the presence of basement-cored, downward-facing antiformal synclines. These structures were formed during the Devonian–Carboniferous Alice Springs Orogeny and in the past were explained as erosional relics of fold nappes indicating large horizontal crustal shortening within the Australian continent. This notion is in stark contrast with both the uncomplicated homoclinal structure that contains the 'nappes' and with seismic data suggestive of a simple crustal structure formed during only modest intraplate shortening. Balanced and sequentially restored sections across the Razorback 'nappe' and its vicinity show that such downward-facing synformal anticlines can be produced by emplacement of a basement cored tectonic wedge along shortcut thrusts in the footwall of a crustal-scale (Redbank) shear zone which initially formed during the Mesoproterozoic. The forelandward-propagating wedge proper is formed by basement and the lower two successions of the Amadeus Basin. Higher sedimentary successions accommodate shortening by hinterlandward backthrusting above a detachment horizon which is hosted in carbonates and evaporites of the Bitter Springs Formation. During the formation of the homocline which characterises much of the northern margin of the Amadeus Basin, the tectonic wedge was rotated through 90° and now forms a downward-facing antiformal syncline. The orogenic shortening indicated by this succession of structural events is about 19 km which is compatible with seismic data. The proposed model explains the existence of downward-facing synformal anticlines as folded basement-cored tectonic wedges; although they resemble parts of fold nappes, these folded tectonic wedges do not necessarily imply large amounts of crustal shortening. © 1999 Elsevier Science Ltd. All rights reserved.

## 1. Introduction

In the past decades, considerable advances in understanding the kinematic evolution of structures and the ability to restore crustal-scale sections has meant that regional structural studies are an effective way to quantify orogenic shortening (Price, 1986; Behrmann et al., 1991; Fermor and Moffat, 1992; Jadoon et al., 1994). However, in terrains with coupled basement and cover deformation, the downward continuation of geometries of upper crustal structures can be uncertain and estimates of shortening are to some extent model dependent (Brown, 1988; Spang and Evans, 1988; Cook, 1988). In part, this uncertainty has been the motivating force to explore deeper crustal levels by seismic studies. In some instances the combination of deep seismic studies with regional cross-section balancing have led to a profound re-evaluation of the degree of crustal shortening (e.g. Herrman et al., 1997). A good example of the discrepancy between regional shortening estimates based on existing geological models and geophysical interpretations is the intracratonic Palaeozoic Alice Springs Orogen in central Australia (Fig. 1). Here, estimates of crustal shortening based on a thin-skinned model were > 70 km (> 50%) (Teyssier, 1985) whereas subsequent deep seismic data (Goleby et al., 1989, 1990; Wright et al., 1991) showed the deformation was thick-skinned (i.e. involving the lower

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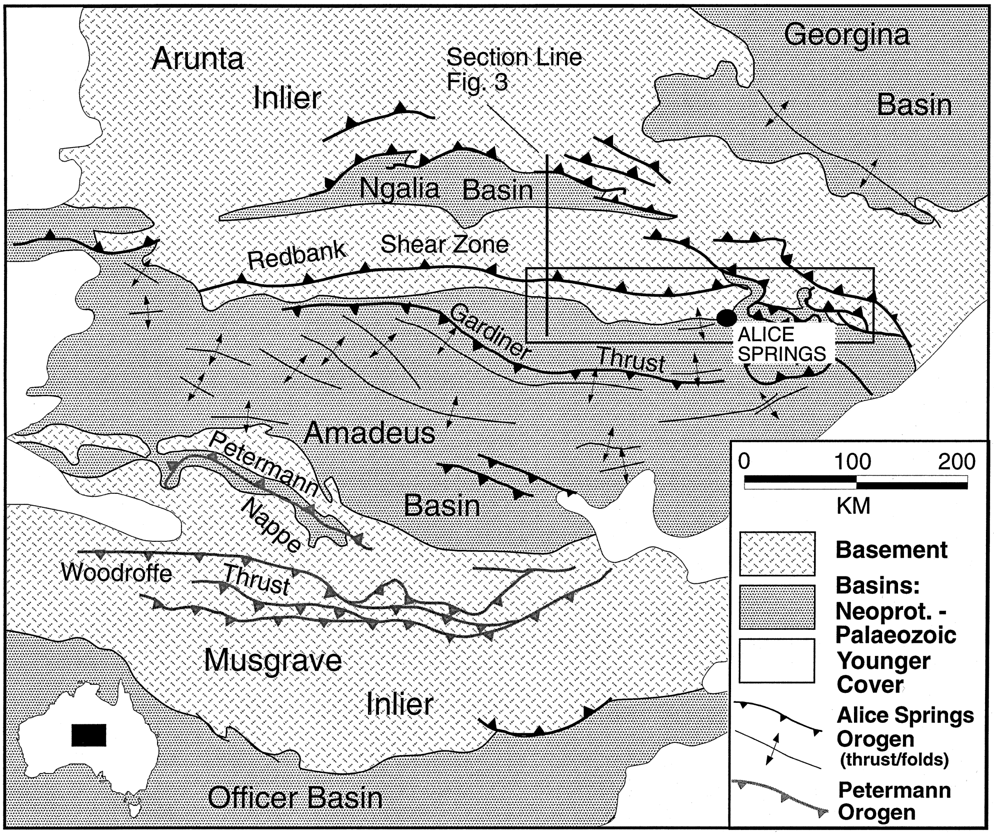

Fig. 1. Regional map of Central Australia showing the Alice Springs and Petermann orogens. Box shows the location of inset map of Fig. 2.

crust and upper mantle), requiring maximum crustal shortening of about 32 km (>22% over a length scale of 110 km) (Shaw et al., 1991a, 1992).

An intriguing feature of the Alice Springs Orogeny is the presence of several ‘Alpine-style’ basement-cored, downward-facing antiformal synclines along the northern margin of the Amadeus Basin (Fig. 2). These structures have been interpreted to represent the erosional remnants of the frontal parts of fold nappes comparable to regional structures found in the Alps (Milnes, 1978; Merle and Guillier, 1989; Kurz et al., 1998). Models describing the development of such ‘Alpine-style’ nappe structures involve considerable shortening, a conclusion apparently at odds with the relatively limited shortening implied by the seismic data, and the simple structures that host these presumed nappes (Shaw et al., 1992). This suggests either: (1) the seismic data are misleading, which is unlikely given the apparent geometric simplicity of the deep crustal structures (Shaw et al., 1991a,b, 1992), or (2) basement-cored nappe-style structures can form in the absence of major crustal shortening. In this paper we present a kinematic model for the development of the Razorback Nappe which lies close to the deep seismic line in the western MacDonnell Ranges (Figs. 2 and 3). Our balanced and retrodeformable model demonstrates that the nappe-style geometry may simply result from the superposition of fold generations, neither of which implies large amounts of shortening. As a consequence it may be relevant to ask whether nappe-like structures are a reliable indication of major crustal contraction?

## 2. Background

The Amadeus Basin forms the remnant of a formerly much more extensive depositional system in Central Australia that records a protracted history of sedimentation ranging from Neoproterozoic to Mid-Palaeozoic times (Walter et al., 1995). The southern margin of the basin formed during the Cambrian Petermann Orogeny which resulted in deep exhumation of the Musgrave basement block to the south (Fig. 1). Subsequent to the Petermann Orogeny, sedimentation within the Amadeus Basin expanded from the north towards the south and continued into the late-Devonian until it was terminated at the end of the Alice Springs Orogeny. This Devonian–Carboniferous orogeny created the present northern margin of

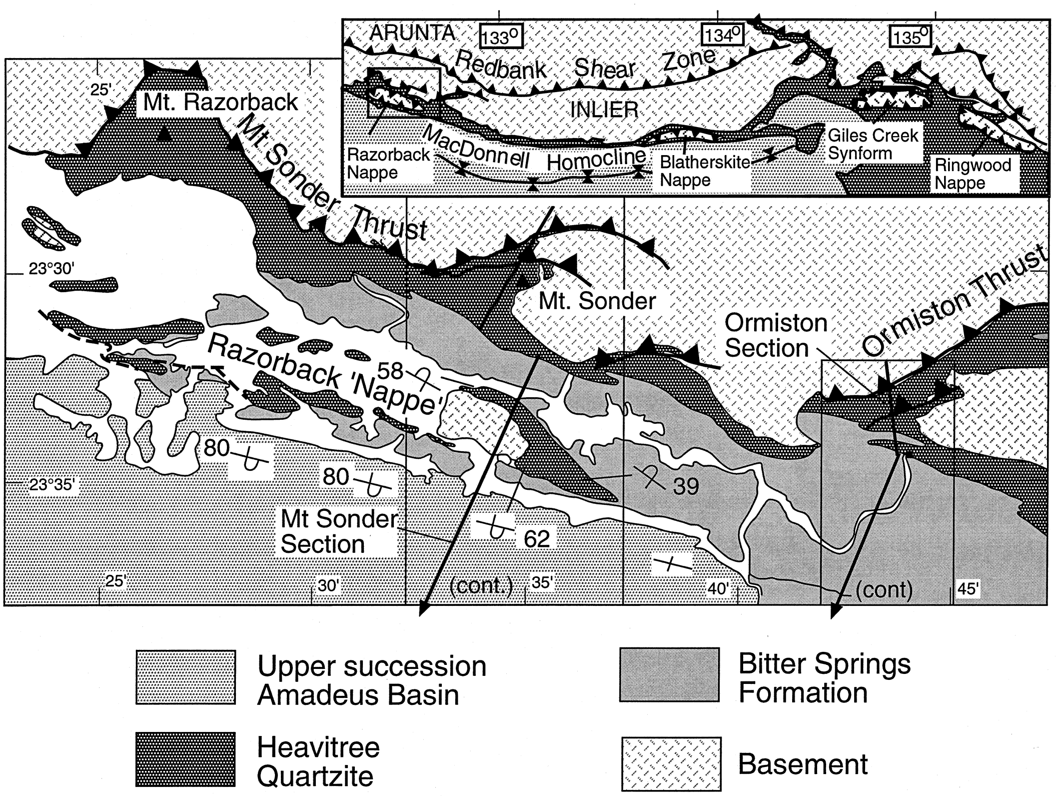

Fig. 2. Map of the Razorback structure, with locations of cross-sections. Location of map in Fig. 5 shown by box on right, location of Fig. 7 by box on left. Inset: map of basement-cored nappe structures at the northern margin of the Amadeus Basin. Note that Heavitree Quartzite and Bitter Springs Formation are shown together by heavy stipple pattern in inset. Cainozoic cover is white.

Amadeus Basin and resulted in exhumation of the Arunta basement inlier which now separates the erosional remnants of the Amadeus, Ngalia and Georgina Basins (Fig. 1). Synorogenic sedimentation during the Alice Springs Orogeny is recorded by the deposition of the Devonian Pertnjara Group sediments in a deep trough along the northern margin of the Amadeus basin.

In the western MacDonnell Ranges west of Alice Springs (Fig. 2), the structural expression of the Alice

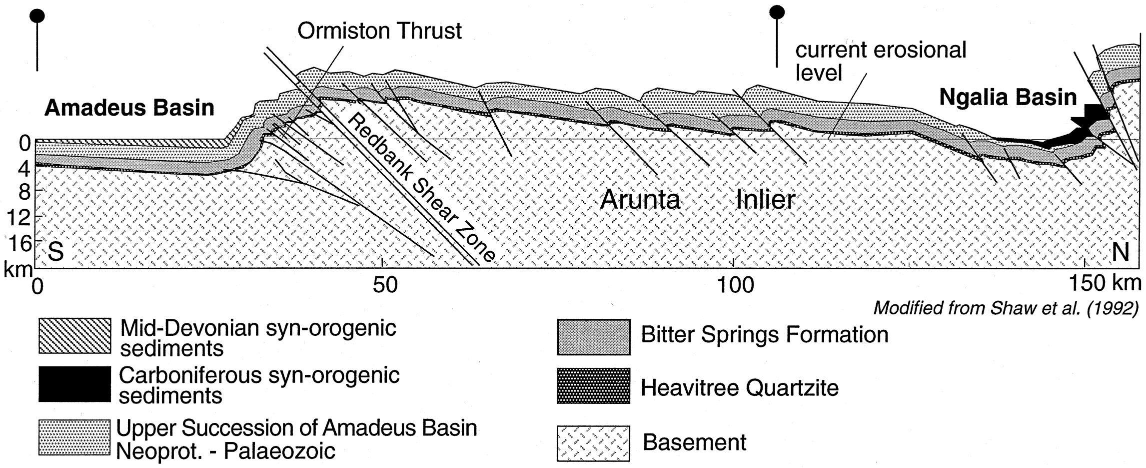

Fig. 3. Simplified section across the northern margin of the Amadeus Basin (modified from Shaw et al., 1992) showing the simple structure of basement culminations and basins. Overall shortening between vertical pin-lines is about 30%.

Springs Orogeny is defined by three distinct structural domains:

1. The Arunta basement province to the north of the Amadeus Basin. This region contains a crustal-scale system of south-vergent thrusts that were operative beneath the now eroded cover. Deep seismic data across the southern third of the inlier indicates these faults dip north at $>45°$ into the lower crust (Goleby et al., 1989; Wright et al., 1991). The principal fault zone is formed by the Redbank shear zone which is interpreted to offset the Moho by $>10$ km. In some instances these faults appear to have reactivated a system of north-dipping Mesoproterozoic thrusts (Shaw and Black, 1991), resulting in a somewhat ambiguous picture of the extent of basement deformation during the Alice Springs Orogeny,
2. The transitional zone between the basement province to the north and the Amadeus Basin to the south which is characterised by coupled basement–cover deformation. The most peculiar feature of this interface between thick-skinned and thin-skinned domains is the presence of large basement-cored nappe-style folds within an apparently simple stratigraphic envelope (Fig. 2).
3. The Amadeus Basin province which is characterised by a thin-skinned (i.e. basement detached) style of shortening, producing structures typical of foreland fold–thrust belts (e.g. Bradshaw and Evans, 1988; Korsch and Lindsay, 1989; Shaw et al., 1991b; Stewart et al., 1991). This thin-skinned deformation apparently continued after deformation in the transition zone had largely ceased (Shaw et al., 1991b).

Thermal indicators, such as conodont alteration indices, suggest that Early Palaeozoic sediments in the MacDonnell ranges were never as deeply buried as the same formation just to the south (Gorter, 1984).

Previous structural studies in the western MacDonnell Ranges have interpreted the nappe-style folds developed at the interface between the Arunta basement province and the Amadeus Basin province to reflect large horizontal displacements (Marjoribanks, 1976). Teyssier (1985) suggests up to 74 km of horizontal displacement, the bulk of which appears to have been accommodated in the transitional zone between the basement of the Arunta Inlier and the Amadeus Basin. However, the notion of large horizontal displacements is at odds with virtually all other datasets which suggest only moderate shortening. Two complementary lines of evidence appear to preclude major contraction in this part of the orogen: (1) Seismic data suggest that the major basement fault zones (e.g. Redbank shear zone and Ormiston Thrust) dip at 35–45°, thus not allowing for large horizontal displacements without significant basement exhumation. (2) $^{40}$Ar–$^{39}$Ar data from biotite and K-feldspar (Shaw et al., 1992) indicate that the basement was exhumed from $\leqslant 12$ km during the Alice Springs Orogeny.

### 2.1. Structures at the interface between Amadeus Basin and Arunta inlier

The northern margin of the Amadeus Basin is characterised by large-scale strike ridges formed by subvertical to steep southerly and (overturned) northerly dips of the entire sedimentary succession in the northern Amadeus Basin. These strike ridges form the MacDonnell homocline which has a total strike length of $>200$ km and is fronted by an asymmetric synclinal zone that merges with sub-horizontal successions of the Amadeus Basin to the south. At the base of the homocline, north-dipping basement thrusts propagate into the synclinal region and the entire structure is geometrically consistent with a large basement culmination (Fig. 3) fronted by a homocline representing the eroded remnant of the $>7$ km thick sedimentary carapace. Thus the basement culmination geometrically resembles in principle the core of a fault propagation fold, with the Redbank shear zone effectively representing a crustal scale ramp.

At the current level of exposure, basement-rooted thrusts only penetrate the lower stratigraphic units of the Amadeus Basin succession, namely the Heavitree Quartzite and the overlying lower part of the Bitter Springs Formation. Whereas the Heavitree Quartzite forms a mechanically competent stratigraphic unit, the Bitter Springs Formation consists of carbonates and, as evidenced in drillholes, thick successions of evaporites (Wells et al., 1970; Lindsay, 1987), which are presumably dissolved at the current outcrop level. At depth the Bitter Springs Formation thus constitutes a mechanically weak layer. Within the homocline, basement-rooted thrusts do not pierce the Bitter Springs Formation and here thrusts are absent in higher stratigraphic units of the upper Amadeus Basin succession. However, thrusts do occur in the upper succession of the Amadeus basin to the south and west of the transects described here. Notably those thrusts that pierce the upper succession are backthrusts with top-to-the-north directed displacement such as the Gardiner Thrust (Fig. 1), producing a triangle-like zone in front of the homocline (Bradshaw and Evans, 1988). In this paper we collectively call all stratigraphic units of the Amadeus Basin above the Bitter Springs Formation, but below the foreland deposits of the Pertnjara Group, the 'upper succession'.

The outstanding feature of the MacDonnell homocline (apart from its strike-length) is the presence of several downward-facing synformal anticlines

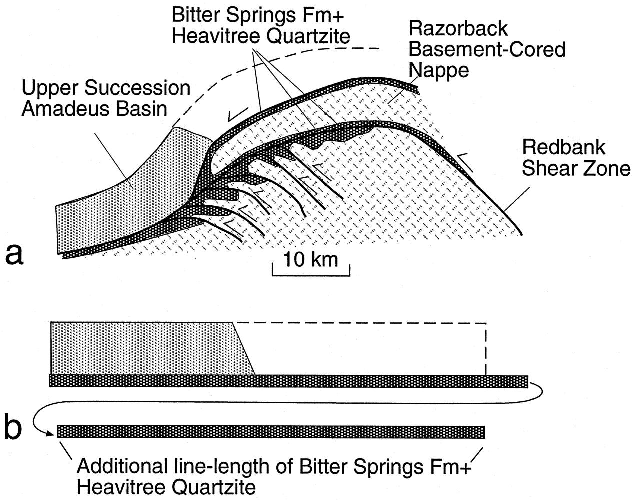

Fig. 4. Sketch adapted from Teyssier (1985) and Marjoribanks (1976). (a) 'Thin-skinned' style of deformation, nappe is emplaced beneath a more or less undeformed cover sequence. (b) Line length discrepancies between units involved in the Razorback nappe and the upper succession of Amadeus Basin.

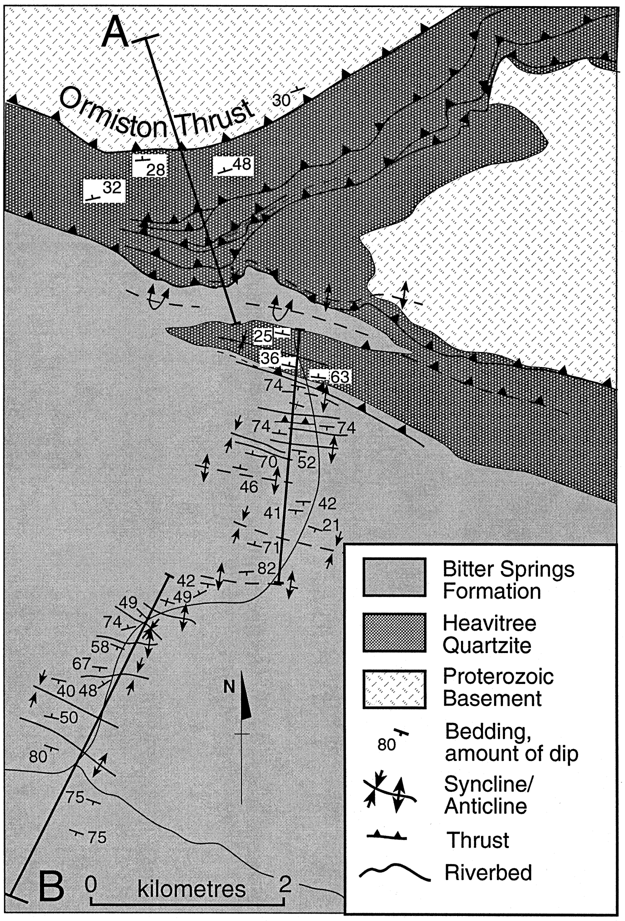

Fig. 5. Strip map of the Ormiston Gorge area. Solid lines indicate trace of composite section A–B based on which cross-section of Fig. 6 was constructed.

embedded within the Bitter Springs Formation (Figs. 2 and 4). These folds are up to 20 km in strike length, up to 5 km wide, and the eroded remnants have canoe-like outcrop patterns defined by a basement core underlain by completely inverted Heavitree Quartzite. In the western MacDonnell Ranges, these folds have been interpreted as erosional remnants of large scale nappe structures (Marjoribanks, 1976; Teyssier, 1985).

The existence of downward-facing fold structures embedded within geometrically simple structures such as the MacDonnell homocline is not easily explained and there is no unifying model for their formation. Most models for the formation of nappe structures along the northern edge of the Amadeus Basin fail to address the constraints placed by the existence of the upper succession. Marjoribanks (1976), (Fig. 4a) effectively implies that nappes were either emplaced after the upper succession was eroded to the current level, a model apparently at odds with the presence of ductile structures in enclosing Bitter Springs Formation or, alternatively, erosion of the upper succession occurred during nappe emplacement as suggested by Dunlap et al. (1995) for the Giles Creek synform in the eastern part of the orogen. Teyssier (1985) and Stewart (1967) draw the cover sequence above the Bitter Springs Formation as a simple carapace beneath which the basement-cored fold nappes of Heavitree Quartzite form more or less complex stacks enveloped by the Bitter Springs Formation. The resulting structure resembles an intercutaneous wedge (Fallot, 1949 in: Jones, 1996) and at first sight it seems plausible that nappes in the MacDonnell Ranges could have propagated exclusively within the mechanically weak envelope of the Bitter Springs Formation. However, this requires a major out-of-sequence movement that forces the nappes through the Bitter Springs Formation and down the face of the homocline. Applying a crude line-length balance to this model shows significant discrepancies in line length between the duplicated lower succession and the mildly warped upper succession of the Amadeus Basin (Fig. 4b).

One of the key constraints in an attempt to model the formation of the downward-facing basement-cored nappes during the Alice Springs Orogeny is the relatively limited amount of shortening that can be accommodated following the thick-skinned models for the Alice Springs Orogeny in the Western MacDonnell Ranges. A section through the central Arunta Inlier (Figs. 1 and 3) suggests shortening was about 32 km or 22% over a length-scale of about 110 km in the deformed section (fig. 12a and b in Shaw et al., 1992). Of this shortening the Redbank shear zone itself accommodated only about 3 km (Shaw et al., 1991a,b) suggesting that significant displacement was accommodated along structures in the immediate footwall of the Redbank shear zone. If the nappes associated with

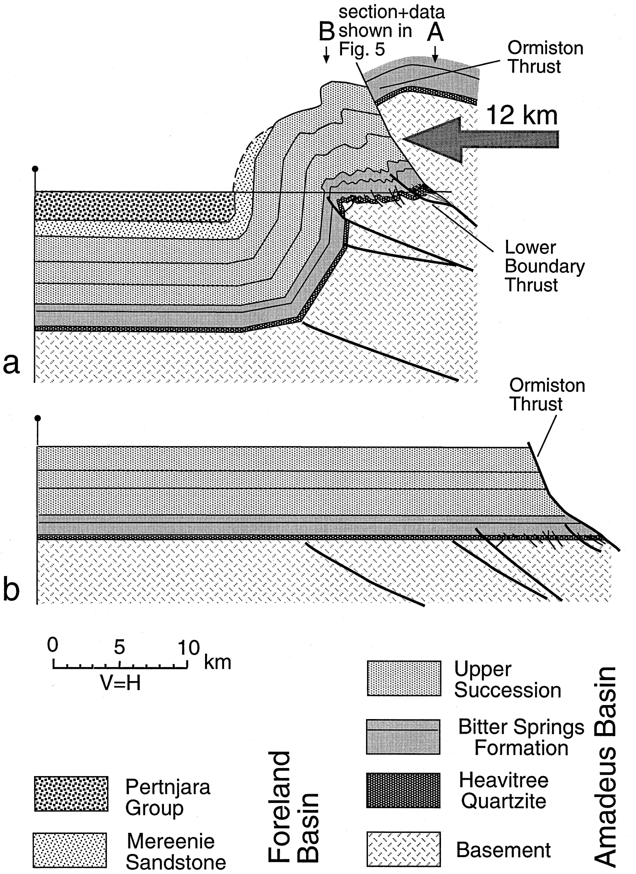

Fig. 6. (a) Cross-section of the Ormiston Gorge area; Points A and B indicate northern and southern endpoints of section line shown in Fig. 5, respectively. (b) Restored section Ormiston Gorge area, using the Ormiston Thrust as a loose line.

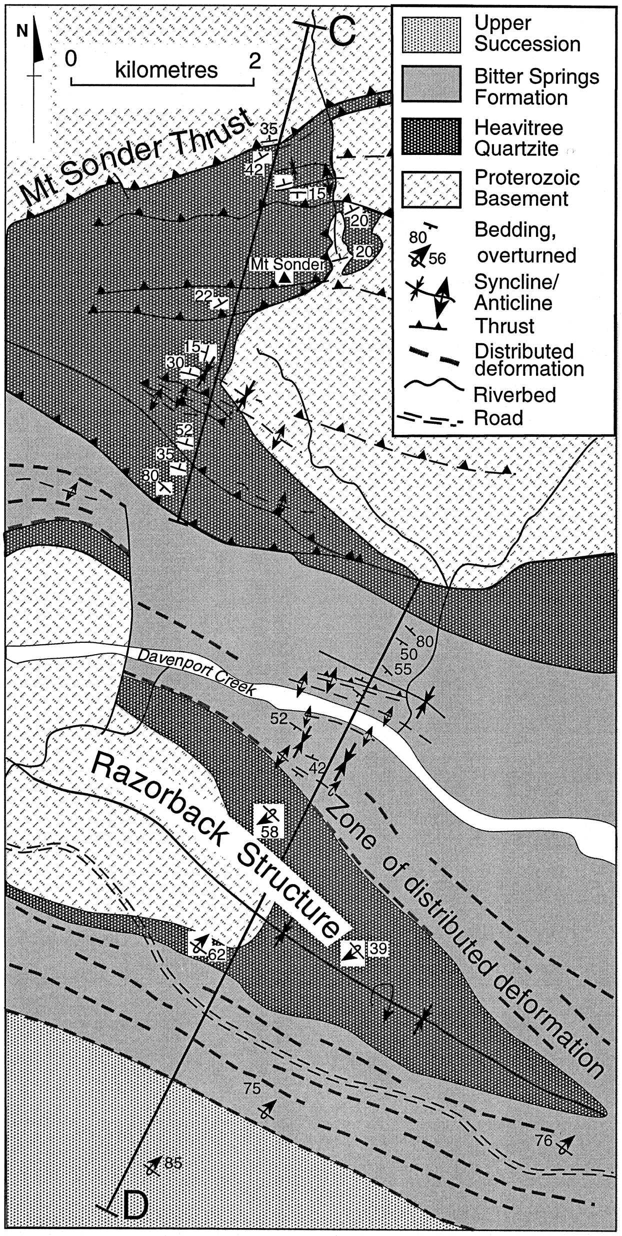

Fig. 7. Strip map of the Mount Sonder area showing the downward facing Razorback structure. Solid lines indicate trace of composite section C–D based on which cross-section of Fig. 8 was constructed.

these footwall structures are included as 'Alpine-style' nappe sheets (e.g. Marjoribanks, 1976; Teyssier, 1985), shortening in the Redbank region must have been well in excess of 50 km. Estimates of such large orogenic shortening were postulated before seismic data became available and imply a thin-skinned style of tectonics, that is, a gentle dip of the principal crustal detachment (Teyssier, 1985). However, subsequently obtained seismic data, and $^{40}$Ar–$^{39}$Ar thermochronology from biotite and K-feldspar showed the invalidity of thin-skinned models for the western MacDonnell Ranges (Goleby et al., 1989, 1990; Shaw et al., 1992).

Here we present the results of structural investigations in the western MacDonnell Ranges, at the northwestern margin of the Amadeus Basin. Based on the excellent base map of Marjoribanks (1974, 1976) augmented by our own mapping, we established balanced and sequentially restored cross-sections across the western MacDonnell Ranges (Figs. 5–8). The 'Ormiston Gorge section' crosses a structurally simple part of the homocline (Figs. 3, 5 and 6), whereas the 'Mount Sonder Section' crosses the Razorback structure (Figs. 3, 7 and 8), which is the westernmost basement-cored nappe structure embedded within the MacDonnell homocline. Based on our investigations we present a kinematically and geometrically admissible model for the formation of basement-cored nappes and the homocline in the western MacDonnell ranges.

## 3. Key structures of the Western MacDonnell ranges

### 3.1. Ormiston Gorge section

Along this section, different structural styles characterise five domains from north to south. The northern-

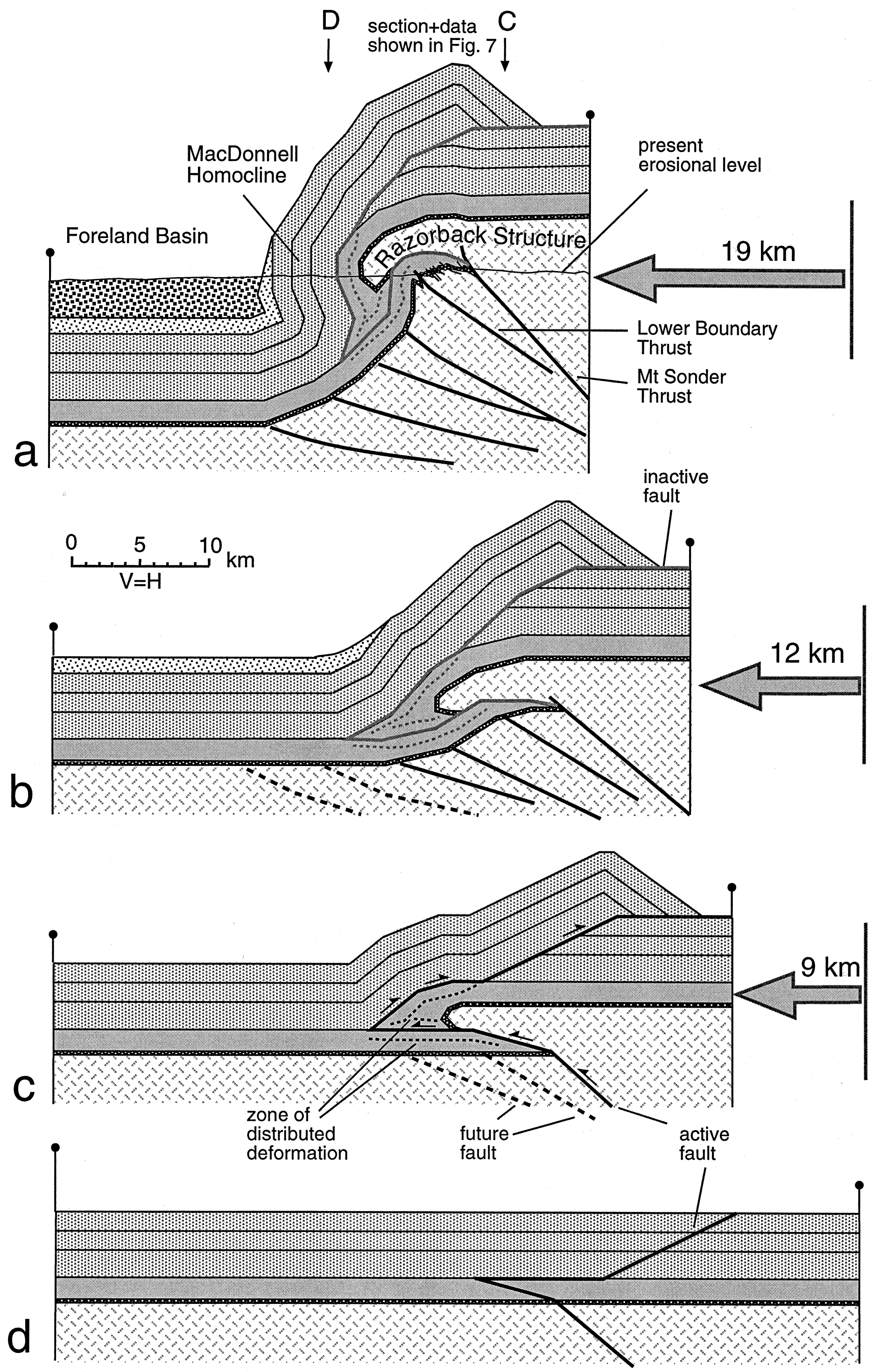

Fig. 8. Sequentially restored cross-section showing the final deformational geometry along the Mount Sonder section. Horizontal arrows on right indicate orogenic shortening in kilometres. (a) Final structure and upward projection of strata in balanced cross-section, note that topography was presumably progressively eroded to source sediments in foreland basin, (b) possible preceding increment showing the initiation of southward tilt of the proto-Razorback structure, (c) emplacement of the proto-Razorback structure in an intercutaneous wedge mainly confined to the Bitter Springs Formation, (d) fully restored section. Legend as in Fig. 6.

most part is formed by the basement of the Arunta Inlier which is bounded to the south by the Ormiston shear zone, with the Ormiston Gorge thrust complex containing interleaved basement and cover. The basement north of the Ormiston shear zone is dominated by coarse-grained Mesoproterozoic plagioclase–K-feldspar–biotite–quartz gneisses in which local leucosomes were developed during partial melting.

The Ormiston shear zone dips about 30–45° north and consists of mylonitic basement rocks with significant grain size reduction. Downdip mineral elongation and slip lineations in conjunction with kinematic indicators such as *S–C* fabrics and shear bands show north-side-up displacement along the shear zone.

The Ormiston thrust complex is marked by three principal thrust repetitions and one minor splay of the Heavitree Quartzite along >35° north dipping thrusts, which branch off the footwall of the main Ormiston shear zone. In the hanging wall of individual thrust sheets, the Heavitree Quartzite is commonly recumbently folded, and where preserved, fold closures plunge gently west. In most cases the lower limbs are attenuated and sheared out along thrusts and only the upper, right-way-up limb is preserved. In some instances thin slivers of basement are incorporated into the hanging wall of individual thrusts. The basement-involved nature of deformation and balancing requirements suggest that the overall displacement along individual thrusts in the Ormiston thrust complex most likely was not in excess of 1 km. Most thrust zones are between 1–4 m thick and are characterised by mylonitisation of the Heavitree Quartzite. Microstructures such as dynamic recrystallisation of quartz and synkinematic growth of white mica indicate greenschist facies metamorphic conditions (i.e. above 300°C) during deformation (e.g. Simpson, 1985). A well developed stretching lineation is visible in outcrop and is defined by quartz and muscovite. In thrust zones the lineation can be parallel to hinges of cm-scale folds that occur exclusively within high strain zones. The southern margin of the thrust complex is formed by a lower boundary thrust which juxtaposes Heavitree Quartzite over the overturned limb of a syncline formed by Bitter Springs Formation (Fig. 6a).

The area between the lower boundary thrust and the homocline is marked at outcrop level by the Bitter Springs Formation which contains open folds with a wavelength of several hundred metres and <200 m amplitude. Accompanying smaller scale folds are commonly disharmonic with bifurcating fold axes and strongly curved axial surfaces. Although the folding is somewhat irregular, most folds plunge gently (<10°) to the west, similar to folds in the Ormiston thrust complex. The structural relief of this zone is low and the overall structural envelope is more or less horizontal (Fig. 6) with only minor north-dipping reverse faults offsetting the Bitter Springs Formation and the underlying Heavitree Quartzite. To the south of the roughly horizontal section of the Bitter Springs Formation, the MacDonnell homocline is characterised by steep southerly dips of the Bitter Springs Formation and the upper succession (Warren and Shaw, 1996).

The southernmost structural province along this transect is marked by the Devonian Pertnjara Group, a foreland deposit related to the encroaching Alice Springs orogeny (Forman et al., 1967; Jones, 1972). Dip angles in this group decrease southward and the northern outcrops of this group were presumably progressively tilted during the formation of the homocline.

The thickness of the upper succession of the Amadeus Basin suggests a maximum potential structural relief of the homocline of about 8–9 km, associated with a horizontal shortening of about 12 km (see restored section, Fig. 6b). The homocline was progressively eroded during its development, and the clasts in the middle to upper successions of the Pertnjara Group record an inverted stratigraphy (Jones, 1972) reflecting the shedding of material from the homocline as it grew. The shortening of the Heavitree Quartzite and the Bitter Springs Formation evident at the current outcrop level appears to be merely an accommodation of shortening in the core of a simple large scale fold (the MacDonnell homocline), and not itself the expression of large scale thrusting. The majority of the shortening in the system is interpreted to have been accommodated along the emergent Ormiston shear zone and other, non-emergent thrusts in the hinterland (north) of the homocline (Fig. 6a).

### *3.2. Mount Sonder section*

Similar to the Ormiston Gorge section, the hinterland part of this section is formed by basement which is bounded to the south by the Mount Sonder Thrust, which is effectively an extension of the Ormiston Thrust and the Mount Sonder thrust complex. The Mount Sonder thrust complex consists of six internal thrusts along which basement and the overlying Heavitree Quartzite is displaced southward (Figs. 7 and 8). The system forms a broad basement-cored culmination with a structural envelope (including axial planes of recumbent folds) that dips gently toward the hinterland on its northern flank and more steeply south on its southern limb (Fig. 8a). Quartzite mylonites in the northern part of the Mount Sonder thrust complex are 0.5–1.5 m thick and contain similar quartz microstructures to the thrusts in the Ormiston section and, in more potassic rocks, the shear fabrics are defined by abundant growth of new muscovite. Basement exposures east of Mount Sonder (Fig. 7) display a network of steeply to moderately north dipping shear zones with north-over-south directed relative displacement. These shear zones vary in width from about 2 cm to over 40 cm and form a network of anastomosing zones of intense deformation, which enclose less deformed basement domains.

The southern boundary of the Mount Sonder thrust complex is formed by a lower boundary thrust that juxtaposes the Heavitree Quartzite over Bitter Springs Formation, which is interpreted to form a footwall syncline with an overturned northern limb (Fig. 8a). This lower boundary thrust effectively separates 'metamorphic' structures (those containing new muscovite) from essentially unmetamorphosed Bitter Springs Formation. Towards the south, the Bitter Springs Formation generally dips steeply to the south and, internally, is irregularly folded. Within the Bitter Springs Formation, dolomite and siliceous layers are crosscut by an irregular network of calcite and quartz veins with slickensides on numerous surfaces; the veins are commonly brecciated. The breccia fragments are enclosed in a micritic matrix and, in conjunction with the abundant veins, may indicate elevated fluid pressures during deformation of the Bitter Springs Formation. Approaching the contact with the Razorback structure (see below), the Bitter Springs Formation displays a wide zone of distributed strain characterised by intense disruption with (mélange-like) domains that contain little or no preservation of the original lithological layering. These highly deformed zones are structurally coplanar with the envelope of the Bitter Springs Formation. The kinematics associated with the intense deformation of this zone cannot be deciphered conclusively.

The Bitter Springs Formation contains the Razorback 'nappe' structure. This structure has a gentle ($>5^\circ$) west plunge and consists of a northern limb of overturned Heavitree Quartzite, a core of Mesoproterozoic basement and a southern limb of overturned Heavitree Quartzite (Figs. 2 and 7). The overturned nature of the Heavitree Quartzite is indicated by abundant sedimentary way-up criteria (mainly trough cross bedding at between centimetre and decimetre scale). These relationships make this structure a synformal anticline (Hobbs et al., 1976), with a wavelength of about 2.5 km. Marjoribanks (1976) and Teyssier (1985) interpreted this structure to represent the erosional remnant of a large scale nappe emplaced over the top of the Mount Sonder thrust complex. South of the Razorback synformal anticline, the Bitter Springs Formation marks the beginning of the homoclinal sequence which is sub-vertical to overturned (Fig. 8a). The homoclinal dips lessen eastward towards the Ormiston section, resuming their more regional south-dipping attitude. The fact that the homoclinal dips lessen to the east, and the Razorback synformal anticline projects eastward above the current erosional surface, suggests that the subvertical to overturned section of the homocline accommodates the additional volume represented by the Razorback 'nappe'.

## 4. Discussion

The structural sections across the Ormiston region reveal a comparably simple geometry in this part of the northern Amadeus Basin margin. The exposed Ormiston thrust complex represents the deeply eroded, internal part of a map-scale fold resembling a fault propagation style fold or tri-shear fold (Erslev, 1991) that displaces basement southward, towards the Amadeus Basin. Seismic data suggest that the Ormiston thrust is a simple, mostly basement-hosted, footwall shortcut thrust (e.g. McClay and Buchanan, 1992) of the Redbank shear zone, which is exposed about 15 km to the north (Fig. 3). Southward displacement along the Ormiston thrust resulted in southward propagation of a basement wedge above which the sedimentary cover of the Amadeus Basin forms a comparatively thin carapace. During the formation of the MacDonnell homocline this carapace was progressively eroded, providing the source for the Devonian Pertnjara Group that filled the foreland depression created by the topographic loading. The Ormiston section indicates a horizontal shortening of 12 km and vertical exhumation of about 8–9 km. The magnitude of this displacement is compatible with the thick-skinned style of deformation envisaged for this part of the orogen and indicates that the gross geometry of the MacDonnell homocline provides a good framework in which to assess the amount of orogenic shortening. Somewhat surprisingly the Redbank shear zone to the north of the Ormiston and Mount Sonder thrust complexes appears to have accommodated relatively little shortening at the current erosion level. $^{40}$Ar–$^{39}$Ar spectra for K-feldspar suggests that movement on the Redbank zone proper was less than $>3$ km before movement was transferred into the footwall Ormiston thrust (Shaw et al., 1992). The Ar–Ar spectra further suggest that the combined thrust wedge, including the Redbank shear zone, was exhumed by an additional $>8$ km, presumably as a consequence of the progressive southward development of thrusts beneath the MacDonnell homocline. Given the Ormiston thrust system dips at approximately 30° (Shaw et al., 1991a,b), exhumation in the order of 8 km would imply shortening of around 12 km. Clearly estimates of shortening based on Ar–Ar data are open to question since they rely on ad hoc assumptions about both the thermal gradient and about the magnitude of post-orogenic erosion required to reveal the current exposure level. In the Ormiston section, however, the broad agreement between estimates of shortening based on structural restoration and those derived from Ar–Ar data suggest that thermal gradients were relatively modest ($\leqslant 35^\circ$C/km) and significant exhumation occurred during thrusting (Shaw et al., 1992)

While shortening along the Ormiston section is modest, horizontal displacements in the Mount Sonder section, which incorporates the Razorback fold structure, appear to be much larger if the current models of nappe emplacement are accepted. Despite the apparently contrasting amounts of displacement indicated by the structures along the Ormiston and Mount Sonder sections, there is no offset of the MacDonnell homocline which, regardless of the *apparent* displacement of structures in its hinterland, forms one continuous east–west-striking feature. This suggests that the shortening associated with the formation of the Razorback structure is overestimated in existing models or that the strike of the homocline is due to processes independent of the deformation that formed the structures in its hinterland. To investigate this point further, we present a set of sequentially restored cross-sections that evaluate the overall shortening in the Mount Sonder section (Fig. 8).

### 4.1. Sequential restoration of the Mount Sonder section

In the cross-sections in Fig. 8, we take the entire Amadeus Basin succession into account, while attempting to maintain line-length balance throughout the deformational history. A crude area balance was also maintained for most units, the obvious exception being the Bitter Springs Formation where area and hence volume balancing is complicated by the presence of evaporitic horizons (Lindsay, 1987) and complex distributed deformation. Importantly, however, its evaporite content makes the Bitter Springs Formation a mechanically weak layer wedged between the mechanically strong Heavitree Quartzite and the overlying upper successions of the Amadeus Basin.

Similar to the arguments of Stewart (1967) for the Blatherskite nappe south of Alice Springs (Fig. 2), we suggest that the Razorback structure was initiated as a wedge that formed during initial south-directed thrusting along the Ormiston shear zone (Fig. 8b–d). This wedge incorporates basement in the core of a fold outlined by Heavitree Quartzite and the Bitter Springs Formation. The wavelength of the fold is broadly given by the across-strike width of the Razorback synformal anticline. The Ormiston shear zone forms a ramp in the basement and presumably in the Heavitree Quartzite, but most likely forms a flat in the less competent Bitter Springs Formation, which represents the main detachment horizon (Fig. 8b). During southward displacement, the basement-cored wedge overrode the portion of the Heavitree Quartzite that now forms the thrust stack of Mount Sonder. Continued deformation in the footwall of the Ormiston thrust resulted in duplication of the Heavitree Quartzite beneath the Razorback fold and formed an antiformal flexure in the overlying nappe as the MacDonnell homocline continued to grow. The current erosional surface intersects the downward facing nose of the refolded Razorback wedge, with the thrust stack now located structurally above the remnant of the Razorback fold (Fig. 8a). In the core of the homocline the upper successions of the Amadeus Basin are not cut by thrust faults and the detachment that led to the initial emplacement of the basement-cored Razorback fold presumably dies out towards the foreland within the Bitter Springs Formation. Our model suggests that the Bitter Springs Formation filled a triangular shaped detachment horizon which formed a detachment-wedge at the base of the upper succession of the Amadeus Basin. This detachment geometry is supported by the intense deformation of the Bitter Springs Formation in the vicinity of the Razorback fold where a diffuse movement horizon within the evaporitic Bitter Springs Formation may have accommodated distributed deformation in a regime of elevated pore pressures (Etheridge, 1983), as suggested by the presence of abundant veined disruption of competent layers. Conceivably this zone of distributed deformation merged into one detachment along which the upper successions were displaced as shown in Fig. 8.

The movement along the Ormiston shear zone leads to duplication of parts of the Heavitree Quartzite and the Bitter Springs Formation in the lower part of the sequence, and to maintain compatibility in the amount of shortening (and line-length balance) between the lower and upper Amadeus Basin successions, the shortening of the lower successions must also be accommodated in the upper succession. Since there is no evidence of early south-vergent thrusts cutting the homocline, we suggest that shortening of the upper succession was accommodated along a south-dipping backthrust(s) (Fig. 8c and d). The geometry of the proposed basement wedge is broadly similar to those described by Price (1986) for parts of the Rocky Mountains of western Canada and by Kraig et al. (1988) for the Rocky Mountain fold-and-thrust belt of the western US. Backthrusting during the formation of such wedges [alternatively named triangle zones by other workers (cf. MacKay et al., 1996) or intercutaneous wedges (cf. Jones, 1996)] is the favourable mode to accommodate regional shortening in the presence of a mechanically weak detachment horizon (Couzens and Wiltschko, 1996). In contrast a forward propagating scenario would be favoured in cases of competent rheologies throughout the stratigraphic succession (Couzens and Wiltschko, 1996). We suggest the structure described here is not an ‘intercutaneous wedge’ as such, since the latter model does not necessarily provide a line length balance between strata displaced in the wedge itself and the overlying rocks. Backthrusting is kinematically compatible with the observed kinematics of thrusts that displace the upper succession to the west and south of the area described here (Fig. 1).

Subsequent to the emplacement of the proto-Razorback structure, the northern part of the entire succession was progressively tilted southward and exhumed (Fig. 8a and b), whereby the Razorback structure reached its final, downward facing position to form the synformal anticline exposed at the current erosional level. The homocline in front of the Razorback structure is slightly overturned to the north, which may be imposed by the ramp angle of the upper detachment to the Razorback structure and the flexure of the section during the initial formation of the Razorback fold.

### *4.2. General implications of the wedge model*

The model presented here explains the Razorback fold structure as a tectonic wedge that was subsequently tilted during the formation of the homocline. Incorporating the shortening accommodated by the tectonic wedge at the front of the homocline into the simple cross-section presented by Shaw et al. (1992) (Fig. 3), increases the overall shortening from the original estimate of 22% (or 32 km) to 27% or >39 km over the same deformed state length of 110 km. The sequence of deformational stages explains the formation of the downward facing Razorback structure without invoking major shortening and involves all stratigraphic successions deposited in the Amadeus Basin prior to the onset of Alice Springs orogenic shortening. The switch from the emplacement of the wedge to the large scale tilting during the formation of the homocline requires a progressive shift of the locus of deformation towards the foreland to the south. A forelandward progression of deformation is typical for most foreland fold and thrust belts (Dahlen and Suppe, 1988). Overall, the model presented here does not require any significant out-of-sequence movement for the emplacement of the Razorback structure; instead the progressive development of the Razorback structure and the homocline is an in-sequence process. A possible exception to this scenario is reflected by the broad culmination of the Mount Sonder thrust complex which may be interpreted to result from internal thickening of the deforming wedge either concomitant or even postdating the southward movement at the front of the homocline. The overall structure of the enveloping surface of the homocline (including the tectonic wedge) resembles basement-involved structures described in the western United States (Spang and Evans, 1988; Cook, 1988; Erslev, 1991; Narr and Suppe, 1993; Schmidt et al., 1993; Chase et al., 1993; Erslev and Rogers, 1993).

On an orogen scale, however, the locus of deformation does not appear to follow a simple foreland prograding model of deformation. A shift in deformation to the hinterland is indicated by the presence of mid- to late Carboniferous syn-orogenic sediments in the northern Ngalia Basin (Wells and Moss, 1983) (Fig. 1), while coeval and earlier (Late Devonian) deformation was occurring in the Amadeus Basin, up to 150 km south of the MacDonnell Ranges (Shaw et al., 1991a,b).

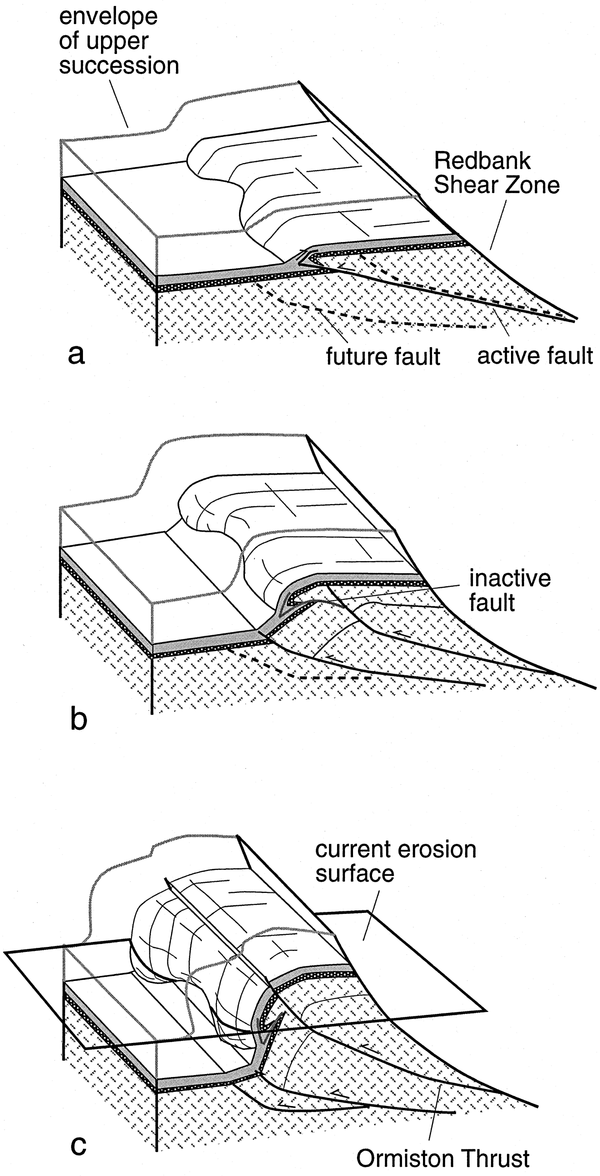

Fig. 9. Schematic Evolution of the tectonic wedges along the northern Amadeus Basin. (a) Insertion of the tectonic wedge along a footwall shortcut thrust of the Redbank shear zone, (b) new thrusts break in the footwall of previously activated thrusts, (c) continuous forelandward breaking of thrusts leads to the formation of homocline.

The emplacement of the Razorback fold appears directly related to the pre-existing structural discontinuity formed by the Redbank shear zone, which prompted footwall shortcut displacement accommodated along the Ormiston and Mount Sonder shear zones. Forelandward-propagating displacement during the formation of further footwall thrusts governed the shortening, leading to the formation of the MacDonnell homocline in the western MacDonnell

Ranges. At outcrop level the actual displacement across the Redbank shear zone was presumably only in the order of 3 km during the Alice Springs Orogeny, whereas over 10 km offset are seismically imaged at depth along the Redbank shear zone. This suggests that most of the upper crustal displacement was taken up by faults located in the footwall of the Redbank shear zone. These upper crustal fault and shear zones merge into one fault zone forming the Redbank shear zone at mid and lower crustal levels.

The preservation of structures similar to the Razorback structure at the present erosional level is directly related to the amount of initial horizontal displacement of the wedge(s). After the southward tilting of the homocline, the only parts of other possible wedges that will be intersected by the current erosional surface are those that were displaced southward beyond the principal tilt axis of the homocline (Fig. 9a–c). This may suggest why structures such as the Razorback fold are not preserved more commonly within the MacDonnell homocline. The succession from wedge emplacement through final homoclinal tilting can be explained by progressive in-sequence forelandward breaking of the principal displacement zones (Fig. 9a–c).

The structural evolution suggested here may have been operative in one way or another along the entire western MacDonnell homocline. In principle the scenario suggested here may also be applied to the northeastern Amadeus Basin where, however, subsequent deformation both in the hinterland and in the foreland of the northeastern basin margin appears more complex than in the western MacDonnell Ranges (Teyssier, 1985; Collins and Teyssier, 1989; Stewart et al., 1991; Dunlap et al., 1995).

The orogenic shortening would have led to the formation of topography at the northern Amadeus Basin margin. This topographic loading in turn caused the crustal flexure that produced the accommodation space for the Pertnjara Group, itself sourced from the encroaching orogen, a scenario very similar to the Rocky Mountains of the western United States (De Celles, 1994; De Celles and Mitra, 1995). The wedge model suggested here requires that shortening during forelandward emplacement of a wedge must be balanced in all the sedimentary successions present at the time of wedge emplacement (e.g. Price, 1986). That is, shortening that is accommodated in the basement and the lower successions, which together form the actual wedge, must have been accommodated also in the upper succession of the Amadeus Basin. There is no evidence for forelandward thrusting (i.e. duplication of strata) in the homocline, where the upper successions are well exposed. Therefore, we suggest that in the upper successions, backthrusting (above the current level of erosion) accommodated the shortening manifest by the forelandward thrusting of the wedge proper which is formed by the lower successions and basement. However, the very existence of the backthrust associated with a wedge is impossible to prove conclusively since the topography created during this wedging was presumably progressively eroded, as shown by Jones (1996) for triangle zones with comparable kinematics in western Canada. The existence of significant topography (potentially related to such backthrusting) in the hinterland of the homocline is supported by the elevated metamorphic grade in the Mount Sonder and Ormiston thrust complexes which rapidly decreases southwards. Indeed, Shaw et al. (1992) inferred rapid heating to >350°C in the Ormiston thrust complex around 375 Ma, which we suggest reflects the time of emplacement of this wedge and the associated backthrust which together create the crustal stacking reflected by this heating event. The deposition of the clastic members of the Pertnjara Group (Figs. 6 and 7), which fills a narrow but deep foreland depression in front of the homocline, also commenced between 370 and 380 Ma and has been related to uplift of a source to the north (Jones, 1991). The northerly derived clastic members of the Pertnjara Group thus provide sedimentological evidence for the erosion of the topography related to the emplacement of the tectonic wedge and the associated backthrusting proposed by our model. This may also explain why thermal indicators such as conodont alteration indices (Gorter, 1984) suggest that Early Palaeozoic sediments in the MacDonnell ranges were never as deeply buried as the same formation just to the south. Our model suggests that rocks in the MacDonnell homocline were uplifted when the Pertnjara Group was deposited.

The obtained shortening estimate of 19 km in the western MacDonnell Ranges agrees with shortening estimated by Shaw et al. (1992) based on seismic and thermochronologic data. Our model for the emplacement of tectonic wedges at the northern margin of the Amadeus Basin does not require significant overall shortening during the formation of these wedges. We suggest these tilted tectonic wedges are in fact a reflection of the modest shortening associated with the Palaeozoic intracontinental Alice Springs Orogeny of Central Australia. Our results suggest the downward facing synformal anticlines such as the Razorback structure are not necessarily related to the existence of classic ‘Alpine-style’ nappes despite their eye-catching geometry, and do not therefore indicate large amounts of orogenic shortening. The presence of downward-facing fold systems in basement terrains is commonly used to infer significant orogenic shortening (e.g. Clarke et al., 1986). If these folds occur within belts that are now steeply dipping, the distinct possibility exists that the magnitude of shortening is considerably less and the downward facing geometry is the result of large scale bulk rotation and not nappe-style overthrusting.

## 5. Conclusions

Our data and observations suggest the following:

1. Balanced and sequentially restored cross-sections show that synformal anticlines that formed at the northern edge of the Amadeus Basin during the mid-Palaeozoic Alice Springs Orogeny can be explained as tilted tectonic wedges. The emplacement of these wedges was associated with significant partitioning of displacement. Basement and the lower two successions of the Amadeus Basin form the wedge proper which propagates towards the orogenic foreland. The same amount of displacement is accommodated by backthrusting of the overlying upper succession above a detachment hosted in carbonates and evaporites of the Bitter Springs Formation. During the regional tilting that leads to the formation of the regional homocline the envelope of the tectonic wedge is also tilted through 90° to form a downward facing synformal anticline.
2. The localisation of basement-involved tectonic wedges appears intimately linked to footwall shortcut thrusting related to the pre-existing crustal scale Redbank shear zone.
3. Balanced sections suggest that formation of tilted basement-cored tectonic wedge structures require a crustal shortening of about 19 km (30%) which is compatible with independent shortening estimates based on geophysical and thermochronologic data. The model presented here removes an apparent conflict between shortening estimates based on geophysically supported thick-skinned models and the presence of 'Alpine-style' basement cored nappes.
4. Erosional relics of basement-cored, downward-facing synformal anticlines may not be reliable indicators of major orogenic shortening, especially in fold belts that contain major steeply dipping zones within which all earlier formed structures are rotated.

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