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Formation and inversion of transtensional basins in the western part of the Lachlan Fold Belt, Australia, with emphasis on the Cobar Basin*

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Abstract—The Palaeozoic history of the western part of the Lachlan Fold Belt in New South Wales was dominated by strike-slip tectonics. In the latest Silurian to late Early Devonian, an area of crust >25,000 km^2 lying west of the Gilmore Suture underwent regional sinistral transtension, leading to the development of intracratonic successor basins, troughs and flanking shelves. The volcaniclastic deep-water Mount Hope Trough and Rast Trough, the siliciclastic Cobar Basin and the volcanic-rich Canbelego–Mineral Hill Belt of the Kopyje Shelf all were initiated around the Siluro-Devonian boundary. They all show clear evidence of having evolved by both active syn-rift processes and passive later post-rift (sag-phase) processes. Active syn-rift faulting is best documented for the Cobar Basin and Mount Hope Trough. In the former case, the synchronous activity on several fault sets suggests that the basin formed by sinistral transtension in response to a direction of maximum extension oriented NE–SW. Structures formed during inversion of the Cobar Basin and Canbelego–Mineral Hill Belt indicate closure under a dextral transpressive strain regime, with a far-field direction of maximum shortening oriented NE–SW. In the Cobar Basin, shortening was partitioned into two structural zones. A high-strain zone in the east was developed into a positive half-flower structure by re-activation of early faults and by formation of short-cut thrusts, some with strike-slip movement, above an inferred steep strike-slip fault. Intense subvertical cleavage, a steep extension lineation and variably plunging folds are also present. A lower-strain zone to the west developed by syn-depositional faults being activated as thrusts soling into a gently dipping detachment. A subvertical cleavage and steep extension lineation are locally present, and variably plunging folds are common. Whereas Siluro-Devonian basin-opening appeared to be synchronous in the western part of the fold belt, the different period of basin inversion in the Cobar region (late Early Devonian and Carboniferous) may reflect different movement histories on the master strike-slip faults in this part of the fold belt, the Gilmore Suture and Kiewa Fault.

INTRODUCTION

THE Palaeozoic history of the Lachlan Fold Belt is divided into three major, contrasting tectonic periods (e.g. Powell 1983, Veevers 1984). The earliest comprises development of a fore-arc basin, an island arc and a back-arc basin in the Ordovician, with widespread deposition of siliciclastic turbidites (e.g. Scheibner 1976, Powell 1983). This regime, destroyed by the end Ordovician–earliest Silurian Benambran Orogeny (Scheibner 1976), was followed in the mid-Silurian to Late Devonian by the development of deepwater marine basins and troughs and their flanking shallow-water, often volcaniclastic, shelves. Coinciding with this extensional event was a period of granitoid emplacement in the middle to upper crust. Although some sedimentary troughs persisted until the Carboniferous, most had been inverted during the late Early to Middle Devonian Tabberabberan Orogeny which preceded deposition of rocks of the fluviatile Lambie Facies, either in intermontane basins or as a fold-belt wide blanket (Scheibner 1976, Veevers 1984).

This paper focuses on the second period in the fold belt's history, that marked by the widespread development of successor basins and troughs, and discusses the evolution of sedimentary basins, specifically the Cobar Basin, in western New South Wales. Little has been written on basin evolution during the Siluro-Devonian history of the Lachlan Fold Belt, and with exception of the Tumut Trough (Powell 1983, Stuart-Smith in preparation) most workers envisage basin development in terms of orthogonal opening and closing. The purpose of this paper is to demonstrate the influence of strike-slip tectonics in basin formation and basin inversion in the Cobar region, and to suggest a model of transtension and transpression on master faults which may apply to other successor basins in the Lachlan Fold Belt.

REGIONAL SETTING

The Cobar Basin was one of several back-arc, intracratonic, deep-water basins which formed in the latest Silurian to late Early Devonian (Pridolian to Pragian, Sherwin in Glen *et al.* 1985b) regional extension event in the western part of the Lachlan Fold Belt (Fig. 1). [The term 'deep water' is used to imply water depths below fair-weather wave base.] Together with the Mount Hope and Rast Troughs, from which it was separated by the Crowl Creek Fault, the Cobar Basin formed the eastern part of the larger Darling Basin (Glen *et al.* 1985b). Flanking the basin were shallow-water, coeval shelves. The Kopyje Shelf, north and east of the Cobar Basin, existed as a scattered area of siliciclastic and limestone deposition between bodies of dry land (Pogson & Felton 1978). It is Lochkovian in age (Sherwin 1985). The Winduck Shelf west of the basin consists mainly of a

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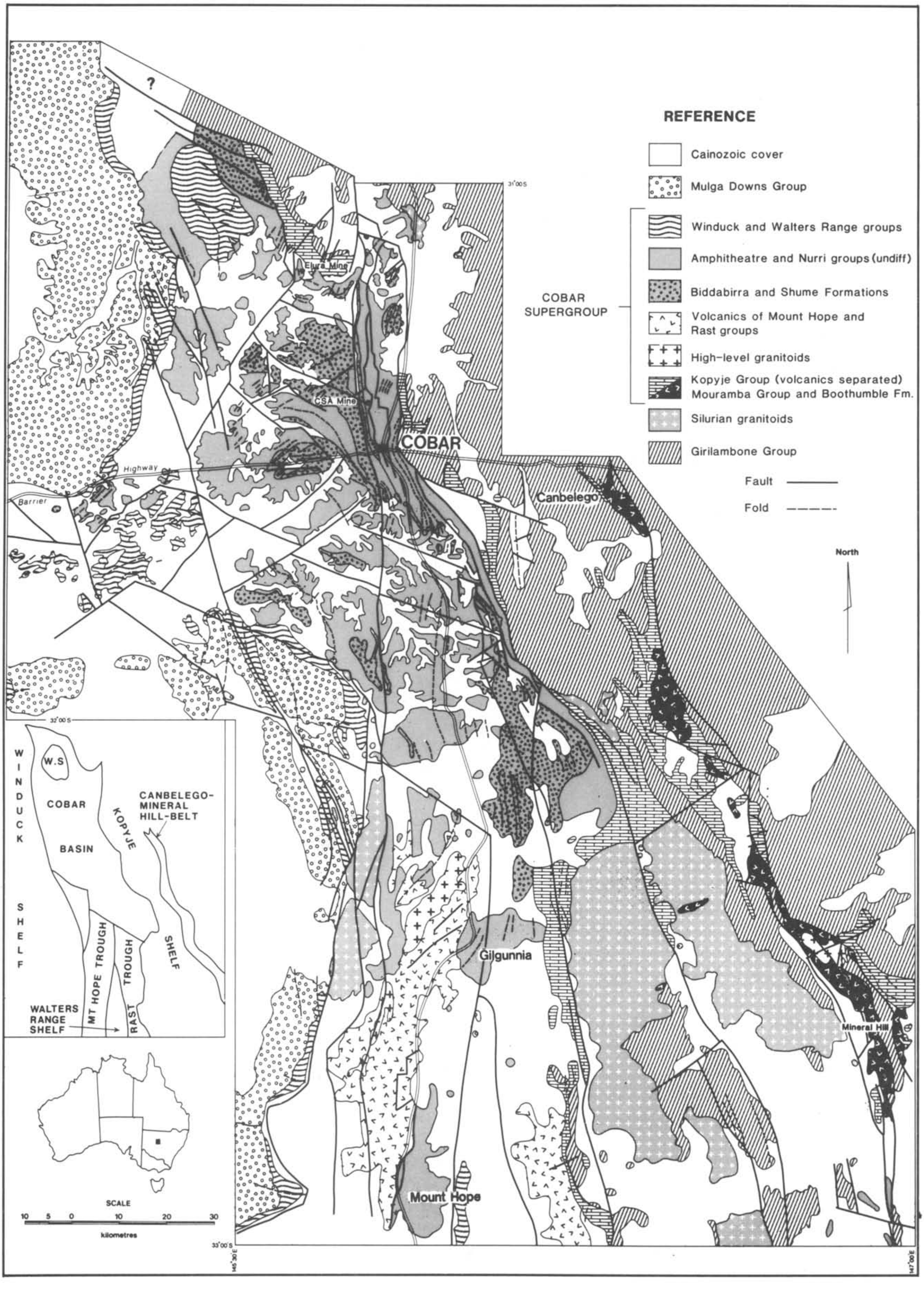

Fig. 1. Location of study area (inset) and simplified map of main geological units in the Cobar region. Inset at bottom shows Devonian extensional elements. Based on mapping by Geological Survey of New South Wales (work by Glen, MacRae, Pogson, Scheibner and Trigg).

Pragian sequence shallowing up from storm sands into littoral sands. Lochkovian elements are also present (Glen *et al.* 1985b). The Winduck Shelf also lies west of the Mount Hope Trough, where it consists of shallow-water to fluvial Pragian siliciclastics (Scheibner 1987a). The Walters Range Shelf is a narrow, equivalent shelf between the Mount Hope and Rast Troughs (Scheibner 1987a, Trigg 1987). The eastern part of the Kopyje Shelf is characterized by a linear zone of felsic, shallow-water volcanics (Pogson & Felton 1987) and is separated out as the Canbelego–Mineral Hill Belt. It was bounded on its southwestern corner by the poorly known Melrose Trough (Glen *et al.* 1985b, MacRae & Pogson personal communication).

Basement to these Devonian basins, troughs and shelves consists of the Ordovician Tallebung and Girilambone Groups (Sherwin 1983, Stewart & Glen 1986) and Silurian granitoids. The Ordovician metasedimentary rocks were deposited in the back-arc Wagga Basin (Pogson 1982) and were multiply deformed and metamorphosed to greenschist–low amphibolite facies at the end of the Ordovician or in the earliest Silurian, with generation of magma at depth (Pogson 1982). Silurian granitoids are mainly post-tectonic and S-type in character, and were emplaced around 420 Ma (Pogson & Hilyard 1981, Shaw & Pogson unpublished data). The I-type Wild Wave Granodiorite is also of this age (Glen et al. 1983). Local syn-tectonic granitoids formed around 440 Ma (Pogson & Hilyard 1981).

The final depositional event in the Cobar region was that of the late Early Devonian to ?Early Carboniferous fluviatile Mulga Downs Group (Glen 1982). This unit forms part of the Lambie Facies developed throughout the fold belt at this time and deformed by the early Carboniferous Kanimblan Orogeny (Powell 1983). The Mulga Downs Group generally rests paraconformably on rocks of the Winduck Group. The presence of only local disconformable and angular unconformable relations constrains deformation of the Winduck Group to the same event (Glen 1982).

ELEMENTS OF BASIN DEVELOPMENT

This section discusses and synthesizes recently collected data on stratigraphic and facies relations in the eastern part of the Kopyje Shelf and in each of the deep-water troughs and basins in the Cobar region. Leaving out the poorly known Melrose Trough, these data indicate that each basin–trough evolved in two stages—an early active syn-rift stage marked by rapid deepening and active faulting, and a more passive post-rift or sag-phase marked by less active sedimentation and by the development of shelf facies adjacent to, and overlapping, basin facies. Faunal data indicate approximate synchroneity in the timing of these two phases over an area of 25,000 km^2.

Cobar Basin

The earliest stage of syn-rift activity commenced with deposition of a locally exposed shallow-water sequence which passes up rapidly from outwash fans into shallow-water clastic deposits with local felsic volcanics (Mouramba Group, MacRae 1987). Developed on a rapidly subsiding, unstable shelf, these sediments were derived from basement to the southeast and east (MacRae 1987). Turbidite deposition, coupled with local felsic volcanism, comprises the rest of the syn-rift phase. Included here are the Nurri Group, along the eastern basin edge and derived from eastern sources (Pogson & Felton 1978, Glen 1987a) and the lower parts of the Amphitheatre Group derived mainly from vein-quartz sources to the northwest and west, but also from granite to the southwest (Glen 1987a, in press) and southeast (MacRae 1987) (Fig. 2). The presence of transported shallow-water fossils in the westerly derived turbidites (Sherwin 1985) suggests that these fan systems were fed from the Winduck Shelf to the west. This contrasts with the fossil-poor nature of the easterly derived turbidites which were probably fed directly by river systems drain-

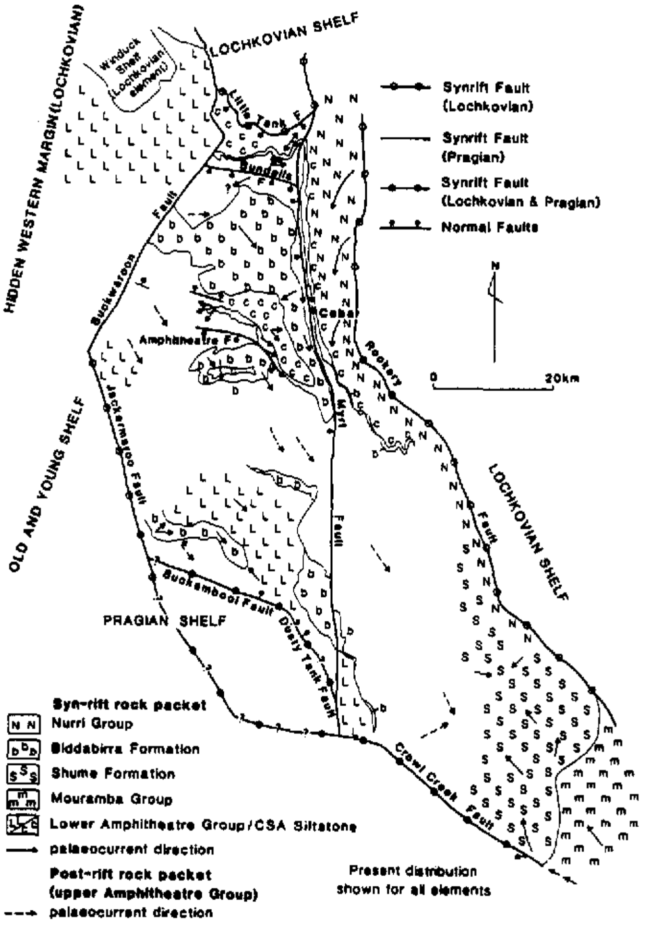

Fig. 2. Interpretative diagram, using present rock distribution of the deformed Cobar Basin, to portray faults active during sedimentation, together with the disposition of syn- and post-rift rock packets. Palaeocurrent directions represent variable sized groups of data presented in MacRae (1988) for southeast corner of basin and Glen (1987a, in press) for remainder. Directions obtained mainly from Bouma C divisions and have been rotated around regional fold axes or about strike.

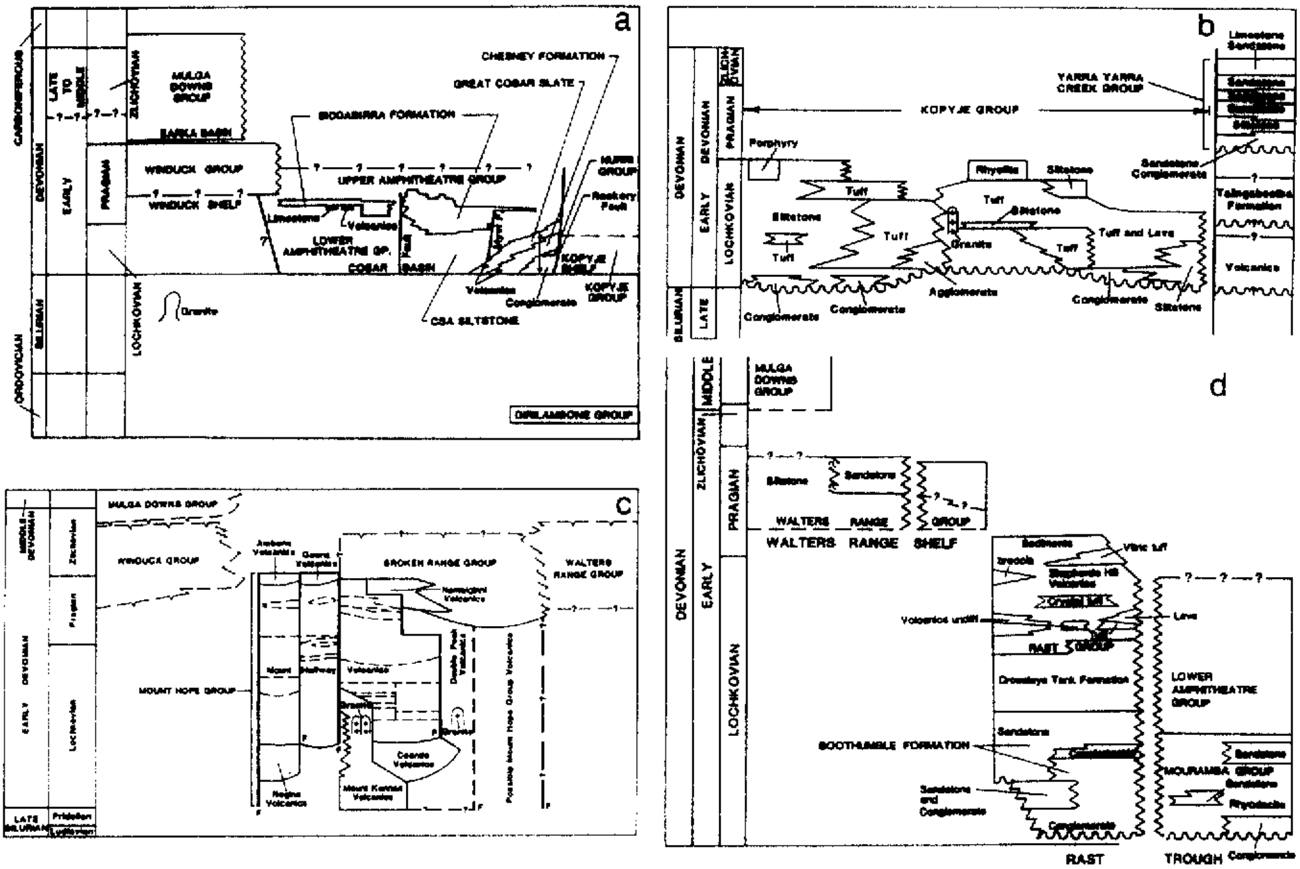

Fig. 3. Rock relation diagrams showing syn- and post-rift elements for Devonian extensional elements in the Cobar region. (a) Cobar Basin, modified from Glen (1987a). (b) Canbelego–Mineral Hill Belt, simplified from Pogson (in press). (c) Mount Hope Trough, simplified from Scheibner (1985). (d) Rast Trough, modified from Trigg (1987).

ing the eastern land bodies and bypassing the Kopyje Shelf. The variation in source areas, cyclic thickness changes in the turbidites from millimetres to metres (Glen 1987a, in press), thickness changes across syn-sedimentary faults (see below), recognition of multiple submarine fan systems and local inversion of the northern part of the basin (with shelf sediments lying on Lochkovian turbidites, Glen in press) all indicate that syn-rift activity continued into the Pragian.

The post-rift phase of basin development is represented by deposition of the turbiditic upper Amphitheatre Group (Fig. 3a) The thinner-bedded nature of bedding (generally <5–10 cm), the more consistent palaeocurrent directions from the northwest and west (Fig. 2), and the more uniform thickness of the unit all imply deposition in a less active environment (Glen 1987a, in press). Although the changeover from the syn- to post-rift deposition is abrupt over a thickness of <100 m, outcrop is not good enough to reveal any possibly low-angle discordances. This sag-phase of basin formation was synchronous with gentle subsidence west of the Cobar Basin, leading to deposition of the upward-shallowing Pragian part of the Winduck Group over older Ordovician and Silurian basement (Glen 1987a) and over older elements of the Winduck Shelf (Sherwin & Henley personal communication) (Fig. 3a). Inferred interfingering of shelf sediments with basin turbidites (Glen 1987a) implies slowing down of basin subsidence and establishment of shelf conditions over the old basin. The absence of Pragian shelf sediments (Glen 1987a, in press) east of the Cobar Basin implies asymmetrical development of the sag phase, with development of a 'half-steer head' geometry.

Canbelego–Mineral Hill Belt

This eastern part of the Kopyje Shelf is characterized by a linear zone of four felsic volcanic centres. Syn-rift subaerial to shallow marine felsic volcanics overlie and interfinger with a Lochkovian clastic sequence which passes up from fluvial to shallow-marine outwash fans into a muddy offshore facies deposited from suspension (Pogson & Felton 1978, Pogson personal communication) (Fig. 3b). An overlying debris flow deposit (Talingaboolba Formation, Pogson & Felton 1978) marks the top of the syn-rift sequence in the southeastern corner of the belt.

Post-rift development is represented by deposition of the Yarra Yarra Creek Group, a Pragian unit of shallow-water to fluviatile clastics and minor limestones which discordantly overlies the Talingaboolba as well as the felsic volcanics of the syn-rift Kopyje Group (Pogson & Felton 1978) (Fig. 3b).

Mount Hope Trough

Syn-rift basin formation in the Mount Hope Trough is reflected by deposition of the Mount Hope Group, and commenced with deposition of the Mount Kennan Volcanics, which passes up from conglomerates and shallow-water sandstones, derived from basement to the northwest, into felsic volcanics (Scheibner 1987a) (Fig. 3c). The remainder of the syn-rift phase is represented by outpourings of submarine tuffs and lavas and interbedded turbiditic sediments. Changes in stratigraphy and in thickness of stratigraphic units between blocks led Scheibner (1985, 1987a) to recognize the presence of syn-rift faulting. Different amounts of subsidence between such faults led him to erect a model of resurgent cauldron subsidence for the trough.

Post-rift subsidence is reflected by deposition of the Broken Range Group, which interfingers with, and laps onto, the Mount Hope Group in the Pragian (Fig. 3c) (Scheibner 1985, 1987a). The Broken Range Group comprises thin bedded ('distal') turbiditic quartz-rich sandstones and siltstones (which locally include felsic volcanics at the base) which thin and fine upward (Scheibner 1987a). Sag subsidence beyond margins of the trough led to establishment of the shallow-water, Pragian Winduck and Walters Range shelves above basement rocks (Scheibner 1987a). In this area, sag-phase subsidence is thus symmetrical and a 'steers-head' geometry is developed.

Rast Trough

Syn-rift basin formation in the Rast Trough is first recognized by the deposition of Lochkovian fluviatile to shallow-water marine conglomerates and sandstones now preserved on the east side of the trough (Mouramba Group and Boothumble Formation, Trigg 1987) (Fig. 3d). The Rast Group (Trigg 1987), a mixed siliciclastic turbidite and deep-water felsic volcanic sequence, occupies the remainder of the syn-rift package. Although Trigg thought this group extended through the Pragian into the Zlichovian, recent palaeontological work by Sherwin (personal communication 1988) suggests that the group is probably early Pragian at the youngest. Sag-phase deposition in this area is restricted to formation of the Walters Range Group on the boundary shelf to the west. There are no outcropping sag-phase deposits in the trough itself—they are either covered by Tertiary cover or have been removed by faulting during basin inversion.

BASIN ARCHITECTURE AND FORMATION

Cobar Basin

Assessment of the syn-depositional architecture of the Cobar Basin, and evaluation of the mode of basin formation are complicated by the recognition that the present structural boundaries and the internal faults formed during basin inversion. Earlier features of basin formation must be inferred through this deformational screen. The criteria used to infer syn-depositional fault activity are the abrupt changes in thickness and/or facies across inversion structures. Syn-depositional faults identified in this way are shown in Fig. 2(a), and their characteristics are shown in Table 1.

Except for the southeast corner, where the Mouramba Group rested unconformably on basement, the eastern margin of the Cobar Basin was defined by the Rookery Fault, which separated it from the hilly country and the locally developed Kopyje Shelf to the east. Activity on this fault was greatest at basin initiation, with the upward thinning and fining nature of the Nurri Group to the west indicating lessening of fault activity towards the top of the Lochkovian (Glen 1987a). This reduction in activity was broadly synchronous with a switch of basin margin tectonism to the western side of the Cobar Basin. Tectonic activity on this edge in the Pragian triggered the development of large submarine fan systems which filled most of the basin with quartz-rich turbidites from sources mainly in the northwest but also in the west and southwest (Glen 1987a, in press). The northwesterly sourced system prograded right across the basin, lapping onto the previously deposited wedge of Nurri Group (Fig. 2) (Glen 1987a). Increasing activity on this western edge with time is reflected by the upward thickening and coarsening cycle of the lower two-thirds of the Amphitheatre Group, up to the end of deposition of the Biddabirra Formation (Glen 1987a). The nature of this western margin in syn-rift times can be only partly deduced. While much of it is covered by rocks of the post-rift package or by Tertiary cover and is thus hidden, part of it probably corresponded to the Jackermaroo Fault which separates Lochkovian shallow-water, rocks on the west from Lochkovian turbidites on the east (Sherwin & Henley personal communication).

Little is known about the northern margin of the Cobar Basin, which is inferred to be the Little Tank Fault, separating shelf sediments on the north from turbidites on the south. The southern boundary, the Crowl Creek Fault, has a better defined history. In the Lochkovian, it separated the siliciclastic Cobar Basin to the north from the deep-water, volcanic-rich Mount Hope Trough to the south (Glen *et al.* 1985a, Scheibner 1987a). Towards the end of the Lochkovian, and broadly synchronous with the switch of tectonic activity from the eastern to the western margin of the Cobar Basin (see above), a submarine fan system was developed off basement granite to the southwest and was channelled along this fault and its extensions to the east (MacRae 1987). Limited spillover south of the fault suggests the presence of N-facing scarp (MacRae 1987).

The reduction of activity on the Rookery and Little Tank Faults, and development of the western margin coincided with the Pragian development of new intra-basinal faults, which are inferred from abrupt thickness changes—mainly in the Pragian Biddabirra Formation (Fig. 2 and Table 1), but also in the CSA Siltstone in the case of the Myrt Fault (Fig. 3a and Table 1). The meridional Myrt Fault with a W-facing scarp ponding sediments derived from the northwest and the WNW-trending Bundella and Amphitheatre Faults with

Table 1.

Fault	Demonstrated age	Activity	Type of fault
Rookery	Lochkovian	Separates shelf from basement, W-facing scarp. Eastern edge of Cobar Basin in north, hinge zone overlapped by interfingering facies in SE corner. Infrabasinal conglomerates and slumped blocks of limestone in basin sediments attributed to faulting	Strike-slip, oblique-slip
Little Tank	Lochkovian (inferred)	Separates shelf from basin	Extensional
Jackermaroo	Lochkovian	Separates basal Lochkovian shelf sediments from basal Lochkovian turbidites.	?Strike-slip, oblique-slip
Myrt	Pragian	W-facing scarp. Dramatic thinning of CSA Siltstone and Biddabirra Fault. Inactive before end of Biddabirra deposition	Strike-slip, oblique-slip
Bundella	Pragian	S-facing scarp, dams Biddabirra Formation to south	Extensional
Crowl Creek	Lochkovian to ?Pragian	Separates volcanics on south from clastics on north. Used as feeder channel for Shume fan. Dams Shume Formation in to north	Extensional
Buckwaroon	Pragian	Biddabirra Formation thicker to east	?

S-facing scarps are defined in this manner. A probable N-facing scarp existed under the western part of the Western Anticline as well (Fig. 2). The greater thickness of the Biddabirra Formation west of the Buckwaroon Fault (Table 1) also suggests a Pragian history on this structure but relations here are unclear.

The mode of basin formation can now be discussed. The pattern of syn-sedimentary faults migrating basinwards with time is not typical of basins which opened by pure shear. Gibbs (1984), for example, has shown that in these cases, extension migrates into the footwall with time (but note the sand-analogue experiments of McClay & Ellis 1987). Nor is the presence of several sets of faults opening synchronously possible in a basin opening by pure extension. Some component of oblique-slip or strike-slip is therefore present and this is supported by the sediment pattern younging basinwards which is similar to pull-apart models (e.g. Crowell 1974). The Cobar Basin thus formed as a transtensional (*sensu* Harland 1971) or mixed-mode (*sensu* Gibbs 1987) basin. In avoiding the term strike-slip basin, I am following the usage of Christie-Blick & Biddle (1985) who restrict this term to a basin formed at a releasing bend on a fault. In a transtensional model, the isolation of the Rookery Fault by the developing Myrt Fault and the presence of intrabasinal conglomerates shed off local uplifts have similarities to braided margins of such transtensional basins. Further support for the eastern margin being a strike-slip–oblique-slip boundary is provided by structures developed during basin inversion. As described below, the eastern margin of the basin is now interpreted as a positive half-flower structure (*sensu* Harding 1985) developed above a strike-slip fault below the Myrt Fault. The WNW-trending 'cross' faults (including the northern bounding fault) are interpreted as thrusts (reactivated normal faults) soling in a flat detachment. Basin formation is thus inferred to have developed by sinistral transtension with the formation of WNW-trending normal faults perpendicular to a NE–SW direction of opening, and with sinistral strike-slip and normal faulting occurring on the eastern basin margin. In this model, the western margin is also transtensional, but this is less easy to demonstrate.

Other basins

In the Mount Hope Trough, work by Scheibner (1987a) has shown that the meridional trough-bounding faults had early syn-depositional histories. The Thule Fault to the west separated land from the shallow-water Mount Kennan Block and on aeromagnetic evidence the fault on the east separated volcanics of the syn-rift Mount Hope Group beneath the post-rift Broken Range Group from ?granite basement to the east (Fig. 4). Syn-depositional faults within the trough itself are inferred on the basis of abrupt facies changes within the Mount Hope Group and also from different local stratigraphies being recognized within separate blocks (Fig. 4) (Scheibner 1987a). Some faults localized volcanic centres. There are no data on the nature of these faults. Scheibner (1987a) suggested they were normal faults in character, but he also recognized the possibility of a transtensional origin for the trough: in such a case the faults would be oblique- or strike-slip.

The Canbelego–Mineral Hill Belt is bounded on the east by the Bluff–Coonara fault system (Pogson & Felton 1978, Pogson in press). The Bluff Fault is inferred to have been an active edge during deposition (Pogson personal communication 1989), and while the Coonara Fault may have also had an early history, later movement has stripped all Devonian rocks off the block to the east. Little is known about the internal, syn-rift geometry of this belt, but it is speculated that the presence of four discrete volcanic centres may reflect localization by releasing bends in strike-slip fault system. There are insufficient data on the Rast Trough.

STRUCTURES FORMED DURING INVERSION OF THE COBAR BASIN

Regional structures formed during inversion of the Cobar Basin are shown in Fig. 5. Variations in geometry, overprinting relationships and total strain are used to divide these structures into three zones—a high-strain zone (Zone 1) along the eastern side of the deformed basin; a lower strain zone (Zone 2) in the central and southwestern part of the basin; and an incompletely known but low-strain zone (Zone 3) in the northwestern part of the basin. These three zones were originally recognized by Glen (1985). The present discussion builds on this earlier work by using the results of age dating and of new mapping in Zone 1 to extend and, in Zone 2, to modify ideas presented in the earlier paper. Both Zone 1 and Zone 2 are divided internally into smaller units—Zone 1 into subzones and Zone 2 into blocks. Zone 3 is not described further.

Structural Zone 1

Zone 1 is a southward-widening, D_1 high-strain zone bounded to the east by the Rookery Fault, to the west by the Myrt Fault–Thule Fault system, to the north by the Yanda Creek Fault and to the south by the Crowl Creek Fault (Figs. 5 and 6). As shown previously (Glen 1985, Glen *et al.* 1985a), Zone 1 contains a regional subvertical S_1 cleavage which overprints an apposition fabric and which also locally overprints an early cleavage oblique to bedding (Glen in press, Hinman & Scott in press); a regional down-dip extension lineation, L_1, and meso- to macroscopic F_1 folds of variable appression. Regular changes in the strike of both F_1 axial planes and S_1 cleavage are used to subdivide Zone 1 into several subzones (Figs 6 and 7) with naming of the zones following Glen (1985). Orientation data are shown in Glen (1985) and that paper also documented the transected nature of F_1 and S_1 relations, especially in Zone 1d in the middle of the zone.

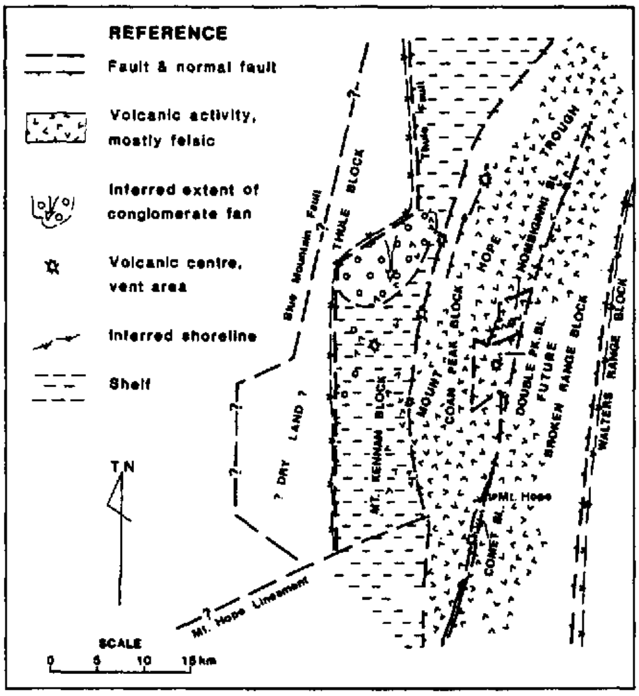

Fig. 4. Interpretative diagram, using present rock distribution, to illustrate faults active during the syn-rift stage of the Mount Hope Trough. From Scheibner (1987a).

Glen (1985) also showed that Zone 1 was fault-bounded and contained two internal NNW-trending faults. More recent work (Glen 1988, 1989) has shown Zone 1 to be highly imbricated with many previously mapped stratigraphic boundaries now re-interpreted as faults. In this discussion, I focus on geometry of these faults, which are inferred to form part of a positive half-flower structure, and which divide Zone 1 into several thrust plates. This discussion will concentrate on the northern part of Zone 1, from Zone 1c north. In the southern part (Zone 1a) recognition of internal faults and discussion of plate geometry is prevented by poor outcrop and by lack of marker units in the homogeneous, poorly outcropping upper Amphitheatre Group.

Myrt Fault and Thule Fault. These faults mark the western boundary of Zone 1. The Myrt Fault is a W-dipping fault which is in part blind and in part emergent. In its central section (Figs. 5 and 6), the Myrt Fault is meridional and emergent, truncating strata on a regional scale in its hangingwall (Zone 2) and locally in its footwall (Cobar Plate). Over this interval, it also displays transcurrent character, having undergone right-lateral faulting and then minor left-lateral faulting during the D_1 and D_2 deformations, respectively, in Zone 2 (described below). The Myrt Fault is blind in its northern extent (north of the Cougar Tank Fault, Fig. 6) where it coincides with a NNE-trending F_1 syncline, and is also blind at its southern extent: south of the Plug Tank Fault (Fig. 6) the Myrt Fault lies beneath the NNW-trending tight to isoclinal F_1 Myrt Syncline which is cored by the post-rift upper Amphitheatre Group. This blind segment of the fault can be traced south to the Zone 1c–1a boundary (Fig. 6). Further south the Myrt Fault links up with the Thule Fault (Glen 1985, Glen 1987a) of unknown dip through a region of poor outcrop which contains the Thule Lineament.

Cobar Fault and Cobar Plate. The Cobar Fault is a W-dipping fault which marks the eastern edge of the steeply (60–80° locally more) W-dipping Cobar Plate. The position of the fault is marked by a zone of quartz-vein rubble lying between W-dipping CSA Siltstone in the hangingwall and folded Great Cobar Slate in the footwall (Fig. 6). For much of its length, the Cobar Fault forms a flat in the Cobar Plate, lying parallel to bedding in both the CSA Siltstone and stratigraphically overlying Biddabirra Formation (Glen in press). Minor lateral ramps occur around the CSA Mine (Fig. 6). but are more significant in the northern part of Zone 1b, where the Cobar Fault has ramped laterally down through the Great Cobar Slate into the top part of the Chesney Formation (Figs. 6a and 8a & b), thereby placing a thin (<150 m) sliver of dirty sandstone over folded Great

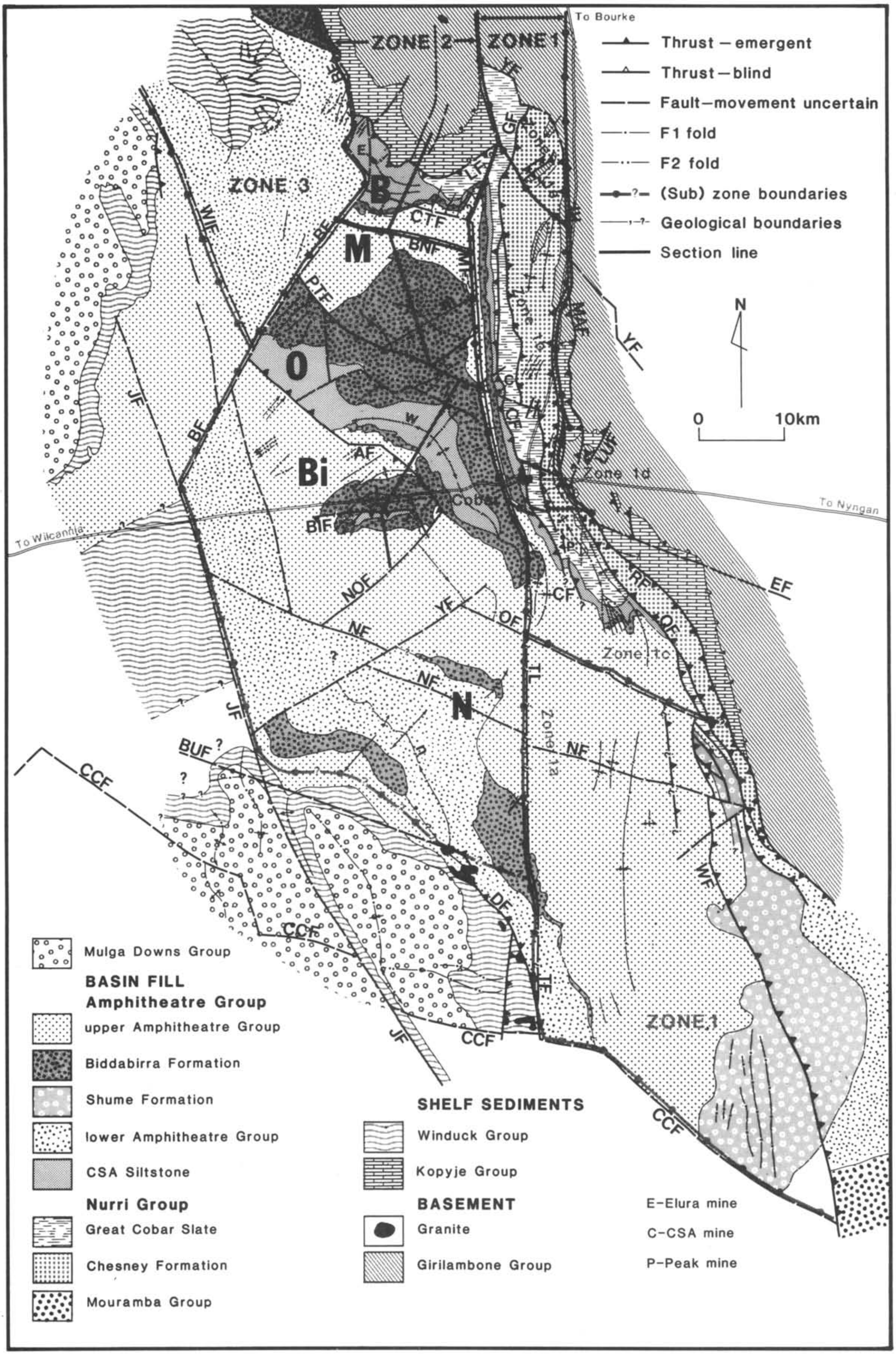

Fig. 5. Map of deformed Cobar Basin, showing stratigraphic units, subdivision into structural zones, subzones and blocks, regional folds and contractional faults. Abbreviations refer to faults and selected folds in structural Zone 2. Faults: AF = Amphitheatre Fault; BF = Buckwaroon Fault; BIF = Biddabirra Fault; BNF = Bundella Fault; BUF = Buckambool Fault; CF = Cobar Fault; CCF = Crowl Creek Fault; CTF = Cougar Tank Fault; DF = Dusty Tank Fault; EF = Elliston Fault; JF = Jackermaroo Fault; LF = Little Tank Fault; LUF = Lucknow Fault; MF = Myrt Fault; MOF = Mopone Fault; NF = Nymagee Fault; NOF = Norwood Fault; O = Oakden Fault; PTF = Plug Tank Fault; QF = Queen Bee Fault; RF = Rookery Fault; TF(L) = Thule Fault (Lineament); WF = Woorara Fault; YF = Yanda Creek Fault. Cross-section line for Fig. 11 also marked. Folds: m = Maryvale Anticline; w = Western Anticline; n = Nullawarra Anticline. For details of Zone 1, refer to Fig. 6.

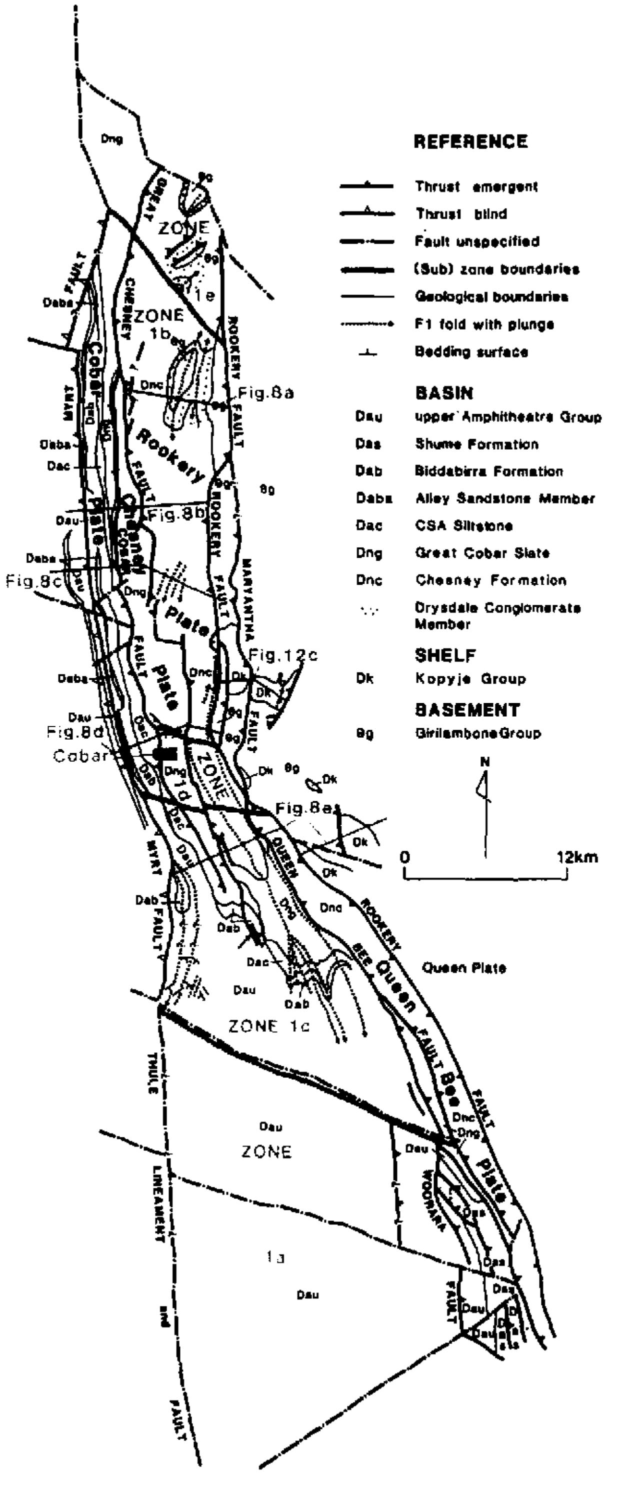

Fig. 6. Map of structural Zone 1 showing major F_1 folds and faults. See text for discussion. Cross-section lines refer to Fig. 8.

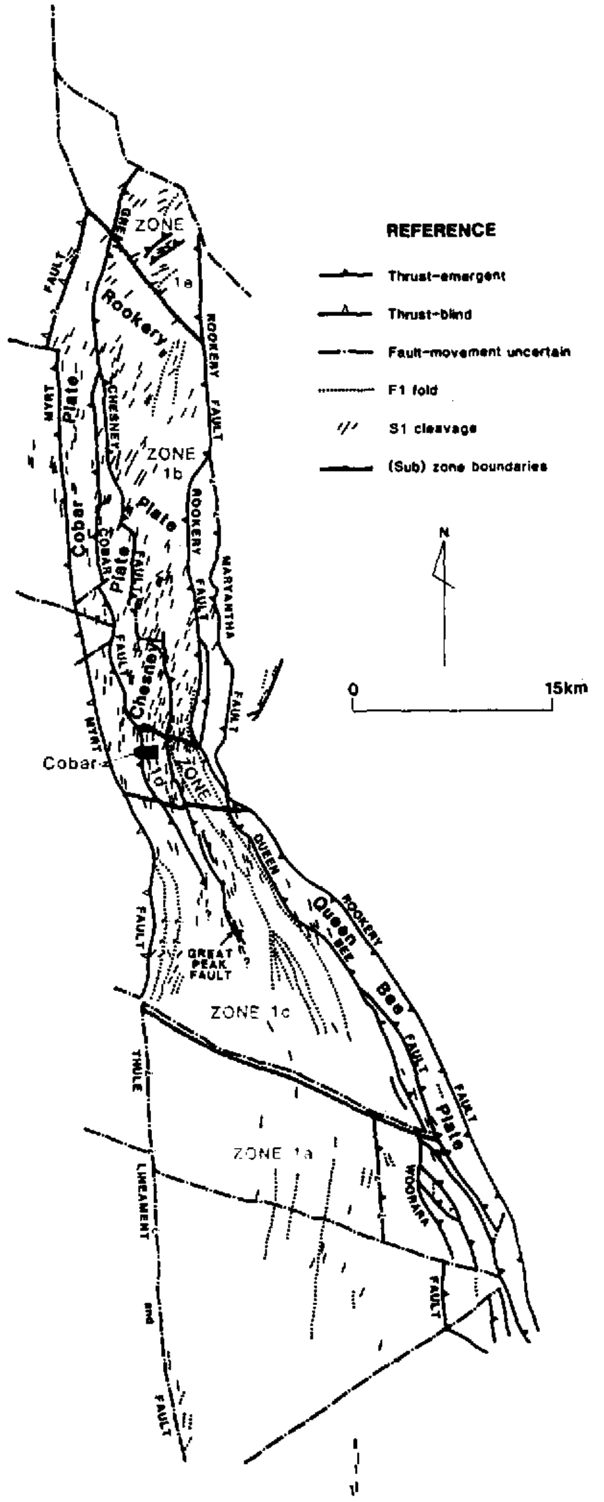

Fig. 7. Strike trajectories of S_1 cleavage and F_1 regional folds in Zone 1. See text for discussion.

Cobar Slate. It is uncertain whether this sliver extends as far north as the truncation of the Cobar Fault by the Great Chesney Fault, or whether the fault ramps back up again in the hangingwall into the Great Cobar Slate. North of this intersection, the Cobar Plate is bounded to the east by the Great Chesney Fault and occupies a triangle zone which extends north to the Yanda Creek Fault. The internal geometry of this plate is unknown in Zone 1e.

The southern extension of the Cobar Plate is uncertain. In the central part of Zone 1c, the Cobar Fault probably terminates with loss of displacement in the hinge area of an F_1 anticline (Figs. 6 and 8e). Recognition of a possible relay fault and possible extension of the Cobar Plate to the south are precluded by poor outcrop.

Internal imbrication of the Cobar Plate occurs around the CSA Mine (Fig. 6) where thrust faults are represented by the generally steeply E-dipping, brittle Footwall Fault—a 0.3–6 m wide zone of brecciated,

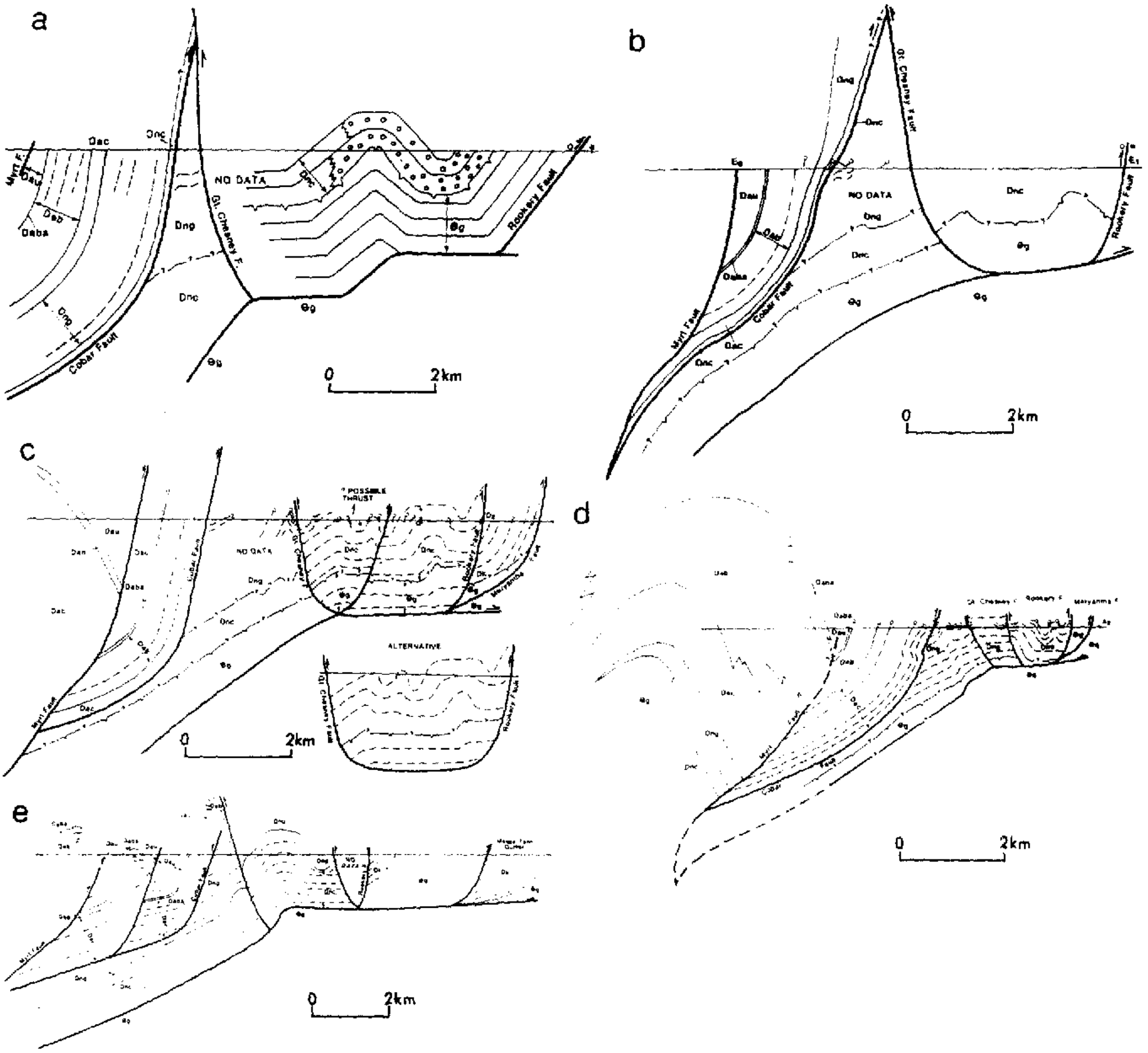

Fig. 8. North to south series of cross-sections through structural Zone 1 and in part extending east of the zone. For discussion see text. Sections were drawn using kink-type constructions of Suppe (1983) which were then modified by rounding hinges and by taking into account limited drill data which suggests faults remain steep down to 1 km or so. Sections are line balanced, but have not removed unquantifiable cleavage strain. They do not take strike-slip movements into account. Sections are not unique, given lack of relief, and absence of subsurface data. Presence of other units at depth (e.g. volcanics) would cause significant changes to the sections. Note that the CSA Siltstone and Great Cobar Slate are, in part, laterally coeval, representing deposition from different fan systems. As a result, Dac in (b) passes up into Dng, and Dac in the Cobar Plate is equivalent to Dng in the Chesney Plate. This means that the Cobar Fault puts Dac on top of Dac equivalent plus older rocks. For abbreviations see Fig. 6.

sheared and silicified siltstone (Kapelle 1970) first identified as a thrust with east-block-up movement by Thomson (1950, 1953)—and also by ductile black chlorite shears. These shears are meridional with steep to gentle E dips (locally very steeply W-dipping) and have a east-over-west sense of shear (Robertson 1974). Robertson (1974) reported dextral and reverse components of slip on some zones, and in some cases, strike-slip striae post-date dip-slip ones (Glen in press).

Ductile structures in the Cobar Plate include a meridional, subvertical S_1 cleavage which lies parallel in strike to bounding faults, a down-dip mineral lineation L_1, mesoscopic F_1 folds and local F_2 folds, and S_2 cleavage.

The Chesney Plate. This plate comprises a triangle zone of mechanically weak Great Cobar Slate lying between the W-dipping Cobar Fault to the west and the steeply E-dipping Great Chesney Fault to the east. Bedding is openly folded by macroscopic F_1 folds, and the regional geometry in the best constrained areas, north and south of Cobar itself, is characterized by a subhorizontal to gently dipping enveloping surface (Figs. 6 and 8e) (Thomson 1950, Glen in press). Internal imbrication is a feature of the Chesney Plate south of the Mopone Fault (Fig. 6), and probably accounts for the great outcrop width of the Great Cobar Slate in this area. These faults are best documented in the area south of Cobar (Andrews 1913, Thomson 1950, Mulholland &

Rayner 1961) where they are indicated by steeply E-dipping quartz veins which commonly display very steeply N-plunging quartz fibres and which formed by crack–seal shear extension (Mode II) movement consistent with east-over-west displacement Glen (1987b). The Great Cobar deposit is faulted on its western side (Andrews 1913, Suppel 1984, Glen 1987b) with the development of talc schist. The fault and mineralization are subvertical to a depth of 700 m before the mineralization becomes more gently E-dipping (Suppel 1984), implying the fault too dips easterly (not to the west as questioned by Glen 1988).

Ductile structures in the Chesney Plate are a subvertical regional S_1, a down-dip L_1 elongation lineation, F_1 folds and small F_2 folds. The relationship between S_1 and bounding faults changes from parallel or slightly oblique in Zones 1c and 1d to markedly oblique (suggestive of sinistral transpression) in Zone 1b (Fig. 7). S_1 overprints a bedding-parallel apposition fabric, random detrital micas and in a few local cases, an earlier diastrophic mica preferred orientation. This early foliation may have formed in the manner described by Mitra & Yonkee (1985)—by rotation of early formed cleavage during a later thrusting event—but it could also represent a localized early shortening event in a transpressive regime.

Great Chesney Fault and related faults. The Great Chesney Fault is a steeply E-dipping fault which marks the contact between the folded and imbricated Great Cobar Slate in the footwall to the west and the folded Chesney Formation in the hangingwall to the east (Figs. 6 and 8). The steep (*ca* 80°) dip of the fault is well constrained 5 km southeast of Cobar at New Occidental Mine (Andrews 1913), and 2.5 km southeast of Cobar at New Cobar Mine (Sullivan 1951, Suppel 1984). The Great Chesney Fault cuts off bedding in both the hangingwalls and footwalls and this is best seen just southeast of Cobar in the hangingwall (Mulholland & Rayner 1961) where the fault cuts off the western limb of a macroscopic F_1 anticline (Fig. 6) (Glen 1987a,b). In this area southeast of Cobar, the Great Chesney Fault is marked by a zone of quartz veins 1–2 m wide and is paralleled by imbricate, quartz-filled faults 50–100 m out in the footwall. All these faults are the sites of copper and gold deposits (Andrews 1913, Glen 1987b). These quartz zones show several sets of veins with the main set parallel to the faults (i.e. steeply E-dipping) being a set of fibrous crack–seal, shear-extension veins with steeply N-plunging fibres (Glen 1987b).

Combined kinematic and stratigraphic data from these faults indicate the following history (Glen 1987b):

(1) a phase of high-angle reverse (east-block-up movement) combined with a dextral strike-slip component (revealed by fibre orientations);

(2) a phase of left-lateral strike-slip movement, revealed by left-stepping overlaps in fault segments (jogs in the sense of Sibson 1985), by en échelon vein arrays and by the presence of WNW-trending cross veins with some (at least) being extensional and containing cross fibres (Glen 1987b).

At the northen end in Zone 1e (Fig. 6), the Great Chesney Fault is inferred to terminate on the Yanda Creek Fault in an area of poor outcrop. At its southern end (northern part Zone 1c, Fig. 6), the Great Chesney Fault ramps laterally up-section into the Great Cobar Slate and becomes lost. In this area, faulting is relayed to the southeast into a zone of closely spaced ductile–brittle faults in the Peak area (Fig. 6)—the Great Peak Fault, Blue Shear and Lady Greaves Shear (Andrews 1913, Thomson 1950, Plibersek 1982). Work by Hinman (Hinman & Scott in press, personal communication 1989) indicates that down to *ca* 500 m these faults have subvertical dips and that the Great Cobar Slate has been downdropped between the rocks of the Chesney Formation. Whether these faults become high-angle reverse at greater depth is unknown. In plan, these faults have braided character (mapping by Hinman), and this suggestion of strike-slip movement is supported by observation in the Blue Shear of subhorizontal striae overprinting vertical ones, and by the presence of steeply plunging asymmetrical mesoscopic folds suggestive of sinistral strike-slip.

As it is followed to the south, the Great Peak Fault ramps up-section into the Great Cobar Slate and then some 2 km further south into CSA Siltstone on the western side (Fig. 6). Here, Schmidt (personal communication 1988) shows it as a W-dipping shear zone separating W-dipping and younging CSA Siltstone in the hangingwall from the E-dipping and younging Great Cobar Slate in the footwall (Fig. 6). This fault dies out some 1 km to the south within a S-plunging anticline and displacement appears to be transferred to two closely spaced ?E-dipping contractional faults to the east which put folded CSA Siltstone or Biddabirra Formation on the east over upper Amphitheatre Group on the west (Fig. 6).

The Mopone Fault (Fig. 6) is the main cross fault in the Great Chesney Fault, but other faults are also present further north within Zone 1b (Fig. 6). Differences in shortening in the Chesney Formation across the Mopone Fault suggest it is a lateral ramp related to thrusting. Later strike-slip activity in this area is indicated by quartz-filled NE-trending faults left-laterally offsetting the Mopone Fault itself (Thomson 1950, Glen in press).

The Rookery Fault. The Rookery Fault marks the eastern edge of the Rookery Plate and Queen Bee Plate, and the eastern edge of structural Zone 1. It is interpreted as a steeply W-dipping fault which places folded basin sediments in the hangingwall against folded shelf sediments and basement in the footwall. The most obvious regional-scale feature of the Rookery Fault is its marked change in orientation opposite Cobar township, where it swings from a northwesterly trend in Zone 1d into a meridional trend in Zones 1b and 1e (Figs. 5 and 6). At its inflection point, the Rookery Fault defines a promontory or indenter in the shape of the deformed

Cobar Basin (Glen 1985, 1988). The Rookery Fault ramps laterally through stratigraphy in both the footwall and hangingwall (Fig. 6). In the footwall, south of the indenter, it ramps up and down from Kopyje Group to basement. North of the indenter, the footwall of the fault contains several rejoining splay faults, outlining one horse of basement Girilambone Group (of unknown structure) and a larger horse of W-dipping and younging Kopyje Group resting unconformably on basement Girilambone Group (Fig. 6). In the hangingwall, the Rookery Fault also ramps across stratigraphy. Whereas south of the indenter these ramps are stratigraphically contained within the Chesney Formation, north of the indenter the fault ramps from Chesney Formation down into Girilambone basement and back up again. Rejoining imbricate splay faults also occur in the hangingwall just north of the indenter, separating unfolded outcrop of Drysdale Conglomerate Member from folded outcrops of Chesney Formation (Fig. 6).

The Rookery Plate. The geometry of the Rookery Plate changes across the indenter in the Rookery Fault. North of the Zone 1d–1c boundary, and extending northwards to Yanda Creek Fault, The Rookery Plate forms a dominantly meridional pop-up structure, between the E-dipping Great Chesney Fault and the W-dipping Rookery Fault (Figs. 6 and 8a–d). South of Zone 1d, the Rookery Plate trends NW and no longer forms a pop-up, being bounded to the east by the E-dipping Queen Bee Fault (Figs. 6 and 8e). The western edge of the Rookery Plate changes southwards across a series of transfer zones from the E-dipping Great Chesney Fault, to the Great Peak Fault and further south to unnamed ?E-dipping faults again, as discussed above. Ductile structures in this plate include a regional S_1 cleavage, close to tight mesoscopic F_1 folds and down-dip mineral and extension lineations (Glen 1985). Local F_2 folds in S_1 are also present.

Several other features of the Rookery Plate are:

(1) the presence of internal imbricates in Zone 1e (Mount Drysdale area, Glen in press) and Zone 1b (mapped by Skrzeczynski & Meates 1977);

(2) the presence of basement (Girilambone Group) within the plate north of the indenter but not to the south (Fig. 6);

(3) changes in the strike of S_1 and F_1 axial planes. From south to north, these change from NE in Zone 1a to NNW in Zone 1c and N opposite the indenter (Zone 1d) and then into NNE and NE in Zones 1b and 1e to the north (Fig. 7).

Glen (1985) showed that these strike swings reflected changes in local shortening directions within Zone 1. Accompanying these strike swings is a change in angular relationships between the strikes of S_1 and F_1 axial planes from parallel or near parallel (in Zone 1a) to parallel to transected (in Zone 1c), markedly transected in Zone 1d (see also Glen 1985) and parallel to transected in Zone 1b (Fig. 7). Also accompanying these strike swings is a change in relationship between the strikes of D_1 structures and bounding faults from (near) parallel south of the indenter to markedly oblique north of the indenter (Fig. 7). Both these changes indicate northwards increasing left-lateral transpression on the Rookery Fault (see below).

Queen Bee Fault and Queen Bee Plate. The Queen Bee Fault is a NW-trending splay from the Rookery Fault, extending south from the Rookery at the Zone 1c–1d boundary as an inferred steeply E-dipping fault which puts openly folded Chesney Formation on the east against folded Great Cobar Slate on the west.

At the Zone 1c–1a boundary, the Queen Been Fault either merges with the Woorara Fault of MacRae (1988) or is in relay with it. This latter fault can be traced south for tens of kilometres and is cross-cut and offset by NE- and NW-trending faults (Pogson *et al.* 1985).

Like the Rookery Plate north of the indenter, the Queen Bee Plate forms a pop-up structure between the W-dipping Rookery Fault to the east and the Queen Bee–Woorara Fault to the west. The geometry of the plate in Zone 1c is apparently simple in the north with open regional folds trending NW, slightly more clockwise than the Rookery Fault, and accompanied by an S_1 cleavage. In Zone 1a and further south, work by Pogson *et al.* (1985) indicated that the Queen Bee Plate is complexly folded and imbricated with a series of E-dipping backthrusts developed off the floor thrust. Duplex structures are locally developed.

Inferred deep structure of Zone 1. The deep structure inferred below Zone 1 is shown in Fig. 8. The key feature of the interpretation is that the surface faults shallow and link into a W-dipping floor thrust (detachment) which underlies all of Zone 1. Presence of this floor thrust is based on repetition of Biddabirra Formation across several imbricates in the Cobar Plate south of the indenter (Fig. 8c), on the repetition of Chesney Formation north of the indenter from the Rookery Plate into the Cobar Plate (Figs. 8a & b), and on the interpretation of surface folds as either fault-bend folds (Figs. 8a & e) or fault-propagation folds (Fig. 8c). Steep surface faults are thus seen as imbricates off this floor thrust. The Rookery and the Cobar Faults are forethrusts; the Great Chesney and imbricates in the Chesney Plate are backthrusts. The Rookery Plate (in Figs. 8a–d) is a pop-up which is itself internally imbricated (in Fig. 8c). The Chesney Plate is a triangle zone.

The facies and thickness contrasts across the Myrt and Rookery Faults discussed earlier indicate that these structures are re-activated syn-depositional faults. The floor thrust is subhorizontal under the Rookery Plate, with lateral changes in its depth indicated by regional plunge changes in F_1 folds and S_0–S_1 intersections. Opposite the indenter, the floor thrust is at a relatively high level (Fig. 8d) and must lie close to or just below the basement–cover contact. The floor thrust deepens gradually to the south as folds plunge S. At the same time the thrust has ramped up to lie at the basement–cover contact (Fig. 8e). Passing north from the indenter, the floor thrust ramps down through basement and is

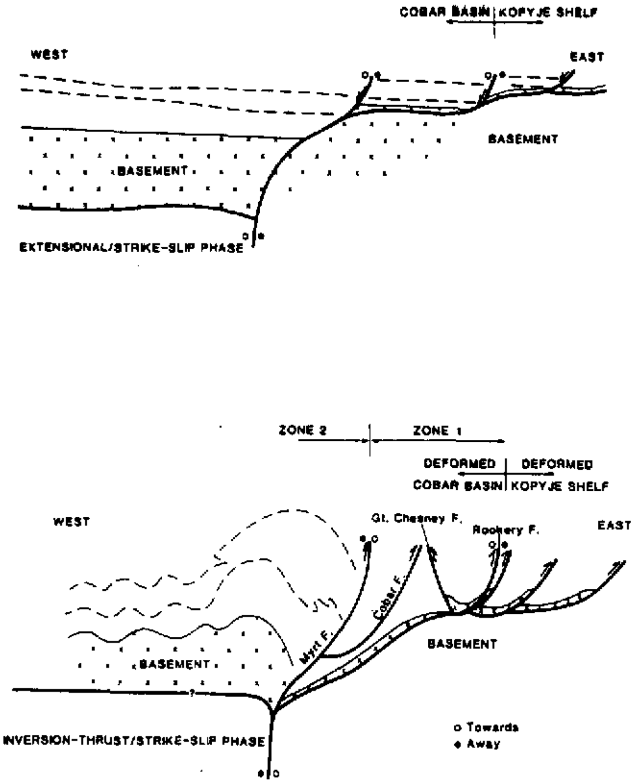

Fig. 9. Cartoon sketch of extensional and contractional phases on the eastern side of the Cobar Basin, showing asymmetrical negative and positive flower structures.

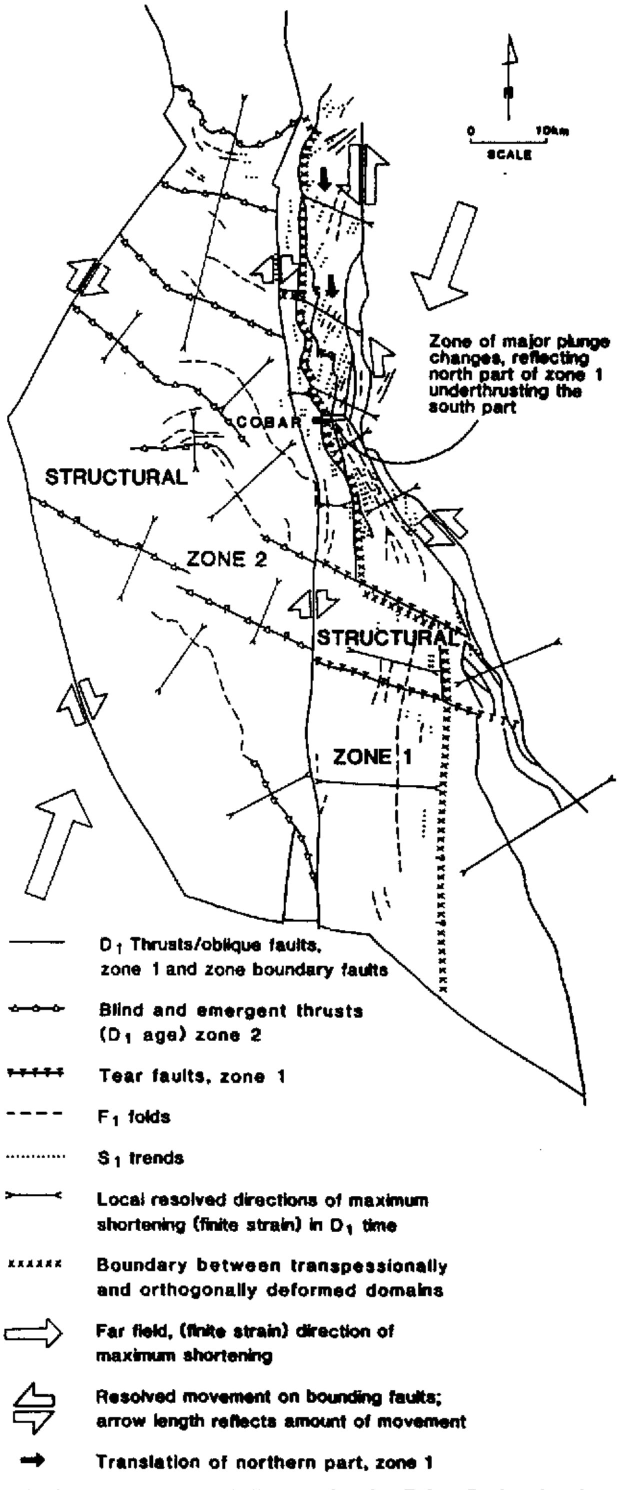

Fig. 10. Summary structural diagram for the Cobar Basin, showing near- and far-field directions of maximum shortening, and resolved strike-slip movement on bounding faults.

inferred to deepen to the north (Figs. 8a–c), perhaps abruptly across the Mopone Fault.

The floor thrust must become W-dipping west of the Great Chesney Fault, but it is uncertain at what stratigraphic level or depth it occurs. In the south of the area (Figs. 8c–e) the Cobar Fault rides on CSA Siltstone in the hangingwall and may sole in Chesney Formation or Great Cobar Slate in the footwall. Further north (Figs. 8a & b) the fault has ramped down-section into the Chesney Formation in the hangingwall and must sole in the Chesney Formation in the footwall.

The Cobar Fault is inferred to merge with the Myrt Fault under the Western Anticline in Zone 2 which is interpreted as a basement-cored fault-propagation fold related to the blind Myrt Fault (Fig. 8d). (Note that balancing across these structures is complicated by major thickness changes in the CSA Siltstone and Biddabirra Formation.)

The floor thrust below Zone 1 does not continue further west into Zone 2 which is characterized by a different structural regime (see below). Consequently it must steepen at depth to ramp through middle crustal levels. The structural style of Zone 1 is therefore that of a positive asymmetrical flower structure developed above a strike-slip fault (Fig. 9) and indicates that Zone 1 was deformed under a transpressional strain regime. Although data are lacking from Zone 1a in the south, this flower structure is inferred to widen southwards from Zone 1c. The sense of strike-slip movement during transpression is suggested by several features.

(1) Left-lateral movement on the Rookery Fault, especially that part north of the indenter, is indicated by oblique relations between that fault and the strikes of D_1 structures (Fig. 7).

(2) NE–SW direction of maximum shortening is indicated for major D_1 structures in Zone 1c south of the indenter and for structures in the Queen Bee Plate in Zones 1a and 1c (Fig. 10). Here, shortening is orthogonal to D_1 structures and bounding faults (Fig. 10).

(3) Transected relations between S_1 and F_1 axial traces, especially in Zone 1d, are indicative of S_1 forma-

tion after F_1 folding in a rotating left-lateral strain regime. The western boundary of this transected domain coincides with the Cobar Fault in the north and can be also recognized to the south (Fig. 10). Structures west of this line reflect the pure shortening component of the deformation.

(4) Left-lateral movement on the Chesney Fault is indicated by the obliquity between the fault and D_1 structures (Fig. 7) and also by the quartz vein data south of Cobar (see above and Glen 1987b).

(5) Right-lateral movement on the Chesney Fault is indicated by the quartz fibre data south of Cobar described above.

(6) A component of right-lateral movement on the Myrt Fault is indicated by resolved strain during the D_1 deformation in Zone 2 (see below), especially in the northern part of that zone. There may have also been minor left-lateral movement on the Myrt Fault during D_2 deformation in Zone 2, but this would have been slight (see below).

These observations lead to a kinematic picture of right-lateral transpressive strain during which time Zone 1 north of the indenter underwent translation to the south (Fig. 10). This would necessarily have involved some underthrusting in the indenter area, and would explain the high level of the floor thrust in this area and the D_1 plunge variations within this area referred to earlier.

Structural Zone 2

Zone 2 occupies the bulk of the deformed Cobar Basin and is of lower D_1 strain than Zone 1 to the east (Glen 1985). It extends from the Myrt–Thule fault system in the east to the Buckwaroon Fault in the west, from the Little Tank Fault in the north to an uncertain boundary in the south which marks the changeover between Devonian and Carboniferous deformations (see below) (Fig. 5).

Two major generations of structures occur in Zone 2. D_2 structures include variably developed S_2 cleavage and variably plunging, upright open F_2 folds which are more prevalent in the northern part of the zone and which refold earlier F_1 folds (Glen 1985, 1987a, Glen *et al.* 1985a). The traces of these F_1 folds vary in strike from meridional to latitudinal and F_1 folds may be accompanied by an uncommon subvertical S_1 cleavage. There is no regional S_1 development as in the higher strain Zone 1 to the east.

A set of WNW-trending faults is also of D_1 age and splits Zone 2 into a series of fault bounded blocks described as follows.

Bundella Block and bounding faults. The Bundella Block constitutes the northern part of Zone 2, being bounded to the north by the Little Tank Fault and to the south by the Bundella Fault (Fig. 5). The Little Tank Fault does not outcrop: its presence as a S-dipping fault is inferred from the abrupt juxtaposition of shelf clastics on the north against basin turbidites on the south, from the widespread development of quartz veining, and from the westward truncation against it of the Great Cobar Slate this being attributed to the fault ramping laterally up-section in the hangingwall. The Bundella Fault along the southern edge of the block is emergent in its western half (where it truncates strata to the south on a regional scale) but passes along strike to the east into the Bundella Syncline.* The fault in this area is inferred to be blind below the syncline. As discussed earlier in this paper, major thickening of the Biddabirra Formation and changes in stratigraphy across this structure indicate it is a re-activated syn-depositional fault which dips to the south.

Internally, the Bundella Block contains open, upright WNW-trending F_1 folds, and accompanying S_1 subvertical cleavage. Both have been folded by NE-trending, upright, open F_2 folds and a subvertical NE-trending S_2 cleavage is locally present. The regional presence of S_1 in this block is atypical for Zone 2 as a whole and indicates higher strain than normal.

Although hindered by poor outcrop, the geometry of the Bundella Block is inferred to comprise a series of N-vergent WNW-trending F_1 folds refolded by F_2 folds. The Elura Mine area is inferred to lie in one such rotated limb, with the NNW-trending folds in this area (Schmidt 1980, 1982) being rotated F_1 structures. Schmidt recognized that these folds were accompanied by an axial-planar S_1 cleavage which contained a down-dip extension lineation. These F_1 structures correspond to F_2 folds recognized by de Roo (1989) from a detailed study extending a few tens of metres out from the orebody. de Roo recognized an early local microscopic, steep S_1 cleavage as well as later D_3 structures (D_2 of this study) and later D_4 minor folds. Work by Lawrie (personal communication 1989) has since indicated that S_1 is a flat-lying fabric which is probably thrust-related (see below).

Maryvale Block and bounding faults. The Maryvale Block is bounded to the southeast by the NE-trending Scummy Tank Fault and more generally to the south by the WNW-trending Plug Tank Fault which shows south block-up sense of movement (Fig. 5). Both faults are obscured by creek alluvium. The Maryvale Block is dominated by NE-trending macroscopic F_2 folds—the Maryvale Anticline itself outlined by the Biddarra Formation, and smaller scale macroscopic folds in the upper Amphitheatre Group in the west of the block (Fig. 5). Plunge changes in the Maryvale Anticline define a NW-trending culmination and depression and these may reflect the presence of early, open folds (Fig. 5). The earliest structures in the block occur along the eastern margin and comprise meridional, mesoscopic F_1 folds and subvertical S_1 cleavage refolded by F_2 folds. F_1 and S_1 lie parallel to F_1 and S_1 in Zone 1 immediately east of the Myrt Fault and their presence just west of the Zone

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*Although I had earlier thought the Bundella Syncline was a NE-trending second generation structure (Glen 1985), its relation to parasitic F_1 folds overprinted by S_2 to the north together with additional dip data confirm the new interpretation.

1–2 boundary here, and in the Olino Block to the south, marks the western limit of the cleavage front related to Zone 1 deformation (Glen 1985).

Olino Block. The Olino Block has an irregular southern boundary comprising the NW-trending Amphitheatre Fault in the west, the NE-trending Norwood Fault further east and a combination of the Nymagee and Oakden Faults in the east (Fig. 5). The regional structures in the blocks are two NW-trending F_1 folds which have been folded by NE-trending F_2 folds which are best developed in the eastern and western part of the block. The NE limb of the Western Anticline contains mesoscopic meridional F_1 folds and transected S_1 cleavage. The southern limb in its central western area contains doubly plunging mesoscopic F_1 folds and a poorly developed S_1 cleavage (Glen in press).

Biddabirra Block. This block is bounded to the south by the NE-trending Norwood Fault (Fig. 5). The western part of this block is characterized by NE-trending F_2 folds and a subvertical S_2 cleavage. Further east, conjugate NE-trending F_2 folds overprint and refold early macroscopic F_1 folds which have mainly latitudinal axial traces but which swing in trend from NE to NW. Although D_1 deformation is more intense here than in many parts of Zone 2, an S_1 cleavage is generally absent (Glen 1985).

Composite Nullawarra Block. The composite Nullawarra Block is dominated by the NW-trending F_1 Nullawarra Anticline which has been refolded by NE-trending F_2 folds (Fig. 5) (Glen 1987a). A local subvertical S_1 cleavage lies approximately axial planar to the F_1 anticline, and a NE-trending S_2 cleavage is variably developed. The northeastern limb of the anticline is cut by the WNW-trending Nymagee Fault, and in the south, the anticline runs into the Dusty Tank Fault (Fig. 5) (Glen 1987a).

Inferred deep structure of Zone 2. The deep structure inferred below the northern part of Zone 2 is shown in Fig. 11. The key feature of the interpretation is that the surface faults shallow at depth and link into a flat-lying floor thrust or detachment which underlies all of Zone 2. This floor thrust is needed to link the Little Tank, Bundella and Amphitheatre Faults, all of which had syndepositional histories as discussed earlier. The presence of the floor thrust is also based on the interpretation of surface folds as either fault-bend folds related to ramps in this detachment or as fault-propagation folds related to splays off this detachment (Fig. 11). The floor thrust is inferred to turn up to the surface at the Little Tank Fault and to become gradually deeper to the south. Transport direction is generally to the north. The Bundella Block may contain unmapped blind or emergent thrusts (Fig. 11) and Glen (1989) speculated that the Elura deposit, localized in a doubly plunging anticline, lies above the termination of one such blind thrust. The Western Anticline in the Olino Block is related to a fault-propagation fold splaying off the floor thrust (and might be replaced by a fault west of the section line), with the southern limb of the anticline being in turn overridden by the Amphitheatre Fault which represents a high level detachment carrying Biddabirra Formation over the upper Amphitheatre Group.

There are several somewhat unsatisfactory aspects of the deep structure below Zone 2 which are not resolvable with the data presently available. These include questions about the level and stratigraphic units bracketed by the floor thrust (it is assumed to lie at the basement–cover interface); whether the floor thrust extends northward at depth, north of the major splay in the Bundella Block; the deep structure under the Maryvale Block—whether the F_2 Maryvale Anticline folds the floor thrust or dies out above it, and how the floor thrust deepens to link with the deeper level floor thrust under the Olino and Biddabirra Blocks.

Two points need further emphasis. Firstly, the Western Anticline when taken as a whole, is a composite feature. The eastern, NNW-trending part is interpreted as a fault-propagation fold above the Myrt Fault (see above) and the western more latitudinal trending part is interpreted as a fault-propagation fold related to the

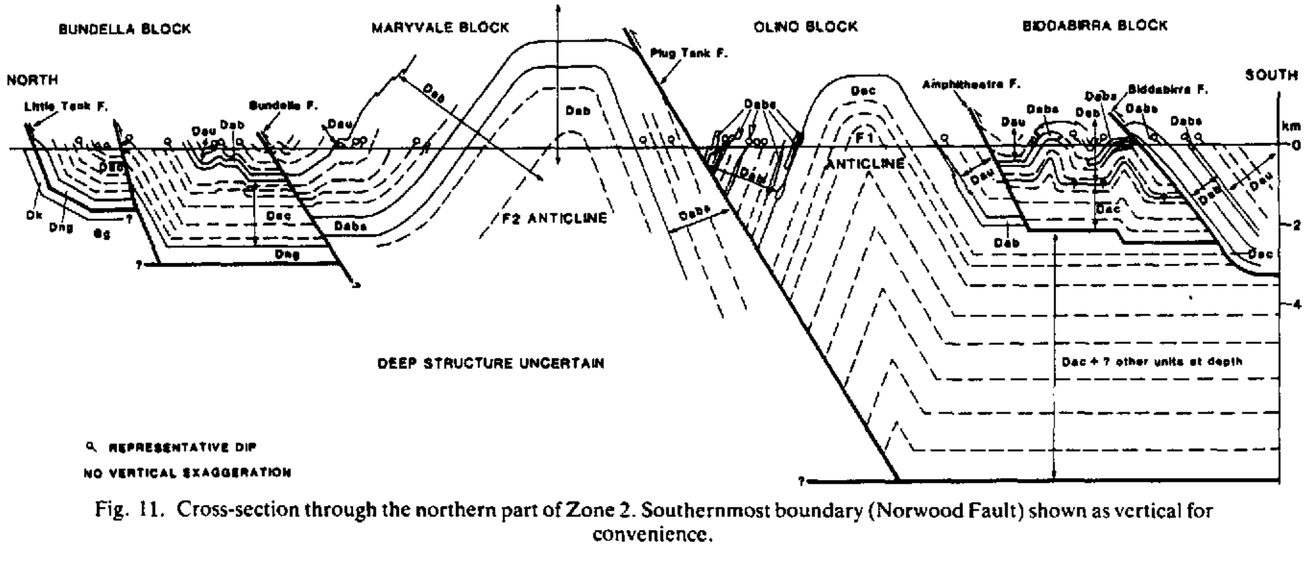

Fig. 11. Cross-section through the northern part of Zone 2. Southernmost boundary (Norwood Fault) shown as vertical for convenience.

detachment in Zone 2. This composite character, related to different fault movements, differs from my earlier interpretation (Glen 1985) wherein the anticline tracked a rotating local shortening direction. Secondly, the interpretation that the WNW-trending faults are thrusts differs from my earlier interpretation of them as having had a left-lateral strike-slip history. The change in interpretation is based on a reassessment of the timing of deformation. Previously, I had suggested, on various grounds, that inversion of the Cobar Basin post-dated deposition of the Mulga Downs Group and was Carboniferous in age (Glen 1985). A consequence of these relations was that the demonstrated strike-slip movement on the WNW-trending faults in the Mulga Downs Group (Glen 1982) could be applied to parallel structures in the Cobar Supergroup. However, K–Ar and ^{40}Ar–^{39}Ar whole-rock dating on rocks in Zone 1 and near the 1–2 boundary (Glen *et al.* 1986, Dallmeyer *et al.* personal communication) suggest that the Cobar Basin was inverted in the late Early Devonian around 400 Ma, before deposition of the Mulga Downs Group and before the Carboniferous deformation of that Group and the underlying Winduck Group.

These observations of WNW-oriented D_1 thrusts in Zone 2 lead to a kinematic picture in which the direction of maximum shortening was oriented NE–SW, approximately perpendicular to the northern and southern margins of the Cobar Basin (Fig. 10). A consequence of this shortening direction is a component of right-lateral slip on the bounding Myrt Fault to the east. The D_2 deformation in Zone 2 involved a switch in the direction of maximum shortening to the NW–SE. Most D_2 structures are of small macroscopic scale and with the exception of the Maryvale Anticline, this deformation would not have led to any significant left-lateral movement on the Myrt Fault. D_2 shortening did, however, generate left-lateral movement on the NNW-trending segment of the Buckwaroon Fault (Fig. 5). The main NE-trending segment of the fault probably underwent vertical (?west block-up) movement at this time.

Inversion of the Cobar Basin—a synthesis

Inversion of the Cobar Basin was accomplished by reversal of movement of syn-sedimentary faults, and took place in a dextral transpressive strain regime. A NE–SW direction of maximum far-field shortening oblique to the basin was resolved into two components by these early basin structures. Local shortenings in Zone 2 were orthogonal to this far-field direction: this led to reversal of movement on syn-depositional normal faults and formation of WNW-trending D_1 thrusts, associated folds and cleavage and resolved right-lateral shear on the Myrt Fault on the eastern edge of the zone. In Zone 1, this far-field direction of maximum shortening was taken up by inversion of a negative half-flower structure which characterized this basin edge during deposition. The Myrt Fault and Rookery Fault were reactivated as oblique thrusts. The Rookery Fault underwent greater inversion and now separates basin sediments from shelf sediments. By contrast, the Myrt Fault underwent limited inversion and is in part blind, being overlain by a syncline cored by rocks of the post-rift packet. The steep dips of these thrusts reflect their origin as syn-depositional oblique-slip extensional faults. The major faults in Zone 1—the Cobar, Great Chesney and Queen Bee—formed as short-cut faults (*sensu* Gibbs 1987, Powell 1987), taking up strain as increasing friction on the steepening Rookery and Myrt Faults inhibited further movement on them. The Queen Bee and Great Chesney Faults formed as backthrusts off a stuck floorthrust (*sensu* Butler 1987). The Cobar Fault is a forethrust. The dextral strike-slip component of inversion is mainly developed north of the indenter in the Rookery Fault—and east of the Cobar Fault—as the northern part of Zone 1 underthrust the southern which deformed more orthogonally.

STRUCTURES FORMED DURING INVERSION OF OTHER TROUGHS AND SHELVES

Kopyje Shelf east of Cobar Basin

Outliers of the Kopyje Group lying immediately east of the Cobar Basin are shown in Fig. 5. Individual outliers are either wholly surrounded by basement Girilambone Group or are in contact along one side with other outliers or with rocks of the Cobar Basin. Previous work (e.g. Felton *et al.* 1985) suggested that these outliers exist as synclinal cores although the western edge of the Meryula 'Syncline' in the north was shown to be faulted against basement (Fig. 12b). Here, I interpret all of these outliers as having a thrust contact with basement. Most of the outliers consist of an unfolded, W-dipping and younging sequence which is overlain on the west, across a thrust, by basement (Figs. 8c and 12a & b). The Lucknow outlier differs in being folded and fault-bounded on both its eastern and western side (Fig. 12c). While the dip of the eastern fault is unknown, this contact is interpreted to be a W-dipping fault which ramped up from within basement locally onto the basement–cover interface. Dahlstrom (1970) pointed out that in this type of situation, thrusts place younger rocks on top of older.

Recognition of these thrust relationships immediately east of the Cobar Basin implies that the floorthrust recognized under the Rookery Plate extends to the east (Figs. 8e and 12c) and that the flower structure extends east of the basin onto the old shelf.

Canbelego–Mineral Hill Belt (Kopyje Shelf)

The Canbelego–Mineral Hill Belt is bounded to the northeast by the Coonara Fault, a regional subvertical structure with east-block-up sense of stratigraphic separation (Pogson & Felton 1978) and to the southeast by the Bluff Fault, which has a west-block-up sense of separation (Pogson in press). The most obvious features of this fault system are the regular changes in strike from NNW or meridional to NW (Fig. 1), changes which are

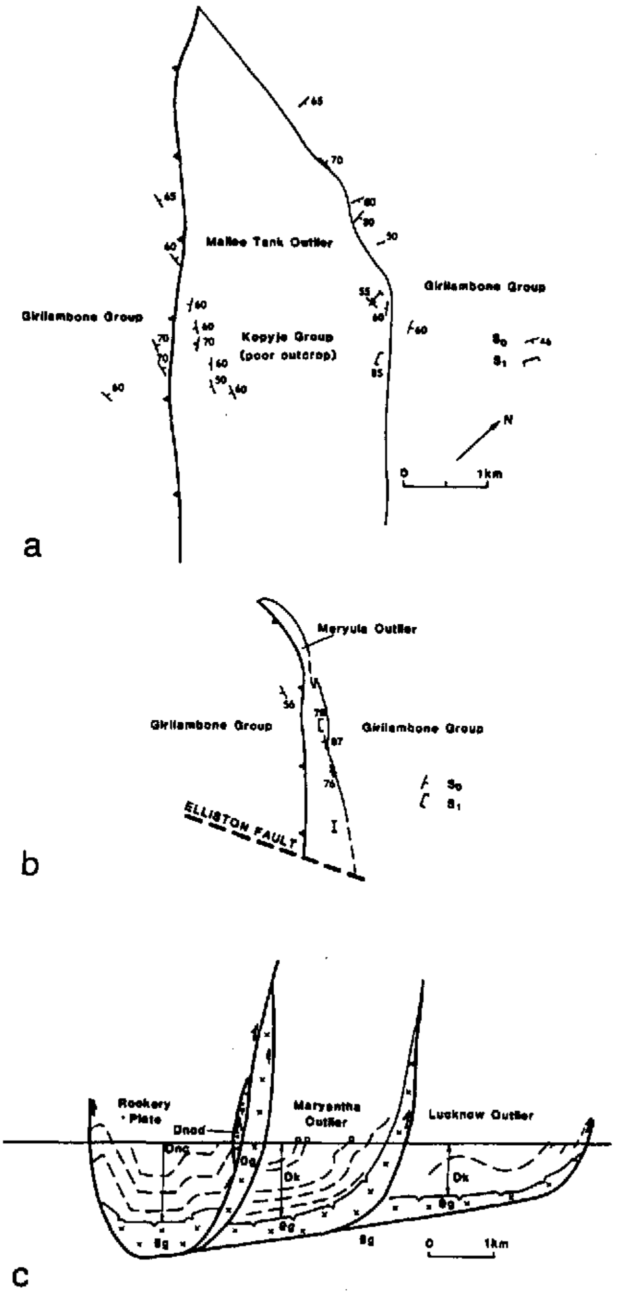

Fig. 12. Basement–cover relationships east of Zone 1. (a) Faulted Mallee Tank Outlier (from Schmidt written communication 1988), shown in cross-section at the eastern end of Fig. 7(e). (b) Faulted Meryula 'syncline' from Felton *et al.* (1985). (c) Cross-section through faulted Maryantha and Lucknow Outliers (mapping in part from Lewington 1980) located in Fig. 6.

similar to those shown by the Rookery Fault described from the eastern edge of the Cobar Basin. The Bluff Fault which bounds the belt to the southeast marks a major strain boundary, separating gently deformed Early Devonian sedimentary rocks east of the belt from highly deformed sedimentary and volcanic rocks within the belt. A similar, but less abrupt strain boundary occurs on the southwestern side of the belt, across the Walker Hill fault system (Pogson in press). On the northeast side, the Coonara Fault separates these same Devonian rocks from Ordovician basement to the east.

Within the belt, Devonian rocks are characterized by one or more subvertical cleavages, and by intense faulting and shearing especially in the south. Major subvertical, gently plunging folds are also present (Pogson in press, personal communication). In most of the Canbelego–Mineral Hill Belt, these internal structures are subparallel to the bounding faults. However, Felton *et al.* (1985) have shown that there is an obliquity in the less deformed northern part (Fig. 1), and in this area a NE–SW direction of maximum shortening, as indicated by internal structures, would produce a component of right-lateral movement on the Coonara Fault. Such a far-field direction of maximum shortening is also indicated for the Canbelego–Mineral Hill Belt as a whole (Fig. 1) and NE–SW shortening would produce variable combinations of local shortening and right-lateral shearing on the differently oriented segments of the Coonara–Bluff fault system. The Canbelego–Mineral Hill Belt is thus interpreted as having been deformed under a dextral transpressional strain regime.

Mount Hope Trough

The Mount Hope Trough is bounded by the Scotts Craig Fault to the east and the Thule Fault to the west (Fig. 1) (Scheibner 1987a). Both are essentially meridional structures, but the Thule Fault shows a zig-zag shape (Fig. 1).

In the southern part of the Mount Hope Trough, mapped folds are meridional and upright and are accompanied by an axial plane, subvertical cleavage (Scheibner 1987a). These structures are parallel in strike to the faults bounding the trough, and are only locally overprinted by the development of a NE-trending, subvertical crenulation cleavage (Scheibner 1987a). Relationships are different in the northern part of the trough west of Gilgunnia (Fig. 1), however, where MacRae (1989) has mapped NE-trending folds and faults oblique to the Scotts Craig Fault. A NW–SE direction of maximum shortening obtained from these folds would produce a component of left-lateral movement on the Scotts Craig Fault, indicating transpressional closure of the northern part of the Mount Hope Trough.

SYNTHESIS AND CONCLUDING DISCUSSION

In the Cobar region, there was a marked synchroneity of basin, trough and shelf-forming processes operating over an area of 25,000 km^2 in the western part of the Lachlan Fold Belt in Devonian times. All the basins and troughs described here underwent an active period of syn-rift upper crustal extension in the Lochkovian (a period of about 5 million years) followed by a passive period of post-rift sag-phase subsidence in the Pragian (a period of about 5 million years). The geographical restriction of major felsic volcanism to the syn-rift stages of evolution of the Mount Hope and Rast Troughs, and to the syn-rift part of the Canbelego–Mineral Hill Belt of the Kopyje Shelf indicates differences in middle and lower crustal thermal regimes which existed on top of the common history of syn- and post-rift basin evolution.

The Cobar Basin is the best studied of these Devonian basins and shows clear evidence of evolution in a strike-slip strain regime. Basin formation occurred during left-lateral transtension and basin inversion occurred in the late Early Devonian under a right-lateral transpressional regime. Of the other depositional elements, the Canbelego–Mineral Hill Belt shows the clearest evidence of having also deformed in a right-lateral transpressive regime. There are insufficient data with which to examine the kinematics of opening along this belt, although its obliquity to the Gilmore Suture (Fig. 13, see below) supports an origin in a left-lateral strain regime (see also Scheibner 1983). The presence of four discrete volcanic centres may reflect the location of releasing bends in such a regime. There are few data with which to assess the kinematics of opening and closing of the Mount Hope and Rast Troughs, although in the former there is clear evidence of syn-depositional faulting which controlled, in part, the locations of volcanic centres. Whether opening and closing were orthogonal or strike-slip are unknown, but I suspect the latter.

In such an environment of documented and suspected strike-slip activity, an important part of any tectonic analysis is to define the master faults. Regional relations suggest that one such fault is the Gilmore Suture (Scheibner 1982, 1987b), which is defined in the Tumut area by the Gilmore Fault Zone (Basden 1982) and further north by a prominent aeromagnetic gradient (Wyatt *et al.* 1980) which in part coincides with the Coonara Fault (Fig. 13). The Gilmore Suture controlled much of the Palaeozoic tectonic history of the western part of the Lachlan Fold Belt, and using aeromagnetic data and satellite imagery, Pogson (personal communication 1989) has traced some of the faults bounding the Cobar Basin, and Rast Trough southwards to link into the suture (Fig. 13).

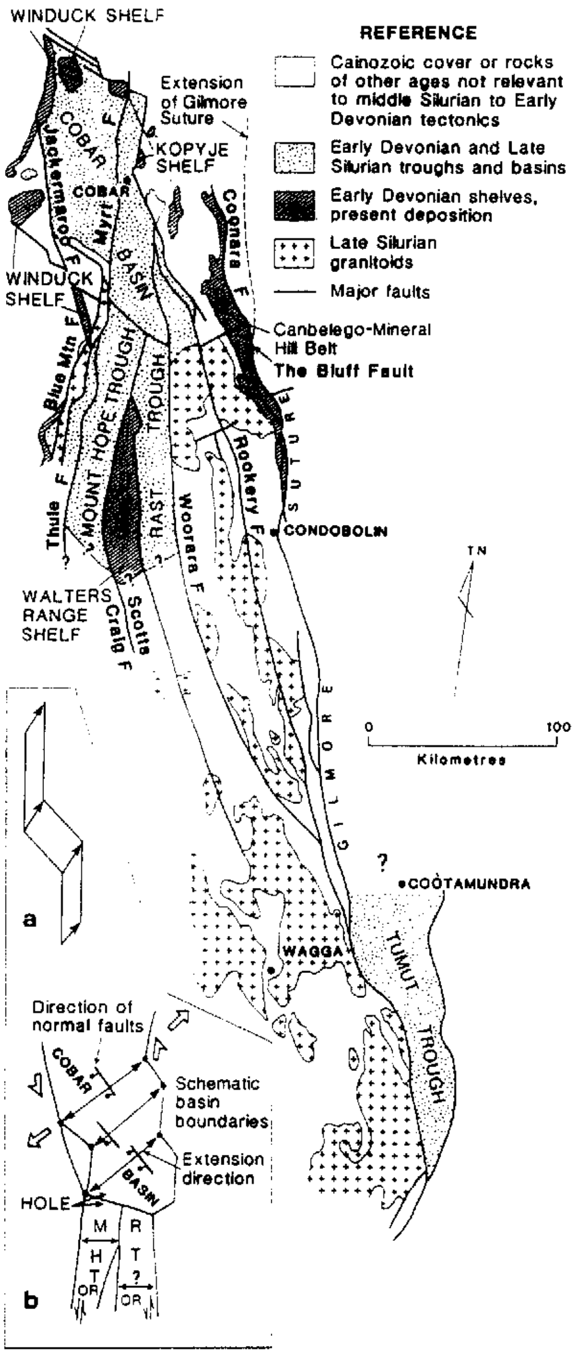

Fig. 13. Regional relations in western part of Lachlan Fold Belt (New South Wales), showing Middle Silurian to Early Devonian depositional elements, late Silurian granitoids and major faults. Simplified from Pogson (1972). Note: all faults except Woorara have both syn- and post-depositional histories. Inset shows: (a) model for oblique extension of an irregularly shaped basin: and (b) application to Cobar region. Holes formed at major changes in amount or direction of extension are filled by volcanics or shallow-level granites.

Scheibner (1982, 1987b) first suggested that the Gilmore Suture formed as an oblique collisional boundary between the Molong Volcanic Arc and the Wagga Basin (a back-arc basin) in the Ordovician–Silurian Benambran Orogeny. In the late Silurian, the en échelon arrangement of granites west of the suture suggests a left-lateral transtensional history on that fault (Fig. 13) (Scheibner 1982) and right-lateral transtension controlled the opening of the Tumut Trough in the mid-Silurian (Powell 1983, Stuart-Smith personal communication 1989). The Tumut Trough was closed by sinistral transpression at the end of the Silurian (Stuart–Smith personal communication 1989) and this closure coincides in time with the opening of basins in the Cobar region, where Cobar Basin and Canbelego–Mineral Hill Belt opened under sinistral transtension. The Mount Hope and Rast Troughs may have opened orthogonally or by transtension, with the latter more plausible. In this case, the relative narrowness of these two troughs compared to the Cobar Basin is explicable in terms of different amounts of extension occurring on variably oriented strike-slip faults (Fig. 13 inset). Closure of the Cobar Basin and Canbelego–Mineral Hill Belt was by right-lateral transpression. The Mount Hope and Rast Troughs probably closed by transpression. Carboniferous movements on the Blue Mountain Fault, Jackermaroo Fault and southern part of the Thule Fault (Fig. 1) post-date deposition of, and deform, the fluviatile Mulga Downs Group and represent the last phase of Palaeozoic faulting in the Cobar region (Glen 1987a, Scheibner 1987a, MacRae 1989). Movement was transpressional, with the strike-slip component varying from dextral on the meridional, northern part of the Jackermaroo Fault (Powell personal communication) and on the Blue Mountain Fault (Scheibner 1985) to locally sinistral and dextral on the NW-trending part of the Jackermaroo Fault and adjacent WNW-trending faults (e.g. Crowl Creek Fault) (Glen 1982). The Jackermaroo–Thule fault system and the Blue Mountain Fault do not extend very far south of the Cobar region (Figs. 1 and 13) before being covered by Mesozoic deposits of the Murray Basin and by Cainozoic cover. From regional aeromagnetic data (Pogson & Scheibner personal communication) these faults might extend south into eastern Victoria to link onto the Kiewa Fault which has dextral strike-slip movement (Morand 1988).

In such a strike-slip environment where faults link into different master structures, basin inversion need not be synchronous. One would expect that the Rast Trough and Canbelego–Mineral Hill Belt may have been deformed in the late Early Devonian (around the same time as the Cobar Basin) since all their bounding structures link into the Gilmore Suture. No data, however, are available. Because the Thule and Blue Mountain faults may link into a different structure, the Kiewa Fault, the western edge (or even all) of the Mount Hope Trough may have deformed at a different time, in the Carboniferous. The later period of inversion would be roughly synchronous with regional inversion of the Winduck Shelf, the overlying Mulga Downs Group and even the western margin of the Cobar Basin (Glen 1982). The largely independent movement on different strike-slip faults explains two previous paradoxes: the lack of any Carboniferous deformation in rocks of the Cobar Basin (which was inverted in the Devonian) either in the field or in argon spectra and the contrast in late Early Devonian deformational styles between rocks of the Cobar Basin, which underwent intense deformation near the eastern margin, and rocks of the Winduck Shelf to the west which underwent only minor block uplift and tilting.

Strike-slip tectonics was thus the dominant structural style in the western part of the Lachlan Fold Belt in New South Wales in the Palaeozoic. Whether this structural style is restricted to this particular part of the fold belt (and extensions to the south) which are bounded by major splays of the Gilmore Suture and Kiewa Fault, or whether other successor basins further east also developed under a similar regime remains to be ascertained. Up to now these basins have been treated as purely extensional in origin (e.g Scheibner, 1976, Veevers 1984).

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