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The Gilmore Fault Zone — the deformational history of a possible terrane boundary within the Lachlan Fold Belt, New South Wales

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The Gilmore Fault Zone is a long-lived imbricate fault system separating the Wagga Metamorphic Belt from the Tumut Block in the Palaeozoic Lachlan Fold Belt. Structures within the fault zone indicate dominantly sinistral transpressional movements during regional deformation in the Siluro-Devonian and mid-Devonian and/or Carboniferous. These movements, in response to lateral compression, resulted in the Wagga Metamorphic Belt being thrust over the Tumut Block. Dextral strike-slip movement may be inferred during Early Silurian regional deformation and subsequent extension. Common structural and metamorphic histories, and lithological correlation of rock units straddling the fault zone, indicate that the Gilmore Fault Zone was not a terrane boundary in the Late Ordovician or Early Silurian. Differences in geophysical expression and crustal composition across the southern part of the zone would be explained if the zone is a reactivated basement fault which corresponds, in part, to an older terrane boundary. The fault zone is interpreted as a splay off a gently west-dipping mid-crustal detachment.

Introduction

The Gilmore Fault Zone (Crook & Powell, 1976; Basden, 1986), also referred to as the Gilmore Suture (Scheibner, 1985), is a major north–northwest-trending tectonic feature extending for several hundred kilometres in the southeastern part of the Lachlan Fold Belt. In its southern part, the zone separates Ordovician metasediments of the Wagga Metamorphic Belt in the west from Ordovician–Early Silurian[2] volcano-sedimentary sequences of the Tumut Block to the east (Fig. 1).

The fault zone, well-defined by aeromagnetic and gravity patterns (Suppel & others, 1986; Wyatt & others, 1980), is interpreted as either (i) a terrane boundary, formed by collision and overthrusting of the Wagga–Omeo Terrane over the Ordovician Molong Volcanic Arc during the Early Silurian Benambran Orogeny (Scheibner, 1982, 1985; Degeling & others, 1986; Suppel & others, 1986), or (ii) a dextral (Cas & others, 1980; Powell, 1983a) or sinistral (Packham, 1987) strike-slip fault which has offset portions of the arc and its associated back-arc basin (Wagga–Omeo Terrane) during the Benambran Orogeny. The fault zone is thought to have been active throughout Silurian extension and the subsequent Siluro-Devonian Bowning Orogeny (Basden & others, 1987; Packham, 1987; Powell, 1983a). The age of the Bowning Orogeny, in the Tumut region, is poorly constrained between the Ludlovian (Blowering Formation) and Early to middle Siegenian (Minjary Formation, Barkas, 1976). Sediments and volcanics of the latter unit form relatively flat-lying strata unconformably overlying meridionally folded older units.

The origin and history of the Gilmore Fault Zone are important in any tectonic reconstruction of the Lachlan Fold Belt. Little detailed work has been done to support the various interpretations of the nature and timing of movements on the zone. This paper details structural investigations on the better exposed southern part of the zone. The oldest preserved structures indicate that the Wagga Metamorphic Belt was thrust over the Ordovician–Early Silurian volcanic sequences in a southeasterly direction during the Siluro-Devonian deformation. Farther north, the overall westward dip of the zone is supported by the gravimetric expression of the fault zone, which shows a westward displacement from the surface position (Suppel & others, 1986). Oblique-slip movement (sinistral reverse) also occurred in the mid-Devonian and/or Carboniferous.

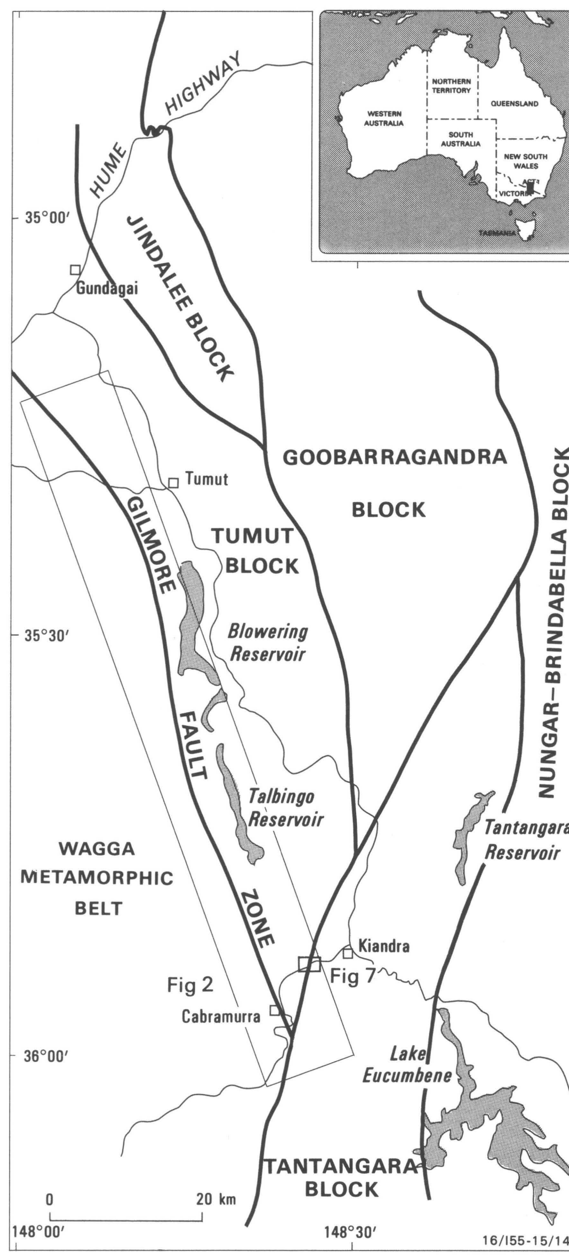

Figure 1. Locality map.
Geology modified after Owen & Wyborn (1979a). Note: The Tumut and Jindalee Blocks correspond to the Gocup and Jindalee Blocks, respectively, of Basden (1990) and the Tumut and Jindalee Terranes, respectively, of Basden & others (1987).

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[2] The Silurian timescale used here follows that of Strusz (1989), whereby the Silurian (435–410 Ma) is subdivided into Early and Late periods at the Wenlockian/Ludlovian boundary at about 420 Ma.

Rocks within the fault zone previously included in the Early to Late Silurian *Tumut Trough* (e.g. Basden, 1986) are here considered to be part of the Ordovician–Early Silurian volcanic sequence. Juxtaposition of these rocks with lithologically similar units west of the fault zone and common structural and metamorphic histories suggest that the Gilmore Fault Zone does not represent a terrane boundary in the Ordovician or Early Silurian. Rather, the Gilmore Fault Zone is interpreted as a reactivated basement fault which may, in part, correspond to a proposed Late Proterozoic–Early Palaeozoic basement terrane boundary suggested by Chappell & others (1988).

Geological setting

The geology of the region is described by Moye & others (1969a,b,c), Basden (1986), Wyborn (1977a) and Degeling (1975, 1977). The detailed geology of the southern part of the Gilmore Fault Zone is shown in Figure 2. A summary of stratigraphic units and relationships is given in Table 1 and Figure 3, respectively.

Ordovician–Early Silurian (Llandoverian) sediments and volcanics of the Molong Volcanic Arc, including the Nacka Nacka Metabasic Igneous Complex, Gooandra Volcanics and Kiandra Group, intertongue with the overlying laterally equivalent Bumbolee Creek Formation and the Tumut Ponds Beds. These units were deformed and metamorphosed during the Early Silurian (Late Llandoverian; Stuart-Smith, 1990a) Benambran Orogeny. They were then unconformably overlain by the Early to Late Silurian (Wenlockian–Ludloverian) Blowering Formation and Ravine Beds, during a period of extensional (transtensional) tectonics which resulted in uplift of Cambrian–Ordovician basement further to the east (Stuart-Smith, 1990b). The Tumut Ponds Serpentinite, present in the Gilmore Fault Zone, is here interpreted to represent part of this basement.

During the Siluro-Devonian Bowning Orogeny both the Ordovician and Silurian metasediments and volcanics were meridionally folded, metamorphosed and intruded by syn-kinematic granitoids (Wondalga and Green Hills Granodiorites, Rough Creek Tonalite and Gocup Granite). Early Devonian sediments and volcanics (Boraig Group, Byron Range Group and Minjary Volcanics) unconformably overlie older rocks and are mildly deformed in the fault zone. Outliers of flat-lying Tertiary basalt and minor sediments (common in the south as hill top cappings) overlie the fault zone, indicating a minimum of subsequent movement on the zone.

Fault zone structures

The Gilmore Fault Zone has three main structural units. From west to east these are:
(1) the deformed eastern margin of the Wagga Metamorphic Belt;
(2) a central belt of subparallel segments of Ordovician–Early Silurian metasediments and volcanics, with faulted allochthonous slivers of serpentinite and tonalite; and
(3) the folded and faulted western margin of the Tumut Block, comprising Ordovician, Silurian and Early Devonian rocks.

Although sharing some common aspects, each of the three structural units has a different structural history. Together, these reveal the long-lived deformation history of the fault zone.

Schematic structural profiles through the Gilmore Fault Zone are given in Figure 2. Stereoplots of the main structural elements are shown in Figure 4. Up to four phases of folding (F_{1-4}) and associated S surfaces (S_{1-4}) affect Ordovician–Early Silurian strata in the Tumut region (Stuart-Smith, 1990a). Only the later two fold phases and surfaces are preserved in the deformed margin of the Wagga Metamorphic Belt and in the central belt.

Margin of the Wagga Metamorphic Belt

The eastern margin of the Wagga Metamorphic Belt, consisting of the Wondalga and Green Hills Granodiorites and a narrow screen of Gooandra Volcanics, is marked by a deformed zone up to 1300 m wide.

Both the metasediments and the normally massive granodiorites are typified in the zone by a variably developed foliation which dips steeply to the west in the north and is subvertical in the south. The intensity of deformation in the granodiorites progressively increases towards the faulted contact with the central belt, from moderately foliated to strongly foliated with ultramylonite (nomenclature after Wise & others, 1984) zones several metres wide at the contact. Apart from deformed and fractured feldspar grains, the rocks are totally recrystallised, with the foliation defined by aligned muscovite, biotite, ribbon-quartz mosaic and polygonised quartz lenses. In the south, most of this zone was differentiated by earlier workers (e.g. Moye, 1953) as the 'Rough Creek Gneissic Granite'.

A mineral-elongation lineation is commonly present and plunges moderately to the northwest (Figs 4a,b). In mylonitic granodiorite, relic deformed primary biotite and muscovite 'fish' (Fig. 5), and asymmetrical lenses or tails of fine-grained polygonised quartz on deformed coarser feldspar grains, consistently indicate oblique-slip movement (sinistral transpressional). In places an *S-C* fabric (Berthé & others, 1979) is well developed between a slightly shallower and more southwest-dipping shear plane and the foliation (Fig. 4c). The intersection of these planes is orthogonal to the mineral lineation, in keeping with a true *S-C* fabric. The shear planes parallel the major fault trend, thus representing synthetic shears, whereas the foliation is slightly oblique to the main fault trend and parallels the S3 cleavage in the adjacent metasediments (Fig. 4e).

The metasedimentary screen of Gooandra Volcanics between Gilmore and Buddong Falls appears to be transitional with amphibolite facies rocks north of the Nacka Nacka Metabasic Igneous Complex to the west (Figs 2, 6). Garnet- and andalusite-bearing schists within 500 m of the complex grade through muscovite-biotite schist to phyllite at 1000 m. This metamorphic zoning is preserved at Valley View, where the screen is at its greatest width but is truncated by the Gilmore Fault Zone to the south and north. There is little evidence of major faulting at the contact between the metasediments and the complex or granodiorites. At Valley View, the metasediments pass from schist to gneiss approaching the complex; minor quartz-feldspar leucosome appears within 100 m of the contact. The structure of the metasediments and the Nacka Nacka Metabasic Igneous Complex, like the deformed granodiorites (Fig. 4a), is dominated by a steeply west-dipping schistosity with an associated northwest-plunging mineral elongation lineation. Compositional banding in the metasediments and mafic rocks mostly parallels the schistosity, which is axial plane to rare gently-plunging isoclinal fold closures. The schistosity, formed during peak metamorphic conditions, is defined by aligned but unstrained micas.

The development of schistosity and peak metamorphism within the deformed margin of the Wagga Metamorphic Belt is

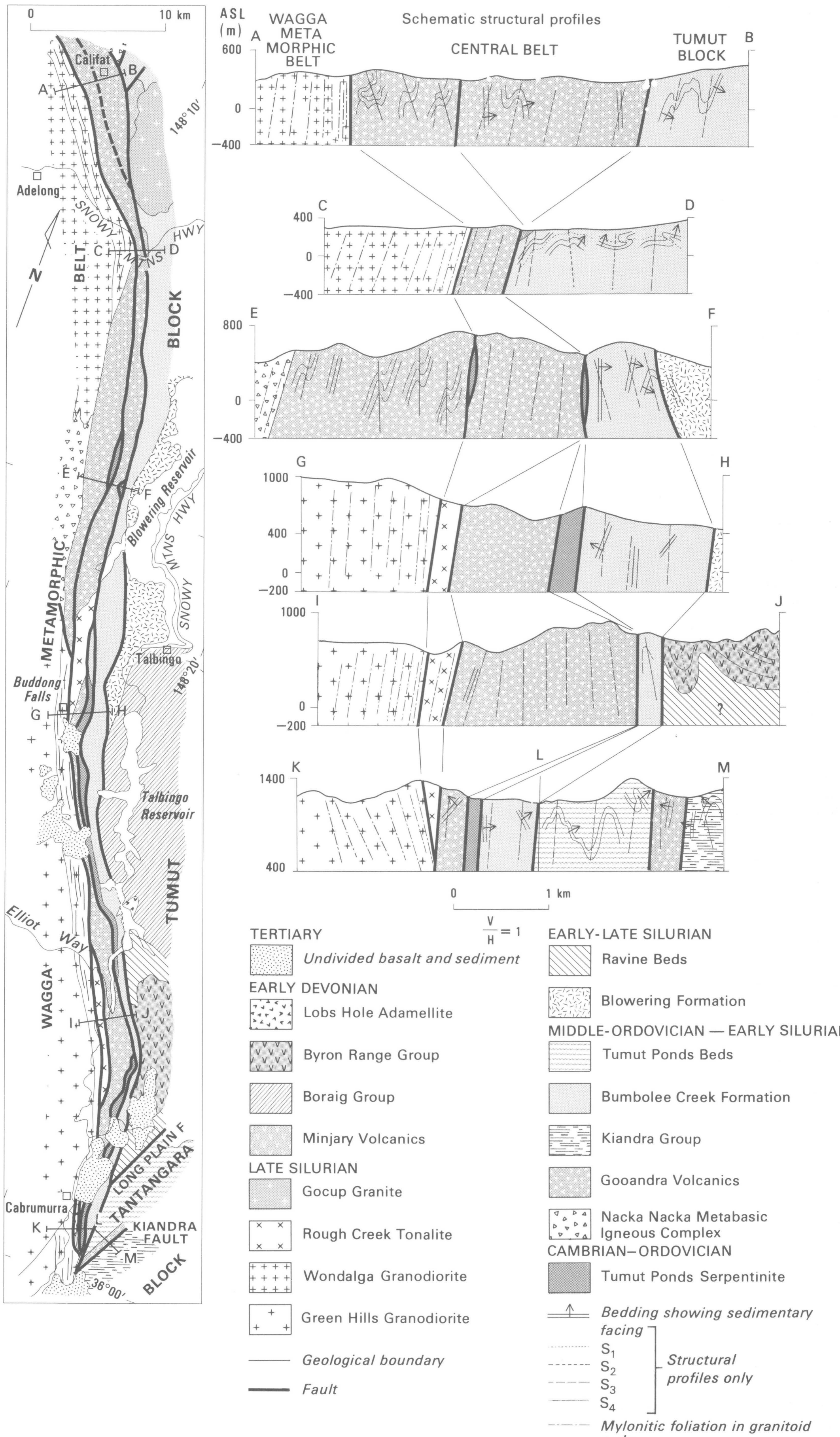

Figure 2. Generalised geology of the southern part of the Gilmore Fault Zone.

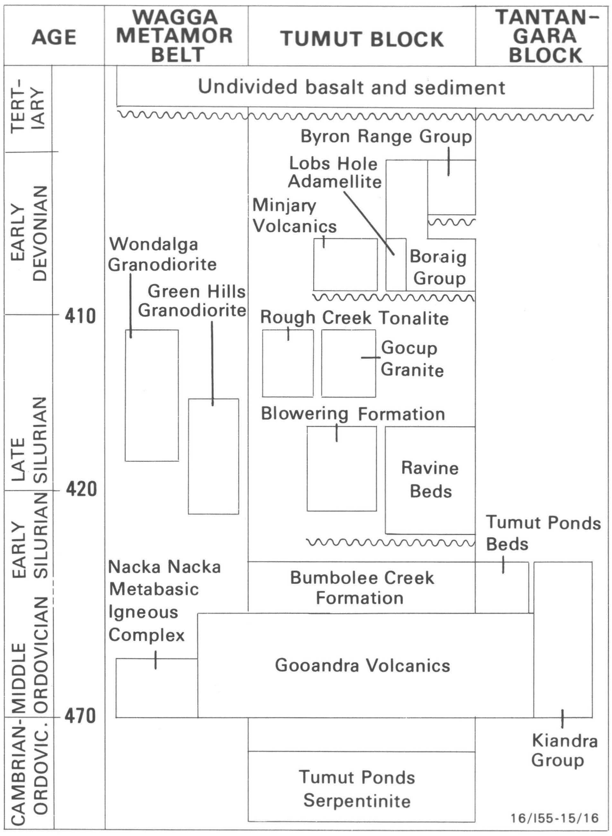

Figure 3. Diagrammatic stratigraphy of units within the Gilmore Fault Zone.

probably Siluro-Devonian. The presence of undeformed late-stage pegmatoid veins cross-cutting foliated phases of granodiorite (Dobos, 1971) indicates that the Late Silurian (Basden, 1986) granodiorite intrusions were emplaced during the deformation. No earlier structures are preserved in either the metasediments or granodiorites. The age, geometry and morphology of the schistosity suggest it is equivalent to the S_3 cleavage in Bumbolee Creek Formation sediments in the Tumut Block to the east (Stuart-Smith, 1990a).

The main metamorphic fabric within the deformed zone of the Wagga Metamorphic Belt is locally overprinted by later deformation spatially associated with the Gilmore Fault Zone. In the Cabramurra area, the mylonitic fabric in the Green Hills Granodiorite is deformed by cataclastic fault zones and subparallel chloritic shear zones with subvertical to gently S-pitching slickenlines. The mineral elongation associated with the mylonitic fabric is rotated (all of the S-plunging lineations on Fig. 4 come from the Cabrumurra area) within the fault and shear zones, both of which are commonly associated with localised chlorite and muscovite alteration. Slickenlines indicate that movement on the chloritic shear zones was mostly reverse (either east or west side up) with a dextral strike-slip component. In the Valley View area, the metamorphic foliation in the metasediments is tightly folded by a steep east-dipping, closely spaced, S_4 crenulation cleavage within 700 m of the fault (Fig. 4d). The cleavage, associated with east-verging folds, may be related to later reverse (i.e. west side up) movements of the Gilmore Fault Zone. The age of both this cleavage and the cataclasis mentioned above is unknown, but is probably either mid-Devonian or Carboniferous (see below).

Central belt

The central belt is mainly metasediments and volcanics of the Gooandra Volcanics, with narrow discontinous allochthonous slivers of Rough Creek Tonalite and Tumut Ponds Serpentinite along the bounding faults. The belt, up to 3 km wide in the north, narrows southwards and pinches out about 4 km south of Cabramurra. All the units are characterised by a foliation or cleavage which parallels the foliation (both S_3 in Fig. 4a and S plane in Fig. 4b) in the Wagga Metamorphic Belt to the west and the S_3 cleavage (Fig. 4k) in metasediments of the Tumut Block to the east.

Rough Creek Tonalite

Massive, fractured and extensively chloritised bodies of equigranular coarse-grained biotite tonalite occur along the western margin of the central belt. Mostly, the margins of the tonalite bodies are converted to mylonite with structural elements (only limited data) parallel to mylonites in the adjacent deformed granodiorites (Fig. 4i). The mylonitic foliation consists of broken feldspar and quartz grains in a strongly foliated phyllonitic matrix of muscovite, chlorite and ribbon quartz. South of Cabramurra, this fabric is rotated and crosscut by secondary foliated chlorite-rich and muscovite-rich zones. Slickenlines on the latter zones pitch steeply or shallowly to the south (Fig. 4i). Both fabrics may have been the result of either continuous mylonitisation or two separate deformations as is indicated in the adjacent Green Hills Granodiorite.

Although only tectonic contacts were found, the presence of foliated fine-grained aplitic margins to the northernmost body of tonalite possibly represent chilled margins, indicating the tonalite may intrude the Gooandra Volcanics.

Tumut Ponds Serpentinite

Numerous slivers of ultramafic and mafic rocks (up to 600 m wide and 25 km long) occur along the length of the central belt within the major fault zones. The rocks include mostly massive to schistose serpentinite, and minor meta-pyroxenite, serpentinised harzburgite (Van Der Oever, 1984), talc schist, metabasalt and amphibolite. Typically, the margins of the bodies are schistose serpentinite with a well-developed *S-C* fabric. This fabric is dominated by a subvertical *C* plane, which parallels the major faults and the main foliation (S_3 cleavage) in adjacent rocks (Figs 4g,h). A subhorizontal mineral elongation is present on the *C* plane orthogonal to the intersection of the plane and a vertical north–northeast-trending flattening foliation (S plane). The orientation of the fabric indicates mostly sinistral strike-slip movement with a minor reverse component, the *C* planes forming synthetic shears to the main faults.

The metamorphic grade of the mafic and ultramafic rocks is lower greenschist facies, similar to tonalite, metasediments and volcanics within the central belt. Pyroxenites are altered to actinolite/tremolite, and mafic rocks to chlorite + epidote assemblages. Near Section Creek, 7 km north of Cabramurra, the western margin of the main serpentinite body consists of a chloritic breccia containing rotated clasts of massive meta-pyroxenite and foliated hornblende amphibolite. The body therefore represents an allochthonous sequence which may have been derived from a Cambrian–Ordovician basement similar to that proposed for other serpentinite bodies in the region (Stuart-Smith, in press).

Metasediments and volcanics

Metasediments and volcanics of the Gooandra Volcanics occupy most of the central belt. The rocks are characterised by a steeply west-dipping penetrative slaty cleavage or schistosity which parallels the foliation in adjacent granitoids slightly

Table 1. Summary of stratigraphy of units within the Gilmore Fault Zone.

	Unit	*Description*	*Field relationships*	*Remarks*
TERTIARY	T	Basalt, minor limonitic pebble conglomerate and sandy clay at base.	Unconformably overlies older units	Forms flat-lying capping
EARLY DEVONIAN	Lobs Hole Adamellite (Dgl)	Porphyritic granophyric leucogranite	Intrudes Dlv.	Subvolcanic intrusion comagmatic with Dlv (Barkas, 1976).
	Byron Range Group (Dls)	Shale, limestone and arenite.	Unconformably overlies Ssr and basal part of Dlv Faulted against Oub.	Shallow-marine (Moye & others, 1969c).
	Boraig Group (Dlv)	Rhyolite, rhyolitic tuff, siltstone, shale, volcanilithic arenite and cobble conglomerate.	Unconformably overlies Ssr and Sbd. Unconformably overlain by Dls (Moye & others, 1969c). Faulted against Oub.	Shield volcanic complex (Owen & others, 1982).
	Minjary Volcanics (Dvm)	Rhyolitic ignimbrite, tuff and minor polymictic conglomerate and arenite.	Unconformably overlies Oub and Sgc.	Shallow-marine to subaerial. Early to middle Seigenian brachiopods and corals (Barkas, 1976).
LATE SILURIAN	Gocup Granite (Sgc)	Pink coarse-grained muscovite-biotite granite.	Intrudes Oub. Unconformably overlain by Dvm.	Pre-dates Siluro-Devonian meridional upright folds. ?Deformation ages 409 ± 2 Ma [(K-Ar on muscovite) and 402 ± 2 Ma (Rb-Sr whole rock) (Richards & others, 1977).
	Rough Creek Tonalite (Sgr)	Coarse-grained equigranular chloritised biotite tonalite.	Allochthonous fault slices. Probably intrudes Ovg.	Synkynematic S-Type granitoid (Wyborn, 1977a).
	Wondalga Granodiorite (Sgw)	Medium-to-coarse-grained biotite granodiorite.	Intrudes On and Gisbornian Wagga Metamorphic Belt metasediments.	Synkynematic l-type granitoid (Basden, 1986).
	Green Hills Granodiorite (Sgg)	Coarse-grained equigranular muscovite-biotite granodiorite.	Intrudes On and Gisbornian Wagga Metamorphic Belt metasediments.	Late synkynematic S-type granitoid (Wyborn, 1977a; Basden, 1986). Ages 406 ± 6 Ma 419 ± 6 Ma, 422 ± 6 Ma (K-Ar on biotite; Webb, 1980).
EARLY SILURIAN	Ravine Beds (Ssr)	Shale, slate, chert, graded coarse-grained volcanilithic arenite and conglomerate.	Unconformably overlain by Dlv and Dls faulted against Oub.	Late Wenlockian to early Ludlovian (Labutis, 1969).
	Blowering Formation (Sbd)	Massive dacitic ignimbrite.	Uncomformably overlies and faulted against Oub. Unconformably overlain by Dlv.	Flows and subvolcanic intrusions. Coeval with 429 Ma Goobarragandra Volcanics (Owen & Wyborn, 1979a).
EARLY SILURIAN	Tumut Ponds Beds (Out)	Graded thickly bedded fine- to coarse-grained quartz-intermediate arenite, slate, and minor quartz-rich arenite.	Lateral equivalent of Oub ?Conformably overlies Ovg.	Deep-marine turbidite sequence.
	Bumbolee Creek Formation (Oub)	Phyllite, slate, silty slate, thinly bedded graded fine- to coarse-grained quartz-rich arenite, minor massive coarse-grained quartz-intermediate arenite and pebble conglomerate.	Lateral equivalent of Out. Conformably overlies Ovg (Stuart-Smith, 1988).	Deep-marine turbidite sequence.
MIDDLE ORDOVICIAN	Kiandra Group (Ovk)	Fine- to coarse-grained and pebbly mafic volcaniclastic metasediments, silty slate.	Faulted against Ovg.	Deep- to shallow-marine, locally subaerial. Late Darriwilian to ?late Gisbornian (Owen & Wyborn, 1979a).
	Gooandra Volcanics (Ovg)	Interbedded fine- to medium-grained mafic volcaniclastic metasediments, silty slate, metabasalt, minor quartz-rich arenite, quartz-intermediate arenite, laminated black chert, metarhyolite and polymictic pebble and cobble conglomerate.	Lateral equivalent of On. Conformably overlain by Oub and Out.	?Late Darriwilian to ?early Gisbornian (Owen & Wyborn, 1979a).
	Nacka Nacka Metabasic Igneous Complex (On)	Amphibolite, metagabbro.	Intruded by Sgw and Sgg. Lateral equivalent of Ovg.	Age 465 ± 6 Ma and 467 ± 6 Ma (K-Ar on hornblende, Webb, 1980).
CAMBRIAN ORDOVICIAN	Tumut Ponds Serpentinite (COs)	Serpentinite, talc schist, serpentinised harzburgite, metabasalt and amphibolite inclusions.	Faulted against other units.	Age unknown. Forms allochthonous tectonic slices within the Gilmore Fault Zone. ?Part of Jindalee Group.

oblique to the main fault trend (Fig. 4k). The cleavage is correlated with the S_3 cleavage in the units east of the fault, on the basis of its meridional trend and associated fold styles. The cleavage is axial plane to variably-plunging, upward-facing, steeply inclined, tight to isoclinal folds. The variation in fold plunge may be a result of either earlier recumbent folding such as occurs to the east in the Bumbolee Creek Formation, or of heterogeneities in strain or both. There is no evidence of downward-facing folds or older structures. However, this may be an artifact of the greater intensity of the deformation in the Gilmore Fault Zone. Within the belt, bedding is mostly parallel to cleavage and the degree of metamorphic recrystallisation and associated strain is higher than east of the fault zone. Conglomerate pebbles which are undeformed east of the Gilmore Fault Zone are flattened and stretched within the the S_3 surface (Fig. 7), forming a prominent elongation lineation which

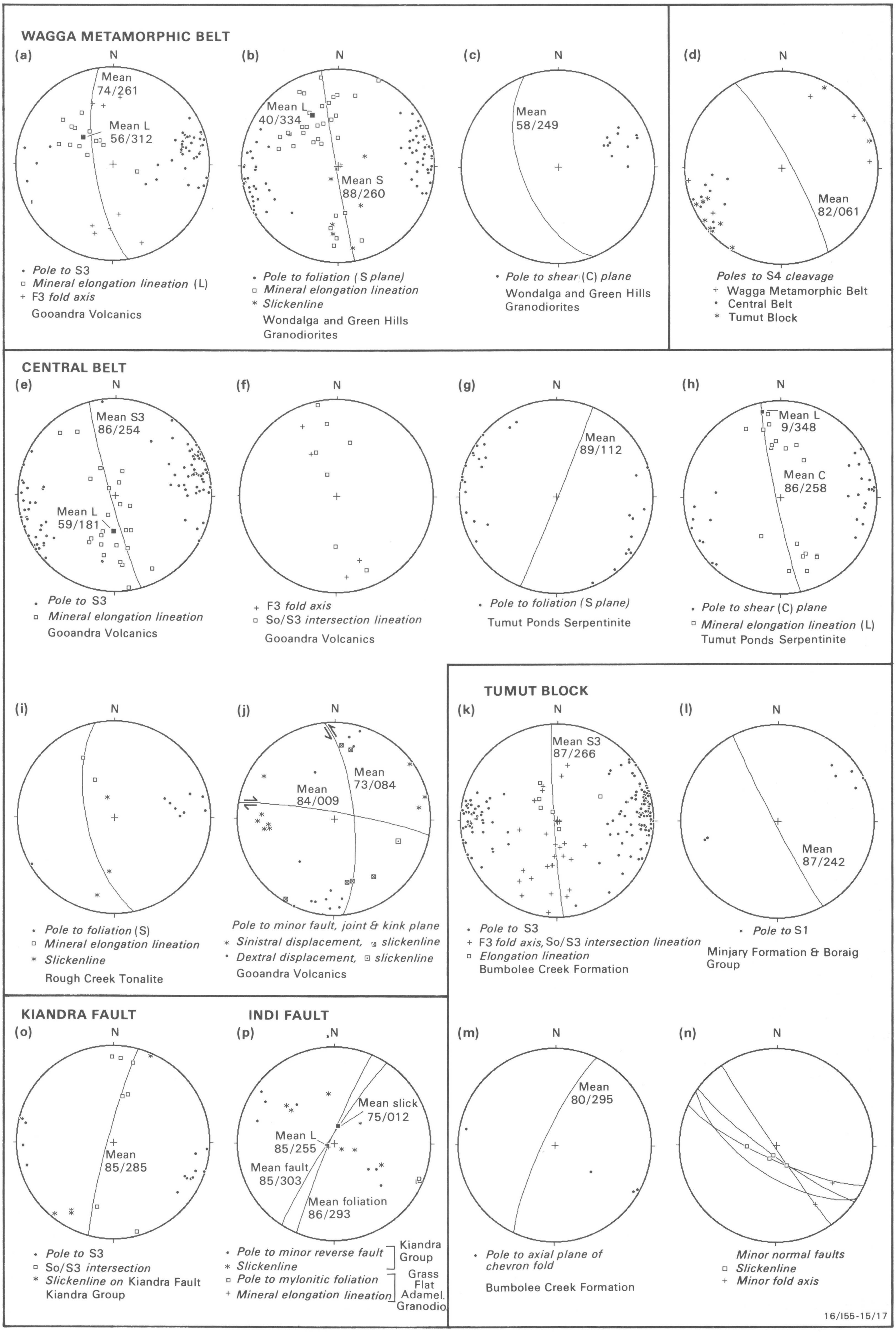

Figure 4. Equal area stereoplots of the main structural elements of all units within the Gilmore Fault Zone.

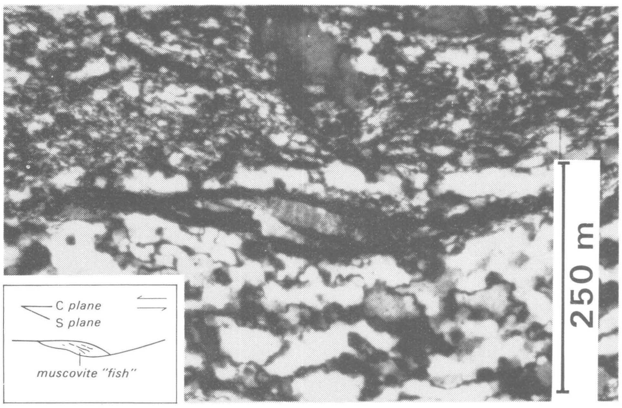

Figure 5. Photomicrograph of muscovite 'fish' in the mylonitic margin of the Wondalga Granodiorite, showing indicated movement direction.

plunges moderately to the south (Fig. 4e). This lineation is also marked by the extension direction of boudinaged quartz veins and a mineral-elongation lineation in quartz–feldspar porphyries (flows or dykes?). The lineation may reflect an earlier movement history not seen in the syn-kinematic Late Silurian granitoids or preserved in the serpentinite. This appears likely as, in several places approaching the fault contact with the Wondalga Granodiorite, the lineation in the metasediments is progressively rotated into parallelism with the lineation in the granodiorite. Older units in the belt are thrown against younger units east of the Gilmore Fault Zone, so the earlier movement history was probably reverse (i.e. west side up).

Metamorphic grade is greenschist facies, with meta-pelites and arenites typified by fine-grained foliated chlorite and muscovite, and metabasalts by actinolite + chlorite + epidote assemblages. Biotite is also common in metasediments north of Gilmore and south of Talbingo Reservoir (Fig. 6). In the latter area, S_3 micas are overgrown by randomly oriented muscovite and biotite indicating possible contact metamorphic overprinting.

Sinistral strike-slip movements are indicated by minor structures in the central belt which post-date the S_3 cleavage (Fig. 4j). Minor joints and faults are commonly present and parallel conjugate widely to closely spaced, steeply dipping kink bands (Fig. 4j). East-trending kink bands rotate the penetrative S_3 cleavage with a consistent dextral sense of shear, whereas those trending north have a sinistral symmetry. The symmetry and orientation of the conjugate kink bands is consistent with sinistral strike-slip movement on the Gilmore Fault Zone. This sense of movement is also supported by the presence of minor subhorizontal to northwest-dipping reverse faults and spatially associated with the kink bands. In the north, only the east-trending kink is present. The lack of a conjugate set in this area indicates that the kinks were not a result of layer-parallel shortening but rather may have been the result of sinistral shear on the Gilmore Fault Zone, which here forms an acute angle with the S_3 cleavage. In keeping with shear band experimental data of Harris & Cobbold (1984) and Williams & Price (1990), the kinks would have developed as R′ (P′) shear bands with P the most active shear paralleling the S_3 cleavage.

A steep east–northeast-trending S_4 crenulation cleavage (Fig. 4d) is locally present in the central belt, particularly next to the major faults where it is most intensely developed. The cleavage is axial plane to open F_4 folds, and F_3 folds are rotated into recumbent orientations. Consistent eastward-vergences, the spatial association of the cleavage and its parallelism to the main faults suggest that it is probably related to late reverse

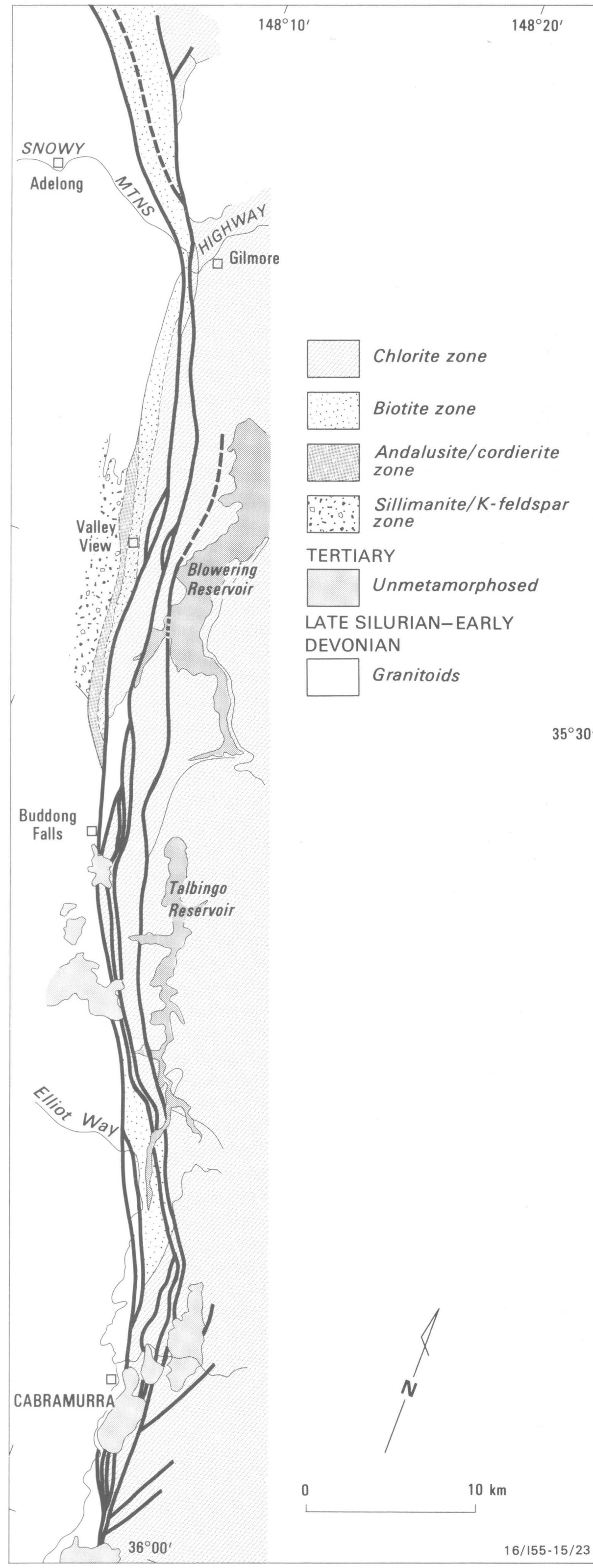

Figure 6. Metamorphic zones in Ordovician to Early Devonian strata.

Identification of zones is based on the mineralogical critera described by Wyborn (1977a). The zones correlate with zones established by previous workers in the region, as follows:

Chlorite Zone = Zone B of Wyborn (1977a); low grade zone of Vallance (1953, 1967) and Guy (1969); chlorite zone of Joplin (1947) and Rogerson (1977).
Biotite Zone = Zone C of Wyborn (1977a); biotite zone of Smith (1969).
Andalusite/cordierite Zone = Zone E of Wyborn (1977a); knotted schist zone of Joplin (1947), Vallance (1953) and Guy (1968); andalusite/cordierite zone of Rogerson (1977).
Sillimanite/K-feldspar Zone = Zone E of Wyborn (1977a); high grade zone of Vallance (1953), Guy (1968); K-feldspar zone of Rogerson (1977).

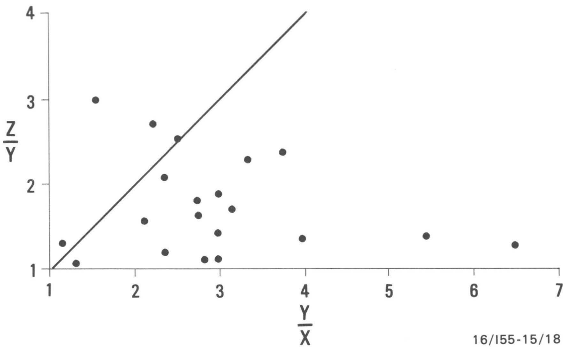

Figure 7. Flynn diagram of quartzite pebbles in Gooandra Volcanics conglomerate, Central Belt (Califat area).

movements on the fault zone. As there is no relationship between the cleavage and other minor structures, its age cannot be determined. The cleavage may be equivalent to a similarly trending crenulation in the Wagga Metamorphic Belt to the west and a spaced cleavage present in Early Devonian sediments abutting the Gilmore Fault Zone to the east.

Margin of the Tumut Block

In the study area, the western margin of the Tumut Block comprises poly-deformed flysch of the ?Ordovician–Early Silurian Bumbolee Creek Formation unconformably overlain by Silurian (Wenlockian–Ludloverian) and Early Devonian felsic volcanics and shallow-marine sediments. Within 2 km of the Gilmore Fault Zone, all the units are affected by deformation associated with movements on the zone.

Throughout the Tumut Block, the Bumbolee Creek Formation has a complex deformation history (Stuart-Smith, 1990a). Early recumbent east–west folds (F_1) are widespread, commonly with an associated axial-plane slaty cleavage (S_1). South of the Gocup Granite, the F_1 folds are refolded by coaxial open upright folds (F_2) with an axial crenulation cleavage (S_2). Both periods of folding pre-date intrusion of the Gocup Granite and are probably Early Silurian in age (Stuart-Smith, 1990). These early folds are refolded by Siluro-Devonian near meridional-trending upright folds (F_3) with a steep west-dipping penetrative axial spaced cleavage (S_3) (Fig. 4k).

The F_3 folds dominate regional structures in the area, particularly in the deformed margin against the Gilmore Fault Zone. Within this margin, F_3 folds are tight to isoclinal, whereas elsewhere they are tight to open. Except in the 'strain shadow' areas, immediately north and south of the Gocup Granite, there is little evidence of F_1 or F_2 folds in the deformed margin, owing to the intensity of the F_3 folding and the parallelism of the different S surfaces. Mostly beds are upright where younging is determined. F_3 axes plunge to the south and north, reflecting either or both earlier fold geometries and heterogeneity of strain. In the south, where the formation forms a narrow faulted-bounded strip adjacent to younger units, F_3 folds are isoclinal and plunge subvertically parallel to a pebble elongation lineation. This lineation, where present, parallels that in the adjacent central belt, suggesting a common origin. As with the central belt, the extension lineation may reflect an earlier movement history not present in Silurian (Wenlockian–Ludloverian) and younger units. Older units in the belt are thrown against younger units east of the Gilmore Fault Zone, so the earlier movement history was probably reverse (i.e. west side up). Anticlockwise rotation of the S_3 cleavage into the fault zone indicates a component of sinistral shear either during this or a later movement(s) on the fault zone.

The Silurian (Wenlockian–Ludloverian) and Early Devonian units are downthrown against either the Bumbolee Creek Formation or Gooandra Volcanics along the eastern margin of the Gilmore Fault Zone. Where exposed, this fault contact dips steeply (70°) to the west. The younger units east of the fault are tightly folded within 1 km of the fault, with a penetrative foliation locally present in the Silurian (Wenlockian–Ludloverian) units. Within the Early Devonian units, a spaced cleavage (Fig. 4l) parallels the main fault trend and may correlate with the S_4 cleavage in older units.

Slickenlines on minor steep west-dipping reverse faults in the Byron Range Group indicate a sinistral strike-slip component of displacement. Post-Early Devonian sinistral strike-slip movement is also indicated by normal faults in the Bumbolee Creek Formation and Minjary Volcanics in the Gilmore area (Fig. 4n). Post-S_3 sinistral strike-slip movement is also consistent with locally developed northeast-trending chevron folds, showing a sinistral symmetry, in the Bumbolee Creek Formation south of Cabramurra (Fig. 4m).

Relationship to Long Plain, Kiandra and Indi Faults

The Gilmore Fault Zone terminates in the south near the junction between the Long Plain, Kiandra and Indi Faults. The Long Plain and Indi Faults have previously been regarded as part of the one continous fault system (e.g. Wyborn, 1977a). However, this study establishes that the Gilmore Fault Zone truncates the Long Plain and Kiandra Faults east of Cabramurra (Fig. 2) and continues farther southwards where it becomes continuous with the Indi Fault.

The north–northeast-trending Long Plain Fault separates meridional-trending Silurian and Early Devonian rocks of the Tumut and Goobarragandra Blocks to the north from tightly folded north–northeast-trending Ordovician–Silurian volcanic and flysch sequences of the Tantangara Block (Owen & Wyborn, 1979a,c) to the south. The fault has been described as a west-dipping reverse fault farther to the north where its strike is more northerly (Wyborn, 1977b; Owen & Wyborn, 1979b). In the study area, a section through the fault was examined along the Cabramurra–Kiandra road.

At this locality (Fig. 8), tightly folded strata in the Tumut Ponds Beds east of the fault young westwards and become progressively overturned approaching the fault. Within 250 m of the fault, bedding, dipping 70° southeast, parallels a penetrative cleavage and the inferred fault contact. Northwest of the fault, the cleavage in slate of the Ravine Beds is rotated clockwise from a near vertical north-trending orientation into parallelism with the fault at the fault contact. Rare quartz-fibre lineations present on the cleavage surface pitch about 60° northeast. The above structures are all consistent with dextral reverse movement on the Long Plain Fault.

Mainly dextral strike-slip movement is also indicated for the Kiandra Fault, which parallels the Long Plain Fault about 3 km to the southeast. At Tumut Ponds Dam, the fault is marked by a siliceous breccia with subhorizontal slickenlines (Fig. 4o). The movement on both the Kiandra and Long Plain Faults is probably mid-Devonian and/or Carboniferous (see following section).

South of Cabramurra, the Gilmore Fault Zone swings southwards beneath a Tertiary basalt capping, emerging as the Indi Fault. The fault throws mylonitic rocks of the Green Hills Granodiorite against the Ordovician Kiandra Group. The contact between both units was examined where exposed along

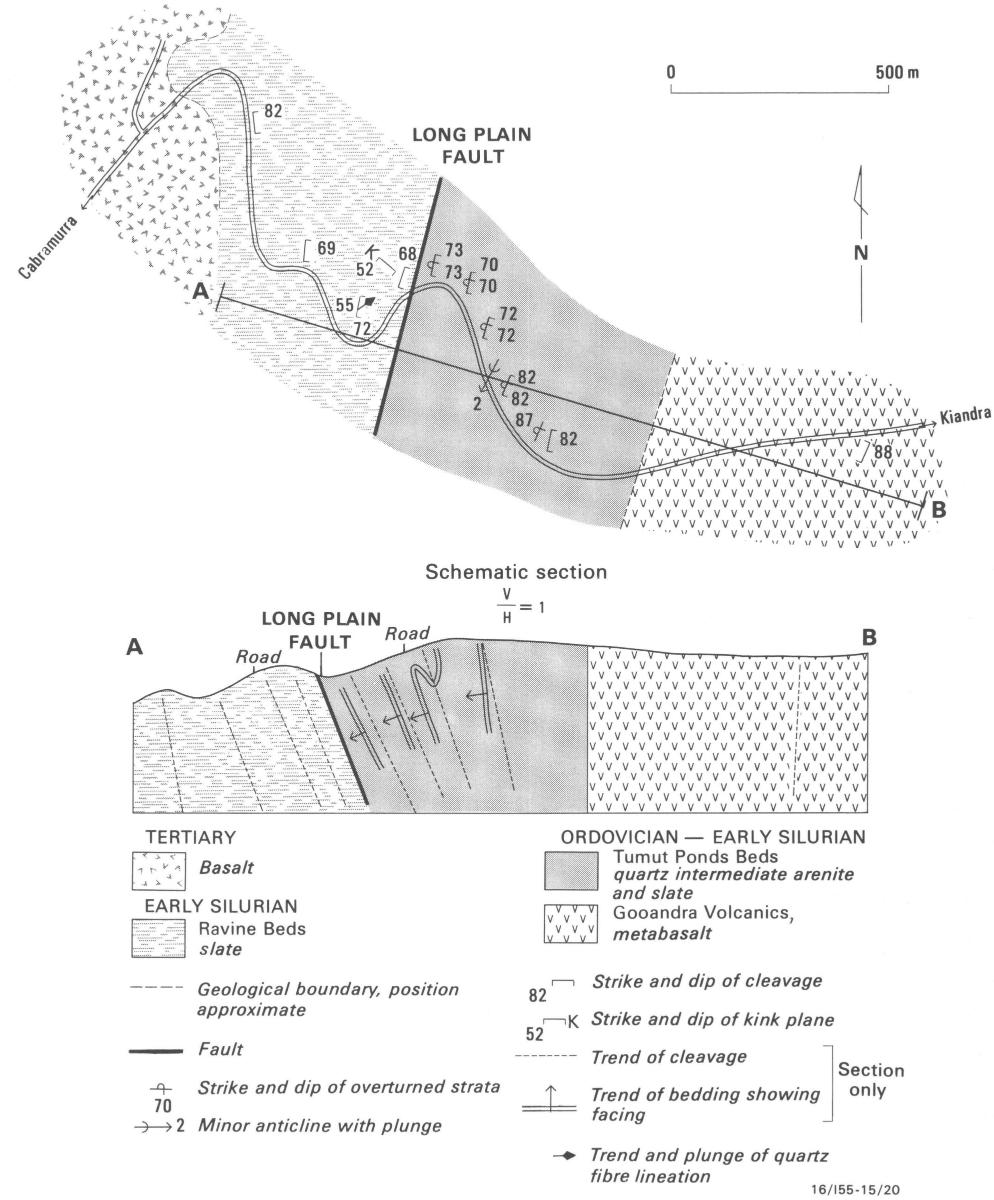

Figure 8. Geological sketch map and section across the Long Plain Fault, Cabramurra–Kiandra road.

the Geehi Dam access road (Locality A, Fig. 9). Here the fault dips steeply to the west and is marked by a 20 m wide ultramylonite zone in the granodiorite. Reverse movement is indicated by a near vertical mineral-elongation lineation (Fig. 4p) in the mylonite and slickenlines on minor synthetic shear zones in adjacent metabasalt of the Kiandra Group. There is no evidence to support interpreted sinistral displacement (Wyborn, 1977a) or large-scale dextral displacement (Vandenberg, 1978).

The indicated movement direction on the Indi Fault is close to that in the mylonitic zone within the Gilmore Fault Zone along the margin of the Wagga Metamorphic Belt, and is compatible with the interpreted east–west compression in southeastern Australia during Silurian (e.g. Chappell & White, 1976; Scheibner, 1976; White & others, 1976), mid-Devonian (Wyborn, 1977b; Powell, 1984) and Carboniferous (Powell & Veevers, 1984) times.

Discussion

Movement history

Pre-Siluro-Devonian

Owing to the penetrative nature of the Siluro-Devonian deformation (Bowning Orogeny) and the associated metamorphism, no earlier movement history is recorded in fault zone structures. However, it is likely, considering the structural history of the Wagga Metamorphic Belt and the Tumut Block, that the fault zone existed before this time. Folds pre-dating Silurian granitoid intrusion and trending 080° are present in both the Wagga Metamorphic Belt (e.g. Rogerson, 1977) and the Tumut Block. In the latter area they are recumbent, and zones of consistently south or north-facing folds are separated by minor faults which parallel the Gilmore Fault Zone (Stuart-Smith, 1988). These faults probably acted as accommodation structures (e.g. tear faults) during recumbent folding. The Gilmore Fault Zone may have been similarly active during the

Early Silurian deformation (Benambran Orogeny) when folding took place. The attitude of the folds, which also occur elsewhere in the Lachlan Fold Belt, is thought to be a result of dextral shear on the major fault zones (Cas & others, 1980; Powell, 1983a, 1984; Fergusson, 1987).

The Gilmore Fault Zone forms the western extent of Early Silurian north–south extension in the Tumut region (Stuart-Smith, 1990b). The partioning of this extension from the adjacent blocks requires strike-slip displacement on the bounding faults which parallel the extension direction. Movement on the Gilmore Fault Zone during this period may have been either dextral (Powell, 1983a, 1984) or sinistral (Packham, 1987).

Early Silurian

The earliest preserved structures within the Gilmore Fault Zone were synchronous with meridional folding of the Ordovician and Silurian rocks in the region during the Siluro-Devonian Bowning Orogeny. A subvertical elongation lineation, developed on the penetrative west-dipping cleavage (S_3) axial-plane to the folds, reflects an east–west principal compression direction and eastwards thrusting of the Wagga Metamorphic Belt over the Tumut Block. This accompanied thermal uplift associated with (and possibly postdating) widespread granitoid intrusion and regional metamorphism in the Wagga Metamorphic Belt. The Indi Fault, having an orientation orthogonal to the principal compression direction, became the thrust front as the Wagga Metamorphic Belt overrode the Tumut and Tantangara Blocks. Numerous lineaments parallel to the Indi Fault within the Wagga Metamorphic Belt (Fig. 9a) probably reflect smaller, but similar, reverse faults.

As deformation progressed, the principal compression direction rotated slightly to the northwest, creating transpressional conditions, and movement on the fault zone became oblique (sinistral reverse). The S_3 cleavage was rotated in an anticlockwise direction. In the mylonitic margin of the Wagga Metamorphic Belt and the adjacent central belt, the elongation lineation rotated from a steep westerly plunge to a more moderate northwesterly plunge. Only this latter orientation was preserved in allochthonous bodies of Rough Creek Tonalite and the margin of the Wagga Metamorphic Belt where thermal gradients were still high following granitoid intrusion.

Displacement does not appear to be confined to the boundary between the Wagga Metamorphic Belt and the Tumut Block at this time. Mylonitic rocks within the Wondalga Shear Zone (Basden, 1986), farther to the west within the Wagga Metamorphic Belt, are typified by a southwest-dipping foliation with an elongation lineation plunging 50° northwest (Veness, 1973). The parallelism of fabric elements in this zone to those in mylonites within the Gilmore Fault Zone suggests a common origin. Indeed, lineaments on Landsat images (Fig. 9a) indicate that the shear zone links up with the Gilmore Fault Zone. Thus the Wondalga Shear Zone and the Gilmore Fault Zone probably represent parts of a braided or imbricate oblique-slip (sinistral reverse) fault system.

Post-Early Devonian

Following deposition of Early Devonian shallow-marine sediments and volcanics, renewed southeast-directed thrusting of the Wagga Metamorphic Belt is indicated by downfaulting and folding of the Early Devonian rocks next to the Gilmore Fault Zone and the northwest pitch of rare slickenlines on minor faults. A crenulation cleavage (S_4), locally present in older units and parallel to a spaced cleavage in Early Devonian pelites, may have formed during this movement. The crenulation is axial plane to open east-verging folds.

The *S-C* fabric present in serpentinite bodies within the Gilmore Fault Zone and other minor structures such as kinks, joints, chevron folds and normal and reverse faults within Ordovician and Silurian metasediments and volcanics, forms a typical Riedel shear zone consistent with sinistral strike-slip movement on the Gilmore Fault Zone (Fig. 10). In the south, interaction with the north–northeast-trending Long Plain Fault Zone is interpreted to be the cause of minor retrograde cataclastic zones associated with dextral transpressional shear zones which deform the mylonitic fabric along the margin of the Wagga Metamorphic Belt.

The Riedel shear zone fabric of the Gilmore Fault Zone is also paralleled on a regional scale by the development of northwest-trending sinistral and northeast-trending dextral strike-slip faults and north-trending thrust faults throughout the southeastern part of the Lachlan Fold Belt (Fig. 9b). Such fabrics can be developed at any scale (Tchalenko, 1970). This is illustrated by the marked similarity of the strike-slip fault pattern in southeastern Australia (Fig. 9b) to that developed in a much larger area in eastern Turkey by the collision of the Arabian Plate with Eurasia (Fig. 11).

The movement history of the Gilmore Fault Zone is very similar to that outlined for the Mooney Mooney Fault Zone (Stuart-Smith, in press) and other faults in the region. In the Brindabella–Tantangara region, Wyborn (1977b) interpreted two periods of fault movement (one during the Late Silurian and the other post-mid Devonian) corresponding to episodes of lateral compression. Vandenberg (1978) describes both reverse and sinistral movement on the Kiewa Fault which parallels the Gilmore Fault Zone, forming part of the western margin of the Wagga Metamorphic Belt. However, recent work on the latter fault indicates that dextral strike-slip movement preceded mid-Devonian sinistral strike-slip movement (Gray & others, 1988). The only constraint on the timing of sinistral strike-slip movement on the Gilmore Fault Zone is that it post-dates the Siluro-Devonian S_3 cleavage. However, throughout the region deformation associated with east–west compression occurred during the mid-Devonian (Powell, 1983a, 1984) and Carboniferous (Powell & Veevers, 1984). All or most of the structures which post-date the Siluro-Devonian deformation in the Gilmore Fault Zone are therefore probably also either mid-Devonian and/or Carboniferous.

Serpentinite emplacement

S-C fabrics in allochthonous slices of ultramafic and mafic rocks (Tumut Ponds Serpentinite) within the Gilmore Fault Zone are consistent with the youngest structures found in the Ordovician and Silurian units. This does not necessarily imply a post-Siluro-Devonian age for their emplacement. Stuart-Smith (in press) found that successive deformations in the Coolac Serpentinite readily obliterated earlier fabrics. It is not suprising that *S* and *C* surfaces are the only Riedel shear elements present. In both the Coolac and Tumut Ponds Serpentinites, the *C* plane approximates the Y shear (Fig. 10) direction, which develops experimentally only during the residual stages of deformation (Tchalenko, 1970). The Tumut Ponds Serpentinite, like the Coolac Serpentinite, may well represent part of the Cambrian–Ordovician basement exposed elsewhere in the region as metamorphic core complexes (Stuart-Smith, 1990b) which were emplaced during Early Silurian extension in the region.

Crustal structure and terrane accretion

The crustal structure beneath the Gilmore Fault Zone in the Tumut region is poorly known. However, some interpretations can be made from limited seismic, gravity, surface structural and granitic source data available.

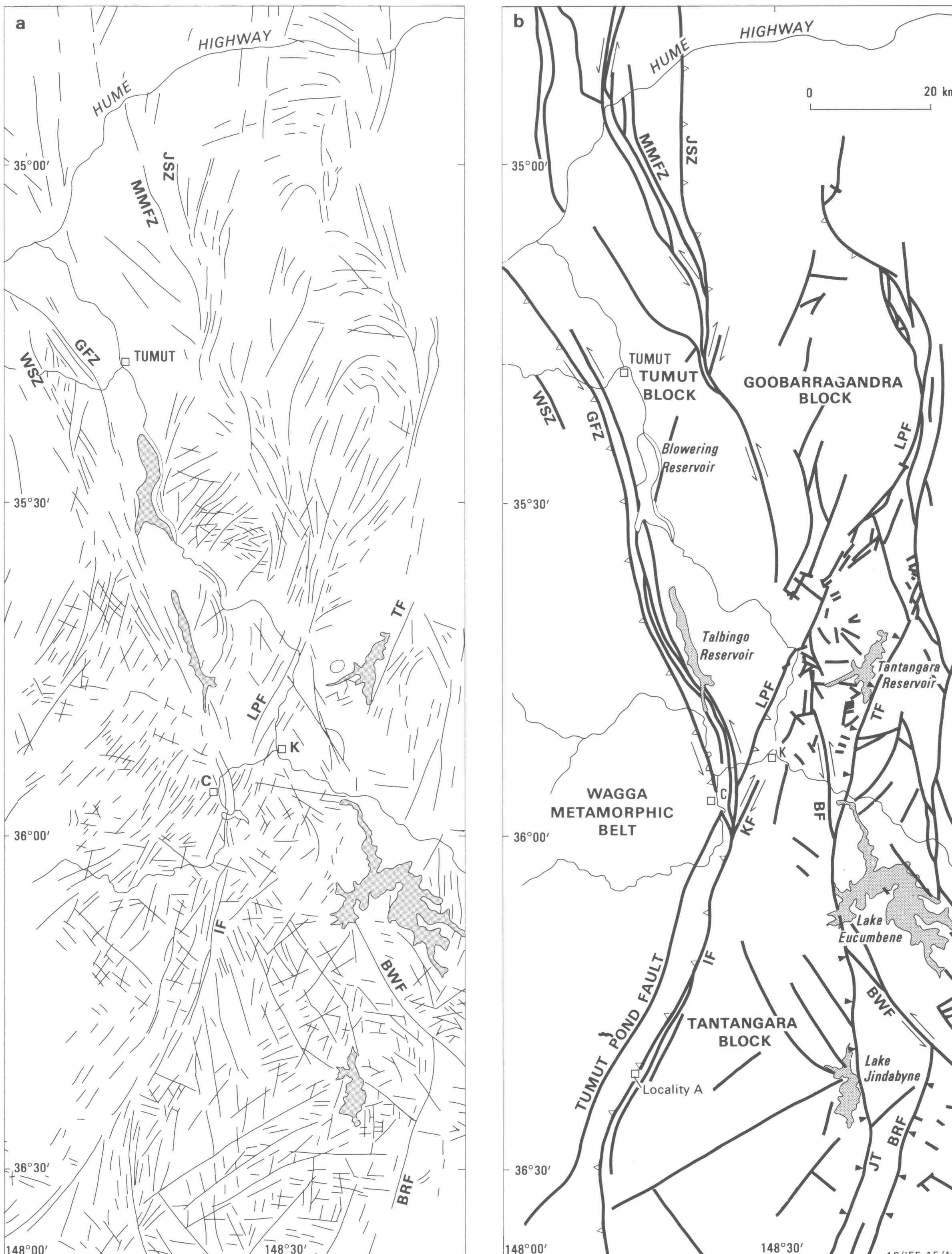

Figure 9. Sketch maps of (a) Landsat lineaments, (b) mapped faults (modified from Owen & Wyborn, 1979a,b; Owen & others, 1982; Wyborn, 1977b).

BRF Barneys Range Fault, BF Berridale Fault, C Cabramurra, GFZ Gilmore Fault Zone, IF Indi Fault, JT Jindabyne Thrust, JSZ Jugiong Shear Zone, K Kiandra, LPF Long Plain Fault, MMFZ Mooney Mooney Fault Zone, TF Tantangara Fault, T Tumut, TPF Tumut Ponds Fault, WSZ Wondalga Shear Zone.

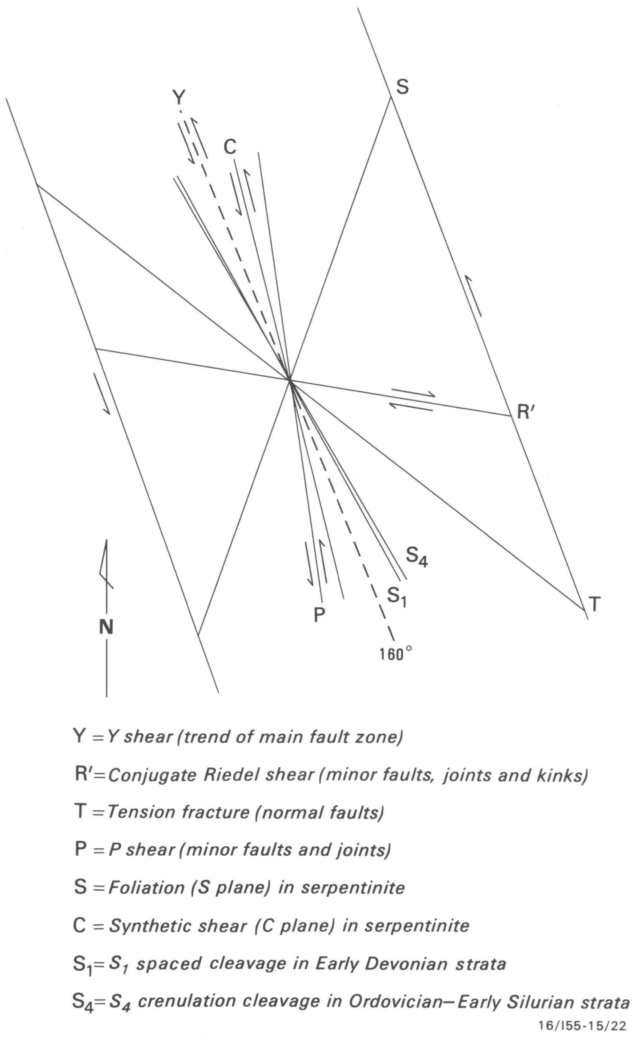

Figure 10. Angular relations between mid-Devonian structural elements of the Gilmore Fault Zone.
Riedel terminology modified from Biddle & Christie-Blick (1985).

The Tumut seismic traverse (Leven & Rickard, 1987) provides limited information about the upper crust under the Tumut Synclinorial Zone and the adjacent Goobarragandra Block. Major fault zones traversed by the survey (e.g. Mooney Mooney Fault Zone) are represented as vertical non-reflective zones which separate different packages of reflectors (Leven & others, 1988a,b). Between 10 and 20 km depth, most reflectors dip eastwards and are truncated by strong continuous gently west-dipping reflectors. These latter reflectors, corresponding to a low velocity zone present on regional seismic refraction profiles at about 16–35 km depth (Finlayson & others, 1979), are interpreted as a mid-crustal detachment linking the Gilmore Fault Zone with the Mooney Mooney Fault Zone, Long Plain Fault and other major faults in the region (Fig. 12). Mid-crustal detachments have also been invoked in structural interpretations by Fergusson & others (1986) and Glen & Vandenberg (1987) for other areas of the Lachlan Fold Belt. The presence of a mid-crustal detachment could accommodate both the vertical and horizontal displacements indicated for the Gilmore Fault Zone. The seismic character of the vertical faults in the Tumut area (i.e. near vertical reflection-free zones terminating in a mid-crustal horizontal reflectors) is characteristic of intraplate strike-slip zones (Lemiski & Brown, 1988; Burchfiel & others, 1989) rather than continental transform zones which are represented by continuous through-going crustal fractures (Lemiski & Brown, 1988).

Allochthonous bodies of Cambrian–Ordovician greenstone sequences (e.g. Tumut Ponds Serpentinite) in the Gilmore Fault Zone and elsewhere in the Tumut region probably represent tectonic slices originally obducted onto a thin Late Proterozoic to Early Palaeozoic crust underlying Ordovician strata throughout the Lachlan Fold Belt (Wyborn, 1988). The extent of the greenstone sequence in the subsurface (shown in Figure 12) is based on correlation of packages of short reflectors similar to those recorded in the Bullawyarra Schist in the Jindalee Block. Gravity and magnetic profiles in the region, dominated by shallow Early Silurian tholeiitic intrusions and the large body of Coolac Serpentinite in the Mooney Mooney Fault Zone, do not enable distinction of Silurian, Ordovician and older basement rocks at depth (R. Musgrave, Australian National University, personal communication, 1989). However, short wavelength (<250 km) residual Bouguer gravity anomalies (Murray & others, 1989) and magnetic anomalies (Wellman, 1989) reflect major differences in the trends of deep crustal structures either side of the Gilmore Fault Zone over a 'reworked' zone up to 100 km wide (Wellman, 1989).

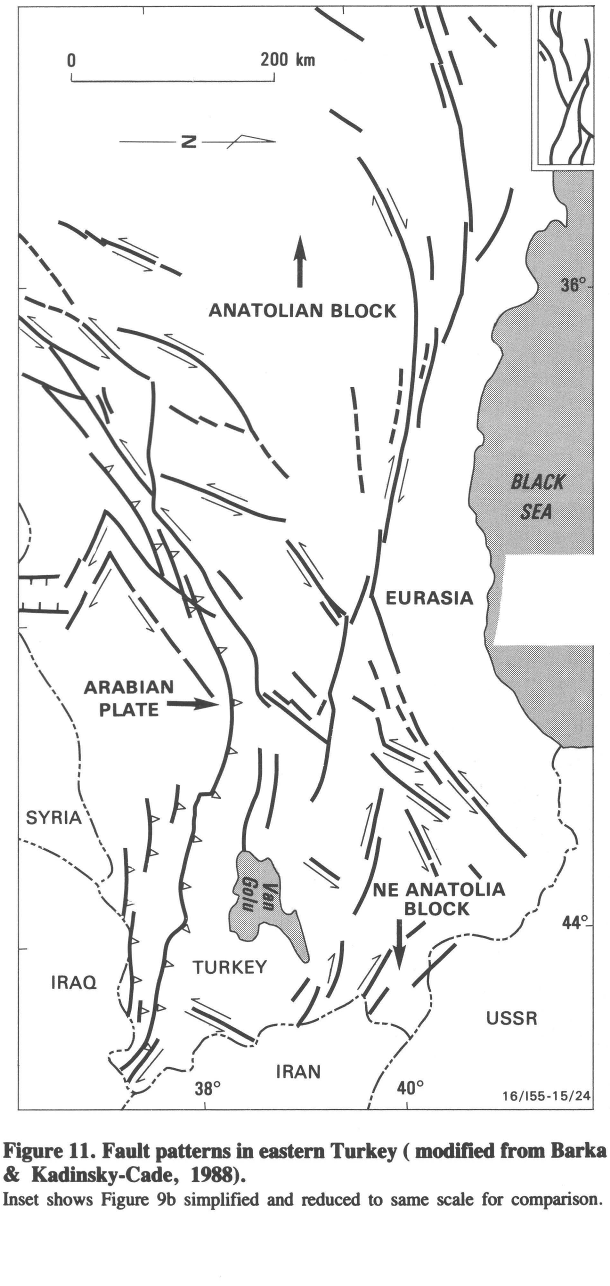

Figure 11. Fault patterns in eastern Turkey (modified from Barka & Kadinsky-Cade, 1988).
Inset shows Figure 9b simplified and reduced to same scale for comparison.

On the basis that granitoid source data may provide some information about the nature of the mid to lower crust in the region, Chappell & others (1988) interpreted Late Proterozoic to Early Palaeozoic terranes of different composition beneath the Lachlan Fold Belt. The boundary between their 'Kosciusko' and 'Wagga' basement terranes corresponds in part to the southern part of the Gilmore Fault Zone. Silurian S-type felsic volcanics and granitoids in the region were derived from partial melting of an immature feldspathic metasedimentary source (Chappell, 1984) at pressures of 5 to 6 kb (Wyborn & others, 1981). The source regions for these melts would be on the upper and lower plate, west and east respectively of the interpreted west-dipping Gilmore Fault Zone (Fig. 12). Thus the Gilmore Fault Zone may well represent an older reactivated basement fault separating Late Proterozoic–Early Palaeozoic terranes.

The Gilmore Fault Zone is unlikely to represent a terrane boundary in the Ordovician–Early Silurian formed by collision of the Wagga–Omeo Terrane with the Molong Volcanic Arc. Basden & others (1985) suggested that the Nacka Nacka Metabasic Igneous Complex (Wagga Metamorphic Belt) may be part of the volcanic arc. This study concurs with the suggestion of Basden & others; rocks here interpreted as Gooandra Volcanics occur on both sides of the fault zone, and are laterally continuous with the correlative Nacka Nacka Metabasic Igneous Complex. Thus volcanic rock units comprising the volcanic arc straddle the supposed terrane boundary. In addition, both 'terranes' share a common metamorphic (Wyborn, 1977a) and structural history.

Movement on the Gilmore Fault Zone has been demonstrated during the Late Silurian and post-Early Devonian (probably mid-Devonian and/or Carboniferous), and can be inferred as far back as the Early Silurian Benambran Orogeny. However, this movement cannot account for the differences in basement gravimetric and magnetic patterns and the inferred mid to lower crustal composition across the fault zone. The Gilmore Fault Zone therefore most likely represents a reactivated basement fault which corresponds, in part, to a Late Proterozoic–Early Palaeozoic terrane boundary interpreted by Chappell & others (1988).

Conclusions

The Gilmore Fault Zone is a long-lived imbricate fault system, up to 6 km wide, separating the Wagga Metamorphic Belt from the Tumut Block. Structures within the fault zone indicate two periods of dominantly sinistral transpressional movement: during regional deformation (Bowning Orogeny) in the Siluro-Devonian, and in the mid-Devonian and/or mid-Carboniferous. The movements, in reponse to lateral compression, resulted in the Wagga Metamorphic Belt being thrust over the Tumut and Tantangara Blocks. The Indi Fault, continuous with the

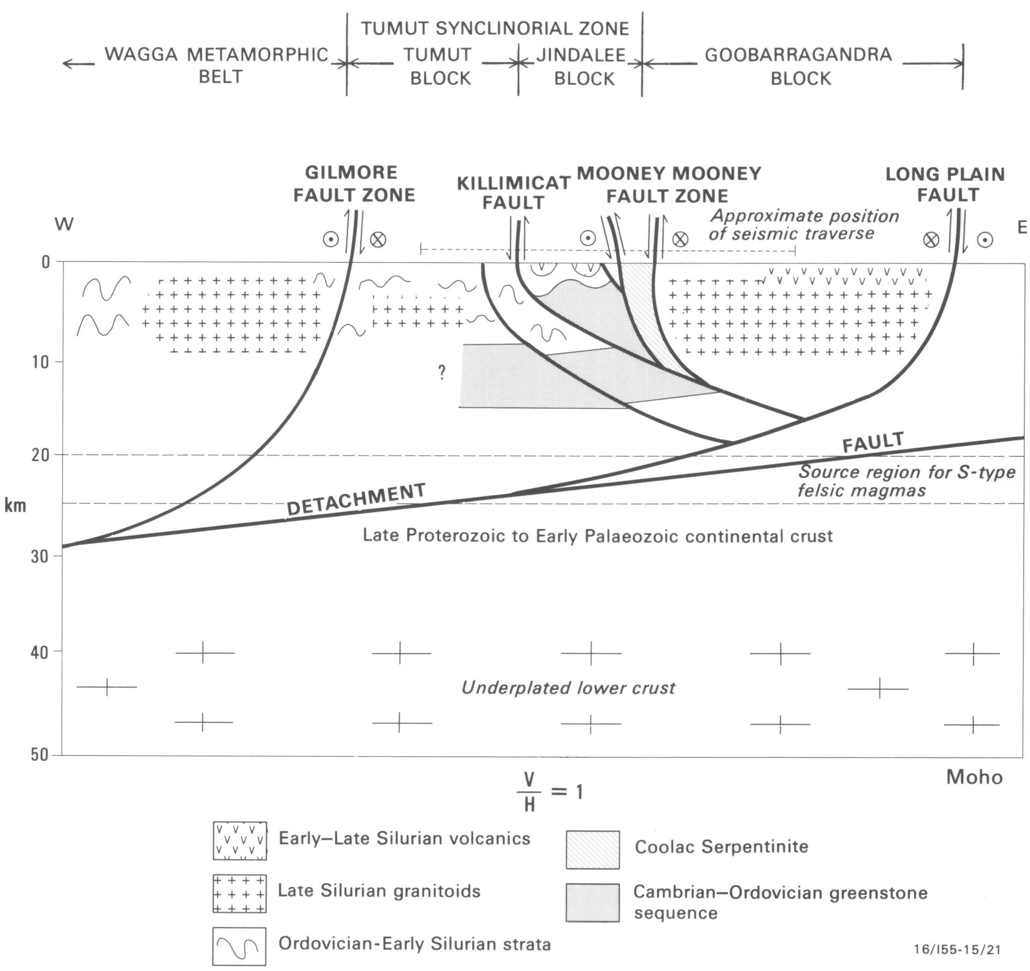

Figure 12. Schematic crustal profile for the Tumut region, showing relationship of major faults to interpreted mid-crustal detachment, based on the Tumut seismic traverse.

Gilmore Fault Zone, formed as a thrust front. An earlier strike-slip history is inferred during Early Silurian regional deformation (Benambran Orogeny) and subsequent Early Silurian extension.

Common structural and metamorphic histories, and lithological correlation of Ordovician–Early Silurian volcanic sequences straddling the fault zone, indicate that the Gilmore Fault Zone does not represent a terrane boundary in the Late Ordovician or Early Silurian as suggested by some previous workers. Differences in geophysical expression and crustal composition across the zone can be explained by the zone being a reactivated basement fault linked to a mid-crustal detachment.

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