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Basement control on the deformation of cover basins: an example from the Cobar district in the Lachlan Fold Belt, Australia

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Abstract—Early Carboniferous deformation of ensialic Early Devonian to ?Early Carboniferous sedimentary basins in the Cobar district was controlled by movement on reactivated basement faults. Two cover zones, each with different structures, reflect differences in basement geometry, particularly the frequency and orientation of pre-existing faults. Zone 1, a high-strain zone on the eastern edge of the deformed basins, has a vertical cleavage and down-dip lineation characteristic of slate belts. Zone 2, a low-strain zone to the west, bears the imprint of wrench tectonics, at least in the early part of the history of its deformation. The boundary between Zones 1 and 2 is a sharply defined cleavage front and is localized along a major fault.

In Zone 2, NW-trending F_1 folds developed initially as a response to left-lateral movement on WNW-trending basement faults. Later F_1 folds trending west suggest rotation of the direction of local maximum principal stress, perhaps as resistance to sliding of basement blocks developed. Further rotation of this local stress direction led to the formation of NE-trending F_2 folds and to left-lateral movement on bounding N- and NNE-trending faults.

In Zone 1, deformation was more intense and controlled by high-angle reverse movement (with some left-lateral displacement) on N- and NW-trending basement faults, leading to D_1 folding, cleavage formation and vertical extension in the cover. Shortening was both oblique and parallel to the eastern margin of the basin. At an early stage of deformation, before cleavage formation, Zone 1 may have been locally coupled to Zone 2. Subzone boundaries defined by abrupt changes in strike of S_1 and F_1 in Zone 1, probably represent reactivated faults which acted as hinge lines separating areas deforming in response to different directions of shortening. Except for possible folds contributing to abrupt changes in strike of D_1 structures, regional D_2 structures are absent from Zone 1. This contrasts with the well-developed F_2 folds in Zone 2.

INTRODUCTION

UNLESS a décollement surface is developed, the deformation of a cover sequence is largely controlled by, and will reflect, deformation of the basement. The reaction of basement to a new stress field will be controlled by the existing structural geometry and by the P/T environment. There are two broad end-member situations reflecting the penetrative nature of the ensuing basement deformation. The first situation is one in which renewed deformation is penetrative and occurs by reactivation of existing cleavage planes and tightening of folds, or by the formation of new cleavages and folds if pre-existing structures are in an unsuitable orientation for additional movement. The second situation is where renewed deformation of basement is largely, or solely, controlled by movement on old or new widely spaced anisotropies, consisting of shear zones, mylonite zones or faults. Structures in cover rocks will reflect these two different situations. In the first, cover structures will be penetrative and reflect the orientation of the basement structures. In the second, cover structures may be zonal or non-penetrative and may not be parallel to basement structures.

This paper is concerned with the second type of control—where reactivated basement faults control the nature of deformation in the cover. This example is in Cobar district of the Palaeozoic Lachlan Fold Belt of eastern Australia, where structures developed during the Carboniferous inversion of Devonian to ?Carboniferous ensialic sedimentary basins reflect movement on elements of a rhegmatic pattern which was probably established by the latest Ordovician to earliest Silurian.

REGIONAL GEOLOGY

The Cobar region in central western New South Wales lies at the intersection of three tectonic trends (Fig. 1).

(1) a NNW (locally N) regional grain, shared by regional aeromagnetic and Bouguer gravity anomalies (Wyatt *et al.* 1980), by major faults, by the shapes of elongate Silurian granitoids and by the morphotectonic structural units of Scheibner (1974);

(2) a NE grain reflected by the Cobar–Inglewood Lineament through Cobar (Scheibner 1973), by the Darling River Lineament, by folds southwest of Cobar, and by Permian troughs in the subsurface southwest of Cobar and

(3) WNW-trending lineaments of the Lachlan River Lineament (Scheibner 1973, Scheibner & Stevens 1974).

Within this regional framework, the following simple basement-and-cover relation has been recognized. Basement rocks consist of ?Cambro-Ordovician turbidites and cherts intruded by Silurian granitoids (Pogson & Felton 1978). Sediments were multiply deformed and metamorphosed to low grades in the latest Ordovician or earliest Silurian. NNW- and some WNW-trending faults formed in this deformation (Pogson 1982). Cover sediments are divided into two units. The first is the Early Devonian Cobar Supergroup which accumulated as deepwater sediments ± volcanics in the Cobar Basin, the Mount Hope Trough, the Rast Trough (Fig. 1) and as shallow-water sediments ± volcanics on flanking shelves (Pogson & Felton 1978, Barron *et al.* 1982, Glen 1982a,b). Boundaries between shelves and deeper-water areas were, in general, fault-controlled. The sec-

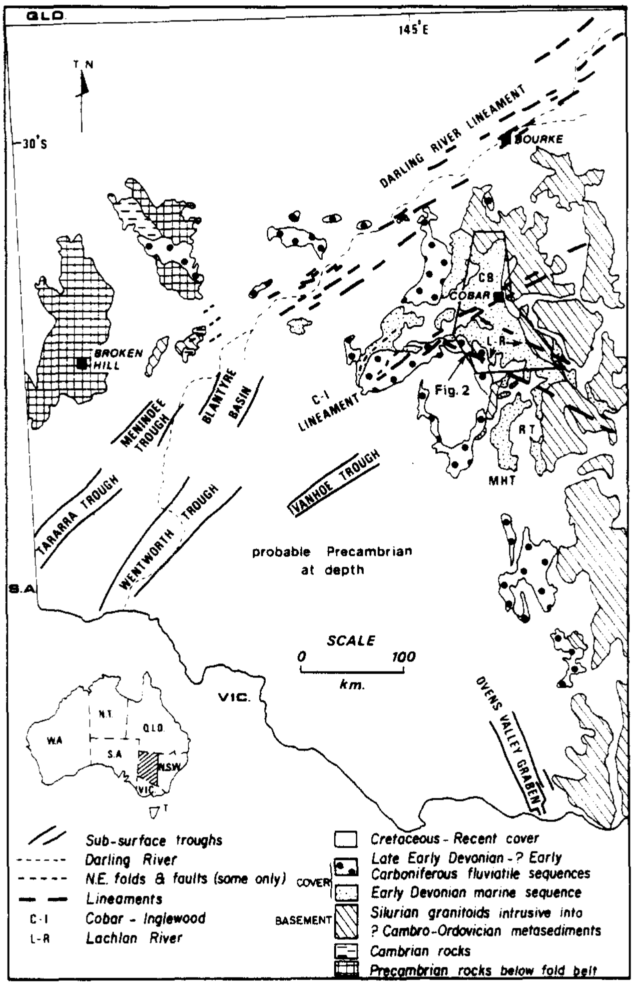

Fig. 1. Western New South Wales showing outcrops of principal rock subdivisions, major tectonic elements and location of the Cobar district. CB, Cobar Basin; MHT, Mount Hope Trough; RT, Rast Trough. Geology from Scheibner (1974) with modifications in the Cobar area based on recent mapping by Baker, Felton, Glen, MacRae, Pogson, Scheibner and Trigg (all Geological Survey of N.S.W.).

ond unit, overlying this marine unit, is the fluviatile Mulga Downs Group which was deposited in the Ravendale Basin (Scheibner 1974). Boundaries between the Mulga Downs Group and the Cobar Supergroup are generally paraconformable. Localized angular unconformities reflect folding of shelf sediments, a result of basement faulting, before deposition of the fluviatile unit (Glen 1982a).

Deformation of the Mulga Downs Group was probably part of the Early Carboniferous Kanimblan Orogeny, better defined east of Cobar (Burns & Embleton 1976, Powell *et al.* 1977). The deformation of the Cobar Supergroup is also Carboniferous in age, and not Devonian as previously regarded, for three reasons—the lack of widespread unconformity between the Cobar Supergroup and the Mulga Downs Group, the map-scale concordance of formations in both units and the congruence of folds in both units (Fig. 2).

Structures discussed in this paper occur in rocks of the Cobar Supergroup and Mulga Downs Group within the outlined area in Fig. 1. Outcrop of fluviatile rocks is good; that of marine and basement rocks poor. Although basement rocks cropout north, east and locally southwest of Cobar, there is no information about their nature beneath the cover sequences. Structural complexity within this area contrasts with simpler patterns south and west of Cobar, and reflects control of the cover deformation by elements of the WNW-, N-, NW- and NE-trending basement structures.

STRUCTURES IN COVER ROCKS AROUND COBAR

Major structures in cover rocks around Cobar (Fig. 2) are based on 1:60,000 scale mapping aided by Landsat imagery. At map scale, NW- to NE-trending F_1 folds are overprinted in parts of the district by NE-trending F_2 folds which, in the north, are themselves overprinted by N-trending D_3 structures. Based on the degree of development and orientation of structures of the three generations, the Cobar district has been divided into three, approximately meridional, structural zones (Fig. 3). Structures in the easternmost two zones (Zones 1 and 2) are discussed here. Differences in structure between Zones 1 and 2 were first recognized by Andrews (1913), who thought that the less intense structures to the west (Zone 2) were younger than those to the east (Zone 1). This westwards dying-out of cleavage and the westwards change of folds from regular to 'more irregular and complex' was also noted by Baker (1978, p. 48).

Structures in Zones 1 and 2 are shown in Figs. 3, 4(a) & (b), 5 and 6, and are summarized in Table 1. The diagrams and the table indicate major structural differences between Zones 1 and 2. Zone 1 contains NW- to NE-trending F_1 folds and cleavage, the latter containing down-dip mineral, and localized stretching, lineations. Zone 2 contains W- to NW-trending F_1 folds which are folded by NE- and locally NW-trending regional F_2 folds which are absent in Zone 1. The regional S_1 cleavage of Zone 1 is absent in Zone 2. The small subzone, 2b (not shown in Table 1), is characterized by generally N-trending, vertical cleavage, by local N- to NNW-trending, open, gently plunging folds (Schmidt 1980, Archibald 1983) and by a fold just west of the Myrt Fault (Fig. 3). North of the boundary between subzones 2a and 2b, this cleavage overprints NE-trending F_2 folds; it is thus labelled S_3.

Points arising from Table 1 which require explanation are the nature of the Myrt Fault (see below), my interpretation of Robertson's (1974) pyrrhotite lineations and striations as lying in S_1 (corresponding to S_2 of Robertson, his S_1 being bedding-parallel cleavage), and the nature of WNW-trending F_2 folds in the Mulga Downs Group in the southeast corner of subzone 2a. WNW-trending folds overprinting F_1 or S_1 are rare in the Cobar district. They are grouped as being products of part of the D_2 event because no overprinting relations between them and NE-trending F_2 folds have been observed. Glen (1982b) distinguished between NE-trending F_{2a} folds and NW-trending F_{2b} folds, here grouped together. Also note that NW-trending F_1 folds in the southeast corner of subzone 1a probably occur in

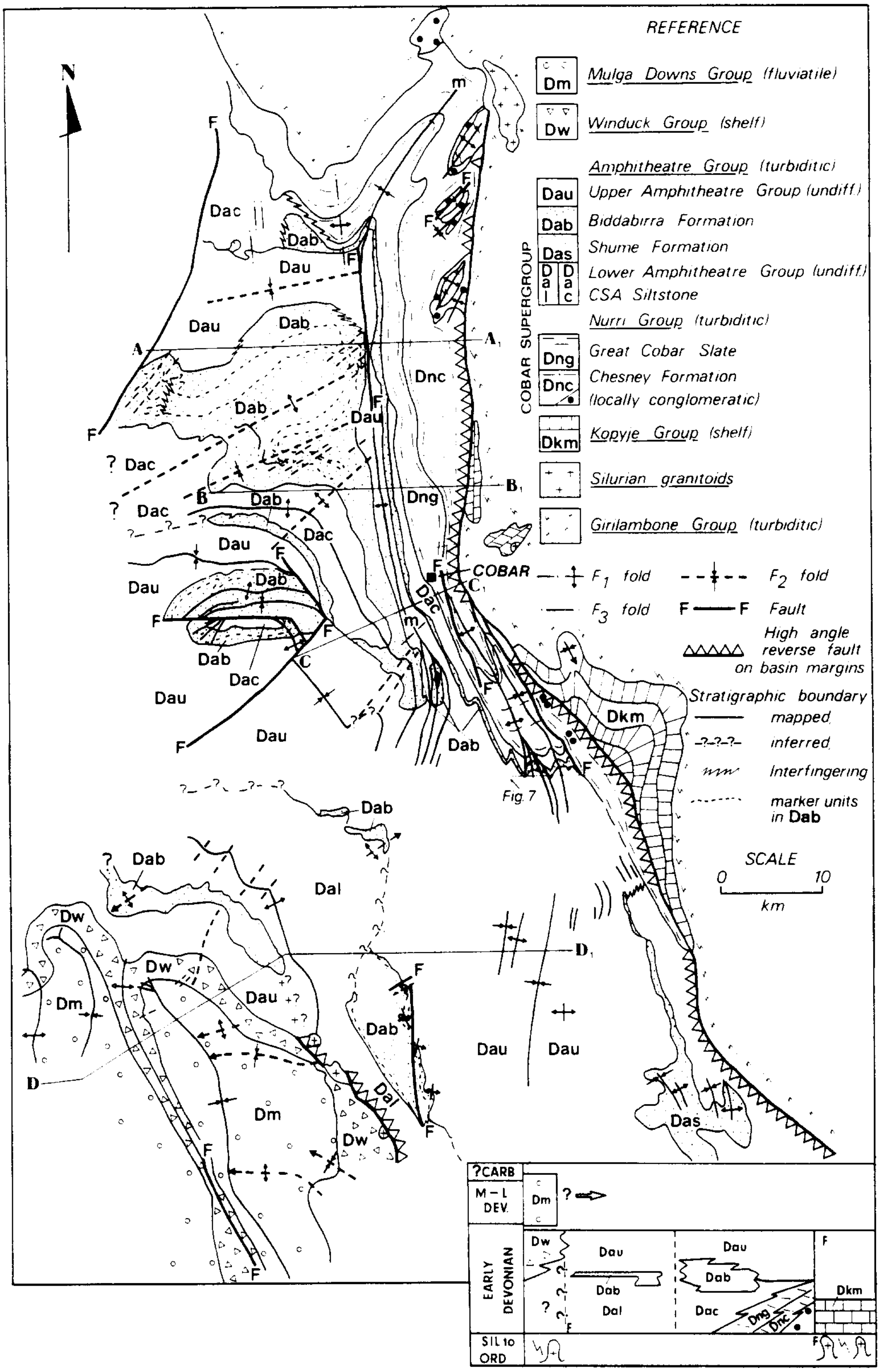

Fig. 2. Simplified geology of the Cobar district. Based on mapping by Glen (in prep, in press), Baker (1977), Felton *et al.* (1985) and Schmidt (E.Z. Co. of Australasia Ltd., unpub.). A–A_1, etc. cross-section lines (see Fig. 7). Inset shows rock relations—basin turbidites are separated by a fault scarp from shelf sediments to the east, and possibly also to the west.

as yet unmapped fault slices; their relation to NNW- to NNE-trending F_1 folds in this subzone is thus unclear.

NATURE OF ZONE AND SUBZONE BOUNDARIES

Eastern boundary of Zone 1

The Rookery Fault marks the eastern boundary of Zone 1. This fault, steeply dipping at the surface and presumed to be a high-angle reverse fault, juxtaposes Early Devonian deep-water sediments of the Cobar Basin on the west against basement and Early Devonian shelf sediments on the east. The Rookery Fault probably represents reactivation of an Early Devonian normal fault, the scarp of which marked the eastern edge of the Cobar Basin (Fig. 2 inset, Glen 1982b).

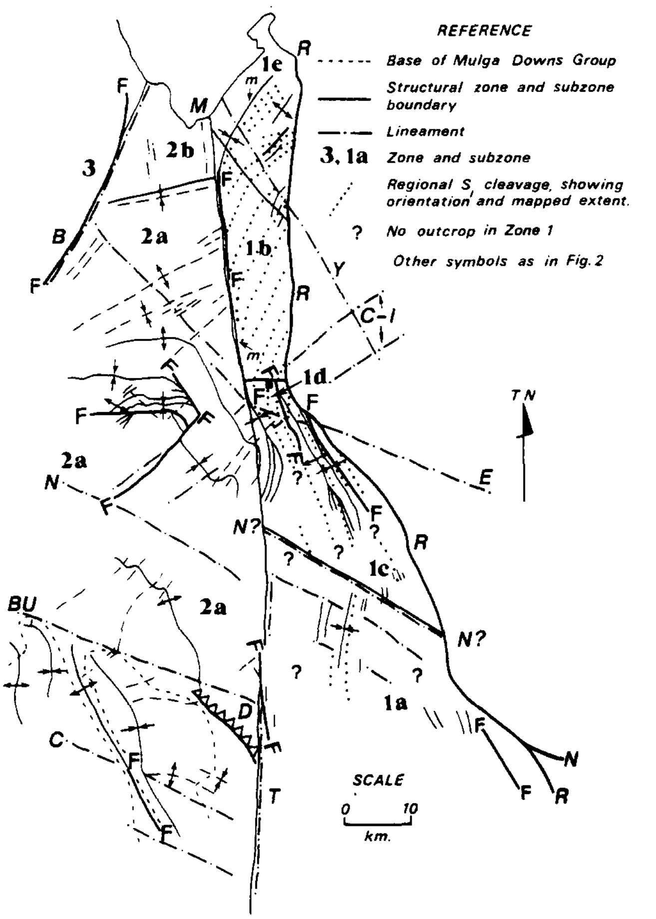

Fig. 3. Structural map of the Cobar area, showing major structural elements, lineaments, and zones and subzones. Lineament and fault names: **C**, Crowl Creek; **BU**, Buckambool; **T**, Thule; **N**, Nymagee; **E**, Elliston; **C-I**, Cobar-Inglewood; **M**, Myrt Fault; **R**, Rookery Fault; **B**, Buckwaroon; **D**, Dusty Tank Fault; **Y**, Yanda: **m**, Myrt Syncline.

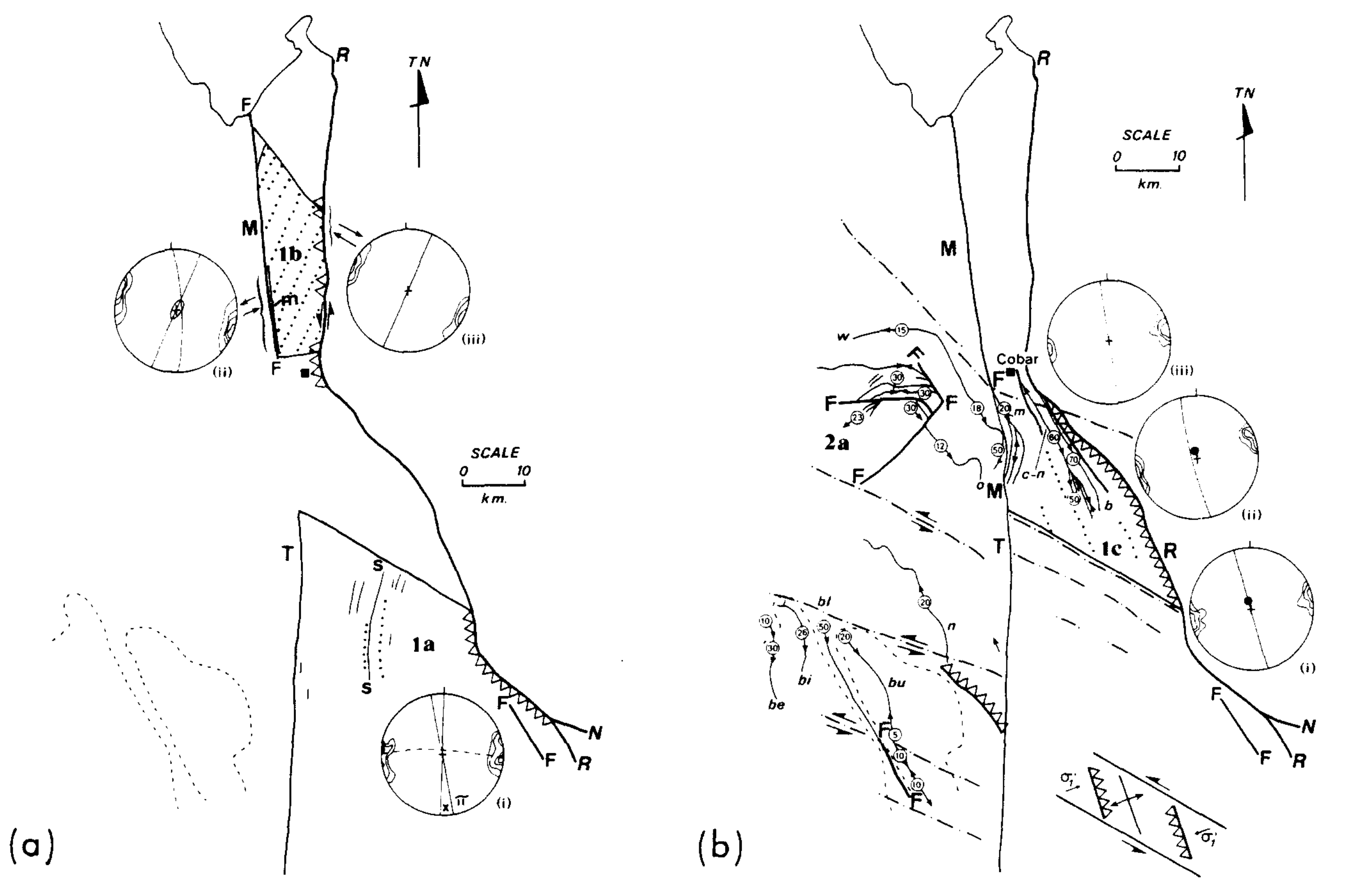

Fig. 4. (a) Subzones 1a and 1b showing F_1 folds and S_1 trends. Abbreviations as in Fig. 3. Equal-area stereograms (these and all others are lower-hemisphere projections): (i) S_1 poles. $n = 22$. Contours at 5, 9, 18, 23 and 27% per 1% unit area. Two maxima present: the dominant corresponding to an S_1 orientation of 006°/90°, the secondary are to 352°/90°. Dashed line is girdle to S_0 poles, Shearlegs Syncline (**S–S**). π-axis plunges 8 to 181°. (ii) S_1 poles. $n = 75$. Contours at 1, 20, 40 and 71% per 1% unit area. Maximum corresponds to S_1 oriented 025°/90°. Second girdle (S_1 360°/80°E) corresponds to cleavage in a N–S strip in the western part of the subzone. Contour around centre corresponds to L_1 orientation (from Robertson 1974). Data includes that in Baker (1977). (iii) Poles to S_1. $n = 42$. Contours at 2, 10 and 33% per 1% unit area. Maximum corresponds to S_1 orientated 025°/90°. Data from Baker (1977). (b) Subzones 1c and 2a, showing F_1 folds and plunges, S_1 trends (subzone 1c), faults, lineaments with movement, and subzone boundaries. For explanation of stress diagram see text. Abbreviations: **b**, Beechworth Syncline; **c–n**, Chesney–Narri Anticline; **m**, Myrt Syncline; **w**, Western Anticline; **o**, Oakden Syncline; **n**, Nullawarra Anticline; **bu**, Buckambool Syncline; **bl**, Bulgoo Anticline; **bi**, Bindi Syncline; **be**, Belford Anticline. Other symbols as in Fig. 3. Equal-area stereograms: (i) S_1 poles, Dng. $n = 27$. Contours at 7, 26 and 52% per 1% unit area. Maximum corresponds to S_1 orientated 344°/90°. L_1 ($n = 6$) represented by a black dot on S_1. (ii) S_1 poles, Dnc. $n = 10$. Contours at 10, 20 and 50% per 1% unit area. Maximum corresponds to 346°/88°W. L_1 ($n = 2$) represented by a black dot near S_1. (iii) S_1 poles, Dab. $n = 17$. Contours at 6, 24 and 50% per 1% unit area. Maximum corresponds to S_1 orientated 353°/90°.

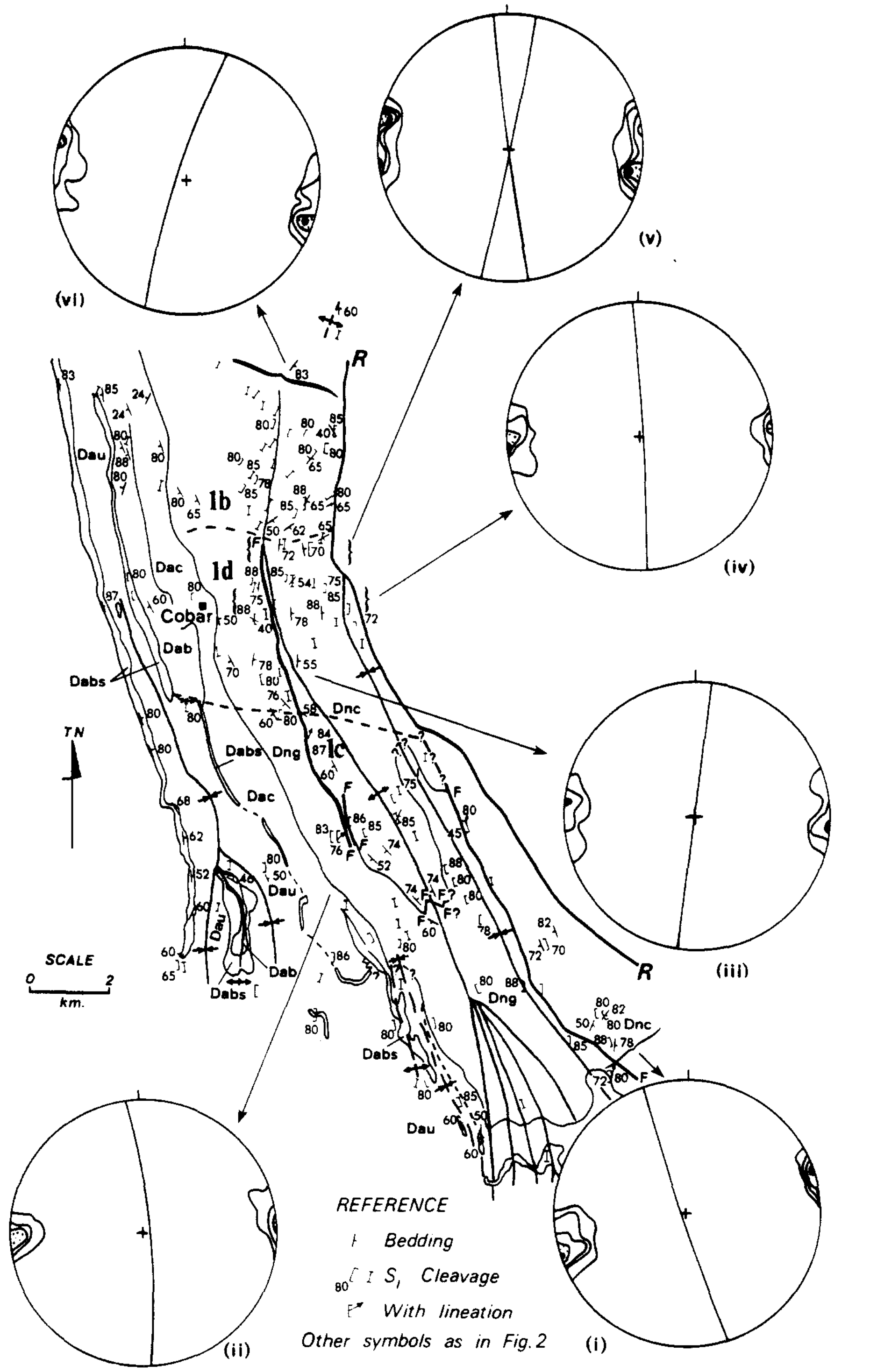

Fig. 5. Structural relations between subzones 1c, 1d and 1b, showing curvature of S_1 and F_1. Equal-area stereograms: (i) S_1 poles, Dng & Dnc, n = 19. Contours at 5, 21, 42 and 84% per 1% unit area correspond to S_1 orientated 340°/88°W. (ii) S_1 poles, Dng & Dnc, n = 27. Contours at 4, 38 and 41% per 1% unit area. Maximum corresponds to S_1 orientated 356°/85°E. (iii) S_1 poles, Dng & Dnc, n = 20. Contours at 5, 30 and 85% per 1% unit area. Maximum corresponds to S_1 orientated 006°/90°. (iv) S_1 poles, Highway traverse, Dnc, n = 15. Contours at 7, 27 and 40% per 1% unit area. Maximum corresponds to S_1 orientated 357°/88°E. (v) S_1 poles, Railway traverse. Dng & Dnc, n = 27. Contours at 4, 15, 26, 33 and 48% per 1% unit area. Maximum corresponds to S_1 orientated 013°/90°, secondary to 355°/90°. (vi) S_1 poles, subzone 1b, Dnc & Dng, n = 14. Contours at 7, 43, 50 and 57% per 1% unit area. Maximum corresponds to S_1 orientated 019°/84°W.

Table 1. Summary of structural elements and their orientations in various subzones of Zones 1 and 2

Subzone	Subzone 1a (Fig. 4a)	Subzone 1b (Fig. 4a)	Subzone 1c (Fig. 4b)	Subzone 1d (Fig. 5)	Subzone 1e (Fig. 6)	Subzone 2a (Figs. 4b and 6)
Subzone boundaries to east and west.	Rookery Fault to east, Thule Lineament to west.	Rookery Fault to east, Myrt Fault to west.	Rookery Fault to east, Myrt Fault to west.	Rookery Fault to east, Myrt Fault to west.	Rookery Fault to east, Myrt Fault to west.	Myrt Fault and Thule Lineament to the east, Buckwaroon Fault to the west.
Subzone boundaries to north and south.	To north—WNW hinge line about which F_1 traces and S_1 rotate from NNE to NW.	To north—NW hinge line about which S_1 rotates from NNE to NE. To south—poorly defined boundary about which S_1 rotates from N to NNE.	To north—poorly defined hinge marked by rotation of S_1 from NW to N. To south—WNW hinge defined by rotation of S_1 from NW to N.	To north and south—poorly defined by rotation of S_1.	To south—NW hinge line about which S_1 rotates from NNE to NE.	Boundary to north is poorly defined by incoming of D_1 structures.
D_1 structures.	F_1. NNW- to NNE-trending, upright folds, with interlimb angles of 50–70° Gentle plunges, e.g. Shearlegs Syncline (stereogram i). S_1. Mapped parallel to F_1 axial traces. Inferred to be axial planar. NNW- to NNE-trending, subvertical. *Faults*. High-angle, reverse. NNW-trending in southeast corner.	F_1. Rare, probably because of poor outcrop. Myrt Syncline trends 025° before running into Myrt Fault. To south, it reappears as upright, very gentle S-plunging fold trending 350°; tight to isoclinal. Poorly defined anticline in southeast corner. S_1. S_1 trends 360°/80°E in strip along western margin of subzone, in core and just in E limb of 350°-trending Myrt Syncline. Transects that fold. More generally, S_1 trends 025–028°/90° in south and 025°/90° in south (stereograms ii & iii). L_1. Subvertical plunges in 360°/80°E S_1. Defined by pyrrhotite and by striations on S_1 (Robertson 1974).	F_1. Three regional NW-trending, upright folds. Myrt Syncline trending 340° is upright, tight to isoclinal, with gentle (20°) S plunge. Splays to south. Tight Chesney–Narri Anticline plunges 50–60° S in south, but 30° S at northern end. Splays to south. Tight Beechworth Syncline plunges 50–70° S. S_1. Mapped parallel to F_1 traces. Axial planar to rare mesofolds. NNW trend, vertical, or subvertical dip (stereograms i, ii & iii). L_1. Down-dip pyrrhotite lineation (stereograms i & ii). *Faults*. High-angle reverse, at low angles to fold axes.	F_1. Axial traces of Chesney–Narri Anticline and Beechworth Syncline rotate from NNW trend in south to N trend in north. Accompanied by plunge reversals—folds plunge N at northern ends. Myrt Syncline unrotated, trends 350°. S_1. Dominantly N-trending and vertical (stereograms iii, iv & v). S_1 transects F_1. *Faults*. High-angle reverse, at low angles to F_1.	F_1. Myrt Syncline, upright, trends 038°, plunges S. Other folds have NE trends, are probably upright and plunge S, or to both N and S. S_1. NE trends, varying from 060°/85° E in inner arc to a more general 040–052°/90° (stereograms ii, iii & iv). Anomalous S_1 trend (072°/90°) W of NE fault. L_1. Pebbles locally elongate and steeply N-plunging (stereogram iii). *Fault*. NE trend.	F_1. Folds in the Mulga Downs Group are upright, NW-trending with low plunges. Bulgoo Anticline (localized over the Jackermaroo Lineament) is the tightest; it shallows to the south and passes into a fault. Buckambool Syncline changes plunge through the horizontal, the northernmost culmination coinciding with the Crowl Creek Lineament. Other folds plunge S. Further north, the Nullawarra Anticline is upright with gentle, variable plunges: it trends NW in the south. Further north, the enveloping surface to the folded trace trends WNW. Oakden Syncline, an open, upright fold with gentle plunge, trends NW except in the south where it has been folded by F_2. Western Anticline is upright, open and gently plunging. Trends vary from W and WSW in the north to NW in the south. Further south, F_2 folding causes steepening of plunge and rotation of trend to NNE. Other folds, also upright and open, have a general W trend, swinging to NW at eastern ends and NE at western ends. S_1. Rare. Includes local vertical fractures in hinge zones in Mulga Downs Group, and rare NW-trending subvertical cleavage near the hinge of the Nullawarra Anticline. *Faults* include NW-trending high-angle reverse faults and others of probable strike–slip character.
D_2 Structures.	None definitely identified.	Minor crenulations, with NE-trending axial planes and steep hinges.	Minor NE-trending kink planes with steep hinges and crenulations in S_1.	Some local F_2 kink bands and steep crenulations in S_1. Kink bands and axial planes trend NE, ENE and WNW, with steep hinges (Fig. 8a).	None definitely identified.	F_2. F_2 folds in the south occur as second-order perturbations on F_1 limbs. They are upright with NE to ENE trends. In the north, F_2 folds are the dominant structures. They have NE trends, gentle plunges both to the NE and SW and are open. Plunges steepen, and folds splay in a steep zone just west of the Myrt Fault. S_2 includes NE-trending vertical fractures in the Mulga Downs Group, and vertical S_2 cleavage (stereogram v) in parts of subzone, especially in west.
Relation between D_1 structures and the eastern and western boundaries.	F_1 and S_1 lie at low angles to Thule Lineament and to Rookery Fault.	S_1 lies oblique to Myrt and Rookery Faults.	F_1 and S_1 lie at low angles to Rookery Fault.	S_1 and F_1 are oblique to Rookery Fault. S_1 oblique to Myrt Fault. Myrt Syncline parallel to Myrt Fault.	S_1 and F_1 oblique to Myrt and Rookery Faults.	Both D_1 (and D_2) structures lie oblique to bounding faults.

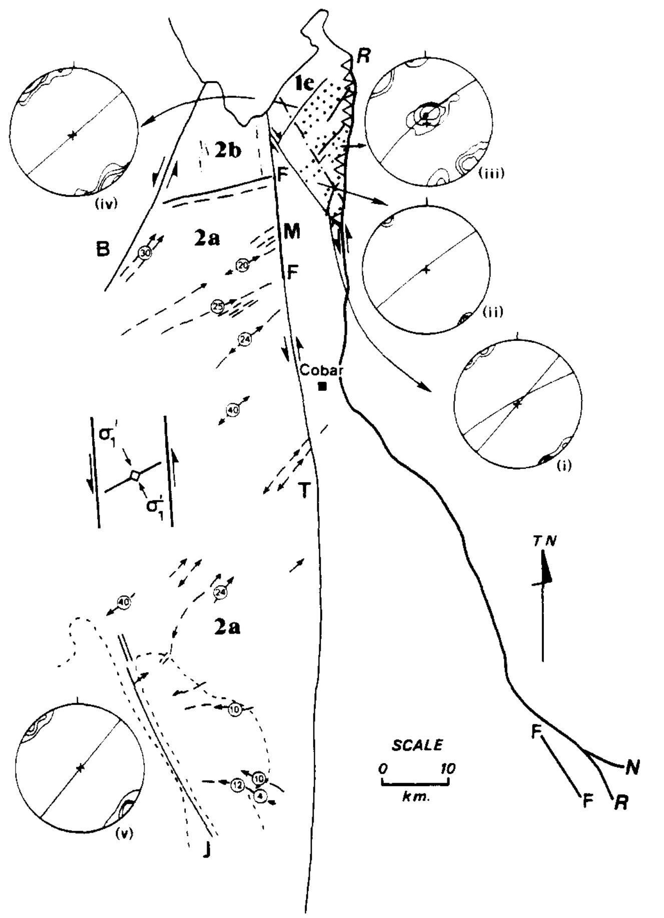

Fig. 6. Subzones 1e, 2a and 2b showing F_1 folds, S_1 and faults (subzone 1e), F_2 folds with plunge (subzone 2a), F_3 (subzone 2b) and zone and subzone boundaries. Abbreviations as in Fig. 3. Equal area stereograms: (i) S_1 poles, Dnc, n = 6. Contours at 17 and 67% per 1% unit area. Corresponds to spread of S_1 between 042°/90° and 060°/85°W. (ii) S_1 poles, Dng & Dnc, n = 5. Contours at 20, 40 and 80% per 1% unit area. Maximum corresponds to S_1 orientated 052°/87°W. Data from Baker (1977). (iii) S_1 poles and L_1, Dnc. S_1, n = 28. Contours at 4, 11 and 39% per 1% unit area. Maximum corresponds to S_1 orientated 051°/80°W. Includes data from Baker (1977) and Lewington (Getty Oil Development Co., unpublished). L_1: n = 33. Contours at 3, 12, 18 and 52% per 1% unit area. Maximum corresponds to 80° to 360°. (iv) S_1 poles, Dnc & Dng, n = 28. Contours at 4, 7, 14 and 25% per 1% unit area. Maximum corresponds to S_1 orientated 048°/90°. Data from Baker (1977). (v) S_2 poles, subzone 2a, Dau, n = 20. Contours at 5, 40 and 50% per 1% unit area. Maximum corresponds to S_2 orientated 040°/90°.

Boundary between Zones 1 and 2

North and just south of Cobar the boundary between Zones 1 and 2 marks the western extremity of regional S_1 development. This boundary corresponds to an inferred basement fault (the Myrt Fault), which projects through cover rocks, intersecting the present land surface in only one area (Figs. 2 and 7, Section **A–A**$_1$), but which probably occurs in subsurface cover rocks, as far south as the latitude of Cobar. Over this interval, the Myrt Fault localizes the 350°-trending Myrt Syncline in the cover rocks. Further north, the Myrt Syncline swings to the northeast; to the south, it swings to the southwest. In cross-section, the Myrt Fault is shown lying in, or below, the steep western limb of the Myrt Syncline (Fig. 7, sections **A–A**$_1$, **B–B**$_1$). Further south of Cobar, poor outcrop precludes accurate positioning of the boundary between Zones 1 and 2. I believe the boundary coincides with the Thule Lineament (Fig. 3), which lies between the Myrt Fault to the north and the Thule Fault to the south.

The boundary between Zones 1 and 2 also marks a change in fold geometry. In the northern part of the district, open F_2 (sections **A–A**$_1$, **B–B**$_1$, Fig. 7) and F_1 (section **C–C**$_1$, Fig. 7) folds in Zone 2 tighten eastwards into the Myrt Syncline. On the eastern side of the Myrt fault, bedding dips remain steep, steeper than in Zone 2, in tight F_1 folds (Fig. 7). Cleavage is generally restricted to the eastern limb of the Myrt Syncline; some localized occurrences lie just in the western limb. In the southern part of the district, changes in fold geometry are not so obvious in cross-section, although a gradual west-to-east decrease in the interlimb angles of F_1 folds is apparent (section **D–D**$_1$, Fig. 7).

Western boundary of Zone 2

The western boundary of Zone 2 is the Buckwaroon Fault, which coincides, for most of its length, with the Buckwaroon Lineament.

Subzone boundaries in Zone 1

Zone 1 is divided into five subzones (Fig. 3), each characterized by internally uniform cleavage orientations. Relations such as those illustrated in Fig. 5, which is used as a model because of better outcrop in the area depicted, suggest that these changes in orientation do not reflect the presence of more than one generation of cleavage. Subzone boundaries, therefore, reflect the general abrupt change in orientation of S_1 cleavage. The boundary between subzones 1a and 1c is a WNW-trending hinge line; that between subzones 1b and 1e is a NW-trending hinge line. The boundary between subzones 1b and 1d is not well defined; nor is that between subzones 1c and 1d, although it may define a WNW-trending hinge line along strike from the Elliston Fault to the east.

The orientations of zone and subzone boundaries just discussed are not random, but are expressions of the rhegmatic framework of the district. Other elements of this pattern are discussed below.

SIGNIFICANCE OF TECTONIC TRENDS IN COVER ROCKS

Elements of the rhegmatic pattern visible in cover rocks (Fig. 3) include mapped faults, boundaries between zones and subzones (faults and hinge lines) and lineaments on which no movement can be identified, but which probably correspond to fracture zones. These elements are grouped into four sets with different trends: WNW, NNW, N and NE. Table 2 summarizes evidence suggesting a long history of pre-Devonian, Devonian (syn-sedimentary) and Carboniferous (syn-deformational) movement.

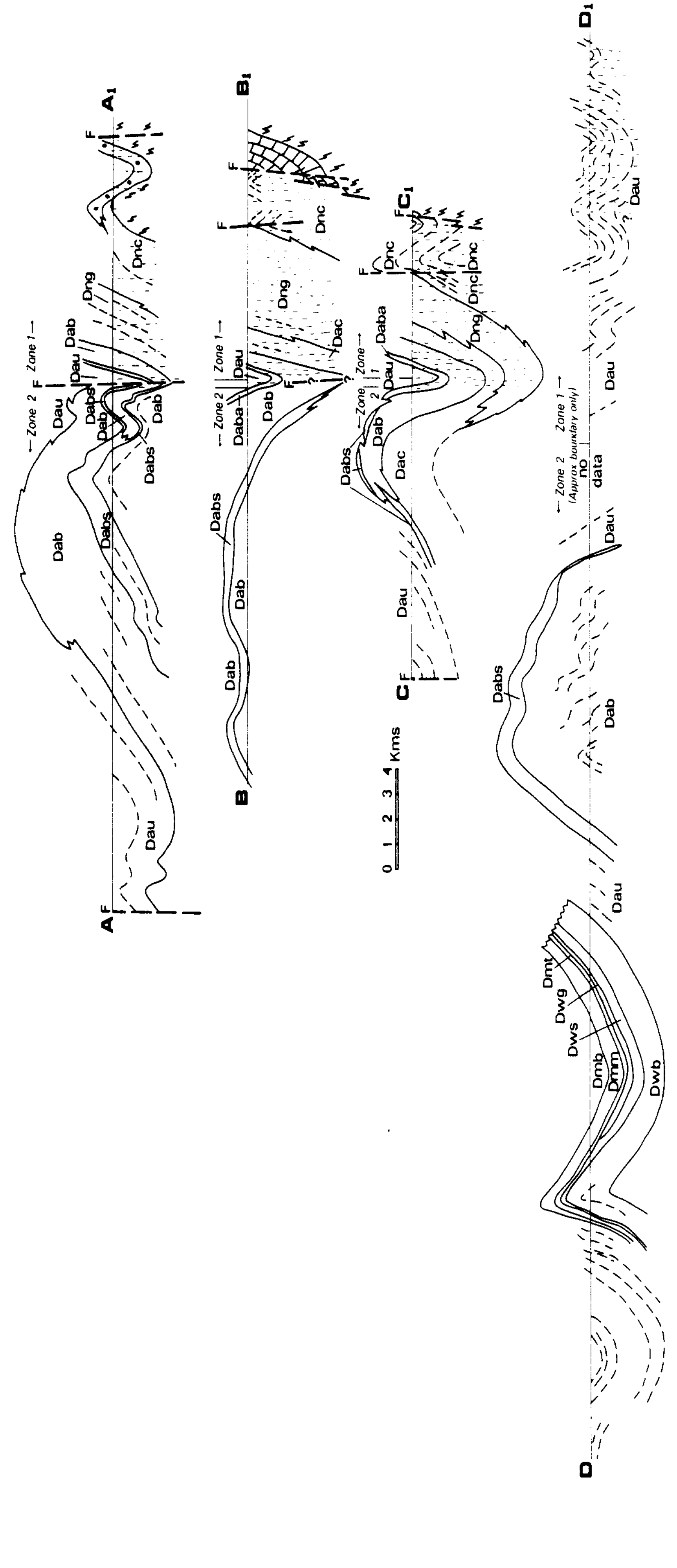

Fig. 7. Cross-sections from Fig. 2 showing difference in structural style between Zones 1 and 2. The boundary between Zones 1 and 2 (sections A–A$_1$, B–B$_1$, C–C$_1$) lies in a steep zone on the western limb of the Myrt Syncline. See text for details.

Table 2. Elements of rhegmatic pattern visible in cover and basement units, with summary of data indicating prolonged tectonic activity

Set	Elements	Silurian history	Early Devonian history	Mid-Devonian history	Carboniferous history
WNW set	Subzone boundaries in Zone 1, lineaments in Zone 2.	Extension of Nymagee Lineament to east controlled emplacement of Silurian granite (D. Pogson, pers. comm.). Extension of Crowl Creek Lineament to east controlled emplacement of Silurian dykes (Glen *et al.* 1984).	Crowl Creek Lineament marks a change from narrow Mount Hope Trough to the south (characterized by submarine volcanics with interbedded sediments, Barron *et al.* 1982) to the turbidite-rich, broad Cobar Basin to the north (Glen 1982a).	WNW fault just south of Buckambool Lineament controlled pre-Mulga Downs Group folding of Cobar Supergroup (Glen 1982a). WNW faults controlled palaeoflow of basal unit of Mulga Downs Group (Glen *et al.* in press).	Movement on subzone boundaries in Zone 1. Crowl Creek Lineament corresponds to anticlinal culmination in Buckambool Syncline (Glen 1982a). Crowl Creek Lineament shows minor right-lateral offset in axial trace of Buckambool Syncline and eastern limb of Bindi Syncline.
NNW set	Part of Rookery Fault, Yanda Lineament, Jackermaroo Lineament, 1b/1e subzone boundary.	Extension of Rookery Fault to south controlled dyke emplacement in Silurian (Glen *et al.* 1984).	Rookery Fault marked fault-bounded eastern edge of Cobar Basin. Jackermaroo Lineament associated with rapid east-to-west thinning of shelf sediments. Dusty Tank Fault in southeast corner of Zone 2 marked local western margin of basin (Glen in press).	?	Rookery Fault and Dusty Tank Fault are high-angle reverse faults. Jackermaroo Lineament in part faulted and localizes Bulgoo Anticline.
N set	Part of Rookery Fault, Myrt Fault, Thule Lineament.	?	Rookery Fault marked eastern edge of Cobar Basin. Extension of Thule Lineament to south marked western edge of Mount Hope Trough (Barron *et al.* 1982). Myrt Fault associated with abrupt west-to-east thinning of Biddabirra Formation.	?	All three faults are zone boundaries. Rookery Fault is high-angle reverse fault. Left-lateral movement on all three.
NE set	Cobar–Inglewood Lineament (others present in Mount Hope Trough to south—E. Scheibner, pers. comm.).	?	?	?	Parallel to F_2 folds—? controlled direction of folding.

Elements of the N- and NW-trending sets are the most persistent in the Cobar district (Fig. 2). They include major faults which bracket WNW-trending elements. Most of the WNW-trending elements occur in Zone 2, with some left-lateral (?) offset of the Nymagee Lineament on the Thule Lineament, but some also occur in Zone 1 as subzone boundaries. There is no direct extension of the Crowl Creek and Buckambool Lineaments from Zone 2 into Zone 1. However, an extension of the Crowl Creek Lineament can be identified east of the Rookery Fault (Glen *et al.* 1984). The Cobar–Inglewood Lineament (Scheibner 1973) is a broad zone passing through Cobar. With the exception of a right-lateral fault southwest of the town, there is no direct correlation between the lineament and structures in cover rocks. However, F_2 folds lie parallel to this trend suggesting that it may represent a direction of weakness.

COMPARISON OF STRAIN BETWEEN ZONES 1 AND 2

The greater strain in Zone 1 compared with Zone 2 is indicated by the regional presence of cleavage and by the greater appression of F_1 folds. One way of quantifying this strain difference is by calculating amounts of shortening from differences between folded and assumed initial lengths of stratigraphic boundaries in cross-sections perpendicular to fold axes.

shortening $(-e)$

$$= \frac{\text{folded length} - \text{initial length}}{\text{initial length}} \text{ (Ramsay 1967).}$$

Shortening values for F_1 folds in Zone 2 range from 10 to 12% (Buckambool Syncline, Oakden Syncline) to 30–32% (Bindi Syncline, Nullawarra Anticline, Western Anticline). The Bulgoo Anticline, located over the Jackermaroo Lineament, has anomalously high shortening for this zone (66%, more typical of Zone 1) and is surrounded by folds within which shortening is 10–30%. Average shortening for folds in Zone 2 along Section **D–D**$_1$ (Fig. 7) is 18%. Further north in the F_2-dominated part of Zone 2, a profile section through the Biddabirra Formation (Fig. 2) gives a shortening of 30%. By contrast, shortenings for F_1 folds in Zone 1 range from 40 to 70% (Chesney–Narri Anticline, Beechworth Syncline), with the Myrt Syncline showing shortenings of 70–86%. The average shortening in Zone 1 is 62%, excluding the poorly defined Shearlegs Syncline in the south from which an anomalous shortening of only 20% was obtained.

F_1 folds in Zone 1 are accompanied by an axial-plane or fanning cleavage (Fig. 8b) which is absent from F_1 folds in Zone 2 (Fig. 8c). Consequently, shortenings obtained from F_1 folds in Zone 1 can be simplistically divided between a fold-forming component and a 'later' imposed flattening component associated with cleavage formation, which caused tightening of the folds. There are few data available to quantify the strain associated with the cleavage-forming event in Zone 1. Pebbles in conglomerate are deformed obviously in only one locality (in subzone 1e). Here, limited (*c.* 20) measurements on rough, irregular joint surfaces gave ratios of 1.5 : 1.1 : 1 and 2.9 : 1.5 : 1 (based on an R_f/ϕ plot [Ramsay 1967]), indicative of constrictional strain. These ratios correspond to shortenings of 39% and 15% assuming no volume change. Elongate grains of pyrrhotite, now altered to iron hydroxides (Fig. 8d), occur in subzones 1b, 1c and 1d. From one locality in subzone 1c, and noting ductility contrasts, Plibersek (1982) obtained shortenings of 29, 41 and 40%, and extensions of 348, 285 and 201%, respectively.

If we ignore the low values, these few strain data from lineations in S_1, coupled with the fold data above, suggest that the fold-derived shortenings in Zone 1 may be partitioned into a component related to flattening (say 40% shortening) and a residual component related to 'original' fold formation (say 20%). This residual component is of similar magnitude to that obtained from F_1 folds in Zone 2.

DISCUSSION AND INTERPRETATION

Interactions east of Cobar between the Australian and Pacific plates were responsible for the Early Carboniferous closing of Early Devonian to ?Carboniferous ensialic basins in the Cobar district (E. Scheibner, pers. comm.). Forces generated by these interactions were transmitted westward. The stresses they induced during basin-closing in the Cobar district were manifested in the cover rocks by two distinct styles of deformation. Zone 2 is characterized by wrench tectonics, and Zone 1 by slate-belt type cleavage and lineation. Zone 2 is discussed first.

Zone 2

Based on geometrical relations between folds and lineaments in the Mulga Downs Group, I had earlier (Glen 1982a) suggested that F_1 folds in these rocks developed as a cover response to left-lateral movement on WNW-trending basement faults. This suggestion is here extended to include the formation of all F_1 folds in Zone 2. The inset stress diagram in Fig. 4(b) summarizes the model. A regional direction of maximum principal stress, σ_1, lying between ENE and ESE, was resolved into a component of left-lateral movement on WNW-trending faults which separate basement blocks. Movement on these faults in turn generated, in cover rocks, a NE–SW direction of local maximum principal stress, σ_1'. This in turn gave rise to the development of NW-trending F_1 folds and high-angle reverse faults. F_1 folds are upright, gently plunging and consistent with folds formed in models of wrench tectonics (e.g. Wilcox *et al.* 1973).

F_2 folds in Zone 2 (Fig. 6) lie at various acute angles to the Myrt Fault and Thule Lineament on the east and the Buckwaroon Fault on the west. These relations suggest that F_2 folds developed in response to σ_1' oriented NW–SE, associated with left-lateral movement on these bounding faults. Combining these two sets of relations, it is possible to suggest possible deformation histories for Zone 2.

I will begin by considering left-lateral movement on WNW-trending basement faults. These movements must be minor because the faults stop at the NNE-trending Buckwaroon Fault, and movement was impeded by the block lying just west of that fault. The amount of sliding of basement blocks consequently depends upon how much movement can be accommodated by internal shortening. Because shortening in the southern part of Zone 2 can be accommodated by high-angle reverse movement on the Jackermaroo Fault, more WNW-movement is possible here than in the north of the zone.

However, in both parts of Zone 2, there comes a critical stage where simple WNW sliding ceases unless it is accommodated by penetrative internal deformation. Such deformation, resulting in the hypothetical formation of cleavage and folds in basement would set up a new direction of σ_1' in cover rocks, oriented NW–SE, that is at a high angle to the Buckwaroon Fault and perhaps controlled by the trend of the Cobar–Inglewood Lineament. This would result in the formation of NE-trending F_2 folds and also in left-lateral movement on N–S-trending faults (Myrt Fault and Thule Lineament) and NNE-trending ones (Buckwaroon Fault) (Fig. 6, stress diagram).

Alternatively, at this critical stage, stress build-up in Zone 2, caused by resistance to movement on WNW-trending faults, was relieved by movement on N- and NNE-trending faults. This resulted in left-lateral movement on these bounding faults, with consequent development of a NW–SE direction of σ_1' and NE-trending F_2 folds (Fig. 6, stress diagram). In the first case, wrench movement on the faults is a consequence of the orientation of σ_1'. In the second case, wrench movements on the faults set up a NW–SE direction of σ_1' which led to the formation of NE-trending F_2 folds. How much the F_2 fold pattern is due to one or the other, or to a combination of both these histories is difficult to say. In the second case, there would be a rapid switch in directions of σ_1' through 90° from NE–SW to NW–SE. In the first case, one would expect a more gradual rotation. Three items of evidence which may be adduced to support the first case are listed below.

(1) If left-lateral movement on the Zone 1/2 boundary fault led to the generation of F_2 folds in Zone 2, where are the equivalent F_2 folds in Zone 1? F_2 structures in Zone 1 are restricted to minor kinks and crenulations. The absence of F_2 folds in subzones 1a and 1c (but note the poor outcrop and second-order nature of F_2 folds in

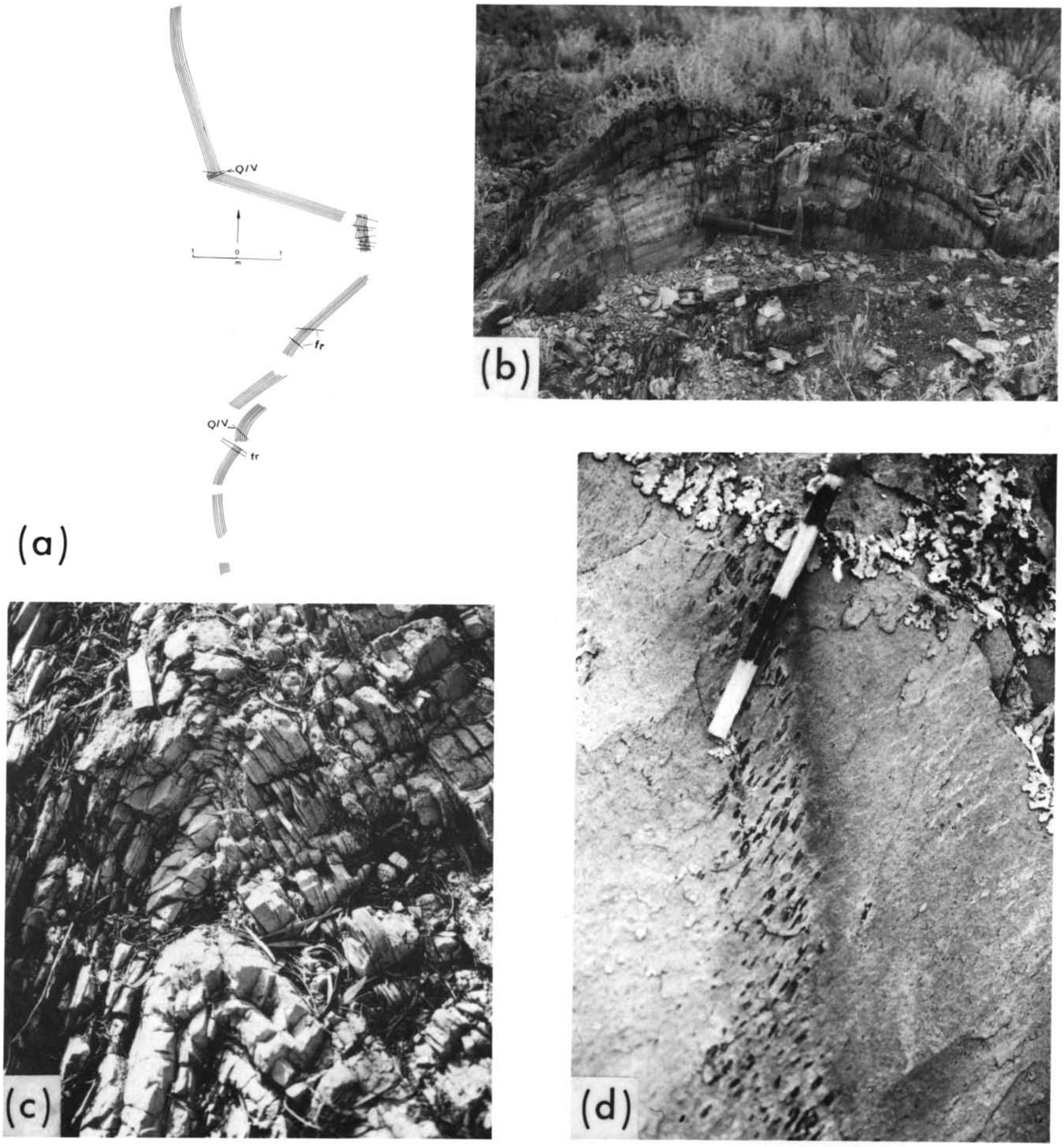

Fig. 8. (a) F_2 folds in S_1, immediately east of Cobar in subzone 1d (GR 899141 Wrightville 1 : 100,000 Sheet). F_2 structures are a combination of broad open folds and tighter zones containing NE- and WNW-trending crenulations. **Q/V** quartz vein; **fr**, fracture. (b) F_1 fold from Zone 1 (subzone 1c, GR 934075 Wrightville 1 : 100,000 Sheet), showing slightly fanning S_1 cleavage. Hammer for scale. (c) Typical F_1 fold from Zone 2 (Amphitheatre area, subzone 2a, GR 741123 Wrightville 1 : 100,000 Sheet), showing lack of S_1 cleavage and folded bedding fissility in mudstone bed. 5 cm long tape for scale. (d) View of cleavage plane in Great Cobar Slate (subzone 1c, GR 965073 Wrightville 1 : 100,000 Sheet), showing S-plunging S_0/S_1 intersection and steep N-plunging mineral lineation, L_1, defined by elongate hydrated iron-oxide aggregates. Match with 1 cm markings for scale.

the south of Zone 2) means that F_2 structures were either suppressed in Zone 1 or they correspond to NNE-trending D_1 structures in the north of that zone. Any possible equivalence between F_2 in Zone 2 and S_1 in subzones 1b and 1e raises questions about the temporal correlation of events across the Zone 1/2 boundary. I argue that S_1 in Zone 1 and F_2 in Zone 2 are not equivalent for several reasons. S_1 contains a down-dip mineral-, and locally an elongation-, lineation. This is inconsistent with formation by horizontal simple-shear which would result in a horizontal elongation direction. Additional arguments against the equivalence of S_1 in Zone 1 and F_2 in Zone 2 are the presence of a N-trending S_1 foliation in subzone 1b (in a strip just east of the Zone 1/2 boundary) and the presence of local NE-trending F_2 kinks and crenulations overprinting S_1.

The second deformation history may still apply if we equate F_2 in Zone 2, not with S_1 in Zone 1, but with F_1 in subzones 1b and 1e. It seems unlikely, however, that the second event in the low-strain zone was equivalent to the first event in the high-strain zone at the eastern edge of the deforming sedimentary basins.

(2) There is some evidence to support the gradual rotation in Zone 2 of σ_1' through 90° from NE–SW through N-S to NW–SE. This is the presence of F_1 folds with axial traces curving westwards from NW trends into E–W and even SW-trends at their western extremities (Fig. 3). This curvature is not thought to be related to refolding—such a process would create space. It must, therefore, be an integral part of the formation of the F_1 folds, indicating rotation of σ_1' from NE–SW through N–S to NW–SE. In this last orientation, σ_1' was perpendicular to local F_1 folds, but, more generally, to F_2 folds.

(3) The lack of F_1 folds and the greater development of F_2 folds in the northern part of Zone 2 also support the first case, because basement blocks beneath this area would have undergone less left-lateral movement on WNW-trending faults than those beneath the southern part of Zone 2, before shortening was relieved by penetrative deformation leading to F_2 folding in the cover rocks.

Zone 1

The well-developed cleavage and down-dip lineation in Zone 1 give it the character of a slate belt. The first stage in understanding the deformation history of this zone is to explain the regional swings in the strike of D_1 structures: from N in the south through NW, then N into NNE and finally NE in the north. The simplest explanation is that the swings are caused by late-stage (F_2) folding, mimicking on a regional scale uncommon mesoscale folds such as those illustrated in Fig. 8(a), where both NE- and WNW-trending F_2 fold axial surfaces with vertical hinges rotate S_1 from N into NE and NW trends. Similar relations on a regional scale could explain the strike swings of S_1 and F_1 in Zone 1, with possible F_2 hinge lines parallel to WNW and NE elements of the rhegmatic pattern. Megakinks described by Powell *et al.* (1985) from the south coast of New South Wales are somewhat similar, but the possible F_2 fold axes in Zone 1 are not directly comparable with the megakinks because they do not possess kink band geometry and there is no concentration of meso-scale kinks within 'kink bands' or adjacent to 'kink band boundaries'.

The difficulty with the above model of F_2 folding of a once-planar S_1 is that it cannot explain the following features: (a) the different relationships between the Rookery Fault and D_1 structures north and south of Cobar; (b) plunge variations between subzones; and (c) the transected relations between S_1 and F_1 so obvious in subzone 1d (Fig. 5). These features are an integral part of the D_1 deformation pattern and the interpretation of them given below also explains the D_1 strike swings.

Subzone 1a is the northern structural continuation of the Mount Hope Trough to the south. Both structural assemblages are characterized by meridional, upright folds and vertical cleavage, broadly parallel to trough and basin boundaries, and indicate E–W shortening. Subzone 1c may have a similar history in that folds, cleavage and faults formed subparallel to the Rookery Fault. However, here the NW trends of D_1 structures suggest shortening from the northeast. The small angle between the fault and the D_1 structures may indicate that there was some left-lateral movement on the Rookery Fault. However, another feature of subzone 1c and part of subzone 1d is that D_1 structures are similarly orientated to F_1 folds in Zone 2. Although S_1 cannot have formed in a regime of left-lateral shear on WNW-trending faults, possessing a vertical rather than a horizontal extension lineation, it is possible that F_1 folds developed in this regime in the same way as NW-trending F_1 folds in Zone 2. The similarity between the shortening in the F_1 folds of Zone 2 and the fold-forming part of the shortening of the F_1 folds in Zone 1 are observations consistent with this interpretation.

If F_1 folds in subzones 1c and 1d formed in an environment of left-lateral shear on WNW-trending faults, these subzones must have been coupled to zone 2 early in their history, and become decoupled later, when S_1 and L_1 were formed. The transected fold/cleavage relations so obvious in subzone 1d, and in the western part of subzone 1c, may indicate a time delay between folding and cleavage formation (e.g. Powell 1974). If so, what caused the change in deformation history from wrench style to slate-belt style? Presumably, increased shortening at the eastern edge of the Cobar Basin, which was only partially relieved by high-angle reverse movement on the Myrt Fault and Thule Lineament, with decoupling of Zones 1 and 2. This increased shortening was the cause of the formation of S_1 and L_1 and the steepening of fold plunges in subzone 1c. Further north, in subzone 1d, the local E–W shortening direction, reflected by the N–S orientation of S_1 oblique to F_1, may itself be a reflection of a promontory (sense of Thomas 1983) defined by the shape of the Rookery Fault immediately east of Cobar (Fig. 3). This promontory may have been an original palaeogeographic feature.

North of Cobar, S_1 and F_1 in subzones 1b and 1e, lie at higher angles to the Rookery Fault than south of Cobar in subzones 1a, 1c and 1d. These relations suggest that the northern part of Zone 1 underwent shortening oblique to the Rookery Fault with the formation of NNE- and NE-trending D_1 structures and a combination of high-angle reverse faulting and left-lateral slip along the Rookery Fault. A WNW direction of shortening for subzone 1b could have been easily accommodated by movement on the Elliston Fault (Fig. 3). The Yanda Lineament may have exercised a similar role for subzone 1e. Simple wrench tectonics without shortening in these subzones would not have resulted in vertical elongation. In this model, different orientations of S_1 in Zone 1 reflect different local directions of shortening. Boundaries between the zones probably represent reactivated lines of basement weakness. While the model satisfactorily accounts for the formation of D_1 structures and for the swing in strike of D_1 structures in Zone 1, it does not exclude some F_2 folding (suggested earlier) which may have accentuated the swings in strike of F_1 and S_1 structures.

CONCLUSIONS

Structures formed during Early Carboniferous closing of ensialic basins in the Cobar district reflect control exerted by the reactivation of faults in the underlying basement. Basement reacted to this new deformation in two ways, reflected by two distinct structural zones in the cover. Zone 1, a high-strain zone at the eastern edge of the deformed basins, is separated from Zone 2, a lower-strain zone to the west, by a major structural break which defines an abrupt S_1 cleavage front in the district.

I envisage that the basement below Zone 2 is bounded by major N- and NNE-trending faults, and that it is cut by widely spaced WNW-trending faults and by local NW-trending faults. Left-lateral movement on WNW-trending faults led to the formation of NW-trending F_1 folds in the cover rocks. There is some evidence to suggest that as this sliding became inhibited by a block to the west, there was local redistribution of stresses leading to rotation of F_1 folds in the west and southwest and to the formation of NE-trending F_2 folds. Left-lateral movement on the bounding N- and NNE-trending faults also occurred at this time.

The basement below Zone 1 is probably more highly faulted than that under Zone 2, with faults generally trending N or NW. Some WNW-trending faults are also present. Zone 1 probably deformed by a combination of oblique and parallel shortening, controlled by high-angle reverse (and left-lateral) movement on basement faults. At an early stage of deformation, there may have been some coupling with Zone 2 and some left-lateral movement on WNW-trending faults. I envisage that zones of high-angle reverse faults in the basement are overlain in the cover by zones of S_1 cleavage and vertical extension. Coalescence of several such cleavage zones resulted in the formation of a regional cleavage within Zone 1.

The conclusion that basement faults controlled the nature of deformation in the cover is of general interest, because it suggests that even in areas of simple deformation style, such as slate belts, it may be possible to recognize individual blocks, each characterized by slightly different deformation histories. Somewhat analogous basement-fault control on the generation of structures in the overlying cover has been described from the French Alps by Graham (1978, p. 127) who noted that ". . . strongly cleaved zones seemed to coincide with cataclastic deformation zones in the basement which seem themselves to be reactivated Hercynian ductile shear belts", and from the Proterozoic Willyama Complex (New South Wales) by Thomson (1969) and Glen *et al.* (1977). In the Willyama Complex retrograde schist zones of D_3 age were reactivated during the Ordovician Delamerian Orogeny when they localized folds and faults in the overlying Adelaidean sediments.

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