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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

STEPHEN MARSHAK

Department of Geology, University of Illinois, 1301 W. Green St., Urbana, IL 61801, U.S.A.

and

T. FLÖTTMANN

Department of Geology and Geophysics, University of Adelaide, GPO Box 498, Adelaide, SA 5001, Australia

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Abstract—The regional map pattern of structural trends in the Early Paleozoic Adelaide fold–thrust belt of South Australia resembles an upright letter 'S'. In general, structures in the fold–thrust belt verge toward the Gawler craton to the west, so the northern curve (Nackara Arc) of the 'S' is a salient, whereas the southern curve (Fleurieu Arc) is a recess. The map-view axial trace of the Nackara Arc coincides with the thickest portion of the Adelaidean (Late Proterozoic) basin, and the map-view axial trace of the Fleurieu Arc coincides with the intersection between the Adelaidean and Kanmantoo (Cambrian) basins. Our structural analysis of the Adelaide fold–thrust belt demonstrates that the cross-sectional structural geometry of the Nackara Arc contrasts markedly with that of the Fleurieu Arc. In the Nackara Arc, the belt consists of open detachment folds that probably formed above an evaporite-hosted décollement, whereas in the Fleurieu Arc, the belt consists of an imbricate fan of basement-involved thrusts. Further, the foreland edge of the Nackara Arc coincides with a blind ramp whose strike parallels fold axes of the arc, whereas the foreland edge of the Fleurieu Arc coincides with emergent thrusts that cut obliquely across earlier formed folds of the arc. In the transition region between the two arcs, the fold–thrust belt consists of an intensely sheared basal duplex overlain by open folds. Structural contrasts between the Nackara and Fleurieu Arcs indicate that the two curves did not form in the same way. We present a model for development of these curves based on a comparison of their structural features to those of curves in other fold–thrust belts, and based on previous studies of curve formation using sandbox analogs. We suggest that curvature of the Nackara Arc reflects the control of basin stratigraphy on the width of a fold–thrust belt, while curvature of the Fleurieu Arc reflects oroclinal bending of the fold–thrust belt when it impinged on the southeastern corner of the Gawler craton. Our model explains the structural contrast between the two arcs and illustrates correlations between fold–thrust belt curve formation and pre-deformational basin geometry. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Structural and topographic trends in orogenic belts typically change systematically along strike, and thereby define map-view curves. Numerous paleomagnetic studies (e.g. Lowrie & Hirt 1986), field structural studies (e.g. Marshak & Tabor 1989, Platt *et al.* 1995), and laboratory or numerical-analog studies (Marshak & Wilkerson 1992, Marshak *et al.* 1992) lead to the conclusion that no single tectonic process creates all curves. Possible processes leading to curve formation include: intersection of non-parallel orogens, interaction of an orogen with obstacles in the foreland, plan-view rotation of crustal blocks, along-strike change in pre-deformational basin stratigraphy, along-strike variation in hinterland boundary loads (due to collision of irregular continental margins), and interaction of an orogen with a strike-slip fault. Some of these processes result in non-rotational curves, whose formation did not involve rotation of structures (fold hinges, cleavage and fault traces) around a vertical axis, whereas others result in rotational curves (or oroclines; cf. Carey 1955, Marshak 1988), whose formation did involve rotation of structures around a vertical axis. Structures of a non-rotational curve form with approximately their present map-view shape, while structures of a rotational curve either change trend during their development, or later, in response to a subsequent deformation event. In order to constrain kinematic models for the tectonic evolution of an orogen, researchers must first understand how its map-view curves developed.

The Adelaide fold–thrust belt in South Australia, a portion of the Cambro-Ordovician Delamerian orogen, contains two well exposed oppositely facing map-view curves (Fig. 1), making the belt an excellent natural laboratory for gaining insight into curve-development processes. The northern curve, a salient known geographically as the Nackara Arc, is antitaxial (convex toward the foreland), whereas the southern curve, a recess known geographically as the Fleurieu Arc, is syntaxial (concave toward the foreland). Because of these curves, the Adelaide fold–thrust belt resembles an upright letter 'S' in map view; the axial traces of the curves trend approximately northwest (Fig. 1). The origin of this 'S'-shape remains conjectural. Coward (1976) suggested that the curves developed because the entire belt was subjected

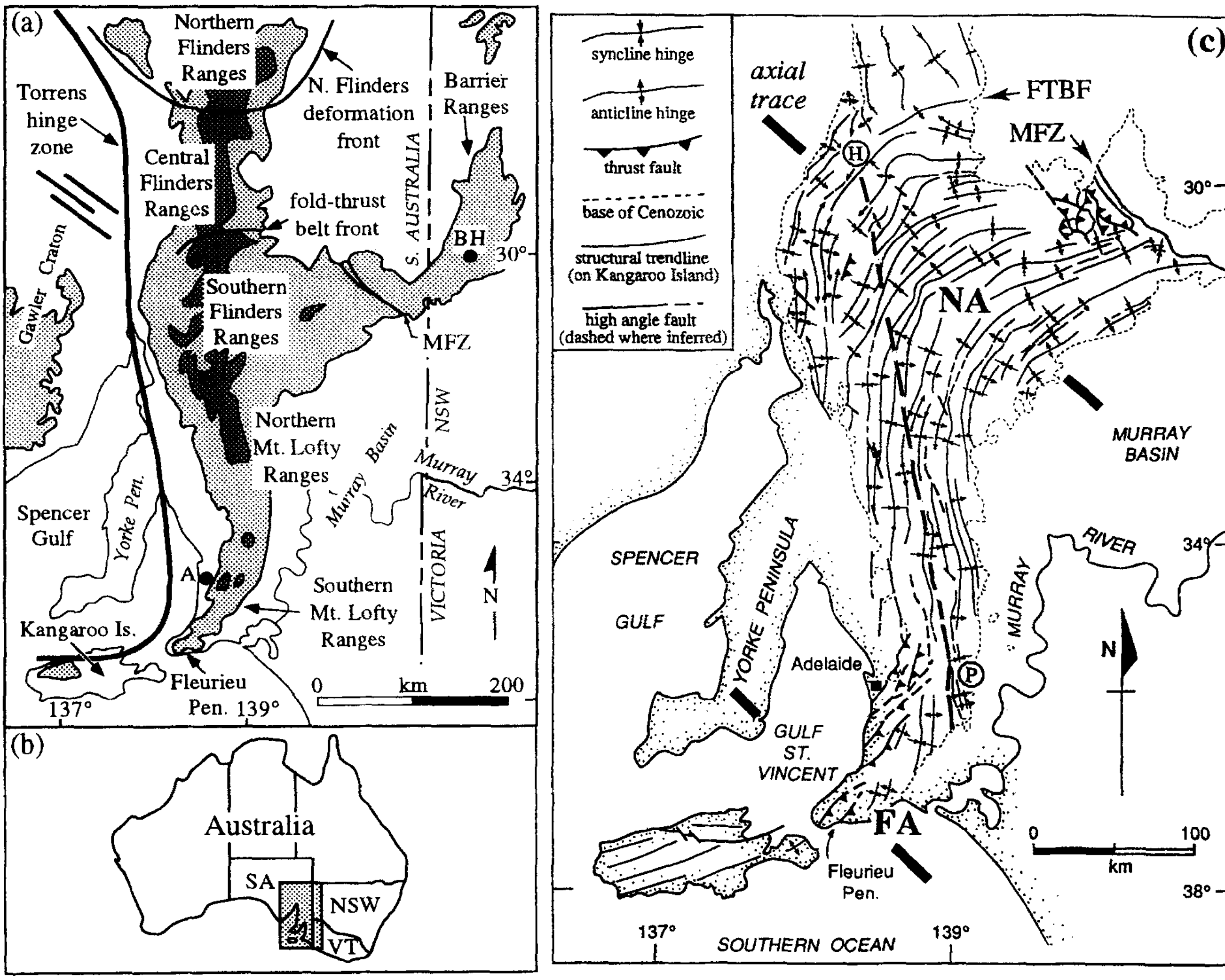

Fig. 1. (a) Regional map of Adelaide fold–thrust belt and adjacent regions. Heavy line (THZ) is the Torrens hinge zone, the syndepositional basin hinge. Straight black lines west of the THZ represent ≈800 Ma dikes. Medium stippled areas are at elevations of 200–500 m, and heavy stippled areas are at 500–1000 m. BH = Broken Hill, A = Adelaide, KI = Kangaroo Island, MFZ = MacDonald fault zone, NSW = New South Wales. Topography adapted from Preiss (1987). (b) Location map showing the area of (a) with respect to the states of South Australia (SA), Victoria (VT), and New South Wales (NSW). (c) Detail of the Adelaide fold–thrust belt showing principal fold traces and overall curved structural trends. NA = Nackara Arc, FA = Fleurieu Arc, P = Palmer; H = Hawker (heavy black line between these two towns is the Palmer–Hawker line), FTBF = fold–thrust belt front (northern extent of the Adelaide fold–thrust belt), MFZ = MacDonald fault zone. Standard symbols indicate anticline and syncline hinge traces. Thin dashed line indicates edge of Adelaidean and Kanmantoo outcrop (≈200 m contour of (a)).

to a northwest-trending strike-slip sinistral shear couple (Fig. 2a), while Crawford & Campbell (1973) and Clarke & Powell (1989) suggested that the belt was sheared between two east–west-trending dextral strike-slip faults (Fig. 2b). In contrast, Daily *et al.* (1973) suggested that the curves reflect lateral variations in basin geometry, and Mancktelow (1981, 1990) suggested that the Fleurieu Arc is due to compression against a curved cratonic margin. We analyzed thrust-system geometry, style of strain accommodation, and occurrence of tectonic overprinting throughout the Adelaide fold–thrust belt in order to test models of its curve formation. Our results yield 'admissible' (see Marshak & Woodward 1988) cross-sectional models of the belt and new insight into the formation of fold–thrust belt curvature in general.

GEOLOGICAL SETTING OF THE ADELAIDE FOLD–THRUST BELT

We define the Adelaide fold–thrust belt as the exposed western edge of the Delamerian orogen between Kangaroo Island and the MacDonald fault zone (Fig. 1, cf. Coney *et al.* 1990). This region includes the Mt. Lofty Ranges and the Southern Flinders Ranges, which together form a 600 km-long by 50 to 200 km-wide belt of hills whose average peak elevations range between 200 and 500 m (Fig. 1). At its northeastern limit, the fold–thrust belt terminates against the MacDonald fault zone, which forms the contact between Adelaidean strata and a region of exposed basement known as the Willyama block. At its northern limit, the fold–thrust belt borders

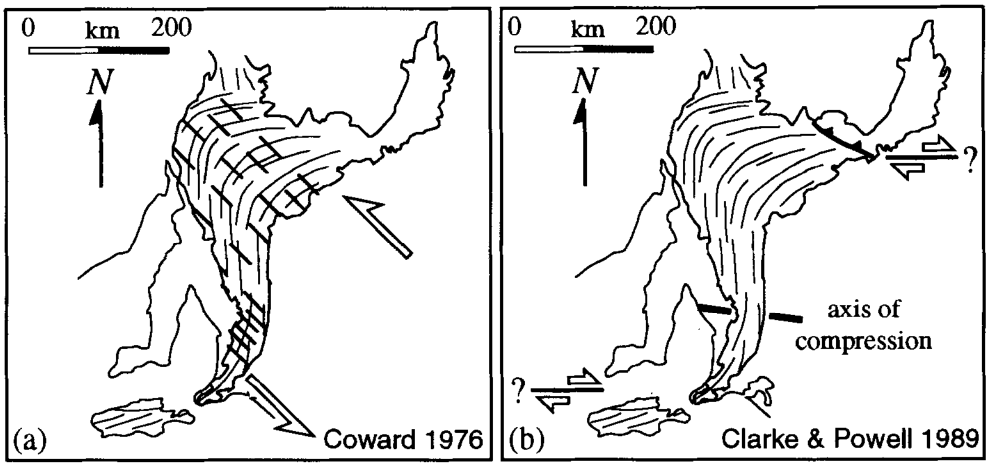

Fig. 2. Two previous models for the curvature of the Adelaide fold–thrust belt. Thin continuous line defines the coastline, medium continuous line indicates 200 m topographic contour around the Flinders and Mt. Lofty Ranges, and thin discontinuous lines within this contour indicate structural trends (cf. Fig. 1). Shear arrows on the figures are taken from the original published figures. (a) Coward's (Coward, 1976) regional sinistral shear zone. Short NW-trending line segments are Coward's depiction of shear trajectories within the fold–thrust belt; (b) Clarke and Powell's (Clarke & Powell, 1989) shear on E–W-trending dextral strike-slip faults. Arrows labeled "axis of compression" follow Clarke and Powell's depiction of the compression direction, and heavy lines are their depiction of proposed strike-slip faults.

the Central Flinders Ranges, a region that does not contain a fold–thrust belt structural assemblage (Rutland *et al.* 1981, Preiss 1987). On its western flank, the belt borders the Gawler craton, and on its eastern flank, the belt borders the Murray Basin.

Regional studies suggest that the Delamerian orogen, and its southern continuation in Antarctica, the Ross orogen, formed during Cambro-Ordovician times at the onset of contractional deformation along the paleo-Pacific margin of Gondwana, when volcanic arc terranes accreted to the continent (Flöttmann *et al.* 1993 and references therein). The resulting orogenic shortening inverted the Late Proterozoic Adelaidean and the Cambrian Kanmantoo sedimentary basins, which fringed the eastern and southern boundaries, respectively, of the Gawler craton. In the Murray Basin, Cenozoic strata now bury much of the Delamerian orogen, but uplift of the orogen's foreland, beginning in the Eocene exposed the Adelaide fold–thrust belt (Howchin 1918, Sprigg 1946, Campana 1955, Lemon & McGowran 1989) and seismic activity continues in the region today (Greenhalgh & Singh 1988).

The Adelaide fold–thrust belt involves four principal lithotectonic units (Table 1, Fig. 3), which we briefly define below in order of decreasing age:

(1) *Crystalline Basement:* Basement in the Adelaide fold–thrust belt consists of 1.6 Ga granitoid, gneiss, and schist (Parker, 1993). Exposures of these rocks occur in the Willyama block at the east end of the Nackara Arc, in the Weekeroo Hills just west of the MacDonald fault zone, and in thrust slices along the Fleurieu Peninsula (Fig. 3; Glen *et al.* 1977, Berry *et al.* 1978, Clarke *et al.* 1986, 1987, Grady *et al.* 1989).

(2) *The Adelaidean Supersequence:* Throughout most of its outcrop belt, this unit consists of unmetamorphosed to very low-grade sandstone, mudstone, and diamicton, but in the Southern Flinders Ranges, it also includes a lower unit of evaporites and intercalated tuffs (the Callana Group; Preiss 1987). Adelaidean strata vary from an estimated thickness of 200 m on Kangaroo Island, to about 5 km thick on the Fleurieu Peninsula, to over 10 km thick in the Nackara Arc (Preiss 1993). Thus, in the Adelaide fold–thrust belt, the Adelaidean Supersequence thickens substantially from south to north. Fanning *et al.* (1986) obtained a date of 802 Ma from the basal tuffs of the supersequence, and strata from the top of the unit contain Ediacaran fauna. Thus, deposition of the entire unit occurred in the Late Proterozoic. Considering the composition and thickness of the Adelaidean Supersequence, Jenkins (1990) suggested that the strata represent the fill of a rift or passive-margin basin (Von der Borch 1980) that formed along the eastern edge of the Gawler craton in the Late Proterozoic. The north–south-trending Torrens hinge zone defines the western edge of this basin. West of the hinge zone, stratigraphic units thin abruptly. Of note, the thickest portion of the Adelaidean Supersequence lies along strike of NW-trending ≈800 Ma dike swarms (including the Gairdner dike swarm) exposed in the Gawler Craton, and may overlie an ≈800 Ma plume head (Zhao *et al.* 1994).

(3) *Cambrian Strata (Kanmantoo and Normanville Groups)*: Exposures of Cambrian strata, which exist only in the southern portion of the Adelaide fold–thrust belt, include two units. The older unit, known as the Normanville Group, consists of platformal sediments and intercalated tuffs. Cooper *et al.* (1992) obtained dates of 524 Ma on zircons from the tuffs. The younger Kanmantoo Group (Daily & Milnes, 1973) consists of clastic strata, including turbidites, which attain a maximum thickness of over 8 km adjacent to growth faults (Flöttmann *et al.* 1994, Daily & Milnes 1973). Deposition of the Kanmantoo Group represents renewed subsidence of the southern Australia margin in Cambrian times (Von

Table 1. Principal stratigraphic units of the Adelaide fold–thrust belt

Age	Unit Name	Principal Lithologies
Cenozoic	various formations	conglomerate, sandstone, siltstone
Cambrian (0.53–0.50 Ga)	Kangaroo Island Group	sandstone, siltstone, evaporite
	Kanmantoo Group	turbidites (graywacke and shale)
	Normanville Group	limestone, shale, sandstone, volcanic rocks
Upper Proterozoic (0.8–0.6 Ga)	Adelaidean Supersequence	
	Wilpena Group	quartzite, shale, siltstone, dolomite
	Umberatana Group	diamicton, shale, siltstone, dolomite
	Burra Group	shale (slate), siltstone, quartzite, dolomite
	Callana Group	sandstone, conglomerate, evaporite, volcanic rocks
Middle Proterozoic (≈ 1.6 Ga)	various basement units	granite, gneiss, schist

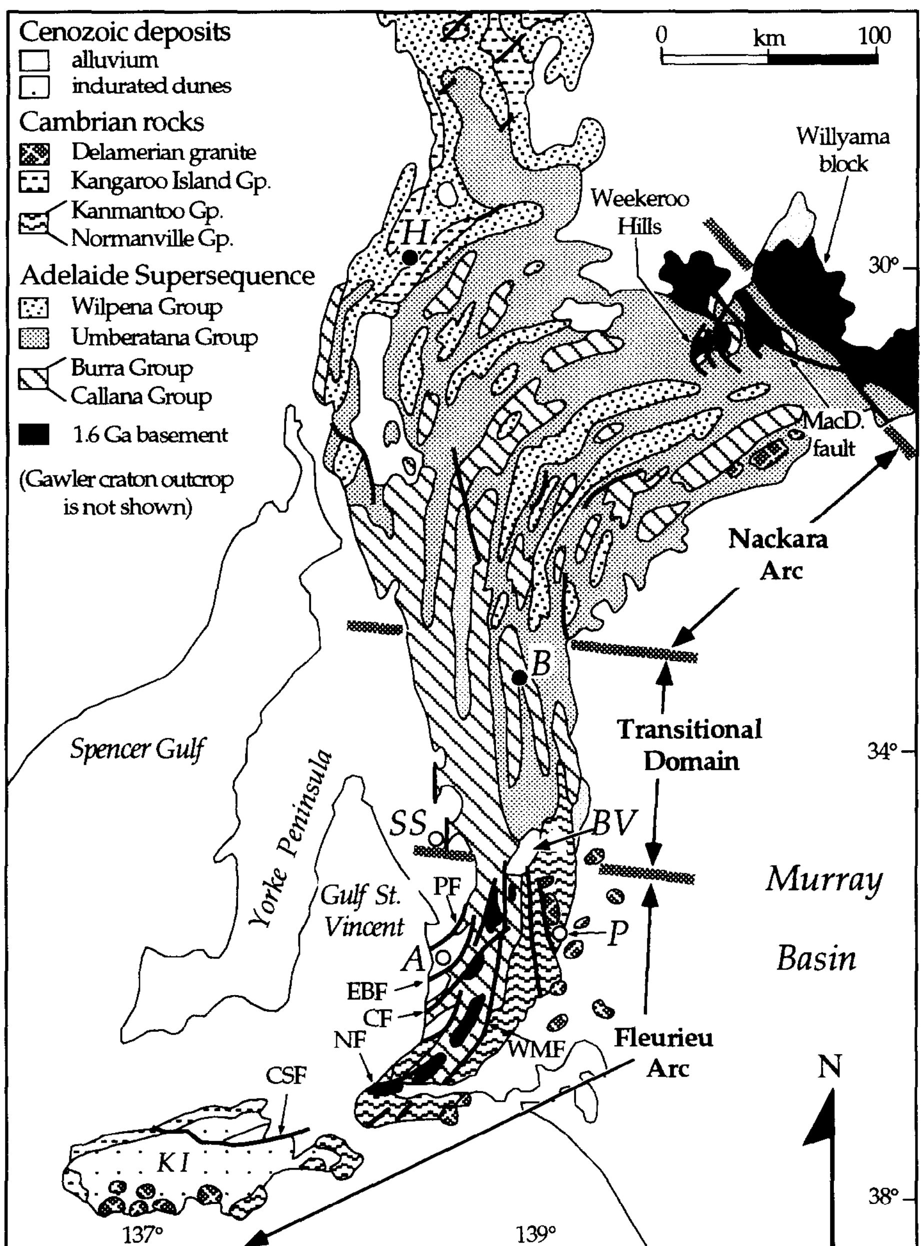

Fig. 3. Simplified geologic map of Adelaide fold–thrust belt (based, in part, on Thompson, 1983). Map area corresponds to area of Fig. 1(c). Limits of the three structural domains are indicated by thick shaded lines. A = Adelaide, SS = Salters Springs, BV = Barossa Valley, B = Burra, H = Hawker, KI = Kangaroo Island, P = Palmer, PF = Para fault, EBF = Eden-Burnside fault, CF = Clarendon fault, NF = Normanville fault, CSF = Cygnet-Snelling fault, WMF = Williamstown–Meadows fault.

der Borch 1980). The greatest thickness of Kanmantoo strata appears to lie to the east and south of the greatest thickness of Adelaidean strata, indicating that the depocenter of the Kanmantoo basin did not coincide spatially with the depocenter of the Adelaidean basin. In fact, the Kanmantoo basin probably cut obliquely across the southern end of the Adelaidean basin (Flöttmann & Cockshell 1996). The point of intersection between these two basins appears to lie along the axial trace of the Fleurieu Arc, and defines the southeast corner of the Gawler craton.

(4) *Delamerian Granitoids*: Delamerian igneous activity resulted in the intrusion of two suites of plutons along the inner edge of the Adelaide fold–thrust belt (Fig. 3). The older suite consists of synkinematic (I-type) granites, samples of which yield an age of 516 Ma (Foden *et al.* 1990, Sandiford *et al.* 1992). Metamorphic aureoles, which occur in strata around these intrusions, contain complex polyphase folds (Kleeman & White 1956, Offler & Fleming 1968, Dymoke & Sandiford 1992). The younger suite consists of postkinematic (A-type) granites, samples of which yield an age of about 490 Ma (Jenkins & Sandiford 1992, Turner *et al.* 1992).

OBSERVATIONS

Methodology

We divided the Adelaide fold–thrust belt into three structural domains named, from north to south: the Nackara Arc, the Transitional Domain, and the Fleurieu Arc (Fig. 3, cf. Rutland *et al.* 1981). Within each domain, we made two or three cross-strike transects, along which we examined fold and fault geometry, fabric orientation (Fig. 4) and style (Figs. 5 and 6), and kinematic indicators. We then compared structural features of the Adelaide fold–thrust belt to those of comparable tectonic settings (especially the Appalachian foreland of the U.S.A.) in order to find analogs that could provide insight into the deep geometry of the Adelaide fold–thrust belt, for at present there is little subsurface data available for South Australia.

Nackara Arc

Within the Nackara Arc, structural and topographic trends change from N–S to N70°E (Fig. 5a), and the width of the exposed fold–thrust belt, as measured perpendicular to strike, varies from 75 km to 180 km. Structural style along the border of the Nackara Arc domain varies markedly with location.

The MacDonald fault zone bounds the northeastern edge of the Nackara Arc and juxtaposes 1.6 Ga basement of the Willyama block against Adelaidean strata. This fault zone has a NW–SE trace and therefore cuts diagonally across the arc's regional structural grain. We found two suites of structures within the MacDonald fault zone. The younger suite consists of brittle mesoscopic faults (oriented 295°,65°NE) bordered by bands of breccia and coated by quartz-fiber slip lineations. The slip lineations rake between 25° and 85° and record strike-slip (dextral) to reverse-slip (top-to-the-west) displacement (Fig. 4). These brittle faults cut across an older suite of near-vertical mylonitic shear zones in which foliation strikes NW. In granitoid of the Willyama block, the shear zones anastomose around phacoidal lenses of less sheared granite and contain subhorizontal mineral lineations. In Adelaidean diamicton of the Nackara Arc, shear zones of the MacDonald fault zone appear as bands of stretched clasts with subhorizontal long axes. Asymmetry of granitoid phacoids, *C–S* fabrics (Fig. 5b), pressure shadows around feldspar porphyroclasts, pressure shadows around diamicton clasts, and mica fish all record a dextral shear sense during shear-zone movement. This shear sense matches the shear sense for the MacDonald fault zone defined by map-scale deflection of elongate granitoid bodies in the Willyama block adjacent to the zone—10 km NE of the fault zone, the granitoid bodies trend NE, whereas within 5 km of the fault zone they swing to an E–W trend.

The Weekeroo Hills, which lie immediately to the west of the MacDonald fault zone, contain a 40 km-wide (measured perpendicular to transport) imbricate fan of east-dipping thrust faults. These faults emplaced slivers of basement westward over Adelaidean strata (Forbes 1989). In each thrust slice, basal Adelaidean strata form a lunate belt around the eastern edge of the basement exposure.

A topographic escarpment delineates the curving northern and western boundaries of the Nackara Arc. The eastern portion of this boundary (northeast of Hawker) separates a series of N50°–70°E-trending parallel ridges (Fig. 5a) to the south from NNW-trending elongate domes and basins to the north. We saw no evidence for an emergent fault along this segment of the boundary. Beginning at the apex of the Nackara Arc (near Hawker) and continuing SW, an east-dipping thrust fault defines the boundary between the Nackara Arc and the nearly flat-lying strata covering the Gawler craton to the west (N. Lemon pers. comm. 1992). Adelaidean strata of the Nackara Arc adjacent to this contact contain only local spaced cleavage, and ridges of resistant strata in the arc intersect the boundary at an acute angle. These ridges taper to progressively lower elevations to the south.

A discontinuous chain of Delamerian granitoids partly fringes the inner boundary of the Nackara Arc, where it borders the Murray Basin (Fig. 3). The boundary between Adelaidean strata and the granitoid bodies, at least locally, is a smooth planar NW-dipping shear zone. Phyllitic foliation in strata adjacent to the contact dips to the NW, suggesting that movement on the shear zone involved top-to-the-southeast movement.

In the interior of the Nackara Arc, regional mapping (Dalgarno & Johnson 1966, Binks,1968) reveals large upright to slightly inclined NW- to W-verging first-order folds with amplitudes of about 400 m, wavelengths of about 20 km, and maximum limb dips (at the ground

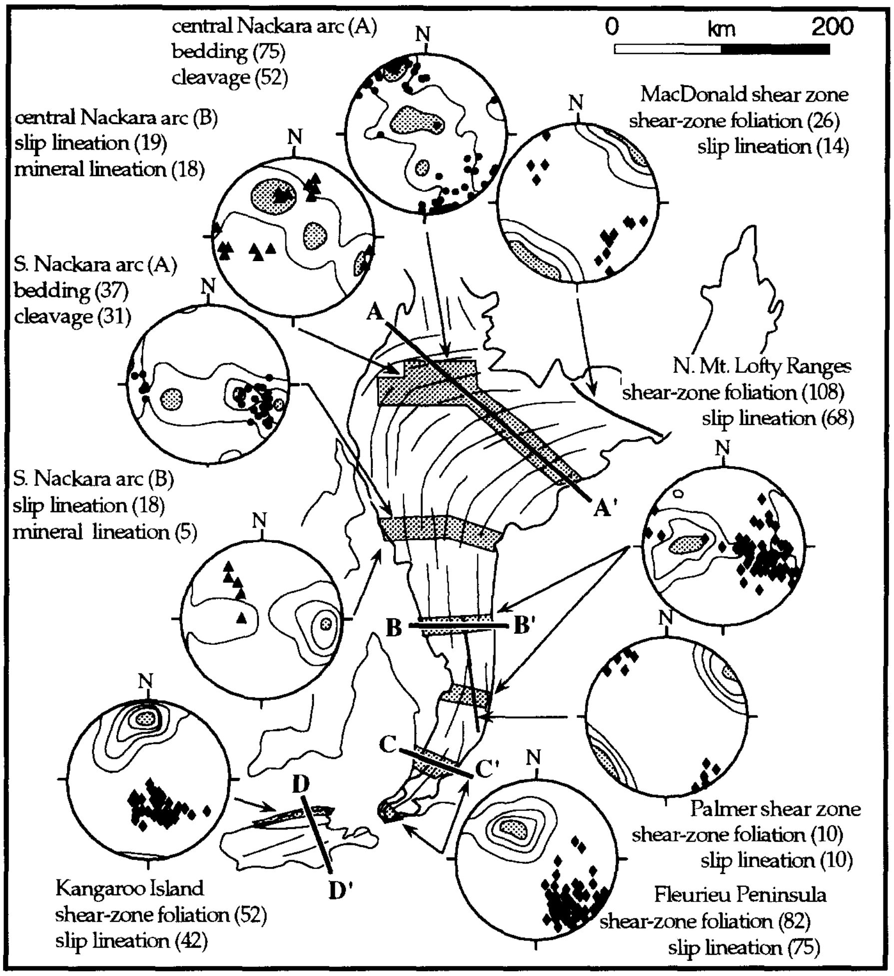

Fig. 4. Synoptic equal-area plots of structural data along the traverses shown by stippled boxes, along the MacDonald fault zone, and along the Palmer shear zone. Map area corresponds to Fig. 1(c). Thin broken lines within the 200 m contour represent structural trendlines. Heavy lines are cross-section lines for Fig. 9. The domain name, the structural feature that is contoured, and the structural feature plotted as points (with the numbers of measurements in parentheses) are listed beside each plot. The area within the highest contour is shaded for emphasis. Contour interval is 2% except for South Nackara (A and B) and Central Nackara (B) plots, where contour interval is 1.6%.

surface) of 35°. Folds are gently doubly plunging; anticline culminations roughly lie along the axial trace of the arc. Emergent faults appear to be rare in the interior of the Nackara Arc (Dalgarno & Johnson 1966).

As recognized by Bell (1978), metamorphic grade increases slightly from NW to SE across strike in the Nackara Arc. In general, pelitic units contain slaty cleavage and sandy units contain spaced cleavage. Slaty cleavage (S_1) dips 70°–87°SE (Fig. 4), parallel to the axial plane of regional first-order folds (except along the southeastern edge of the domain). Locally, pelitic strata contain an S_2 crenulation cleavage which wrinkles the S_1 cleavage, but has the same strike as the S_1 cleavage.

Two distinct types of lineations occur in Adelaidean strata of the Nackara Arc. The first type consists of fibrous quartz tails on pyrite grains in slate (Fig. 5c). This penetrative lineation, which looks like a faint streaking on cleavage planes, rakes 50° to the SW in the northeastern portion of the domain, where cleavage strikes N70°E, but rakes 90° (i.e. downdip) in the southeastern portion of the domain, where cleavage strikes nearly N–S (Fig. 4). The second type of lineation consists of quartz slip fibers that occur in sheets on bedding-plane surfaces. These non-penetrative lineations rake downdip throughout the Nackara Arc, regardless of bedding strike.

Transitional Domain

The 120 km-long by 60 to 100 km-wide Transitional Domain of the Adelaide fold–thrust belt forms a gradational link between the Nackara and Fleurieu Arcs. Within the Transitional Domain, fold axes, as well as fault and cleavage traces, trend N–S. Structural style of this domain changes from west to east. Along a west to east transect, we identified two distinct N-trending subdomains—the 20 km-wide Salters Springs Subdomain in the west and the Burra Subdomain in the east.

The Salters Springs Subdomain contains strongly crenulated coarse phyllite, mylonitized quartzite, and foliated micaceous marble. All these lithologies contain a strong downdip (i.e. east-plunging) mineral lineation defined by streaks of white mica, and most rocks also contain quartz and/or calcite veins. Original bedding

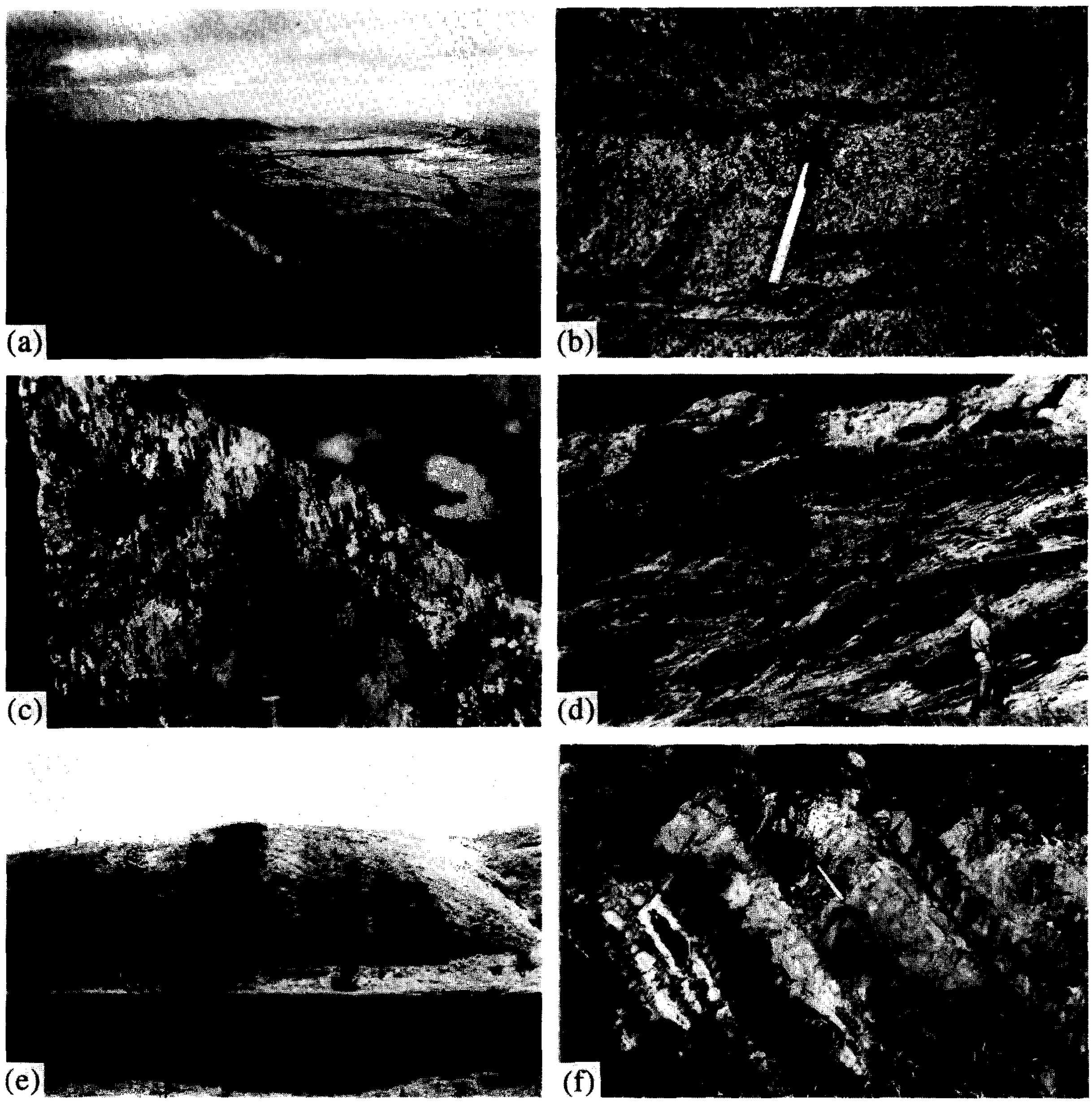

Fig. 5. Photos of structures in the Adelaide fold–thrust belt. (a) Oblique air view, taken looking northeast, of the Nackara Arc's curving deformation front 15 km northeast of Hawker. (b) Horizontal outcrop surface containing shear zones in granite along the MacDonald Fault Zone. White pen parallels older foliation in granite, and black pen parallels southeast-trending shear zones. (c) Penetrative mineral lineation defined by fibrous tales on pyrite grains of slate in the Nackara Arc. Surface is a weathered foliation plane exposed 20 km south of the Weekeroo Hills. Pencil end for scale. Black line emphasizes lineation trace. (d) View looking south of a vertical outcrop face in Salters Springs Subdomain, 5 km north of Salters Springs. Shallow-dipping mylonitic foliation surrounds west-dipping phacoids. Phacoid is outlined in black. Person indicates scale. (e) Hill face in Burra Subdomain, 30 km ENE of Salters Springs, showing near-vertical beds of sandstone and slate. The thick dark bed is a massive sandstone. Cows for scale; (f) View of vertical outcrop face, looking north, showing spaced cleavage in siltstone of the Burra Subdomain 10 km east of Burra. Bedding (indicated by long black lines) dips east and cleavage dips west.

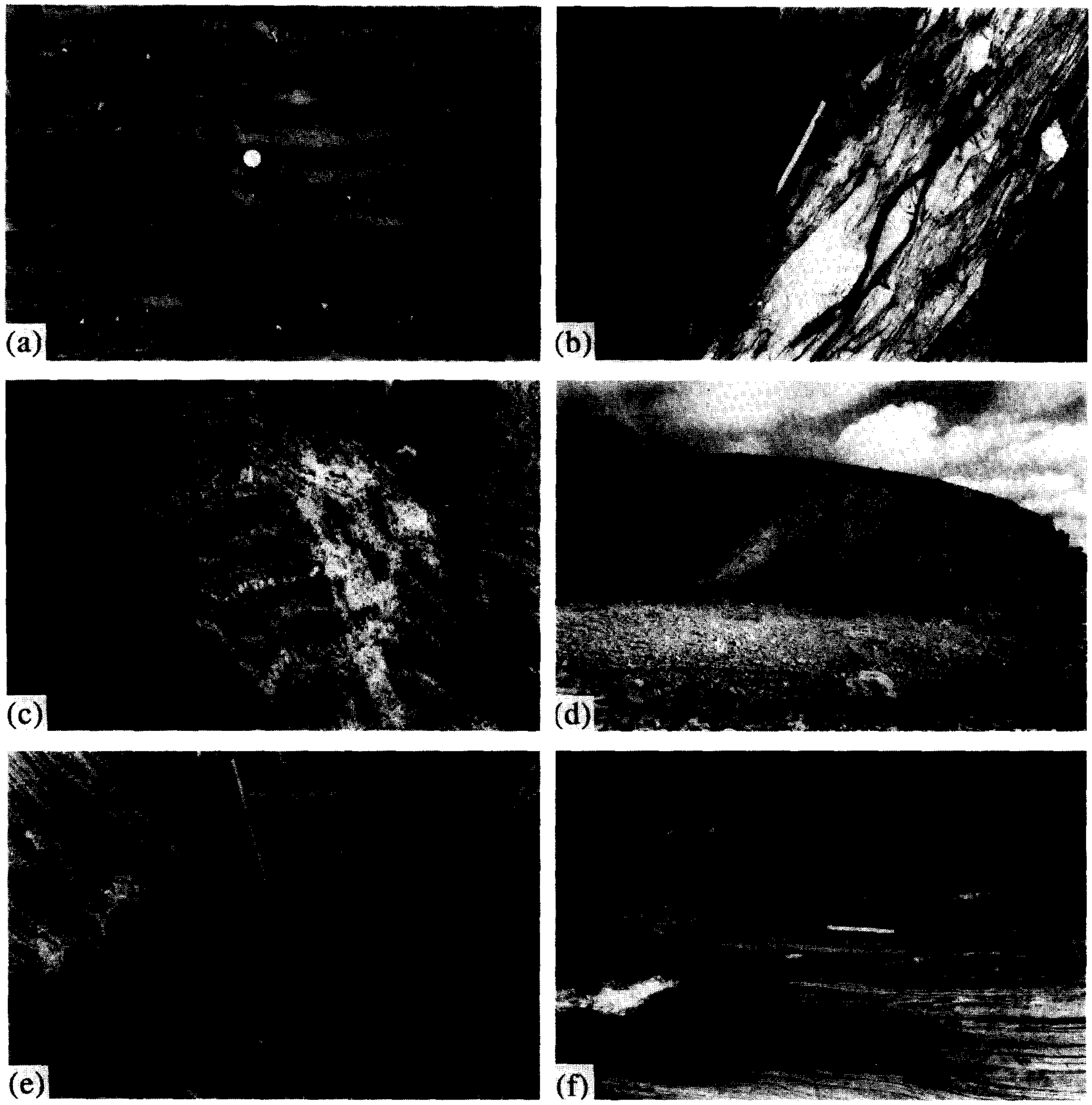

Fig. 6. Photos of structures in the Adelaide fold–thrust belt (cont.). (a) Siltstone bedding surface cut by spaced cleavage domains along west edge of the Fleurieu Arc, 10 km south of Adelaide. Coin for scale. South is to the right. (b) View of vertical outcrop face, looking south, showing tails (highlighted) on cobbles in diamicton in the Fleurieu Arc, 10 km southeast of Adelaide. Pencil for scale. (c) Vertical outcrop face, 15 km NNW of Palmer, exposing gneissic layering following original bedding in the metamorphosed Kanmantoo Formation. (d) Beach cliff exposing Kangaroo Island shear zone, viewed looking west, as exposed at Kangaroo Gully. Asymmetry of the large phacoid, highlighted in black just left of center, indicates reverse-sense shear. (e) Asymmetric crenulation in the Kanmantoo Group above the Kangaroo Island shear zone, north side of Kangaroo Island. View looking east. Pencil for scale. (f) Horizontal outcrop face showing foliation-parallel shear zones containing *en echelon* extension veins, near Cuttlefish Bay, Kangaroo Island. Northeast is to the right of the photo. Pen for scale.

within the subdomain has been transposed into a shallow east-dipping phyllitic schistosity, as indicated by the occurrence of rootless isoclinal folds (of quartzose layers in phyllite) whose limbs parallel foliation planes. Variations in the intensity of transposition and in the degree of foliation development define anastamosing shear zones that surround lenses of less sheared rock in the Salters Springs Subdomain (Fig. 5d). Kinematic indicators in these shear zones (e.g. *C–S* fabrics, rolled porphyroclasts, and asymmetric mesoscopic folds) indicate a thrust sense of shear, with top-to-the-west movement.

The contact between the Salters Springs Subdomain and the Burra Subdomain occurs in a 500 m-wide (in map view) covered interval. In contrast to the Salters Springs Subdomain, the Burra Subdomain consists of a monotonous sequence of low-grade slate, metasandstone, and metadiamicton (Fig. 5e). Coarser lithologies within the subdomain contain only spaced solution cleavage, and the slates do not display phyllitic luster. In diamictons of the subdomain, we did not find pressure shadows around clasts. Folds within the subdomain are upright to slightly inclined, and have wavelengths of up to 10 km. In the eastern two-thirds of the subdomain, fold axial surfaces and cleavage planes dip westwards (Fig. 5f), indicating that structural vergence in this region is to the east (Fig. 4; cf. Preiss 1987).

Fleurieu Arc

The Fleurieu Arc includes the Mt. Lofty Ranges, the Fleurieu Peninsula, and Kangaroo Island. Within this domain, structural trends progressively change from N–S, north of Adelaide, to NE–SW on the Fleurieu Peninsula, to about E–W on Kangaroo Island.

Fleurieu Peninsula. The western edge of the Fleurieu Peninsula forms the coast of the Gulf St. Vincent. Along this coast, structurally controlled ridges of the fold thrust belt intersect the coastline at an acute angle. North of Adelaide, the westernmost and structurally lowest outcrops of the fold–thrust belt consist of Adelaidean quartzite and phyllite of the Para thrust sheet (e.g. Mancktelow 1990). These strata, which have been strongly deformed into inclined NW-verging tight folds with wavelengths of 10 to 15 m, contain an axial-planar cleavage that dips about 70°SE and a hinge-zone crenulation that trends parallel to fold axes. At the latitude of Adelaide, this folded interval lies in the low hills to the west of the 200 m-high escarpment that defines the west edge of the Mt. Lofty Ranges. The base of this escarpment is a shear zone, the Eden-Burnside fault, in which Burra Group quartzite contains a mylonitic foliation, pelites contain a very strong asymmetric crenulation cleavage, and bedding has been transposed into foliation. At the top of the escarpment, above the shear zone, outcrops of the Eden-Burnside thrust sheet consist of massive quartzite folded into upright to slightly inclined open folds. Farther to the southeast, where the sheet curves toward the coast, it includes argillaceous carbonates that contain spaced solution cleavage (Fig. 6a, Waldron & Sandiford 1988). Cleavage intensity, defined by a decrease in domain spacing, increases progressively to the ESE, indicating that strain increases in this direction (Flöttmann *et al.* 1994). In strongly cleaved diamictons of the Eden-Burnside sheet, pressure-shadow tails developed adjacent to clasts in the plane of cleavage. These tails, which are up to three times the diameter of the clast they border, define a down dip lineation (Fig. 6b). SE-dipping thrusts locally cut the Eden-Burnside sheet; 1.6 Ga basement gneiss occurs in the cores of hanging-wall anticlines above these thrusts (Fig. 3).

The SE-dipping Clarendon fault truncates the southeastern edge of the Eden-Burnside sheet (Offler & Fleming 1968, Mancktelow 1990). Movement on this thrust placed a sheet of 1.6 Ga basement gneiss over Adelaidean strata. Retrograde metamorphism in the thrust zone transformed originally high-grade gneiss into greenschist-grade mylonite (Steinhardt 1991) containing *C–S* fabrics, mica fish, and tails on porphyroclasts that record top-to-the-northwest movement (Flöttmann *et al.* 1994). The Para, Eden-Burnside, and Clarendon faults were reactivated during the Cenozoic and control current topography at the western front of the Mt. Lofty Ranges.

Shear on the SE-dipping Williamstown–Meadows fault along the SE edge of the Clarendon sheet emplaced Adelaidean strata and Kanmantoo Group strata over basement gneiss of the Clarendon sheet (e.g. Offler & Fleming, 1968). Kinematic indicators in this younger-on-older fault clearly record top-to-the-northwest movement. Kanmantoo strata of the Williamstown–Meadows sheet generally contain phyllitic cleavage, except where they have been metamorphosed into biotite–quartz gneiss by synkinematic Delamerian intrusions (Fig. 6c).

Several Delamerian intrusions in the southeastern portion of the Fleurieu Arc cluster along a N10°W-trending shear zone, the Palmer shear zone, that can be traced from the town of Palmer to the Barossa Valley. This shear zone, which cuts obliquely across local structural trends of the fold–thrust belt, may link with a N10°W-trending structural discontinuity that cuts across the Transitional Domain and the Nackara Arc. Along the discontinuity (line P–H on Fig. 1c), regional fold-hinge traces abruptly terminate. Exposures of mylonite in the Palmer shear zone contain a steeply dipping foliation and subhorizontal (05°/350° plunge and bearing) mineral lineation (Fig. 4). *C–S* fabrics in the mylonite record a sinistral shear sense.

NE-trending faults truncate N-trending folds and fabrics along the western edge of the Fleurieu Peninsula. Based on this observation, Offler & Fleming (1968) suggested that this region was subjected to two phases of deformation—the first resulting in top-to-the-west transport and the second resulting in top-to-the-northwest transport. Development of Cenozoic basins adjacent to the NE-trending faults suggests that they were reactivated during the Cenozoic.

Kangaroo Island. Exposures of pre-Cenozoic strata occur only on the coastal platforms and sea cliffs of Kangaroo Island, as Cenozoic sediments cover the interior of the island. With the exception of a small slice of Adelaidean strata exposed at the eastern tip of the island, all the pre-Cenozoic strata are Cambrian. The Cambrian Kangaroo Island Group crops out along the north coast of the island. This relatively thin (<2500 m-thick) unit consists of fossiliferous shallow-marine rocks containing sediment derived by erosion of platform strata that once covered the southern margin of the Gawler craton (Thomson 1969, Daily *et al.*, 1979, 1980, Belperio & Flint 1992). Cambrian strata of southern Kangaroo Island comprise the Kanmantoo Group, a unit up to 7000 m-thick dominated by thick accumulations of deep-water clastic sedimentary rocks (Sprigg & Campana 1953, Daily & Milnes 1973, Flint, 1978, Daily *et al.* 1979, Belperio & Flint 1992). Along the south and southeastern coasts of the island, Delamerian pegmatite and granitoid intrusions metamorphosed and, locally, partially melted Kanmantoo Group rocks (Mitchell 1990).

The boundary between the Kangaroo Island Group and the Kanmantoo Group corresponds with a gradient on gravity and magnetic profiles (Belperio & Flint,1992, Van der Stelt *et al.* 1992) that represents an abrupt increase in depth to basement (Belperio & Flint, 1992). This boundary also corresponds with a change in the trends of fold axes, fault traces, and fabric traces. North of the boundary, structures trend between E–W and N85°W, whereas south of the boundary, they trend N60°–75°E. We studied this boundary in two coastal exposures, one near Kangaroo Gully and the other near American River, and at both of these localities, found it to consist of an E–W-striking and S-dipping mylonitic shear zone (Fig. 6d), the Kangaroo Island shear zone (Marshak & Flöttmann 1992, Flöttmann *et al.* 1995). Mylonites in the shear zone contain mineral lineations with a rake of 70°–90°, and *C–S* fabrics that record top-to-the-north transport (Fig. 4). A progressive decrease in relative shear strain, manifested by the gradual change from penetrative mylonitic fabric into spaced asymmetric crenulation cleavage (Fig. 6e), occurs in the hanging-wall block above the Kangaroo Island shear zone (Fig. 7). The Cygnet–Snelling fault, a Cenozoic structure manifested by a topographic escarpment that bounds a basin near American River, lies along the north side of the Kangaroo Island shear zone.

Farther south, away from the Kangaroo Island shear zone and its margins, foliation spacing and style, as well as metamorphic grade in the Kanmantoo Group, vary with location, as typified by exposures along the south shore and eastern tip of Kangaroo Island. This region contains N55°E-trending folds with SE-dipping axial surfaces, and mesoscopic SE-dipping shear zones (see also Thomson 1969, Flöttmann *et al.* 1995). Mineral lineations in the shear zones rake between 0° and about 70° to the NE on foliation planes, suggesting that, in marked contrast to the Kangaroo Island shear zone itself, shear in the southern part of Kangaroo Island involved oblique-slip and strike-slip movement. Kinematic indicators show that the dip-slip component of this movement resulted in reverse displacement. The geometry of en echelon vein arrays in foliation-parallel strike-slip zones (Fig. 6f) suggests both sinistral and dextral movement.

INTERPRETATION

Structural models of the Adelaide fold–thrust belt

MacDonald fault zone model. Previous authors interpreted the MacDonald fault zone to be either a west-verging thrust fault (Clarke & Powell,1989) or a strike-slip fault with an unspecified shear sense (Glen *et al.* 1977). Our mapping indicates that there were two separate phases of motion on this near vertical fault—an early (but post-Adelaidean) ductile phase and a later brittle phase. We found that the ductile phase resulted in dextral strike-slip, and that the brittle phase resulted in both dextral strike-slip and reverse-slip movement. Considering the position and orientation of the MacDonald fault zone and our new evidence that dextral strike-slip movement occurred on the fault while presently exposed Adelaidean strata were still deeply buried, we suggest that the fault acted as a Delamerian lateral ramp along which Adelaidean strata in the fold–thrust belt moved to the northwest relative to the Willyama basement block. This interpretation could be tested by dating the shear zone. Conceivably, the fault initiated either as a transfer fault bounding the northeast edge of the Adelaidean basin, or as an extensional fault associated with the NW-trending Gairdner dike swarm and its correlatives.

Nackara Arc model. Several of the structural features we observed in the Nackara Arc resemble regional structural patterns exposed in the Pennsylvania salient of the Appalachian fold–thrust belt in the eastern U.S.A. Both regions are antitaxial curves, bounded at the foreland edge by a structural and topographic front, and shortening at shallow crustal levels in both regions was accommodated primarily by folding, so neither region contains numerous emergent thrusts. Because of these similarities, we suggest that subsurface studies of the Pennsylvania salient potentially provide insight into the the subsurface structure of the Nackara Arc.

In the internal portion of the Pennsylvania Salient (the Valley and Ridge Province), surface folding reflects passive buckling of relatively ductile strata above a duplex involving relatively rigid strata, whereas on the external portion of the curve (the New York Plateau) surface folds reflect buckling or fault-propagation folding of strata above a regional subhorizontal décollement located in an evaporite horizon (Davis & Engelder 1985, Geiser 1988). Slate and other clastic units of the Nackara Arc overlie a regionally extensive evaporite horizon (the Callana Group; Coates 1965, Preiss 1987), so we propose that the Nackara Arc resembles the New York Plateau

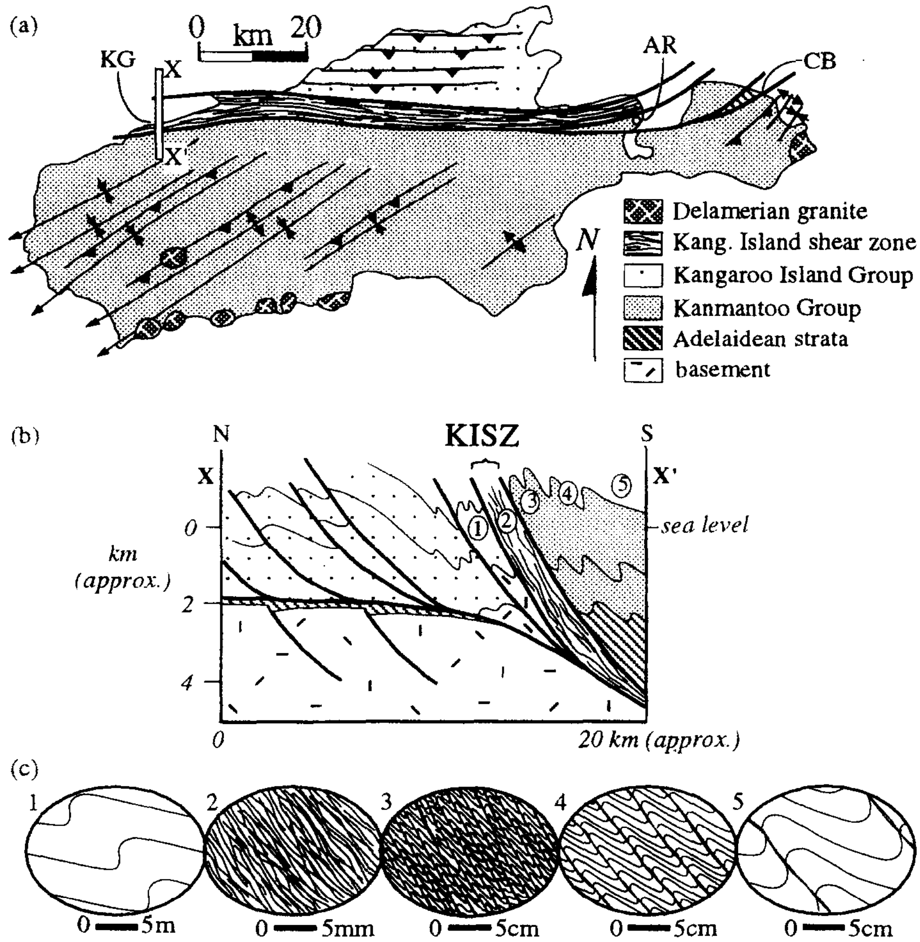

Fig. 7. Geologic features of Kangaroo Island. (a) Sketch map of the Kangaroo Island shear zone. KG = Kangaroo Gully, AR = American River, CB = Cuttlefish Bay. (b) Cross-section sketch (not to scale) along XX'. KISZ = Kangaroo Island shear zone. The numbers correspond to the sketches in (c). (c) Sketches showing the progressive change in fabric along XX'. Sketch 1 illustrates asymmetric folding without crenulation cleavage north of the Kangaroo Island shear zone. Sketch 2 illustrates mylonitic foliation in the shear zone. Sketches 3–5 illustrate progressively decreasing intensity of crenulation cleavage in the hanging wall as a function of distance from the shear zone.

segment of the Pennsylvania salient, and consists of detachment folds and/or fault-propagation folds formed above an evaporite-hosted décollement. Figure 8(a) provides an admissible deformed-state cross section of this concept, and illustrates explanations for several other observed features of the Nackara Arc.

The western edge of the Nackara Arc coincides with the Torrens hinge zone, across which Adelaidean strata abruptly thin. If, as suggested by Von der Borch (1980) and Jenkins (1990), the Adelaidean basin was a rift or passive-margin basin, then the Torrens hinge zone represented the boundary between thinned crust and the normal-thickness crust. If, as we propose, shortening in the Adelaide fold–thrust belt of the Nackara Arc only involves strata above a detachment at the base of the Adelaidean Supersequence, then pre-Adelaidean normal faults may be preserved at depth in this domain, as we depict on section AA' (Fig. 8).

At the ground surface, the foreland boundary of the Nackara Arc along the Central Flinders Ranges resembles the Appalachian front along the foreland edge of the Pennsylvania salient, in that both are topographic features that define the abrupt termination of fold–thrust belt structures. The Appalachian front overlies a ramp at depth that links the basal detachment within the Pennsylvania salient with a shallow-level blind thrust to the foreland. Because of the similarity between the Appalachian front and the foreland edge of the Nackara Arc, we propose that the northern portion of the foreland edge of the Nackara Arc also overlies a blind ramp, which possibly links the basal detachment within the arc to a décollement beneath the Central Flinders Ranges (Fig. 8). Emergent thrusts that occur along the western edge of the Nackara Arc may represent Cenozoic splays that cut upwards from the blind ramp.

The southeast structural vergence that we observed along the Murray Basin margin of the Nackara Arc indicates that backthrusting occurred along this boundary. We suggest, by analogy to structural models of the hinterland boundary of other fold–thrust belts (e.g. the Sevier fold–thrust belt in Utah, Bruhn *et al.* 1986; the Hudson Valley fold–thrust belt in New York, Marshak & Tabor 1989), that this backthrusting emplaced Adelaidean strata southeastward and up the NW-dipping forelimb of a subsequently eroded or subsided ramp anticline. This suggestion implies that an internal portion of the Adelaide fold–thrust belt once lay to the southeast of the Nackara Arc, an idea supported by aeromagnetic (Brown *et al.* 1988) and drilling (Rankin *et al.* 1991) studies that document the existence of Delamerian

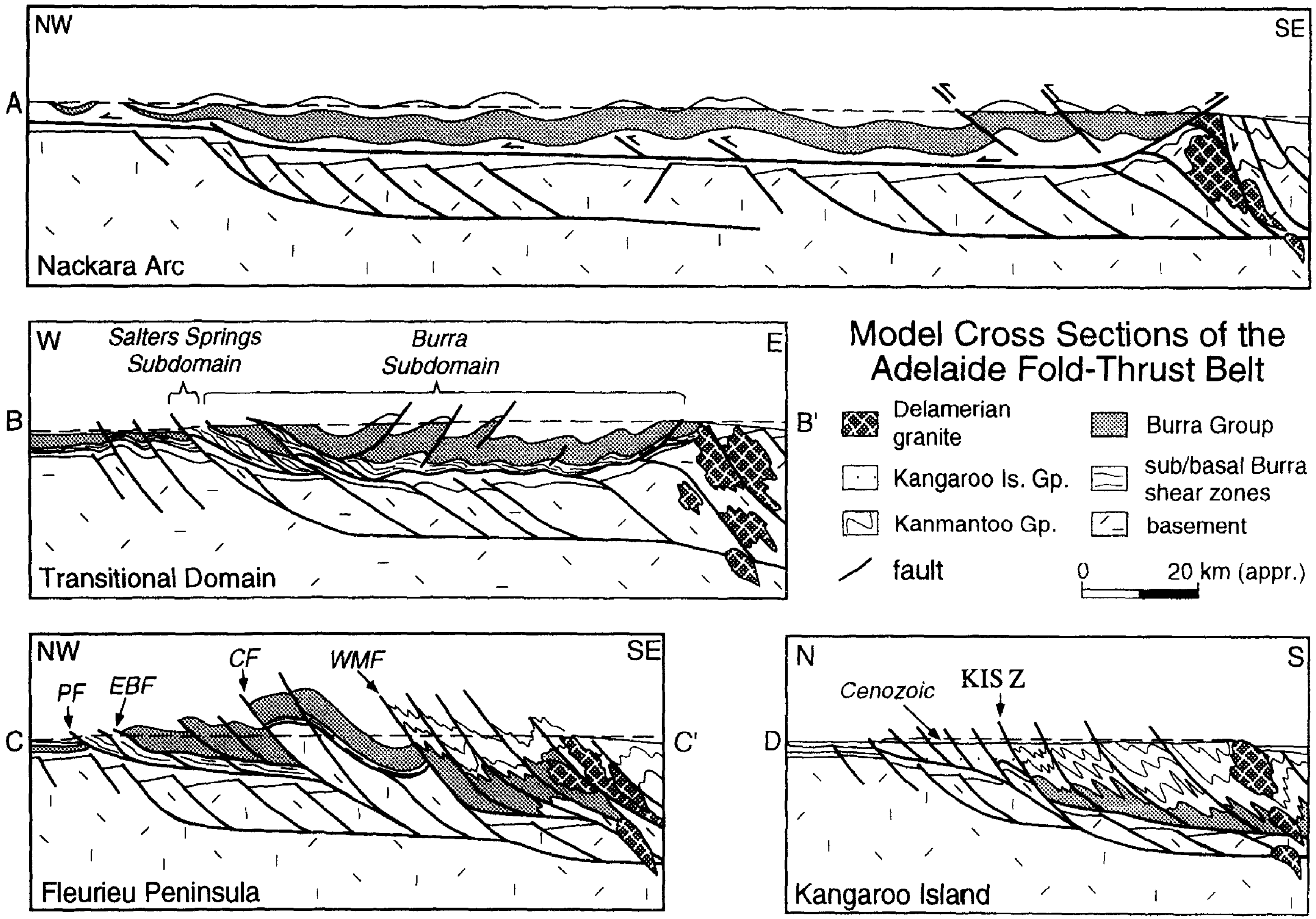

Fig. 8. Model cross sections illustrating our interpretation of structural style in the different domains of the Adelaide fold–thrust belt. Section-line locations are shown on Fig. 4. Marker units are patterned and identified. Unpatterned areas above the Burra are Wilpena and Umberatana Groups, and unpatterned areas below the Burra are the Callana Group and equivalents. On sections CC′ and DD′, areas decorated with mesoscopic folds contain Kanmantoo Group. WMF = Williamstown–Meadows fault, CF = Clarendon fault, EBF = Eden-Burnside fault, PF = Para fault, KISZ = Kangaroo Island shear zone.

structures beneath Cenozoic sediment of the Murray Basin. Subsidence of the Murray Basin region implies that the region underwent extensional faulting. This faulting may represent Delamerian syntectonic orogenic collapse, and/or Cenozoic extension, and thus in Fig. 8 (section AA′) we show normal faults cutting Delamerian basement beneath the sedimentary cover. Interestingly, if the Murray Basin region initially developed due to Delamerian syntectonic orogenic collapse, then its initial formation resembles that of the Panonian Basin in eastern Europe (B. C. Burchfiel pers. comm. 1992), which formed behind the active Carpathian fold–thrust belt (cf. Royden & Burchfiel 1989).

Transitional domain model. We suggest that the contrast in structural style that distinguishes the Salters Springs Subdomain from the Burra Subdomain reflects a contrast in the magnitude of shear strain and in the degree of syntectonic metamorphism, because: (1) the transposition of bedding into foliation that we observed in the Salters Springs Subdomain requires a relatively greater degree of shear strain than does the development of the disjunctive slaty cleavage that we observed in the Burra Subdomain (e.g. Ramsay & Huber 1983), and (2) the formation of a coarse-grained phyllite requires higher temperatures and/or more alteration by metamorphic fluids than does the formation of slate (Mason 1978). Considering that the transition between the two subdomains occurs in an interval that is less than about 200 m wide (as measured perpendicular to the regional dip), the transition must represent an abrupt strain gradient, and therefore must be a shear zone. We conclude, therefore, that the Salters Springs Subdomain represents an intensely sheared sequence (a duplex or schuppen zone) lying beneath a detachment that separates the Salters Springs Subdomain from the lesser strained Burra Subdomain (Fig. 8, section BB′). Dip variations in the Burra Subdomain, which overall define a regional-scale synclinorium, imply that either the detachment is not planar or that regional-scale detachment folds or fault-propagation folds developed in the Burra Subdomain by shortening above the detachment. The regional structural geometry of the Transitional Domain, as portrayed in our model, resembles that of the southern Appalachian foreland (cf. section 18 by Woodward and Gray, in Woodward 1985).

By analogy to the geometry of the Sevier fold–thrust belt along the Wasatch front in Utah (Bruhn *et al.* 1986) or to that of the Hudson Valley fold–thrust belt (Marshak & Tabor 1989), the eastward vergence of structures in the Burra Subdomain represents out-of-the-syncline back-thrusting to accommodate progressive development of the regional synclinorium. In our model, the eastern margin of the regional synclinorium slipped east, up the forelimb of a subsequently eroded or subsided anticline at the boundary between the fold–thrust belt and the now subsided internal part of the Delamerian orogen (Fig. 8, section BB′).

We speculate that coarser metamorphic minerals formed in the Salters Springs Subdomain than in the Burra Subdomain because the sandstones and carbonates of the former provided a fluid conduit for hot, reactive fluids expelled from the Delamerian orogen during formation of the fold–thrust belt. These fluids reacted with the strata to create metamorphic minerals, a process that has been documented in other orogens (cf. Oliver 1986, Bethke & Marshak 1990). Perhaps the relatively impermeable slate above acted as a seal, so the hot fluids did not enter and react with the overlying slate.

Fleurieu Arc model. The western edge of the Fleurieu Arc, as exposed on the Fleurieu Peninsula, resembles the western edge of the Transitional Domain, in that the structurally lowest outcrops expose a craton-verging shear zone, composed of mylonitized quartzite and phyllite, overlain by a thrust sheet of non-mylonitic strata. However, the Fleurieu Arc differs from both the Transitional and Nackara Arc domains in the following ways: (1) thrusts in the Fleurieu Arc place 1.6 Ga basement gneiss over Adelaidean strata within 25 km of the western edge of the fold–thrust belt; we did not find basement-involved thrusting in the other domains; (2) the eastern half of the thrust belt contains Cambrian Kanmantoo Group strata, a unit not exposed to the north. Kanmantoo strata moved up to the NW over 1.6 Ga basement gneiss and its Proterozoic (Adelaidean) cover, thereby creating a younger-on-older thrust relationship; (3) sedimentary units of the Adelaide fold–thrust belt reach a higher metamorphic grade (upper greenschist to amphibolite) in the Fleurieu Arc than in the other domains; (4) cross-cutting relations between younger thrusts and earlier-formed thrust sheets on the Fleurieu Peninsula suggest a two-phase deformation history (Offler & Fleming 1968), a feature not observed in the other domains; (5) only older units of the Adelaidean Supersequence crop out in the Fleurieu Arc-younger units, which crop out in the other domains, either were not deposited or were subsequently eroded away in the Fleurieu Arc; (6) simple bed-length restoration of our Fleurieu Peninsula cross section indicates that minimum cross-strike shortening in this portion of the Fleurieu Arc due to folding and faulting (i.e. not including fabric development) is about 50%, far greater than the cross-strike shortening in the Nackara Arc (about 10–15%, based on Fig. 8).

Figure 8 (section CC′) provides an admissible cross-sectional model of the Fleurieu Peninsula that explains the above similarities and differences. As indicated by this cross section, we suggest that the northwesternmost outcrops of the fold–thrust belt in the Fleurieu Arc expose an intensely sheared schuppen zone (duplex) involving units from the lower part of the Adelaidean Supersequence. This geometry resembles the geometry of the Salters Springs Subdomain to the north. The lower schuppen zone of the Fleurieu Arc may overlie remnants of an older extensional basin whose foreland edge coincides with the Torrens hinge zone, for this portion of the crust must have been stretched during formation of the Adelaidean basin. Thrust sheets of less strained rock (as indicated by fabric intensity and degree of transposition) overlie the basal schuppen. Westward transport of basement slices over younger strata, in the region east of the Clarendon fault, could represent inversion of pre-Delamerian normal faults (cf. Marshak & Alkmim 1989). The younger-on-older juxtaposition of Kanmantoo Group over basement along the Williamstown–Meadows fault requires that this thrust was originally a major normal fault at the western edge of the Kanmantoo basin. Effectively, basin inversion during Delamerian contraction emplaced the deep basin fill (Kanmantoo Group) northwestward over the Kanmantoo basin margin.

As shown in the cross-sectional model of Fig. 8 (section DD′), the structural geometry of Kangaroo Island resembles that of the Fleurieu Peninsula, but there are differences between the two regions. On Kangaroo Island, the Kangaroo Island shear zone plays the role of the Williamstown–Meadows fault, in that it is movement on the Kangaroo Island shear zone that uplifts deep-basin Kanmantoo strata. On Kangaroo Island, however, the foreland boundary of the Kanmantoo basin lies much closer to the foreland than it does on the Fleurieu Peninsula. This geometry implies that the Kanmantoo basin cuts across the pre-existing Adelaidean basin. To the foreland of the Kangaroo Island shear zone, shortening of Kangaroo Island Group strata may have occurred by basement-detached thrusting (i.e. shortening above a detachment that lies above 1.6 Ga basement) or by inversion of Kanmantoo-age basement-penetrating normal faults. The occurrence of cleavage in Kangaroo Island Group rocks suggests that these rocks underwent layer-parallel shortening, as typically occurs in association with basement-detached faulting, so our model cross section illustrates this interpretation.

The contrast in structural-trend orientation between the regions north and south of the Kangaroo Island shear zone, coupled with the observation that the NE-trending structures south of the shear zone appear to be truncated by it, suggest that movement on the Kangaroo Island shear zone post-dated and cut across structures formed during an earlier phase of deformation. Transport directions during the two phases were not parallel—the first phase, recorded by structures south of the Kangaroo Island shear zone, resulted in oblique-slip transport to the northwest, whereas the second phase, recorded by the Kangaroo Island shear zone itself, resulted in up-dip transport to the north. Strike-slip shear observed in the core of the Fleurieu Arc at the east tip of Kangaroo Island formed subsequent to first-phase foliation development, and thus may post-date the first phase of deformation.

Curve formation in the Adelaide fold–thrust belt

Nackara Arc formation. We propose that the Nackara Arc formed primarily because of pre-deformational along-strike variation of stratigraphy in the Adelaidean basin. This proposal is based on previous studies which demonstrate that stratigraphy affects the width of a fold–thrust belt in two ways. First, as shown by Marshak *et al.* (1992) using sandbox models, the width of a thrust wedge is linearly proportional to the initial thickness of the deforming layer (Fig. 9a & b). Second, as shown by Davis & Engelder (1985) using critical-taper theory, the width of a thrust wedge depends on the strength of the detachment horizon. Thus, a salient develops where a fold–thrust belt involves thicker section of strata, and/or where the belt forms above a weak evaporite horizon that pinches out along strike. We suggest that this concept applies to the Nackara Arc because the region of the arc overlies the thickest portion of the Adelaidean basin and overlies the Callana Group evaporite. In other words, when inversion of the Adelaidean basin occurred during the Delamerian orogeny, the Adelaide fold–thrust belt propagated farther towards the northwest in the region that is now the Nackara Arc, because strata in this region were thicker than in regions to the north or south, and because strata in this region lay above a weak evaporite

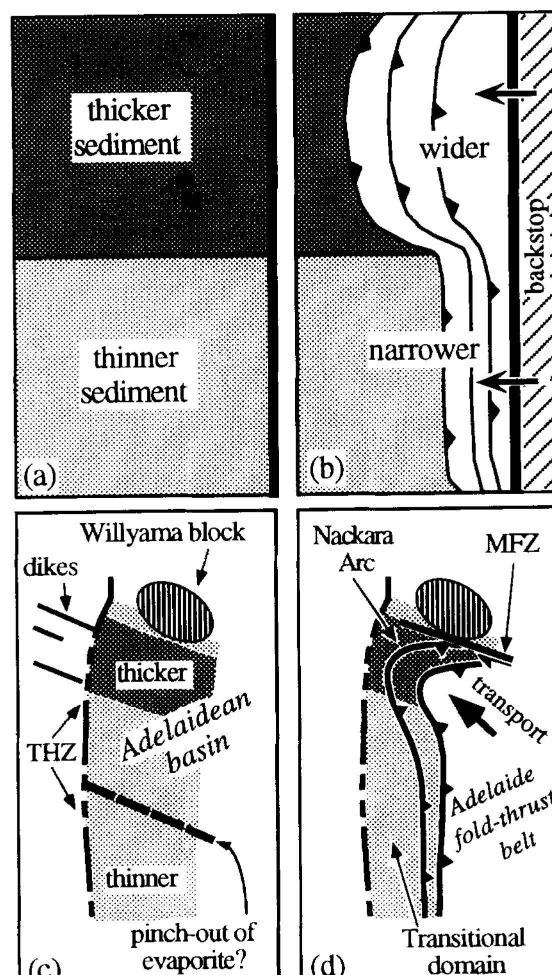

Fig. 9. Sandbox analogy for the development of curves. (a) Map-view sketch of a sandbox (≈35 × 20 cm) showing the result of uniform displacement to the left. Heavy black line represents backstop and arrows indicate direction of backstop movement. Where sand was originally thicker, thrusts propagate farther into the foreland (based on Marshak & Wilkerson 1992). (b) Schematic diagram illustrating how the sandbox analogy explains origin of the Nackara Arc. Nackara Arc forms in the thicker portion of the Adelaidean basin, between the Willyama block (a basement high) and the pinch-out of an evaporite glide horizon to the south.

(Fig. 9c & d). In this regard, the Nackara Arc resembles many other fold–thrust belt salients, including the Pennsylvania salient of the Appalachians. Sandbox models suggest that salients which form because of along-strike variations in stratigraphic thickness are non-rotational curves (Marshak *et al.* 1992), so we suggest that the Nackara Arc is largely non-rotational. Strike-slip interaction between the fold–thrust belt and the MacDonald fault zone at the northeast end of the curve, however, may have resulted in local oroclinal rotation of adjacent thrust sheets (cf. Paulsen & Marshak 1995).

Based on our observations, we can rule out several alternative explanations for the Nackara Arc. Specifically, the lack of evidence for fold-interference structures or for cross-cutting non-parallel cleavages indicates that the Nackara Arc domain has undergone only one phase of folding. Thus, the two limbs of the curve cannot represent the crossing of two nonparallel fold belts. The steep plunge of mineral lineations and the lack of penetrative arrays of mesoscopic strike-slip faults (see Marshak *et al.* 1982) suggests that there has been minimal, if any, tangential extension (stretching parallel to fold hinges) during the development of the curve, as would occur if the curve had formed by bending once-straight folds with fixed endpoints (Ries & Shackleton 1976, Marshak 1988). In fact, the presence of a west-verging imbricate fan of thrusts in the Weekeroo Hills implies that along-strike shortening, not stretching, occurred locally in the arc. We did not find field evidence for strike-slip movement along the northern boundary of the Nackara Arc, as required by models that relate the curve to dextral shear on an E–W-trending strike-slip fault at its northern boundary.

Fleurieu Arc formation. We concur with Mancktelow (1981) that the Fleurieu Arc initially formed because of interaction between the propagating Adelaide fold–thrust belt and the southeastern corner of the Gawler craton, much like layers of soil squeeze around a tilting foundation block (Fig. 10). When the thrust front reached the corner of this relatively rigid block, it could no longer propagate westward because of a lack of glide horizons. Continued shortening resulted in the development of greater cross-strike shortening strains at the corner, as manifested by the development of basement-involved thrusts and by the occurrence of intense fabrics in the core of the Fleurieu Arc and, as noted by Mancktelow (1981), by stretching parallel to strike. South of the corner, foreland propagation of the thrust front continued farther west, but younger thrusts forming to the foreland initiated with progressively more easterly traces relative to previously formed thrusts, and thereby truncated folds and fabrics of earlier formed thrust sheets. Transport on these younger thrusts resulted in oroclinal bending of the thrust sheets that had already formed to the hinterland (Fig. 11 & 11b). This bending was locally accommodated, perhaps, by strike-slip shear along foliation planes (Fig. 6f). Continued strain in the hinterland resulted in oblique shear and the consequent development of oblique mineral lineations (Fig. 11c & 11d). The last phase of movement reflected the final closing of the Kanmantoo basin along the southern boundary of the Gawler craton. This event resulted in formation of the nearly E–W-trending Kangaroo Island

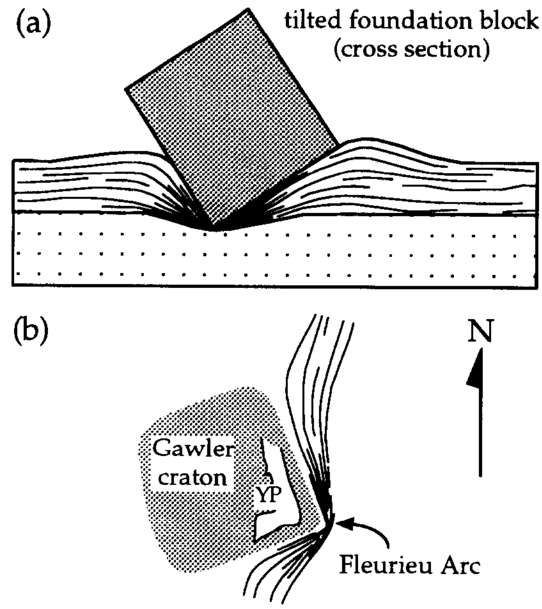

Fig. 10. Analogy between the interaction of the Adelaide fold–thrust belt with the corner of the Gawler craton and the geometry of compaction and deformation associated with building foundation failure. (a) Cross section showing deformation in soft clay that developed when a grain elevator sank into its substrate and tilted (adapted from Beavis 1985, p. 172). (b) Same geometry as shown in (a), only tilted on its side to represent geometry of the Adelaide fold–thrust belt at the corner of Gawler craton. Thin lines represent structural trendlines in the belt. YP = Yorke Peninsula.

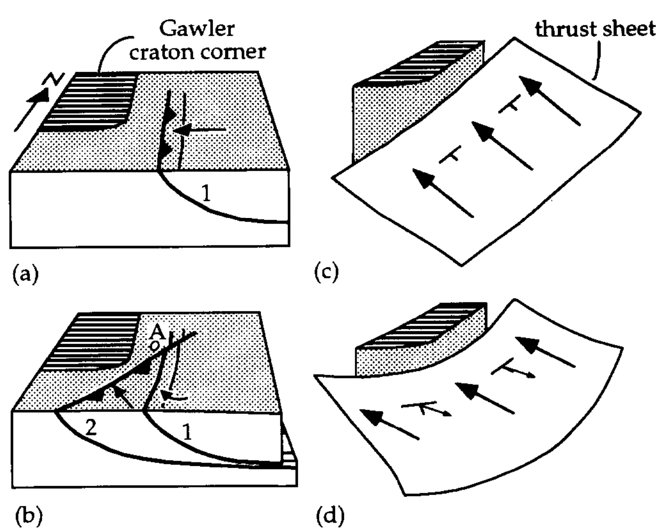

Fig. 11. (a) Block diagram sketch illustrating first phase of deformation in the Fleurieu Arc region, resulting in west-directed thrusting. Lined region represents the Gawler craton, thin line east of the thrust represents a north–south-trending fold trace. (b) At a later time, thrust 2 forms. Motion on thrust 2 is to the northwest. Thrust sheet above thrust 1 rotates, and first-phase structures are oroclinally bent (as indicated by the curved arrow). New fault cross-cuts earlier structure. A = Adelaide. (c) Sketch (not to scale) illustrating an east-dipping thrust surface approaching the corner of the Gawler craton. The top surface of the Gawler craton block corresponds to the area shown in parts (a) and (b). (d) After the thrust sheet is oroclinally bent, oblique shear develops on the thrust surface.

shear zone. Downdip lineations on this shear zone imply that this final phase of movement represents clockwise rotation of the shortening direction in the southern Adelaide fold–thrust belt.

CONCLUSIONS

Our study shows that thrust-system geometry and deformation fabrics change markedly along the length of Adelaide fold–thrust belt, thereby dividing the belt into three distinct domains (Nackara Arc, Transitional Domain, Fleurieu Arc). We present cross-sectional models of the belt in which we interpret the Nackara Arc as a train of detachment folds above a basement décollement, the Transitional Domain as a passively folded slate belt above an intensely sheared schuppen zone, and the Fleurieu Arc as an imbricate fan of basement-involved thrusts bounded on the southeast by the inverted Kanmantoo basin margin. We have also provided new interpretations of specific structures within the belt, most notably the MacDonald fault zone (which we suggest acted as a lateral ramp during the Delamerian orogen), the Kangaroo Island shear zone, and the Williamstown–Meadows fault.

Our structural models emphasize that the Nackara and

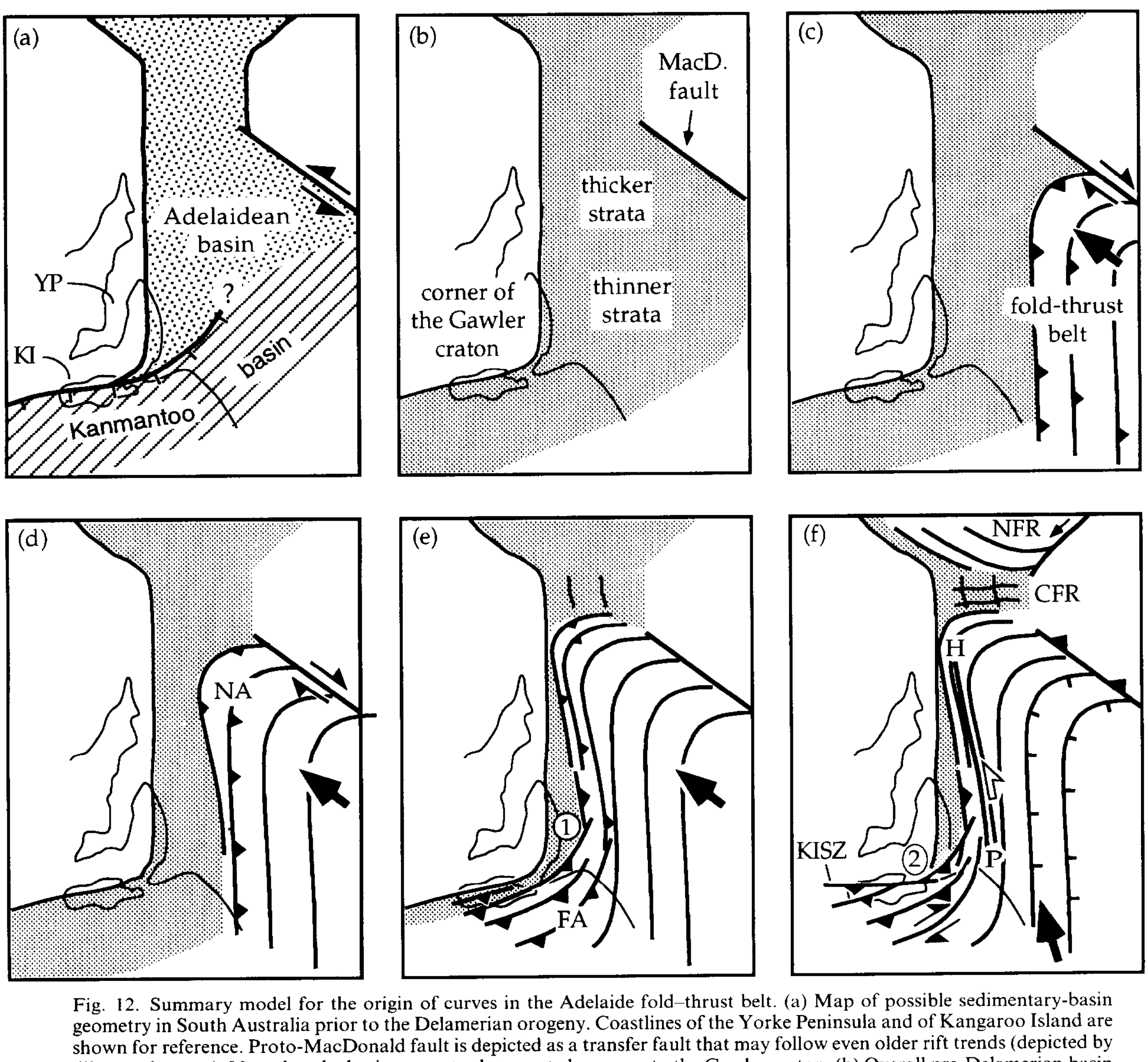

Fig. 12. Summary model for the origin of curves in the Adelaide fold–thrust belt. (a) Map of possible sedimentary-basin geometry in South Australia prior to the Delamerian orogeny. Coastlines of the Yorke Peninsula and of Kangaroo Island are shown for reference. Proto-MacDonald fault is depicted as a transfer fault that may follow even older rift trends (depicted by dikes to the west). Note that the basin geometry has created a corner to the Gawler craton. (b) Overall pre-Delamerian basin shape, showing thicker basin fill in the region that ultimately evolves into the Nackara Arc. (c & d) Successive stages in the development of the fold–thrust belt. New folds bulge toward the craton in the region where basin strata are thicker. The initiation of faults with curved traces may also reflect their interaction with the MacDonald fault zone, which acts as a lateral ramp during these stages of deformation. A large arrow represents the regional transport direction. (e) Interaction of the belt with the corner of the Gawler craton. Structures at the southern end of the fold thrust belt rotate to a northeast–southwest trend, and strike-slip movement occurs on surfaces parallel to structural trends. Younger, northeast-trending faults truncate older north–south-trending faults at location 1. (f) Final stage of deformation, during which closure of the Kanmantoo basin may accompany a regional change in shortening direction, displacement on the Palmer–Hawker line (PH), and development of the Kangaroo Island shear zone (KISZ). The latter truncates older structures at location 2. Deformation in the Central and Northern Flinders region (CFR, NFR) and initial subsidence of the Murray Basin region (indicated by normal fault symbols) may also have occurred at this time.

Fleurieu Arcs formed in different ways (as summarized in Fig. 12). Overall, the Nackara Arc is a non-rotational arc whose curvature largely reflects the shape that its folds had when first formed during propagation of the fold–thrust belt northwestward toward the Gawler craton. The folds, however, may have undergone local rotation adjacent to the MacDonald fault zone. Curvature in the Nackara Arc originated because of along-strike variation in the thickness of strata in the Adelaidean basin, and because of limited distribution of an evaporite glide horizon in the subsurface. The Fleurieu Arc, in contrast, formed in response to interaction between the propagating Adelaide fold–thrust belt and the relatively rigid corner of the Gawler craton. During this interaction, new faults developing in the foreland to the south of the corner had progressively more easterly trends. Movement on these faults led to oroclinal rotation of earlier-formed thrust sheets. The final phase of shear in the Fleurieu Arc resulted in top-to-the-north movement, and thus may represent a clockwise rotation of the regional shortening direction. Our work emphasizes that structural analysis provides insight into the formation of curves in fold–thrust belts, that curvature overall reflects pre-deformational basin geometry along irregular cratonic margins, and that no single mechanism explains the origin of all curves.

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