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Character and kinematics of faults within the turbidite-dominated Lachlan Orogen: implications for tectonic evolution of eastern Australia

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Abstract—Fault zones within turbidite-dominated orogenic systems, typified by the Lachlan Orogen of eastern Australia, are characterised by higher than average strain and intense mica fabrics, transposition foliation and isoclinal folds, poly-deformation with overprinting crenulation cleavages, and steeply to moderately plunging meso- and micro-folds. They have a different character compared to the brittle–ductile fault zones of classic foreland fold-and-thrust belts such as the Appalachians and the Canadian Rocky Mountains. Multiple cleavages and transposition layering record a progressive shear-related deformation history. An intense mica fabric evolves initially during shortening of the overlying sedimentary wedge, but is progressively modified during rotation and emplacement to higher structural levels along the steep parts of inferred listric faults. The deformed wedge outside the fault zones generally undergoes one phase of deformation, shown by a weak to moderately developed slaty cleavage which is parallel to the axial surface of upright, subhorizontally plunging chevron-folds. Other faults within the turbidites of the Lachlan Orogen include the steep zones of 'ductile' strike-slip deformation that bound a centrally located, high *T*/low *P* metamorphic complex. Characterised by *S*–*C* mylonites, these ductile shear zones indicate a southward passage of the metamorphic complex as a crustal wedge, with emplacement to higher structural levels along a leading-edge, ductile thrust-fault. Ar–Ar dating constrains the timing of regional deformation to be mostly Late Ordovician through Silurian across the Lachlan Orogen. Faults in the low grade turbidite sequences record the kinematic evolution of the developing Lachlan Orogen and indicate progressive deformation associated with simultaneous, eastward propagating and migrating deformation fronts in both the western and eastern parts of the fold belt. These deformation fronts are related to 'accretionary style' deformation at the leading edges of overriding plates, in an inferred southwest Pacific-type subduction setting from the Late Ordovician to the mid-Devonian, along the former Gondwana margin. The fault zones effectively accommodate and preserve movements within the structurally thickening, migrating and prograding accretionary wedge. © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

Faults and shear zones occur at all scales in orogenic systems. Such faults and shear zones contain shear sense criteria (e.g. Simpson and Schmid, 1983) and slip plane information (e.g. Arthaud, 1969; Aleksandrowski, 1985). These data can be used as kinematic indicators to provide important constraints for the tectonic evolution of orogenic systems (e.g. Hickman *et al*., 1978; Daly, 1986, 1988; Ratschbacher *et al*., 1991). Fault zone data along with information from penetrative deformation elements within thrust sheets have also been used to constrain the directions of plate movements (e.g. Baird and Dewey, 1986). Fault zones in low grade meta-sedimentary sequences have been more difficult to interpret, but meso- to micro-folds and crenulation cleavages have been recently used to provide kinematic information (e.g. Mosher and Berryhill, 1991; Burks and Mosher, 1996). Major fault zones of the Lachlan Orogen (Fig. 1) can therefore help define the tectonic evolution of eastern Australia, and consequently eastern Gondwana, during the Early to Middle Palaeozoic. Metamorphic crystallisation ages of slates constrain the timing of deformation, whereas structural relationships within fault zones dictate the kinematic and relative chronology of deformation across the fold belt. Fault zone structures reflect the movements responsible for the crustal thickening and development of crust of continental character for eastern Australia.

Fault zones within the chevron-folded meta-sedimentary sequences of the western Lachlan Orogen, eastern Australia have recently been interpreted to reflect imbrication processes within an oceanic setting (Foster *et al*., 1996; Gray *et al*., 1997; Gray and Foster, 1997; Foster *et al*., 1998). They are considered to form within thick (> 5 km), sediment wedges above

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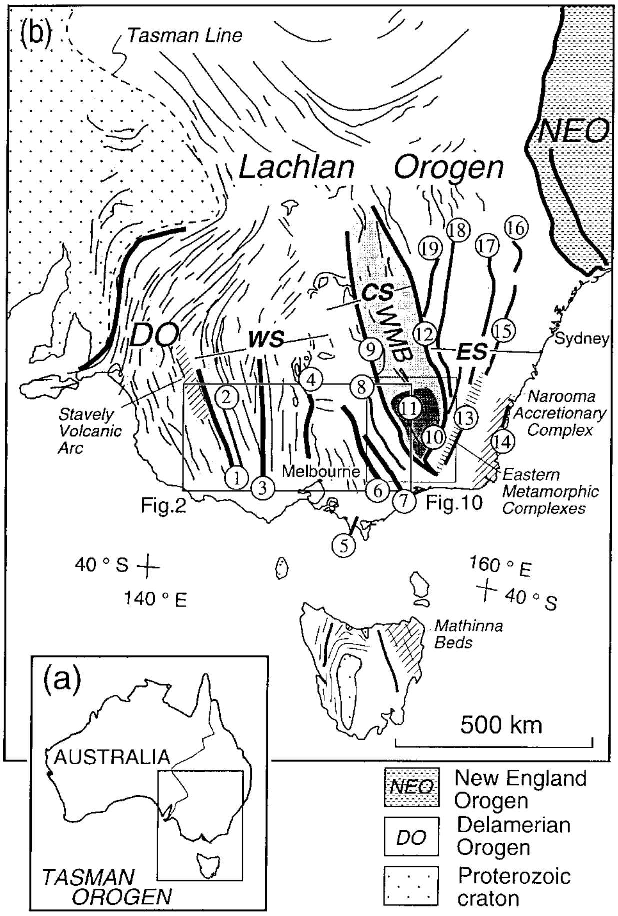

Fig. 1. Structural trend map of the Palaeozoic Tasman Orogenic Belt of southeastern Australia combining aeromagnetic trend lines and outcrop traces from both regional maps and satellite images. Two thirds of the area shown is hidden by cover sequences of younger sedimentary basins. WS: western subprovince Lachlan Orogen, CS: central subprovince Lachlan Orogen, ES: eastern subprovince Lachlan Orogen. heavy lines: faults; light stipple: Early Palaeozoic Delamerian Orogen (DO); dashes: Late Palaeozoic New England Orogen (NEO); shading: Wagga–Omeo Metamorphic Belt (WMB); dashed line: cratonic line demarcating Proterozoic (coarse stipple) from Palaeozoic crustal rocks to the east. 1: Woorndo–Moyston Fault Zone; 2: Stawell–Ararat Fault Zone; 3: Avoca Fault Zone; 4: Heathcote Fault Zone; 5: Waratah Fault Zone; 6: Mt Wellington Fault Zone; 7: Governor Fault Zone; 8: Wonnangatta Fault Zone; 9: Kiewa Fault Zone; 10: Indi Fault Zone; 11: Ensay Fault Zone; 12: Gilmore Fault Zone; 13: Yalmy Fault Zone; 14: Narooma high strain Zone; 15: Yarralaw Fault; 16: Razorback Fault; 17: Copperhannia Fault; 18: Coolac–Narromine Fault Zone; 19: Parkes Fault.

subduction zones. This interpretation is based on: (1) contemporaneous deformation and sedimentation (Foster *et al.*, 1996, 1998; Gray and Foster, 1997; Foster and Gray, in review); (2) intermediate pressure metamorphism of the turbidites associated with a low geothermal gradient (Offler *et al.*, 1996, 1998a); and (3) the presence of relict intermediate to high-pressure metamorphic assemblages within associated fault-bounded mafic volcanic rocks (Spaggiari *et al.*, 1998). Furthermore, the western Lachlan Orogen shows clear similarities with well recognised accretionary complexes such as the Shimanto and Kodiak Accretionary Complexes of Japan and Alaska, respectively (e.g. Byrne, 1986; Fisher and Byrne, 1987; Sample and Moore, 1987). There is similarity in both geometry and structural style at the meso- and micro-scales, as well as lithological association and gradients in strain (e.g. Fisher, 1990; Fisher and Byrne, 1992; Tillman and Byrne, 1995). Faults within the turbidite-dominated Lachlan Orogen are polydeformed zones of transposition layering and intense crenulation cleavage. They clearly have different character to fault zones in carbonate–shale sequences of typical foreland fold-and-thrust belts (see Table 1). These faults are largely dominated by brittle–plastic processes in both the internal and external parts of the thrust system (cf. Wojtal and Mitra, 1988). We suggest that the fault zones in the Lachlan Orogen typify those at the intermediate levels of subduction-related accretionary complexes. Deformation is distinctly non-coaxial and dominated by transposition of earlier fabrics, mica growth and pressure solution.

This paper firstly describes the nature of the faults within the turbidite-dominated Lachlan Orogen, and secondly relates the geometry and minor structure of fault zones to the regional deformation kinematics which are used to constrain key aspects of the tectonic evolution of the fold belt. A companion paper (Foster and Gray, in press) provides the geochronological constraints on the timing of deformation based on $^{40}Ar/^{39}Ar$ dating of micas in cleaved slates, syntectonic quartz veins, and granitic mylonites. The paper demonstrates that the faults in turbidite-dominated orogens have a particular character related to accretionary wedge-type thrust-belts, and that the tectonic evolution of the Lachlan Orogen of southeastern Australia from the Late Ordovician through Silurian time involves three migrating belts of deformation.

GEOLOGICAL BACKGROUND

The Lachlan Orogen of southeastern Australia (Fig. 1) is dominated by low-grade meta-sedimentary rock sequences with a centrally-located, shear-zone bounded, high *T*/low *P* metamorphic complex (Wagga Metamorphic Belt; WMB, Fig. 1) (Coney *et al.*, 1990; Gray, 1997). It has similarities to the 'Turkic' type orogenic systems of Sengor and N'atalin (1996), where crust of continental thickness and character forms by deformation and subduction–accretion of former, major turbidite-fan systems originally on the deep ocean floor. In this scenario massive shortening and structural thickening of the sediment dispersal system leads to eventual accretion with the adjacent cratonic regions, and growth of 'continental' crust.

The Lachlan Orogen, characterised by chevron-folds cut by a series of linked fault-systems, consists of three separate and distinct subprovinces (Fig. 1). These show differences in rock type, metamorphic grade,

Table 1. Thrust-belt types based on rock association and structural style

Thrust-belt type	Accretionary wedge type	Foreland fold-and-thrust belt
Rock association	deep water turbidites, chert and oceanic crust (meta-basalt, gabbro, ultramafics)	passive margin limestone, dolomite, shale sequence ± clean sandstone
Fault geometry	leading imbricate fan involving tiered detachments oceanic crust duplexes	imbricate fan with out-of-sequence thrusts basement and basement-cover duplexes
Fault-zone style	poly-deformed high strain zone up to 4 km width crenulation cleavages and transposition layering marked non-coaxial deformation (fibres in pressure shadows)	mylonitic shear zones (up to 1 km width) in basement (hinterland) to narrow brittle zones with cataclasites (foreland) (up to 500 m width)
Metamorphism	greenschist to sub-greenschist (turbidite-dominated thrust-sheets) greenschist (intra-zone faults) intermediate-high P metamorphism: blueschist–greenschist transition (inter-zone faults)	dominated by sub-greenschist metamorphism (foreland) *CAI:T ~ 150–300°C P ~ 200–500 MPa *CAI: conodont alteration indice
Thrust-sheet style	fold-dominated chevron-folding 1 dominant cleavage (slaty type) marked strain gradient towards faults	fault-dominated imbricate stack fault-bend and fault-break folds 1 or more cleavages (stylolitic spaced types) commonly transecting folds
Shortening	50–70% (over 800–1000 km length scales)	30–50% (over 100–200 km length scales)
type examples	western Lachlan Orogen Kodiak Accretionary complex	Appalachian fold-and-thrust belt Sevier (Canadian Rocky Mountain) fold-and-thrust belt

structural history and geological evolution (Gray, 1997); the western and central subprovinces are dominated by a turbidite succession consisting of interbedded quartz-rich sandstones and black shales. The eastern subprovince consists of mafic volcanics, volcaniclastic rocks and limestone, as well as quartz-rich turbidites and extensive black shale in the easternmost part (VandenBerg and Stewart, 1992). Structurally, the western subprovince consists of an east-vergent thrust-system with alternating zones of northwest- and north-trending structures (Gray, 1988; Gray and Willman, 1991a,b). Slivers of 'oceanic' crust with relict transitional blueschist–greenschist assemblages are preserved within major faults which bound these structural zones (Spaggiari *et al*., 1998). Metamorphic grade of the turbidites is epizonal (greenschist facies) or lower, with b_0 lattice parameters of white micas in the slates indicating intermediate pressure metamorphism (*c*. 400 MPa) and a low geothermal gradient existing between 450–430 Ma (Offler *et al*., 1996, 1998a). The central subprovince is dominated by northwest-trending structures and consists of a southwest-vergent thrust-belt (Fergusson, 1987a,b; Fergusson and Gray, 1989). This is linked to a fault-bounded high *T*–low *P* metamorphic complex (Wagga Metamorphic Belt: WMB, Fig. 1; Morand and Gray, 1991). The eastern subprovince is dominated by a north–south structural grain and east-directed thrusting associated with 'inverted' mid-Silurian extensional basins in the west and north (Glen, 1992; Gray, 1997). In the most eastern part of the eastern subprovince an east-vergent thrust system (Fergusson and VandenBerg, 1990) links into an older accretionary complex further to the east (Miller and Gray, 1996, 1997; Offler *et al*., 1998b) (Fig. 1).

Faults can be subdivided into associations within the low grade turbidite wedges (western Lachlan Orogen), the high grade metamorphic complex (Wagga–Omeo Metamorphic Belt: central Lachlan Orogen), and the eastern Lachlan Orogen. Those within and bounding the metamorphic belt are mylonite zones with classic shear sense indicators (see Morand and Gray, 1991).

FAULTS WITHIN THE TURBIDITE-DOMINATED WESTERN LACHLAN OROGEN

Within the low grade turbidite wedges there are several orders of faults, best exemplified within the western Lachlan Orogen (Figs 1 & 2). Major inter-zone faults, containing remnant slivers of oceanic crust, and intra-zone faults within the turbidite wedge have high-strain zones up to 4 km wide showing intense development of transposition layering and crenulation cleavage (Figs 3 & 4). Minor lower displacement (< 100 m) reverse faults are narrow, brittle deformation zones associated with auriferous quartz veins. Characteristics of these fault sub-sets are presented in Table 2, and individual fault zones are described in detail below.

Inter-zone faults

Inter-zone faults are major bounding faults to the structural zones within the turbidites of the western

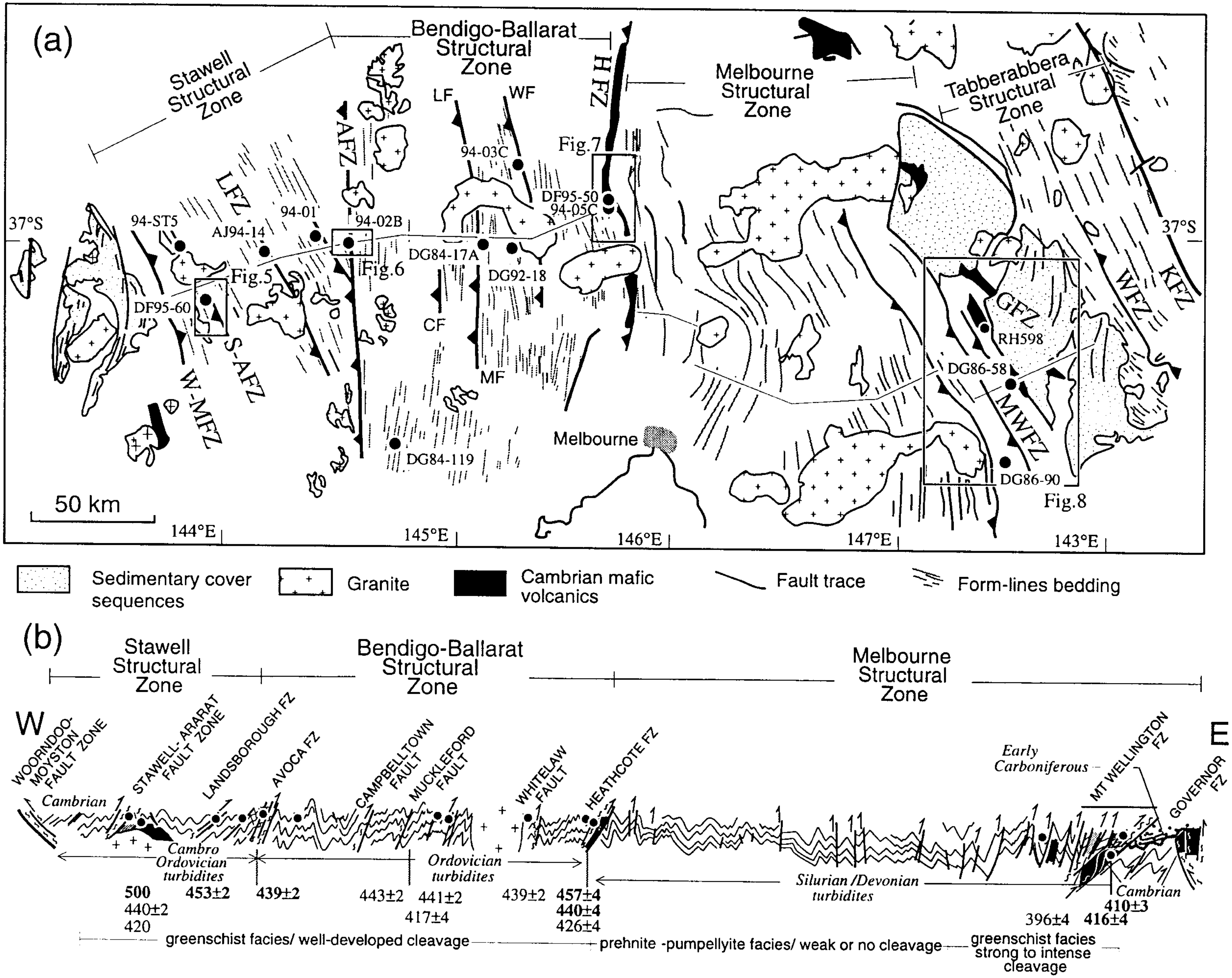

Fig. 2. (a) Structural trend map of the western subprovince of the Lachlan Orogen showing positions and age data for argon geochronology samples. Faults are shown as heavy lines and include: W–MFZ: Woorndoo–Moyston Fault; S–AFZ: Stawell–Ararat Fault Zone; LFZ: Landsborough Fault Zone; PFZ: Percydale Fault Zone; AFZ: Avoca Fault Zone; CF: Campbelltown Fault; LF: Leichardt Fault; MF: Muckleford Fault; WF: Whitelaw Fault; HFZ: Heathcote Fault Zone; MEFZ: Mt Easton Fault Zone; MWFZ: Mt Wellington Fault Zone; GFZ: Governor Fault Zone; WFZ: Wonnangatta Fault Zone; KFZ: Kiewa Fault Zone. Locations of Figs 5–8 are shown. (b) Accompanying structural profile with heavy dots showing positions for argon geochronology samples. A summary of Ar–Ar ages is listed below the section, along with description of degree of cleavage development and the grade of metamorphism.

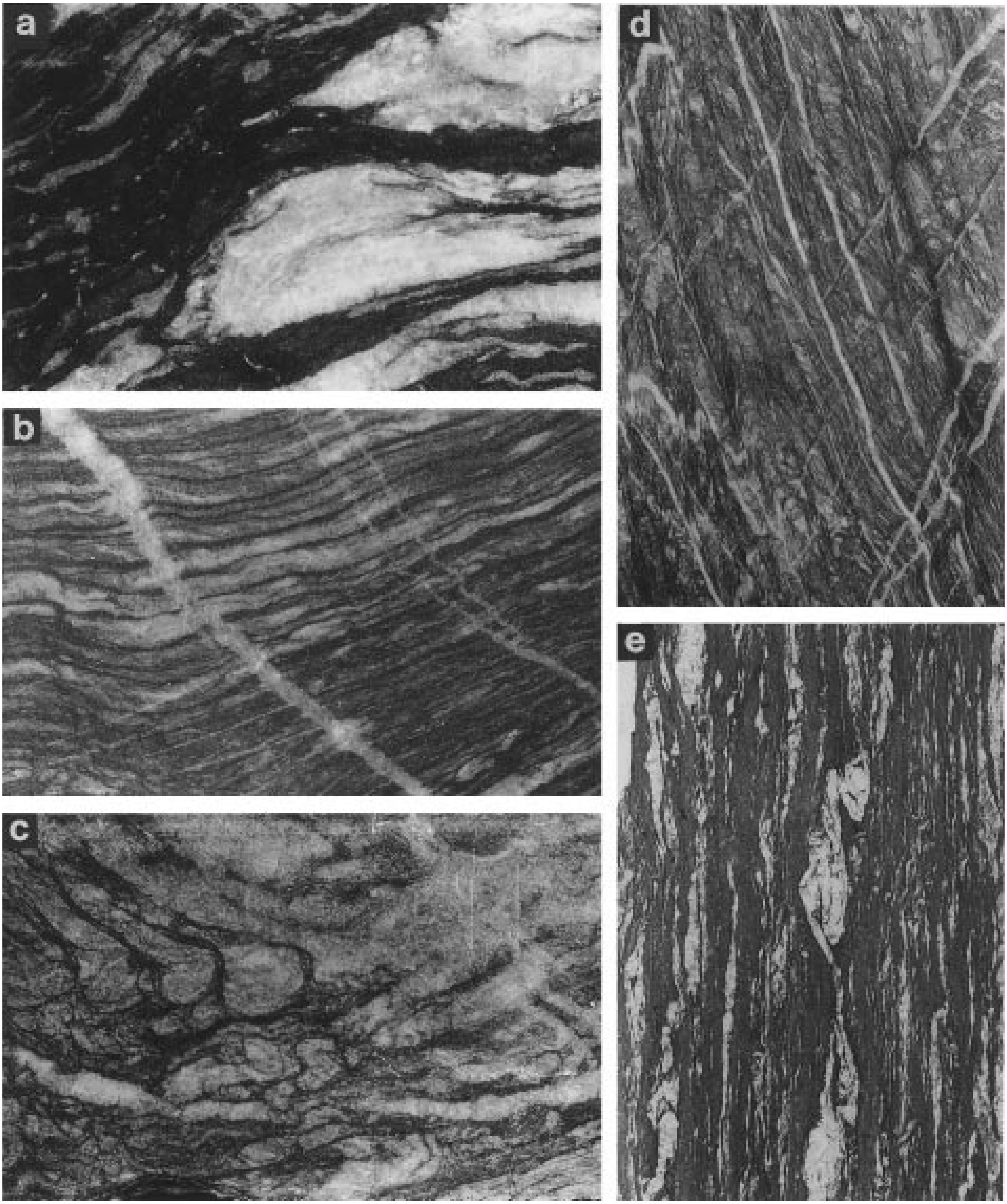

Fig. 3. Photographs of structural relationships in fault zones from the western Lachlan Orogen. Photographs showing detailed structures within drill core through the Stawell–Ararat Fault Zone (a–d), and a photomicrograph from the Mount Wellington Fault Zone, (e). (a) Isoclinal fold hinge in quartz vein within transposition layering. Base of photo is 6 cm. (b) Strongly developed transposition layering producing a ‘segregation layering’ effect. Quartz veins are isoclinally folded and are now oriented subparallel to the ‘layering’. Base of photo is 5 cm. (c) Multiple foliations within zone of transposition layering. Relict earlier layering (bottom right) overprinted by younger Sm fabric (top of photo). Base of photo is 6 cm. (d) Strongly developed crenulation cleavage developed by tight crenulations within an earlier transposition layering. Base of photo is 4 cm. (e) Asymmetric isoclinal folds within quartz vein in strongly transposed layering from the Mount Wellington Fault Zone, Licola–Jamieson Road. Base of photo is 4 cm.

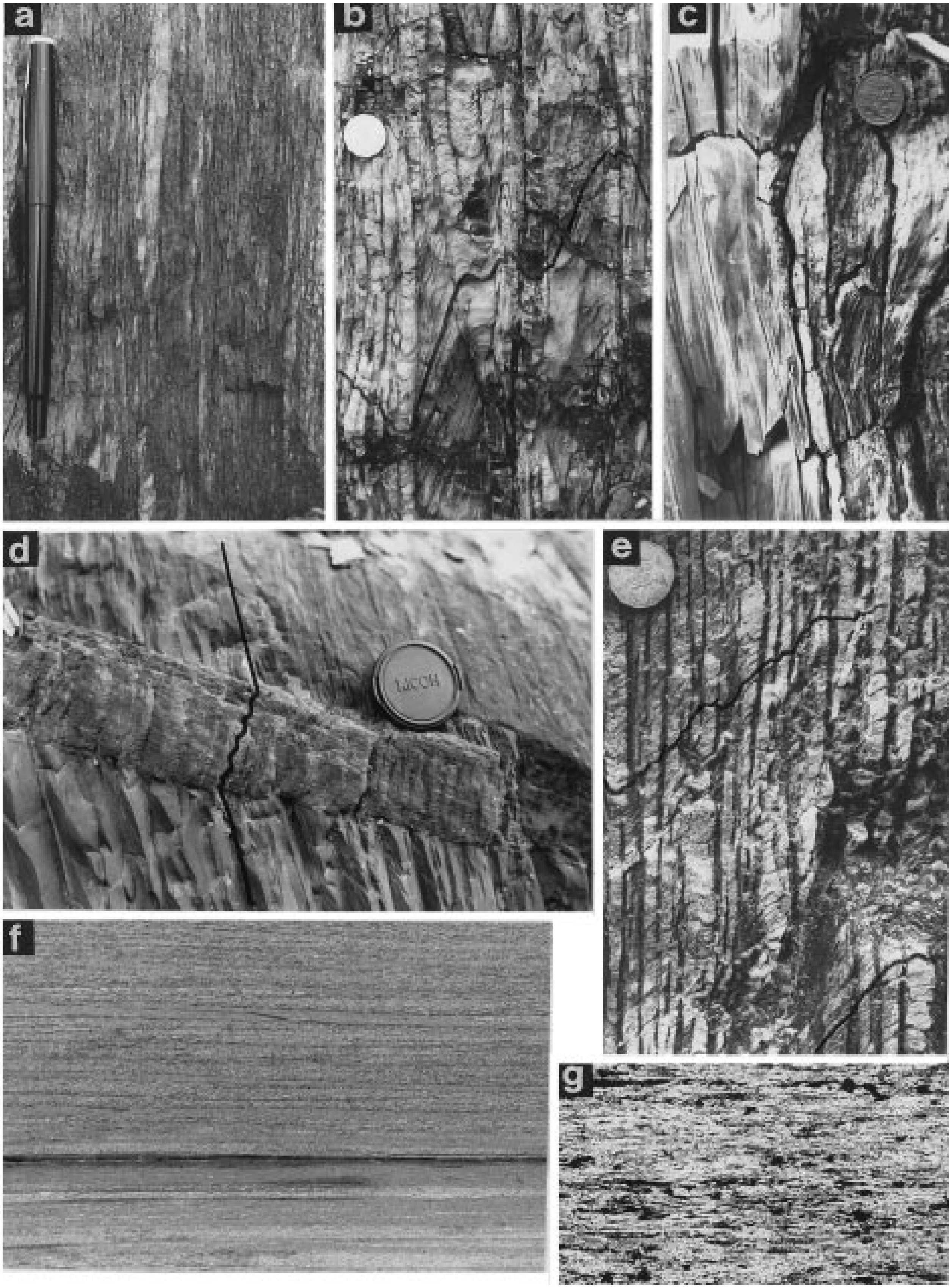

Fig. 4. Photographs of structural relationships in fault zones from the western Lachlan Orogen. (a) Transposition layering developed in pelite, in the hanging wall of the Heathcote Fault Zone, Red Hill. (b) Intensely developed crenulation cleavage in psammite from the Avoca Fault Zone, 6 km west of Avoca. (c) Isoclinally folded quartz vein subparallel to transposition layering within pelite, Heathcote Fault Zone, 1 km west of Heathcote. (d) Zone of crenulation cleavage associated with a kink-like zone within laminated siltstone and black mudstone, as part of the footwall to a minor reverse fault. Crusoe Reservoir, Bendigo. (e) Intense crenulation cleavage in psammite of the hanging wall to the Avoca fault Zone, Devils Kitchen region south of Ballarat. (f) Photomicrograph of intense transposition layering consisting of isoclinally folded thin siltstone and mudstone layers, Mount Wellington Fault Zone in phyllonite zone of the Fullarton Fault. Base of photo is 3 cm. (g) Intense mica fabric associated with the transposition layering in the pelite layer of (f). Base of photo is 1.5 cm.

Table 2. Types of faults within the western Lachlan Orogen

Fault type	Inter-zone	Intra-zone	Intra-zone
		Major (throw: 5–10 km)	Minor (Throw < 500 m)
Fault geometry	•leading imbricate fan geometry •duplex zone largely within Cambrian units •subvertical bounding faults linked by steeply-dipping internal faults	•imbricate fan geometry •listric reverse faults •steep (> 60° dip) in upper crust	•steep reverse fault (> 60° dip) •occur as isolated faults within folded stratigraphy •occur in planar arrays •cross-cut fold structures with bedding-parallel segments (west limb of folds) and bedding-discordant segments (east limbs of folds)
Fault style	•chaotic zone of broken formation and fault-bounded slabs of chert, basalt and minor turbidite (up to 10 km in width) •strongly foliated serpentinite-matrix melange with Franciscan-type 'knockers' •intense crenulation cleavage and transposition layering in hanging wall turbidites	•shallow levels: broken formation and mud-matrix melange (e.g. Waratah Fault Zone, MZ) •deeper levels: poly-deformed high strain zone up to 4 km wide •intense crenulation cleavage and transposition foliation	•narrow (commonly < 50 cm thick) cataclasite zone and/or en échelon gash veins •may have local crenulation cleavages in either footwall or hanging wall •commonly contain Au mineralisation
Rock association	cherts, meta-basalt (tholeiite), boninites, black shales	turbidites	turbidites
Fault spacing	100–120 km	15–20 km	50–100 m
Detachment level	Within upper 1–2 km of former Cambrian or older oceanic crust ~21–22 km present depth	turbidite–oceanic crust interface ~17 km present depth	
Examples	Heathcote Fault Zone Mt Wellington Fault Zone Avoca Fault Zone Governor Fault Zone (central Lachlan Orogen)	Whitelaw Fault (BBZ) Muckleford Fault (BBZ) Landsborough Fault (SZ)	Wattle Gully Fault, Chewton (BBZ) Deborah Fault, Bendigo (BBZ) (see Cox *et al*., 1991, figs 11–13)

BBZ: Bendigo–Ballarat Zone; SZ: Stawell Zone; MZ: Melbourne Zone.

Lachlan Orogen (Fig. 1). Spaced at 100–150 km these are fault zones with widths of 4–10 km and lengths in excess of 100 km (Fig. 1). Inter-zone faults are major splays which are considered to link to a major mid-crustal décollement (see Gray *et al*., 1991). They include the Woorndoo–Moyston, Stawell–Ararat, Heathcote and Mount Wellington Fault Zones (Fig. 2). Most contain slivers of Cambrian metavolcanic rocks and have a duplex-like character with imbricated slices within a complex fault-bounded zone (cf. Gray and Willman, 1991a, fig. 17; Gray, 1997, fig. 8). Metavolcanics within the Stawell and Heathcote Fault Zones contain relict Na-amphiboles indicative of intermediate to high pressure metamorphism (cf. Nicholls, 1965; Wilson *et al*., 1992, p. 123; Spaggiari *et al*., 1998).

Woorndoo–Moyston Fault Zone. The Woorndoo–Moyston Fault Zone (Fault 1: Fig. 1; W–MFZ: Fig. 2) is a major, east-dipping, northwest-trending fault zone defining the western margin of the Lachlan Orogen (Foster and Gleadow, 1992; Cayley and Taylor, 1996; Foster *et al*., 1996; Gray *et al*., 1997). The exposed length of the fault is ~50 km, but it extends for at least 200–300 km as shown in regional geophysics and gravity images (Moore, 1996; Gray *et al*., in press). It separates prehnite–pumpellyite facies rocks (Mt Dryden Volcanics) on the west (footwall) from amphibolite facies rocks (Mt Ararat sequence) on the east (hanging wall) (Cayley and Taylor, 1996). The fault zone consists of a strongly deformed, 0.5–1 km wide zone of transposed layering in psammo–pelitic rocks with infolded blocks/pods of mafic schist. Transposed layering defining the fault zone is north-northwest striking, dips steeply west, and contains moderately to steeply south-plunging rootless, microscale fold hinges. This layering appears to truncate the west-dipping structures and layering of the Stawell Structural Zone within the hanging wall of the fault zone.

Geochemical and isotopic data of rocks east and west of the Woorndoo–Moyston Fault Zone indicate that the fault zone separates different lithospheric blocks. Even though these data do not identify a single fault, they probably mark the steeply dipping, deep crustal boundary between the two fold belts. The Woorndoo–Moyston Fault Zone coincides firstly with a major isotopic discontinuity in the basalts of the Newer Volcanic Province, separating low initial $^{87}Sr/^{86}Sr$ ratios in the west from high ratios in the east (i.e., the Mortlake Discontinuity: Price *et al*., 1996). Secondly, it coincides with a boundary between highly sodic *c*. 400 Ma plutons to the west and more typical I-type plutons of similar age to the east (Chappell *et al*., 1988). Significant reactivation of the fault zone occurred during Mesozoic rifting (Foster and Gleadow, 1992). Kilometre-scale vertical displacements occurred on the southern part of the Woorndoo–

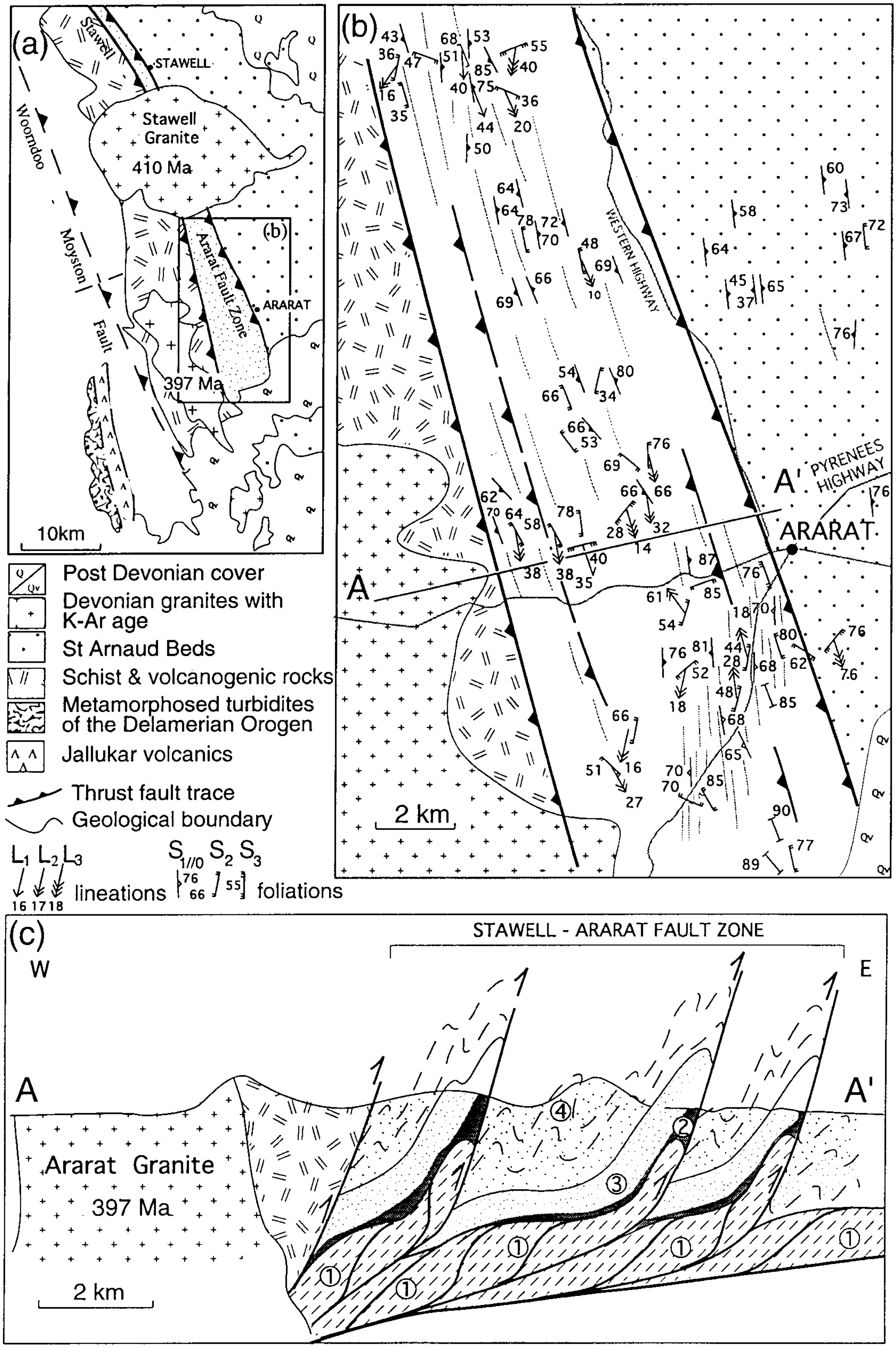

Fig. 5. Geological map of the Stawell–Ararat Fault Zone, western subprovince of the Lachlan Orogen (see Fig. 2 for location). (a) Regional map of fault zone showing the ages of post-tectonic granitoids that intrude into the fault zone (K/Ar ages from Richards and Singleton, 1981). (b) Detailed structural map of the fault zone south of the Stawell Granite (based on mapping by Chintock, 1995). (c) Structural profile along line A–A′ shown in map (b) (modified from Chintock, 1995).

Moyston Fault Zone resulting in 1–2 or more kilometres of erosion to the east, on the Lachlan Orogen side of the fault (Foster and Gleadow, 1992). On the west side of this fault, on the more stable crust of the Delamerian Orogen and Stavely volcanic arc (Fig. 1), very little denudation occurred at this time, preserving poorly lithified Permian glacial strata.

Stawell–Ararat Fault Zone. The Stawell–Ararat Fault Zone (Fault 2: Fig. 1; SAFZ: Fig. 2) is a major, 50 km long (exposed length only), northwest-trending zone of intense deformation near the western margin of the Stawell Structural Zone. In the north near Stawell (Fig. 5a), it is a 2 km wide zone of complex deformation consisting of a strong to intensely deformed sequence of tholeiitic basalts overlain by cherts and volcaniclastic sedimentary units. These are in turn overlain by complexly deformed turbiditic successions (Watchorn and Wilson, 1989; Wilson *et al.*, 1992). The structurally lowest part consists of a fault-bounded, duplex-like series of northeast-dipping slivers of schist, mafic tuffs and porphyritic mafic volcanics containing pillows (Watchorn and Wilson, 1989; Wilson *et al.*,

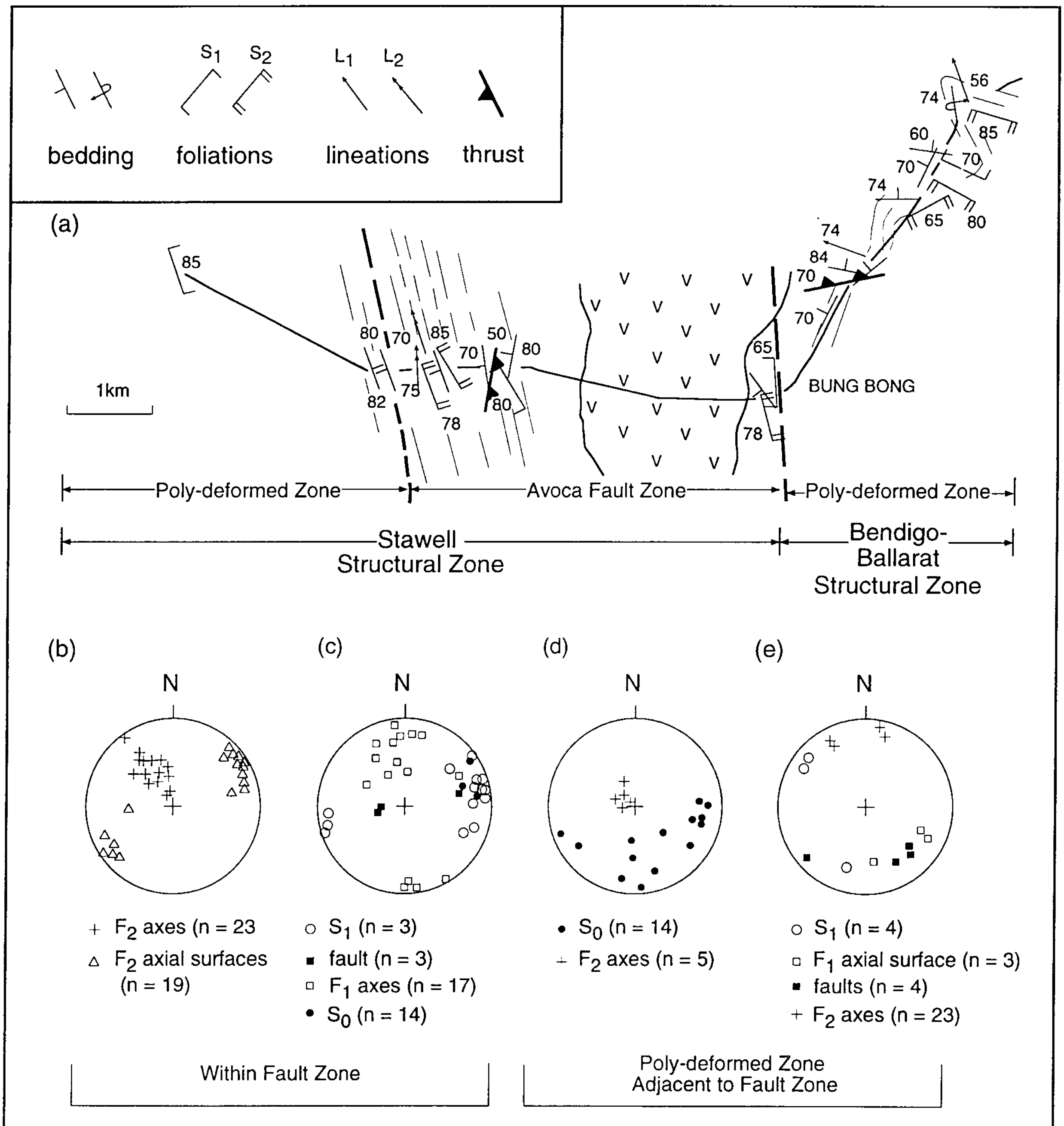

Fig. 6. Structural relationships for part of the Avoca Fault Zone, western subprovince of the Lachlan Orogen (see Fig. 2 for location). (a) Structural map showing intense development of a crenulation cleavage within the fault zone and effects in the footwall north of Bung Bong. Stereonets (b) and (c) show structural data from the fault zone, and stereonets (d) and (e) show structural data from the polydeformed zone adjacent to the fault (modified from Gray & Willman, 1991a, fig. 15).

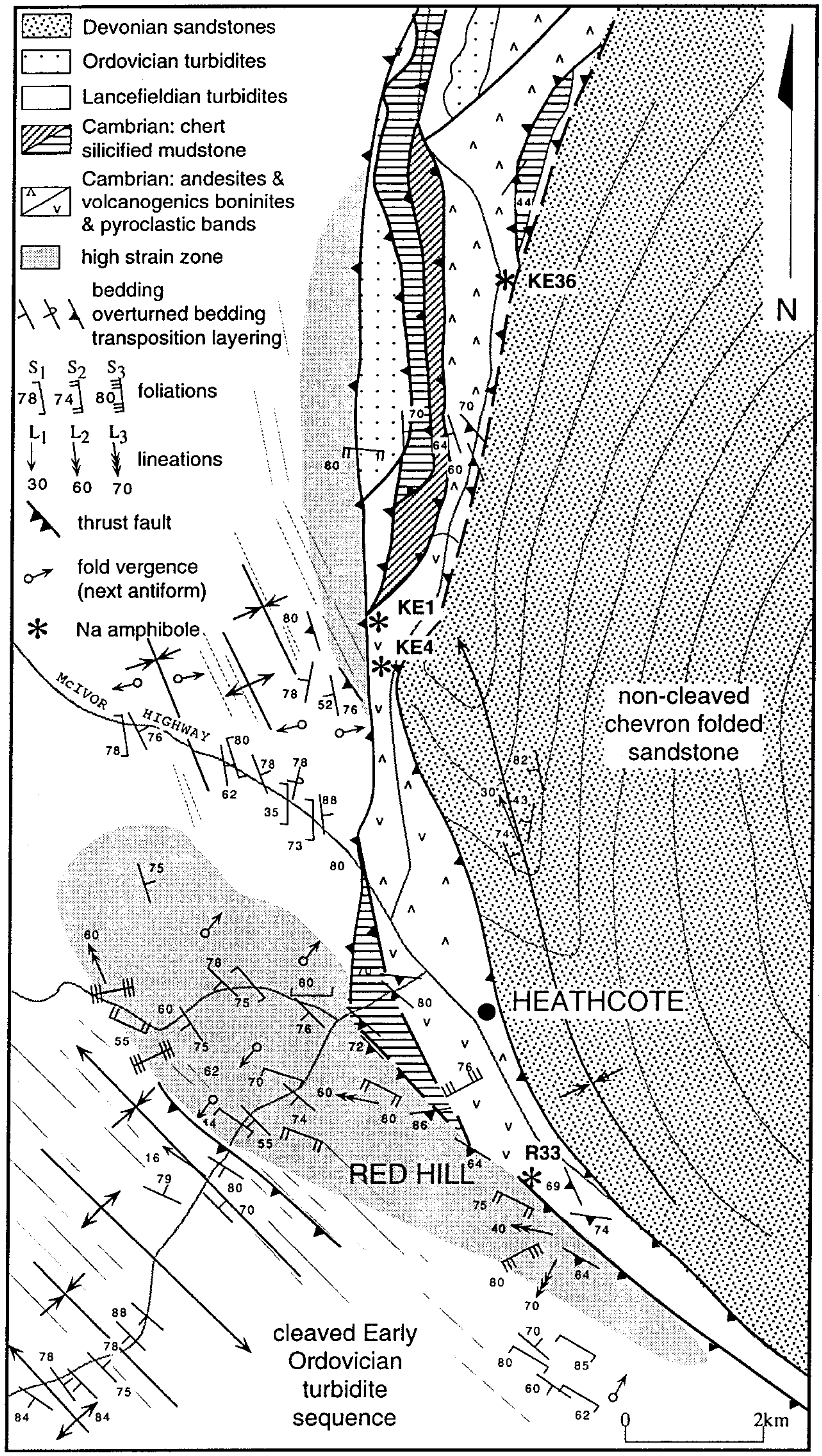

Fig. 7. Map of part of the Heathcote Fault Zone near Heathcote, western subprovince of the Lachlan Orogen (see Fig. 2 for location) (modified from Crawford *et al.*, 1984, fig. 2; and Gray and Willman, 1991a, b, fig. 8). Cambrian rocks in a zone of varying width (< 2.5 km) are bounded by faults which truncate fold structures in both the footwall (non-cleaved chevron folded Silurian sandstone) and hanging wall (cleaved Early Ordovician turbidite sequence). Zones of intense deformation accompanied by strong transposition layering (grey shaded regions) occur in the immediate hanging wall of the 'roof' thrust to the Cambrian sequence. Stars indicate localities and sample numbers (from Nicholls, 1965) where relict blueschist mineral assemblages have been located.

1992). The pillow basalts preserve a strong planar S_1/S_2 fabric that parallels a plane of flattening within the basalts. Phenocryst orientation data from the basalt give a tectonic strain ratio X:Y:Z = 4.9:2.3:1 and k-factor of 0.25 (Wilson *et al.*, 1992).

To the south, the Stawell–Ararat Fault Zone increases in outcrop width where it is an approximately 6–7 km wide, northwest-trending zone of intense deformation (Fig. 5b). Drill-hole and aeromagnetic data (Chintock, 1995) indicate repetition of stratigraphy across the fault zone, requiring four major breaks (see Fig. 5c). The fault repetition involves a sequence of metabasalt and volcanogenic metasedimentary rocks overlain by turbidites which dominate the surface exposure (Wilson *et al.*, 1992; Chintock, 1995). Rocks within the fault zone show transposition layering, isoclinal folding and multiple sets of crenulation cleavages (Fig. 3 a–d). The transposition layering defines the fault as a steeply west-dipping zone that contains shear lenses (cf. Ghosh and Sengupta, 1987, fig. 12) preserving earlier-formed crenulation cleavage fabrics. The shear lenses consist of asymmetric meso-

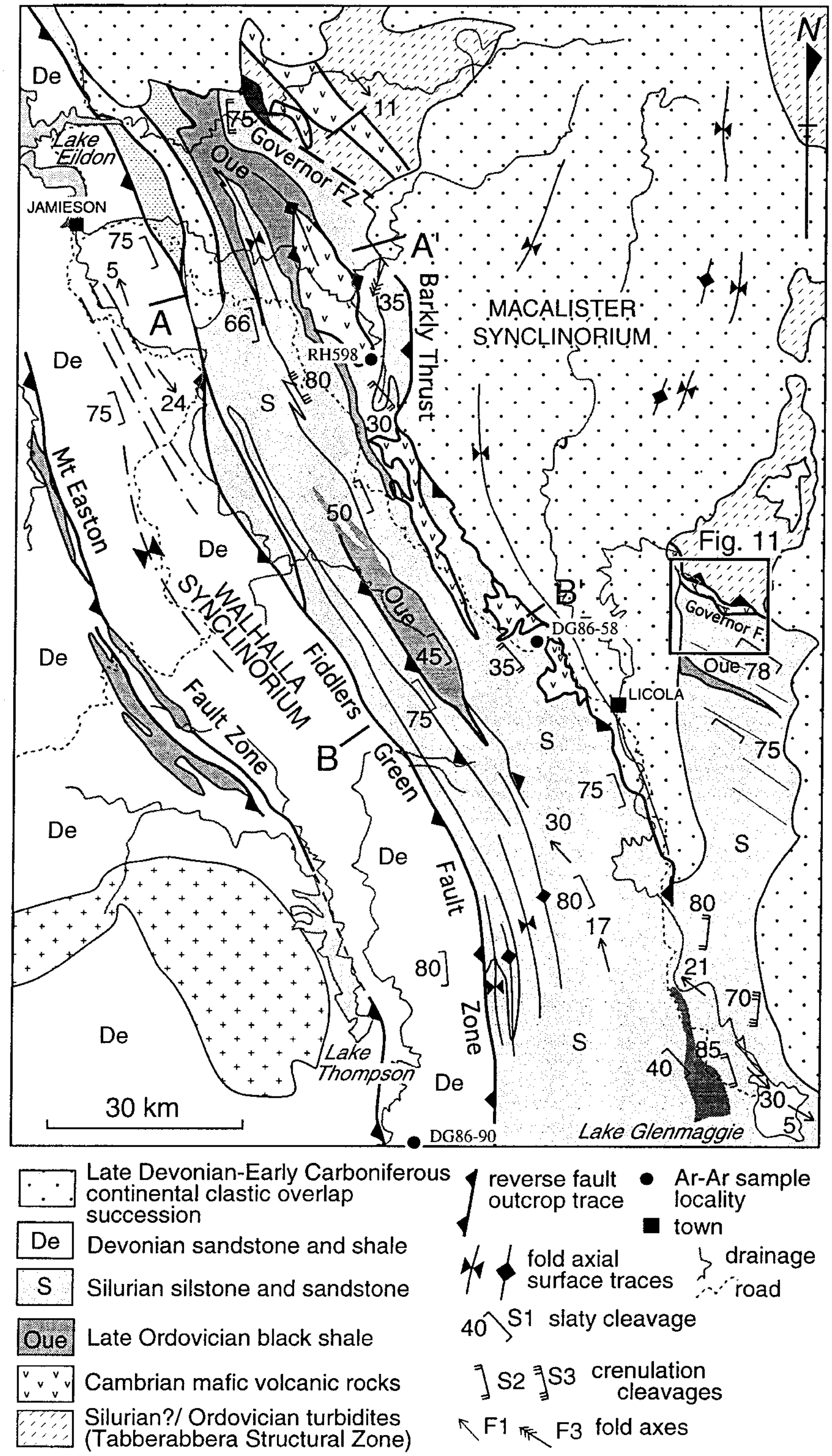

Fig. 8. Geological map of the Mount Wellington Fault Zone along the eastern margin of the Melbourne Structural Zone, western subprovince of the Lachlan Orogen (see Fig. 2 for location) (modified from 1:50,000 scale mapsheets of VandenBerg *et al.*, 1995; Gray, 1995). Position of section lines A–A′ and B–B′ are shown.

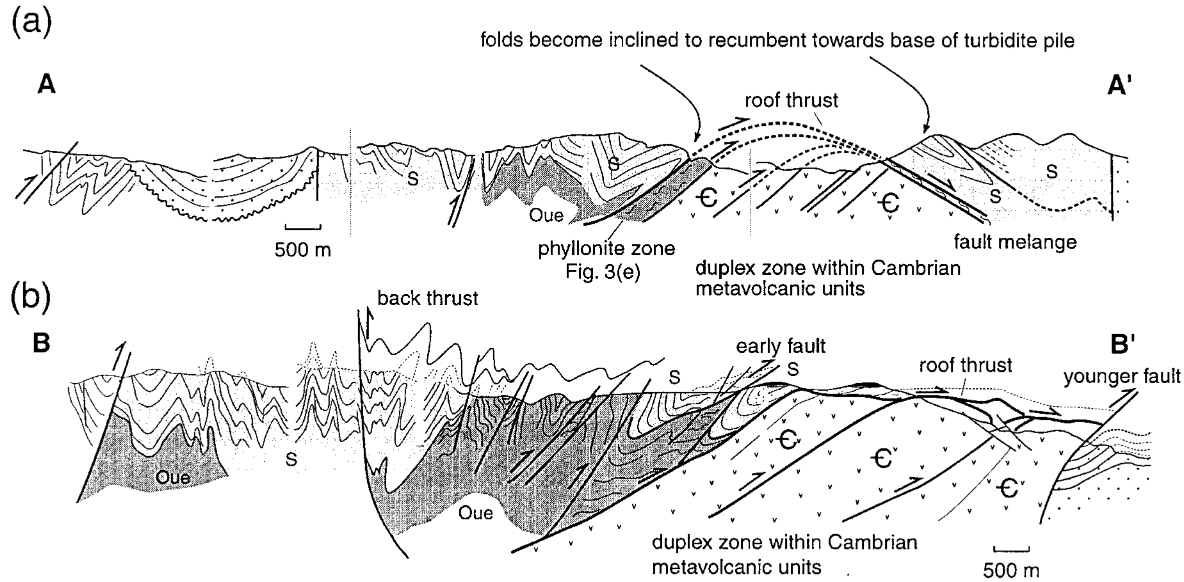

Fig. 9. Structural profiles across the Mount Wellington Fault Zone, western subprovince of the Lachlan Orogen. See Fig. 8 for location. (a) Section A–A′, and (b) section B–B′ (both modified from cross-sections on 1:50,000 scale map-sheets from VandenBerg *et al*., 1995).

fold pairs in the first-formed fabric and have hinges and common limbs consisting of isoclinal crenulations and limbs defined by intensely modified S_1 fabrics. This transposition layering is really a combined S_1/S_2 fabric as the S_1 layering was intensified during the development of the now isoclinal, asymmetric mesofolds. The crenulation cleavage within these zones is at a low angle to S_1 and hence dips steeply west. Both these cleavages are refolded by asymmetric mesofolds whose axial surface crenulation cleavages now dip gently to the east and southeast (see Fig. 5b).

The earliest fabric shows strong non-coaxial west-over-east sense of shear by curved fabrics in pressure shadows in the basal Mine Series black slate at Stawell, and recrystallised tails on plagioclase megacrysts in feldspar–hornblende schists of the Mount Ararat sequence to the south (see Wilson *et al*., 1992, fig. 10).

Avoca Fault Zone. The Avoca Fault Zone (Fault 3: Fig. 1; AFZ: Fig. 2) is a linear, 130 km long (exposed length only), north-trending, steeply west-dipping, 5 km wide fault zone of heterogeneous deformation. It coincides with a major change in structural trend from the northwest in the Stawell Structural Zone to more north–south in the Bendigo–Ballarat Structural Zone (Fig. 2). The fault zone separates fossiliferous Castlemaine Supergroup to the east from unfossiliferous quartz-rich turbidites of inferred Cambrian–Early Ordovician age to the west (Gray, 1988; Gray and Willman, 1991a; Wilson *et al*., 1992; Morand *et al*., 1995; Taylor *et al*., 1996). Deformation is not just restricted to the fault zone itself, but is distributed over a zone at least 20 km wide to the west of the fault zone, as indicated by the deflection of the northwest-trending fold and fault structures of the Stawell Structural Zone into the north–south orientation of the Avoca Fault Zone (Fig. 2).

Rocks in the Avoca Fault Zone are polydeformed and dominated by a strong, steeply dipping, northwest–southeast-trending crenulation cleavage (Figs 4b, 6a & b) which locally transposes bedding in the hanging wall immediately adjacent to the fault zone (Gray and Willman, 1991a; Morand *et al*., 1995; Taylor *et al*., 1996). This cleavage is associated with approximately isoclinal, asymmetric, east-verging meso-faults (F_2) spaced at 2–3 m in the highly deformed parts of the fault zone. Crenulations (F_2) associated with this cleavage show marked plunge changes ranging from subvertical to subhorizontal over several centimetres (Fig. 6b). Less deformed rocks within the fault zone show mesoscopic F_1 folds, an S_1 spaced cleavage, quartz veining and faulting (see Gray and Willman, 1991a, fig. 15b). These F_1 folds plunge moderately northwards and have subvertical north-trending axial surfaces (Fig. 6c). Cleavage–bedding relationships, mesoscopic fold vergence, and the steep westerly-dip of the bedding indicate faulting of a regional anticlinal closure by the Avoca Fault Zone. Outside the fault zone to the west in the Stawell Structural Zone, a greenschist facies quartz-rich turbidite sequence shows inclined, sub-horizontal, northwest-trending F_1 folds associated with a set of west-dipping reverse faults (Wilson *et al*., 1992). Approaching the Avoca Fault Zone these early structures become more north-trending and are overprinted by at least two crenulation cleavage forming events (Gray and Willman, 1991a).

In the southern portion the fault zone is a steep, 2 km wide, polydeformed zone whose boundary is marked by discontinuous pods of ?Cambrian metavolcanics in the hanging wall (Morand *et al*., 1995, fig. 2;

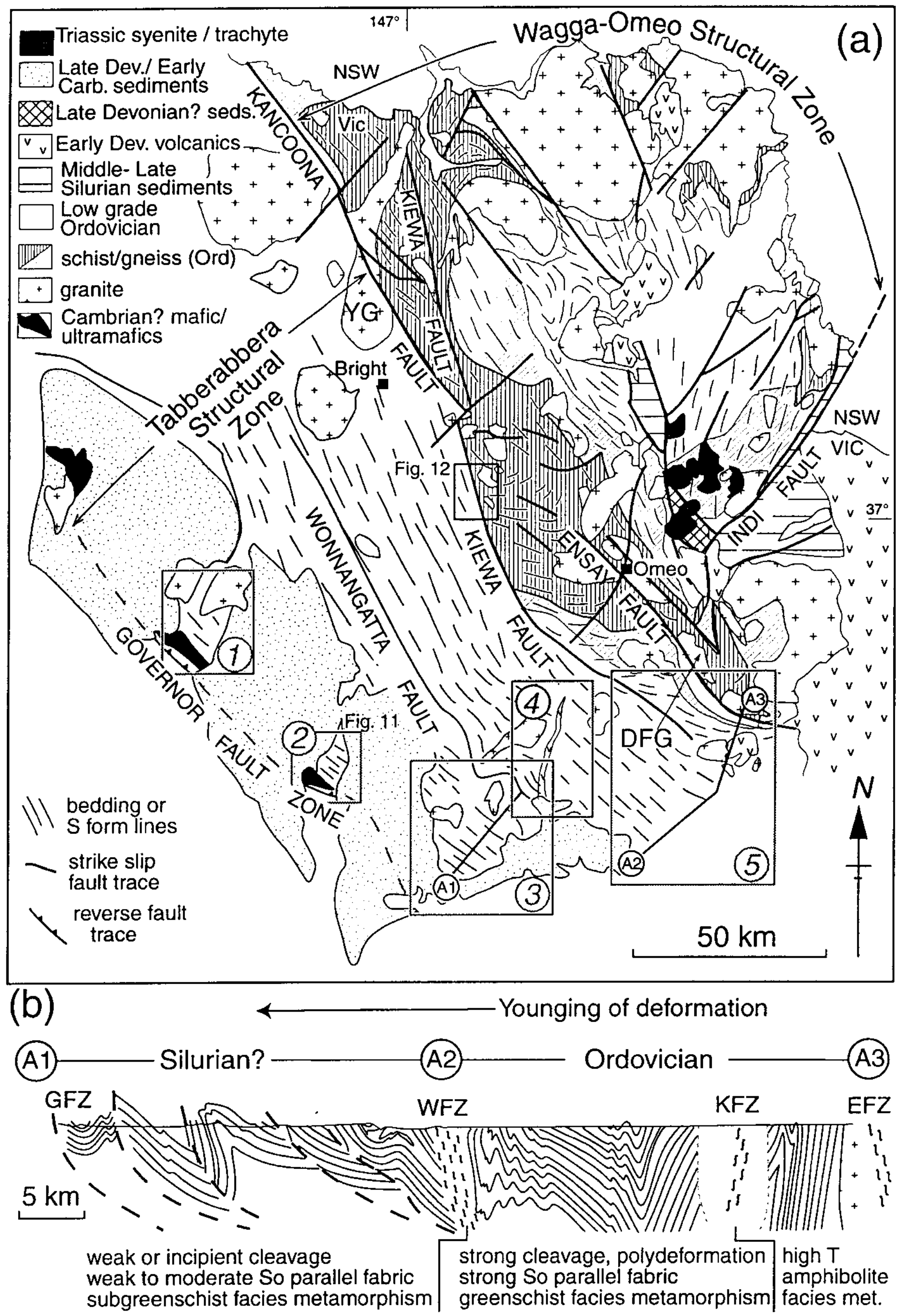

Fig. 10. (a) Geological map of the Tabberabbera Structural Zone and the southern part of the Wagga–Omeo Metamorphic belt, central subprovince of the Lachlan Orogen (see Fig. 1 for location) (modified from Gray, 1988 and Morand and Gray, 1991, fig. 1). Boxes indicate areas of detailed geological work in the Tabberabbera Structural Zone: (1) Fergusson (1998), (2) Andrews (1987), (3) Fergusson (1987a), (4) Fergusson and Gray (1989), (5) Fergusson (1987b). Positions of Figs 11 and 12 are shown. YG: Yackandandah Granite, DFG: Doctors Flat Granite (b) Structural profile A1–A2–A3 across the southern part of the Tabberabbera Structural Zone (modified from Fergusson, 1987a,b). A summary description of degree of cleavage development, intensity of bedding-parallel fabric development, and the grade of metamorphism is listed below the profile.

Taylor *et al.*, 1996). The metavolcanics show intensely flattened vesicles and spherulites, but still show relatively undeformed igneous textures in the interiors of the pods. Interflow sedimentary units show tight to isoclinal folds (Morand *et al.*, 1995). The fault zone is dominated by steeply west dipping to subvertical transposition layering which is transitional into intense crenulation cleavage (Fig. 4e). This encloses shear lenses or zones of asymmetric folded layering up to 0.5 m wide, preserving both earlier and later fold structures (see Morand *et al.*, 1995, fig. 5).

This strong development of a transposition layering in the northern (Gray and Willman, 1991a) and southern (Morand *et al.*, 1995; Taylor *et al.*, 1996) segments of the fault zone is associated with steeply north to northwest-plunging meso- and microfolds within steeply dipping, approximately east-trending sedimentary layering/compositional banding.

The Avoca Fault Zone, unlike the other major fault zones, also shows pronounced footwall deformation in a zone up to 2 km from the eastern fault trace (Fig. 6a). Bedding in this zone is northeast-trending, and has a steep westerly dip, such that all folds plunge steeply to the northwest (Fig. 6d). These are distinct from the regional folds in the Bendigo–Ballarat Structural Zone (Fig. 2) which are upright north-northwest-trending folds with gentle plunges (Gray and Willman, 1991a,b; Cox *et al*., 1991). In this zone early folds are reclined and rotated up to 30° from the regional trend (Fig. 6e).

Heathcote Fault Zone. The Heathcote Fault Zone (Fault 4: Fig. 1; HFZ: Fig. 2) is a linear, 4 km wide, 110 km long (exposed length only), fault-bounded zone of Cambrian metavolcanics and volcaniclastic rocks juxtaposed against less strongly deformed Devonian quartz-rich turbidites of the Melbourne Structural Zone in the east. Tightly folded and cleaved quartz-rich turbidites of the Bendigo–Ballarat Structural Zone occur to the west (Gray and Willman, 1991a,b; Gray *et al*., 1991) (Fig. 2). Structural style and complexity vary along the length of the fault zone. The eastern boundary is characterized by a steeply, west-dipping, reverse fault system. It changes from a fault-bounded zone of essentially homoclinally dipping Cambrian volcanics and clastics in the north, to a structurally complex zone in the central portion near Heathcote where the strike of the fault zone changes to northwest-trending (Figs 2 & 7). In the south, it changes to a single fault which loses stratigraphic displacement within a Late Ordovician sandstone sequence. There, homoclinally-dipping, conformable Cambrian through Ordovician strata define the hanging wall sequence, which suggests that the Cambrian metavolcanics underlie the turbidites of the western subprovince of the Lachlan Orogen. Where the Cambrian metavolcanics are fault-bounded, they are strongly foliated near the faults and in places contain pods of serpentinite, amphibolite and blueschist (Nicholls, 1965; Crawford, 1988, Spaggiari *et al*., 1998). They also contain small, northeast-trending, intra-folial folds which have steeply west or east plunging axes (Gray and Willman, 1991a). The metavolcanics are heterogeneously deformed such that relict igneous and metamorphic textures can be observed.

In the structurally complex central portion, the fault zone consists of imbricated slices of earliest Ordovician (Lancefieldian) to late Early Ordovician (Darriwillian) quartz–turbidites and black shale, Cambrian shale, metavolcanics and chert (Fig. 7). The turbidite slices tend to have homoclinal dip with cleavage dipping less steeply than bedding, folds with gentle south plunge, and reverse faults with westerly dip (Gray and Willman, 1991a, fig. 12). Lancefieldian rocks immediately to the west of the fault zone show a transition into a 1 km wide zone of high strain or intense deformation characterised by intense development of an S_2 crenulation cleavage (grey region, Fig. 7) which is gradational into a subvertical east–southeast trending transposition foliation (Fig. 4a). Relict, rootless, isoclinal fold-hinges in quartz veins, a strong down-dip stretching lineation, and asymmetric 'Z' shaped mesoscopic folds also occur in this high strain zone adjacent to the fault (Fig. 4b). These meso-folds have subvertical west-northwest-trending axial surfaces and generally have steep west or northwest plunges. The transposition foliation is sporadically overprinted by southwest steeply-plunging northeast-trending meso-folds and associated S_3 crenulation cleavage (Gray and Willman, 1991a, fig. 10) (Fig. 7). Relict less-deformed pods containing bedding and slaty cleavage show isoclinal folding, very low bedding–cleavage angles and markedly curved subvertical quartz-fibres in pressure shadows. These features are the same as those observed along other major faults within the slate belt (Gray and Willman, 1991b). In the footwall, the western limb of a northwest-plunging syncline is also overridden and truncated by the fault zone (Fig. 7). This fold is markedly tighter than other folds in the Melbourne Structural Zone where Silurian and Devonian rocks are folded into more open meridional folds with wavelengths on the order of 3–4 km (see VandenBerg, 1988, fig. 4.1; Gray, 1995, fig. 4).

Mt Wellington Fault Zone. The Mt Wellington Fault Zone (Fault 6: Fig. 1; MWFZ: Fig. 2) is a 20 km wide, 135 km long (exposed length only), northwest-striking zone of intense deformation in largely Silurian rocks between the Governor and Fiddlers Green Fault Zones (Fig. 8) along the eastern margin of the Melbourne Zone (Murphy and Gray, 1994; Gray, 1995; VandenBerg *et al*., 1995). Silurian strata show inclined folds, have intense foliation, macroscopic faulting, contain horses or Ordovician black shale/slate and structurally overlie Cambrian? metavolcanics (Harris and Thomas, 1954; VandenBerg, 1978; Murphy and Gray, 1994; Gray, 1995; VandenBerg *et al*., 1995) (Figs 8 & 9). In the hanging wall there is a transition from non- to poorly-cleaved rocks, with little or no strain ($XZ < 1.4$) and open, upright folds in the Melbourne Structural Zone to the west, to rocks with intense cleavage (Figs 3e, 4f & g) and higher strains ($10{:}1 < XZ < 15{:}1$), associated with inclined asymmetric folds in the Mount Wellington Fault Zone (Gray, 1995, fig. 4). The fault zone contains a series of folded, early-formed, stratigraphically-controlled, bedding-parallel faults (VandenBerg *et al*., 1995). It has been interpreted as part of a sole-thrust to an east-vergent thrust system which incorporates the Stawell, Ballarat and Melbourne Structural Zones (Fergusson *et al*., 1986; Murphy and Gray, 1994; Gray and Mortimer, 1996).

The Mount Wellington Fault Zone changes character along strike as a function of structural level and amount of displacement. To the south towards Lake Glenmaggie (Fig. 8), the fault zone consists of inclined regional folds with strongly developed, west-dipping cleavage, separated by poly-deformed 'slide' zones of intense deformation and brittle faults (see Murphy and Gray, 1994). Northwards the zone loses the complex, poly-deformed character particularly where the Melbourne Zone is dominated by east-trending fault and fold structures (see Fig. 2; Gray and Mortimer, 1996). In map pattern (Fig. 8) fault-bounded slices of Late Ordovician black mudstone/slate have tapered ends, are elongated subparallel to the regional strike of the fault zone and show variations in younging, vergence, amount of strain and degree of metamorphism (see Gray, 1995; VandenBerg *et al.*, 1995). The Ordovician slices occur west of the Cambrian inliers (Figs 8 & 9) and are therefore structurally higher. Some occur as isolated slices within the turbidites, or are in fault contact with the metavolcanics. Most tend to have moderately southwest-dipping S_1 cleavage, steeply southwest-dipping bedding with vergence to the southwest indicating derivation from the overturned eastern limbs of regional asymmetric F_1 anticlines (see Gray, 1995). The bounding faults are aligned and subparallel to the regional foliation (Fig. 8) and tend to dip moderately to steeply southwest.

The Cambrian inliers (Fig. 8) have complex internally imbricated stratigraphy truncated by a 'roof' thrust and therefore have the appearance in section of the upper part of a duplex system (Fig. 9a & b). The largest inliers consist of an internally faulted sequence of andesitic lavas, agglomerates, boninites, pillowed and massive tholeiitic basalts, and gabbroic–doleritic intrusives (Crawford, 1988; Hendrickx, 1993; VandenBerg *et al.*, 1995). Aeromagnetic data suggest that these inliers are part of a single large horse with dimensions 45 km long and 5 km wide, and that the outcrop pattern is a series of windows (see VandenBerg *et al.*, 1995). The inliers show heterogeneous deformation with massive, largely undeformed cores that preserve the original igneous textures, stratigraphy and mineralogy of burial metamorphism (prehnite–pumpellyite and prehnite–actinolite facies; Crawford, 1988; Hendrickx, 1993). Towards their margins, the inliers show increasing effects of deformation with development of a strong foliation defined by chlorite, tremolite/actinolite fibres, and granular epidote (metabasalts). Within the largest inlier (Fig. 8) contacts between units are strongly foliated shear zones up to 100 m wide showing augen structures and S–C fabrics with a top to the east sense (Hendrickx, 1993). Bounding faults tend to be north–northwest trending, brittle zones of silicification and brecciation up to 30 m wide (Hendrickx, 1993).

Intra-zone faults

Major intra-zone faults include the Campbelltown, Leichardt, Muckleford, Sebastian and Whitelaw faults (Bendigo–Ballarat Structural Zone) the Stawell–Ararat, Landsborough and Percydale faults (Stawell Structural Zone), and the Waratah and Mt Easton Faults (Melbourne Zone) (Fig. 2a). They are approximately meridional reverse faults which have linear map traces from 25 to 100 km in length, a spacing of approximately 20 km, and a steep westerly dip. Throws are on the order of 1 to 2 km, and the faults generally place lowermost Ordovician (Lancefieldian) over either mid Early Ordovician (Chewtonian–Castlemainian) or latest Early Ordovician (Darriwilian–Yapeenian) rocks. At the present level of exposure these faults all dip at 60° or greater (Fig. 2b), but are considered to have listric form and flatten with depth as suggested by deep crustal seismic profiling of the Heathcote Fault Zone (see Gray *et al.*, 1991). For up to 500 m–1 km from the fault traces, the hanging walls of these faults always consist of homoclinally west-dipping and younging earliest Ordovician (Lancefieldian) strata, with a synclinorial closure to the west. Style and character of intra-zone faults are best exemplified by the Whitelaw Fault (see Gray and Willman, 1991a,b) for deeper levels and the Waratah Fault Zone for shallow levels (Table 2).

Whitelaw Fault (Bendigo–Ballarat Zone). The Whitelaw Fault (WFZ: Fig. 2) is characterised by a 20 m wide polydeformed, north–northwest trending fault zone, with moderate to steeply east-plunging meso-folds and a subvertical northwest-trending axial surface crenulation cleavage (Gray and Willman, 1991a, fig. 4). The fault separates earliest Ordovician (Lancefieldian) beds on the west from latest Early Ordovician (Darriwilian) beds to the east. Within the hanging wall up to 1 km away from the Whitelaw Fault trace, pyritic slates show a strong, subvertical, downdip lineation defined by quartz fibre pressure shadows on pyrite (see Gray and Willman, 1991b, fig. 5). Chevron folds in the turbidite succession of the hanging wall of the Whitelaw Fault show a change in axial surface dip direction, increased fold tightness ($<30°$) and markedly higher strains ($XZ>9{:}1$) within 3 km of the fault trace (see Gray and Willman, 1991b, fig. 6a–c). The background fold-interlimb angle for chevron folds from 3–8 km distance from the Whitelaw Fault is between 30° and 50°, and the background XZ strain representing the structurally highest parts of the thrust sheet is between 4.0 and 6.9 (Gray and Willman, 1991b, fig. 6).

Waratah Fault Zone (Melbourne Zone). The Waratah Fault Zone (Fault 5: Fig. 1) occurs along the eastern margin of the Melbourne Structural Zone and has a map length of about 40 km. It consists of a deformed region up to 500 m wide where fault-melange/gouges, cataclasites, and fault-breccias surround and incorporate lenses and pods of less deformed rocks. The major fault plane is a steep, northeast-striking, brittle fault which juxtaposes a weakly cleaved, chevron-folded turbidite sequence with minor quartz veins (< 1%) (Early Devonian Liptrap Formation) against heavily veined and fractured limestone (Early Devonian Bell Point Limestone). Effects of faulting in the turbidites are shown by a 100–150 km wide zone of tectonic melange and refolding, with minor subsidiary brittle-faulting and cataclasis extending up to 500 m from the major fault trace. Veining and cataclasis in the limestone are most pronounced up to 100 m from the main brittle fault.

The Waratah Fault may form part of a wrench transfer zone between east-vergent structures in the Melbourne Zone (e.g. Gray, 1995) and west-vergent structures in the Mathinna Beds of northern Tasmania (e.g. Woodward *et al.*, 1993) (Fig. 1). Subvertical, strike-slip fault zones, such as the Waratah Fault Zone, can occur within the frontal parts of accretionary wedges (Sample *et al.*, 1993, fig. 1). The nature and extent of cataclasis and veining, as well as the inferred relatively shallow depth of faulting ($\sim$3 km) for the Waratah Fault suggest that it developed in the shallower parts of the migrating and structurally thickening, sedimentary wedge. Scaly-matrix melange and mud diapirism as dykes and meshwork veinlets in the fault-melange zone (Gray *et al.*, in press, Fig. 3) are typical of fault zones in accretionary complexes (e.g. Moore, 1978). These melange zones have been shown to be regions of fluid flow (e.g. Vrolijk, 1987; Vrolijk *et al.*, 1988). Stable isotope and geochemical data from rocks within and adjacent to the Waratah Fault Zone are consistent with this fault zone being an important fluid conduit.

Minor faults

These are typically low displacement (< 50 m) east- and west-dipping reverse faults which strike approximately parallel to fold axial surface traces. Most of these structures are accommodation structures that have developed during fold-tightening (Cox *et al.*, 1991; Gray and Willman, 1991a). They are brittle zones, generally less than 10 cm in thickness, which have associated gold–quartz veins either as extension vein arrays or laminated to massive, within-fault quartz veins (see Cox *et al.*, 1991, fig. 11, 1995; Cox, 1995, fig. 4; cf. Fisher and Byrne, 1987, fig. 3). Many of these veins show fibrous form and have crack–seal inclusion bands indicative of repeated opening and sealing events (see Cox, 1995, fig. 8; cf. Fisher and Brantley, 1992, fig. 4). Crenulation cleavages are locally developed in the footwalls to some of these faults (Fig. 4d).

FAULT ZONES WITHIN THE CENTRAL LACHLAN OROGEN

The central Lachlan Orogen (CS: Fig. 1) is made up of a northwest-trending metamorphic belt (Wagga–Omeo Metamorphic Belt) with a turbidite dominated thrust-belt along the southwestern margin (Tabberabbera Zone) (Fig. 10). The major faults are the Governor (Fault 7: Fig. 1) and Wonnangatta Fault Zones (Fault 8: Fig. 1) of the Tabberabbera Structural Zone (Fig. 10), and the Kiewa (Fault 9: Fig. 1), Kancoona (Fault 9: Fig. 1), Indi (Fault 10: Fig. 1), Ensay (Fault 11: Fig. 1), and Gilmore (Fault 12: Fig. 1) Fault Zones of the Wagga–Omeo Metamorphic Belt (WMB: Fig. 1; Fig. 10).

Governor Fault Zone

The Governor Fault Zone (Fault 7: Fig. 1; Fig. 10) is a northwest-trending fault zone that defines the southwestern margin of, and is the leading fault for, the Tabberabbera Structural Zone (VandenBerg *et al.*, 1995; Fergusson, 1998) (Figs 2 & 10). Exposure of the fault is limited to two valleys. In the northern valley (circled 1, Fig. 10a) the frontal region consists of a series of strongly deformed cherts and silicified black mudstones containing slices of ultramafic boninitic lava and breccia and intercalated volcaniclastic rocks (VandenBerg *et al.*, 1995). The fault zone west of the main Cambrian metavolcanic-chert slice consists of steeply dipping, tectonic melange (Fergusson, 1998; Spaggiari *et al.*, 1998). Within this slice metavolcanics consist of steeply dipping, northeast younging, fault-bounded, shoshonitic and tholeiitic basalts and andesites, and volcaniclastics (Crawford, 1988; VandenBerg *et al.*, 1995).

In the southern valley (circled 2, Fig. 10a) it is a complex, 1–1.5 km wide, subvertical zone bounded by steep faults (Fig. 11 a & b). The zone is dominated by a major sliver of serpentinised cumulate peridotite, with clinopyroxenite and podiform chromite, in fault contact with smaller slices of steeply-dipping Cambrian volcaniclastic sandstones and fossiliferous limestones, and Late Ordovician graptolitic black shales (Andrews, 1987). *S*–*C* fabrics indicate northeast over southwest simple shear during internal deformation and serpentinisation of the peridotite with NE–SW directed compression, deduced from slip normal analysis after Arthaud (1969) of slickensided fracture surfaces within the ultramafic unit (Andrews, 1987). Emplacement from the northeast is suggested by the *S*–*C* fabrics and increasing intensity of deformation towards the southern margin of the peridotite, and the vergence of folds within the turbidites to the northeast (Andrews, 1987) (Fig. 11b).

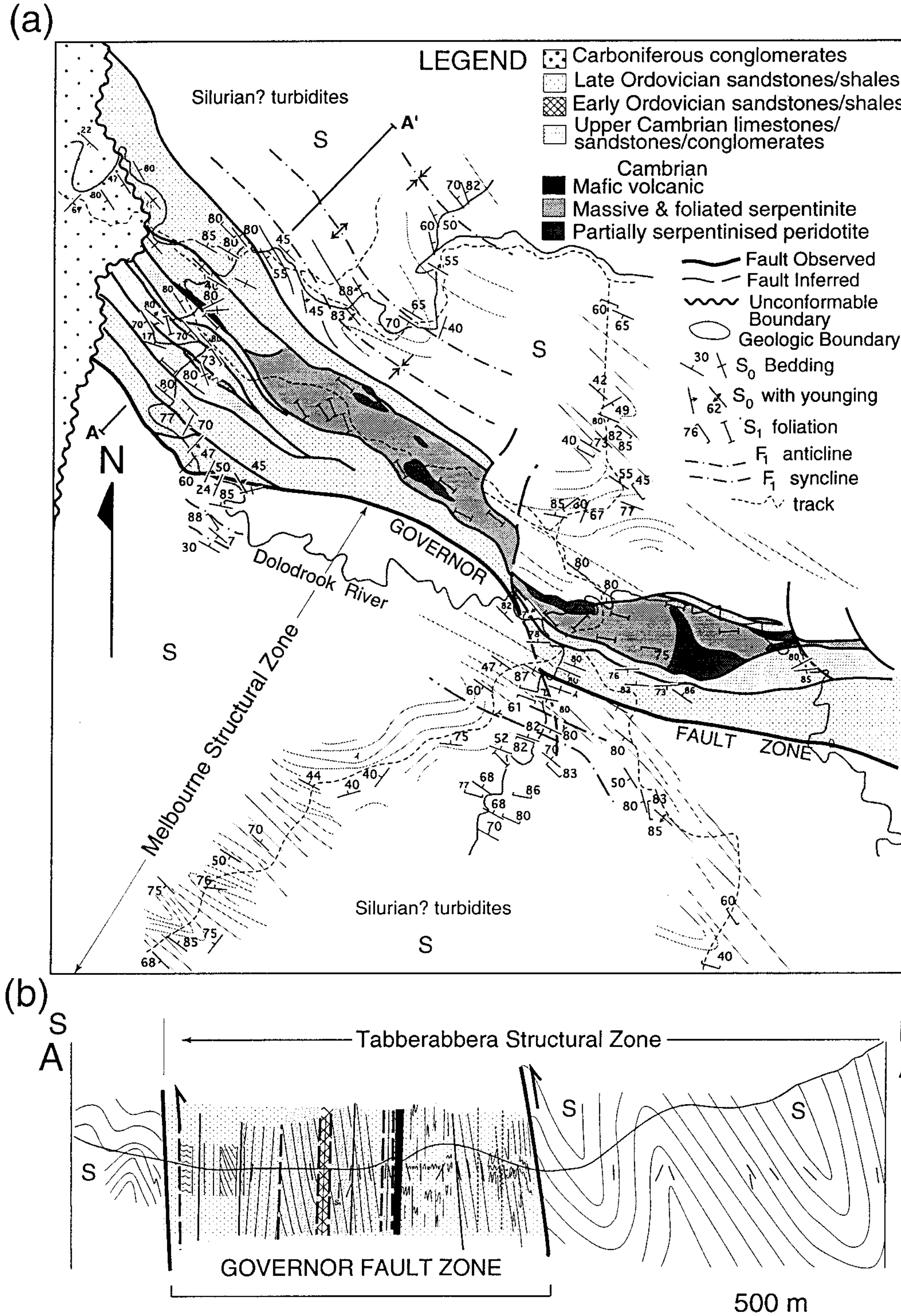

Fig. 11. (a) Structural map of part of the Governor Fault Zone, Dolodrook River, central subprovince of the Lachlan Orogen (see Fig. 10 for location) (based on mapping by Andrews, 1987 and unpublished data kindly given to us by Peter Sorensen-Ward). (b) Structural profile across the Governor Fault Zone incorporating the Dolodrook Inlier (from Andrews, 1987).

Wonnangatta Fault Zone

The Wonnangatta Fault Zone (Fault 8: Fig. 1; Fig. 10a) or Wonnangatta Line of Fergusson (1987a) is a steeply dipping 2 km wide, melange zone that juxtaposes weakly metamorphosed, simply deformed Silurian? turbidite strata against polydeformed, low greenschist grade, metamorphosed Ordovician turbidites (Fergusson, 1987a,b; Fergusson and Gray, 1989; Fergusson, 1998) (Fig. 10b). The melange consists of phacoidal, boudinaged, sandstone fragments and cm–km scale chert blocks within a scaly mudstone matrix

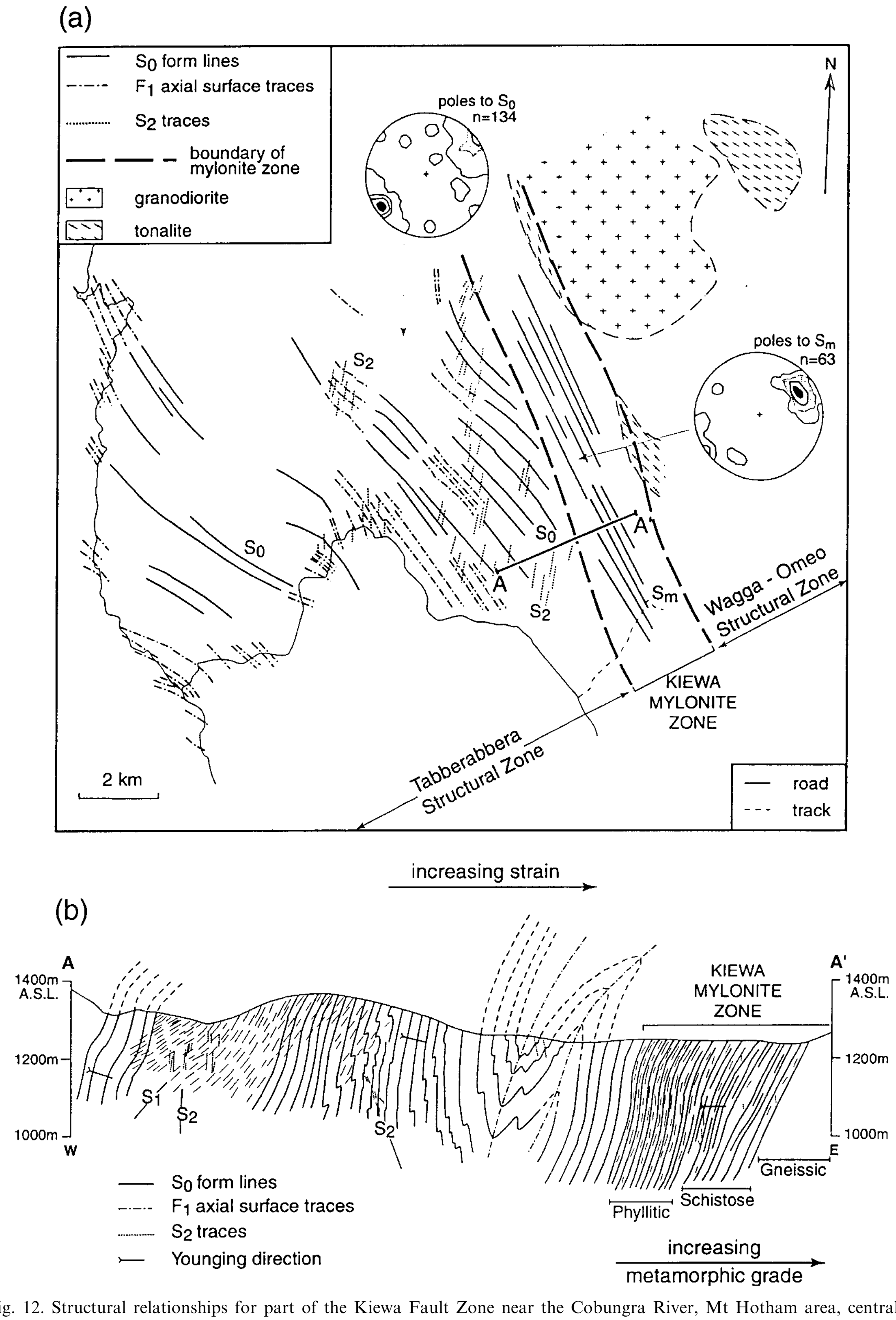

Fig. 12. Structural relationships for part of the Kiewa Fault Zone near the Cobungra River, Mt Hotham area, central subprovince of the Lachlan Orogen. (a) Structural map of the fault zone (see Fig. 11 for location) (based on mapping by Scott, 1985 and Brownscombe, 1986). (b) Structural profile across the Kiewa Fault Zone (from Scott, 1985, and Scott, unpublished data) [see (a) for location].

(Fergusson, 1987a, fig. 13a–d). Slightly turbid and rounded shapes of sandstone fragments, and disruption and injection of mudstone suggest melange formation relates to deformation of partly unconsolidated sediments (Fergusson, 1987a, pp. 50–51). Scaly cleavage within the zone is subparallel to slaty cleavage in the domains adjacent to the fault zone.

Metamorphic Zone Faults (central subprovince)

Major fault zones both within and bounding the Wagga–Omeo Metamorphic Belt (WMB: Fig. 1) are mylonite zones containing mylonitised schist, gneiss and granite (Gray, 1988; Morand, 1990; Morand and Gray, 1991). They include the Kiewa, Kancoona, Ensay and Indi Fault Zones, which have wide mylonite zones containing *S–C* tectonites (Figs 10, 12 & 13). The northwest-striking Kiewa, Kancoona and Ensay Fault Zones show evidence of major dextral strike-slip movement during the Late Silurian to Early Devonian time, as shown by stretching lineations and mylonite fabrics cutting Late Silurian and Early Devonian plutons (Morand and Gray, 1991). These fault zones do not preserve evidence of any earlier movement. The Indi Fault is a west dipping, north–northeast striking thrust, with mylonite fabrics indicating east-directed thrusting (Morand and Gray, 1991, figs 10 and 11a). This movement occurred during the Late Silurian to

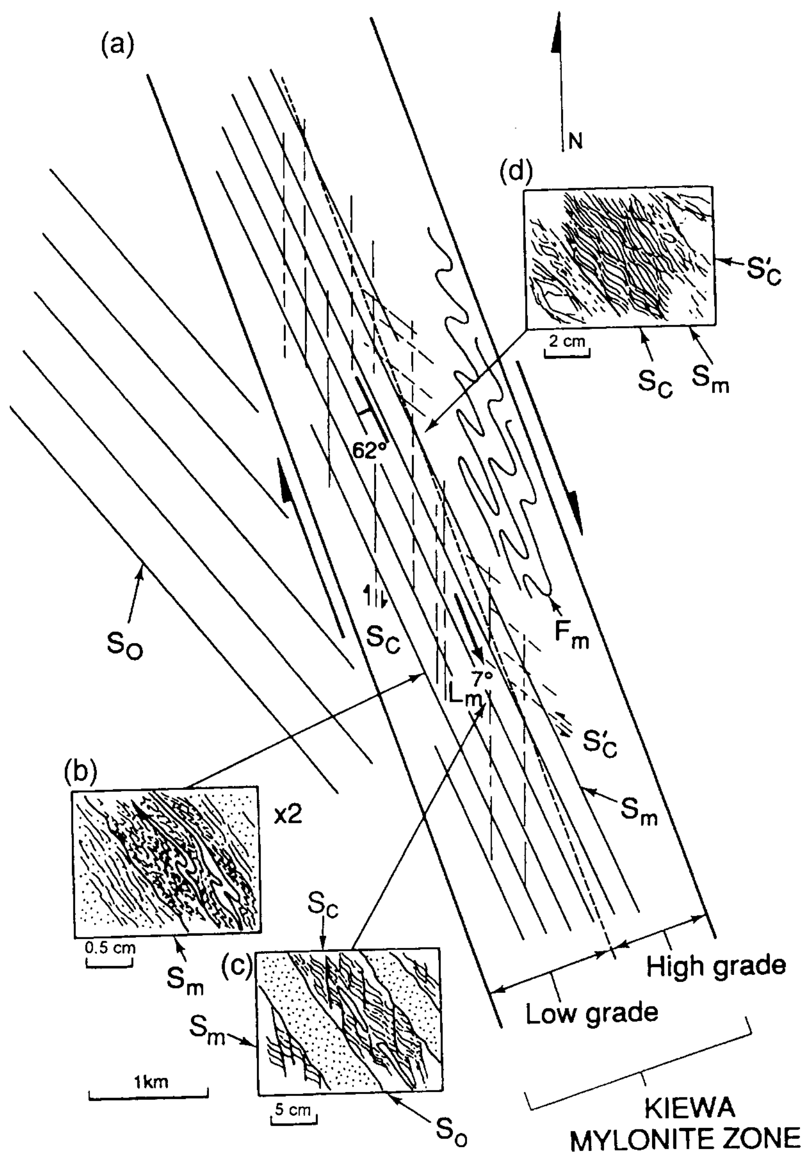

Fig. 13. Schematic structural relationships within the Kiewa Fault Zone bounding the Wagga–Omeo Metamorphic belt, central subprovince of the Lachlan Orogen (modified from Scott, 1985, fig. 34). (a) Map view showing form lines of various overprinting structural elements, with detailed sketches of structural relationships shown in (b), (c) and (d). Mesoscopic structures indicating dextral shear strain include shear bands (S_c) and meso-folds in the dominant foliation (S_m), with bedding preserved in the low grade, western part of the mylonite zone. In the high grade part on the eastern side [see (a)] dextral shear strain is reflected by asymmetric folds (F_m) in S_m, with S_c (synthetic) and S'_c (antithetic) shear bands reflecting a component of flattening strain across this part of the mylonite zone.

Early Devonian, contemporaneous with folding and cleavage development in adjacent Silurian strata. Major displacement on these boundary faults, characterised by dextral movement on the Kiewa, Kancoona and Ensay Fault Zones, and thrusting on the Indi Fault Zone, therefore occurred during and after the Early to Middle Silurian metamorphism, but before overprinting of the mylonites by a meridional, Middle Devonian crenulation cleavage (Morand and Gray, 1991; Gray, 1997).

Kiewa Fault Zone. The Kiewa Fault Zone (Fault 9: Figs 1 & 10) is a steeply west-dipping, strike-slip fault which marks the western boundary of the Wagga–Omeo Metamorphic Complex, generally juxtaposing migmatite against low grade slate (Fig. 10a). Over most of the 200 km exposed strike-length, it is high grade mylonite zone up to 2 km wide characterised by mylonitic layering and subhorizontal lineation, and is transitional into the low grade and high grade rocks at its western and eastern margins, respectively (Fig. 12 a & b). The fault is marked by a rapid increase in metamorphic grade from the protomylonites along the western margin, to mylonite with progressively phyllitic, schistose and finally gneissic appearance (Fig. 12b). Boundaries between these various textural subzones of mylonite are graditional with rocks of adjacent textural types anastomosing in and out of each other across narrow transition zones (Scott, 1985; Morand and Gray, 1991). Throughout most of the fault zone, the mylonitic layering dips moderately steeply to the southwest, trends at a low angle to the zone boundaries, and is cut by small shear bands at an angle of about 20° to the zone boundaries indicating dextral movement for the zone (Fig. 13), consistent with other shear sense indicators such as folded veins and mica-fish (see Morand and Gray, 1991, fig. 4a–c).

Within the protomylonite subzone, fault rocks commonly show compositional banding which resembles bedding, although it is sometimes strongly transposed. In the phyllitic subzone, mylonitisation is more obvious, although compositional layering is still recognisably bedding and there is weak development of shear bands (Fig. 13) (Scott, 1985). Within the schistose mylonite, shear bands are well developed in pelitic layers, and psammitic layers are either boudinaged or complexly folded with axes parallel to the extension lineation on mylonitic foliation (Scott, 1985). In the high grade gneissic mylonite subzone, there are transitions from protomylonite to gneissic mylonite. Protomylonites show compositional banding, representing transposed original bedding, and have a well developed biotite–fibrolite foliation enclosing porphyroblasts of feldspar and cordierite (Morand and Gray, 1991). With increasing deformation, strong transposition and attenuation of layering is accompanied by development of feldspar 'augen' (Morand and Gray, 1991, fig. 4a). Shear bands are well developed towards the centre of the mylonite and frequently occur as conjugate sets (Fig. 13).

The most strongly deformed part of the fault zone is a relatively narrow zone of ultramylonite which separates schistose and gneissic mylonites on the low and high grade sides, respectively (Fig. 12b). These rocks are extremely fine grained, with thin compositional banding, and have minor shear band development at a low angle to the layering (Scott, 1985). Folds are locally developed throughout the fault zone but are much more significant on the high grade side (Fig. 12b). Near the eastern margin of the gneissic mylonite they have steep plunges and are open with axial surfaces orthogonal to the lineation (Scott, 1985). These are reoriented and become progressively tighter towards the centre of the mylonite where they usually have axial surfaces parallel to the mylonitic foliation and axes parallel to the stretching lineation. On the low grade side of the fault, northwest-trending, east-verging F_1 folds which are developed in zones spaced at intervals of 1.5 to 1.75 km are oblique to the Kiewa fault zone (Fig. 12a). Immediately adjacent to the fault, bedding is overturned and dips steeply west subparallel to the mylonitic layering of the fault zone. Vergence of minor F_1 folds indicates a major F_1 antiform to the west (Scott, 1985). A steeply dipping, north–northeast trending crenulation cleavage S_2 overprints the mylonitic layering on the low grade side of the fault (Morand and Gray, 1991, fig. 3; Fig. 12a & b).

Kancoona Fault Zone. The Kancoona Fault Zone (Fig. 10) is a splay off the Kiewa Fault Zone (Morand and Gray, 1991, figs 1 & 2) marking the northwestern edge of the Wagga–Omeo Metamorphic Complex (WMB: Fig. 1). This fault zone has an approximate width of 600 m and cuts across the metamorphic zones at a low angle. Along most of its length, a narrow belt of cordierite zone schist lies between sillimanite–K-feldspar gneiss and the fault, with biotite and chlorite zone slate (Tabberabbera Structural Zone) against the fault to the west. The boundary between the mainly gently dipping foliation in the gneiss and the steeply dipping mylonites of the Kancoona Fault Zone is sharp (Fig. 10). Microstructures in the gneiss however, show the influence of the fault up to 500 m east of the mylonite zone. Mesoscopic structure in the mylonite zone is dominated by a northwest-striking, subvertical mylonitic *S–C* foliation. A relict shape fabric (*S*) curves into *C* with dextral asymmetry, where the angle between *S* and *C* is typically about 25° (Sandiford *et al*., 1988, figs 2 & 6; Morand and Gray, 1991, fig. 8). Schistose mylonite grades westwards into slate and psammite of the biotite and chlorite zones of the Tabberabbera Structural Zone. Structure in the low grade Ordovician rocks is relatively simple, with a set of close to tight, asymmetric, gently plunging, northwest-trending folds. As the Kancoona Fault Zone is approached, these folds become tighter, the axial sur-

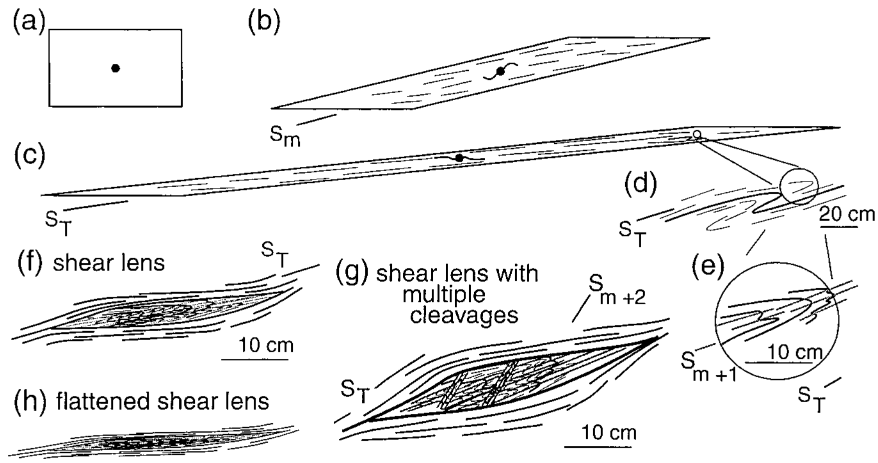

Fig. 14. Schematic diagram illustrating the development of successive crenulation cleavages, 'shear lenses' (after Ghosh and Sengupta, 1987) and transposed layering during 'transposition cycling' (after Tobisch and Paterson, 1988) within the basal, high strain zone of the turbidite thrust sheets typical of the western subprovince of the Lachlan Orogen. (a) Initial state; (b) moderate shear strain ($1 < \gamma < 10$) showing strong fabric development with pressure shadow showing curved fibres indicating non-coaxial deformation in basal zone of thrust sheet; (c) extreme shear strain ($\gamma > 10$) with development of intense transposition layering (S_T) in basal zone of thrust sheet; (d) close up of transposition layering (S_T) with minor fold; (e) enlargement of hinge of fold in (d) showing axial surface crenulation cleavage (S_{m+1}) with minor fold; (f) shear lens preserved within transposition layering with a minor fold-relict and the axial surface crenulation cleavage (S_{m+1}); (g) shear lens with multiple cleavages (S_{m+1} and S_{m+2}), recording the progressive, cyclical nature of the deformation during development of the transposition layering (S_T). With increasing strain the angle decreases between S_{m+1} and S_{m+2}; (h) flattened shear lens which develops with continued deformation and increasing strain. Compare with photographs in Figs 3 and 4.

face cleavage becomes steeper, and a crenulation cleavage develops subparallel to the fault zone (Morand and Gray, 1991).

Where the Kancoona Fault Zone cuts the Middle Devonian Yackandandah Granite (YG, Fig. 10) it consists of a 3.5 km wide shear zone of *S–C* mylonite with a 7 km sinistral displacement (Sandiford *et al.*, 1988; Morand and Gray, 1991). Within the shear zone, two vertical surfaces, *S* and *C*, are developed, with *C* parallel to the shear zone boundaries and *S* curving into *C* with sinistral asymmetry (Sandiford *et al.*, 1988). *C* surfaces are spaced at about two or three centimetres, and the angle between *S* and *C* is about 20°–25° in the centre of the shear zone and 30°–45° in the outer parts (Sandiford *et al.*, 1988; Morand and Gray, 1991, figs 14 & 15). Stretching lineations are subhorizontal and are widespread throughout the length of the shear zone in the granite (Sandiford *et al.*, 1988).

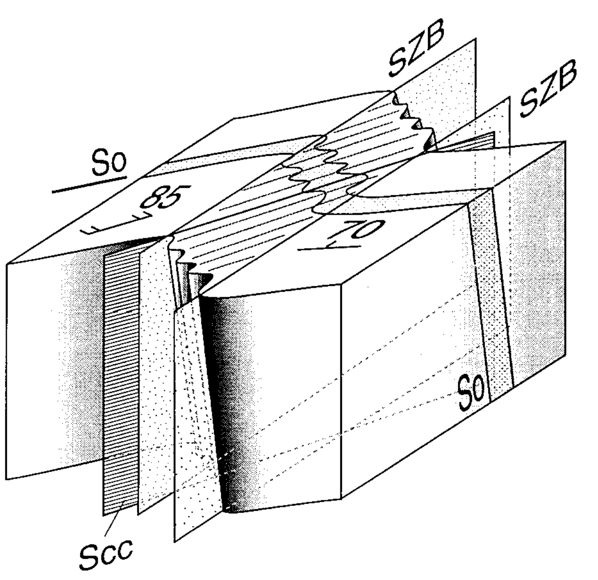

Fig. 15. Schematic block diagram of transpressive shear zone in steeply dipping, low grade (greenschist facies) interbedded sandstone and mudstone sequences. Crenulation cleavages (S_{cc}) form oblique to the shear zone boundaries (SZB) and have associated steeply-plunging meso- and micro-folds. The shear zone is oblique to the moderately to steeply-dipping sedimentary layering (S_o) in both the footwall and hanging wall. The S_{cc} can therefore be used to indicate sense of shear displacement along shear zones. High strain zones occurring within psammo–pelite turbidite sequences that have oblique or wrench-type movements.

Ensay Fault Zone. The Ensay Fault Zone (Fault 11: Figs 1 & 10) consists of a northwest-trending, approximately 1 km wide zone of mylonite and cataclasite which cuts metamorphic isograds and several granitic plutons (Morand and Gray, 1991, fig. 9; Morand, 1990, 1992). The most important of these is the foliated Doctors Flat Granite (DFG, Fig. 10), an I-type granitoid with a Siluro–Devonian K–Ar biotite age (Richards and Singleton, 1981).

In the northwest, the fault zone consists of mylonitized gneiss with mainly biotite + muscovite + quartz mineral assemblages and two, slightly oblique (20°), steeply southwest-dipping mylonitic foliations (*S* and *C*) indicating dextral shear (Morand and Gray, 1991, fig. 4d). In places *S* is less obvious and overprinted by fracturing and brecciation, with cataclasite preferentially developed along some *C* surfaces (Morand and Gray, 1991). The central part of the Ensay Fault zone adjacent to the Doctors Flat Pluton is mainly mylonite cut by shear bands (C) with dextral asymmetry. Both are vertical, C striking approximately parallel to the fault zone and S usually striking more westerly than C. Mylonite along this section of the fault is derived from both granite and gneiss.

Indi Fault Zone. The Indi Fault Zone (Fault 10: figs 1 & 10) is moderately WNW-dipping mylonite zone defining the eastern boundary of the Wagga–Omeo Metamorphic Complex (Morand and Gray, 1991, fig. 10). Folded Silurian strata of greenschist facies grade forms the footwall, and gneiss, schist and granite forms the hanging wall. Where the fault zone separates Silurian acid to intermediate volcanics from high grade metamorphics and granite, the eastern part of the mylonite zone is composed of mylonitized volcanics which are fine-grained, strongly layered and lineated (VandenBerg and Allen, 1988). On the western side of the fault zone, mylonites are derived from granite and high grade metamorphic rocks and are medium-grained with feldspar porphyroclasts. Mylonites in the Indi Fault Zone have a schistosity defined by alternating quartz- and mica-rich layers. Shear bands and mica fish, and a down-dip stretching lineation indicate west-over-east movement consistent with reverse faulting or thrusting (Morand and Gray, 1991, fig. 11a).

FAULT ZONES WITHIN THE EASTERN LACHLAN OROGEN

Fault zones in the eastern subprovince of the Lachlan Orogen (ES, Fig. 1) consist of both brittle, high-angle reverse faults (see Glen and VandenBerg, 1987; Fergusson and VandenBerg, 1990) and deeper level shear zones. The shear zones either occur along the east side of plutons (Begg *et al*., 1988; Burg and Wilson, 1988; Paterson *et al*., 1990; Tobisch and Paterson, 1990), or on the eastern side of metamorphic complexes which define the eastern metamorphic belt of the eastern Lachlan Orogen (Fig. 1; see Glen, 1992, table 2, 1995). The shear zones are characterised by high strain, multiple cleavages, mesoscopic sheath folds, transposition layering, shear bands and S–C fabrics, and quartz c-axis fabrics all of which indicate west-over-east shearing. 'Thrusting' deformation produced gneissic banding, mylonitic layering and secondary foliations in the granites, and complex, polyphase folding in the wallrocks (see Paterson *et al*., 1990). Shear zones range from hundreds of metres up to 5 km in width. The brittle, reverse faults of the eastern subprovince generally occur in the more external part of the Yalmy–Bungonia thrust-belt (after Fergusson and VandenBerg, 1990) (includes Fault 13: Yalmy Fault Zone; Fault 15: Yarralow Fault; Fault 16: Razorback Fault; Fault 17: Copperhannia Fault; Fig. 1). In the southern part, structural repetition or interleaving of the Ordovican and Silurian turbidite package is responsible for an inferred listric-fault system (Glen and VandenBerg, 1987). To the north, the faults are steep (dips $>60°$) as in the western Lachlan Orogen, and clearly cut the chevron-folded sequences (see Fergusson and VandenBerg, 1990).

Outboard of these rocks to the east, large scale imbrication within a turbidite, chert, basalt and melange sequence of mid-Cambrian to Late Ordovician age, is considered part of a mid-Palaeozoic subduction complex in the eastern part of the Lachlan Orogen (Miller and Gray, 1996, 1997). Early fault zones (Fault 14: Fig. 1) are layer-parallel, high strain zones consisting of broken formation and strong to intense bedding-parallel cleavage (Miller and Gray, 1996, figs 7 & 8). Fabrics within the high strain zones are transitional into coherent bedding with a slaty cleavage at a low angle to bedding. Turbidites in the vicinity of these high strain zones have a very pronounced bedding-parallel slaty cleavage. This fabric locally crosscuts bedding, is axial surface to isoclinal folds in quartz veins, and therefore of a tectonic and not sedimentary origin (Powell and Rickard, 1985; Wilson and de Hedouville, 1985), and is probably related to subduction (see Miller and Gray, 1996). Cherts below the turbidites show multiple folding events and zones of stratal disruption with intense veining and stylolitisation. The structurally lowest units, including deformed pillow basalts and block-in-matrix melange, show strong planar-linear fabrics. In the block-in-matrix-melange, prolate-shaped pods of sandstone and chert are aligned subparallel to the bulk extension direction defined by mica pull-aparts and pressure shadows on pyrite within the scaly-fabric mudstone matrix (Miller and Gray, 1996, figs 7 f & g). Mica neocrystallisation and pressure solution are the dominant deformation mechanisms at the base of the complex. The complex is further chopped up by significant later brittle faulting (Miller and Gray, 1997).

SIGNIFICANCE OF DEFORMATION WITHIN FAULT ZONES

Major fault zones in these structurally thickened turbidite wedges of the Lachlan Orogen are wide zones of high strain, intense mica fabrics and complex, poly-deformation (Figs 3 & 4). Deformation must involve "transposition cycling" (after Tobisch and Paterson, 1988), where an initial fabric develops in simple shear and with progressive deformation at high strains, becomes refolded and develops strong to intense zones of crenulation cleavage which are transitional into transposition layering (see Fig. 14; Mawer & Williams, 1991). A kinematic model for initiation and development of small scale crenulation cleavage (see Gray and Durney, 1979, fig. 17) requires crenulation of an existing anisotropy (S_{n-1}) once it enters the field of incremental shortening (phase n) to develop a new cleavage S_n. S_n will remain stable provided S_{n-1} remains in the

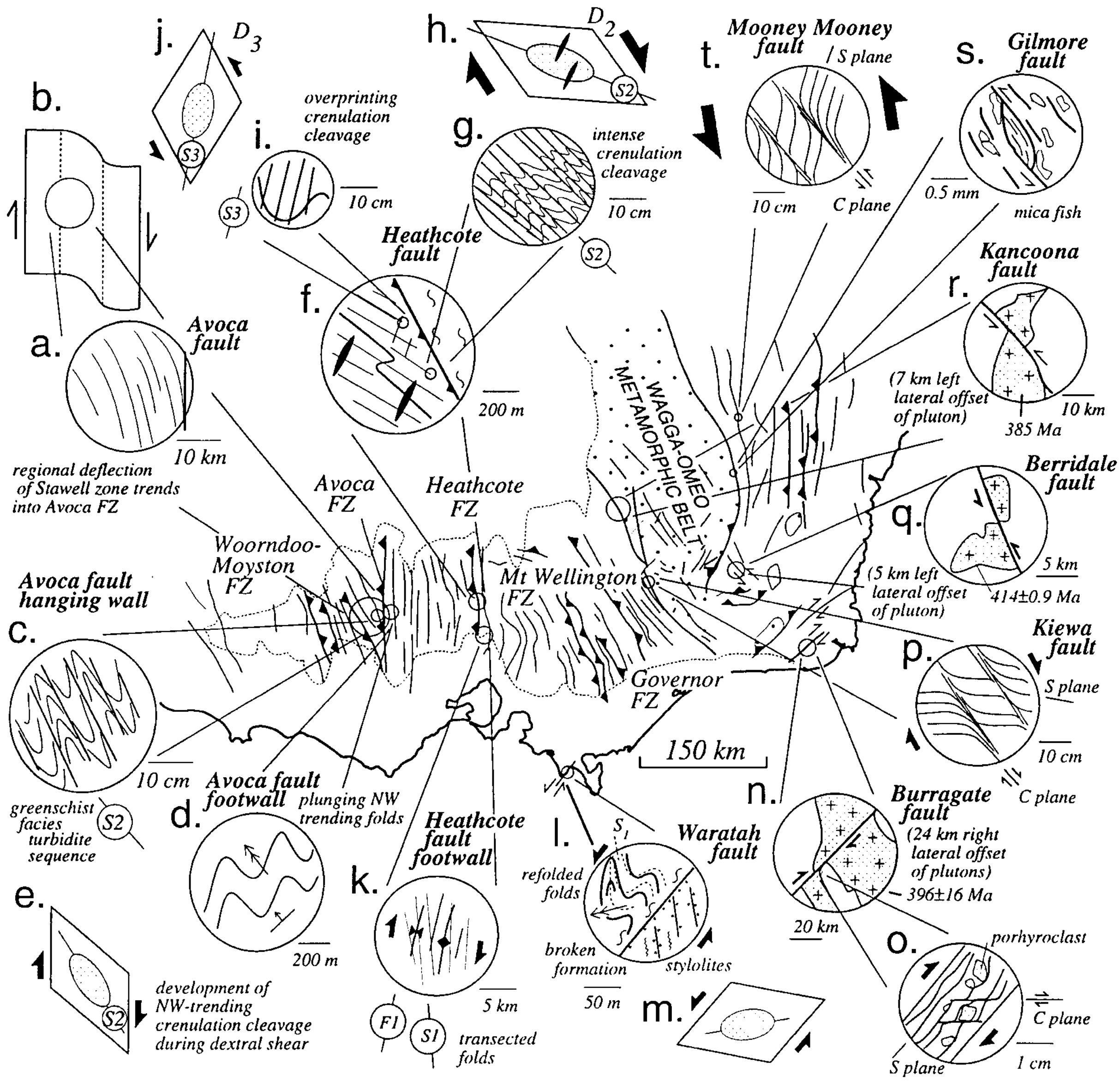

Fig. 16. Various kinematic indicators of movement along faults in the Lachlan Orogen of southeastern Australia. Mylonitic shear zones exhibit classic shear bands and *S–C* fabrics (o, p, s, t), truncations and offset of granitic plutons (n, q, r), whereas the lower metamorphic grade high strain zones in the psammo–pelite sequences record overprinting crenulation cleavages as kinematic indicators (c–j), and deviations of regional structural trends (a, b). The eastern sub-province of the Lachlan Orogen is dominated by wrench and/or oblique slip movements on both faults and shear zones, particularly in the Early Devonian period (cf. Begg *et al.,* 1988).

field of progressive crenulation shortening and S_n within the field of incremental extension. If neither holds then a new crenulation S_{n+1} will be initiated. Strain history data (Gray and Durney, 1979; Fisher, 1990; Burks and Mosher, 1996) indicate that an obliquity of about 45° of the incremental extension direction with the slaty cleavage must occur before initiation of a distinct new cleavage or crenulation lineation. Such behaviour commonly occurs during non-coaxial deformation in shear zones. Fault zones of the western Lachlan Orogen are clearly zones of higher strain exhibiting strong non-coaxial behaviour (see Gray and Willman, 1991a,b; Wilson *et al*., 1992; Gray, 1995) which accords with strain softening along faults as potential weak zones in the chevron-folded wedge. Mica growth within these 500 m–1 km thick zones of higher strain is an integral part of the strain softening process (see Gray, 1995). Metamorphic mica defines an almost continuous interpenetrating fabric at the scale of the grains (e.g. Fig. 4f). It is this growth of mica which has enabled the dating of deformation throughout the structurally-thickened turbidite wedges of the western Lachlan Orogen (see Bucher *et al.,* 1996; Foster *et al*., 1996, 1998; Foster and Gray, in press).

The fault zones truncate fold structures in both hanging wall and footwall (e.g. Figs 6 & 11) requiring that folding either predated or was synchronous with 'thrusting'. Geochronological data also suggest that most of the faults post-date folding, with crystallisation ages of cleavage micas in the fault hanging walls being older than the crystallisation age for the dominant mica generation in the fault zones (cf. Foster *et al*., 1996, 1998). Development and propagation of the major detachment/décollement at the base of the turbidite succession was however, probably ongoing with folding in the turbidite succession of the wedge proper (Foster and Gray, in press). Modelling of accretionary prisms (e.g. Davis *et al.,* 1983; Wang and Davis, 1996) requires attainment of a critical taper prior to significant movement on the basal fault or décollement. In sediment prisms dominated by thick (>5 km thickness) sequences of interbedded sandstones and mudstones, this takes place by chevron-folding within the wedge accompanied by later imbrication, where the overall shortening is dominated by folding (60–65%) and that related to faulting is significantly lower (<15%) (see Gray and Willman, 1991a, b). We argue that this deformation scenario is the structural tem-

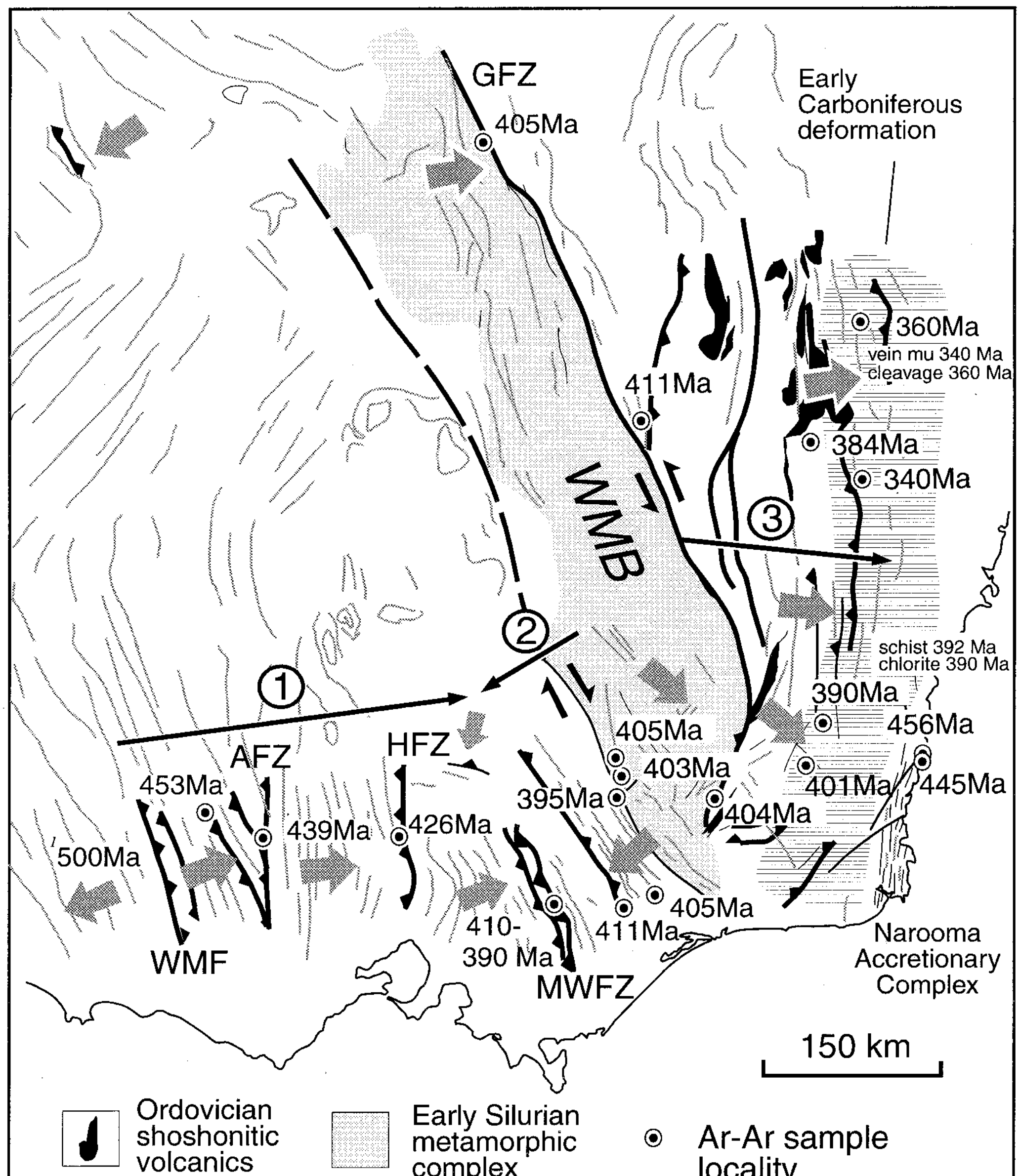

Fig. 17. Map of the Lachlan Orogen, southeastern Australia showing ages of deformation based on Ar–Ar geochronology (Foster *et al*., 1996, 1998; Foster and Gray, in press) and the various vergence belts (modified from Gray, 1997, figs 14 & 15; and Gray *et al*., 1997, fig. 7). Grey arrows indicate directions of tectonic transport ('tectonic vergence') based on the dip of the major faults and regional fold asymmetry. The thin black arrows define the three belts (circled numbers 1, 2 and 3) of deformation that were operating concurrently from the Late Ordovician through Early Devonian periods. Note the distinct belt of Early Carboniferous deformation (360–340 Ma deformation ages) which separates the Narooma Accretionary Complex (456–445 Ma deformation ages) from the northwestern part of N.S.W. that underwent deformation in the period 411–384 Ma. These data are important in the tectonic interpretation of Lachlan Orogen development (see text).

plate for deformation in these oceanic settings (see also Foster and Gray, in press).

Mesoscopic structural features within fault zones, such as obliquely trending crenulation cleavages and steeply-plunging folds (Fig. 15; cf. Burks and Mosher, 1996), suggest that the major faults of the western Lachlan Orogen may have had oblique and/or wrench movement components at various stages in their history (Fig. 16). These structures clearly overprint the regional folds and cleavage. This suggests that either the oblique/strike-slip movements came after the major dip-slip reverse movements which emplaced the turbidites to their present crustal levels, or that during progressive deformation later movements may have had oblique components which caused the development of fault-zone oblique crenulation cleavages and transposition layering. Many faults have locally adjacent zones of one or more crenulation cleavages; for example the Avoca (Fig. 16c) and Heathcote (Fig. 16 f, g & i) Fault Zones and zones of rotated folds (for example the footwall of the Avoca Fault; Fig. 16d). The extent of these features suggests localized transcurrent shear strain adjacent to the faults along significant parts of their lengths (Fig. 16). Subvertical northwest-trending crenulation cleavages associated with variably northwest-plunging folds potentially reflect dextral shear strain (Fig. 16 c & d). These are overprinted locally by subvertical northeast-trending crenulation cleavages associated with variably northeast-plunging folds possibly indicative of late sinistral shear strain along some of the faults in the western subprovince (Fig. 16 i & j).

Relative to other major faults in the western Lachlan Orogen, the Avoca Fault Zone (Fig. 6) has a much greater oblique/strike-slip component of displacement. This fault has less throw than other inter-zone faults, as Early Ordovician (Lancefieldian) rocks are present in the footwall and unfossiliferous Cambro–Early Ordovician rocks occur in the hanging wall (see Cas and VandenBerg, 1988, fig. 3.2). Mainly though, it shows significant effects of a widely distributed zone of dextral shear strain (up to 20–25 km away from the fault zone). This is shown by the swing in the regional structural trends of the Stawell Structural Zone (Figs 2 & 16a, b), the strong northwest-trending crenulation cleavages both within and oblique to the north-striking fault zone (Fig. 16 c & e) and the zone of moderately northwest-plunging folds in the footwall (Fig. 16d). These folds in the footwall are both oblique to the fault zone and the adjacent structures in the Bendigo–Ballarat Structural Zone. Shear displacement analysis (after Ramsay and Graham, 1970) based on the swing of the regional structural trends into Avoca Fault Zone (western side of the fault only) gives a total shear displacement of 18.2 km (Gray, unpublished data). The calculated shear strain (γ) across this part of the fault zone is 3.63.

SIGNIFICANCE OF FAULTS FOR KINEMATIC EVOLUTION OF THE LACHLAN OROGEN

Major fault zones of the Lachlan Orogen can provide constraints on the tectonic evolution of eastern Australia (Fig. 17). Structural relationships within fault zones dictate the kinematic and relative chronology of deformation across the fold-and-thrust belt, and reflect the movements responsible for crustal thickening in the orogen. Combined with the metamorphic-mica crystallisation ages, which delimit the timing of deformation, the fault zones provide power-

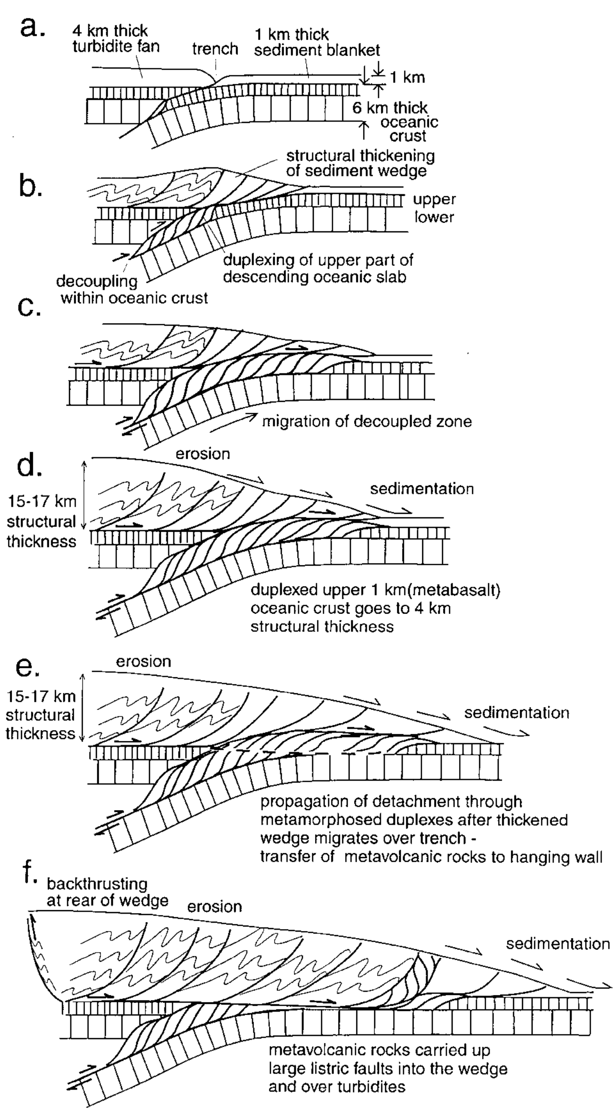

Fig. 18. Cartoons (a–f) illustrating model for the structural evolution of leading-imbricate fan fault systems in an oceanic setting above a subduction zone. The fault system is characterised by tiered detachments which propagate within the upper part of the oceanic crust and at the sediment–basaltic layer contact. The model requires 'peeling' of the upper ~1 km of oceanic crust (basaltic layer) as a trenchward propagating duplex. At the same time the turbidite wedge undergoes structural thickening as part of a deformation front at the trench. Syntectonic sedimentation is ongoing as the deforming wedge achieves a critical taper (d–e).

ful constraints on the structural and tectonic evolution (see also Foster and Gray, in press).

In the western Lachlan Orogen, both interzone and intrazone faults reflect a progressive eastwards migrating deformation front from 450 Ma to 400–380 Ma (see Foster *et al*., 1996, 1998; Gray *et al*., 1997). Fold and fault structures, as well as strain data and kinematic data from curved fibres in pressure shadows, require east-directed thrusting (cf. Gray and Willman, 1991b; Gray, 1997). Similar strain gradients and non-coaxial strain histories have been recorded in the Kodiak Accretionary Complex (Fisher, 1990; Fisher and Byrne, 1987) and the central slate belt of Taiwan (Tillman and Byrne, 1995). The major fault zones contain fault-bounded slivers of Cambrian metavolcanics of oceanic affinities, and Franciscan-like 'knockers' in a chaotic melange which record evidence of intermediate *P* metamorphism (Spaggiari *et al*., 1998). These slivers are considered to result from 'peeling' of the upper oceanic layers by a duplex mechanism during subduction (Fig. 18; cf. Bernstein-Taylor *et al*., 1992; Kimura and Luden, 1995). The chevron-folded turbidites represent the structurally thickened accretionary-type sediment wedge overlying the duplexed metavolcanics. Both are subsequently emplaced to higher structural levels when faults develop listric form as they splay off the basal décollement at the base of the 'wedge' (Fig. 18 e & f). Mesoscopic structure within fault zones, in particular fault zone-oblique crenulation cleavages, suggests strike-slip motion along many of the major faults, after the thrust-emplacement and thrust-juxtaposition of folded and cleaved blocks. The magnitude of lateral displacement appears to be small (< 50 km; Fig. 16b) such that these structures presumably record adjustments within the deforming accretionary sediment-wedges through time.

In contrast, deformation in the central and eastern subprovinces, although of similar age has a different character, different tectonic parameters, and perhaps a different tectonic history. Deformation in the Tabberabbera Zone of the central subprovince of the Lachlan Fold belt migrates southwestwards from ~440 Ma to 400 Ma (Foster and Gray, in press). Mylonitic shear zones bounding the Wagga–Omeo Metamorphic Belt were active as a combined wrench–thrust system in the period 400–410 Ma (Fig. 17). Fault kinematics, shown largely by *S*–*C* fabrics in the mylonite zones (Figs 13 & 16 o, p, t) and offset plutons (Fig. 16 n, q, r), requires emplacement of the metamorphic complex as a southward-moving wedge at this time, but the amount of displacement is enigmatic (cf. Morand and Gray, 1991, Fig. 11). Field relations (Fig. 16r) suggest movement on the Kiewa–Kancoona fault system is < 50 km (see also Sandiford *et al*., 1988; Morand and Gray, 1991, fig. 12). In the eastern subprovince deformation in the Narooma Accretionary Complex: (Miller and Gray, 1996, 1997; fig. 1) was at 450–440 Ma (see Offler *et al*., 1998), whereas deformation inboard was between 380 Ma and 340 Ma (Fig. 17; Lu *et al*., 1996; Foster and Gray, in press). Shear zones bounding the granites, and the localised high *T*/low *P* metamorphic complexes of the eastern metamorphic province, along their eastern margins were active at ~380 Ma and are part of a major east-directed thrust system (cf. Fergusson and VandenBerg, 1990). The cleaved lower grade rocks to the east and some of their associated brittle fault zones were mainly active at ~360–340 Ma (Fig. 17; Foster and Gray, in press). The major interface between the inland and coastal belts may therefore not be a simple strain-dependent transition as originally proposed by Miller and Gray (1997). Late Silurian–Early Devonian granites of the eastern subprovince are cut by an apparent conjugate set of brittle–ductile shear zones which have sinistral displacement along north–northwest trending structures (e.g. Berridale Fault; Fig. 16q) and dextral displacement along northeast-trending structures (e.g. Burragate Fault; Fig. 16n). This conjugate fault/shear zone system truncates and therefore post-dates the east-directed thrust system. Lateral displacements are again < 50 km (Fig. 16 n & q).

Maximum convergence and therefore maximum structural development over much of the Lachlan Orogen took place in the Late Ordovician through Silurian period (cf. Gray *et al*., 1997; Gray and Foster, 1997). The geometry, and complex transport directions and timing (Figs 16 & 17) are unlike those associated with the classic orogenic systems of North America, involving thrust-imbrication of passive margin sequences towards the cratonic interior (cf. Price and Hatcher, 1983). Wrench movements along fault and shear zones are limited (commonly < 50 km where determined) so that major lateral displacements within the southeastern Lachlan Orogen are considered unlikely. The Lachlan Orogen is distinctly similar to the Turkic-type orogenic system of Sengor and Okurogullari (1991) which are dominated by low metamorphic grade, turbidite–chert–basalt sequences and significant volumes of granitoids. The Lachlan Orogen contains a centrally-located high *T* metamorphic complex, which now bears some symmetry relationships to the trends and vergence belts of the preserved relicts of the Silurian migrating deformation fronts (cf. Gray, 1997). The high *T*/low *P* metamorphism of this part of the Ordovician turbidite wedge has similarities to the Chugach Metamorphic belt, the high grade metamorphosed part of the Kodiak Accretionary Complex (e.g. Hudson and Plafker, 1982; Sisson and Pavlis, 1993). Here metamorphism has been attributed to subduction of a spreading ridge beneath the subduction–accretion system (e.g. James *et al*., 1989; Sisson and Pavlis, 1993). Metamorphism in the central subprovince of the Lachlan Orogen has been linked to a double subduction system during the late Ordovician and Silurian (Gray *et al*., 1997, fig. 13; Soesso *et al*., 1997, fig. 3). The distinct higher geothermal gradient required for high T metamorphism and granite generation in the eastern subprovince from Silurian through early Devonian times, have been linked to an eastwards migrating heat source. This has been related to roll-back along the long lived subduction zone outboard of the developing Lachlan Orogen (Powell, 1983; Foster and Gray, in press, Fig. 12).

SIGNIFICANCE OF FAULT ZONES FOR WEDGE DEFORMATION

The deformation fronts in the western Lachlan Orogen have been treated as migrating, structurally thickened, sediment wedges above subduction zones (Fig. 18; Foster *et al.*, 1996; Gray *et al.*, 1997; Gray and Foster, 1997). The fault zones play an important part in the structural thickening of these wedges (cf. Wang and Davis, 1996; Gutscher *et al.*, 1998). Where the wedges are dominated by a thick turbidite sequence, such as that inferred for the western subprovince of the Lachlan Orogen, the décollement/high strain zone at the base of the wedge accommodates initial shortening of the wedge via chevron folding. Crystallisation ages of the micas from the cleaved slates from within the wedge (Fig. 2; Foster and Gray, in press) indicate that in general fault zone propagation tends to lag behind the folding and consequent cleavage development in the wedge proper (i.e. in the fault hanging walls). This early structural thickening may relate to attainment of the critical taper necessary for movement of the wedge 'proper' along the basal décollement (e.g. Davis *et al.*, 1983; Dahlen, 1990; Wang and Davis, 1996; Gutscher *et al.*, 1998). The faults propagate in the direction of tectonic transport with attainment of this critical taper. The major inter- and intra-zone faults propagate off the major décollement at the base of the turbidite pile (Fig. 18). The fault spacing probably reflects the mechanics of Coulomb wedges, the thickness of the pile, the frictional strength of the basal fault, and the strength of the fault 'beam'. Strength of the fault beam is defined by the thickness of the various litho-structural components; including: (1) the whole system 'beam' made up of the deformed turbidite and basalt package for the inter-zone faults; and (2) the turbidite package for the intra-zone faults. These faults form leading-imbricate fan 'thrust' systems, where the turbidite–basalt stratigraphy requires tiered detachments (Fig. 18; see also Gray, 1995). The changing strike patterns between the different structural zones within the western subprovince may also reflect changing plate motion across the inferred western subduction zone (see Gray and Foster, 1997, figs 11 & 12). Small changes in subduction directions ($<40°$) over time between 450 Ma and 380 Ma may explain the inferred wrench components for faults such as the Avoca Fault Zone (Fig. 16).

CONCLUSIONS

Turbidite-dominated orogenic systems, such as the Tasmanides of eastern Australia, involve continental growth/recycling by deformation and structural thickening of very large, subcontinent size, subduction–accretion complexes. Faults within the turbidite sequences of the Lachlan Orogen of eastern Australia are typical of such subduction–accretion orogens. They become weak zones in the sedimentary wedges, and are wide zones (~5–10 km width) of strong to intense cleavage and transposition layering, with multiple cleavages recording continued foliation development by 'transposition cycling' in a thrusting-related shear regime. The fault zones represent strain-softened zones in the basal parts of the major thrust sheets, and are dominated by mica growth which can be dated by the Ar–Ar method to track the migrating deformation fronts in the developing subduction–accretion system. These are deeper-level faults where faulting is considered to have occurred at depths of between 6 and 17 km in the structurally thickening wedge (Foster *et al.*, 1996). They are different from, and have distinct character relative to, the major fault zones of the classic thrust-belts of the Appalachians and the Canadian Cordillera (see Table 1). Some of the faults, such as the Waratah and Wonnangatta Fault Zones (faults 5 and 8, Fig. 1), represent shallower level deformation in the developing subduction–accretion system. These are characterised by block-in-matrix melanges and mud-injection zones, typical of the frontal, shallow level parts of modern accretionary complexes (e.g. Moore, 1978; Moore and Allewardt, 1980).

Tectonic evolution of the Lachlan Orogen of southeastern Australia from the Late Ordovician through Silurian time has been considered to involve three migrating belts of deformation linked to subduction (Foster *et al.*, 1996; Gray *et al.*, 1997, fig. 13; Gray and Foster, 1997). These migrating belts coincide with the east-vergent 'thrust' system in the western subprovince, the southwest-vergent 'thrust' system linked to the shear zone-bounded high T metamorphic complex in the central subprovince, and the east-vergent 'thrust' system in the eastern subprovince (see Gray, 1997). The fault zones are an integral part of the deformation process, as the sediment wedges are structurally thickened showing horizontal shortening up to ~70% and vertical elongation up to ~300%. Thrusts within the structurally thickened, sediment wedges have finite lengths of 100–200 km, whereas wrench faults bounding the high T Wagga–Omeo Metamorphic belt (Fig. 1) have lengths up to 700–800 km. They form linked systems of thrust and wrench faults. Observed and calculated shear displacements across these wrench shear zones are low (<50 km). Calculated shear displacements across the other low grade, fault zones is also low (<50 km), suggesting that the inferred, large scale lateral migrations of 'terranes' such as in western

North America are unlikely for the Lachlan Orogen. Steeply dipping, overprinting crenulation cleavages oblique to fault zone boundaries (e.g. Fig. 15) presumably record adjustments within the deforming turbidite wedge through time.

In conclusion, mica crystallisation within fault and shear zones records the progression of deformation through time. Tectonic evolution of monotonous turbidite sequences can therefore be mapped out using Ar–Ar geochronology to determine crystalline ages of both cleavage phengites in fault zones and white mica from syntectonic quartz veins (Foster *et al.*, 1998). This can be done within different vergence belts, which are defined by regional fold asymmetry and regional fault dip. The timing of emplacement of elongate granitoid bodies can also be used to map out migrating 'magmatic fronts'. Such spatial and temporal variations in deformation, metamorphism and magmatism show how subduction–accretion complexes in monotonous turbidite sequences evolve through time and eventually form crust of continental thickness and character.

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