Australian Journal of Earth Sciences (1999) **46**, 343–354

Structural geometry and controls on basement-involved deformation in the northern Flinders Ranges, Adelaide Fold Belt, South Australia

E. PAUL, T. FLÖTTMANN AND M. SANDIFORD

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

In the northern Flinders Ranges, Neoproterozoic and Cambrian sedimentary rocks were deformed and variably metamorphosed during the *ca* 500 Ma Cambro-Ordovician Delamerian Orogeny. Balanced and restored structural sections across the northern Flinders Ranges show shortening of about 10–20%. Despite the presence of suitable evaporitic detachment horizons at the basement–cover interface, the structural style is best interpreted to be thick-skinned involving basement with only a minor proportion of the overall shortening accommodated along stratigraphically controlled detachments. Much of the contractional deformation was localised by the inversion of former extensional faults such as the Norwest and Paralana Faults, which both controlled the deposition of Neoproterozoic cover successions. As such, both faults represent major, long-lived structures which effectively define the present boundaries of the northern Flinders Ranges with the Gawler Craton to the west and the Curnamona Craton to the east. The most intense deformation, which resulted in exhumation of the basement along the Paralana Fault to form the Mt Painter and Babbage Inliers, coincides with extremely high heat flows related to extraordinarily high heat-production rates in the basement rocks. High heat flow in the northern Flinders Ranges suggests that the structural style not only reflects the pre-Delamerian basin architecture but is also a consequence of the reactivation of thermally perturbed, weakened basement.

Key words: Adelaide Fold Belt, Delamerian Orogeny, Flinders Ranges, geothermal heat flow, structural geometry.

INTRODUCTION

The Adelaide Fold Belt in South Australia forms the western part of the Delamerian Orogen (*ca* 500 Ma) and is the oldest part of the Tasman Fold Belt system of mainland eastern Australia (Coney *et al.* 1990). It comprises deformed Neoproterozoic and Cambrian sediments of the Adelaide Geosyncline (Sprigg 1952; Preiss 1987) that fringe the Proterozoic cratonic margin of southeastern Australia (Gawler Craton). The Adelaide Fold Belt is subdivided into four main structural domains: the southern Adelaide Fold-Thrust Belt, the Nackara Arc in the east, the central Flinders Ranges in the mid-north and the northern Flinders Ranges in the far-north (Figure 1). Recent studies have focused mainly on the structural and metamorphic evolution of the southern Adelaide Fold-Thrust Belt and the Nackara Arc (Jenkins 1990; Mancktelow 1990; Jenkins & Sandiford 1992; Sandiford *et al.* 1992, 1995a, b; Flöttmann *et al.* 1994; Marshak & Flöttmann 1996; Flöttmann & James 1997). These studies reveal a coherent fold-thrust belt, formed as a consequence of a west-northwest-tapering orogenic wedge, with the structure dominated by large-scale arcuate fold trends. The Nackara Arc is a broad arc of northwest-verging folds formed above regional basement-cover décollements. The southern Adelaide Fold-Thrust Belt consists of an imbricate fan of north–south-trending folds and east- to southeast-dipping basement-involved thrusts which are interpreted as inverted growth faults (Marshak & Flöttmann 1996; Flöttmann & James 1997). The northern Flinders Ranges are dominated by broad, south-verging open folds (Figure 2). As in the southern Adelaide Fold-Thrust Belt, the northern Flinders Ranges are characterised by basement-involved deformation (e.g. Mt Painter and Mt Babbage Inliers), although in the northern Flinders Ranges the overall level of strain is much lower raising the question of what controls basement involvement in this region.

The principal aims of this paper are to: (i) document the structural geometry of the northern Flinders Ranges and (ii) consider the factors controlling basement involvement. Of particular interest is the inversion of basin-forming structures in the evolution of this region. We begin by reviewing the stratigraphic and structural setting of the northern Flinders Ranges using published as well as new structural data collected along several north–south traverses. Then we attempt to quantify shortening and exhumation using balanced and restored regional cross-sections. This provides a geological and geometrical framework in which to understand key aspects of the structural evolution of the northern Flinders Ranges.

REGIONAL GEOLOGICAL FRAMEWORK

In the Adelaide Fold Belt (Figure 1), Palaeoproterozoic to Mesoproterozoic cratonic basement is overlain by a thick Neoproterozoic to Cambrian sedimentary package. This sedimentary package is deformed and metamorphosed and now confined to a region of elevated topography forming the Flinders and Mt Lofty Ranges, the topography reflecting the reactivation of the fold belt during the Tertiary

(Figure 1). The Neoproterozoic sequences consist of basal carbonates with evaporites and clastics, glaciomarine deposits and postglacial sequences (Preiss 1987), followed by transgressive Early Cambrian shallow-marine sands and deeper water carbonates and shales (Preiss 1987). Deposition of Neoproterozoic sediments is attributed to a succession of rift and sag phases, with the main rifting commencing at around 800 Ma (Fanning *et al.* 1986; Jenkins 1990). Deposition terminated during the Cambro-Ordovician Delamerian Orogeny.

In the southern Adelaide Fold-Thrust Belt, the Neoproterozoic–Cambrian sequences were shortened and folded into large-scale west-vergent and largely northeast–southwest-trending folds (Jenkins 1990; Mancktelow 1990; Flöttmann *et al.* 1994) with mylonitic reverse faults accommodating the bulk of the shortening (Flöttmann *et al.* 1994; Flöttmann & James 1997). Total shortening exceeds 50% in the south where basement is exposed in a number of thrust-bound inliers along the western margin of the orogen (Flöttmann *et al.* 1994; Marshak & Flöttmann 1996; Flöttmann & James 1997) (Figure 1). In the Nackara Arc, Delamerian shortening led to the formation of an arcuate, northwest-verging belt (Marshak & Flöttmann 1996). The central Flinders Ranges represent the least-deformed part of the Adelaide Fold Belt. The basement beneath this region formed a local high on which somewhat condensed Neoproterozoic sequences were deposited.

The regional structure of the northern Flinders Ranges (Figure 2) is dominated by large-scale open folds. The overall east-northeast- and locally west-northwest-trending fold axes suggest approximately north–south shortening. In the north and northeast, folds are truncated by diapiric structures reflecting mobilisation of evaporites of the Callanna Group prior to and during Delamerian deformation (Lemon 1985). Most of the diapirs coincide spatially with faults suggesting that diapirism was localised by faulting (Coats 1973). Two basement inliers in the northeastern Flinders Ranges, the Mt Painter and the Babbage Inliers separated by the Terrapinna Corridor, expose metamorphosed Mesoproterozoic and Palaeoproterozoic sedimentary and igneous rocks (Figure 2). The eastern margin of the basement inliers coincides with the Paralana Fault, which defines the boundary between the northern Flinders Ranges and the adjacent Curnamona Craton further to the east. The western boundary of the northern Flinders Ranges with the Stuart Shelf coincides with the Norwest Fault (Figure 2).

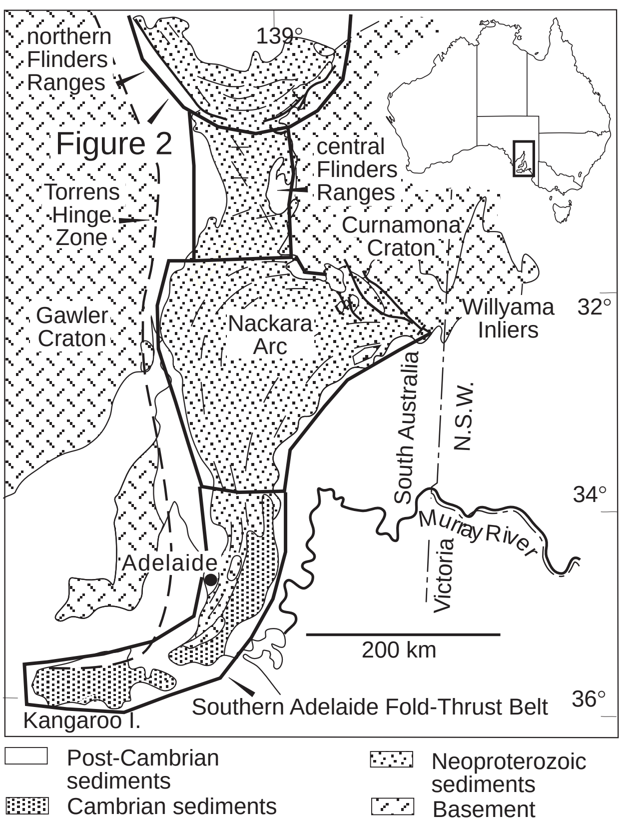

Figure 1 Regional map of the Adelaide Fold Belt exposed in the Mt Lofty and Flinders Ranges, including the main stratigraphic units. Location of Figure 2 is indicated.

In most of the Adelaide Fold Belt, metamorphic conditions during the Delamerian Orogeny did not exceed biotite grade but sequences in the southern Adelaide Fold-Thrust Belt have locally experienced significantly higher grade metamorphism with migmatites developed around syntectonic intrusives (Offler & Fleming 1968; Mancktelow 1990; Sandiford *et al.* 1995a). In most of the northern Flinders Ranges the metamorphic grade is sub-greenschist facies. However, in the vicinity of the Mt Painter Inlier metamorphic grades locally reach amphibolite facies (Coats & Blisset 1971; Mildren & Sandiford 1995; Preiss 1995) with estimated peak metamorphic temperatures of 500–550°C attained at depths of only 10–12 km (Mildren & Sandiford 1995). The Mt Lofty and Flinders Ranges represent a region of elevated heat flow in the order of 90 mWm^{-2} (Cull 1982) and are part of the southern portion of the 'Central Australian heat flow province' (Sass & Lachenbruch 1979). Most of the heat flow (~70 mWm^{-2}) is derived from crustal heat sources within the Palaeoproterozoic to Mesoproterozoic basement with the remaining ~20 mWm^{-2} representing the 'reduced' or mantle heat flow (Sandiford *et al.* 1989).

Stratigraphic relationships and thickness distribution

Neoproterozoic strata of the northern Flinders Ranges comprise, in order of decreasing age, the Callanna, Burra, Umberatana and Wilpena Groups (Figure 3). The Callanna Group includes a basal quartzite overlain by dolomitic marbles and evaporites as well as basalts, rhyolites and tuffs (Preiss 1987). The Lower to Middle Burra Group consists mainly of siltstone and dolomite (Skillogalee Dolomite). The Upper Burra Group represents a transgressive cycle, comprising mainly silty and carbonaceous dolomite, quartzite, shale and siltstone. The 'Sturtian' glacials of the Lower Umberatana Group consist mainly of glaciomarine diamictite, quartzite, laminated siltstone and partly turbiditic sequences. The Middle Umberatana Group comprises a thick succession of thinly laminated and partly calcareous siltstone of the Tapley Hill Formation and represents a major transgression after a period of glaciation (Preiss 1987). Thinner successions of shale, sandy limestone and dolomite dominate the upper part of the Umberatana Group (Preiss 1987). The Wilpena Group records two transgressive–regressive cycles (Preiss 1987) comprising a range of lithologies including finely laminated dolomite, siltstone (Brachina Formation), shale with interbeds of limestone and dolomite (Bunyeroo Formation), shale, siltstone and dolomite (Wonoka Formation), and cross-bedded feldspathic quartzite and sandstone (Billy Springs Formation and Pound Quartzite). Cambrian sedimentary rocks form a northward-thinning wedge, the upper successions of which may represent synorogenic deposits derived from the encroaching orogenic wedge of the Nackara Arc (Haines & Flöttmann 1998) (Figure 1).

In order to provide an appropriate framework for section balancing, we have re-evaluated the thicknesses of all stratigraphic units using data from published maps (Coats 1969, 1973; Forbes 1965; Preiss 1986, 1987, 1993) (Figures 3, 4). In doing so we have assumed that the basin formation/subsidence is driven by lithospheric stretching followed by cooling and regional thermal subsidence (McKenzie 1978). In view of the intracratonic setting of this rift we assume that the thickness of the sedimentary record at any given point in the dataset approximated the accommodation space during deposition. Figure 3 represents a composite lithostratigraphic north–south section and shows that the overall sediment pile is thickest in the central part and thins gradually to the north. This composite section also shows that whilst sequences of the regional subsidence phase (Middle–Upper Umberatana Group and younger) display lateral thickness continuity between subsections A–A′ to E–E′, the thickness of earlier rift sequences (Burra Group) increases considerably between subsections C–C′ and E–E′. A major discontinuity exists between subsections E–E′ and F–F′ and coincides with an east–west-trending zone in which the projected extensions of the Norwest and Paralana Faults merge (Figure 2). Due to the lack of relevant data, for this compilation we have estimated the thicknesses of the lowermost Callanna Group (~1–1.3 km, thickening towards the south) and the Lower Burra Group (~0.5–2 km).

Generalised isopach maps for the major Neoproterozoic units and their cumulative thicknesses are presented in Figure 4. The Callanna and Lower Burra Groups have been excluded from this compilation due to the lack of relevant regional-scale data. As shown in Figure 4 the location of the depocentres shifts considerably through time. The Upper Burra Group depocentre is located in a northwesterly trending corridor, northwest of the Norwest Fault. The southwestern margin of this depocentre is abrupt,

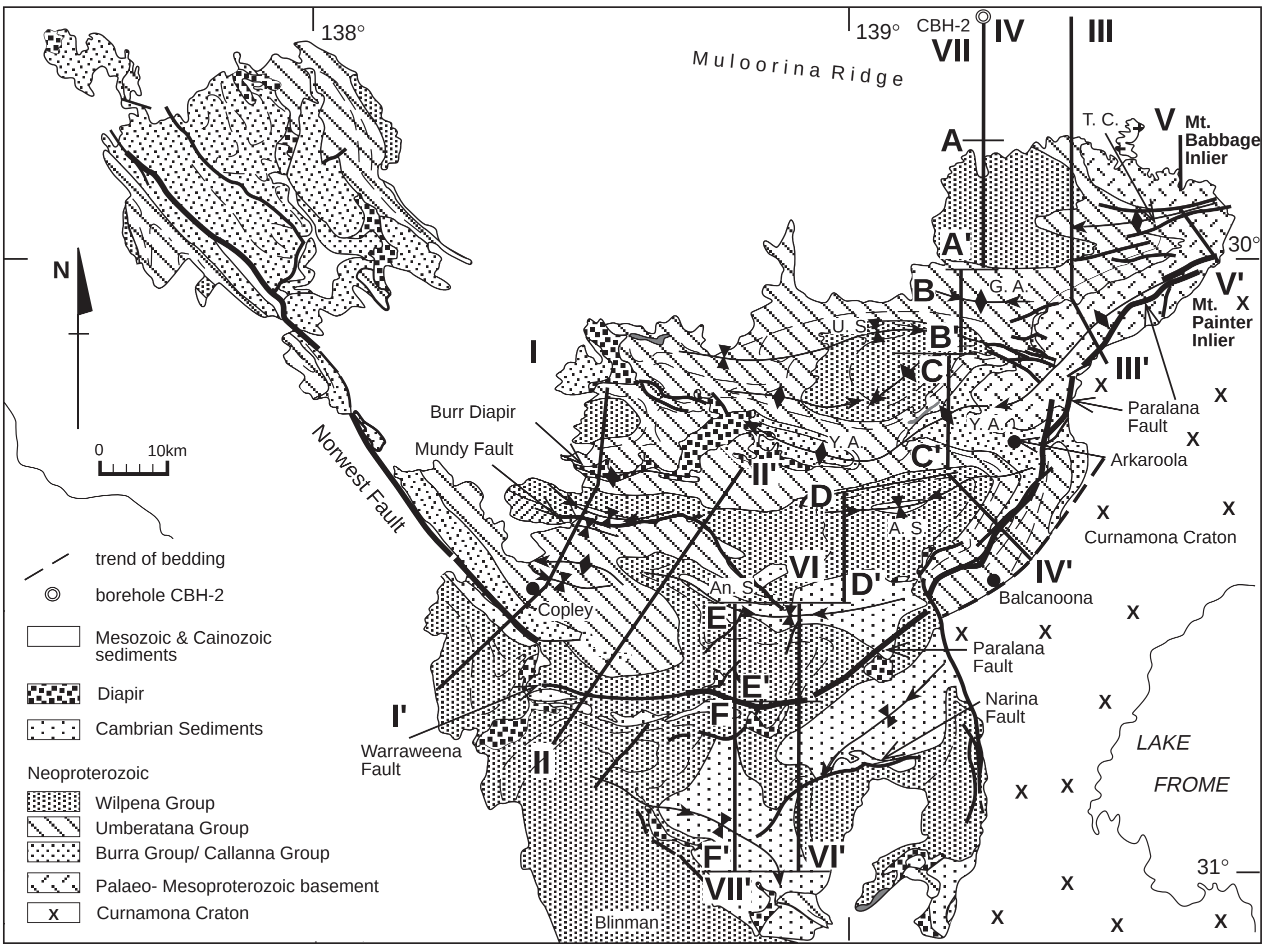

Figure 2 Generalised geological map of the northern Flinders Ranges showing the main stratigraphic components, trends of major anticlines, synclines, faults and the location of balanced cross sections (I–VII). The locations of individual lithostratigraphic sections (A–A′ to F–F′), shown in Figure 3 are indicated. T.C., Terrapinna Corridor; Y.A., Yankannina Anticline; A.S., Arkaroola Syncline; U.S., Umberatana Syncline; An.S., Angepena Syncline; G.A., Gladstone Anticline.

coinciding with the southwestern extension of the Paralana Fault (Figure 2). Elsewhere in the northern Flinders Ranges, the Upper Burra Group is absent or only developed as a veneer. The main depocentre of the Lower Umberatana Group is located in the northeast in a west-northwesterly trending corridor known as the Yudnamutana Trough (Preiss 1993). The eastern termination of the Yudnamutana Trough coincides with the Paralana Fault. Its northeastern margin has no obvious surface expression but might coincide with the basement high of the Muloorina Ridge, which defines the approximate northern limit of Proterozoic sedimentation (Preiss 1987, 1993), while the south-southwestern margin trends northwest in the vicinity of Arkaroola. The deposition of the Middle–Upper Umberatana Group marks the onset of regional subsidence with a northwesterly trending depocentre that coincides with, but extends over a much greater area than, the earlier rift-related depocentres. The Wilpena Group covers most of the northern and central Flinders Ranges, its relatively uniform thickness reflecting dominantly regional thermal subsidence. The compilation summarised in Figure 4 demonstrates that the Norwest and Paralana Faults played a prominent role during early rift-related Neoproterozoic deposition, with depocentres developed on the hangingwall sides of both faults.

REGIONAL STRUCTURAL CROSS-SECTIONS

The results of the previous section have identified the Norwest and the Paralana Faults as two fundamental structures across which we have constructed seven balanced and restored structural cross-sections. The cross-sections are constructed perpendicular to the principal fold trends, which are assumed to reflect the principal shortening direction which is approximately north–south. We have used the key-bed method for the section balancing, which uses competent sequences with more or less constant stratigraphic thickness and lateral continuity as marker horizons (Woodward *et al.* 1989). The most suitable key beds are the Pound Quartzite, the Tapley Hill Formation, the Lower Umberatana Group and the Burra Group. Structural data are mainly based on existing geological maps (Forbes 1965; Coats 1969, 1973) and were supplemented and improved by detailed structural mapping where road access was possible. Due to the lack of relevant data we have estimated the thickness for the Callanna Group (~1–2 km, thickening towards the west) in all sections. The horizontal and vertical scales are equal in all the sections.

Sections I and II illustrate the geometry across the Norwest Fault. The detailed variations of stratigraphic thickness was evaluated using data from Coats (1973) and Forbes (1965). Sections III to V illustrate the geometry across the Paralana Fault. The structure across the southern part of the northern Flinders Ranges, where the Norwest and Paralana Faults converge, is illustrated by section VI. Section VII is a composite section designed to illustrate the overall structural geometry of the northern Flinders Ranges. It combines the structural elements of the sections I to VI and the thickness distribution of the parallel north–south lithostratigraphic section shown in Figure 3.

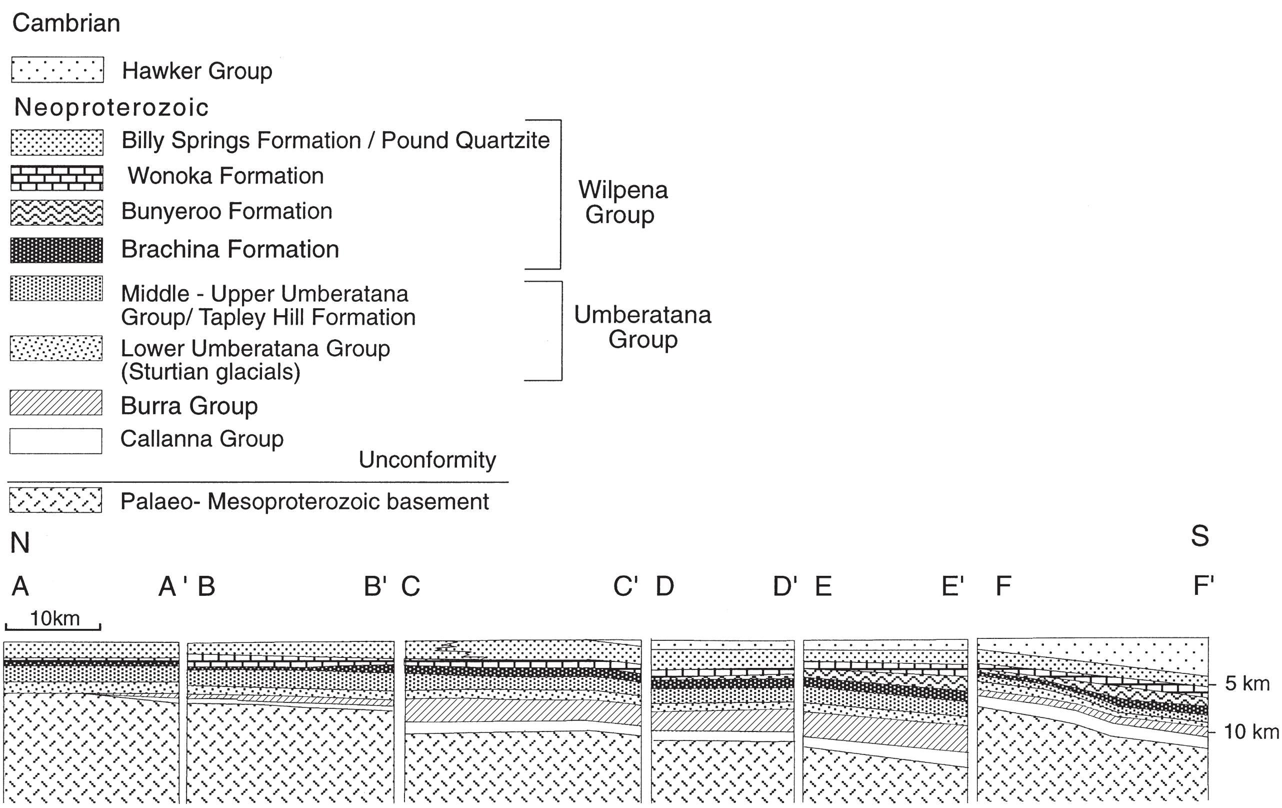

Figure 3 North–south-oriented standard lithostratigraphic column of the Neoproterozoic and Cambrian sedimentary rocks through the northern Flinders Ranges. Location of individual lithostratigraphic sections is shown in Figure 2.

Norwest Fault transects (sections I, II)

The structural geometry of sections I and II (Figures 5, 6) is characterised by a pop-up geometry between the northeast-dipping Norwest Fault and the southwest-dipping Mundy Fault, and interpreted to be a consequence of basement involvement at depth. Across both faults the thicknesses of the Callanna and Burra Groups change considerably indicating that both faults acted as major synsedimentary (growth) faults. In section I–I′ the deposition of early rift sequences was accommodated by opening a rift graben between the Norwest Fault and a set of south-dipping faults north of the Mundy Fault, which subsequently facilitated the ascent of the Burr diapir (Figure 5a, b). The most dramatic change in thickness is evident in section I–I′ (Figure 5c), where the Burra Group is <600 m in the southwestern footwall but increases to a maximum thickness of 5.3 km in the hangingwall of the Norwest Fault.

In section II–II′, the extension of the Norwest Fault is blind, with its subsurface continuation indicated by a south-vergent, fault-tip propagation fold (Figure 6). The outcropping Warraweena Fault (Figure 6a) shows no reverse displacement and acted as a minor growth fault during deposition. The differential thickness of the Burra Group across the Norwest Fault varies by up to 1.5 km, suggesting considerable variation in displacement during the growth stages of the Norwest Fault. Younger sequences in both sections show approximately constant thickness, indicating that the Norwest Fault was mainly active during the deposition of the Callanna and Burra Groups. Shortening in both sections is only minor (~12% for section I–I′ and 15% for section II–II′) with the majority of the shortening in section I–I′ localised across the Norwest Fault where the juxtaposition of Burra Group with Wilpena Group and Cambrian sequences furthermore implies some 7 km of differential exhumation (Figure 5b, c). The Burr diapir in the north of section I–I′ reflects mobilisation of Callanna Group evaporites during deformation. Unlike in section I–I′, the Norwest Fault in section II–II′ does not propagate into higher stratigraphic units, with the shortening being more distributed and mainly accommodated by vertical displacement of basement.

Steeply dipping major growth faults in the restored sections are interpreted to terminate at depth near the brittle–ductile transition during early rifting (not shown in sections). We note that we apply this interpretation also for the remaining restored sections.

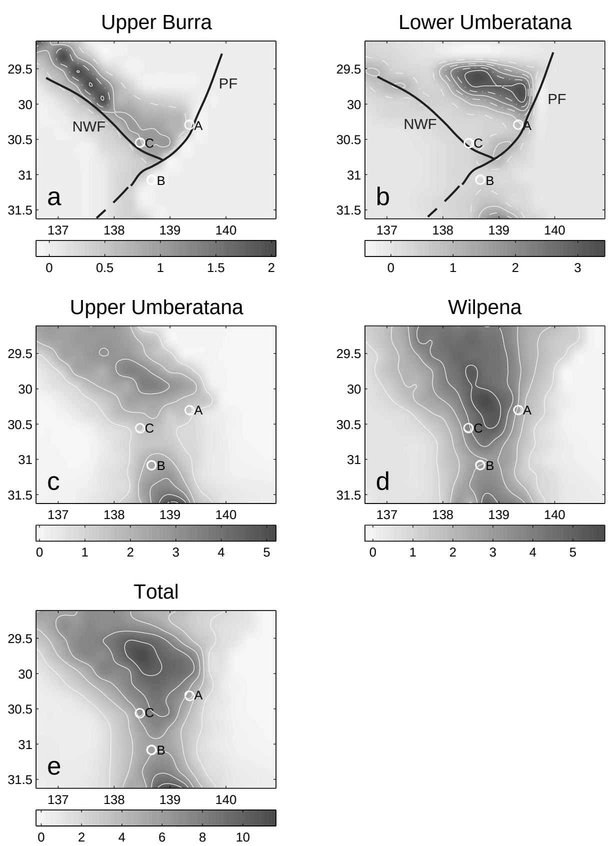

Figure 4 Isopach maps of Neoproterozoic sequences in the northern Flinders Ranges. Solid contours represent 1 km intervals, dot-dashed contours represent 500 m intervals. A, Arkaroola tourist resort; C, Copley; B, Blinman; NWF, Norwest Fault; PF, Paralana Fault.

Paralana Fault transects (sections III–V)

Sections III and IV (Figures 7, 8) show an increase in strain intensity from undeformed Neoproterozoic sedimentary rocks in the north, towards folded and faulted sedimentary rocks in the hangingwall of the Paralana Fault. The latter is a steep northwest-dipping, basement-penetrating structure along which basement has been exhumed to form the Mt Painter Inlier (Figure 7b). Restored sections III and IV show a dramatic change in sedimentary thickness across the Paralana Fault, with the entire Neoproterozoic succession as little as a few hundred metres thick in the footwall of the Paralana Fault and as much 12 km thick in the hangingwall. Syndepositional displacement on the Paralana Fault is most evident in the Callanna, Burra and Lower Umberatana Groups, accommodating the opening of the ‘Yudnamutana Trough’ depocentre during deposition of Lower Umberatana Group glacials (Preiss 1987) (Figures 4b, 7c).

The structural geometry in these sections is characterised by open anticlines interpreted as fault-propagation folds developed as a consequence of basement involved deformation between steeply south- and north-dipping basement structures. Reverse movement along the Paralana Fault and fold geometries suggest an overall southeast-directed transport. In section IV, in the vicinity of the Gladstone Anticline, the Burra Group thickens towards the south, whereas the Middle to Upper Umberatana Group sequences thicken towards the north. This is suggestive of a steep underlying basement structure with varying movement history through time. The overall shortening along sections III and IV is ~20%. Much of the shortening is concentrated across the Paralana Fault as well as individual anticlines (e.g. Yankannina Anticline in sections III and IV). The bulk of the shortening in section III is concentrated in the anticline formed in the hangingwall of the Paralana Fault. Exhumation of the Mt Painter Inlier is interpreted to be accommodated by the Paralana Fault and southeast-dipping basement structures, indicated as dashed lines, resembling an overall flower-structure geometry. Estimated differential exhumation of the basement across the Paralana Fault in the line of the section III is 13 km (Figure 7b) and is consistent with metamorphic evidence suggesting that Burra Group in the hangingwall experienced metamorphic pressures of ~300 MPa (Mildren & Sandiford 1995), while sedimentary rocks in the footwall on the western margin of the Curnamona Craton are essentially unmetamorphosed.

Section V is a schematic section across the east-northeast-trending Terrapinna Corridor that separates the Mt Painter and Babbage Inliers (Figure 9a). The structural geometry is dominated by a pop-up-like exhumation of the Mt Painter Inlier between the Paralana Fault and south-dipping faults along the southern margin of the Terrapinna Corridor. The contact between the Lower Umberatana Group glacials of the Terrapinna Corridor with the Babbage Inlier is interpreted as an intact unconformity, albeit highly sheared, whereas along the southern margin of the Terrapinna Corridor the glacials are overthrust by the Mt Painter Inlier. The thickness of the Lower Umberatana Group is not well-constrained, but is estimated to have not exceeded 1000 m. In the Terrapinna Corridor, glacials of the Lower Umberatana Group are asymmetrically folded with axial planes dipping steeply south-southeast. Strain intensity is relatively high and evidenced by a well-developed northeast-trending slaty cleavage in the glacial sequences and a shear foliation in granites along the margin of both basement inliers. Fold asymmetry, cleavage orientation and a consistent down-dip lineation in the glacials suggests northwest-directed transport (Figure 9b).

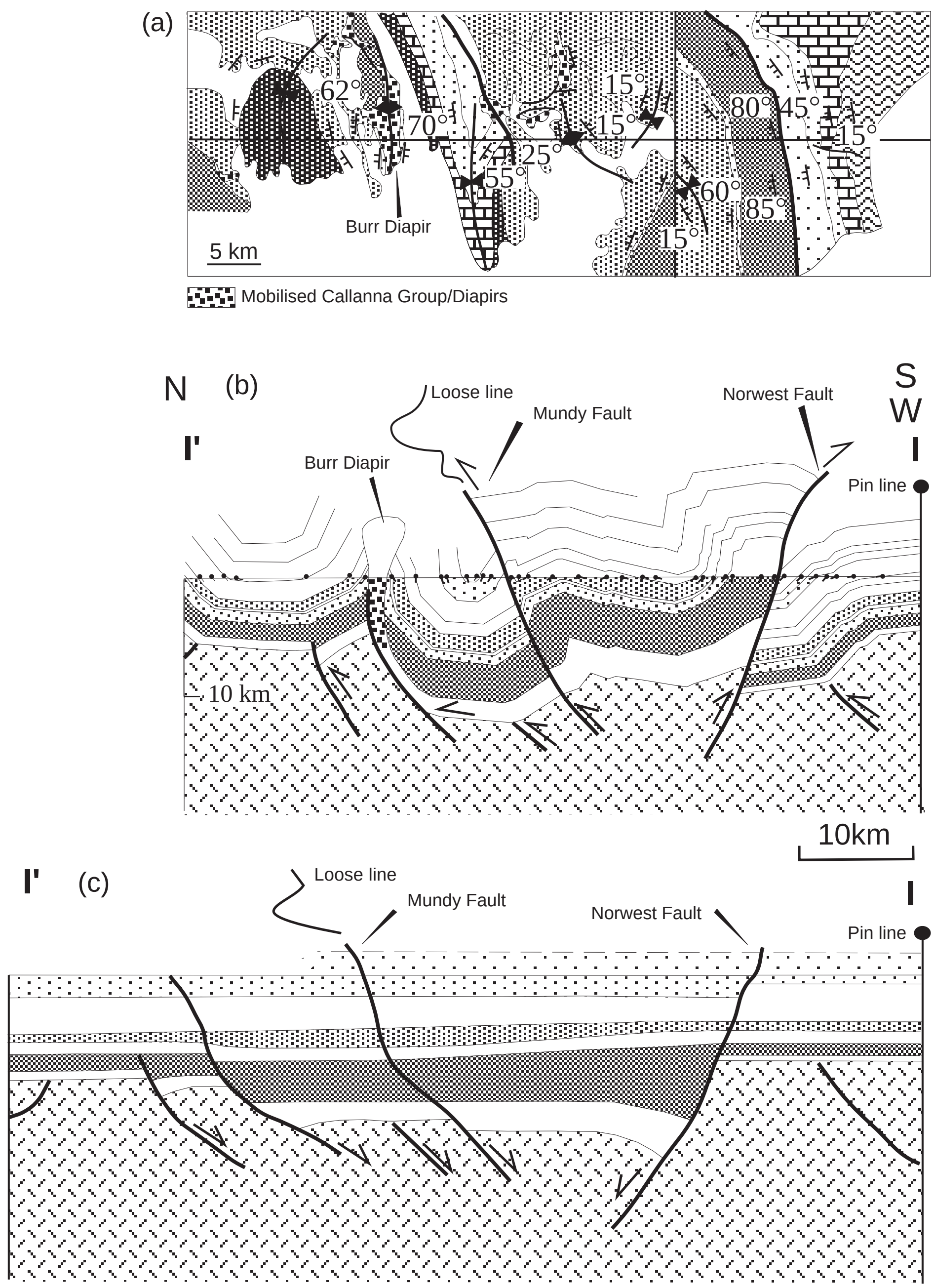

Figure 5 Copley section (I′–I). (a) Simplified strip map showing the geology along the section line. Major anticlines and synclines are marked. Symbols as in Figure 3. Post-Cambrian deposits are unshaded. Solid vertical lines indicate changes in the orientation of the section line (see also Figure 2). (b) Pop-up geometry between the Norwest and Mundy Faults. (c) Restored Copley section. The restored section shows deep segmentation of the basement during early rifting and deposition of the Callanna and Burra Groups. Note the rollover geometry in the hangingwall of the Norwest Fault in the restored section. Diapiric structures are schematic only. Mundy Fault has been chosen as 'loose line' due the structural 'disturbance' caused by the Burr diapir. The thickness of Cambrian sedimentary rocks (top lithology only shown in restored section) is only estimated and indicated as dashed line.

Southern transect (sections VI, VII)

Section VI shows a pair of north-dipping, basement-penetrating structures (the Narina and Paralana Faults) to the north of which the thickness of many of the sequences, and particularly the Burra Group, increase considerably (Figure 10a, b). The overall geometry shows gentle open folding, with an overall shortening of ~6% (Figure 10a). Shortening is accommodated by reverse slip across the Narina Fault, where shale and siltstone of the Wilpena Group in the hangingwall are juxtaposed with Lower Cambrian limestone, and by basement doming causing the antiform south of the Angepena Syncline. In this section, the Paralana and the Mundy Faults are non-emergent, but inferred from the overlying anticline (Figure 10a).

The composite, meridional section (section VII, Figure 11) indicates that overall shortening across the central part of the northern Flinders Ranges is in the order of 11%.

DISCUSSION

The descriptions provided in the previous sections imply that the structural geometry of the northern Flinders Ranges is strongly influenced by basement-involved deformation that is largely coupled with the overlying Neoproterozoic and Cambrian cover. The main structural characteristics are open, mainly south-verging folds often associated with pop-up geometries formed between steeply dipping reverse faults (sections I–VI). Our data suggest that the structural geometry in the northern Flinders Ranges is a consequence of variably intense basement-involved deformation involving strain concentration and reverse slip along major basement-rooted faults. Potential décollement horizons, such as the evaporitic Callanna Group, appear to have been of minor significance in accommodating shortening, although such horizons did play an important role during the formation of diapirs.

The major faults in the northern Flinders Ranges, including the Norwest, Paralana and Mundy Faults, significantly controlled the deposition of Neoproterozoic sequences, in particular the Burra and Lower Umberatana Groups. Total sediment thickness increases across the Norwest and the Paralana Faults from veneers (a few hundred metres) above the cratons on either side of the northern Flinders Ranges to over 10 km in the central part of the ranges. During Burra Group time depocentres were concentrated in a narrow northwest-trending graben bounded by the Norwest and the Mundy Faults (sections I, II and VI), which acted as growth faults in this interval. Rift-related depocentres clearly shifted through time (Figure 4), with this shift accommodated in part by right-lateral strike-slip displacement along the Paralana Fault which acted as a transfer fault during northeast-directed extension (Figure 12a, b). During Yudnamutana times the depocentre shifted to the east–west-oriented Yudnamutana Trough in the northeastern part of the basin (Figures 4, 12b, c).

The onset of north–south-directed Delamerian shortening reflects an overall left-lateral transpressional regime, with the inversion of former extensional faults significantly influencing the style, geometry as well as intensity

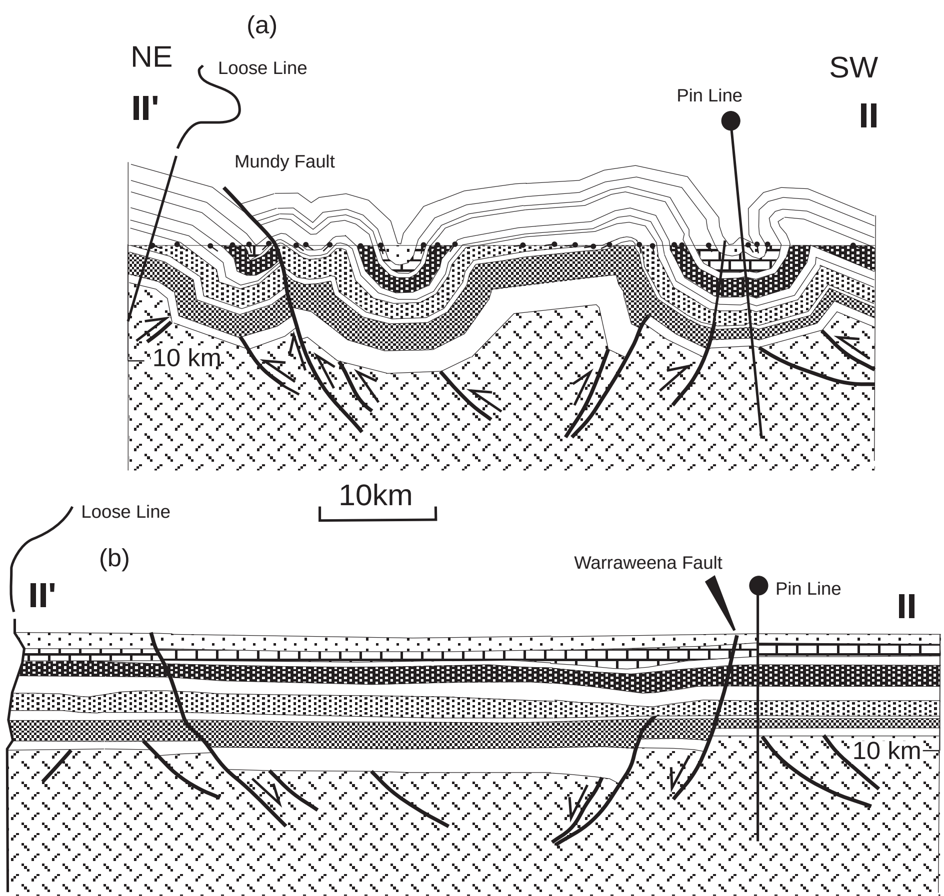

Figure 6 Warraweena– Mundy Faults section (II–II′). (a) Balanced Warraweena–Mundy Faults section shows a pop-up geometry between the two faults. (b) Restored Warraweena–Mundy Faults section. Again strong segmentation of basement with formation of rift graben between both faults. Kinks in loose lines may be due to differential displacement in different sediment packages, variations in internal strain or mobilisation of the Callanna Group. For symbols see Figure 3.

of deformation (Figure 12d). Most of the shortening strain is localised across the Norwest and Paralana Faults, as well as in their hangingwall depocentres, which coincide with the deepest parts of the basin.

In the southern Adelaide Fold-Thrust Belt and the Nackara Arc, Delamerian deformation can be interpreted to result as a consequence of a northwest-tapering orogenic wedge in which sediment thicknesses increase to the southeast. These parts of the orogen thus follow models developed in classic fold-thrust belts in which the orogenic wedge is formed by stacked successions of passive-margin sediments, with tectonic vergence towards the thinner, western foreland part of the orogen (Figure 1). In the northern Flinders Ranges the general distribution of sedimentary rocks (Figure 3) defines a north-tapering sequence, yet the asymmetry of folds indicates an overall southward tectonic transport. Together with the dominance of pop-up geometries, which reflect the reactivation of growth faults (McClay & Buchanan 1992), this suggests that simple orogenic wedge models do not adequately account for the observed structural geometry. We suggest that the geometry may be better described in terms of intracratonic basin inversion, with deformation focused along the structures that define the main depocentres (Figure 12). The overall south-vergent geometry appears to be due to the more pronounced inversion of north-dipping growth faults, with a somewhat less pronounced inversion of south-dipping faults (sections III, IV and VII). The exhumation of the Mt Painter Inlier is mainly controlled by the reactivation of the Paralana Fault (section III), as well as by the reactivation of south-dipping faults bordering the Terrapinna Corridor (section V; Figure 12e). One of the

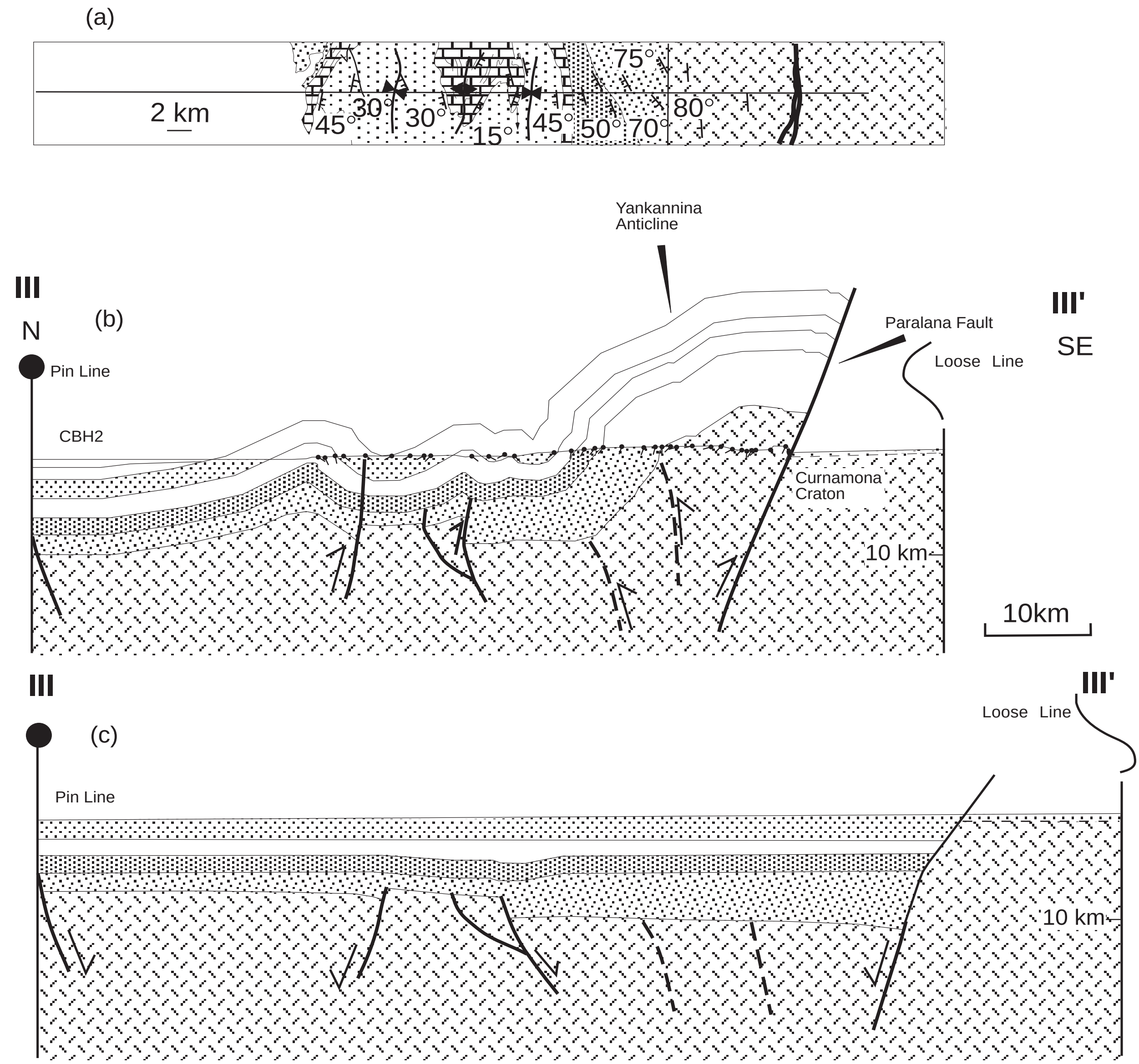

Figure 7 Mt Painter section (III–III′). (a) Simplified strip map showing the geology along the section line. Major anticlines and synclines are marked. Post-Cambrian deposits are unshaded. Solid vertical line indicates change in the orientation of the section line (see also Figure 2). (b) Balanced Mt Painter section. (c) Restored Mt Painter section. Restored section shows the formation of the ‘Yudnamutana Trough’ during Lower Umberatana Group times. Steeply north- and south-dipping basement structures segment the basement and form a wide graben structure separated by the horst structure of the Terrapinna Corridor. For symbols see Figure 3.

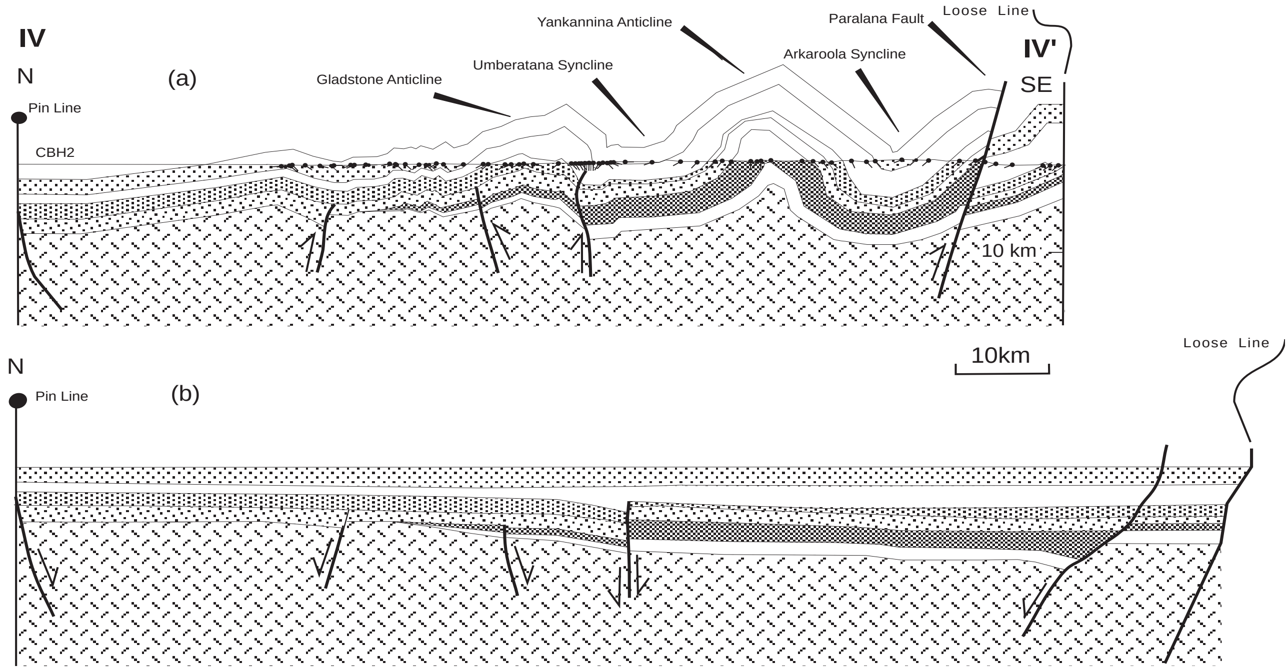

Figure 8 Balcanoona section (IV–IV′). (a) Balanced Balcanoona section. (b) Restored Balcanoona section. In the balanced as well in the restored section the northern pin line corresponds to the location of borehole CBH-2. Restored section shows segmentation of basement during the early rifting periods and the development of a horst and graben system with most of the sediments accumulated in the hangingwall of the Paralana Fault. For symbols see Figure 3.

most surprising features in the northern Flinders Ranges is the intensity of basement involvement given that the average shortening across them is only between 10 and 20%.

In many ways, basement involvement in fold and thrust belts is a poorly understood phenomenon (Rodgers 1987, 1995). In the southern Adelaide Fold-Thrust Belt, basement-involved deformation is observed within an imbricate fan with overall shortening in the order of 50%. The majority of strain, however, is accommodated by local stratigraphically controlled décollements near or at the base of the sedimentary package (Flöttmann *et al.* 1994). In the northern Flinders Ranges, stratigraphically controlled décollements appear to have played only a minor role in the accommodation of strain, although in both parts of the fold belt exhumation of basement is linked to inversion processes along former extensional faults. It is interesting to note that the exposed basement of the Mt Painter Inlier records anomalously high heat flow (Sass & Lachenbruch 1979; Cull 1982), related to extraordinarily elevated heat production rates, especially in the Mesoproterozoic basement gneiss (with a mean heat production of 10 μWm^{-3} and

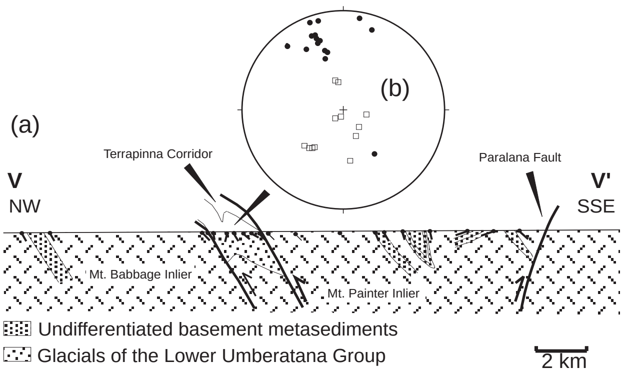

Figure 9 (a) Schematic cross section across the Terrapinna Corridor (V–V′). (b) Lower hemisphere projections of cleavage poles (●), and stretching lineations of sheared glacials in the Terrapinna Corridor (□).

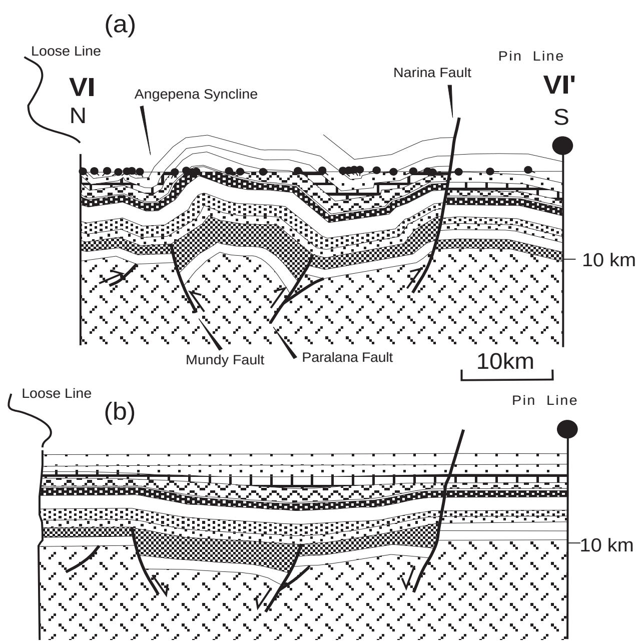

Figure 10 Paralana–Narina Faults section (VI–VI′). (a) Balanced Paralana–Narina Faults section. (b) Restored Paralana–Narina Faults section. For symbols see Figure 3.

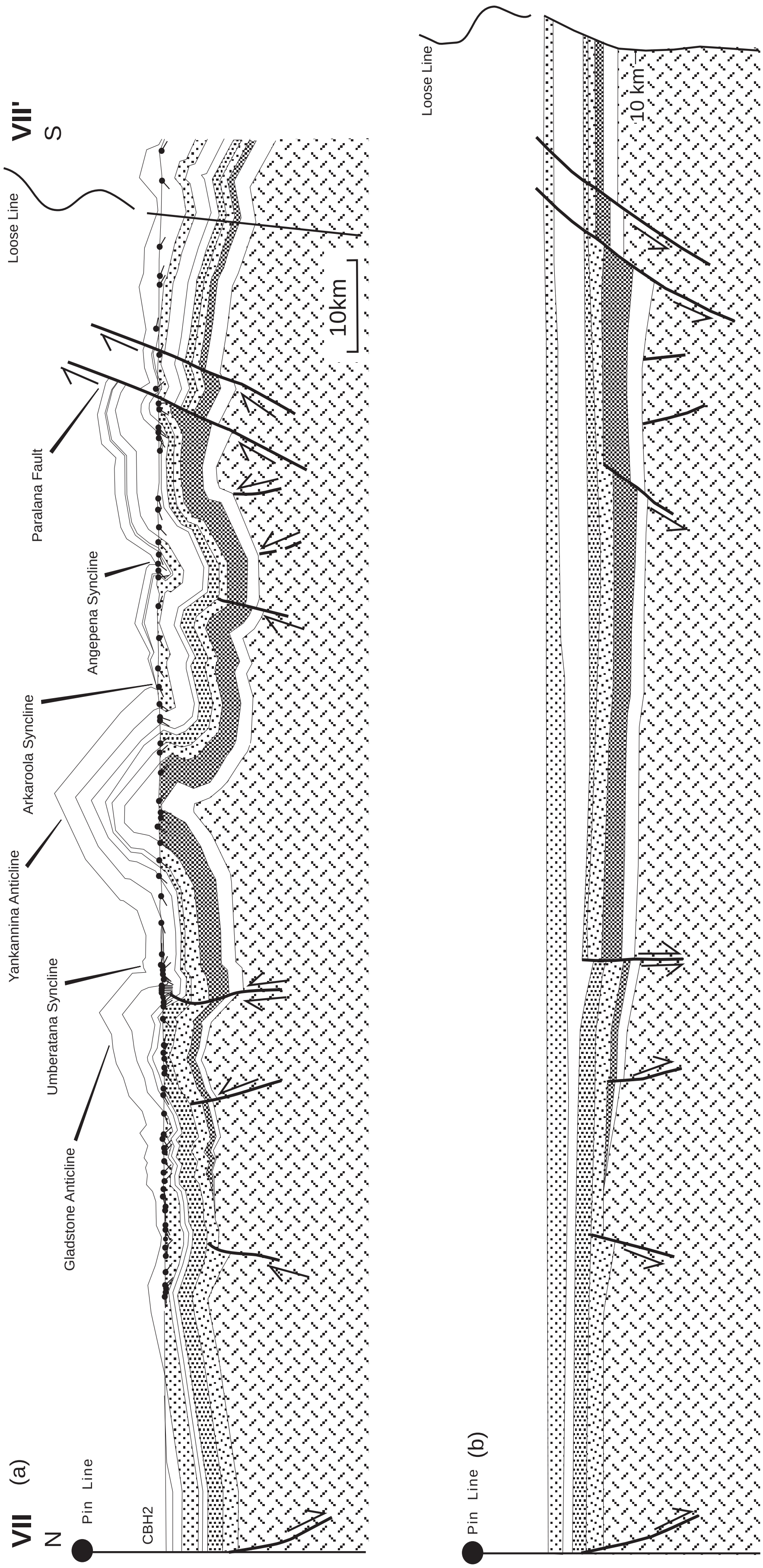

Figure 11 Composite section through the northern Flinders Ranges. (a) Balanced composite section through the northern Flinders Ranges. (b) Restored composite section through the northern Flinders Ranges. For symbols see Figure 3.

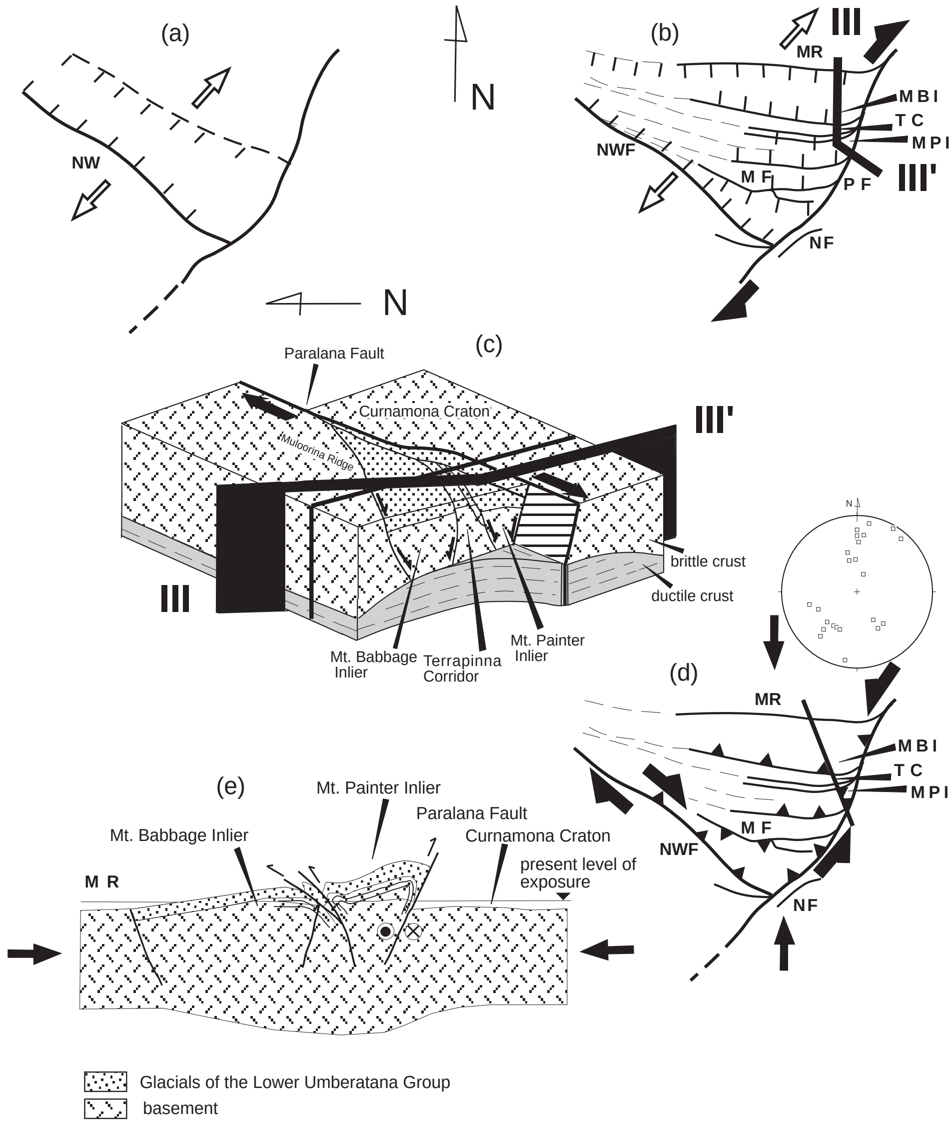

Figure 12 (a, b) Cartoon in scale to Figure 4a, b showing the evolution of the early rift stages in the northern Flinders Ranges. White arrows indicate a constant northeast–southwest extension; thick black arrows indicate the relative movement of the Paralana Fault. Thick black solid line parallels line of section III–III′. (c) Block model illustrating the opening of the Yudnamutana Trough accommodated by synthetic and antithetic splay faults during dextral strike-slip movement along the Paralana Fault. Black solid wall parallels line of section III–III′. (d) Cartoon showing the main reactivated structures during the Delamerian basin inversion. Stereoplot shows lower hemisphere projection of cleavage poles collected throughout the ranges. Black thin arrows indicate the main shortening direction; black thin solid line parallels thin solid line in (c), as well as the interpreted model section across the Terrapinna Corridor in (e). (e) Model section [not in scale to (c, d)] showing the pop-up geometry across the Terrapinna Corridor due to sinistral transpressive inversion, which we suggest as a template for the evolution of the northern Flinders Ranges. NWF, Norwest Fault; MR, Muloorina Ridge; MF, Mundy Fault; NF, Narina Fault; PF, Paralana Fault; MBI, Mt. Babbage Inlier; TC, Terrapinna Corridor; MPI, Mt Painter Inlier.

heat flow as high as 126 mWm^{-2}; Sandiford *et al.* 1995b). Delamerian metamorphic conditions reaching maximum temperatures of 500–550°C at depths of ~10 km (Mildren & Sandiford 1995), recorded by the Burra Group directly above the basement unconformity in the Yankannina Anticline, imply average upper crustal geothermal gradients of ~50°C/km during the Delamerian deformation. Sandiford *et al.* (1989) have noted that this anomalous radiogenic basement heat production in the northern Flinders Ranges has its manifestation in the modern day heat flow of ~90 mWm^{-2}. Importantly, Sandiford *et al.* (1989) have demonstrated that such elevated heat flow will have an important influence on the deformation intensity in the northern Flinders Ranges because of the potentially and profound weakening of the crust and the upper mantle. Sandiford *et al.* (1989) have further shown that this weakening effect will be strongly modulated by the thickness of the sedimentary package. This suggests that the overall structural style of basement-involved deformation as well as variations in deformation intensity in a generally low-strain environment of the northern Flinders Ranges is a consequence not only of the pre-Delamerian basin architecture, but also of the reactivation of highly radiogenic and so thermally weakened basement.

ACKNOWLEDGEMENTS

We thank Wolfgang Preiss, Peter Haines and Pat James for interesting discussions and the Sprigg family in Arkaroola for their generosity and hospitality during our field studies in the Mt Painter region. Wolfgang Preiss is also thanked for comments on an earlier draft of this manuscript. We thank Dick Glen and Mike Fischer for their constructive criticism which helped to improve the manuscript.

REFERENCES

Coney P. J., Edwards A., Hine R., Morrison F. & Windrim D. 1990. The regional tectonics of the Tasman orogenic system, eastern Australia. *Journal of Structural Geology* **12**, 519–543.

Coats R. P. 1969. Mt. Painter Province map sheet. *Geological Survey of South Australia Geological Atlas 1:250 000 Special Series*.

Coats R. P. & Blisset A. H. 1971. Regional and economic geology of the Mt. Painter province. *Geological Survey of South Australia Bulletin* **43**.

Coats R. P. 1973. Copley map sheet. *Geological Survey of South Australia Geological Atlas 1:250 000 Series, sheet H54-9*.

Cull J. P. 1982. An appraisal of Australian heat flow data. *BMR Journal of Australian Geology & Geophysics* **7**, 11–21.

Fanning C. M., Ludwig K. R., Forbes B. G. & Preiss W. V. 1986. Single and multiple grain U–Pb zircon analysis for the early Adelaidean Rooks tuff, Willouran Ranges, South Australia. *Geological Society of Australia Abstracts* **15**, 71–72.

Flöttmann T. & James P. 1997. Influence of basin architecture on the style of inversion and fold thrust belt tectonics—the southern Adelaide Fold-Thrust Belt, South Australia. *Journal of Structural Geology* **19**, 1093–1110.

Flöttmann T., James P., Rogers J. & Johnson T. 1994. Early Palaeozoic foreland thrusting and basin reactivation at the Palaeo-Pacific margin of the southeastern Australian Precambrian Craton: a reappraisal of structural evolution of the southern Adelaide Fold-Thrust Belt. *Tectonophysics* **234**, 95–116.

Forbes B. G. 1965. Marree map sheet. *Geological Survey of South Australia Geological Atlas 1:250 000 Series, sheet H54-5*.

Haines P. W. & Flöttmann T. 1998. Delamerian Orogeny and potential foreland sedimentation: a review of age and stratigraphic constraints. *Australian Journal of Earth Sciences* **45**, 559–570.

Jenkins R. J. F. 1990. The Adelaide Fold Belt: tectonic reappraisal. *Geological Society of Australia Special Publication* **16**, 395–420.

Jenkins R. J. F. & Sandiford M. 1992. Observations on the tectonic evolution of the southern Adelaide Fold Belt. *Tectonophysics* **214**, 27–36.

Lemon N. M. 1985. Physical modelling of sedimentation adjacent to diapirs and comparison with late Precambrian Oratunga breccia body in the Central Flinders Ranges, South Australia. *American Association of Petroleum Geologists Bulletin* **69**, 1327–1338.

McKenzie D. 1978. Some remarks on the development of sedimentary basins. *Earth and Planetary Science Letters* **40**, 25–32.

Mancktelow N. S. 1990. The structure of the southern Adelaide Fold Belt, South Australia. *In*: Jago J. B. & Moore P. S. eds. *The Evolution of a Late Precambrian—Early Palaeozoic Rift complex. The Adelaidean Geosyncline,* pp. 369–395. Geological Society of Australia Special Publication **16**.

Marshak S. & Flöttmann T. 1996. Structure and origin of the Fleurieu and Nackara Arcs in the Adelaide fold-thrust belt, South Australia: salient and recess development in the Delamerian Orogen. *Journal of Structural Geology* **7**, 891–908.

McClay K. R. & Buchanan P. G. 1992. Thrust faults in inverted extensional basins. *In*: McClay K. R. ed. *Thrust tectonics*, pp. 93–104. Chapman & Hall, London.

Mildren S. & Sandiford M. 1995. Heat refraction and low-pressure metamorphism in the northern Flinders Ranges, South Australia. *Australian Journal of Earth Sciences* **42**, 241–247.

Offler R. & Fleming P. D. 1968. A synthesis of folding and metamorphism in the Mt. Lofty Ranges, South Australia. *Journal of the Geological Society of Australia* **15**, 245–266

Preiss W. V. (Compiler) 1986. *Adelaide Geosyncline and Steward shelf: Precambrian and Palaeozoic Geology (with special reference to the Adelaidean). 1:600 000 scale*. Department of Mines and Energy, Adelaide.

Preiss W. V. 1987. The Adelaide Geosyncline—late Proterozoic stratigraphy, sedimentation, palaeontology and tectonics. *Geological Survey of South Australia Bulletin* **53**.

Preiss W. V. 1993. Neoproterozoic. *In:* Drexel J. F., Preiss W. V. & Parker A. J. eds. *The Geology of South Australia,* Vol. I, pp. 171–203. Geological Survey of South Australia, Adelaide.

Preiss W. V. 1995. Delamerian Orogeny. *In:* Drexel J. F. & Preiss W. V. eds. *The Geology of South Australia,* Vol. II, pp. 45–61. Geological Survey of South Australia, Adelaide.

Rodgers J. 1987. Chains of basement uplifts within cratons marginal to orogenic belts. *American Journal of Science* **287**, 661–692.

Rodgers J. 1995. Lines of basement uplift within the external parts of orogenic belts. *American Journal of Science* **295**, 455–487.

Sandiford M., Bingemer A. & Hand M. 1995b. Basement involved deformation, heat production and low-pressure metamorphism in the Adelaide Fold Belt and some wider implications. *Geological Society of Australia Abstracts* **40**, 146.

Sandiford M., Foden J. D., Zhou S. & Turner S. P. 1992. Granite genesis and mechanisms of convergent orogenic belts with application to the Southern Adelaide Fold Belt. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **83**, 83–93.

Sandiford M., Fraser G., Arnold J. & Farrow P. 1995a. Some causes and consequences of high-T and low-P metamorphism in the Eastern Mount Lofty Ranges, South Australia. *Australian Journal of Earth Sciences* **42**, 233–240.

Sandiford M., Paul E. & Flöttmann T. Sedimentary thickness variations and deformation intensity during basin inversion in the Flinders Ranges, South Australia. *Journal of Structural Geology* **20**, 1721–1731.

Sass J. H. & Lachenbruch A. H. 1979. The thermal regime of the Australian continental crust. *In:* McElhinny M. W. ed. *The Earth—its Origin, Structure and Evolution.* Academic Press, London.

Sprigg R. C. 1952. Sedimentation in the Adelaide Geosyncline and the formation of a continental terrace. *In:* Glaessner M. F. & Sprigg R. C. eds. *Sir Douglas Mawson Anniversary Volume*, pp. 153–159. University of Adelaide, Adelaide.

Woodward N. B., Boyer S. E. & Suppe J. 1989. Balanced geological cross sections: an essential technique in geological research and exploration. *American Geophysical Union Short Course in Geology* **6**.

Received 30 January 1998; accepted 14 October 1998