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Influence of basin architecture on the style of inversion and fold–thrust belt tectonics—the southern Adelaide Fold–Thrust Belt, South Australia

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Abstract—The southern Adelaide Fold–Thrust Belt involves Neoproterozoic (Adelaidean) strata deposited during protracted rift and sag phases, and an overlying Cambrian (Kanmantoo) sequence represented by a thick wedge of turbidites, rapidly deposited in an eastwards-deepening basin, deeply incised into the underlying rocks. The belt was deformed during the Delamerian orogeny, developed at the southeastern margin of the Australian craton during early Palaeozoic NW-directed displacement. During this shortening event the margin of the Kanmantoo Basin was reactivated and formed a significant strain guide that controlled key features of the fold–thrust belt.

Strain-integrated and restored sections reveal contrasting geometric and kinematic styles along the strike of the belt. A transpressional zone is developed at the steep basin margin in the south, oriented oblique to the structural grain. The central parts of the belt are dominated by strong buttressing, growth fault reactivation and basement-involved footwall shortcut thrusting. In the northern part of the belt, shortening is accommodated by homogeneous folding above a master décollement. These variations in regional structural style and internal strain partitioning reflect significant variations in the original Kanmantoo Basin margin geometry.

Rheological parameters control the partitioning of strain associated with pervasive fabrics, for example cleavage and transposed bedding. Folding is accompanied by negative line-length changes (shortening) in the northern part of the belt. In its thrusted central part, pelites commonly show positive line-length changes. Psammites were least affected by line-length changes and thus provide key beds for section balancing. Pervasive strain makes a full restoration of cross-sections impossible. However, incorporating regional strain data assists establishment of balanced and restorable sections, which provide a powerful tool in understanding both pre-deformational basin geometry and its shortening. © 1997 Elsevier Science Ltd.

INTRODUCTION

The external parts of many orogens are formed by fold–thrust belts which displace the infill of pre- or synorogenic sedimentary basins towards the cratonic foreland. Classic examples of such basin inversion in foreland fold–thrust belts include the Appalachians, Rocky Mountains, Alps and Himalayas (Pfiffner, 1981; Price, 1981; Mitra, 1988; Jadoon *et al.*, 1994). Additional structural complexity in fold–thrust belts often results from the contractional reactivation of fault systems that were active during sediment deposition and controlled the geometry of the margins and internal architecture of sedimentary basins (Butler, 1989; McClay and Buchanan, 1992).

We present evidence of the significance of original basin architecture during contractional deformation in the foreland portion of the southern Adelaide Fold–Thrust Belt of southeast Australia. This evidence is based on regional re-mapping of major thrust sequences, finite-strain analysis and section balancing. The Adelaide Fold–Thrust Belt (Fig. 1) flanks the eastern margin of cratonic southeast Australia, and contains rocks that were deposited in two sedimentary basins that were superposed during successive depositional episodes and subsequently deformed and metamorphosed during the early Palaeozoic Delamerian orogeny (Thomson, 1969a; Mancktelow, 1990; Jenkins and Sandiford, 1992). The older Adelaidean Basin overlies Mesoproterozoic basement and is filled by northwards-thickening successions of dominantly clastic sedimentary rocks including glacio-marine deposits. These are successively overlain by Lower Cambrian platformal deposits of the Normanville Group and the Middle Cambrian Kanmantoo Group, which is generally attributed to a turbiditic depositional environment (Daily and Milnes, 1973). The Kanmantoo Basin is strongly curved in the Fleurieu Arc and forms an apparent syntaxial bend towards the foreland (the Fleurieu Arc, Fig. 1).

The superposed Neoproterozoic Adelaidean and Cambrian Kanmantoo Group rocks form the transition from the Archaean through to the Mesoproterozoic cratons that form the western part of Australia to the early to middle Palaeozoic sedimentary prisms characteristic of the younger Phanerozoic orogens of the Tasman Fold Belt of eastern Australia (Coney *et al.*, 1990; Glen, 1992). In particular the strongly incised western margins of the Adelaidean and Kanmantoo basins form the demarcation (the "Torrens Hinge Line" of Thomson, 1969a) between areas strongly deformed during the Delamerian orogeny and little or undeformed veneers of platformal rocks that overlie the cratonic basement further to the west.

Apart from regional structural descriptions (Jenkins, 1990; Mancktelow, 1990; Flöttmann *et al.*, 1994; Marshak and Flöttmann, 1996) or detailed descriptions of local deformation features (Talbot, 1963; Mills, 1973; Steinhardt, 1991; Flöttmann *et al.*, 1995), a comprehensive study of structural style and partitioning of shortening strain in the southern Adelaide Fold–Thrust Belt has not yet been attempted.

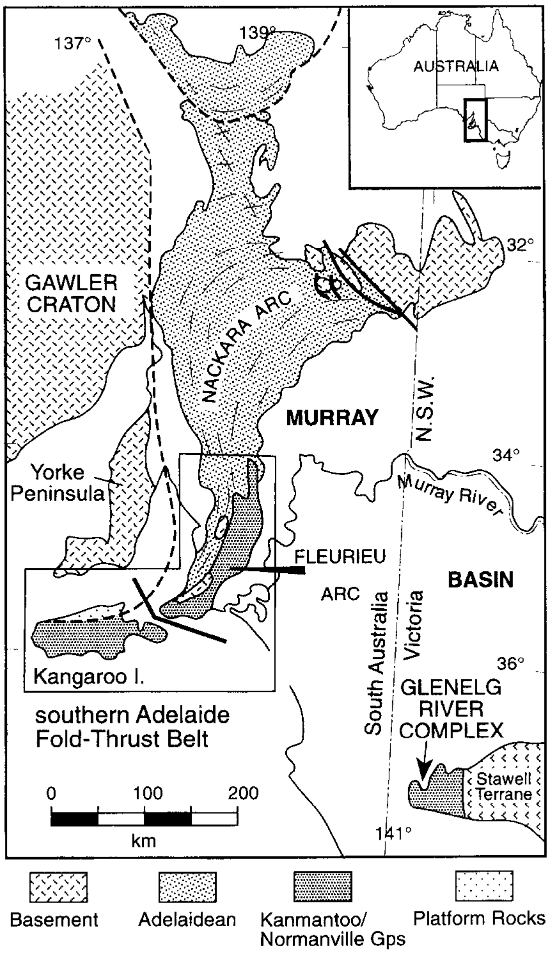

Fig. 1. Principal elements of the Delamerian orogen in South Australia. The box outlines the southern Adelaide Fold–Thrust Belt given in Fig. 2. The location of the seismic transect of Fig. 3 is given by a solid line between Fleurieu Peninsula and Kangaroo Island.

Here we give a synthesis of the tectonic evolution of the southern Adelaide Fold–Thrust Belt that is based on five line-length balanced and restored cross-sections across critical parts of the belt. The key advantage in attempting to apply the balancing/restoration technique is to produce geologically viable and restorable cross-sections which furthermore may also provide insights into key geometric features of the sedimentary basin prior to the onset of orogenic contraction. Rocks of the southern Adelaide Fold–Thrust Belt are affected to varying degrees by pervasive fabrics. To validate the cross-sections further, we therefore incorporated regional strain data where possible. Our results suggest that the balancing and restoration of cross-sections is a useful method to constrain the amount and geometry of shortening even in more pervasively deformed parts of fold–thrust belts. Partitioning of strain related to orogenic contraction in the southern Adelaide Fold–Thrust Belt is strongly influenced by two factors, namely the pre-existing basin margin configuration and the lithological variations.

TECTONIC SETTING

The Delamerian orogen (which includes the southern Adelaide Fold–Thrust Belt and its northern extension the Adelaide Fold Belt) in Australia, and the formerly contiguous Ross orogen in Antarctica, record the onset of Palaeozoic convergence along the proto-Pacific margin of Gondwana (Flöttmann *et al.*, 1993) and the accretion of outboard volcanic arc terranes. Contractional orogenesis, however, was preceded by Neoproterozoic continental extension. This appears related to a fundamental rift–drift event that presumably separated the North American and eastern Gondwana cratons and thereby formed the continental margin of eastern Australia and Antarctica (Dalziel, 1991; Moores, 1991). Repeated Neoproterozoic rift and sag phases (Von der Borch, 1980; Jenkins, 1990) between ~800 and ~540 Ma (Fanning *et al.*, 1986; cf. Cooper *et al.*, 1992) are evidenced by deposition of the thick sequence of well-stratified glaciomarine Adelaidean rocks which overlie and onlap the Mesoproterozoic basement in South Australia. Subsequent to the deposition of Early Cambrian platformal rocks, renewed but localized Cambrian extension is attested by the deposition of the Middle Cambrian Kanmantoo Group at the southeastern exposed margin of Adelaidean rocks. The Kanmantoo Group comprises marine turbidites that were rapidly deposited between 526 and 518 Ma (Sandiford *et al.*, 1992; Foden, personal communication) in the Kanmantoo Trough (Daily and Milnes, 1973; Flöttmann *et al.*, 1994; Flöttmann and Cockshell, 1996).

During the Delamerian orogeny both the Neoproterozoic Adelaidean and the Cambrian basins were deformed in the Adelaide Fold–Thrust Belt. The northern part of this fold–thrust belt is formed by the antitaxial (see Marshak, 1988) Nackara Arc (Fig. 1) (Rutland *et al.*, 1981; Marshak and Flöttmann, 1996), which consists mainly of thick Neoproterozoic rocks of very low to low metamorphic grade (Bell, 1978). The structure of the Nackara Arc is characterized by distributed strain which is expressed by map-scale, open folds formed above a basal detachment that is only emergent along the western boundary of the fold–thrust belt (Marshak and Flöttmann, 1996). Deformation in the Nackara Arc characteristically does not involve basement (Marshak and Flöttmann, 1996).

More or less coincident with the occurrence of the Kanmantoo Group, the along-strike orogenic infrastructure changes dramatically. The term *southern* Adelaide Fold–Thrust Belt is applied from the northern outcrop margin of the Kanmantoo trough to the southernmost outcrops of the Delamerian orogen on Kangaroo Island approximately 220 km to the south (Fig. 2). The southern Adelaide Fold–Thrust Belt includes a zone of exposed basement inliers, which form an elongate culmination (Jenkins, 1990). This basement culmination occurs almost exclusively to the west of the Kanmantoo Group, which is in fault contact with the basement on

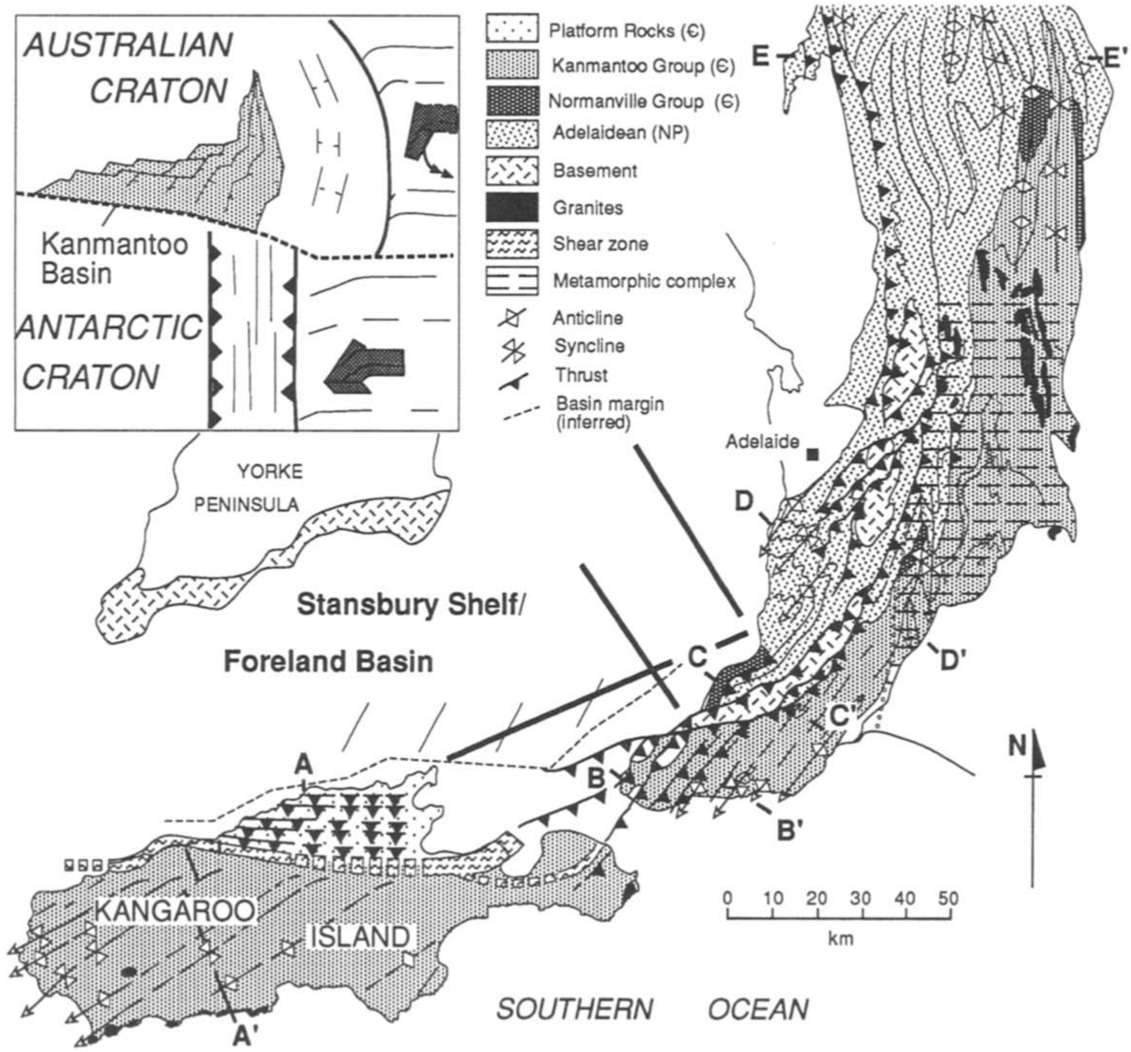

Fig. 2. Simplified structure of the southern Adelaide Fold–Thrust Belt, Fleurieu Peninsula and Kangaroo Island. Solid lines between Yorke and Fleurieu peninsulas give the location of additional seismic lines (MESA, 1992) utilized in the interpretations given in this paper. The northern margin of the Kangaroo Island platform is interpreted from aeromagnetic data. Inset sketches contrast tectonic scenarios at Antarctic and Australian segments of the palaeo-Pacific margin during the early Palaeozoic. The Antarctic margin is characterized by significant and protracted upper-plate shortening possibly related to a shallow subduction angle. The Australian margin is characterized by significant upper-plate extension possibly related to roll-back of the down-going slab and only episodic shortening. The different amounts of net upper-plate shortening along the advancing (Antarctic) and retreating (Australian) segments of this margin (compare Royden, 1993) are accommodated along a large-scale strike-slip fault (stippled) which controls the geometry of the southern Kanmantoo basin. Є, Cambrian; NP, Neoproterozoic.

southern Fleurieu Peninsula. Elsewhere a northwards-widening wedge of Adelaidean rocks occurs between the Kanmantoo Group and the basement inliers. The western margins of the basement inliers are mostly formed by emergent, gently E-dipping reverse faults. Similarly, a continuous fault system has been postulated by Clarke and Powell (1989) who suggested the Kanmantoo Group to be an allochthonous unit, a significant portion of which is of higher metamorphic grade than the underlying Adelaidean rocks. These elevated metamorphic grades are confined to the eastern part of the southern Adelaide Fold–Thrust Belt where Buchan style metamorphism is related to the intrusion of synkinematic granites (Mancktelow, 1990; Dymoke and Sandiford, 1992; Jenkins and Sandiford, 1992). In this eastern metamorphic belt, multiple, but mainly homoaxial, deformation occurs (Offler and Fleming, 1968; Mills, 1973; Marlow and Etheridge, 1977; Fleming and White, 1984; Mancktelow, 1990).

Recent work (Flöttmann *et al.*, 1994) suggests that the Kanmantoo Group was deposited during southeastwards-increasing subsidence controlled by growth faults that were subsequently reactivated during the Delamerian orogeny. Major faults also delineate the spectacular 90° bend of the southern margin of the Kanmantoo Basin which trends southerly for about 160 km but trends west for about 200 km on Kangaroo Island and southern Fleurieu Peninsula (Figs 1 & 2). This basin shape is a consequence of a formerly postulated and recently confirmed syndepositionally active strike-slip regime at

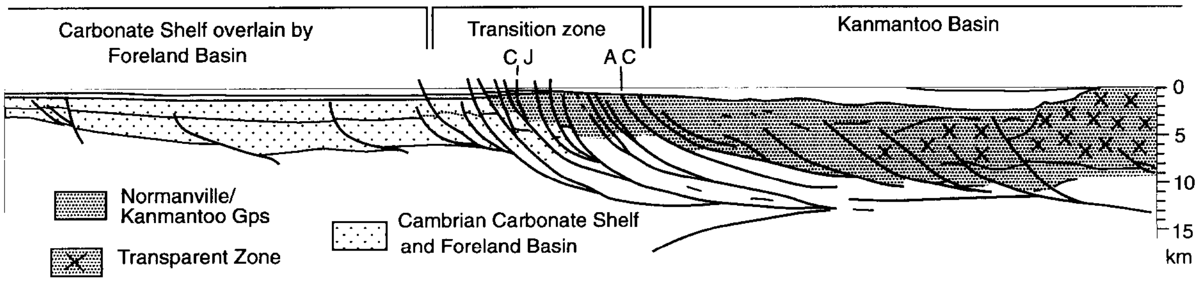

Fig. 3. Interpretation of offshore seismic survey through Backstairs Passage (after Flöttmann and Cockshell, 1996; Flöttmann *et al.*, in press) (see Fig. 1). Notice prominent faults in the transition zone between the carbonate shelf and the Kanmantoo Basin. Transparent zone shows few reflectors and is interpreted to consist of late to post-kinematic granites. CJ, Cape Jervis; AC, Aaron Creek shear zone. Vertical = horizontal scale.

the boundary of the now separated Antarctic and Australian continents (Baillie, 1985; Flöttmann, 1994) (see the inset in Fig. 2).

At the southern part of the exposed Kanmantoo Basin the total thickness of Kanmantoo Group rocks is in excess of 8 km, but the underlying Adelaidean rocks are only 1–2 km thick. To the west, the rocks of the Kanmantoo Basin are flanked by a Cambrian platform sequence as imaged by seismic surveys in the Gulf St Vincent (Flöttmann and Cockshell, 1996) (Figs 2 & 3). Platformal successions may be overlain by a foreland basin succession of Upper Cambrian age (Flöttmann *et al.*, in press). On northern Kangaroo Island the platform is constituted by a Middle Cambrian clastic sequence (Kangaroo Island Group, Daily *et al.*, 1980). At its northernmost outcrop limit the Kanmantoo Group is less than 3 km thick. Here Cambrian strata occur in the core of the Karinya Syncline where they are fully enclosed in a thick sequence (> 9 km) of Adelaidean rocks and with no basement involved in the regional deformation.

The relationships outlined above suggest that there is a spatial coincidence between the depositional style of the Kanmantoo Group, emergent thrusting, basement involvement and, perhaps to a lesser extent, higher metamorphic grade. In particular the occurrence of basement inliers is a common feature in otherwise thin-skinned (i.e. basement-detached) fold–thrust belts, but the role of their involvement in the orogenic shortening is often poorly understood (Hatcher and Hooper, 1992; Rodgers, 1995).

Here we examine the three-dimensional responses to Delamerian orogenic contraction in the southern Adelaide Fold–Thrust Belt and attempt to test if some key aspects of the structural style may be the product of the variation in basin geometry and the variable basin-margin configuration of the Kanmantoo Basin and its subsequent reactivation.

Based on previous mapping (Mancktelow, 1981, 1990; Flöttmann *et al.*, 1995; Preiss, 1995) we have subdivided the southern Adelaide Fold–Thrust Belt from south to north into five domains. These are: (a) the Kangaroo Island domain, which is characterized by an E–W-trending margin of the Kanmantoo Basin; (b) the Southern Fleurieu domain, characterized by a wide zone of distributed basin margin reactivation; (c) the Myponga–Normanville domain, characterized by basement-involved reactivation of both platform and the Kanmantoo Basin; (d) the Central Fleurieu Peninsula domain (Adelaide region), where thicker Adelaidean strata are wedged between basement and the Kanmantoo Basin; and (e) the Karinya domain, where Kanmantoo Group strata are enclosed within the Adelaidean strata, and basement is not involved in the deformation. Each domain illustrates a different response to Delamerian contraction, and each appears controlled by a different architecture of the original basin.

SECTION BALANCING AND STRAIN ANALYSIS

Balanced cross-sections provide a powerful tool in establishing the geometry of deformed rock packages (e.g. Sanderson, 1982; Woodward *et al.*, 1986, 1989; Geiser, 1988; Mitra and Wojtal, 1988; Mitra and Fisher, 1992). Balanced cross-sections can only be established precisely in rocks that lack pervasive internal strains. Pervasive deformation leads to significant geometric rearrangement expressed by the formation of pervasive fabrics in addition to the 'geometric' shortening expressed by the meso- or mega-scale structures. In more intensely deformed rocks the validity of cross-sections and their restoration should be tested by an assessment of 'internal' strain taken up by the formation of pervasive fabrics (Woodward *et al.*, 1986; Protzman and Mitra, 1990; Gray and Willman, 1991; Dittmar *et al.*, 1994; Mitra, 1994; Kirkwood, 1995; Gray, 1995).

Metamorphic grade in the southern Adelaide Fold–Thrust Belt increases eastward. Very low (chlorite) grade is dominant in the west; biotite grade occurs mainly east of the basement inliers and amphibolite-grade metamorphism with local migmatization is reached in the easternmost parts of the belt. We have attempted to produce balanced cross-sections in rocks of chlorite–biotite grade where pervasive deformation is expressed by the formation of axial-planar cleavages and by transposed bedding. Many regional fault and thrust

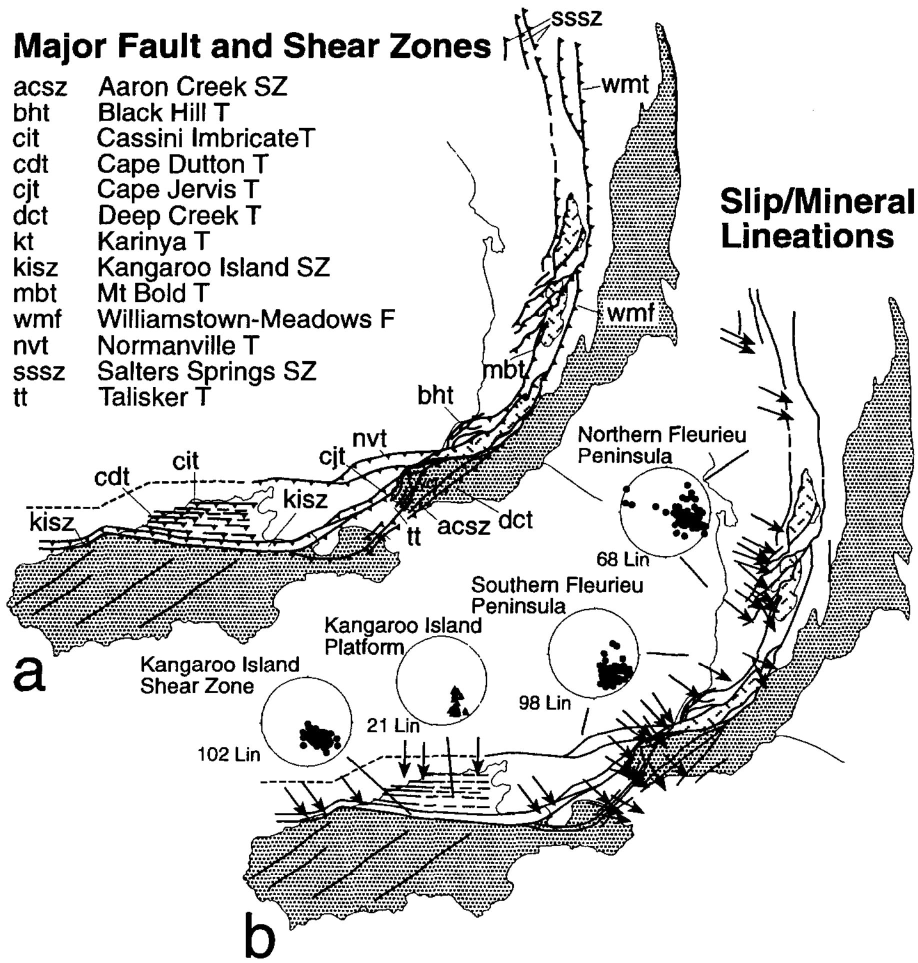

Fig. 4. (a) Synoptic map of major mapped thrust and fault systems in the southern Adelaide Fold–Thrust Belt. (b) Distribution and stereographic presentation of displacement-related lineations.

zones were recognized for the first time during this study and are shown in Fig. 4(a).

Regional strain analyses were carried out at about 200 locations along the transects through the southern Adelaide Fold–Thrust Belt. The strain data are used to determine relative changes in line length due to internal strains that developed as a consequence of cleavage formation or transposition of bedding.

In sequences with a pronounced stratification of units of contrasting rheological properties, strain analyses were used to establish the average change of line length for each lithology of the sedimentary pile (cf. Mitra, 1994; Von Winterfeld and Oncken, 1995). Lithological contrasts are less pronounced in the turbiditic sediments of the Kanmantoo Group, and here the dominant bulk lithology (i.e. impure and gritty sandstones) was sampled preferentially, as suggested by Dittmar *et al.* (1994).

Strain data were obtained using the R_f/ϕ and Fry methods or using pressure shadows around rigid grains. Throughout the southern part of the fold–thrust belt, strains are variable with a slight dominance of flattening (Fig. 5, see also Table 1) suggesting possible volume loss during deformation. Geochemical analyses indicate volume losses in the range of 10–20% (Gessner, 1996). In the north, where shortening is mainly accommodated by folding, plane strain is dominant. Elongations used to derive principal line-length changes were calculated using the equations given by Von Winterfeld and Oncken (1995).

Cross-sections were constructed parallel to the local displacement vectors (Fig. 4b). The foreland-ward pin line is always the left margin of each section. In all sections vertical and horizontal scales are equal. The hinterland-ward part of sections A–A′, C–C′ and D–D′ is not fully balanceable/restorable owing to limited outcrop. Sections on northern Kangaroo Island and the southern Fleurieu Peninsula are based on almost fully outcropping coastal exposures. These sections include some section offsets due to interruptions of the across-strike outcrop. The balancing and restoration were carried out on competent key marker horizons in which line-length changes due to internal strain are minimal, whereas less competent units were balanced and restored using the available strain data. Thicknesses of individual stratigraphic units were measured where possible, otherwise thickness estimates rely on the compilation by Preiss

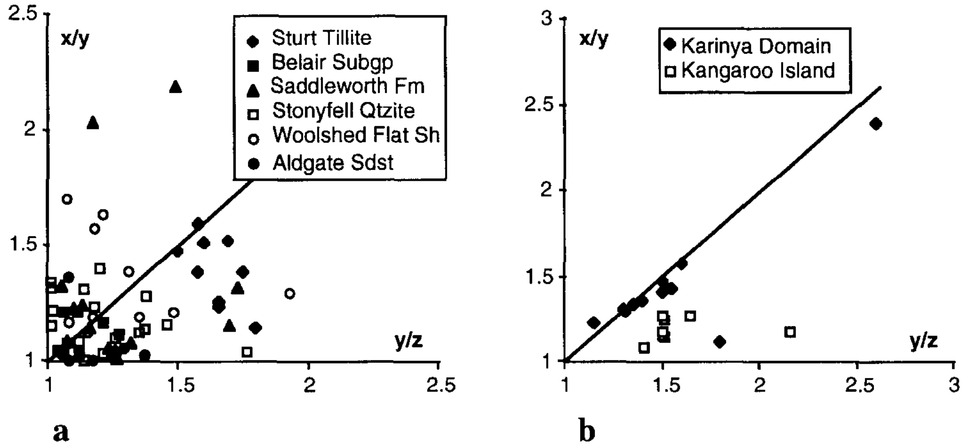

Fig. 5. Flinn diagram of strain analyses (see Table 1). (a) Strain geometries of the different lithologies of the Burra Group. (b) Dominantly plane-strain geometry of the Karinya Domain and flattening strain geometries of the Mt McDonnell Formation on Kangaroo Island.

(1987, 1995). Even by integrating the available strain data, sections may not be fully restorable due to pervasive strains. Strain integration, however, helps to minimize strain-compatibility problems between lithologies with contrasting mechanical behaviour.

THE KANGAROO ISLAND DOMAIN—OBLIQUE WRENCHING

Kangaroo Island consists of three contrasting stratotectonic zones: the Kangaroo Island platform in the north; the central Kangaroo Island shear zone; and the basinal zone in the south (Flöttmann *et al.*, 1995) (Figs 2 & 6).

Drillholes on the Kangaroo Island platform (Belperio and Hibburt, 1994) show that Mesoproterozoic basement is unconformably overlain by siltstones and shales of the Mt McDonnell Formation (~650–1300 m in thickness), the basal unit of the Kangaroo Island Group (Daily *et al.*, 1980) which is overlain by the Stokes Bay Sandstone (700 m). As Kangaroo Island Group rocks outcrop only along the coast, the section of Fig. 6(a) is a composite of several dog-legged subsections.

Fibres, slickensides and mineral-slip lineations on the Kangaroo Island platform (Fig. 4b) give consistently down-dip, due N- to NNE-(010°) directed, displacement vectors. Significantly oblique displacement components appear absent on the Kangaroo Island platform.

Across the Kangaroo Island platform, the macroscopic structures (Figs 4 & 6a) show a northward waning of deformation intensity. Between the thrusts at the southern part of the Kangaroo Island platform, strata are deformed by tight, N-verging, asymmetric chevron folds. Fold limbs can be sheared along a pervasive cleavage, which dips at 70–80°S. Throughout the Kangaroo Island platform, deformation on a granular scale is dominated by diffusional processes. Local occurrences of quartz subgrains and deformation lamellae suggest that deformation took place mainly in the brittle–ductile transition.

North of the Cape Dutton Thrust (Fig. 4a), indications of pervasive deformation are absent and layering dips only gently southward. Here shortening is accommodated by localized imbricate thrusts, in the hangingwall of which layering steepens into parallelism with the 45–55°S-dipping thrust planes (Fig. 6a). The northernmost Cassini Thrust is accompanied by a leading imbricate fan, in which five reverse faults are spaced about 100 m from each other (Fig. 4a).

Throughout the Kangaroo Island platform, internal strains are low (see Fig. 6a) and strain increases slightly in the hangingwall of individual thrusts. Using the average of internal strains the Mt McDonnell Formation shows a negative line-length change of −5% (Fig. 6b, inset column). In the Stokes Bay Sandstone, pervasive fabrics are absent. Measured ellipticities of passive markers show subhorizontal (X) long axes. This suggests that the observed ellipticities are a compaction phenomenon rather than being induced by orogenic strain. In essence, neither formation displays a significant change in line length due to internal strain. The 30% overall shortening indicated by comparing the restored and deformed section of Fig. 6(a & b) is thus mainly due to geometric shortening accommodated by folding and faulting. The majority of the northern zone is detached above the basement, but basement is inferred to be involved in the deformation north of the Kangaroo Island shear zone.

The steeply S-dipping Kangaroo Island shear zone separates the northern platformal and the southern basinal part of the island. The shear zone can reach thicknesses of up to 2 km and the tectonites are of mid to upper greenschist-facies metamorphic grade, but of uncertain stratigraphic position. Details of the internal character of the shear zone are described in Flöttmann *et al.* (1995). All kinematic indicators along the Kangaroo Island shear zone indicate NW-directed transpressional kinematics. The principal displacement vector plunges

Table 1. Strain data

Sample No.	E (°)	$R(X/Z)$	$R(Y/Z)$	$1+e_1$	$1+e_3$	dL (%)
Sturt Tillites						
93521c	85	2.42	1.60	1.54	0.64	−36.1
93522	83	2.57	1.69	1.57	0.61	−38.4
9110154	84	2.52	1.58	1.59	0.63	−36.6
9110155	57	2.08	1.66	1.38	0.66	−24.7
9110153	68	2.21	1.50	1.48	0.67	−28.8
911015-3	90	2.04	1.66	1.36	0.67	−33.4
911015	54	2.19	1.58	1.45	0.66	−22.4
9110155	73	1.80	1.80	1.22	0.68	−30.3
9110153	73	2.42	1.75	1.50	0.62	−35.9
Matt 177	90	2.05	1.80	1.33	0.65	−35.3
Belair Subgroup						
v108	35	1.41	1.21	1.07	0.82	−4.0
v109	35	1.15	1.12	1.06	0.92	0.5
v110	35	1.41	1.27	1.10	0.80	−3.1
v111	35	1.09	1.04	1.00	0.96	−1.6
v92	63	1.28	1.06	1.16	0.90	−5.8
Saddleworth Formation						
R158	12	1.39	1.05	1.23	0.88	20.1
R26	58	1.40	1.13	1.20	0.86	−7.6
R300	23	2.37	1.17	1.69	0.71	29.2
v98	32	1.29	1.23	1.11	0.86	1.5
v99	32	1.29	1.26	1.10	0.85	0.7
K63	40	2.27	1.73	1.44	0.63	−12.7
k220	10	3.26	1.49	1.92	0.59	69.4
se 2110	42	1.42	1.32	1.09	0.80	−7.1
se2111	40	1.32	1.26	1.11	0.84	−2.5
se 2112	22	1.35	1.10	1.22	0.90	15.3
sf 222	40	1.16	1.07	1.08	0.93	1.0
911089	14	1.96	1.70	1.31	0.67	21.5
CE 215	23	1.28	1.27	1.09	0.85	3.8
C 217	27	1.33	1.16	1.15	0.87	6.8
Stonyfell Quartzite						
R28	21	1.35	1.01	1.22	0.90	15.8
R157	39	1.45	1.18	1.21	0.84	1.1
R160	39	1.14	1.14	1.04	0.92	−1.2
R161	75	1.49	1.14	1.25	0.84	−14.6
R145	22	1.34	1.11	1.17	0.88	11.3
R81	66	1.15	1.07	1.07	0.93	−4.7
R221a	23	1.33	1.01	1.21	0.91	14.0
k168,1	70	1.25	1.21	1.09	0.87	−11.0
k171	20	1.83	1.76	1.19	0.68	6.8
K183.2	60	1.24	1.02	1.05	0.88	−8.9
k185	50	1.51	1.35	1.19	0.79	−10.0
k227	70	1.21	1.12	1.07	0.88	−10.3
k237	75	1.16	1.01	1.10	0.95	−4.3
v107	66	1.55	1.37	1.21	0.78	−18.1
sf21-1	16	1.76	1.38	1.03	0.74	−0.7
sf22-3	54	1.38	1.26	1.15	0.83	−9.0
BS 128	12	1.68	1.20	1.33	0.79	27.9
CW 218	30	1.69	1.46	1.25	0.74	3.3
Woolshed Flat Shale						
R82	19	1.39	1.17	1.18	0.85	12.7
R223	24	1.26	1.08	1.14	0.90	8.5
R186	26	1.97	1.21	1.47	0.75	18.3
sj232	10	1.60	1.35	1.24	0.77	20.9
v94	32	1.81	1.31	1.36	0.75	6.0
MBE 152	11	1.29	1.15	1.13	0.88	11.7
BS 122	5	1.80	1.48	1.30	0.72	28.4
R273	14	1.82	1.07	1.46	0.80	36.7
9110227	2	3.83	2.97	1.70	0.44	68.8
9110221	15	2.50	1.93	1.48	0.59	27.2
R333	6	1.85	1.18	1.43	0.77	40.7
Aldgate Sandstone						
R340	20	1.10	1.06	1.05	0.95	3.2
k165	35	1.47	1.08	1.26	0.86	7.2
sj 241	60	1.17	1.17	1.05	0.90	−6.7
v93	70	1.36	1.29	1.13	0.83	−14.8
v102	80	1.40	1.37	1.13	0.80	−18.9
MB200	69	1.08	1.08	1.03	0.95	−4.1
k246	80	1.08	1.05	1.01	0.96	−4.0
Karinya domain						
94451	2	6.20	2.60	2.45	0.4	141.3
94452	75	1.80	1.35	1.34	0.74	−23.8
94455	69	2.20	1.50	1.48	0.64	−29.1
94456	76	1.40	1.15	1.19	0.86	−13.4
944510	60	1.70	1.31	1.30	0.8	−16.3
94489	69	2.20	1.55	1.46	0.65	−29.9
94484	74	2.50	1.60	1.57	0.61	−34.9
94485	65	1.70	1.30	1.30	0.78	−18.3
94485b	65	2.10	1.50	1.43	0.68	−26.5
94485	65	2.00	1.80	1.30	0.65	−29.9
94485c	65	1.90	1.40	1.37	0.65	−22.7
Kangaroo Island Mt McDonnell Formation						
931143	22	2.08	1.65	1.38	0.66	13.0
95198	32	1.53	1.41	1.18	0.77	0.7
931151	25	2.53	2.16	1.44	0.57	2.5
931136	34	1.73	1.51	1.19	0.70	−5.9
95191a	58	1.72	1.50	1.25	0.73	−19.2
95191	51	1.75	1.50	1.27	0.72	−15.3
95193	45	1.87	1.51	1.32	0.71	−11.0
95195	42	1.90	1.50	1.34	0.71	−9.0

E, the angle between the x-axis of the strain ellipse and bedding; $R(X/Z)$ and $R(Y/Z)$ give the ratios between the long and short axis and the intermediate and short axis of deformed objects, respectively; $1+e_1$ and $1+e_3$ are calculated maximum and minimum pricipal stretches, respectively; and dL gives the relative change of line length with respect to bedding. Samples are listed from west to east on Fleurieu Peninsula and from north to south on Kangaroo Island.

towards 147° at the western part of the Kangaroo Island shear zone and 137° in the east. Strain data were only locally obtainable from elongated andalusite porphyroblasts and yield minimum (X:Z) strain estimates of 4:1 and 5:1 (Fig. 6a).

The eastern extension of the Kangaroo Island shear zone is characterized by two separate branches which show a change in map trend from E–W to NE–SW. The northern branch shows less pervasive strain and less intensely developed phyllonites but more discrete thrusts and large-scale complexly overfolded zones with intense, partly transposed cleavage development in northerly overturned folds.

The basinal zone on southern Kangaroo Island displays only extremely poor inland outcrop, and is composed exclusively of the Cambrian Kanmantoo Group which shows regional biotite-grade metamorphism, reaching amphibolite-facies conditions around isolated synkinematically intruded granitoids.

Where exposed, the structure of the southern zone

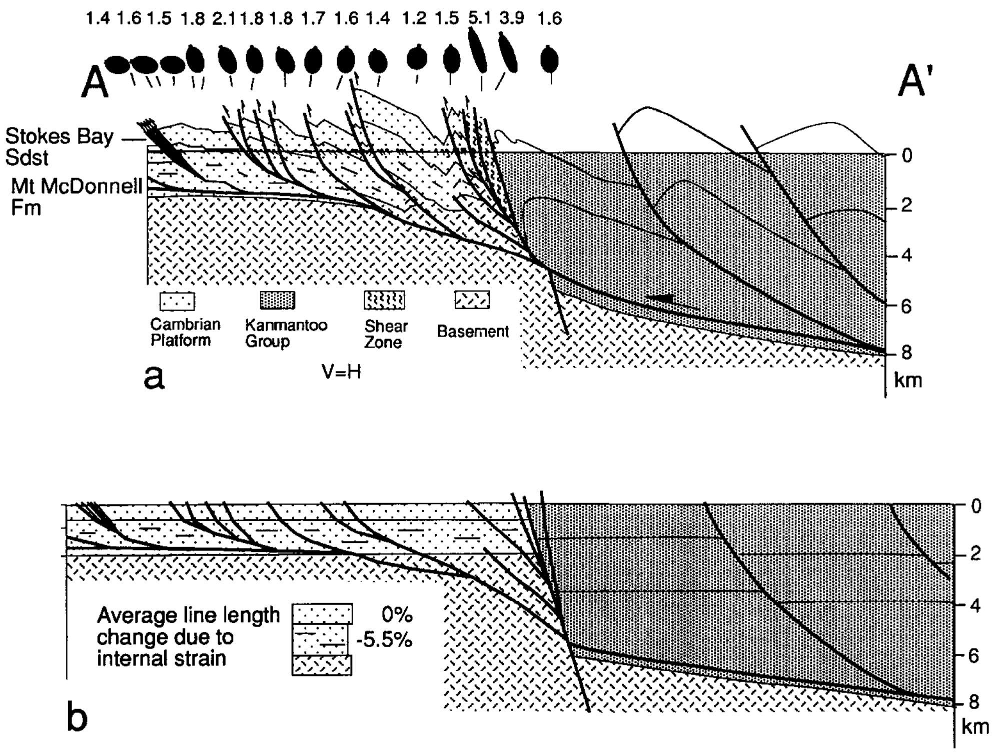

Fig. 6. (a) Composite cross-section across Kangaroo Island. Ellipses give amount and orientation of finite strain in the X–Z section. (b) Restored section of Kangaroo Island platform. Strain data show minimal line-length changes owing to internal strain. Notice the steep northern boundary of the Kanmantoo Basin which is only schematically restored owing to the lack of continuous outcrop. The stratigraphic column shows line-length changes in individual units.

appears to be dominated by anticlines with wavelengths of 4–8 km, but synclines of shorter (2–4 km) wavelength (Flöttmann *et al.*, 1995). This geometry suggests that the folding may be related to reverse faults, with probably only minor displacement.

Notably the Kangaroo Island shear zone cuts the WSW-trending fold axes obliquely. The principal oblique-slip displacement vectors along the Kangaroo Island shear zone are, however, perpendicular to the trend of the fold-axial surface traces (Fig. 4a & b). Adjacent to the shear zone, deformation in the Kanmantoo Group is intense with quartz veining tens of metres in length parallel to axial planes of meso-scale folds which suggests that a significant fluid flux accompanied the shearing.

SOUTHERN FLEURIEU DOMAIN—REACTIVATED GROWTH FAULTS

Similarly to Kangaroo Island, the southern Fleurieu Peninsula can be subdivided into three principal zones (Figs 2 & 3): the (Stansbury) carbonate shelf to the northwest; a highly strained transitional zone; and, to the southeast, the Kanmantoo Basin proper (section B–B′, Fig. 7a)

The offshore Stansbury shelf which is located beneath the current Gulf St Vincent was identified by seismic profiling (Fig. 3). Its principal early Palaeozoic succession consists of up to 4 km of a thick shelf sequence (Flöttmann and Cockshell, 1996). The seismic image shows only very little internal deformation in the Stansbury shelf area.

The interface between the Stansbury shelf and the Kanmantoo Basin proper is a marked transitional zone (Fig. 3) which has an across-strike width of 18 km and is characterized seismically by strong reflectors that dip southeasterly at ~45–60°. Many of these reflectors are correlated with onshore faults, some of which represent reactivated former normal faults at the western margin of the Kanmantoo Basin (Flöttmann *et al.*, 1994). The faults sole out into a subhorizontal basal detachment at depth of about 8–12 km.

Onshore, the western part of the transitional zone consists of an imbricate fan (Fig. 7a) which displaces the lowermost units of the Kanmantoo Group (Carrickalinga Head and Backstairs Passage Formations). The imbricate faults dip between 60° and 70° towards the southeast (145°) and displacement is towards the northwest. Since there is no flat detachment horizon discernible in the seismic section, the imbricate faults are presumably rooted in basement which is overlain by about ~1500–2000 m of Neoproterozoic (Adelaidean) strata and about 200 m of Normanville Group rocks. The thickness of the Adelaidean strata is inferred from the exposed thickness further to the north.

In the eastern part of the transitional zone, thrusts are more closely spaced and shortening between thrusts is

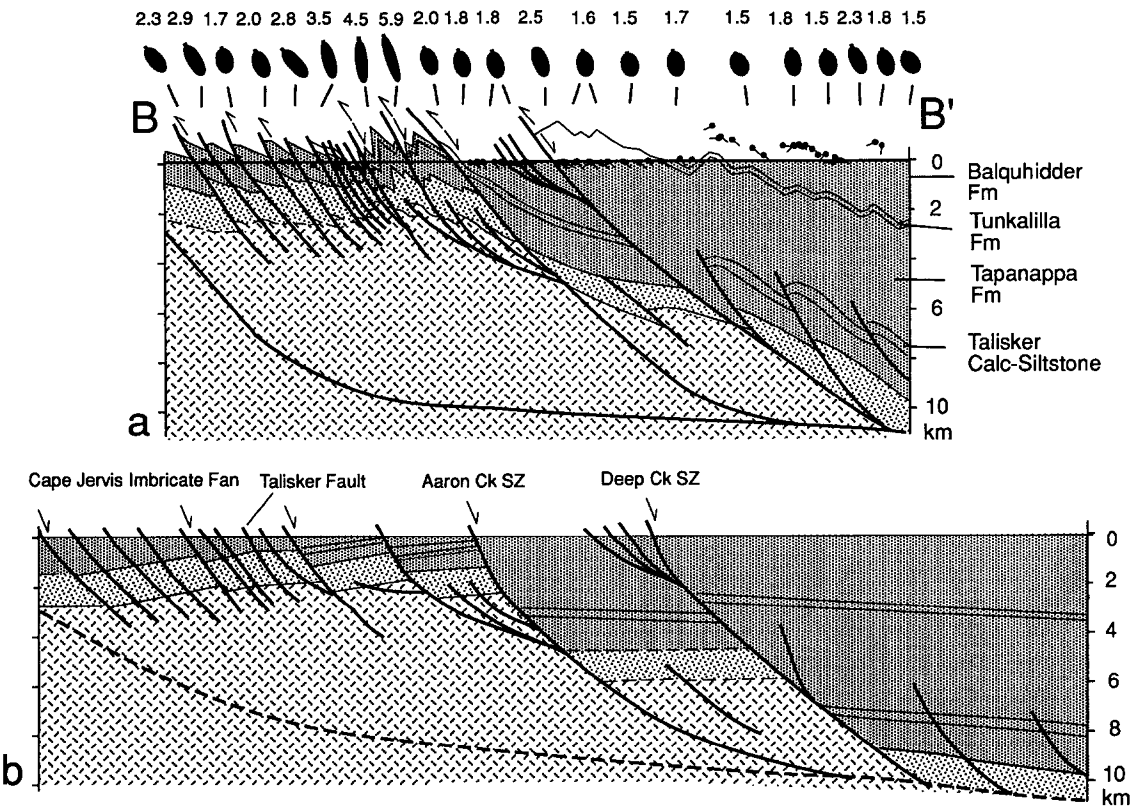

Fig. 7. (a) Section across the Kanmantoo Basin, southern Fleurieu Domain based on surface and seismic data. (b) Kanmantoo Basin section, restored; the dashed line gives the approximate position of the basal detachment to allow area balancing of basement in the deformed and restored section. Notice that basement must be intensely deformed between the Talisker Fault and the Aaron Creek shear zone.

increasingly accommodated by folding, the tightness of which increases eastward (Mancktelow, 1990; Flöttmann *et al.*, 1994).

The Aaron Creek shear zone (Figs 4 & 7a) marks the principal boundary between the transitional zone and the Kanmantoo Basin proper. Substantial eastward thickening of the E-dipping Tapanappa Formation across both the Aaron Creek shear zone and the Deep Creek Fault suggests that both these structures behaved as normal faults during Tapanappa deposition. Strain within the Kanmantoo Basin further east is accommodated by map-scale open folding.

Characteristic of both the transitional zone and the Kanmantoo Basin are faults with reverse sense-of-shear-indicators, that display normal net stratigraphic offset, for example the Aaron Creek shear zone and the Deep Creek Fault. Furthermore, the restored section (Fig. 7b) demonstrates dramatic thickness changes within the lower stratigraphic members across these faults, which are therefore interpreted to constitute former growth faults along which strain was localized during their Delamerian reactivation. The transitional zone forms the principal western margin of the Kanmantoo Basin, and shows the most significant strain accommodation along this section (Fig. 7a).

To elucidate the systematic changes in strain accommodation, strain data were collected along the section every 500–1000 m, with spacing closer in more complexly deformed areas. As suggested by Dittmar *et al.* (1994), strain analyses were dominantly carried out in lithologies most representative of the bulk of the Kanmantoo Group, which we chose as impure gritty sandstones of the Tapanappa Formation (which also fortuitously contains abundant clasts that can be used as strain markers) or comparable lithologies of other units. Preliminary strain data are recorded in Flöttmann *et al.* (1994); the results given here are based on over 30 additional strain measurements.

The results reveal three strain domains in the outcropping parts of this section. The Cape Jervis imbricate fan (Fig. 7a & b) shows strain magnitudes between 1.7 and 3.5 with an average of about 2.5. The estimates of the internal strain show that this fan underwent a positive line-length change of about 19%. The most highly strained segment along this cross-section is between the Talisker and Aaron Creek faults (Figs 4a & 7a & b), where strains as high as 6.3 were recorded with an average of 3.7. Here the overall change in line length is +22%. In the eastern Kanmantoo Basin proper, the average strain recorded in internal fabrics is clearly lower at about 1.7 and the line-length extension is about 4.4%. The overall shortening along this section is about 42%, with maximal shortening of up to 57% between the Talisker and Aaron Creek faults.

CARRICKALINGA SECTION—CAMBRIAN PLATFORM SHORTENING

This section shows the characteristics of basement involvement during deformation of adjacent basinal Adelaidean and Kanmantoo Group rocks. Here these units are also juxtaposed with a veneer of Cambrian platformal rocks that crop out at the western margin of the southern Adelaide Fold–Thrust Belt.

Adelaidean rocks at the western margin of this section are about 4 km thick and are overlain by the Lower Cambrian Normanville Group which comprises carbonates and phosphatic platformal rocks. At the western outcrop limit the Normanville Group is unconformably overlain by very low grade metamorphic clastic sediments of the lowermost Kanmantoo Group (Carrickalinga Head Formation) which was deposited in a proximal depositional environment (P. Haines, personal communication 1996).

Structurally the western part of this section is characterized by homoclinal westerly dips due to fault-bend folding over non-emergent thrusts (Fig. 8a). This is supported by offshore seismic profiling which shows subhorizontal bedding about 3 km offshore, suggesting that deformation wanes rapidly towards the west (Fig. 3).

To the east a 45°E-dipping (Black Hill) thrust zone juxtaposes the Normanville Group with Adelaidean strata. Further east, increasingly older Adelaidean rocks are then exposed along two major thrust zones. Regional anticlines with overturned western limbs characterize hangingwall deformation of these thrust zones in this part of the section and in similar structural positions further north. This structural style suggests that the anticlines initiated as fault-propagation folds and were subsequently cut by the propagating thrusts (cf. Suppe, 1985). Slip lineations and quartz fibres plunge towards 140° (Fig. 4b), and kinematic indicators show NW-directed reverse sense of displacement.

A basement culmination that forms the 5-km wide Normanville–Myponga inlier is overthrust along the Normanville Thrust onto Adelaidean rocks that form an overturned syncline in the footwall. The eastern margin of the basement inlier is in fault contact (Williamstown Meadows Fault) with a thin Middle Adelaidean sequence which in turn is in fault contact with the lower Kanmantoo Group along the southern part of the Williamstown–Meadows Fault. The Normanville Group is not exposed east of the basement inlier. Twenty kilometres further south, this fault juxtaposes the Kanmantoo Group with the eastern margin of the basement inlier (Steinhardt, 1991). At both localities fault systems at the eastern margin of basement inliers display reverse sense of shear, but place younger over older strata. This suggests that this fault system initiated as normal faults during the deposition of the Kanmantoo Group and was reactivated during the Delamerian orogeny. Shortening along the Carrickalinga section is 44% (Fig. 8) and the majority of the shortening is taken up between the western foreland-dipping zone and the Kanmantoo Basin boundary fault (cf. Bührer, 1995).

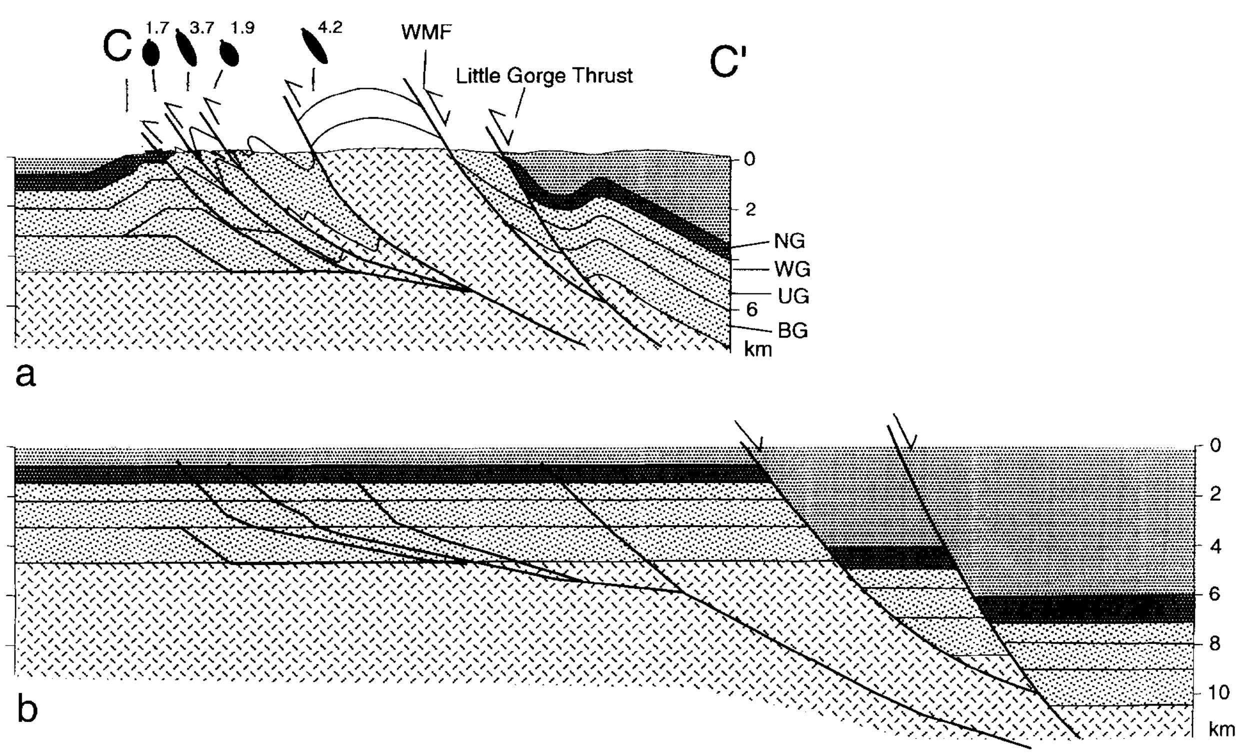

Fig. 8. (a) Carrickalinga section, blind frontal detachment (offshore) was interpreted from seismic data. Abbreviations: NG, Normanville Group; WG, Wilpena Group; UG, Umberatana Group; BG, Burra Group. (b) Carrickalinga section, restored; line-length restoration east of the Williamstown–Meadows Fault (WMF) is schematic only.

There are insufficient strain data to estimate the amount of internal shortening along this section.

CENTRAL SECTION—FOOTWALL SHORTCUT FAULTING

The western part of this section transects Adelaidean rocks of very low metamorphic grade, characterized by steeply W-dipping to overturned E-dipping limbs of folds that developed due to subsurface ramping over non-emergent thrusts. To the east the shortening is accommodated by a zone of moderately (20–45°) E-dipping thrusts that form an imbricate fan. The easternmost thrusts of the imbricate fan undercut basement, which forms the highly deformed core of a ramp-related anticline. Several mapped basement-cored ramp anticlines (Fig. 2) expose basement or the unconformably overlying autochthonous Aldgate Sandstone, which at this latitude forms the base to the Adelaidean sequence.

East of this ramp anticline, the Williamstown Meadows Fault (Fig. 4a) forms one of the principal structural features of the whole belt. Although in the poorly exposed outcrops it displays reverse-fault kinematics, the net stratigraphic offset is still that of a normal fault (Fig. 9a). East of the Williamstown Meadows Fault, the upper Adelaidean strata are overlain by the Kanmantoo Group, with local occurrences of intercalated Normanville Group. Therefore the Williamstown Meadows Fault is regarded as the principal basin-bounding extensional fault during the deposition of the Kanmantoo Group, as shown in the restored section (Fig. 9b). East of the Williamstown Meadows Fault the eastern part of this transect is influenced by elevated (greenschist-facies) metamorphic grades and here shortening is accommodated by regional fold structures.

Within the Adelaidean sequence, sedimentary layering of rock units with different rheological properties leads to a significant vertical and, at outcrop level, lateral partitioning of internal shortening strains during Delamerian contraction (Fig. 9c). This is particularly the case within the imbricate fan, where, for example, mesoscale cleavage shows significant refraction between pelitic and psammitic layers. Using the strain data to estimate the stratigraphy-specific strain responses, significant changes of line length are apparent due to the geometry and intensity of internal strain. The Aldgate Sandstone shows small negative line-length changes (−6%), whereas the overlying Woolshed Flat Shale and the Skillogalee Dolomite show significant positive line-length changes, which are on average +25%. The line length of the overlying Stonyfell Quartzite remains almost unchanged (−1%), whereas the overlying Saddleworth Formation, which contains interlayered shales and sandstone units, shows about +10% line-length extension. The sandstones and quartzites of the Belair Subgroup show insignificant line-length changes, whereas the Sturtian glacials show a line-length change of −32%. Variation in the amount of finite strain and different orientation of the X–Z plane of the finite-strain ellipsoid lead to strain refraction between different lithologies. Differential line-length changes can also be accommodated by layer-parallel detachment-style deformation at the interface between competent and incompetent rocks (Fig. 9c) (cf. Mitra, 1994).

These results suggest that section restoration of this part of the fold–thrust belt must take the different responses to shortening into consideration. Thus, the principal approach in section construction was based on line-length balancing of the psammitic units, which seem least affected by internal strain, a procedure suggested by Woodward *et al.* (1989). In the restored section the pelitic units have to be thickened according to the amount of extension taken up by internal deformation as shown in Fig. 9(c). The overall shortening across this section is about 50%.

THE KARINYA DOMAIN—HOMOGENEOUS SHORTENING

This section is characterized by a noticeably thickened sequence of Adelaidean rocks (up to 9 km) as the Adelaidean Basin deepens and widens northwards. Below the Rhynie Sandstone (Fig. 10a), equivalent to the Aldgate Sandstone, which forms the lowermost Adelaidean unit further south, the lower portion of the section is here formed by the Callana Group (Thomson, 1969b) typically containing evaporites. In the Karinya domain, intense deformation is confined to the western margin of the fold belt. Here Callana Group rocks form the basal Salters Springs shear zone with W- (foreland) directed kinematics in which strains of up to 6:1 are recorded (Fig. 10a).

The Adelaidean rocks are characterized by low metamorphic grade and distributed internal deformation is accommodated by upright map-scale folds of kilometre wavelength and some hundred metres of amplitude. At the eastern edge of the belt the thickness of Kanmantoo Group rocks, which are here of a distal facies (P. Haines, personal communication 1995), is only about 3 km and the rocks are fully enclosed by Adelaidean strata in the Karinya Syncline. At the western margin of the Karinya Syncline the Kanmantoo rocks have a disconformable contact with the underlying Adelaidean rocks. At its eastern contact the Kanmantoo Group is marked by a W-dipping fault with top-to-the-east directed reverse-sense kinematics, but normal stratigraphic offset. Consequently, this fault is interpreted as a former W-dipping growth fault that controlled the Kanmantoo Group deposition at the northern part of the Karinya Syncline.

Along this section, strain is clearly concentrated along the principal detachment that crops out along the western part of the belt. Above this detachment the central section shows a geometric shortening of about 22% (Fig. 10b). Internal strain shows a homogeneous average

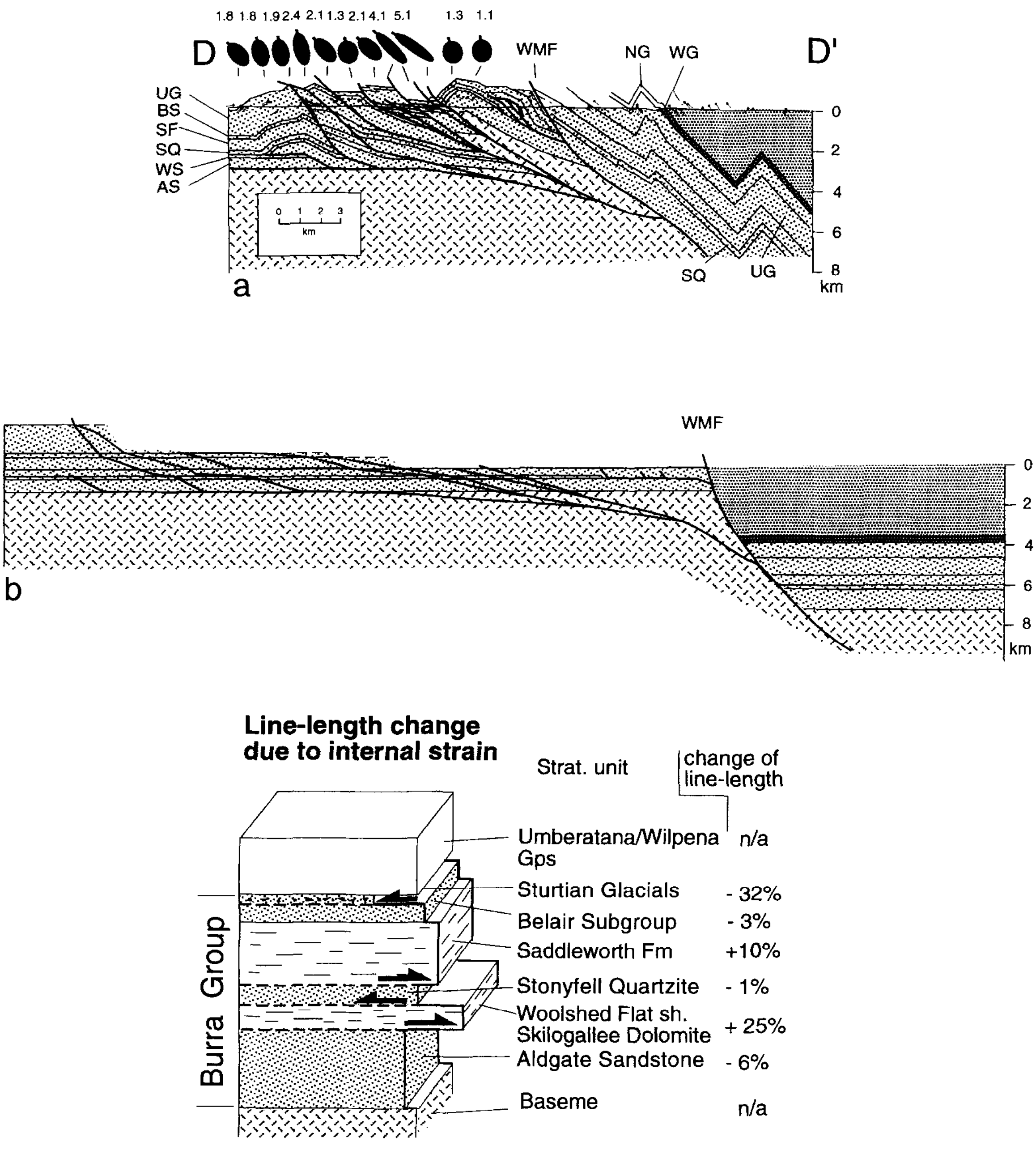

Fig. 9. (a) Section across central Fleurieu Peninsula. Notice eastwards-increasing strain and low-angle relationship between the long axes of strain ellipses and bedding, minimal strain in the basement-cored ramp anticline. Abbreviations: AS, Aldgate Sandstone; WS, Woolshed Flat Shale and Skilogallee Dolomite; SQ, Stonyfell Quartzite; SF, Saddleworth Formation; BS, Belair Subgroup/Sturtian Glacials; UG, Umberatana Group; Ng, Normanville Group; WG, Wilpena Group; WMF, Williamstown–Meadows Fault. (b) Restored section; line-length restoration east of the Williamstown–Meadows Fault (WMF) is schematic only. (c) Block diagram of relative line-length changes based on strain analyses (see Fig. 5a and Table 1) for the different units of the Burra Group. Note the minimal line-length change in psammitic units (stippled). Line lengths of shaly units (hatched) are positive, i.e. increased due to internal strain. At the interface between lithologies of contrasting strain compatibility interformational slip may result (arrows).

shortening of about 24%, which leads to an estimate of overall shortening of about 35% (Fig. 10c). The homogeneous distribution of strain in X–Z sections suggests that these structures within the Adelaidean rocks of the fold–thrust belt deformed passively over non-emergent faults that merge into the detachment represented at outcrop level by the Salters Springs shear zone.

It is noticeable, however, that at this latitude the Kanmantoo Group is entirely floored by the Adelaidean rocks. Consequently there appears to be no influence of a former basin margin on the strain distribution within this section. The strain geometry here suggests that the overall sequence was more or less homogeneously shortened.

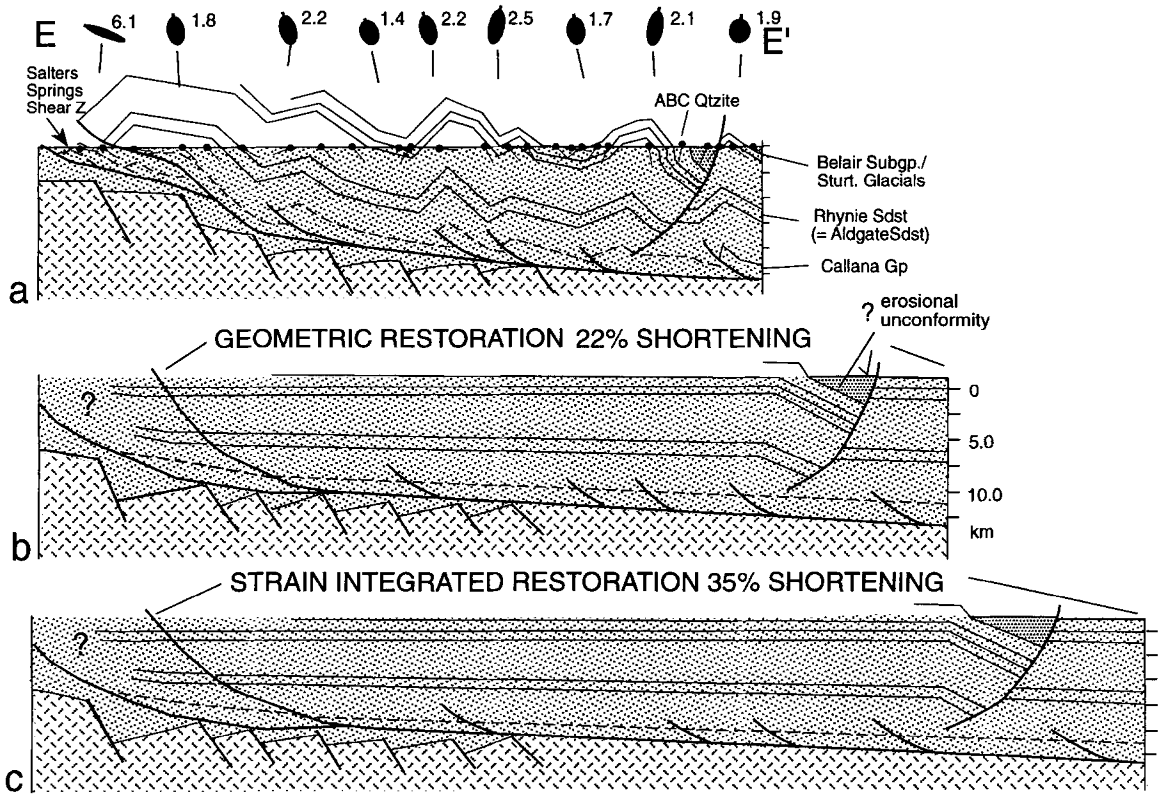

Fig. 10. (a) Karinya section. Principal detachment in the Salters Springs shear zone is overlain by regionally folded rocks with homogeneous internal strain. Kanmantoo Group deposition appears to be controlled by a W-dipping normal fault. (b) Geometric restoration of sequences above the principal detachment. (c) Strain-integrated restoration gives an overall shortening of 35% above the principal detachment.

DISCUSSION AND CONCLUSIONS

The southern Adelaide Fold–Thrust Belt contains two sedimentary basins that record sediment deposition during consecutive Neoproterozoic and Cambrian crustal attenuation. The Adelaidean strata were deposited during repeated rift and sag phases over a protracted period of about 260 Ma. In contrast, the accommodation space for the Kanmantoo Basin was created during rapid subsidence over only about 8 Ma. The sedimentary prism of the Kanmantoo Group thickens across major E-dipping faults that were active during deposition. This led to a fundamental incision in the Adelaidean strata, and its underlying basement, at the southern margin of the Kanmantoo Basin. The Basin thus overlies and effectively cross-cuts the underlying Adelaidean strata as it swings from a northerly trend on eastern Fleurieu Peninsula to a westerly trend on Kangaroo Island. In the north the Kanmantoo Basin narrows and tapers out in the Karinya Syncline where Adelaidean strata floor the less than 3 km thick, more distal facies, Kanmantoo Group. To the south the outcrop geometry of the Kanmantoo Basin margin is related to a major strike-slip regime which was located south of the currently outcropping depositional extent of the Kanmantoo Group.

During the Delamerian orogeny both basins were shortened and displaced towards the orogenic foreland in the west. Along the entire length of the southern Adelaide Fold–Thrust Belt slip vectors related to Delamerian displacement plunge consistently towards ~120–140°, with the exception of the northern Kangaroo Island platform (Fig. 4). However, the structural geometry and strain accommodation are significantly different in the Adelaidean and Kanmantoo basins.

Contrasting structural styles in the fold–thrust belt

Of interest is the style and localization of basement involvement during Delamerian contraction, which appears broadly correlated with the geometry and incision-style of the Kanmantoo Basin margin. On southern Kangaroo Island, NW-directed Delamerian displacement results in NE-trending folds above a master detachment, which presumably undercuts the steep former basin margin fault. The marked obliquity between the general displacement vector and the trend of the Kangaroo Island shear zone is accommodated by dextral transpression at this part of the basin margin (Fig. 11a & b). This results in minor vertical and northward displacement during deformation at the southern part of the Kangaroo Island platform (Figs 6a & 11b). Thrusting on the Kangaroo Island platform is N-directed. This is explained in terms of a partitioning of the

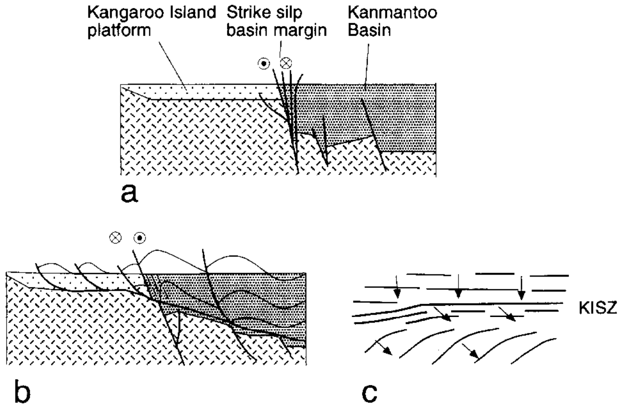

Fig. 11. Cartoon of possible basin configuration and principal elements of reactivation on Kangaroo Island (see Fig. 2 for legend). (a) The northern Kangaroo Island platform sedimentary rocks overlie basement. The boundary with the northern Kanmantoo Basin is formed by a steeply S-dipping fault zone, which is related to a strike-slip component during basin formation at this part of the basin margin (notice the general absence of Adelaidean rocks). (b) Reactivation of the basin margin leads to strain concentration at the steep basin margin buttress formed by the W-trending Kangaroo Island shear zone. The shortening vector is towards 320° and thus has a significant component of dextral transpression which results in minimal involvement and translation of basement onto the Kangaroo Island platform. (c) Partitioning of the overall NW-directed displacment (indicated by SW-plunging lineations shown by arrows) into the transpressional component along the steeply S-dipping Kangaroo Island shear zone (KISZ) and a N-directed component on the Kangaroo Island platform.

overall NW-directed displacement into a transpressional component along the steeply S-dipping Kangaroo Island shear zone and a N-directed component on the Kangaroo Island platform (Fig. 11c).

In contrast, on southern Fleurieu Peninsula, basement is exhumed to the current outcrop level but the position of basement inliers with respect to the western margin of the Kanmantoo Basin changes systematically along the strike of the orogen. The southern Normanville–Myponga inlier is thrust towards the west over Adelaidean rocks. At its northern margin, steeply westwards-overturned Adelaidean strata are juxtaposed with platformal rocks of the Cambrian Normanville Group in the footwall of the Myponga–Normanville inlier.

At this latitude the eastern margin of the basement inliers are also formed by steeply E-dipping thrust zones, forming part of the southern extension of the Williamstown–Meadows Fault. Towards the north, however, the eastern margin of the basement inliers is formed by a northwards-widening wedge of Adelaidean rocks that occur on either side of the Williamstown–Meadows Fault (Figs 4 & 12a & b).

The principal geometrical relationships suggest that the basement inliers form up-thrust segments of the western Kanmantoo Basin margin, which were undercut and exhumed along footwall shortcut thrusts (Fig. 12b & c), features commonly developed during the reactivation of former deeply incised basin margins (McClay and Buchanan, 1992).

The along-strike variation in juxtaposition of different rock units on Fleurieu Peninsula could be related to varying proportions of displacement taken up by the principal inversion fault and footwall shortcut thrusts, respectively. Adjacent to the Normanville–Myponga inlier the eastern margin of the basement is in contact with Kanmantoo Group rocks along a reverse fault. The different styles of juxtaposition could be reconciled by different amounts of lateral translation vs vertical exhumation along these different fault systems. At the southern margin the ratio of displacement along the footwall shortcut thrust-principal reactivated growth fault was such that the Kanmantoo Group is now fault-bounded with basement at the eastern margin of the inlier (Fig. 12b). Further north the amount of vertical displacement along the principal growth fault (Williamstown–Meadows Fault, Fig. 5a) is greater, and Adelaidean rocks are juxtaposed with those Adelaidean strata that overlie the ramp anticlines related to footwall shortcut thrusting (Fig. 12c). This implies that at the southern basement inliers, a greater amount of Delamerian reactivation was accommodated along the footwall shortcut thrust which led to a stronger exhumation of basement. Further north, exhumation along the principal reactivation fault was more substantial and leads to the contact relationships specific to that area, i.e. Adelaidean–Adelaidean contact and a non-faulted contact of Adelaidean and Cambrian rocks.

Styles of pervasive strain accommodation

On southern Fleurieu Peninsula, geometric shortening is mainly accommodated by thrusting of major packages and to a lesser extent by folding. Internal strain within the Adelaidean rocks appears mostly influenced by rheological contrasts between individual lithologies. The dominance of low-angle relationships ($<30°$) between individual lithologies and the major displacement horizon led to significant positive line-length changes in pelitic units. This suggests that the thicknesses of these units were greater prior to the onset of deformation (Fig. 9c), a conclusion supported by geochemical analyses which also suggest a volume loss between 10 and 20% for these lithologies.

Strain heterogeneity within the Adelaidean rocks of this region thus shows that cross-section balancing must initially rely on balancing and restoration of key marker horizons such as the Aldgate Sandstone and the Stonyfell Quartzite.

The cross-section of the Karinya domain reflects a remarkably different distribution of macroscopic and internal strain accommodation. Here orogenic shortening was accommodated by regional-scale folding in a belt that developed above a master detachment emergent at the western orogenic front. Pervasive strains suggest a noticeable average line-length shortening of 24% across the entire belt at this latitude (Fig. 12d).

The contrast between positive line-length changes in the Central Domain (Adelaide region) and negative line-

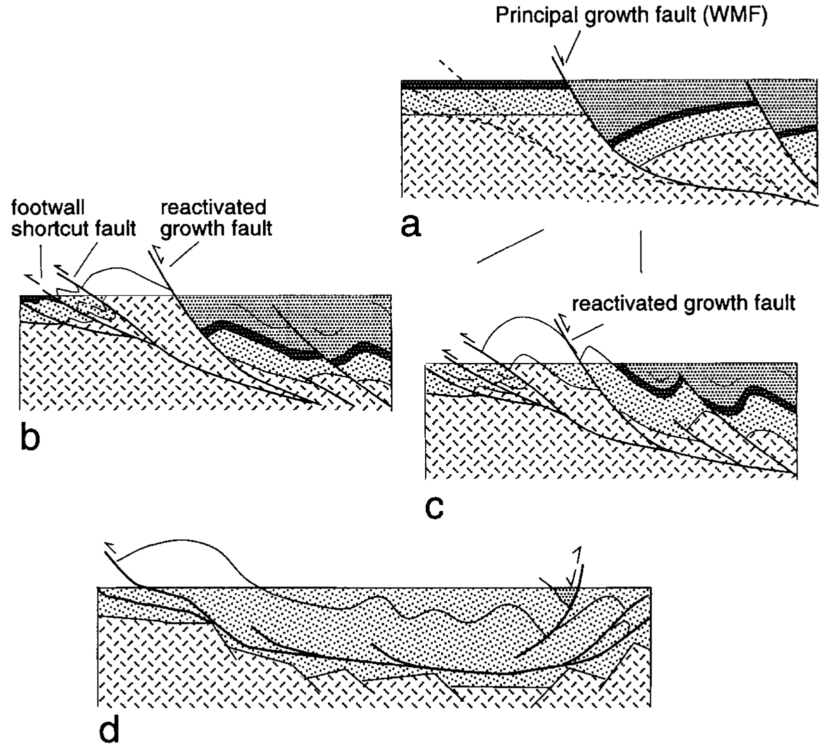

Fig. 12. Cartoon of basin configuration and principal elements of basin reactivation on southern Fleurieu Peninsula (see Fig. 2 for legend). (a) Possible setting after the deposition of the Kanmantoo Group: the Normanville Group forms a shelf above the Adelaidean rocks, the principal basin-margin fault is formed by the Williamstown–Meadows fault (WMF) which dips towards the ESE. (b) Horizontal displacement during the Delamerian orogeny is accommodated along footwall shortcut thrusts which involve substantial basement slivers in the core of ramp anticlines. At the southern part of the Kanmantoo Basin, displacement along footwall shortcut thrusts and the Williamstown–Meadows Fault leads to juxtaposition of the Kanmantoo Group and basement. (c) Further north displacement is less on footwall shortcut thrusts but greater on principal growth faults (the Williamtown–Meadows Fault), and Adelaidean rocks occur on both sides. Northwards-increasing exhumation along the Williamtown–Meadows Fault produces the northwards-widening belt of Adelaidean rocks between the basement inliers and the Kanmantoo Group. (d) Homogeneous shortening above the master detachment along the Karinya section. Note that the Kanmantoo Basin margin does not influence the distribution of internal strain.

length changes in the Karinya area may be intimately linked to the different modes of shortening accommodated in both sections. In the Central Domain, footwall shortcut thrusting and imbrication are the dominant modes of shortening in the western foreland part of the belt. Here rocks are bracketed by shallow reverse faults, i.e. the angle between bedding and local finite-strain ellipsoids is low and line lengths, at least of pelitic layers, are consequently extended. Further north in the Karinya domain, shortening at outcrop level is mainly fold-accommodated where the angle between bedding and cleavage is high and consequently line lengths of bedding are, in general, shortened.

Within the Kanmantoo Basin internal strain leads to generally positive line-length changes. These are again the consequence of the generally low angle between the E-dipping strata and the X–Z plane of the finite-strain ellipsoid. This low angle may result from shortening of a sedimentary prism that was overall southeastwards thickening as a consequence of the rapid opening and deepening of its accommodation space. The results of the strain analysis show that the modification of line length within the outcropping domains of the Kanmantoo Group that were examined along the south coast of Fleurieu Peninsula is relatively insignificant in terms of the overall balancing/restoration procedure. The maximum differential change in line length is less than 20% between the Talisker–Aaron Creek area and the Kanmantoo Basin proper. This suggests that, although strains can vary laterally and within the deforming wedge, their overall differences at the scale at which the section is balanced (1:50 000) are almost negligible.

The strain magnitude in X–Z sections within the Kanmantoo Group of the southern Fleurieu Peninsula increases towards the foreland. This appears clearly related to the fact that strain is focused along former normal faults that were initiated during the basin formation and which are the prime locus for strain accommodation during the reactivation of the Kanmantoo Basin. In particular the steep incision along the transition zone forms a buttress along which strain was concentrated during basin reactivation. This would be unusual were the deformed sedimentary package onlapping onto its cratonic margin, as appears to be the case in many fold–thrust belts where the foreland-ward translation of thrust sheets is not buttressed by former basin

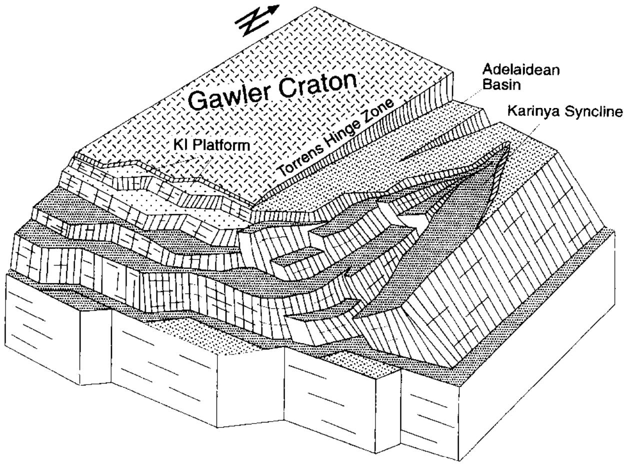

Fig. 13. Schematic block diagram of the principal extensional (N–S-trending) and oblique wrench (E–W-trending) fault systems active during the opening of the Kanmantoo Basin.

margins (e.g. Woodward *et al.*, 1986; Protzman and Mitra, 1990; Dittmar *et al.*, 1994). The rigid buttress formed by the northwestern margin of the Kanmantoo Basin, however, prevents the transmission of significant shortening strains onto the Stansbury shelf, as evident from its minimal internal deformation shown by the seismic profiling (Fig. 3).

Influence of original basin geometries on the structural style of the southern Adelaide Fold–Thrust Belt

The relationships described here suggest that the localization of thrust-related displacement during the Delamerian orogeny, which is characteristic of the southern Adelaide Fold–Thrust Belt, may in fact be a direct consequence of the geometry and intensity of the extensional incision of the Kanmantoo Basin margin (Fig. 13). During the contractional cycle the deeply incised W-trending basin margin on Kangaroo Island was transpressionally reactivated. Here the overall oblique shortening led to a strong buttressing and chanelled fluid flow but minimal displacement of basement across the major basin-bounding fault zone now formed by the Kangaroo Island shear zone. In contrast on southern Fleurieu Peninsula, the basin margin faults are oriented more or less normal to the principal displacement vector. Here footwall shortcut thrusts undercut and up-thrust the steep basin margin which now occurs as basement-cored ramp anticlines in the southern Adelaide Fold–Thrust Belt. At the northern portion of the Kanmantoo Basin, basement is not involved in the Delamerian reactivation. Here the distal sediments of the Kanmantoo Basin are markedly thinner and the basin opening was not associated with fault-incision into the basement. Delamerian deformation along the Salters Springs–Karinya section is exclusively controlled by the dynamics of the wedge of Adelaidean rocks and their underlying detachment. This deformational style continues northwards into the southern Flinders Ranges. The Karinya domain is thus transitional between the thrust-dominated shortening of the southern Adelaide Fold–Thrust Belt and the fold-dominated shortening of the Nackara Arc.

The relationships discussed above suggest that a combination of key factors influence the lateral variation in structural style and strain partitioning that characterize the deformational style of the southern Adelaide Fold–Thrust Belt during the Delamerian orogeny. Little variability occurs in the vector of orogenic shortening, which is about 120–140° throughout the area investigated. The variability in structural style between transpressional shortening, basement-involved thrusting or regional folding appears to be strongly influenced by the relationship between the orientation of the Kanmantoo Basin margin and the displacement vector. At the northern end of the Kanmantoo Basin the incision does not influence the strain distribution.

CONCLUSIONS

The presented data and results suggest the following.

(1) The map-scale structural characteristics of the southern Adelaide Fold–Thrust Belt appear to be intimately related to the combined reactivation of both the Adelaidean and the superposed and deeply incised Cambrian Kanmantoo Basin. The three-dimensional geometry of the margin of the strongly curved Kanmantoo Basin is a key influence on contrasting kinematic and structural regimes developed during shortening related to the early Palaeozoic Delamerian orogeny. Variation occurs along the strike of the orogen from dextral wrench-dominated on Kangaroo Island in the south to a transitional regime characterized by strong buttressing and growth-fault reactivation on southern Fleurieu Peninsula. Basement-involved footwall shortcut thrusts, which take up most of the shortening, characterize the central parts of the southern Adelaide Fold–Thrust Belt, whilst in the north shortening is accommodated by homogeneous folding above a master décollement.

(2) The interpretation given is based on strain-integrated balanced and restored cross-sections. Rheological parameters appear to be a key controlling factor for strain partitioning in these rocks; the partitioning of pervasive strain makes a full restoration of these sections difficult, although the incorporation of regional strain data assists the establishment of balanced and restorable sections in more pervasively deformed parts of the orogen.

(3) The findings presented here suggest that the distribution and partitioning of contractional strain in fold and thrust belts can be significantly influenced by the internal geometry of sedimentary basins. Conversely an improved understanding of regional strain distribution and styles of shortening accommodation

may be key aids in establishing the pre-deformational basin geometries.

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