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Middle Palaeozoic thrusting in the eastern Lachlan Fold Belt, southeastern Australia

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Abstract—Early to Middle Palaeozoic clastic and volcanic strata in the Goulburn–Bungonia region, 150 km southwest of Sydney, are divided by the N-trending Yarralaw Fault into two domains. In the western domain major E–W shortening formed folds, axial-planar cleavage and W-dipping contraction faults in all pre-Upper Devonian units. This deformation formed an anticlinorium cored by a W-dipping thrust system with an overturned E-younging limb. In the eastern domain upright flattened chevron folds occur in Ordovician strata with stratal repetition along steep contraction faults spaced at intervals of 1 km or less. Zones of tectonic mélange occur in the hangingwalls of these faults and have a well-developed scaly fabric, with a steeply plunging striation, overprinting a bedding-parallel cleavage in mudstone. In interbedded Silurian shale and limestone a classical stair-step trajectory is recognized for the Frome Hill Fault which duplicates the succession and has undergone back-rotation to its present steep dip. Overall, thrusting progressed from east to west with deformation in the eastern domain pre-dating intrusion of the Early Devonian Marulan Batholith, whereas farther west deformation continued into the Middle Devonian. The folds and thrusts in the Goulburn–Bungonia region are part of a major fold-thrust zone that extends throughout the eastern Lachlan Fold Belt, and which was formed in the Middle Silurian to Middle Devonian during a period of plate convergence between Gondwana and the palaeo-Pacific Ocean. The fold-thrust zone is inferred to have an arc-frontal arc setting above a W-dipping subduction zone, and the deformation relates to underthrusting of an allochthonous terrane with major shortening in the hangingwall block.

INTRODUCTION

THRUSTING is widely recognized in many orogenic belts but has only recently been considered as a major process in the evolution of the Lachlan Fold Belt (LFB) (e.g. Glen & VandenBerg 1987) in southeastern Australia (Fig. 1). In this paper we describe and discuss the implications of thrusts and related structures, in the Goulburn–Bungonia region (Fig. 2), which are part of a zone of folds and imbricate thrusts (defined herein as the Bungonia–Delegate fold-thrust zone—BDFTZ) that occupies the eastern part of the LFB. We relate development of the fold-thrust zone to convergence in an arc–frontal arc region undergoing compression due to underthrusting of a continental fragment from the east (cf. Glen & VandenBerg 1985, Scheibner 1985, 1987).

REGIONAL SETTING

The LFB (Fig. 1) is an enigmatic feature with a unique orogenic history related to complex interactions between Gondwana and the adjoining palaeo-Pacific Ocean. The main problem encountered in understanding the tectonics of the LFB is to explain the conversion of the extensive Ordovician continental-margin deep-marine turbidite wedge into a craton by Late Carboniferous time, and how the widespread Middle Silurian to Middle Devonian silicic magmatism and convergence relates to this process. Cas (1983) and Powell (1984) have adopted a classic palaeogeographic approach to solve the problem.

The Ordovician palaeography of the LFB was thought to consist of: (1) a western continental margin; (2) a wide central zone of deep-marine quartz turbidites forming continental margin deposits in a marginal sea; (3) an island arc; (4) an accretionary prism with a western fore-arc basin and an eastern subduction complex (Cas *et al.* 1980, Powell 1984). The main problem with this arrangement is that the sedimentary succession in elements (2) and (4) is much the same and there is no evidence for a volcanic source in either the back-arc or the fore-arc basins. The contact between the island arc and the quartz-rich turbidite succession of the apparently adjoining basins is not a facies interdigitation as would be expected in this setting. The contact is probably faulted, and is a candidate for a terrane boundary. The map trace of the contact is folded by the Carboniferous deformation in the northeastern LFB and the contact has a geometry consistent with a major overthrust with the island arc succession (defined herein as the Parkes Terrane) in the hangingwall block and the continental

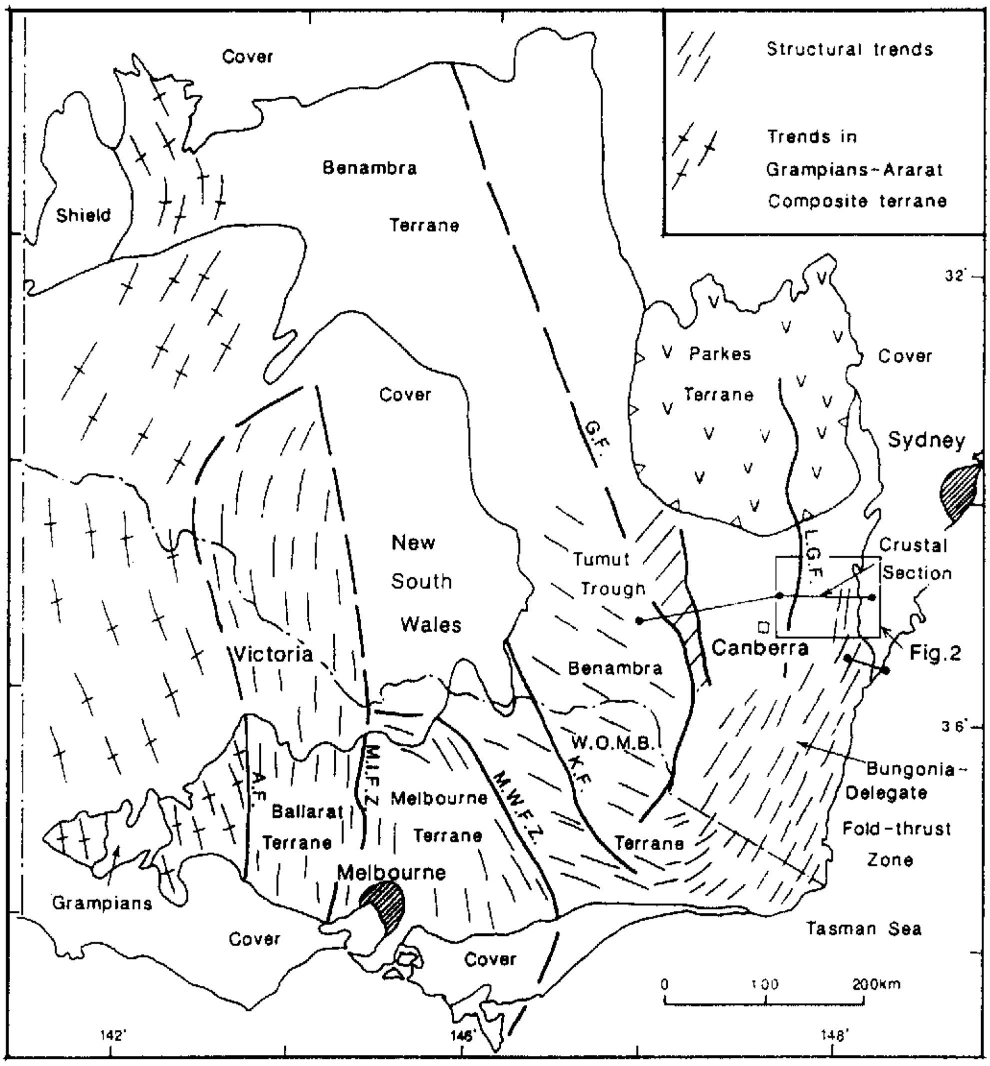

Fig. 1. Tectonostratigraphic terrane map of the Lachlan Fold Belt in southeastern Australia (modified from Fergusson *et al.* 1986). The principal changes to the map of Fergusson *et al.* (1986) are the recognition of a separate Parkes Terrane within the Benambra Terrane and the addition of structural trends interpreted from aeromagnetic data flown over cover rocks in northwestern Victoria and southwestern New South Wales (Brown *et al.* 1988). Major faults: A.F. = Avoca Fault (eastern boundary of the Grampians–Ararat composite terrane), M.I.F.Z. = Mt Ida–McIvor fault zone (eastern boundary of the Ballarat Terrane), M.W.F.Z. = Mt Wellington fault zone (eastern boundary of the Melbourne Terrane), K.F. = Kiewa Fault, G.F. = Gilmore Fault, L.G.F. = Lake George Fault, W.O.M.B. = Wagga–Omeo Metamorphic Belt.

margin turbidite wedge (Benambra Terrane) in the footwall. Amalgamation of the Parkes and Benambra terranes occurred in the Early Silurian Benambran Orogeny which involved significant N–S shortening, overthrusting, dextral strike-slip faulting, and high-*T*–low-*P* metamorphism in the Wagga–Omeo Metamorphic Belt (Fergusson 1987).

In the Middle Silurian to Middle Devonian the Benambra–Parkes composite terrane was undergoing a complex history of sedimentation, plutonism (dominantly granitic) and associated volcanism (Cas 1983). Extension and compression affected the terrane with the latter being most common and of greatest extent. Strike-slip faulting also occurred with major dislocations in the western part of the Benambra Terrane and in the adjoining terranes to the west (Fergusson *et al.* 1986). During the Late Devonian a molasse-type succession overlapped the older terrane assemblage and the entire LFB was affected in the Early Carboniferous by a major episode of E–W compression (Powell 1984).

STRATIGRAPHY

The pre-Permian stratigraphy of the Goulburn–Bungonia region is dominated by three major successions (Fig. 3): Ordovician to Early Silurian turbidites and black shale; Late Silurian to Early Devonian mixed sedimentary and volcanic units with associated intrusives; and Late Devonian quartzose clastics (Creaser 1973, Carr *et al.* 1981). East of the Yarralaw Fault the Ordovician succession is overlain with a low-angle unconformity by the Late Silurian to Early Devonian succession (Fig. 3). This consists of basal limestone and shale of the Bungonia Limestone overlain conformably by volcaniclastics, quartzose clastics and primary igneous rocks of the Tangerang Formation and Bindook Volcanic Complex. The latter are extensively intruded by plutons of the Early Devonian Marulan Batholith (Carr *et al.* 1980). West of the Yarralaw Fault, Early Silurian shale has an unknown, probably faulted, relationship with Late Silurian quartz-rich turbidites and

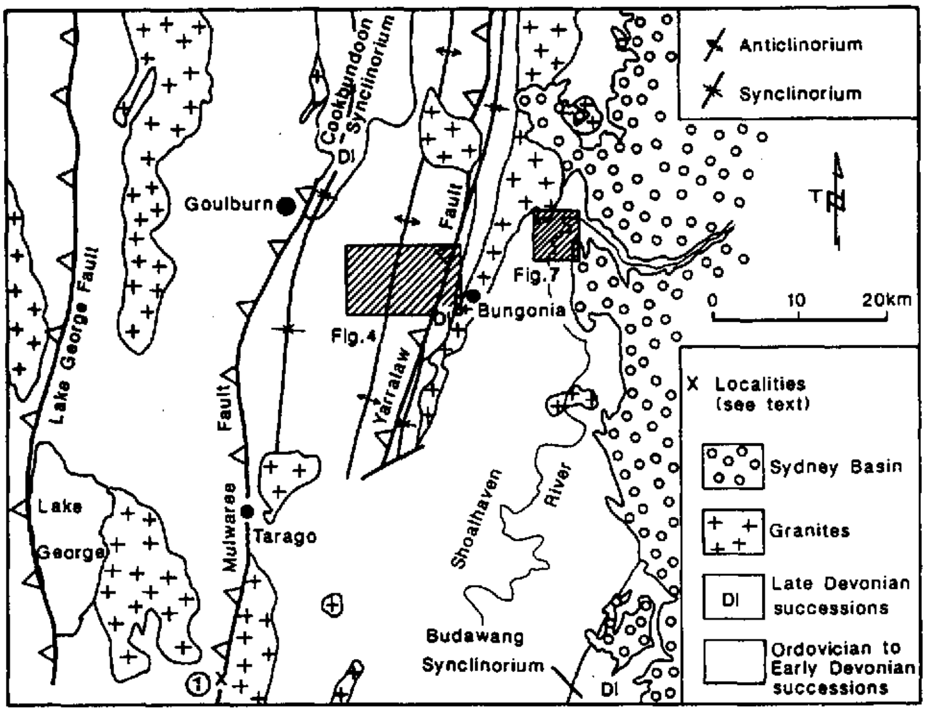

Fig. 2. Regional geology of the northern part of the Bungonia–Delegate fold-thrust zone. The Goulburn–Bungonia region encompasses the northern half of this map and areas mapped in detail are shown in Figs. 4 and 7. The Yarralaw Fault divides this region into two structural domains described in the text.

some limestone of the Wollondilly beds (Naylor 1950, Creaser 1973). Farther west again, the Ordovician succession is faulted against a lithologically similar Late Silurian succession called the Towrang beds by Creaser (1973). These are faulted against the Emsian Murrays Flats beds, containing intermediate to silicic volcaniclastics and volcanics (Creaser 1973), to the west. Early Devonian volcanic and volcaniclastic units are angularly unconformably overlain by gently dipping Late Devonian shallow marine strata of the Lambie Group. The poor exposure along the contact and the scarcity of bedding in the underlying units has prevented resolution of the angularity of this unconformity.

STRUCTURE

The Yarralaw Fault (Fig. 2) separates the Goulburn–Bungonia region into two structural domains. Strata on either side of the fault dip to the west and Late Silurian rocks are interpreted as thrust over Early and Late Devonian successions indicating at least some movement in the Carboniferous deformation.

Domain west of the Yarralaw Fault

Naylor (1950) recognized that the structure of this domain consists of an anticlinorium (Figs. 4 and 5). The core of the anticlinorium consists of well-cleaved Ordovician rocks containing abundant mesoscopic folds. Mesoscopic folds in the Ordovician and Silurian successions are typically tight to close with angular hinges and are gently plunging with some steeper plunges and even reclined folds, especially in areas of intense cleavage development, and reflect rotation of folds in zones of higher strain (Ramsay 1979). Many mesoscopic folds have contraction faults along their axial planes. A gently to steeply W-dipping slaty cleavage in mudstones, and a less intense spaced cleavage in sandstones, is developed in the Ordovician and Silurian successions throughout this domain (Figs. 4 and 5). In the Devonian Murrays Flats beds cleavage is developed in zones separated by poorly cleaved or uncleaved rock.

Exposure is too restricted to map out most of the thrusts thought to occur throughout the domain, but one major fault zone is exposed in a roadcut at locality M on Fig. 4. Bedding has been obliterated throughout the exposure and the rock is a tectonic mélange (30 m thick) with pods of quartz sandstone contained in a matrix of scaly mudstone (Fig. 6a). The scaly fabric in the matrix consists of polished fragments (1–5 mm) of cleaved mudstone with quartz slickenfibres. The pods of sandstone have pinched terminations indicative of ductile extension and formation of pinch-and-swell structure prior to their disruption into separate pods. The rock has formed by brittle shearing of previously cleaved mudstone accompanied by ductile deformation of folded sandstone beds in a steep W-dipping fault zone that occurs on the eastern side of the anticlinorium shown in Figs. 4 and 5.

The association of faults and major fold structures shown in Figs. 4 and 5 is characteristic of fold-thrust zones as shown by cross-sections of the southern Canadian Rocky Mountains (Price 1981). Another feature consistent with a thrust interpretation is the many changes that occur at the small-scale in the orientation of

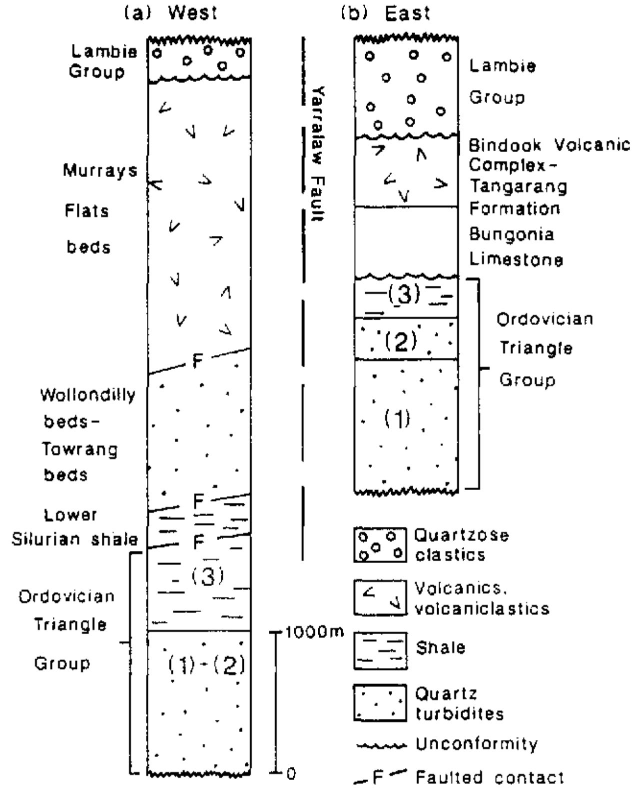

Fig. 3. Stratigraphic columns for the structural domains (a) to the west and (b) to the east of the Yarralaw Fault in the Goulburn–Bungonia region. The Ordovician Triangle Group consists of three units. (1) A thick basal unit containing monotonous predominantly thick-bedded (50 cm–2 m) turbidites with less abundant thin-bedded (<50 cm) turbidites, amalgamated sandstones, mudstones and thin-bedded cherts. (2) A relatively thin interval (probably only 200–300 m) with a monotonous succession of thin-bedded turbidites (stripy facies) with abundant thick-bedded turbidites near the top of the unit. (3) The highest unit consists of approximately 300 m of black shale, siliceous mudstone and some turbiditic sandstone beds. Interbedded sandstone and mudstone, mainly thick-bedded turbidites, form an 80 m thick interval near the base of some sections bracketed between Upper Gisbornian and Eastonian black shales. A complete graptolite succession exists from the Upper Gisbornian (Gi), through Eastonian zones Ea1–Ea4, into the Lower Bolindian (Bo), giving the only reliable indication of age for the Triangle Group.

cleavage and axial planes, especially in dip (Fig. 4). Orientations of these features reflect strain variations in thrust sheets, with upright structures at higher levels and gently dipping, and more highly strained, features at the lower levels in thrust sheets (Sanderson 1979, 1982, Gibson & Gray 1985). The changes in dip of cleavage are most pronounced in the Triangle Group where the cleavage is also better developed.

Strata of the Towrang beds are folded about close folds with a steeply dipping axial plane cleavage (Figs. 4 and 5). Fold shapes are either m-type or they verge to the west, in exposures with homoclinal strata the bedding–cleavage relationships indicate vergence to the west (Fig. 5). These relationships are anomalous as they indicate that the Towrang beds underlie the older Triangle Group. They could result from either compression of a pre-existing system of W-dipping listric normal faults or from backthrusting along an E-dipping fault. The contact between the Murrays Flats beds and the Towrang beds also appears faulted and with a similar geometry to the Towrang beds–Triangle Group contact.

In the Tarago district (Fig. 2) Henry (1975) has mapped a regionally extensive W-dipping slaty cleavage which has been traced to the Goulburn–Bungonia region. Henry also attributed this structure to thrusting and identified low-angle thrusts. Farther south the Mulwaree Fault (Fig. 2, locality 1) consists of highly fractured and sheared fine-grained igneous rocks with a moderate W-dipping shear fabric and small E-verging open kinks which indicate thrust motion along the fault (Fig. 6b). In both the Goulburn–Bungonia region and the Tarago district (Fig. 2) rock units as young as Emsian (Creaser 1973, Henry 1975) are involved in the thrust-related deformation and this shows that the deformation extended into the Middle Devonian.

Domain east of the Yarralaw Fault

To the east of the Yarralaw Fault in the Shoalhaven River area (Fig. 7) the lithological distribution, and most significantly the graptolite ages, indicate that there is substantial fault repetition of the Ordovician Triangle Group. The principal marker unit is the Upper Gisbornian to Lower Bolindian black shale (unit 3) that forms mappable fault slivers throughout the area. Faulted contacts were observed along some black shale contacts and are inferred along others from the graptolite ages.

Strata are typically steeply dipping (>70°) as are the axial planes of most minor folds, all major folds and all the main strike-parallel faults. All structures trend to the NNE and the folds all plunge less than 20° or so (Fig. 7). Folds are angular with narrow hinge zones except in the thickest bedded parts of the succession and have a chevron to flattened chevron style. An axial-planar cleavage is rarely developed, and where found is a crenulation cleavage in mudstones superimposed on a common bedding-parallel cleavage. Within many of the fault slices, where a sense of vergence is discernible, it is typically to the east (Figs. 8–10).

The Frome Hill Fault repeats the Bungonia Limestone (Figs. 7 and 8, cross-section U–V) and is marked by a narrow crush zone with several metres of strongly recrystallized limestone above the fault. In the Triangle Group the major faults all occur along the western sides of the black shale slices and are typically vertical (Figs. 7–10). Many of the black shale slices have steeply dipping eastern faulted contacts that cut out some of the stratigraphic succession and are therefore extensional; but their offset is always substantially less than the faults along the western contacts.

Most of the faults in the Triangle Group are marked by relatively narrow zones of gouge and sheared rock. The most spectacular example occurs in the hangingwall of the fault at locality 3 (Fig. 7) where there is a zone of tectonic mélange up to 100 m in width. The mélange structure is best observed in the mudstone-rich part of the exposure where there are many fault-terminated fragments of quartz sandstone beds with well-preserved sedimentary structures (Fig. 11a). The matrix consists of scaly fabric superimposed on the bedding-parallel cleavage with steeply pitching striations (Figs. 11a and 12a).

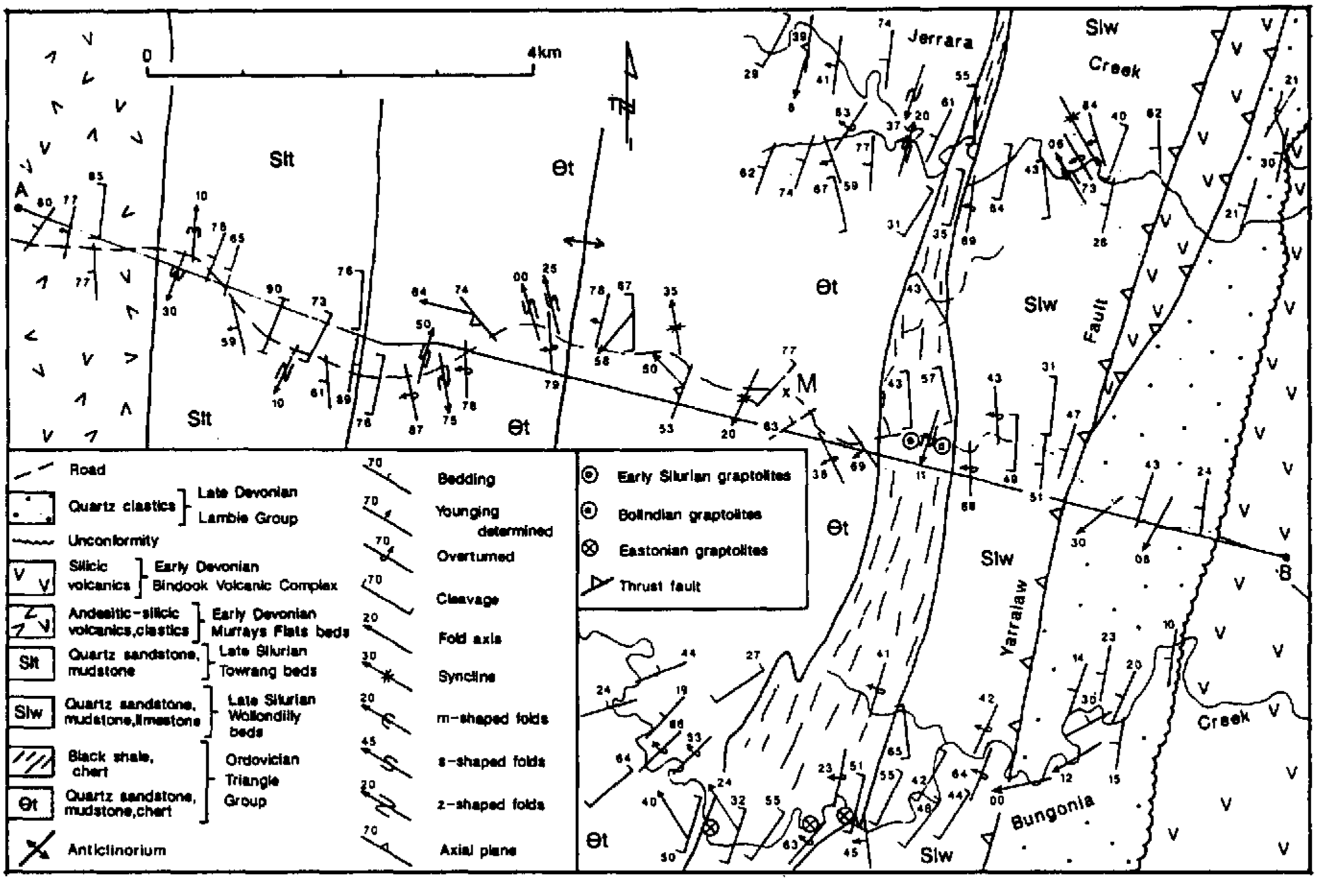

Fig. 4. Map of part of the domain to the west of the Yarralaw Fault (see Fig. 2 for location). The major structure is an anticlinorium cored by the Ordovician Triangle Group (Ot) and containing a major fault marked by a zone of tectonic mélange on its eastern limb (locality M, see text). The core of a synclinorium, which in Fig. 2 occurs in the Lambie Group, is sheared off by the Yarralaw Fault. The location of section A–B, shown in Fig. 5, is indicated.

Boudins show a common sense of asymmetry with clockwise rotated fragments along shears that have a sinistral offset and have the correct orientation for Riedel shears at a low-angle to the shear fabric. Some relatively smaller boudins show anticlockwise rotation along dextral shears at high-angle to the shear fabric and may represent conjugate Riedel shears (Fig. 12a). The overall motion is sinistral oblique-slip, although the inferred slip direction from the orientation of shears is shallower than the striations in the scaly mudstone. Mélanges occur 1 km due east on the Shoalhaven River and contain excellent shear-sense criteria, such as rotated stepped beds, asymmetric boudins and shear bands, that indicate dextral strike-slip motion along the shear fabric (Figs. 11c & d).

A late cross-cutting fault system clearly post-dates the main E-verging imbricate fault system. These are best exposed south of the Shoalhaven River–Bungonia Creek junction where there are three main sinistral strike-slip faults with displacements of the order of 50 m. Both sinistral and dextral faults occur, all typically with subhorizontal quartz-fibre lineations indicating strike-slip displacements (Fig. 12b). Sense of shear is indicated along these faults by: offset distinctive beds, fault-related flexures and asymmetric boudinage structures (as above these are formed by offset along Riedel shears) found within mélange zones along the faults. Orientations of these faults are consistent with a crude conjugate system (Fig. 12b) with the σ_1 principal stress direction orientated WNW–ESE, that is similar to the compression direction for the main deformation. These late faults only affect the Ordovician succession.

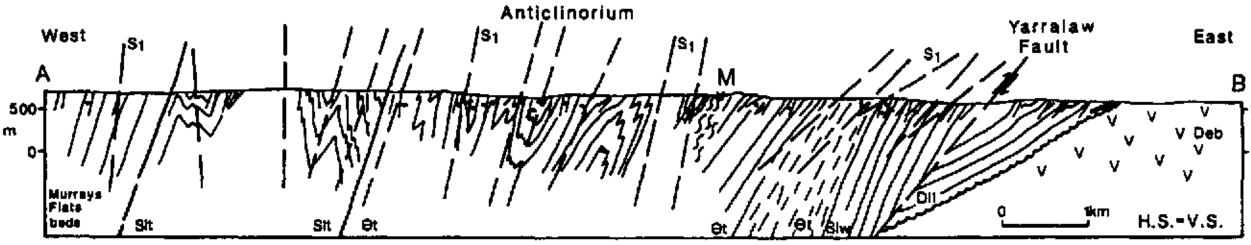

Fig. 5. Cross-section A–B from the domain west of the Yarralaw Fault (see Fig. 4 for location). Dashed lines drawn on the cross-section represent the S_1 cleavage. Note that the Yarralaw Fault thrusts the cleaved Silurian Wollondilly beds (Slw) above the poorly cleaved Late Devonian Lambie Group (Dll) and the Early Devonian Bindook Complex (Deb).

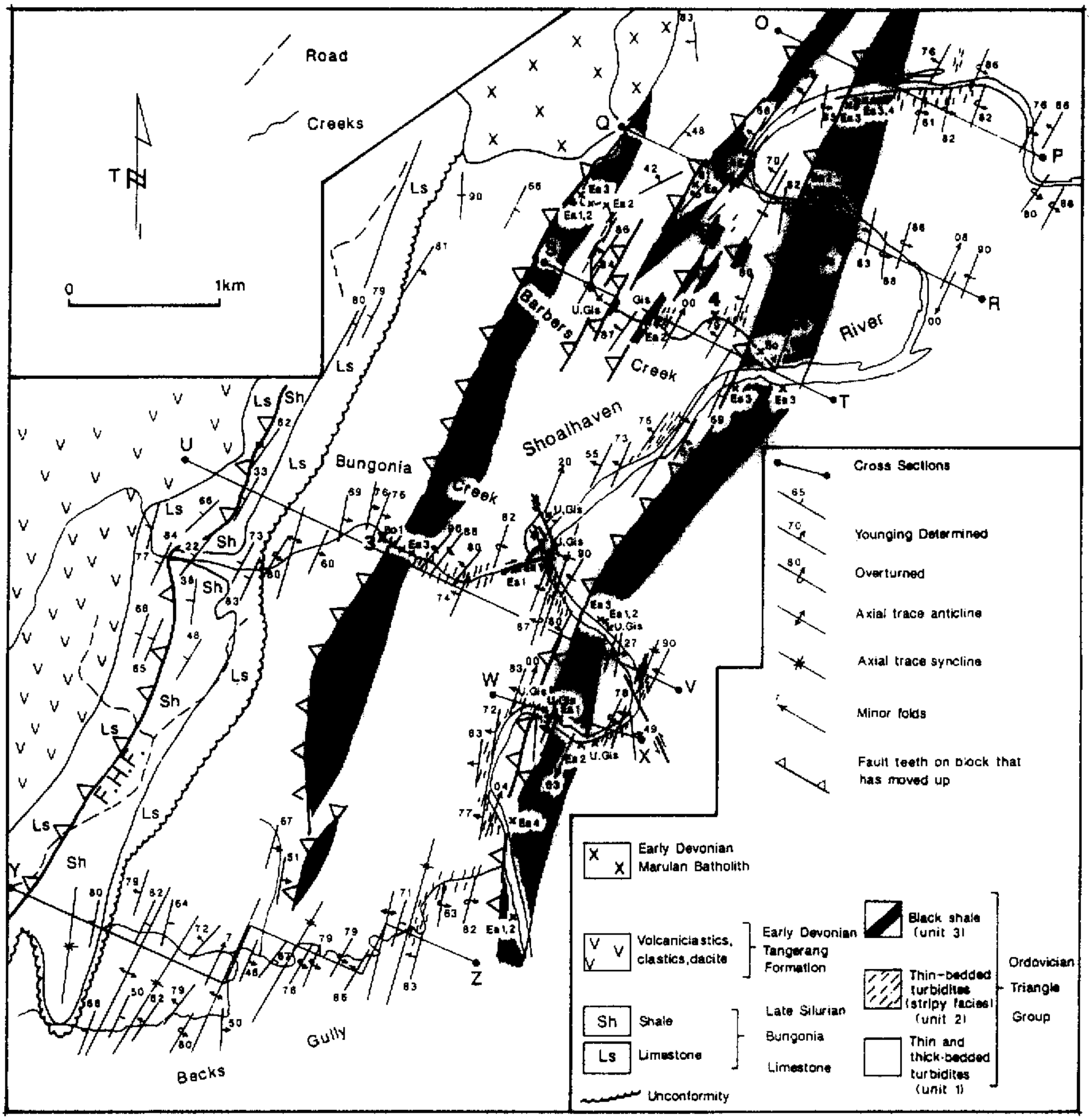

Fig. 7. Map of the Shoalhaven River area east of the Yarralaw Fault (see Fig. 2 for location). F.H.F. = Frome Hill Fault. Note the repetition of the black shale (unit 3) and unit 2 of the Triangle Group along steep contraction faults. The locations of sections shown in Figs. 8–10 are indicated.

The timing of the deformation in the Shoalhaven River area is poorly constrained as it has no associated major break in sedimentation. The minimum age is provided by the Early Devonian Marulan Batholith (Carr *et al.* 1980), which clearly cross-cuts and post-dates all steeply dipping structures in the Bungonia Limestone and the Triangle Group. The contact between these latter two units is a low-angle unconformity probably marking the onset of deformation but most of the deformation must have occurred during the deposition and emplacment of the Lower Devonian Tangerang Formation, of which the upper part is comagmatic with the Marulan Batholith (Carr *et al.* 1980).

Structures in the Lambie Group

The Lambie Group at Goulburn (Fig. 2) is a shallowly dipping to flat-lying succession that forms the eroded keel of the Cookbundoon Syncline. It does not contain the zones of well-developed cleavage that occur in the underlying Murrays Flats beds. East of the Yarralaw Fault near Bungonia there is a strip of gently W-dipping

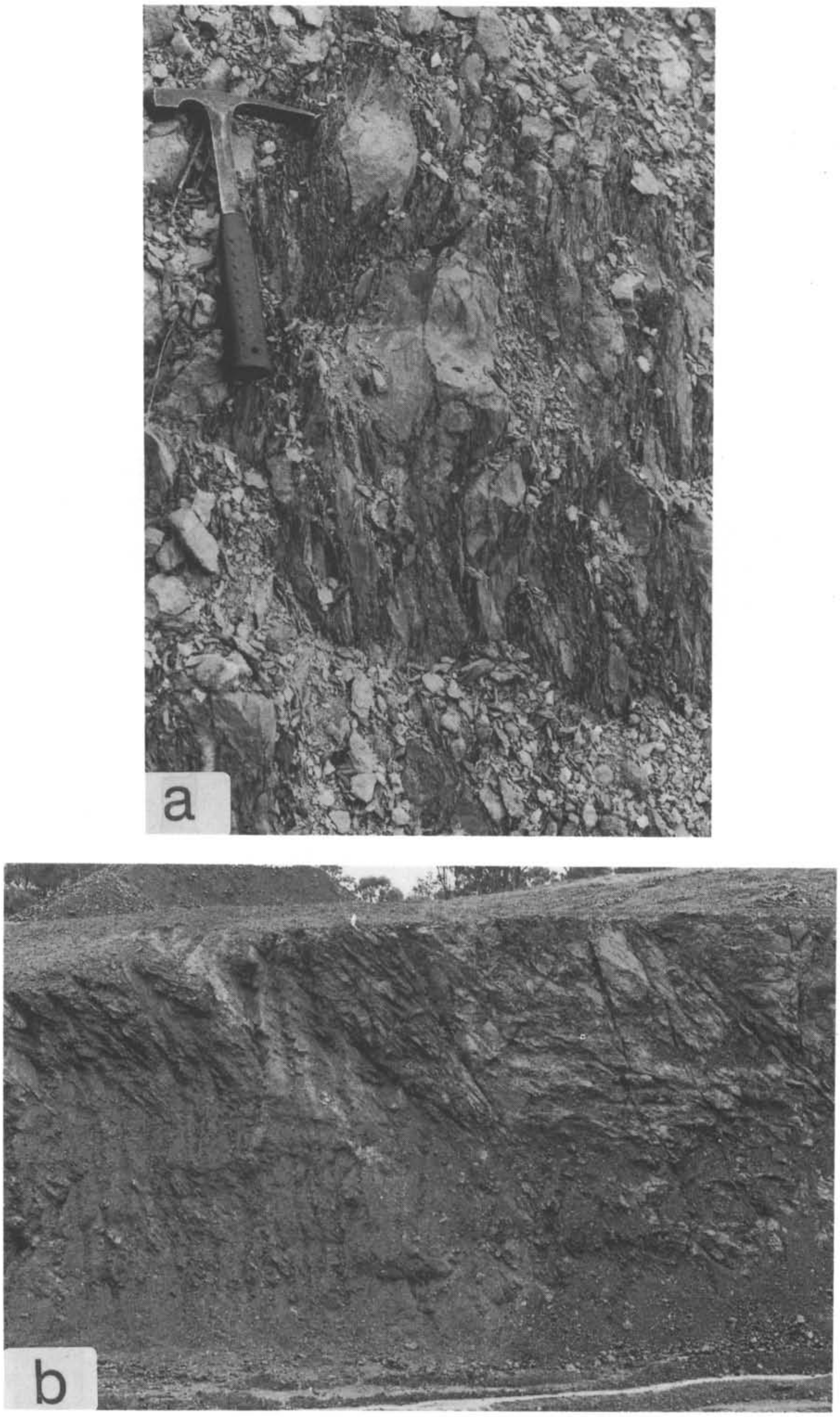

Fig. 6. (a) Tectonic mélange with fragments of sandstone contained in a scaly mudstone matrix from the eastern side of the anticlinorium in Figs. 4 and 5 (locality M). (b) West-dipping shear fabric in igneous rocks along the Mulwaree Fault from locality 1 shown on Fig. 2.

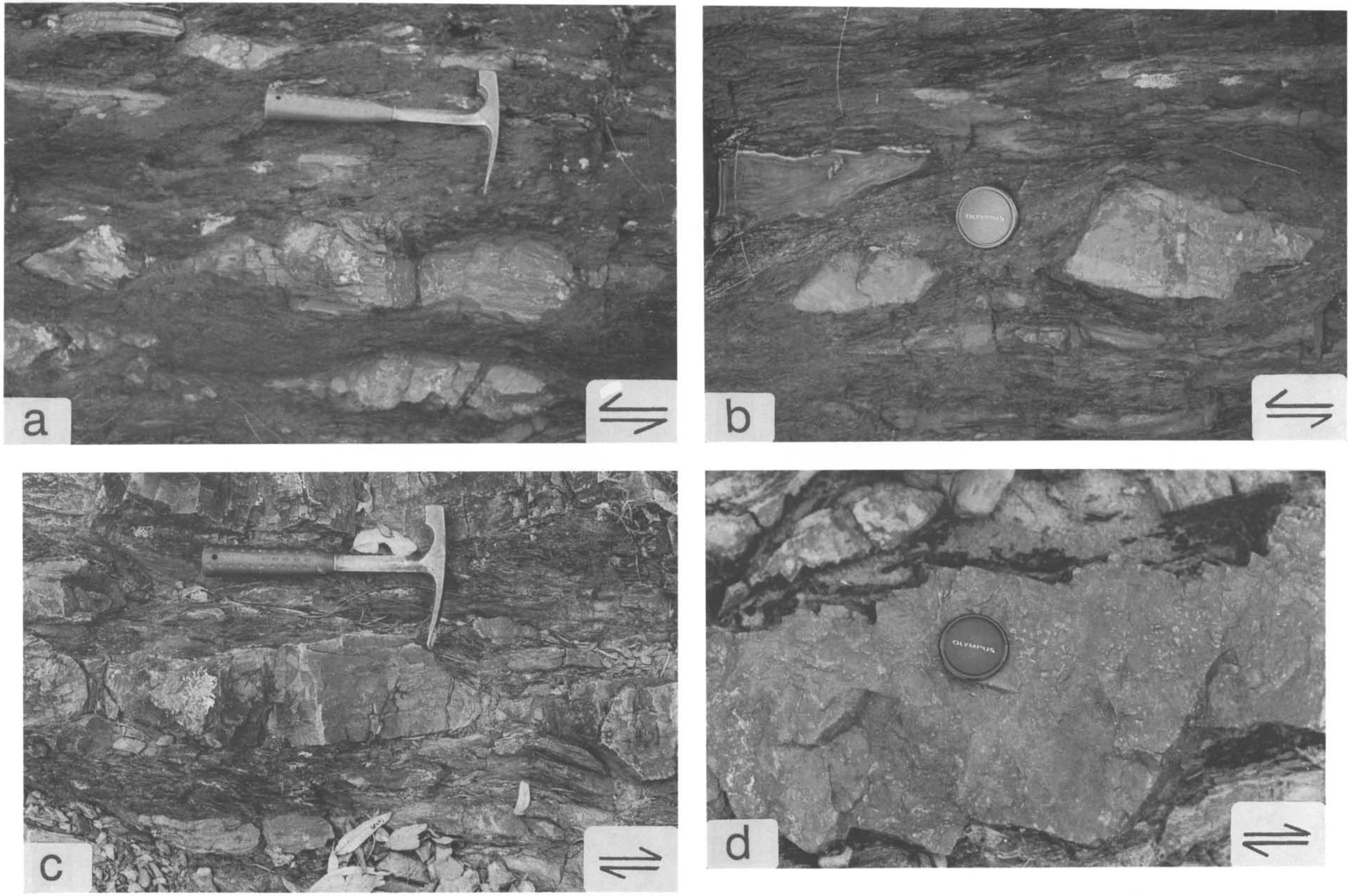

Fig. 11. Structures in the Shoalhaven River area. (a) & (b) Asymmetric boudinage in tectonic mélange from locality 3 (Fig. 7). Note that bedding has rotated clockwise with respect to the orientation of the shear fabric in the mudstone matrix which is parallel to the length of the larger boudins. The asymmetry has formed by rotation along slightly curved sinistral shears which formed as Riedel shears in the main shear zone. (c) Dextral shear bands and associated asymmetric boudinage. (d) Stepped faults in a sandstone boudin indicating overall dextral motion along the shear fabric.

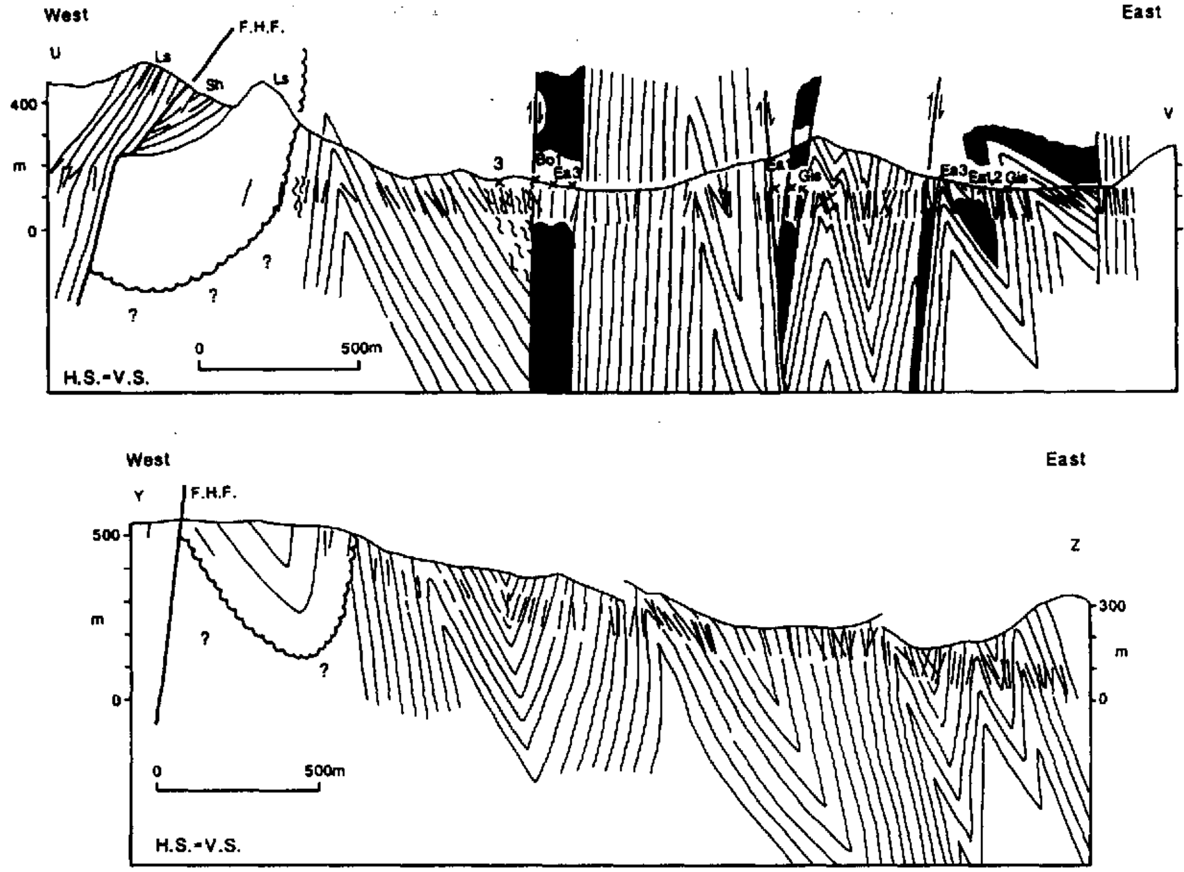

Fig. 8. Cross-sections U–V and Y–Z from the Shoalhaven River area (see Fig. 7 for location). At the western end of cross-section U–V a W-dipping thrust fault (the Frome Hill Fault—F.H.F.) repeats the Bungonia Limestone. At creek level the F.H.F. dips steeply to the west and higher up it flattens to a dip of 50°W and is parallel to bedding in massive limestone above the fault (i.e. a hangingwall flat). In the footwall, shales are cut at a 20–30° angle by the F.H.F. (i.e. a footwall ramp). The first major fault encountered east of the Bungonia Limestone in the Triangle Group is between E-dipping thick-bedded turbidites of unit 1 and steep black shale (unit 3) that youngs to the west from Ea3 to Bo1. Further east two faults repeat the succession. In cross-section Y–Z the black shale (unit 3) is missing and the faults are no longer mappable and as a result the succession appears to have a simply folded upright structure.

strata of the Lambie Group. Strata are usually undeformed with spaced cleavage found in mudstones in the cores of several mesoscopic folds on the Bungonia–Goulburn road (Fig. 4). Mesoscopic and rare macroscopic folds are locally developed. They are broad angular disharmonic structures with steep SW- to WSW-trending axial planes and shallow plunges to the west (Fig. 4). These structures have a style consistent with their origin at a shallow crustal level associated with limited NNE–SSW shortening. These features indicate that the Carboniferous deformation was a relatively mild event in this part of the LFB and anomalous in orientation from normal as this deformation typically reflects E–W compression (Powell 1984).

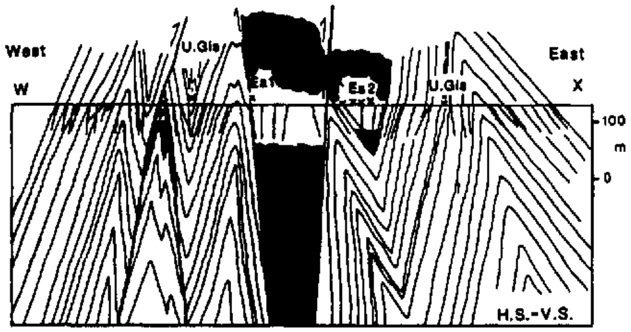

Fig. 9. Cross-section W–X from the Shoalhaven River area (see Fig. 7 for location). This is the best exposed section in the area. The major thrust in the western part of the section has unit 2 with several Z-shaped fold couples in the hangingwall and intensely folded Upper Gisbornian black shale (U. Gis) and underlying turbidites in the footwall. The latter unit has a faulted eastern contact with Eastonian black shales (Ea1).

DISCUSSION

Bungonia–Delegate fold-thrust zone (BDFTZ)

Glen & VandenBerg (1987) have documented thrusting in eastern Victoria east of the Wagga–Omeo Metamorphic Belt (Fig. 1), based on stratal repetition of Early Silurian quartz-rich turbidites and Late Ordovician black shales. Thrusting must have pre-dated intrusion of the cross-cutting granites of Late Silurian to Early Devonian age. Further east in eastern Victoria, Wilson & VandenBerg (1988) described E-verging folds and thrusts that affect Ordovician units and pre-date Late Devonian units.

On the South Coast of New South Wales the structural history outlined by Powell (1983) includes an accretion-

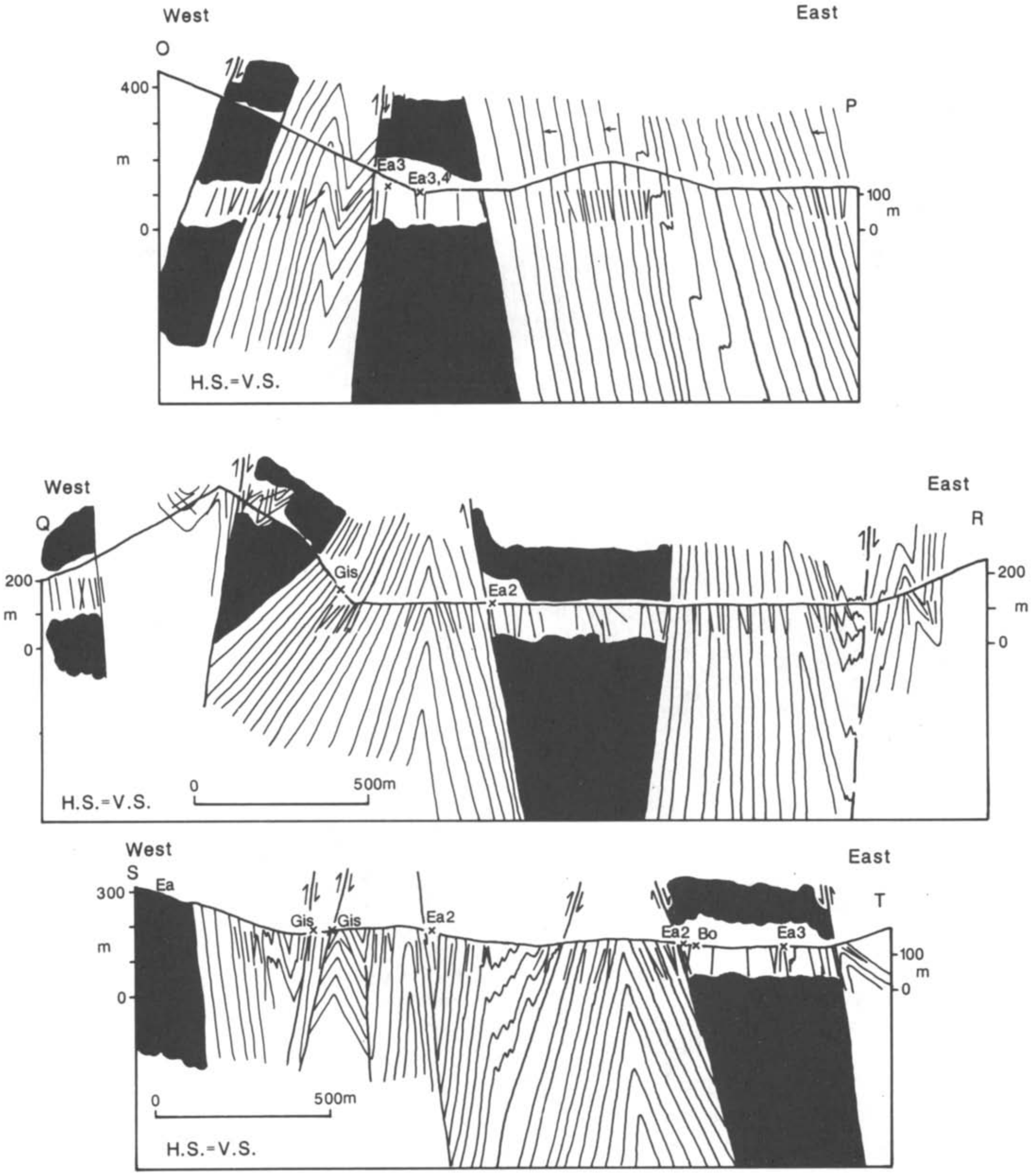

Fig. 10. Cross-sections O–P, Q–R and S–T from the Shoalhaven River area (see Fig. 7 for location). Note that in cross-section S–T there are at least four major contraction faults all with unit 1 in the hangingwall thrust over thin slices of unit 3 in the footwall. In the hangingwall, there are strongly folded zones adjacent to the fault surface with planar strata in the footwall. The major black shale slice at the eastern end of this section has an internally complex structure with stratal repetition and faulted contacts against unit 1. The anticline to the west of this shale slice has different units on either limb and is probably faulted.

ary deformation associated with subduction in the Ordovician followed by regional folding at the end of the Silurian. The Ordovician palaeogeographic scheme is now considered unlikely (see Regional Setting) and the accretionary deformation is discredited and is considered a part of the major end-Silurian deformation. In the Wagonga beds on the New South Wales south coast there are steeply to moderately W-dipping mélanges, with quartz-rich turbidites, bedded cherts and volcanics, that have formed by imbricate thrust faulting and associated disruption. The dominant rocks are the Ordovician quartz-rich turbidites that are everywhere affected by tight to close upright N–S-trending folds. This structural style has been traced westwards into areas where Silurian units are also affected by the same folding—including the Shoalhaven River area. This folding predates Early Devonian granites (Powell 1983, 1984).

We propose that these regions with a Middle Silurian to Middle Devonian history of strong N–S folding, and in some areas documented thrusting, are part of a linear belt of deformation (the Bungonia–Delegate fold-thrust zone—BDFTZ). In most areas the style of this deformation has been assumed to have been controlled by buckling and it has only been in areas with abundant graptolites that the extent of thrust-controlled deformation has been recognized.

In the Canberra region at the western margin of the BDFTZ Silurian units are relatively undeformed whereas they are strongly folded further east in the BDFTZ (Powell 1984). No single feature can be identified as a boundary as occurs in most fold-thrust zones. The northeastern LFB to the west of Sydney (Fig. 1) contains no appreciable deformation of this age and was apparently only strongly deformed in the Carboniferous deformation (Powell 1984). There is an apparent transition between the zone of strong Silurian–Middle Devonian deformation in the south and weak deformation further north (Powell & Fergusson 1979) with no known boundary between the BDFTZ and the northeastern LFB.

Timing of deformation

In the Shoalhaven River area there is a clear paradox as there is no major break in the depositional record marking the timing of the deformation. It is proposed that deformation and sedimentation in the BDFTZ have been synchronous, as occurs in active foreland thrust zones and subduction complexes. Another complication is that magmatism was an active process in the BDFTZ and, in areas where plutonism was abundant, this had a retarding effect on the deformation which generally ceased and continued elsewhere. This is seen in the Goulburn–Bungonia region where deformation east of the Yarralaw Fault ceased with intrusion of the Marulan Batholith whereas it continued until the Middle Devonian to the west.

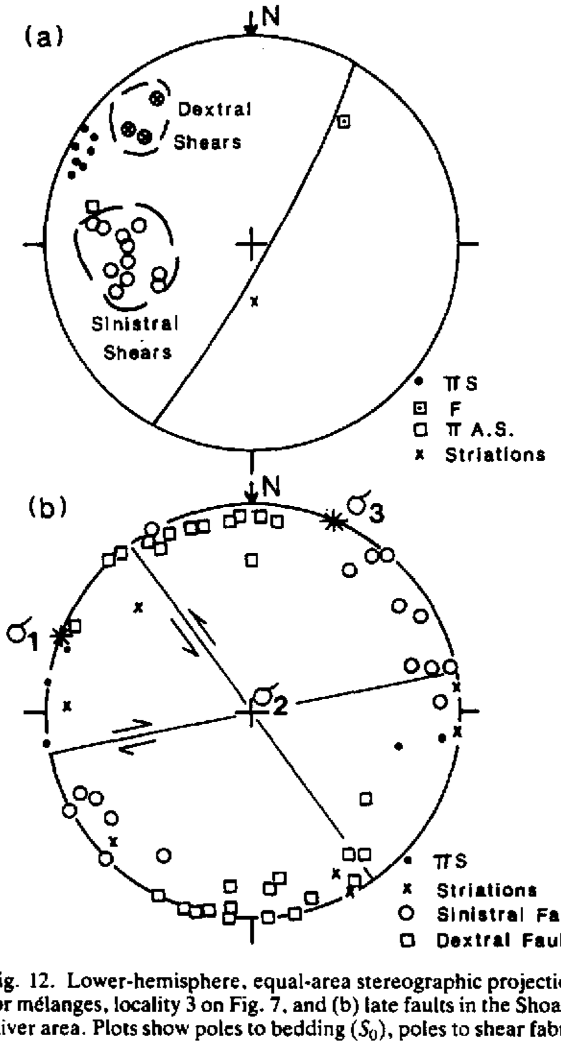

Fig. 12. Lower-hemisphere, equal-area stereographic projections (a) for mélanges, locality 3 on Fig. 7, and (b) late faults in the Shoalhaven River area. Plots show poles to bedding (S_0), poles to shear fabric (S), poles to faults (dextral and sinistral), pole to axial surface of a fold in S (AS), fold axis (F) and striations. Great circle in (a) shows the mean orientation of shear fabric.

Deformation in the BDFTZ must have commenced either in the period of disruption in the Early Silurian following the demise of the Ordovician continental margin sediment wedge or soon after in the Middle Silurian. The low-angle unconformity in the Shoalhaven River area between the Triangle Group and the Bungonia Limestone and between the Akuna Mudstone and Tombong beds at Delegate (Glen & VandenBerg 1987) records ongoing deformation at this time. With the generation of crustally-derived granites in the Late Silurian and most abundantly in the early part of the Early Devonian (Powell 1984) it is clear that the deformation had caused substantial crustal thickening considering that at the end of the Ordovician the crust must have consisted of probable oceanic crust overlain by several kilometres of quartz-rich turbidites (Fergusson 1987). Thus the timing of formation of the BDFTZ is Middle Silurian to Middle Devonian.

Tectonic implications

The most puzzling aspect of the tectonic development of the LFB is the tectonic setting of the Benambra–Parkes composite terrane in the Middle Silurian to Middle Devonian. Powell (1984) explains the tectonic development of this interval as due to a dextral transtensional margin with the formation of a Basin-and-Range province, and this appears to be supported by Scheibner (1987). In contrast, Fergusson *et al.* (1986) related magmatism and the strong E–W shortening at this time to a W-dipping subduction zone at a location east of the present continental margin. Our favoured setting for the LFB in the Middle Silurian to Middle Devonian is that it was a complex E-facing arc with a zone of microplates in the west (now represented by the various terranes in western New South Wales and western Victoria) that have undergone a complex history of strike-slip movements and convergence (Fergusson *et al.* 1986).

In this setting the BDFTZ occupies the arc and frontal arc region of the ancient arc system, an unusual setting for a zone of deformation that resembles the more deformed parts of foreland fold-thrust zones, where back-rotation has steepened most of the structures to form imbricate wedges. The BDFTZ also has structural characteristics typical of subduction complexes dominated by coherent strata. Where thrusting has been identified in the BDFTZ it always has the same eastwards vergence, as was described by Fergusson *et al.* (1986) for Middle Devonian fold-thrust zones in the Melbourne and Ballarat terranes of central Victoria (Fig. 1). The overall eastwards vergence accords with convergence directed from the east. The nature of the backstop of the BDFTZ is ambiguous, but the Early to Middle Silurian Wagga–Omeo Metamorphic Belt probably formed a rigid buttress west of the BDFTZ (Fergusson 1987). Overall in the Victorian sector of the LFB there is a clear westwards-younging of the deformation towards central Victoria (Fergusson *et al.* 1986), and this also occurs in the Goulburn–Bungonia region where in the west the deformation continued into the Middle Devonian whereas further east it ceased in the early part of the Early Devonian.

Westward-directed convergence began in the Middle Silurian with the development of a W-dipping subduction zone within the eastern part of the quartz-rich turbidite wedge and this process formed the toe region of the BDFTZ (i.e. the mélanges on the South Coast of New South Wales). Sometime in the Late Silurian an oceanic plateau entered the subduction zone and underthrust the arc basement, which at that stage consisted of the undeformed Ordovician turbidite wedge. Underthrusting of the oceanic plateau was accompanied by major shortening in the hangingwall block (Fig. 13) and the loss of the oceanic basement of the Ordovician by limited subduction under the arc, and a general younging of the deformation westwards. Other authors, in particular Scheibner (1985, 1987), have argued that LFB tectonics has been controlled by underthrusting of an oceanic plateau. On the crustal section the base of the BDFTZ is drawn at a depth of 15–20 km which represents the deformed thickness of the Ordovician (Fig. 13). All the steeply dipping faults must flatten out to the west at this depth and are shown linking up to form a major detachment above the underthrust oceanic plateau (cf. Fergusson *et al.* 1986, fig. 4).

Undoubtedly extension played a role in the Middle Silurian to Middle Devonian tectonics of the LFB. Extension was widespread in the Middle Silurian during the initiation of many sedimentary basins especially in the northern part of the LFB (Powell 1984) which we relate to the initiation of W-directed subduction. Subsequently extension occurred in several regions at several times, particularly in the late Early Devonian. In the western BDFTZ small amounts of extension were associated with graben formation.

CONCLUSIONS

(1) The BDFTZ is dominated by buckling and imbricate thrusting of a thick monotonous Ordovician quartz-rich turbidite succession that has a structure resembling that of subduction complexes dominated by coherent strata and the more deformed parts of foreland fold-thrust zones. Development of the BDFTZ is responsible for crustal thickening in this part of the LFB and accounts for nearly half of the present crustal thickness.

(2) Timing of formation of the BDFTZ is best constrained by the regional tectonic criteria rather than local geological relationships that can sometimes be paradoxical. Sedimentation, deformation and magmatism appear to have been synchronous processes, as occurs in active arc systems, although in many areas of the BDFTZ intrusion by abundant granitic plutons appears to be associated with cessation of significant deformation.

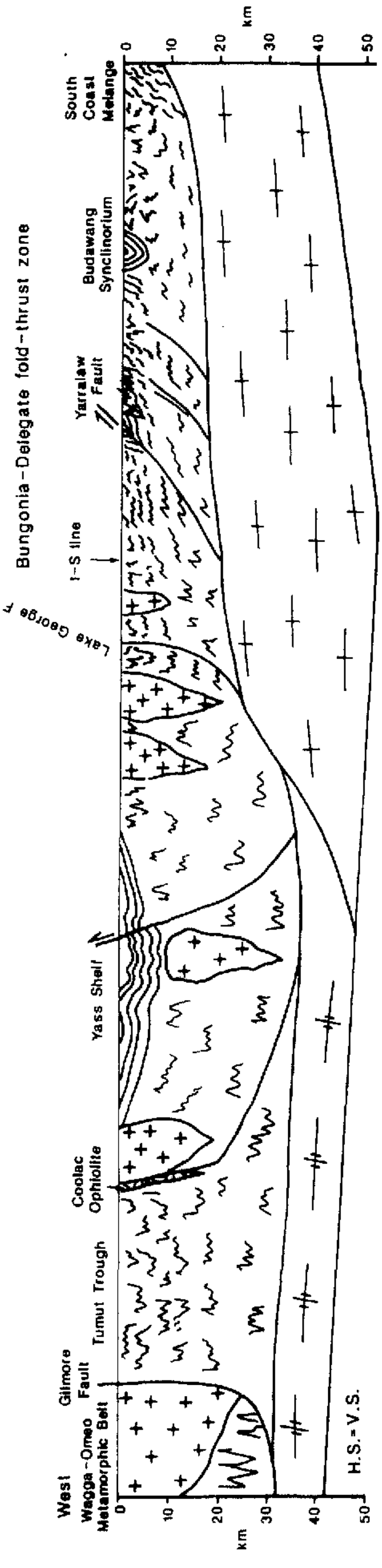

Fig. 13. Crustal section showing the Bungonia–Delegate fold-thrust zone and regions further west (see Fig. 1 for location). Lower crust in the eastern half of the section represents an oceanic plateau underthrust from the east (see text).

(3) The Middle Silurian to Middle Devonian tectonic development of the eastern LFB is related to W-directed subduction with underthrusting of an oceanic plateau and associated development of the BDFTZ in an arc-frontal arc setting.

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REFERENCES

Brown, C. M., Tucker, D. H. & Anfiloff, V. 1988. An interpretation of the tectonostratigraphic framework of the Murray Basin region of southeastern Australia, based on an examination of airborne magnetic patterns. *Tectonophysics* **154**, 309–33.

Carr, P. F., Jones,. J. G., Kantsler, A. J., Moore, P. S. & Cook, A. C. 1981. The geology of the Bungonia district, New South Wales. *Proc. Linn. Soc. N.S.W.* **104**, 229–244.

Carr, P. F., Jones, J. G. & Wright, A. J. 1980. Dating of rocks from the Bungonia district, New South Wales. *Proc. Linn. Soc. N.S.W.* **104**, 113–117.

Cas, R. A. F. 1983. A review of the palaeogeographic and tectonic development of the Palaeozoic Lachlan Fold Belt of southeastern Australia. *Spec. Publ. geol. Soc. Aust.* **10**.

Cas, R. A. F., Powell, C. McA. & Crook, K. A. W. 1980. Ordovician paleogeography of the Lachlan Fold Belt: a modern analogue and tectonic constraints. *J. geol. Soc. Aust.* **27**, 19–31.

Creaser, P. H. 1973. The geology of the Goulburn–Brayton–Bungonia area. Unpublished B.Sc. (Hons.) thesis, Australian National University.

Fergusson, C. L. 1987. Early Paleozoic back-arc deformation in the Lachlan Fold Belt, southeastern Australia: implications for terrane translations in eastern Gondwanaland. In: *Terrane Accretion and Orogenic Belts* (edited by Leitch, E. C. & Scheibner, E.). *Am. Geophy. Un. Geodyn. Ser.* **19**, 39–56.

Fergusson, C. L., Gray, D. R. & Cas, R. A. F. 1986. Overthrust terranes in the Lachlan Fold Belt, southeastern Australia. *Geology* **14**, 519–522.

Gibson, R. G. & Gray, D. R. 1985. Ductile-to-brittle transition in shear during thrust sheet emplacement, Southern Appalachian thrust belt. *J. Struct. Geol.* **7**, 513–525.

Glen, R. A. & VandenBerg, A. H. M. 1985. Evaluation of the I–S line in the Delegate area, southeastern Australia, as a possible terrane boundary. *Geol. Soc. Aust. Abs.* **14**, 91–95.

Glen, R. A. & VandenBerg, A. H. M. 1987. Thin-skinned tectonics in part of the Lachlan Fold Belt near Delegate, southeastern Australia. *Geology* **15**, 1070–1073.

Henry, R. L. 1975. The stratigraphy and structure of the Tarago area, New South Wales. Unpublished M.Sc. thesis, Australian National University.

Naylor, G. F. K. 1950. A further contribution to the geology of the Goulburn district. *J. Proc. R. Soc. N.S.W.* **83**, 279–287.

Powell, C. McA. 1983. Geology of the N.S.W. South Coast and adjacent Victoria with emphasis on the pre-Permian structural history. *Geol. Soc. Aust., SGTSG Field Guide* **1**, 1–118.

Powell, C. McA. 1984. Ordovician to earliest Silurian: marginal sea and island arc; Silurian to mid-Devonian dextral transtensional margin; Late Devonian and Early Carboniferous: continental magmatic arc along the eastern edge of the Lachlan Fold Belt. In: *Phanerozoic Earth History of Australia* (edited by Veevers, J. J.). Oxford University Press, Oxford, 290–340.

Powell, C. McA. & Fergusson, C. L. 1979. The relationship of structures across the Lambian Unconformity near Taralga, New South Wales. *J. geol. Soc. Aust.* **26**, 202–219.

Price, R. A. 1981. The Cordilleran foreland thrust and fold belt in the southern Canadian Rocky Mountains. In: *Thrust and Nappe Tectonics* (edited by Price, N. J. & McClay, K.). *Spec. Publs. geol. Soc. Lond.* **9**, 427–448.

Ramsay, D. M. 1979. Analysis of rotation of folds during progressive deformation. *Bull. geol. Soc. Am.* **90**, 732–738.

Sanderson, D. J. 1979. The transition from upright to recumbent folding in the Variscan fold belt of southwest England: a model based on the kinematics of simple shear. *J. Struct. Geol.* **1**, 171–180.

Sanderson, D. J. 1982. Models of strain variation in nappes and thrust sheets: a review. *Tectonophysics* **88**, 201–223.

Scheibner, E. C. 1985. Suspect terranes in the Tasman Fold Belt System of eastern Australia. In: *Tectonostratigraphic Terranes of the Circum-Pacific Region* (edited by Howell, D. G.). *Circum-Pacific Council Energy Mineral Resour., Earth Sci. Ser.* **1**, 493–514.

Scheibner, E. C. 1987. Paleozoic tectonic development of eastern Australia in relation to the Pacific region. In: *Circum-Pacific Orogenic Belts and the Evolution of the Pacific Ocean Basin* (edited by Monger, J. W. H. & Francheteau, J.). *Am. Geophy. Un. Geodyn. Ser.* **18**, 133–165.

Wilson, C. J. L. & VandenBerg, A. H. M. 1988. Mallacoota Zone. In: *Geology of Victoria* (edited by Douglas, J. G. & Fergusson, J. A.). *Geol. Soc. Aust., Vic. Div.* 23–26.