Australian Journal of Earth Sciences (2003) **50**, 513–523

Fault geometry as evidence for inversion of a former rift basin in the Eastern Lachlan Orogen

D. R. GRAY* AND R. T. GREGORY†

School of Geosciences, Monash University, Melbourne, Vic. 3800, Australia.

Reactivated faults have controlled the inversion of an inferred rift basin formed on weakly attenuated Silurian crust of the Eastern Lachlan Orogen. These included north-trending faults, considered part of the rift-related extensional faulting and silicic volcanism (Snowy River Volcanics), and northeast-trending Silurian inverted faults in the Ordovician and Silurian basement rocks. The elongate, largely north-trending Lower Devonian Snowy River Volcanics, and limestone and mudstone sequences of the Buchan Group now reflect ~20–30% east–west buckle shortening in the rift sequence (Murrindal Synclinorium) and 10% fault shortening due to reactivation of basement faults (Emu Egg Fault and East Buchan faults). Faults generally have steep dips, older over younger movement sense, and varying dip directions along their lengths. A peculiar fault geometry that shows faults changing dip direction laterally about segments of vertical fault dip suggests fault reactivation. This geometry requires a scissors-type rotational motion in the fault plane with increasing displacement away from fault segments with vertical dip (pivot points). Zones of steep fault dip are characterised by marked folding in the footwall and hanging wall where shortening has been accommodated by folding rather than by fault displacement. Such geometries are not typical of faults in fold- and thrust-belts (e.g. Canadian Rocky Mountains and Appalachian Valley and Ridge Province). These faults show similarities with inverted extensional faults in the High Atlas of Morocco and in the extensional fault patterns in the offshore Otway Basin of southwest Victoria. Along with the silicic volcanism, they reflect continental rifting or pullapart of the Eastern Lachlan Orogen during Early Devonian times.

KEY WORDS: basin inversion, Buchan Group, faulting, fault reactivation, Lachlan Orogen, Murrindal Synclinorium.

INTRODUCTION

The Lachlan Orogen constitutes the easternmost third of Australia and shows a diverse 200 million years' history, involving overall convergent deformation from the Late Ordovician through Early Carboniferous period (Gray & Foster 1997; Gray *et al.* 1997; Foster & Gray 2000). However, a marked period of extension in the Central and Eastern Lachlan Orogen is inferred from extensive granitic magmatism and silicic volcanism, accompanied by localised development of rift basins (half-grabens: Cas 1983; Gray 1997; Collins 2001). Subsequent basin inversion is by reactivation of the extensional faults and folding of the rift sequences.

In the Eastern Lachlan Orogen, a voluminous sequence of silicic Snowy River Volcanics defines a broad zone of Early Devonian continental rifting in earlier formed crust (Orth *et al.* 1989). Preserved volcanics map out a 150 km-long, elongate north-trending, broadly synclinorial structure ranging from 10–30 km outcrop width (Figure 1). Maximum width occurs near Buchan as a result of the influence of a northeast-trending basement structure. Present outcrop distribution is dependent upon the combined effects of topography, stratigraphy and structure. The Lower Devonian succession unconformably overlies Ordovician and Silurian quartz-turbidites, Silurian granites and in-faulted Silurian volcanics, volcaniclastics, marine clastics and limestone of the Middle to Late Silurian Limestone Creek graben (Figure 1).

This paper examines structural relationships in the central part of the inverted palaeo-rift system, particularly within the Murrindal Synclinorium near Buchan (Figure 2). Bounding faults along the western and south-eastern margin of the synclinorium have controlled the structural complexity in the synclinorium, particularly at zones where these faults pass through the vertical and change their direction of dip. It is this geometry that indicates reactivation of former extensional fault networks that originally defined the former zone of continental rifting. All grid references (GR) refer to the Murrindal (8523) and Orbost (8522) 1:100 000 topographic map sheets.

*Corresponding author and present addresses: School of Earth Sciences, University of Melbourne, Melbourne, Vic. 3010, Australia (drgray@unimelb.edu.au).
†Department of Geological Sciences, Southern Methodist University, Dallas, TX 75275, USA.

LOCAL GEOLOGY

The Murrindal Synclinorium preserves the upper part (Buchan Group) of an Early Devonian rift sequence of the Buchan Rift (VandenBerg 1988; Orth *et al.* 1989; VandenBerg *et al.* 2000; Willman *et al.* 2002). The sequence was deformed to its present form during the Middle Devonian Tabberabberan orogeny (Talent 1965; VandenBerg 1988). Three lithotectonic units have controlled the structures in the region. These includes the Snowy River Volcanics, a complex sequence of rhyodacitic ignimbrites, the Buchan Caves Limestone (200 m thickness of limestone) and the Taravale Formation (~500 m thickness of calcareous mudstone). In the northern part of the synclinorium, the reefal and bedded limestones of the Murrindal Limestone (~360 m thickness) interdigitate with, and are overlain by, the Taravale Formation (Teichert & Talent 1958; VandenBerg 1988).

The Murrindal Synclinorium is a broad, south-plunging, meridional synclinorium in Lower Devonian limestone and calcareous mudstone of the Buchan Group (Figure 2). It has non-cylindrical form as a result of the changing shape accompanied by variable plunge along its length. The synclinorium changes from a narrow box-shaped fold in the north (limestone sequence) to a broad open synclinorium in the south (mudstone sequence) (Figure 3). These changes are probably controlled by the lithofacies variations from the north to the south within the upper part of the sequence: the predominance of limestone in the north and mudstones in the south (Teichert & Talent 1958 figure 1, plate V). The eastern limb has a general north–south strike with a shallow west-dip, and the western limb has a northeast-southwest strike with a moderate to steep east-dip (Figure 1). This produces an asymmetrical, box-shaped fold in profile (Figure 3a). The plunge changes from a moderate but variably south-plunge in the north (30°/187°) to a gentle south-plunge in the south (7°/174°) (Figure 4a, b).

Minor folds, spaced at ~200–300 m, with wavelengths up to 500 m and amplitudes of 100–200 m, are common in the Taravale Formation mudstone (Figure 5). Minor fold trends mirror the first-order syncline geometry. Folds in the south are more open with wavelengths of approximately 500 m, but in the north are tight with limb dips up to 60° and with wavelengths of 100–200 m (Figure 2). Minor fold orientation is clearly domain-dependent. In the north, the folds are either north- or north-northeast-trending: in the central section north-trending, but with a strong northwest trend adjacent to the southern continuation of the Emu Egg Fault; more north-northwest-trending in the south, and north-northeast-trending in the southeast adjacent to the East Buchan Fault (Figure 2).

Cleavage is not uniformly or pervasively developed across the synclinorium. The limestones sometimes contain a spaced stylolitic cleavage whereas the mudstones sometimes contain a weak reticulate or anastomosing cleavage. Cleavage has a general trend of 160° (Figure 4d), but tends to weakly fan around folds. This is best seen in fold closures in road exposures on the Gelantipy road approximately 1 km north of Buchan.

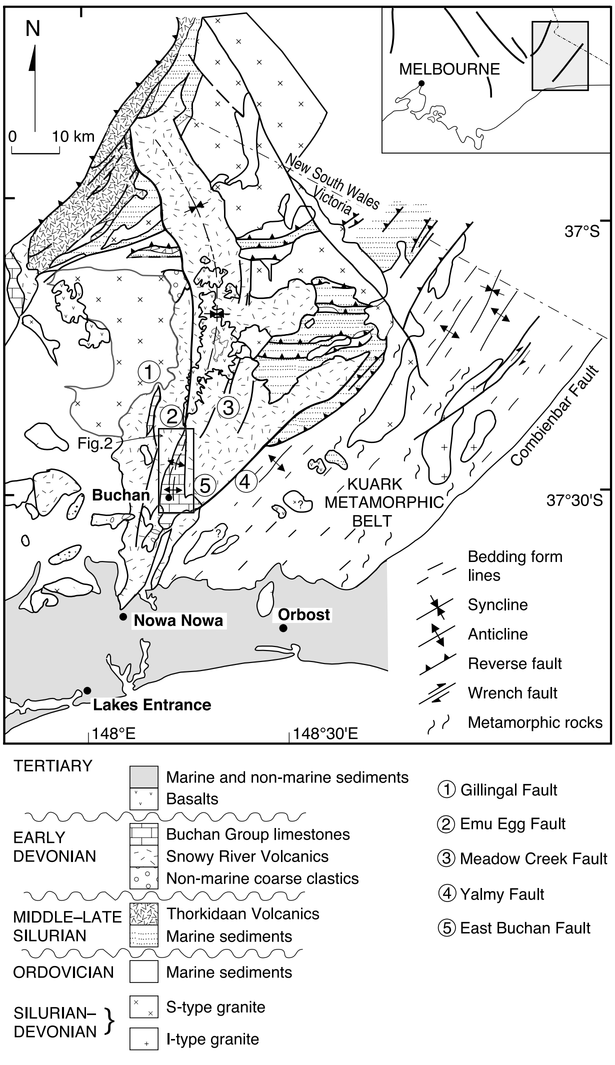
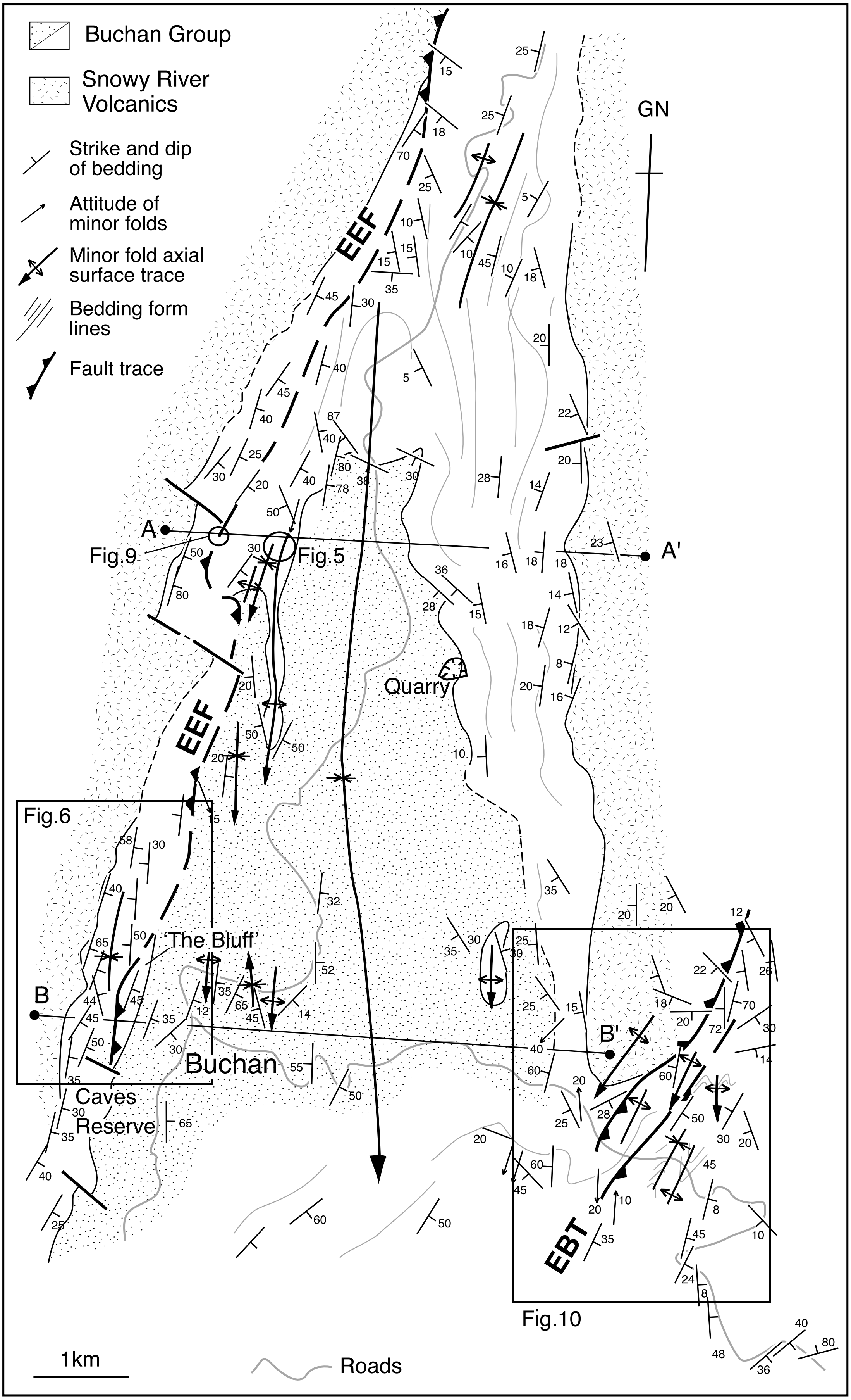


Figure 1 Regional geological map of part of eastern Victoria showing the distribution of the Snowy River Volcanics and Buchan Group (modified from VandenBerg *et al.* 2000 figure 3.66A).

FAULTS

Faults occur along the western and southeastern margins of the synclinorium (Figure 1). Major faults include the East Buchan faults and Emu Egg Fault (Figure 2). The Emu Egg Fault is a major north-trending, regional-scale fault that occurs along the western side of the Murrindal Synclinorium. It loses displacement in the southern part of the synclinorium (VandenBerg *et al.* 2000). The East Buchan Thrust is a part of a major zone of southeast-dipping brittle faults that are subparallel to the major Yalmy–McLauchlan Fault (see VandenBerg *et al.* 2000 p. 304).

Figure 2 Structural map of the Murrindal Synclinorium based on mapping by the authors. Location of the regional profiles A–A′ and B–B′ (Figure 3), the more detailed maps (Figures 6, 9, 10) and photograph (Figure 5) are shown. EEF, Emu Egg Fault; EBT, East Buchan Thrust.


Buchan Group
Snowy River Volcanics
Strike and dip of bedding
Attitude of minor folds
Minor fold axial surface trace
Bedding form lines
Fault trace
GN
EEF
EEF
A
A'
Fig.9
Fig.5
Quarry
Fig.6
'The Bluff'
B
B'
Buchan
Caves Reserve
EBT
Fig.10
1km
Roads

Most faults, although generally not well-exposed, have planar to irregular traces and occur as knife-like discontinuities in outcrop with little or no preserved brecciation or cataclasis. They commonly have associated complex local structure in either the limestone or mudstone within which they commonly occur. Buchan Caves Limestone is generally in the hangingwall, except in the north near Murrindal where Snowy River Volcanics are displaced westwards over Buchan Caves Limestone.

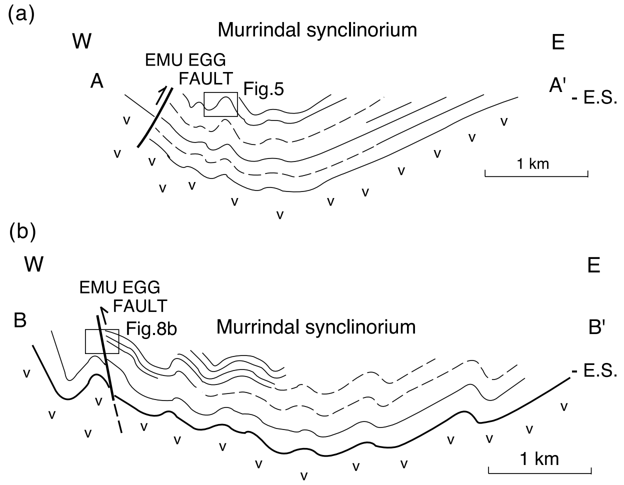


Figure 3 Regional structural profiles (a) A–A′ and (b) B–B′ across the Murrindal Synclinorium (see Figure 2 for location). E.S., level of present-day erosion surface.

These faults are peculiar in that they change dip direction along their lengths. Most faults dip to the east in the southernmost segments but progressively steepen, passing through the vertical and then dipping to the west along their northern segments.

Emu Egg Fault

The Emu Egg Fault is a major strike-fault that extends the entire length of the Murrindal 1:100 000 sheet (Orth *et al.* 1993, 1995). In the Murrindal Synclinorium, it is a steeply dipping north-northeast-trending reverse fault that runs parallel to the margin of the synclinorium (Figure 2). For most of its length in the synclinorium, it occurs in Buchan Caves Limestone. The Emu Egg Fault progressively loses displacement southwards, locally steepens where it crosses the Buchan River north of ‘The Bluff’ (Figures 6, 7a) and changes to a steep east dip from ‘The Bluff’ to the Caves Reserve (Figures 6, 7b) where it terminates within the upper part of the Buchan Caves Limestone.

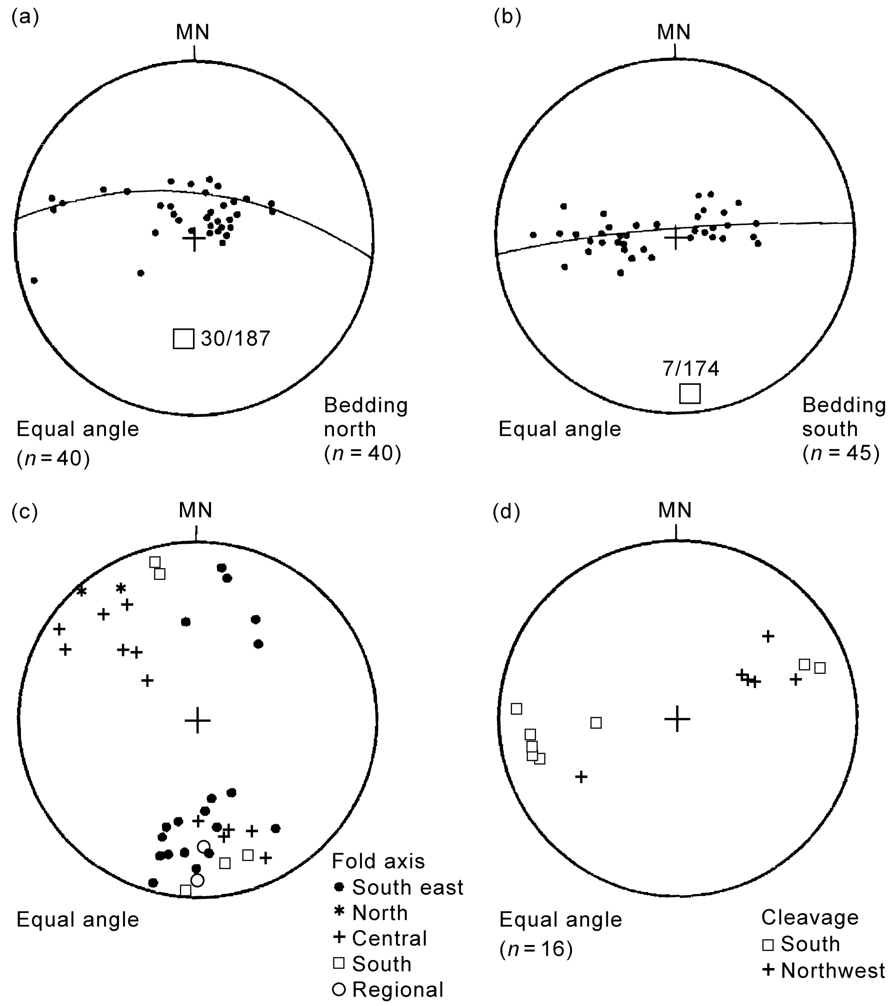


Figure 4 Structural orientation data for the Murrindal Synclinorium. (a) Poles to bedding (northern part of synclinorium). (b) Poles to bedding (southern part of synclinorium). (c) Fold axis attitudes. (d) Poles to cleavage. Best-fit great circles define regional π axes in parts (a) and (b).

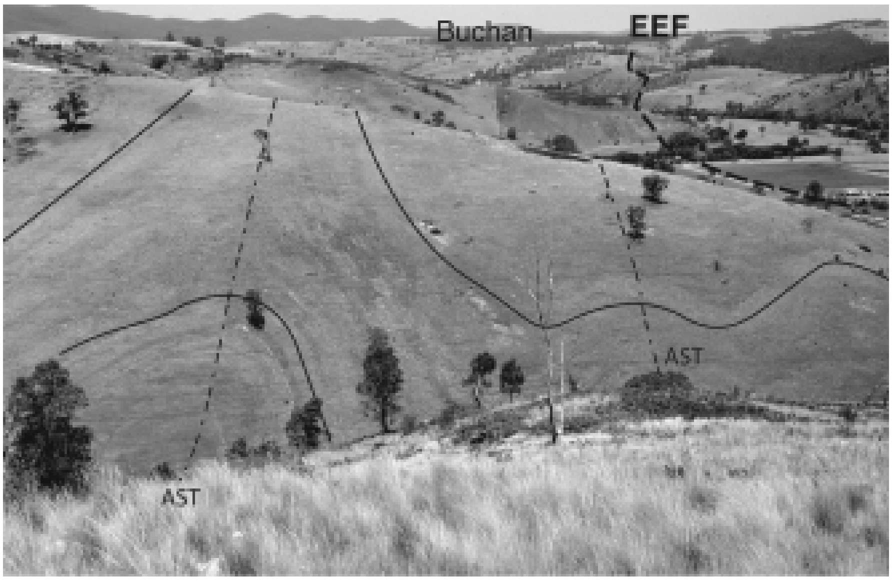


Figure 5 Photograph of folded limestone layer intersection traces in grassy hillsides north of Buchan township (GR 045536). View is looking south (see Figure 2 for location). Approximate profile views of a gently south-plunging anticline and syncline pair. AST, fold axial surface trace; EEF, Emu Egg Fault.

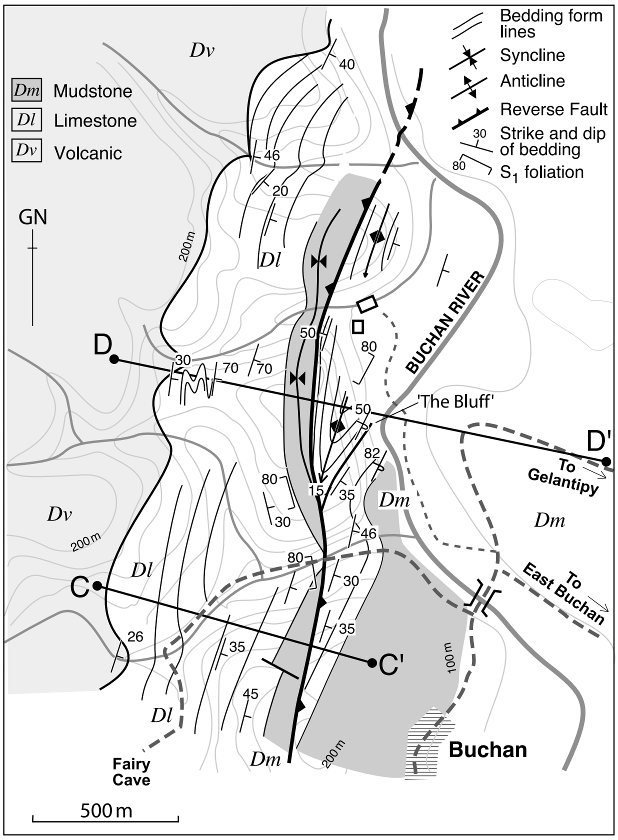


Figure 6 Map of southern portion of Emu Egg Fault (see Figure 2 for location) from the Buchan Caves Reserve (section line C–C′) through 'The Bluff' area on the Buchan River (section line D–D′) (see Figure 7 for section profiles).

Stratigraphic relationships always show hangingwall-up sense of movement, even in the Caves Reserve where it dips to the east (Buchan Caves Limestone over Taravale Formation mudstone: Figure 8b).

At 'The Bluff' (GR 032500) (Figure 2), the fault occurs in folded Buchan Caves Limestone, has small throw (<100 m) and must have a steep east dip, although not well-exposed (Figure 7a). An overturned anticline with knuckle-fold geometry in the limestone is truncated by a low displacement splay fault (Figure 8a), with possibly 50–100 m offset in the Buchan Caves Limestone and Taravale Formation contact that is exposed in the hillside above 'The Bluff' (Figure 6). The splay fault is steeply dipping at the river level and shows rare, weak subvertical slickensides on the fault plane.

On the northern side of the Buchan River, two isolated occurrences of Buchan Caves Limestone have been emplaced against Taravale Formation along this west-dipping segment of the Emu Egg Fault. Where the fault crosses the old Gelantipy coach road (GR 038542), egg-carton-type or small-scale dome and basin fold interference of these northwest-trending folds (set 1) by east–west folds (set 2) occurring in the Buchan Caves Limestone on the hangingwall (exposed in the road bed). Here the fault has a strike of 015° and dips 70°W (Figure 9a, b). At the lower stockyards, Sunny Point Station (GR 038534), this fault juxtaposes a thin slice of Buchan Caves Limestone against Taravale Formation (Figure 2). Minor folds and extensive small-scale faulting are common in both the footwall (Taravale Formation mudstone) and hangingwall (Buchan Caves Limestone) (Figure 4c). These minor folds plunge shallowly to the northwest or southeast (Figure 9c), a more westerly trend than other folds in the synclinorium (Figure 4c).

At Murrindal (GR 057580) to the north, the fault occurs in Buchan Caves Limestone and truncates an overturned syncline in the footwall (Figure 4d). Further north towards the closure of the synclinorium, the fault truncates the hinge and puts Snowy River Volcanics over Buchan Caves Limestone (Figure 2). In this region, rare exposures of minor faults subparallel to the Emu Egg Fault trace show weak subhorizontal slickensides, probably reflecting a late stage component of strike-slip movement.

East Buchan faults

At East Buchan, major northeast-trending folds and faults dominate the structure in this region and farther to the south (Figure 2). These northeast trends are subparallel to the Yalmy–McLauchlan Fault (Figure 1). Structural complexity is associated with a zone of faulting involving two major faults (Figure 10a). Away from these faults,

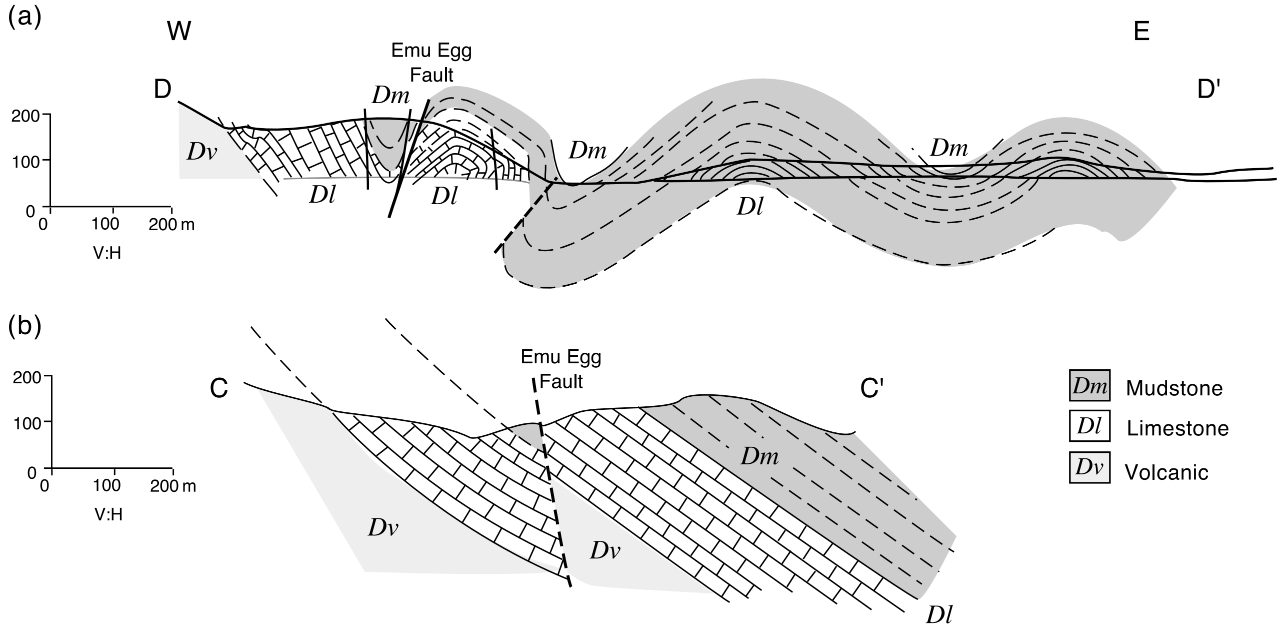


Figure 7 Structural profiles across the Emu Egg Fault in its southernmost segment. (a) Profile D–D′ at 'The Bluff' locality, Buchan River. (b) Profile C–C′ in the Buchan Caves Reserve. See Figure 6 for location of profiles.

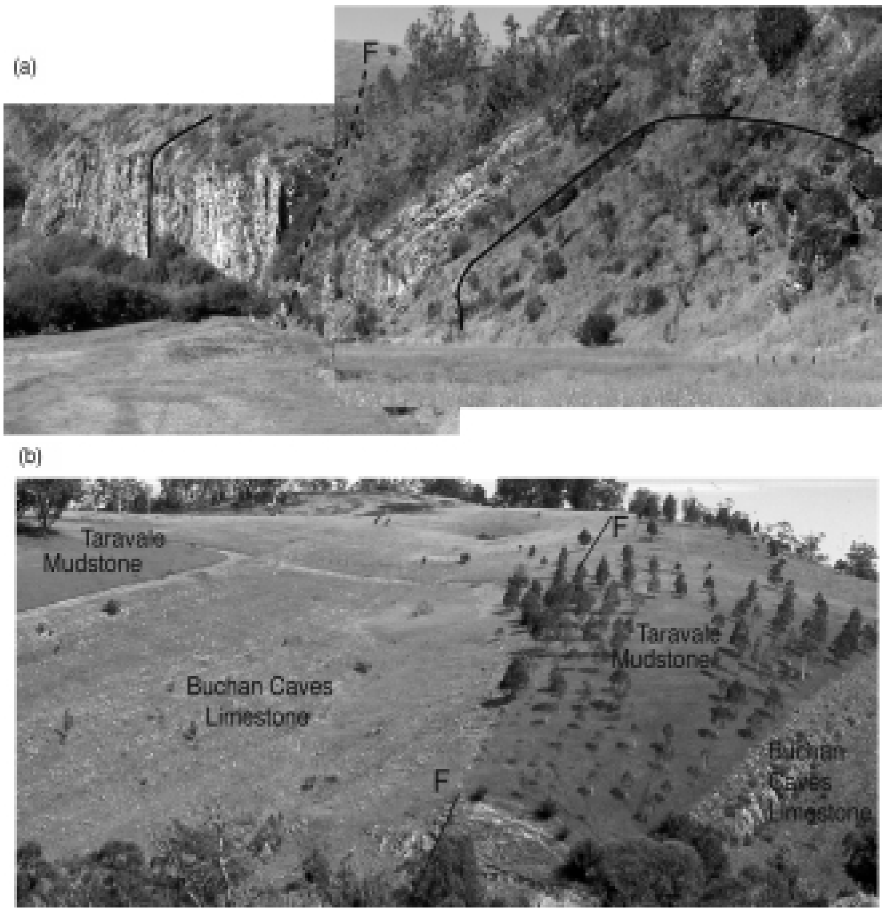


Figure 8 Photographs of the structural geometry of rocks adjacent to the Emu Egg Fault. (a) 'The Bluff' locality, Buchan River (GR 032500) showing knuckle-fold geometry in Buchan Caves Limestone and a steeply east-dipping splay (F) off the Emu Egg Fault. (b) Outcrop trace of Emu Egg Fault (F) on hillside above Fairy Cave, Buchan Caves Reserve (GR 030490).

folds are open and dips are less steep. Minor folds have north-northeast trends and gentle to moderate plunges (<45°) either to the north-northeast or south-southwest (Figure 10b). The major faults have 3-km-mapped strike-lengths and moderate to gentle dips (Figure 10c).

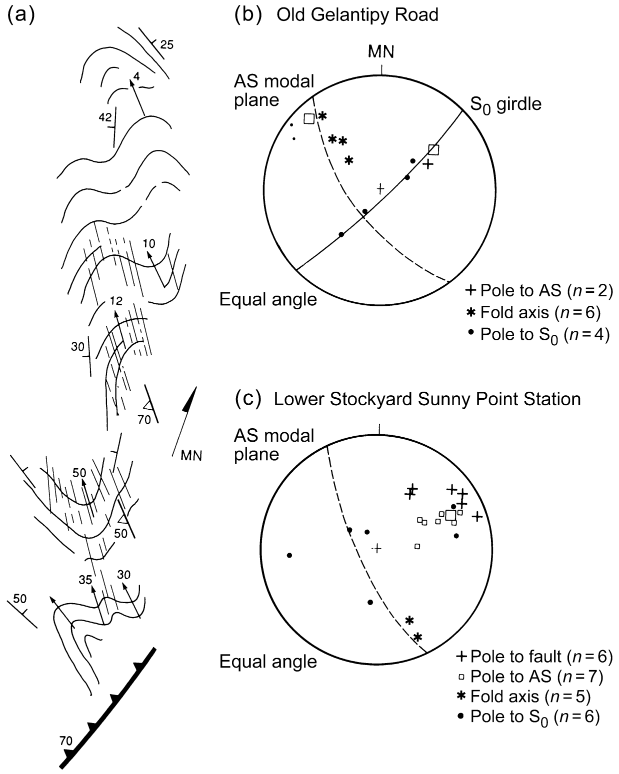


Figure 9 Structural data for the central segment of the Emu Egg Fault in the Murrindal Synclinorium. (a) Structural map of the exposed bedrock where the Emu Egg Fault crosses the old Gelantipy coach track (GR 038542): see Figure 2 for location. (b) Stereonet showing orientation data for the exposure in part (a). (c) Stereonet showing orientation data for the exposure at the Lower Stockyard, Sunny Point Station (GR 038534).

The southernmost fault, referred to as the East Buchan Thrust (Teichert & Talent 1958), has a moderate to gentle east dip (Figures 10a, 11c, d). Folds in the footwall limestones have either kink-like or box-like form (Figure 11c). These folds are oblique to the fault and have associated north-trending more steeply dipping faults (Figure 10b, c). The dip on the northernmost fault changes along its length (Figure 10a). It has a gentle east dip in the cliff exposures south of the Buchan River near the Orbost road bridge (Figures 11c, 12), a steep dip (~70°) where it crosses the Orbost road (Figure 11b), is inferred to have subvertical dip on the ridge between the Murrindal and Buchan Rivers (westernmost fault, Figure 11a), and gentle west dip at the top of the isolated limestone just north of the Basin Road bridge over the Murrindal River. The northern terminations of both faults have not been mapped into the Snowy River Volcanics, although Orth *et al.* (1993, 1995) showed the East Buchan Thrust changing to a more northeast strike and dying out in the Snowy River Volcanics.

Cross-faults

Cross-faults, although not generally exposed, locally offset the stratigraphy (Figure 2). Physiographically, they are reflected by either marked change in stream/river orientation or abrupt terminations and/or offset of ridges. They appear to be subvertical west-northwest-trending strike-slip faults with displacements on the order of 50–100 m. On the western side of the synclinorium, these west-north-west-trending faults have sinistral (left-lateral) displacement sense and apparent strike-lengths on the order of 500 m to 1 km. On the eastern side of the synclinorium, cross-faults trend east-northeast and appear to have dextral (right-lateral) strike-slip displacement.

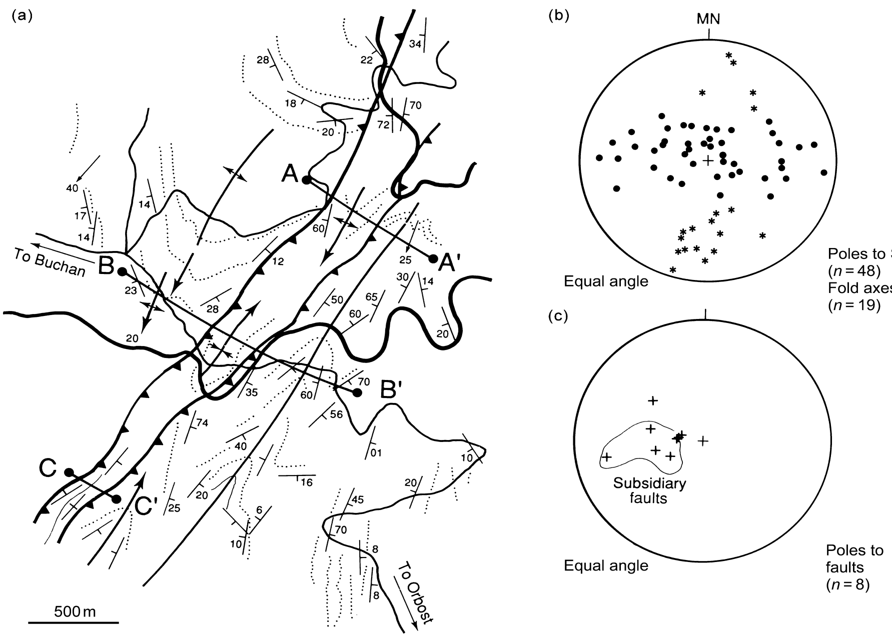


Figure 10 Map and orientation data for the southeastern part of the Murrindal Synclinorium (see Figure 2 for location of mapped area). (a) Structural map showing fault traces (heavy barbed lines), fold axial surface traces, bedding attitudes and bedding form lines (see Figure 11 for section profiles). (b) Poles to bedding and fold axis orientations for the mapped area. (c) Fault orientation data for the mapped area.

DISCUSSION

North-trending structures are predominant in the Murrindal Synclinorium, but northeast trends dominate the southeastern portion. Partitioning of the deformation into north-trending (Emu Egg, Carson Creel and Gillingal Faults) and northeast-trending structures (Yalmy–McLauchlan, New Guinea and East Buchan Faults) is controlled at the regional scale (Orth *et al.* 1993, 1995; VandenBerg *et al.* 2000). However, a general lack of fold-interference patterns suggests that folding and fold orientation are controlled by the local fault systems.

The overall rigid behaviour of the Snowy River Volcanics on the regional scale, reflected by major faults and fracture zones and a lack of minor folding (VandenBerg & Allen 1988), suggests little basement involvement in the regional folding event, although gross layering in the volcanics is folded in places (Figure 1 southeast corner). This either requires detachment between the volcanics and the overlying stratified carbonate–mudstone sequence (thrust model) or activation of old basement faults and former basin-forming extensional faults (fault inversion model). On the southeastern side of the synclinorium, hangingwall/footwall relationships suggest detachment near the base of the Buchan Caves Limestone: lithic sandstone stratigraphically below the limestone occurs in the hangingwall on both faults (Figure 11a, b).

However, the regional nature of the faults is somewhat problematic. Their steep nature (>70°) and dip reversals are not typical of reverse faults, and are more characteristic of extensional fault regimes (Warme 1988; Chantraprasert *et al.* 2001). The fault pattern involving the dip changes has distinct similarities to extensional fault patterns in rift basins. However, footwall and hangingwall stratigraphic relationships require reverse dip-slip movement components, without significant (<10 km) strike-slip movement. There are no major lateral offsets in geological contacts along the presently exposed fault traces (Orth *et al.* 1993, 1995), but obliquity of minor folds to the Emu Egg Fault (Figure 9) and to the East Buchan Thrust (Figure 10b) suggests a component of dextral shear displacement along these faults at some stage in their development. The dip-direction change along the major faults requires greater explanation.

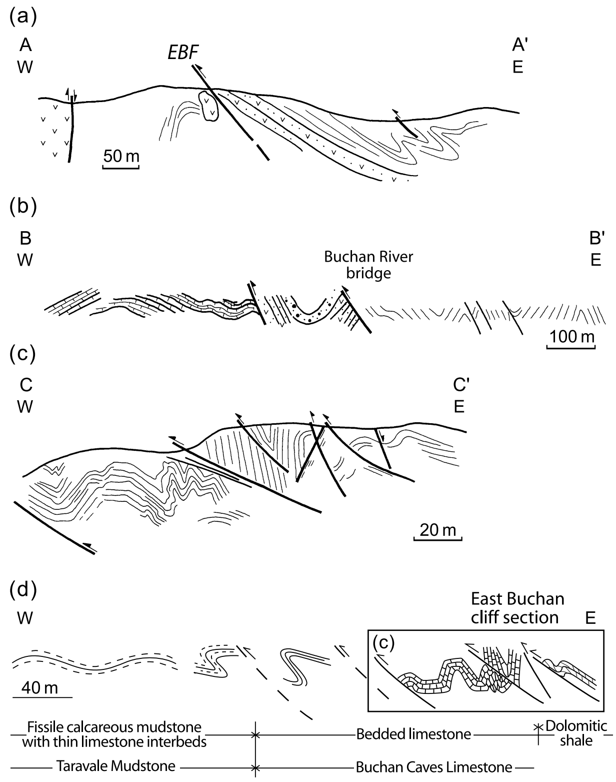


Figure 11 Structural geometry of the East Buchan faults (see Figure 10 for location). (a) Profile A–A′, hillside above the Murrindal River, Buchan East (GR 082489). (b) Composite profile B–B′ based on road exposures along the Orbost Road near the Buchan River bridge, Buchan East (GR 077483). (c) Profile C–C′ showing fold and fault relationships in a the vicinity of the East Buchan Thrust locality (GR 075477): see Figures 11d and 12. (d) Hillside exposure south of the Buchan River bridge, Buchan East, including profile segment shown in part (c).

Figure 12 Exposure of the East Buchan Thrust (type locality) in hillside south of the Buchan River Bridge, East Buchan (GR 075477). View looking south. Students in upper left of photograph provide a scale.

Extensional-fault patterns: the template

Extensional fault patterns in rift basins provide a template for the unusual fault geometry preserved in the Murrindal Synclinorium. Extensional faults in rift basins are generally characterised by a series of isolated fault traces (Figure 13) that show localised regions where faults have opposed dips (i.e. faults have similar strikes but opposite dip directions). Extensional fault arrays also contain collinear, along-strike faults that have opposed dips (see locations 1–3 in Figure 13). Subsequent contractional deformation causes shortening in the rift sequence and reactivation of the early extensional faults within the basement.

With increased displacement, these now reverse faults propagate laterally to join adjacent fault segments. Cover sequences might exhibit linking anticlines (see location b in Figure 13b) that accommodate the shortening between the individual fault structures (former extensional faults). Folding of the cover and basement (Figure 14a, b) can steepen the former extensional faults and also cause rotation of the early extensional faults into flat positions to a thrust-like geometry (e.g. Talaat n Yacoub basin, High Atlas, Morocco: Petit & Beauchamp 1986 figure 6). Broad synclinal form, not unlike that of the Murrindal Synclinorium (Figure 3), can develop with shortening in both the rift sequence (folding) and basement (fault reactivation combined with rotation of locked faults due to homogeneous shortening). The key elements are low-percentage shortening and partial activation of the existing extensional faults. The net result is a broad synclinal warp in the rift sequence cut by small displacement reverse faults (Figure 14a).

In this scenario, the north-trending faults originally reflect east–west pullapart attendant with the silicic volcanism of the Lower Devonian Snowy River Volcanics. Parallelism of the East Buchan Thrust with the Yalmy Fault system (Figure 1) of Late Silurian age (VandenBerg *et al.* 2000) is perhaps more than just coincidence. It is likely that the pre-existing basement structure here has influenced the Buchan rift basin extensional fault array, not unlike that inferred for parts of the Otway Basin (see northern part of Figure 13a). These faults and the observed fold–fault relationships now have classic thrust-belt geometry (Mitra & Wojtal 1988), although the western fault (Figure 10) shows a dip reversal along its northern trace suggesting a more complicated origin than that of simple thrusting.

Basin inversion (Buchanan & Buchanan 1995), resulting from reactivation of normal faults as high-angle reverse faults, is commonly inferred by facies and/or thickness changes across these steeply dipping reverse faults (O'Dea *et al.* 1997; Betts 1999; (for the Mt Isa Inlier); Flöttmann *et al.* 1994 (for the Adelaide Fold Belt)) but such relationships have not been readily observed in the Buchan Group sequence (Orth *et al.* 1989).

Fault development model

The geometry of the major faults of the Murrindal Synclinorium is represented in Figure 15. Steep fault segments are interpreted to have developed by coalescing of the separate former extensional faults with similar strikes but opposed dips. With inversion, as the reverse-fault displacement increases, the faults propagate laterally through zones of folding (Elliot 1976; House & Gray 1982; Simon & Gray 1982) to eventually coalesce. The resultant geometry is a steep-connecting fault with low to zero displacement that preserves the fold shortening in both the footwall and hangingwall. Such geometry necessitates a scissors-type rotational motion in the fault plane, with fault hangingwalls essentially pivoting about the segments that now have vertical dips. This is a consequence of the decrease in displacement towards these segments.

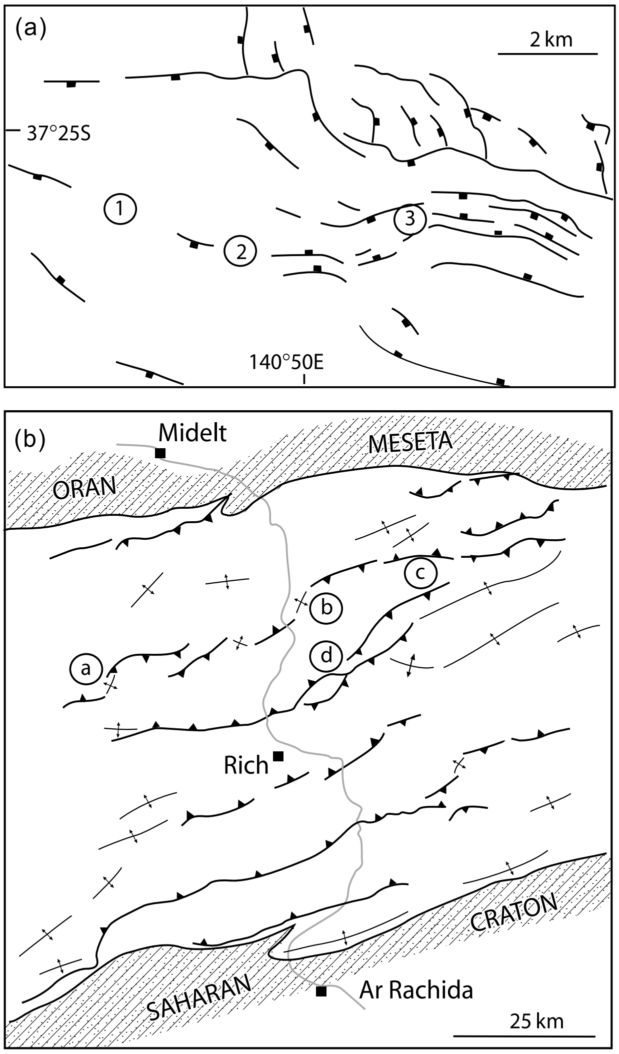


Figure 13 (a) Extensional fault network in the Penola Sub-basin of the Otway Basin, southwest Victoria, Australia (modified from Chantraprasert *et al.* 2001 figure 5). Positions 1, 2 and 3 are segments of co-linear extensional faults that could potentially join on thrust reactivation (fault inversion). (b) 'Inverted' former extensional fault network in the High Atlas of Morocco (modified from Warme 1988 figure 3). Positions a and b show offset fault traces with opposing dips linked by anticlines (oblique orientations with respect to fault traces). Position c shows segments as illustrated in part (a) where co-linear faults could link to form a continuous fault trace as shown at position d.

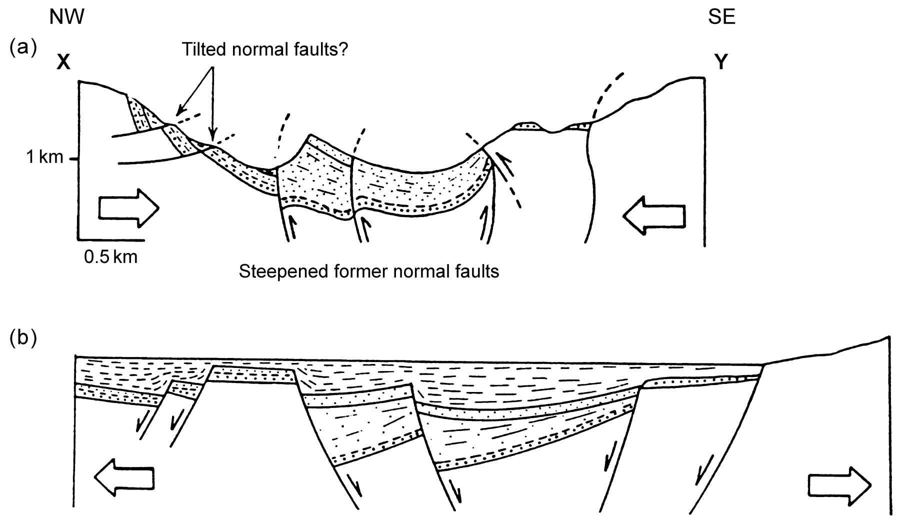


Figure 14 (a) Section across the Talaat n Yacoub basin, High Atlas, Morocco (from Petit & Beauchamp 1986 figure 6) showing a broad synclinal form not unlike the Murrindal Synclinorium with shortening in the rift sequence and some rotation or tilting of former extensional faults on the limbs. (b) Restored or underformed section shown in part (a).

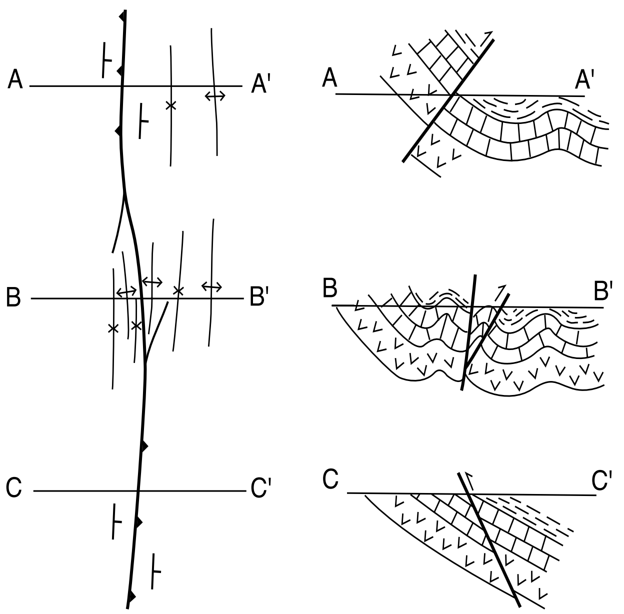


Figure 15 Schematic map and sections (structural profiles) of the link zone between oppositely dipping segments of a now-reverse-fault system. Relationships are based on structural observations along the southern portion of the Emu Egg Fault (Figures 6, 7) and the East Buchan Thrust (Figures 10, 11).

CONCLUSIONS

Low-displacement reverse faults that show dip reversals along their strike lengths are inverted extensional faults. This unusual fault geometry is typical of major faults in the Murrindal Synclinorium of eastern Victoria. They are supporting evidence for regional-scale, Early Devonian lithospheric extension of the amalgamated Central and Eastern Lachlan Orogen (see Gray 1997 figure 18). Silicic volcanism and the recognition of other rift basin elements (Dadd 1994; Giordano & Cas 2001), as well as marked granitic plutonism (Collins 2001), suggest that all of this activity was part of a basin-and-range-style lithospheric extension (Cas 1983; Zen 1996). The extension might have been associated with a post-Late Devonian Cordilleran (Andean) -style Gondwana margin affected by rollback along the outboard subduction zone (Powell 1983; Foster & Gray 2000; Collins 2001).

ACKNOWLEDGEMENTS

This research was undertaken as part of Monash University Second and Third Year Field Mapping Camps in the Buchan area from 1984 to 1989. The writing of the manuscript was done while the first author was under the tenure of an Australian Professorial Fellowship (ARC Discovery Grant DP0210178). The authors acknowledge discussions with Ray Cas, Ian Nicholls and the numerous demonstrators who were involved in the camp in those years. We thank the people of Buchan for providing access to their land and putting up with the inconveniences caused by having university students involved with geological mapping in the Buchan area.

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Received 20 January 2003; accepted 29 April 2003