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The emplacement and fault history of the Coolac Serpentinite, Lachlan Fold Belt, southeastern Australia

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Abstract—The Tumut Synclinorial Zone, located in the Lachlan Fold Belt, southeastern Australia, forms a fault-bounded belt of early Silurian volcanics and flyschoid metasediments of the Tumut Trough. The Mooney Mooney Fault System, containing an extensive ultramafic belt known as the Coolac Serpentinite, forms the eastern margin of the trough. The ultramafics together with mafic volcanics and intrusive grabbroic rocks have been previously interpreted as early Palaeozoic oceanic crust, dismembered and obducted during late Silurian deformation of the Silurian trough sequence. Recent work, however, has unravelled a more complex history involving several periods of movement. The ultramafics and early Silurian volcanics are intruded by early Silurian gabbro and syn-kinematic late Silurian granodiorite. These intrusive relationships indicate that the ultramafic rocks were present in approximately their present structural position prior to deformation of the trough sequence. The ultramafics therefore cannot represent early Silurian oceanic crust, obducted during the Late Silurian deformation. They probably represent either early Silurian or Cambrian–Ordovician mantle-derived material emplaced within a strike-slip fault zone during early Silurian oblique extension.

INTRODUCTION

The Tumut Synclinorial Zone is an early Palaeozoic tectono-stratigraphic province in the southeastern part of the Lachlan Fold Belt. The zone, containing Lower Silurian flyschoid sediments, and felsic and mafic volcanics of the Tumut Trough, is separated from the Goobarragandra Block to the east and the Wagga Metamorphic Belt to the west by major faults (Fig. 1). The Goobarragandra Block comprises mainly Silurian granitoids (Young Granodiorite), their coeval volcanics (Goobarragandra Volcanics) and Silurian mafic intrusions (Micalong Swamp Mafic Igneous Complex). The Wagga Metamorphic Belt consists of Ordovician flyschoid metasediments and volcanics, and Silurian granitoid felsic and mafic intrusions. The generalized geology of the region is shown in Fig. 1. An extensive ultramafic belt, known as the Coolac Serpentinite, forms part of the Mooney Mooney Fault Block (referred to as the Mooney Mooney Terrane by Basden *et al.* 1987) which forms the faulted eastern margin of the trough.

The combination of ultramafic rocks and Silurian sediments in the Tumut Trough is unique in the Lachlan Fold Belt and has led to a vartiety of tectonic models. The trough has been regarded as one of: a subsequently closed marginal sea (Scheibner 1973, Ashley *et al.* 1979); a continental rift (Wyborn 1977, Lightner 1977); a zone of fore-arc collision with a continental margin (Crook 1980); a small ocean-floored transtensional pull-apart basin (Powell 1983a, Packham 1987); a suspect terrane (Basden *et al.* 1987).

The Coolac Serpentinite comprises an ultramafic suite of partly serpentinized harzburgite, serpentinite and minor wehrlite, lherzolite, clinopyroxenite and chromitite (Ashley *et al.* 1971). Harzburgite forms as residual material left after partial melting of the upper mantle (Stern & de Wit 1980). Such melting is usually restricted to speading oceanic ridges (Girardeau *et al.* 1985) or other zones of rising upper mantle formed during continental extension (Bébien *et al.* 1986). Such ultramafic rocks can be emplaced in the upper continental crust either as allochthonous thrust sheets of ophiolite or as Alpine-type intrusions along subvertical crustal fractures. Serpentinization of these ultramafic rocks typically occurs either at the time of their formation (Girardeau *et al.* 1985) or at the time of their emplacement in upper crust (Radhakrishna *et al.* 1987).

Packham (1987) suggested that the Coolac Serpentinite was emplaced in a strike-slip fault zone during the late Ordovician or early Silurian. However, most authors interpret the serpentinite, together with an intrusive gabbroic dyke complex (North Mooney Complex) and basalt (Honeysuckle Beds), as forming a dismembered ophiolitic suite (Ashley *et al.* 1979). This suite was interpreted to be emplaced into the upper continental crust during closure of the Tumut Trough. Closure probably accompanied deformation of the Silurian trough sequence during the late Silurian (at about 417 Ma, Basden 1982).

Previous structural studies (Ashley & Chenall 1976, Basden *et al.* 1987) of the Mooney Mooney Fault Block have indicated reverse movements on a steep E-dipping mylonitic zone within the Young Granodiorite along the eastern margin of the ultramafic belt. Consistent with this interpretation, most authors (e.g. Scheibner 1973, Ashley *et al.* 1979, Crook 1980, Basden *et al.* 1987) interpreted the ultramafics as slices obducted along subsequently steepened E-dipping thrusts. However, Ashley & Chenall (1976) suggested that the faults originated as westward dipping thrusts which were progressively overturned. As they were overturned the sense of displacement inversed.

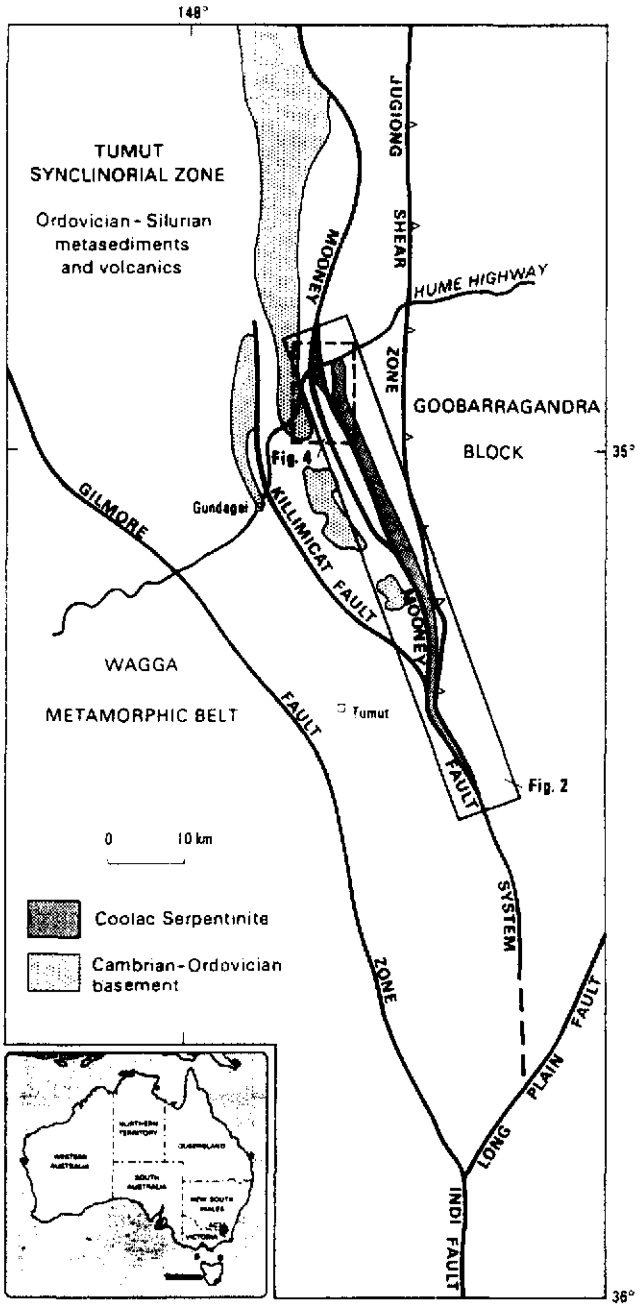

Fig. 1. Location and geological setting of the Coolac Serpentinite.

This paper details the results of a structural study of the Mooney Mooney Fault Block and re-examines the origin and emplacement history of the Coolac Serpentinite in the light of field relations. Critical field relations between the different members of the ophiolite suite are described and the structural fabric of the fault is outlined. The study indicates a more complex movement history than previously described for the Mooney Mooney Fault System which is dominated by strike-slip movements. The concept of a Silurian ophiolitic suite obducted during the late Silurian is rejected. The serpentinite is probably either an early Silurian intrusion or most likely a tectonic slice derived from the underlying Cambrian–Ordovician Jindalee Group and emplaced within the fault system during early Silurian extension.

REGIONAL GEOLOGY

The geology of the Mooney Mooney Fault Block, described in detail by Ashley *et al.* (1971) and Basden (1986), is shown in Fig. 2. The stratigraphy is summarized in Table 1. The block consists of a NNW-trending belt of early Silurian felsic volcanics, mafic volcanics and intrusives, and minor sediments. The belt flanks the western margin of the Coolac Serpentinite, which forms a prominent ridge of ultramafic rocks extending for about 100 km along the western margin of the late Silurian Young Granodiorite. The early Silurian strata were openly to tightly folded about meridional axes and metamorphosed to lower greenschist facies in the late Silurian. Structural inliers of polydeformed metabasic and ultramafic rocks of the Cambrian–Ordovician Bullawyarra Schist (Jindalee Group) occur within the Silurian trough sequence immediately west of the Mooney Mooney Fault Block. These inliers are interpreted as metamorphic core complexes formed during early Silurian extension of the Tumut Trough (Stuart-Smith in press).

Stratigraphic relationships

Significant changes in the stratigraphic correlation of units in the region are indicated by the present structural study of the Tumut Trough. These changes (Fig. 3) result from three discoveries: (1) a conformable contact exists between the Honeysuckle Beds and the Blowering Formation (Stuart-Smith 1988); (2) the Young Granodiorite intrudes both the Coolac Serpentinite and North Mooney Complex; and (3) the North Mooney Complex intrudes the Blowering Formation.

The Honeysuckle Beds (Ashley *et al.* 1971) were previously considered to be one of the oldest units in the Silurian trough sequence (Basden 1986) forming part of a dismembered W-facing ophiolitic suite (the Coolac Ophiolite Suite; Ashley *et al.* 1979). Although the Honeysuckle Beds were originally thought to overlie the Blowering Formation ("Blowering Beds" Ashley *et al.* 1971), and eastward-facing beds were noted by Mangold (1978) and D. P. Thrum (personal communication in Crook & Felton 1975), it was interpreted to be an overturned W-facing sequence which was faulted against the Blowering Formation (Basden 1986).

There is no evidence of a faulted contact between the Honeysuckle Beds and the Blowering Formation. Conformable contacts between basalt and dacite are exposed about 2 km west of 'The Elms' and 1 km north of Big Hill (Fig. 2). At the latter locality the base of the Honeysuckle Beds consists of a sedimentary breccia, up to 2 m thick, comprising clasts of dacite and metabasalt (Stuart-Smith 1988). Stratigraphic facing cannot be determined at this locality. However, the contact dips to the east, conformable with upwards-graded silty laminae in slate horizons within both formations. Throughout the entire Mooney Mooney Fault Block, both the Honeysuckle Beds and the Blowering Formation face eastwards and are upright (no downward-facing beds

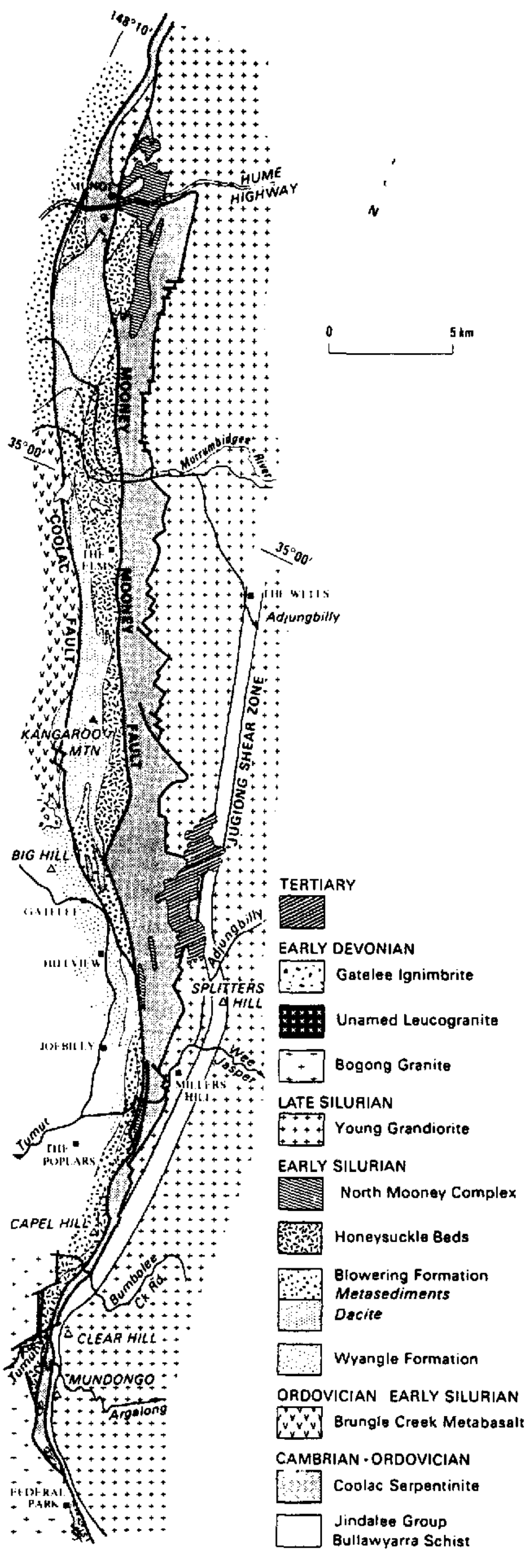

Fig. 2. Generalized geology of the Mooney Mooney Fault Block.

have been found) confirming the original interpretation of Ashley *et al.* (1971) that the Honeysuckle Beds is the youngest Silurian unit in the area directly overlying the Blowering Formation. The younger age of the Honeysuckle Beds is also supported by the occurrence of metabasalt (presently unnamed and not shown on geological maps of the area) overlying Blowering Formation dacite about 3 km northeast of Tumut (Lightner 1977).

The contacts between the ophiolite suite and adjacent units were inferred to be tectonic (Basden *et al.* 1978). The present study establishes that the Young Granodiorite intrudes both the Coolac Serpentinite and North Mooney Complex, and that the North Mooney Complex intrudes the Blowering Formation.

Although the contact between the Young Granodiorite and the western margin of the Coolac Serpentinite is faulted along its entire length, an intrusive relationship is evident about 5 km SE of Mungi homestead where granodiorite dykes and an irregularly-shaped body of granodiorite, about 100 m across, intrude massive harzburgite (Fig. 4). Both the dykes and the intrusive body of granodiorite are separated from the main mass of the Young Granodiorite by a 5 m wide mylonite zone. Farther to the south, where the Tumut–Wee Jasper road crosses the serpentinite belt (Fig. 2), a tectonic inclusion of granodiorite within serpentinite contains xenoliths of serpentinite providing further evidence for an intrusive relationship between both units.

Two kilometres north and 2 km south of Mungi homestead, respectively (Fig. 4), small stocks of Young Granodiorite intrude the North Mooney Complex as well as the Coolac Serpentinite. At both these localities a narrow (<1 m wide) porphyritic fine-grained chilled margin is present surrounding outcrops of coarse-grained granodiorite. There is no sign of tectonism or other evidence to support the interpretation that these outcrops represent thrust klippen (Basden *et al.* 1978).

The main body of the North Mooney Complex forms a dyke complex intruding the Coolac Serpentinite, Honeysuckle Beds and Blowering Formation within an area of about 30 km^2 surrounding the Hume Highway (Figs. 2 and 4). In this area, the complex interrupts the ultramafic belt and the Silurian volcanic sequence and intrusive relations are preserved in the relatively undeformed areas between the major faults in the Mooney Mooney Fault Block. Farther to the south, where the fault block is narrower and deformation more intense, the complex occurs as smaller discontinuous tectonized bodies within the Coolac Serpentinite and the Honeysuckle Beds. In the north the contact between the North Mooney Complex and the Coolac Serpentinite is sharp and irregular, and is well exposed 5 km southeast of Mungi homestead where narrow (<1 m) dykes of gabbro intrude massive harzburgite (Fig. 4). Similar intrusive contacts occur between gabbro and basalt (Honeysuckle Beds) in the same area (Brown 1979) and between gabbro and felsic volcanics (Blowering Formation) 3 km south of Mungi homestead (Fig. 4).

These intrusive relationships show that the North Mooney Complex (426 ± 6 Ma; Webb 1980) intruded

Table 1. Summary of stratigraphy of the Mooney Mooney Fault Block

Unit	Description	Field relationships	Thickness (m)	Remarks
CAINOZOIC				
T	Basalt, dolerite, hematitic ironstone, conglomerate, sandstone and siltstone	Unconformably overlies older units	40	Forms flat-lying capping
EARLY DEVONIAN				
Gatelee Ignimbrite (Dtr)	Rhyolitic ignimbrite, minor basal polymictic conglomerate	Unconformably overlies older units	100	Forms remnants of a sub-horizontal ignimbrite sheet (Ashley *et al.* 1971, Kennard 1974)
Dg	Coarse-grained leucogranite	Faulted against older units		Occurs as tectonic slices with the Coolac and Mooney Mooney Faults. May be Dgb
Bogong Granite (Dgb)	Massive fine- to medium-grained leucogranite, medium- to coarse-grained equigranular biotite granite. Metasediment hornfels rafts	Intrudes and faulted against Oc		I-type granite. Age 410 ± 16 Ma (K–Ar on biotite; Ashley *et al.* 1971)
LATE SILURIAN				
Young Granodiorite (Sgy)	Massive coarse-grained equigranular granodiorite. Minor net-vein complexes with fine to medium-grained hornblende quartz diorite. Mylonitic where cut by Jugiong Shear Zone	Intrudes Oc, Shm. Gradational with Sbd		S-type granite. Age 417 ± 6 Ma (K–Ar on biotite; Evernden & Richards 1962). Coeval with Sbd
EARLY SILURIAN				
North Mooney Complex (Shm)	Gabbro and dolerite. Minor diorite, trondjhemite and albitite	Intrudes Oc, Sbd, Sbl, and Sh. Tectonic inclusions in Oc		Sheeted dyke complex (Brown 1979). Age 426 ± 6 Ma (K–Ar on hornblende; Webb 1980)
Honeysuckle Beds (Sh)	Massive dark green fractured altered meta-basalt. Foliated near fault contacts. Pillow structures common. Minor interbedded meta-shale, silty slate, argillite, graded mafic tuff and rare fine- to coarse-grained quartz-poor arenite. Polymictic sedimentary breccia (basalt and dacite clasts) common at base	Intruded by Shm and Sgy. Conformably overlies Sbl; local basal breccia. Intertongues with Sbd	500	Subaqueous basalt flows and minor intercalated sediments. Water depth <1000 m (Basden 1986)
Blowering Formation (Sbl)	Brown meta-shale and slate with silty laminae and graded very fine- to coarse-grained quartz–intermediate arenite beds. Minor dacite flows, mafic and felsic tuff, and meta-basalt	Conformable E-facing sequence overlying and intertongueing with Sbd. Underlies Sh and intruded by Shm in north	500	Sedimentary volcaniclastic sequence. Lower Middle Ludlovian conodonts in allochthonous limestone clasts (Lightner 1977)
(Sbd)	Massive porphyritic dacite	Conformably underlies and intertongues with Sbl and Sh. Faulted against Oc. Underlain by Sw	1000	Flows and subvolcanic intrusions. Coeval with Sgy and 429 Ma Goobarragandra Volcanics (Owen & Wyborn 1979)
Wyangle Formation (Sw)	Shale, mudstone, fine- to coarse-grained quartz-poor to quartz-intermediate arenite, polymictic conglomerate, diamictite and rare hornblende andesite	Unconformably overlies and faulted against Ojb. Underlies, intertongues with and intruded by Sbd	500	Allochthonous limestone blocks in diamictite contain conodonts of probable late Llandoverian to early Wenlockian age (Lightner 1977)

Table 1. Continued

Unit	Description	Field relationships	Thickness (m)	Remarks
ORDOVICIAN–E. SILURIAN				
Brungle Creek Metabasalt (Or)	Meta-basalt, minor chert and meta-dolerite	Unconformably overlain by Sw		Flows and subvolcanic intrusions
CAMBRIAN–ORDOVICIAN				
Coolac Serpentinite (Oc)	Massive well-jointed harzburgite with rare primary layering, schistose serpentinite, minor talc schist and rodingite dykes. Minor wehrlite, pyroxenite and lherzolite in north. Common tectonic inclusions of gabbro, dolerite and diorite (Shm); meta-basalt (Sh); fine-grained quartzite; biotite schist; and granite. Anthophyllite hornfels adjacent to Dgb	Intruded by Sgy, Shm and Dgb. Faulted against Sbl, Sbd, Sh, Dgb, Sgy and Shm		Forms tectonic slice within the Mooney Mooney Fault System. Part of ophiolitic suite with Ojb?
Bullawyarra Schist (Ojb)	Actinolite (meta-basalt and meta-dolerite)	Faulted against other units		Forms metamorphic core complexes to west. Tectonic slice within Coolac Fault. Part of ophiolitic suite with Oc?

after Silurian volcanism and emplacement of the Coolac Serpentinite but prior to intrusion of the Young Granodiorite. Thus the relationship is analogous to the Micalong Swamp Mafic Igneous Complex (430 ± 9 Ma; Owen & Wyborn 1979) which intrudes the Goobarragandra Volanics and is itself intruded by Young Granodiorite (Fig. 3). The granodiorite is a subvolcanic intrusion chemically related to both the Blowering Formation volcanics and the subaerial Goobarragandra Volcanics (Owen & Wyborn 1979).

STRUCTURES OF THE MOONEY MOONEY FAULT BLOCK

As the Coolac Serpentinite was emplaced in the upper continental crust by at least the late early Silurian, previous models of serpentinite emplacement based on structural studies of the mylonite zone within the granodiorite reflect only part of the tectonic history of the ultramafic belt. This study examines all the units within the Mooney Mooney Fault Block and adjacent areas in an attempt to determine a more complete structural history consistent with the observed stratigraphic relations.

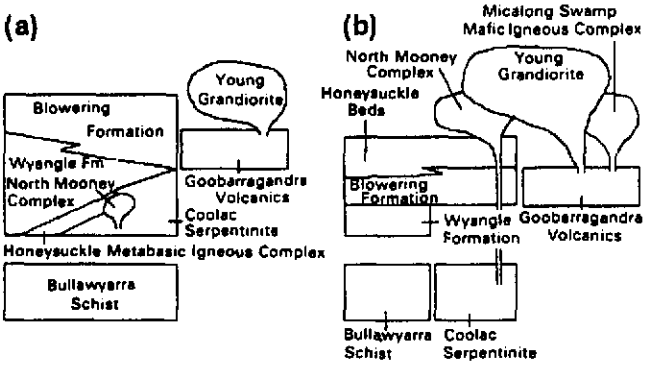

Fig. 3. Diagrammatic stratigraphy of the Mooney Mooney Fault Block: (a) after Basden (1987); (b) this paper.

S-C mylonite fabrics (Berthé *et al.* 1979) are widespread throughout the Mooney Mooney Fault Block, particularly in the Coolac Serpentinite along the Mooney Mooney Fault and in the Young Granodiorite within the Jugiong Shear Zone (Fig. 5a). The fabric is used here to determine movement directions whereby the direction of slip is defined as the normal in the shear plane, to the intersection of the two surfaces (Fig. 5c).

A mineral-elongation lineation on the *C* plane is commonly present in the granodiorite wherever the *S–C* fabric is developed. However, apart from deformed fibrous vein material which shows no geometric relationship to the *S* or *C* surfaces, slickenlines are the only mesoscopic linear element observed on surfaces within the serpentinite. Without the presence of a well-defined lineation associated with the *S–C* surfaces in the serpentinite, it could be argued that the two surfaces are unrelated and therefore cannot be used to determine movement direction. Although mesoscopically both the *S* and *C* surfaces in the serpentinite appear to be composed of platy serpentinite minerals, microscopically the *C* surfaces have a fibrous character compared to the platy minerals forming the *S* surface (Fig. 5b). Furthermore, the fibres are aligned sub-perpendicular to the intersection of the two planes. Thus it is likely that the *S* and *C* surfaces developed synchronously and movement directions can be deduced. In addition the following field relations indicate that the *S* and *C* surfaces formed during the one phase of movement.

(1) *S–C* fabrics in the serpentinite show geometries consistent with observed fault offsets both along the Mooney Mooney Fault and in zones of cross-faulting

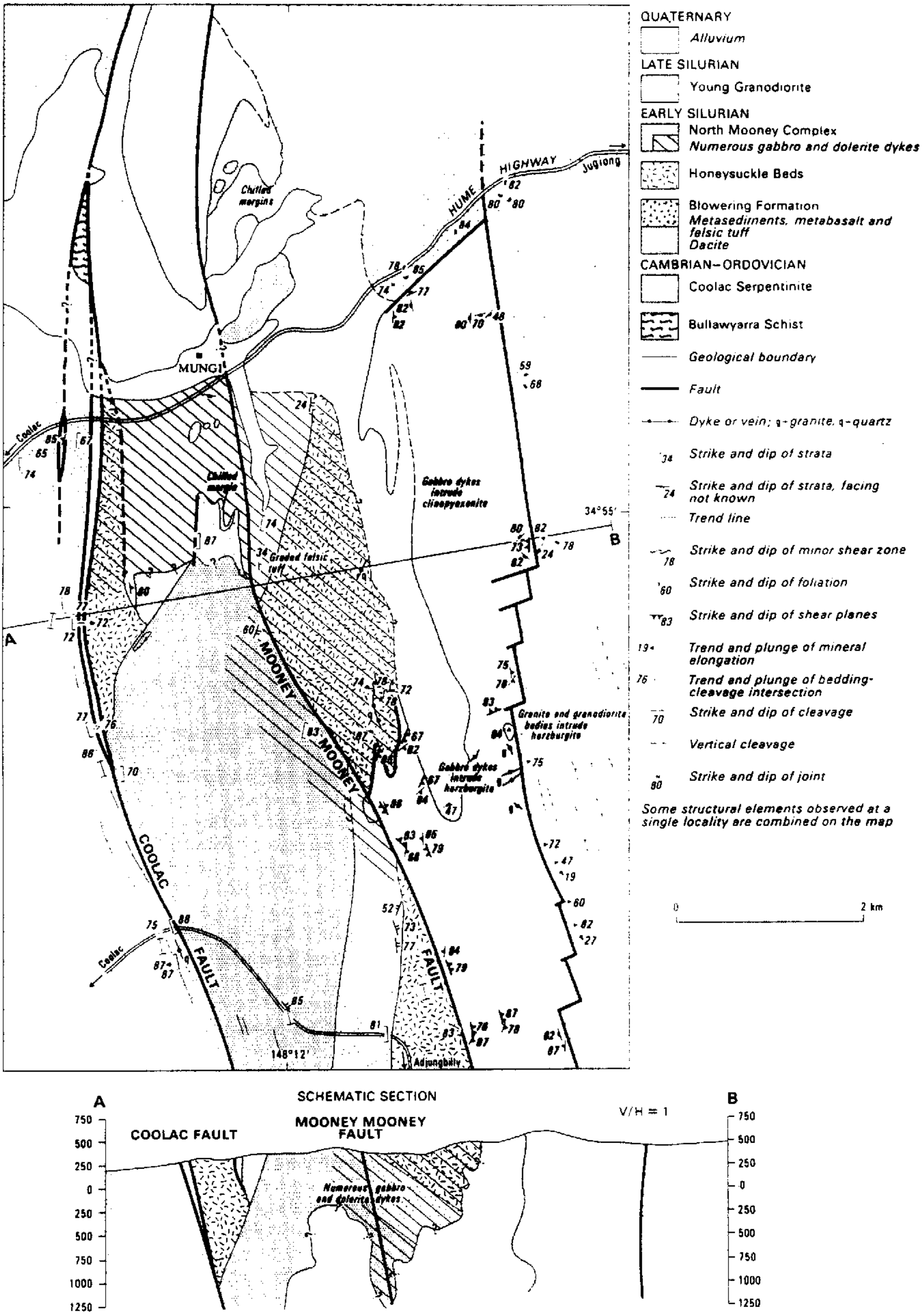

Fig. 4. Geology of the northern part of the Mooney Mooney Fault System.

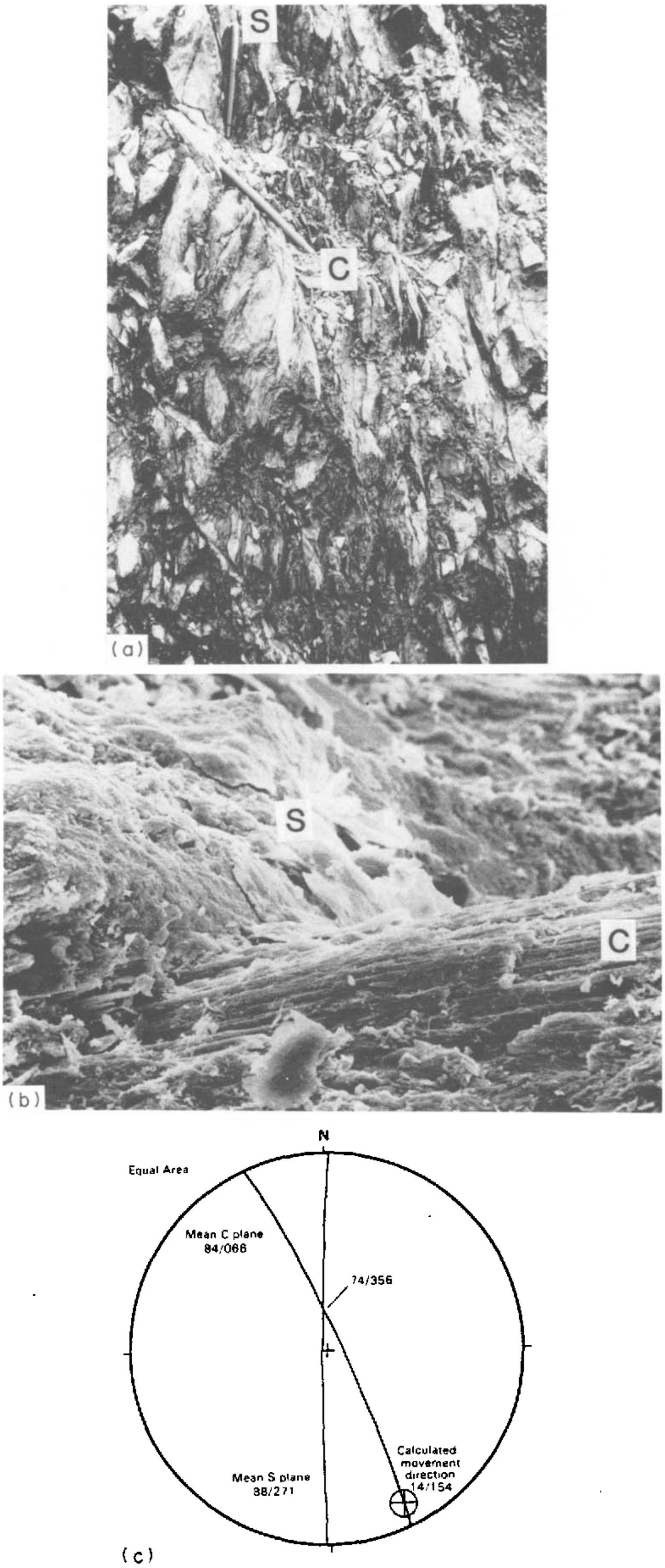

Fig. 5. *S–C* mylonite fabrics within the Coolac Serpentinite: (a) outcrop; (b) SEM image showing fibrous nature of *C* plane serpentine compared to platy serpentine minerals forming *S* planes; (c) stereoplot of mean *S* and *C* planes showing the calculated movement direction for the main schistose serpentinite zone along the Mooney Mooney Fault.

and shearing. If the foliation (*S* plane) was an earlier fabric it would have a constant orientation in both fault orientations.

(2) The normal bisector of the *S* and *C* planes in the serpentinite parallels both slickenlines on fault planes and the mineral-elongation lineation in adjacent mylonitic granodiorite (excluding mylonites within the Jugiong Shear Zone which are older).

The recognition of *S–C* fabrics within the Coolac Serpentinite has enabled a more comprehensive structural analysis of the Mooney Mooney Fault Block than has been previously attempted. Results of this analysis are detailed below. The Mooney Mooney Fault Block comprises units bound within the Mooney Mooney Fault System, an imbricate strike-slip fault zone consisting of the Mooney Mooney Fault, the Coolac Fault and numerous unamed fault splays. The Jugiong Shear Zone and the Killimicat Fault merge with the Mooney Mooney Fault in the south. The main structural elements of the fault system are shown in Fig. 6.

Mooney Mooney Fault System

Coolac Fault. North of Hillview homestead, a fault splay, here named the Coolac Fault, diverges from the Mooney Mooney Fault and extends northwards subparallel to the latter. The Coolac Fault forms the western margin of the Mooney Mooney Fault Block. Tectonic slivers of coarse-grained leucogranite (?Bogong Granite), serpentinite (Coolac Serpentinite) and actinolite schist (Bullawyarra Schist) are present in places (Fig. 2).

North of the Murrumbidgee River, the Coolac Fault forms a deformed zone up to 300 m wide. Within this zone Blowering Formation slate is extensively veined by quartz. The veins are boudinaged with boudin axes plunging gently to the south perpendicular to a quartz-fibre lineation which pitches steeply north on a steep E-dipping to subvertical cleavage. The extension direction, indicated by the quartz-fibre lineation, parallels bedding–cleavage intersections indicating relatively high strains in the zone. Normally, folds in the Blowering and Wyangle Formations in the Tumut Trough are open, upright and have gently plunging axes. In the south, adjacent to the fault, folds become tight with overturned E-dipping limbs within 100 m of the fault.

The extension lineation direction and changes in fold attitude within the deformed zone indicate that movement was near vertical with east-side-up (i.e. reverse). However, the movement history of the fault is more complex. Matching of similar stratigraphic units on either side of the Coolac Fault suggests sinistral strike-slip movement with minor vertical displacement (probably less than 1 km). Structures indicative of sinistral strike-slip movement are also present within faulted slivers of serpentinite near the Hume Highway. The foliation orientation within the serpentinite trends NE, i.e. oblique to the fault surface. The horizontal component of displacement is about 24 km if the allochthonous bodies of leucogranite are indeed faulted slices of Bogong Granite (Fig. 2). There is no means of determining the age relationship between both movements. However, a similar two-stage movement history is indicated in the Jugiong Shear Zone where reverse movement preceded sinistral strike-slip displacement.

Mooney Mooney Fault. The Mooney Mooney Fault separates the main mass of Coolac Serpentinite from Silurian metasediments and volcanics to the west. In the south it merges with the Jugiong Shear Zone where it juxtaposes the early Devonian Bogong Granite and the Silurian Young Granodiorite (Fig 2). In this area, the serpentinite is contact-metamorphosed by the Bogong Granite to an anthophyllite and cordierite-bearing ultramafic hornfels (Ashley *et al.* 1971).

The Mooney Mooney Fault is marked by a 1 km wide zone of deformation. Silurian metasediments and volcanics on the western side of the fault are intensely foliated within 500 m of the fault and are sheared, fractured, silicified and veined by quartz and epidote. Towards the fault, folds become progressively tighter to isoclinal and in places limbs may show small sinistral displacements along the axial cleavage.

Within 500 m of the fault, the Coolac Serpentinite is completely serpentinized and strongly foliated. Schistose serpentinite within this zone is typified by ubiquitous *S–C* fabrics consisting of a steeply E-dipping foliation and a subvertical to steeply ENE-dipping shear plane (Fig. 6d). A sinistral transpressional displacement is indicated. The inferred movement direction is near horizontal or plunges shallowly SE. Progressing eastwards away from the Mooney Mooney Fault the occurrence of schistose serpentinite becomes more localized and finally gives way to fractured serpentinized harzburgite. The fabric in the latter area is typified by narrow (a few cm wide) serpentinite zones enclosing domino-style blocks of more massive serpentinite separated by synthetic shear planes (Fig. 7).

The Coolac Serpentinite–Young Granodiorite contact. In the north, where the Jugiong Shear Zone diverges from the contact between the Coolac Serpentinite and the Young Granodiorite, the serpentinite–granodiorite contact has a step-like morphology, comprising a N-trending faulted contact offset by sinistral NW-trending faults. Both the serpentinite and granodiorite are weakly deformed compared to farther south where the Jugiong Shear Zone forms the contact between the two units.

Deformation along the N-trending contact is variable ranging from localized mylonite development in the north to weakly deformed rocks south of the Murrumbidgee River where massive ultramafics and granodiorite are separated by less than 50 cm of schistose serpentinite. However, in general the ultramafics are serpentinized in a 10 m wide zone adjacent to the contact. *S–C* fabrics within this zone indicate oblique-slip with a sinistral strike-slip component (Fig. 6). Where mylonite is developed in granodiorite, a weak mineral-elongation lineation is commonly present and

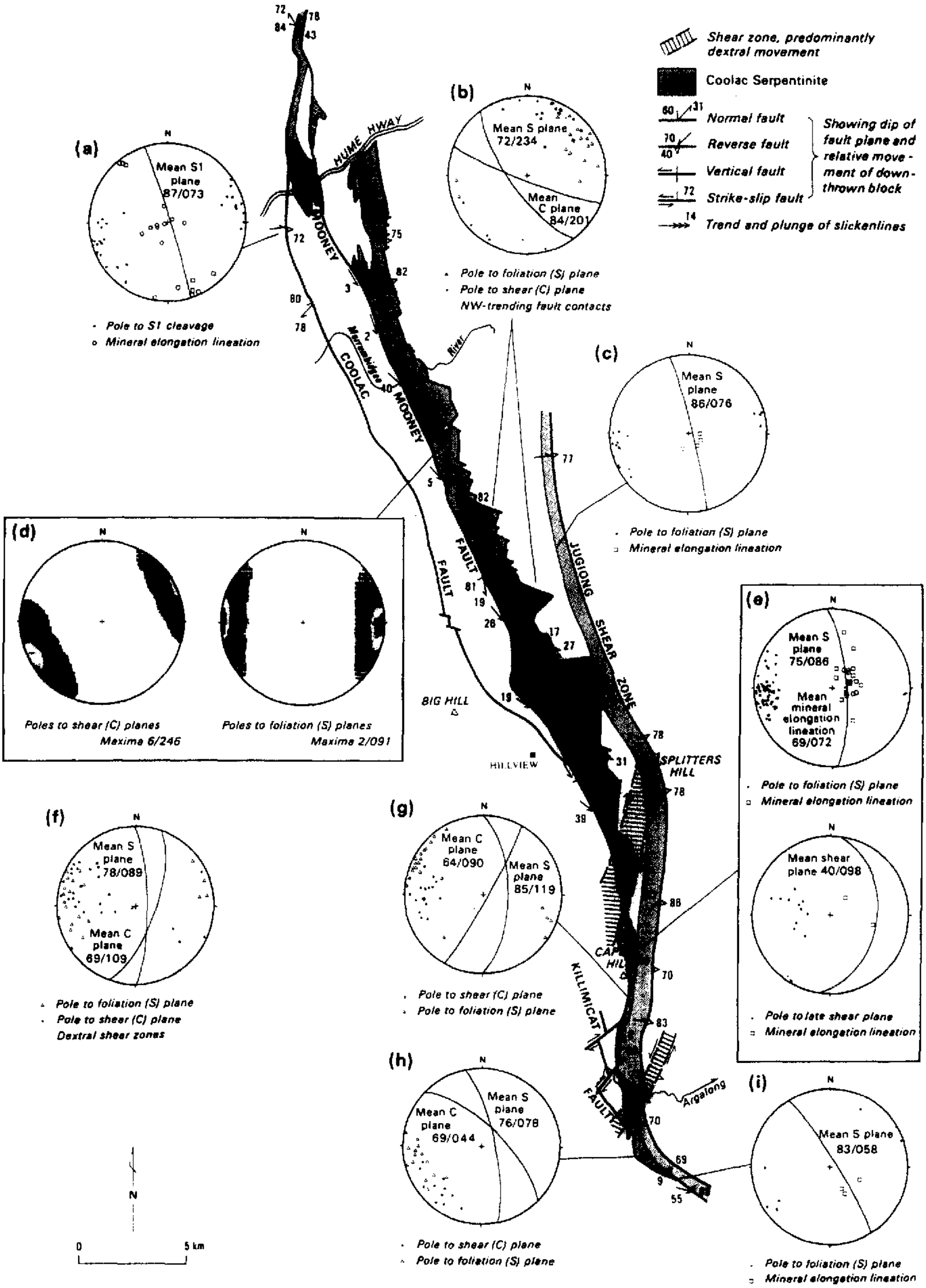

Fig. 6. Structural sketch map of the Mooney Mooney Fault System showing interpreted fault style and kinematics (obtained from *S–C* relationships, mineral-elongation lineations and slickenlines).

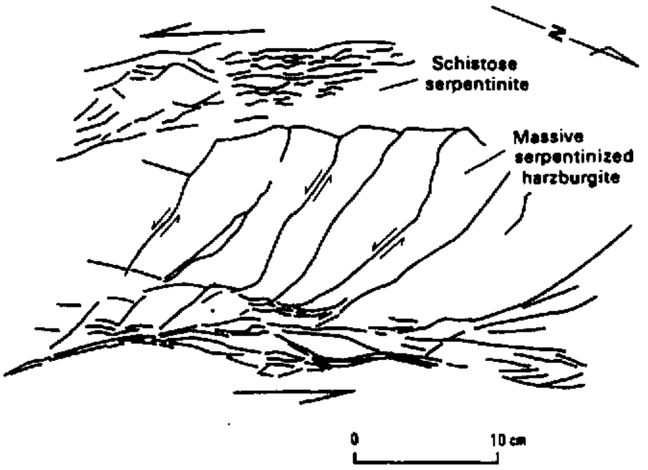

Fig. 7. Outcrop sketch of fault geometry within the Coolac Serpentinite (GR 234038).

parallels the SE movement direction indicated in the adjacent serpentinite.

Like the N-trending contacts, massive harzburgite occurs along the NW-trending contacts with the granodiorite, commonly with a narrow marginal zone, up to 10 m wide, of schistose serpentinite. Within 2–10 m of the contact, massive granodiorite is silicified, fractured and cut by subvertical quartz–albite–epidote veins and chloritic cataclasite zones up to a few cm wide. The cataclasite zones in the granodiorite are parallel to the contact and shear planes (*C* planes) within the serpentinite. A foliation, present in serpentinized zones, trends NW and dips steeply to the SW. *S–C* relations in the serpentinite indicate sinistral transtensional movement consistent with gently SE-pitching lineations on the shear planes and slickenlines on the fault contacts (Fig. 6b).

The N-trending contacts and adjacent deformed zones within the serpentinite and granodiorite are invariably truncated by the NW-trending faults, which in places, extend into the Young Granodiorite. Where the NW-trending faults can be traced into the serpentinite they appear to be rotated into parallelism and merge with the schistose serpentinite zone bordering the Mooney Mooney Fault. These faults are interpreted as splays formed during sinistral strike-slip movement on the Mooney Mooney Fault.

Jugiong Shear Zone

The Jugiong Shear Zone (Basden 1974) forms a N-trending mylonitic zone extending for over 100 km mostly within the Young Granodiorite. Only the southern portion (30 km) of the zone is situated in the Tumut area. The zone has been mapped a further 20 km to the south as part of the Mooney Mooney Fault System (Basden 1986) and probably continues 30 km farther south where it is terminated by the Long Plain Fault (Owen & Wyborn 1979) (Fig. 1). In the Tumut area it forms, for part of its length, the contact between the Coolac Serpentinite and the granodiorite.

The shear zone ranges from 1000 m wide in the north to less than 400 m in the south. The zone is characterized by a weakly to strongly developed, subvertical to steep, E-dipping foliation with a steeply-pitching mineral-elongation lineation in the more intensely deformed rocks (Figs. 6c,e & i). The degree of strain is variable throughout the zone but is generally greatest along the western margin where ultramylonites (terminology after Wise *et al.* 1984) are common.

Within the zone, primary coarse plagioclase crystals are deformed and fractured with most quartz and some K-feldspar crystals recrystallized to fine-grained strained ribbon or unstrained polygonal mosaics. Minor discontinuous quartz veins are in places parallel to the foliation. Deformed asymmetrical biotite 'fish' (Lister & Snoke 1984), commonly replaced by finer-grained foliated biotite and white mica aggregates, define micro-scale *S–C* fabrics which indicate east-side-up (i.e. reverse sense of shear).

The dominant mylonitic fabric of the shear zone is disrupted locally by spaced reverse shear planes and sinistral strike-slip cataclastic zones. Between the Wee Jasper and Bumbolee Creek roads, spaced shear planes (<1 cm apart), dipping moderately to the east, are commonly present in the Jugiong Shear Zone (Fig. 6e). Prominent slickenlines pitch about 90° on the shear plane. The shear planes deform the mylonitic foliation, with indicated reverse movement, and are associated with localized chlorite and minor sphene retrogressive alteration. Similar alteration is associated with cataclasis of the mylonitic rocks within an approximately 10 m wide zone along the contact with the Coolac Serpentinite northwest of Splitters Hill. Here blocks of massive harzburgite and chloritized granitic cataclasite, up to 5 m across, form a tectonic melange. A small lens of serpentinite, within this zone, 2 km northwest of Splitters Hill, contains well-developed *S–C* fabrics which indicate sinistral strike-slip displacement. Both the reverse shears and the cataclastic zones represent later retrograde metamorphism during a deformation event not previously recognized within the Jugiong Shear Zone.

NNE-trending cross-faults and shear zones

The Mooney Mooney Fault System is cut by a number of NNE-trending cross-faults and shear zones which show predominantly dextral strike-slip displacements (Fig. 6). in the south, discrete offsets in the faulted margin of the Bogong Granite pass into wider shear zones within the Coolac Serpentinite and the Young Granodiorite. A broad zone of dextral shearing also occurs within the serpentinite farther north between Capel Hill and Millers Hill. It passes into narrow discrete shear zones displacing the mylonitic foliation in the Young Granodiorite.

Older fabrics in the serpentinite are completely obliterated and an *S–C* fabric, defined by a near vertical, E-dipping foliation and a steeply ESE-dipping shear plane, is ubiquitous (Fig. 6f). Intensely foliated serpentinite in the Capel Hill area grades northwards into fractured and serpentinized harzburgite in the Millers Hill area. Slickenlines on the shear planes are rare, and where present plunge subhorizontally. Mainly dextral strike-slip with a minor reverse displacement is indicated.

Overall the sense of displacement of the NNE-trending shear zones reflects a transpressional regime. The development of these faults post-dates major fault movements in the area. The orientation and sense of displacement of the NNE-trending shear zones is compatible with a conjugate relationship with the sinistral strike-slip faults. Although the angle between the main fault and the NNE-trending faults is rather small for the latter to be a conjugate Riedel (*R'*) shear, this angular relation could be explained by the interplay of brittle and ductile behaviour in granitic and serpentinized ultramafic rocks, respectively. They are similar in orientation and nature to mylonitic zones in the Wondalga Granodiorite (Wagga Metamorphic Belt) which show conjugate and mutually cross-cutting relationships with a NNW sinistral set (Stuart-Smith 1988).

HISTORY OF THE MOONEY MOONEY FAULT SYSTEM

Structural analysis of the Coolac Serpentinite and adjacent rocks in the Mooney Mooney Fault System reveals a complex history of both vertical and horizontal movement. Overprinting relations in the Jugiong Shear Zone indicate that vertical movement preceded sinistral strike-slip movement which in turn was followed by NE-trending dextral strike-slip movement. Structures within the Mooney Mooney Fault reflect only the latter two movements. The Coolac Fault records both vertical and sinistral strike-slip displacement. Thus the Mooney Mooney Fault System represents an imbricate strike-slip fault zone with three distinct phases of movement. An earlier early Silurian strike-slip history can also be inferred (Stuart-Smith in press). However, such movement is not recorded in fault structures. These four periods of movement are shown schematically in Fig. 8.

Early Silurian strike-slip movement

The Tumut Trough is an early Silurian palaeogeographic province which pre-dates structures preserved within the Mooney Mooney Fault System. After restoration of post-early Silurian displacements, early Silurian flysch and volcanics within the trough are juxtaposed against subaerial volcanics of the Goobarragandra Block, separated only by an elongate ultramafic body (the Coolac Serpentinite, Fig. 9a). The lateral continuity across the Mooney Mooney Fault of the correlative Blowering Formation and Goobarragandra Volcanics and their comagmatic relationship to the subvolcanic Young Granodiorite indicate that the fault system does not represent a Silurian terrane boundary as proposed by Basden *et al.* (1987).

The trough was an area of active extension in a NNW direction during early Silurian sedimentation and volcanism (Stuart-Smith in press). As no extensional structures have been documented in the Goobarragandra

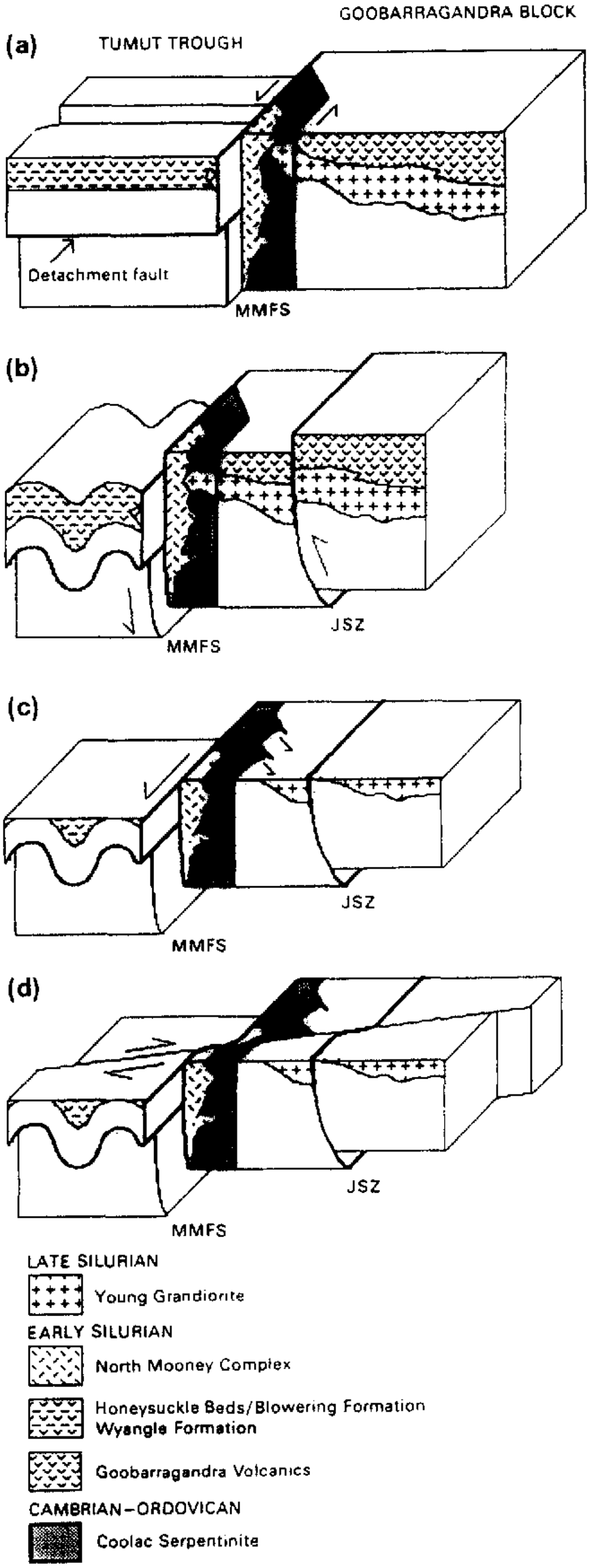

Fig. 8. Diagrammatic sketch showing Silurian and Devonian history of the Mooney Mooney Fault System (MMFS): (a) early Silurian (430–425 Ma)—extension and formation of the Tumut Trough, strike-slip movement (either sinistral or dextral) on the MMFS; (b) late Silurian—folding of trough sedimentary-volcanic sequence, reverse movement on the MMFS and Jugiong Shear Zone (JSZ); (c) mid-Devonian (375 Ma)—sinistral strike-slip movement on the MMFS, formation of fault splays and imbricate structure; (d) mid-Devonian (375 Ma)—local dextral strike-slip faulting.

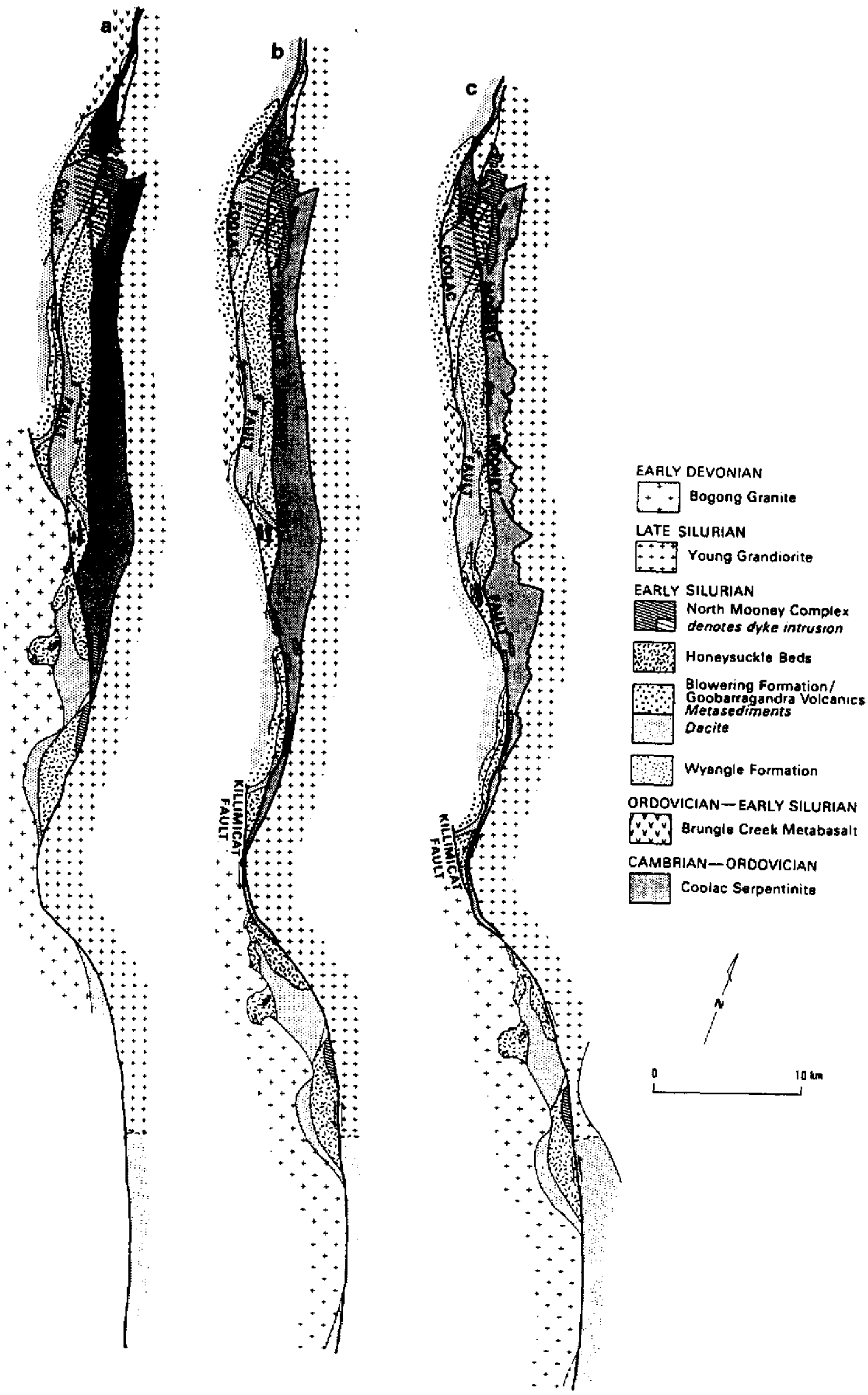

Fig. 9. Geological map showing balanced restoration of mid-Devonian sinistral strike-slip displacement on the Mooney Mooney Fault System after effects of later dextral faulting have been removed: (a) pre-faulting position (i.e. late Silurian); (b) main movement on the Killimicat, Coolac and Mooney Mooney Faults (total displacement = 24 km); (c) final movement on the Mooney Mooney Fault only (4 km). Note, this reconstruction ignores probable minor vertical displacement and is based upon clustering of satellite serpentinite bodies southwest of the main body, grouping of zones of North Mooney Complex intrusions in both the north and south, matching of the serpentinite–granodiorite contact in the north, juxtaposition of leucogranite bodies on the Coolac Fault with the Bogong Granite, and matching of a sedimentary unit at the top of the Blowering Formation across the Coolac and Mooney Mooney Faults in the north.

Block, the Mooney Mooney Fault System which separates the two areas may have acted as an accommodation zone (Fig. 8a). Thus the Mooney Mooney Fault System was probably an active early Silurian strike-slip fault bordering a transtensional basin, the Tumut Trough. As the extension direction was parallel to the Mooney Mooney Fault Zone there is no indication as to whether this displacement was either sinistral or dextral. Both Powell (1983a) and Packham (1987) have interpreted early Silurian strike-slip faulting in their tectonic models of southeastern Australia. Powell (1983a) on the basis of the obliquity of meridional mid-Silurian horsts and grabens in the Lachlan Fold Belt to the NNW-trending Wagga Metamorphic Belt interpreted a dextral strike-slip movement, whereas Packham (1987) suggested mainly sinistral movement to account for displacement of an interpreted Ordovician volcanic arc.

Late Silurian reverse movement

The earliest preserved structures in the Mooney Mooney Fault Block indicate reverse displacements (i.e. east-side-up) on the vertical to steeply E-dipping Jugiong Shear Zone (Fig. 8b). Where the Jugiong Shear Zone diverges from the margin of the serpentinite, the granodiorite–serpentinite contact is not highly deformed and intrusive contacts between the two units are locally preserved. As the granodiorite and capping Goobarragandra Volcanics (or its equivalents) occur on both sides of the Jugiong Shear Zone, total vertical displacement was probably at the most a few km.

The orientation of the foliation in the Jugiong Shear Zone (Figs. 6c,e & i) differs from that in the adjacent serpentinite but is close to the axial plane cleavage in Silurian metasediments and volcanics within the Mooney Mooney Fault Block (Fig. 10). Elsewhere in the Tumut Trough the early Silurian units typically have a subvertical elongation lineation and N-trending foliation sub-parallel to that observed in the Mooney Mooney Fault Block and Jugiong Shear Zone. This similarity in structural geometries, together with indicated lower greenschist-facies metamorphism, suggest that the Jugiong Shear Zone may have formed in response to the same E–W compression which produced N–S-trending upright folds and associated axial plane cleavages in Silurian units throughout the Tumut Trough during the late Silurian.

When the shear zone is restored to remove dextral NE-trending fault displacements (Fig. 11) it is noticeable that the mineral-elongation lineation pitches away from each of the two bends in the zone and maintains a consistent divergence on each of the three segments of the shear zone. This pattern can be explained if the bends were present at the time of formation of the shear zone and that the lineation, originally pitching about 90°, was rotated to its present position by later steepening of the limbs (Fig. 12). Thus the shear zone probably represents a steepened E-dipping thrust.

Apart from minor reverse movement recorded in the Coolac Fault there is no evidence that the Mooney Mooney Fault System was active during the late Silurian deformation. The Coolac Fault may have initiated during this event and been the principal zone of displacement for the fault system. Although minor late Silurian movement may have been possible, mid-Devonian strike-slip faulting can account for observed displacement along the Mooney Mooney Fault.

Mid-Devonian sinistral strike-slip movement

After intrusion of the Bogong Granite (410 ± 16 Ma, Ashley *et al.* 1971) the Mooney Mooney Fault System was reactivated as a sinistral strike-slip fault zone (Fig. 8c). Cross-cutting relationships indicate that movement on the Killimicat and Coolac Faults preceded final movement on the Mooney Mooney Fault. Matching of stratigraphic units across the fault system indicates a total horizontal displacement of about 28 km (Fig. 9). A schistose serpentinite zone, characterized by widespread *S–C* fabrics, developed along the smeared out western margin of the Coolac Serpentinite and chloritic cataclasites formed on the faulted contacts of the Bogong Granite and Young Granodiorite. Fault splays with transtensional sinistral displacements developed off the Mooney Mooney Fault resulting in the step-like morphology of the serpentinite–granodiorite contact.

In the south, where the Jugiong Shear Zone adjoins the Mooney Mooney Fault, retrogressive metamorphism accompanied local deformation of the mylonitic fabric in cataclasite zones along sinistral strike-slip fault zones. Shear planes with reverse displacements developed in a transpressional domain within a restraining

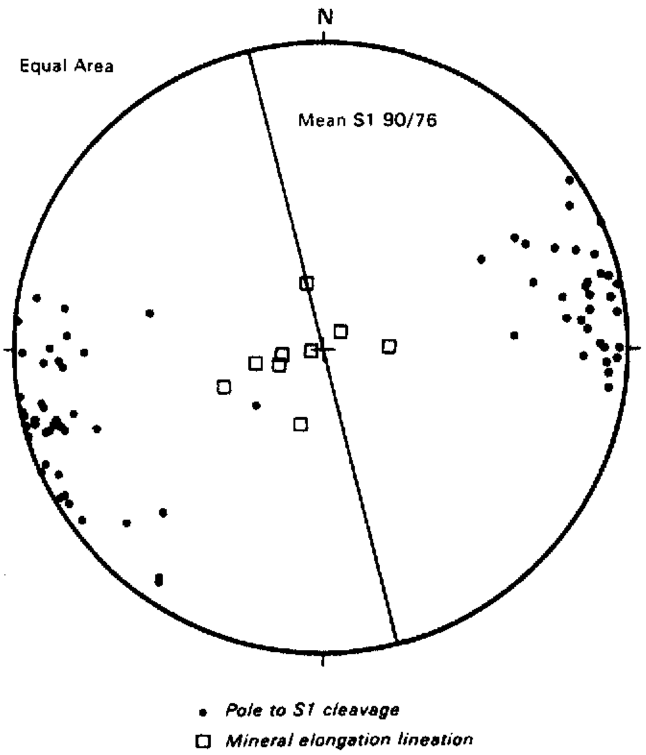

Fig. 10. Stereoplot of main structural elements of all Silurian metasedimentary and volcanic units in the Mooney Mooney Fault Block.

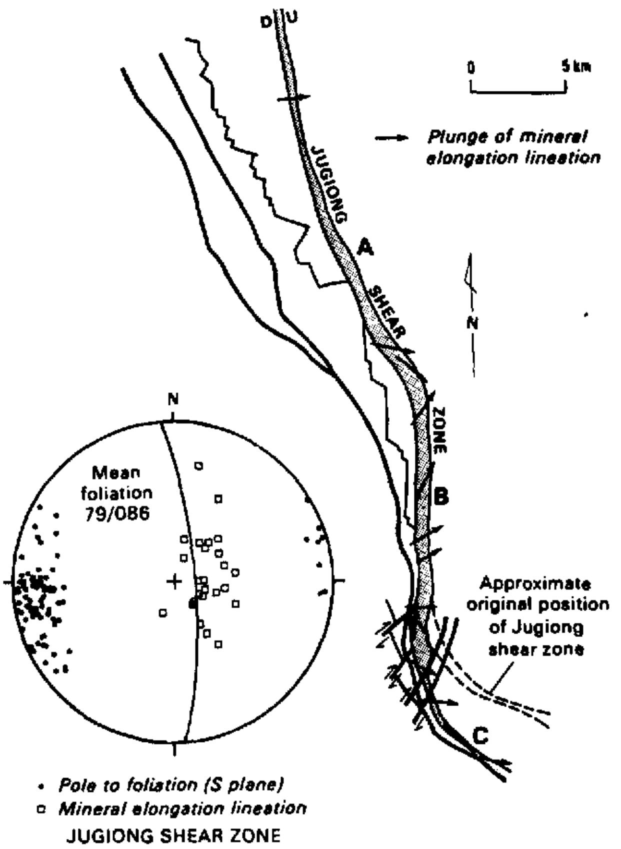

Fig. 11. Structural sketch map of part of the Jugiong Shear Zone showing plunge of mineral elongation lineation.

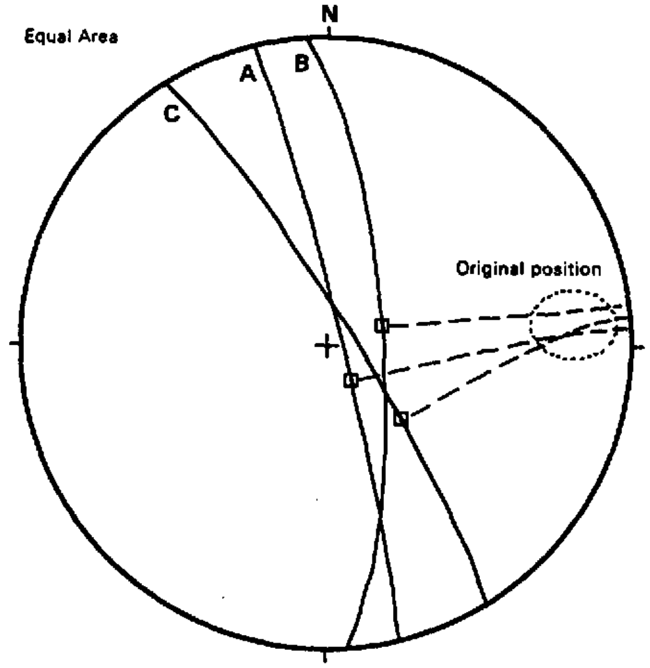

Fig. 12. Equal-area stereoplot showing mean foliations and mineral-elongation lineations for the three limbs (A, B and C) of the Jugiong Shear Zone show in Fig. 11. The differences in orientation of the lineation can be explained by rotation of the limbs from an originally shallow easterly dip with a common E-plunging lineation.

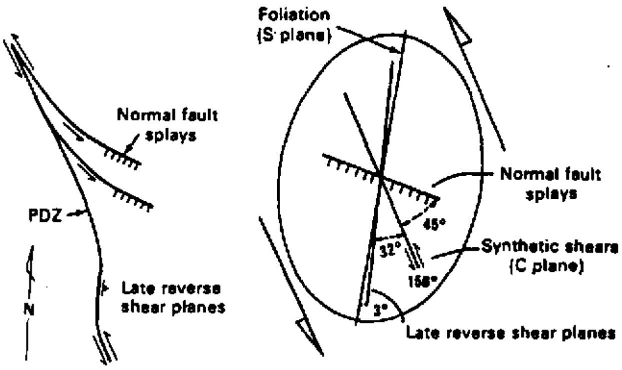

Fig. 13. Angular relations between mid-Devonian structures of the Mooney Mooney Fault System superimposed on a strain ellipse for the overall deformation. PDZ—principal displacement zone.

bend resulting in a classical strike-slip geometry of structural elements (Fig. 13).

Mid-Devonian dextral strike-slip movement

During the final stages of sinistral strike-slip movement of the Mooney Mooney Fault System a conjugate set of NE-trending dextral faults and shear zones developed in the south in localized transpressional zones along the Mooney Mooney Fault (Fig. 8d).

The age of both sinistral and dextral strike-slip movement is poorly constrained. Both post-date the early Devonian Bogong Granite. They are probably mid-Devonian as the orientation, sense of movement and magnitude of displacements are similar to other fault sets throughout southeastern Australia (Beams 1975, White *et al.* 1976, Fergusson *et al.* 1979) where movement is constrained to about 375 Ma (Powell 1983b).

ORIGIN AND UPPER CRUSTAL EMPLACEMENT OF THE COOLAC SERPENTINITE

The discovery of a conformable contact between the Honeysuckle Beds and the Blowering Formation (Stuart-Smith 1988), and the recognition that both units face east in the Mooney Mooney Fault Block is inconsistent with the Ashley *et al.* (1979) interpretation of an ophiolitic suite. The Honeysuckle Beds, rather than being one of the oldest units in the Tumut Trough directly overlying the Coolac Serpentinite (Basden 1986), is instead the youngest Silurian unit in the Trough.

No evidence was found to support the Basden *et al.* (1987) interpretation of a "knocker terrane mélange" overlying the Coolac Serpentinite. The Silurian units within the Mooney Mooney Fault Block do not show mélange characteristics commonly associated with other obducted ophiolitic suites, such as: post-depositional soft-sediment disruption (Karig & Sharman 1975, Theyer 1983, Ricci *et al.* 1985, Donato 1987), transposition foliation (Nelson 1982), rootless isoclinal folds (Ricci *et al.* 1985), the presence of exotic blocks, and a diversity of lithotectonic elements (Hsu 1968, Donato

1987). By comparison, the stratigraphy of the Silurian sediments and volcanics is coherent and only one phase of open to tight upright folding is present. In addition, there is no evidence for medium- to high-pressure metamorphism typically associated with ophiolitic suites (McCraig 1983, Stanley *et al.* 1984, Donato 1987); rocks in the area are metamorphosed to lower greenschist facies (sericite-chlorite–albite-epidote).

The presence of a gabbroic complex (the North Mooney Complex) containing sheeted dykes (Brown 1979) has been cited as one of the main lines of evidence supporting the concept of the Coolac ophiolitic suite. However, Brown (1979) noted the near absence of one-way chilling and the relatively small size of the dykes compared to other ophiolitic dyke complexes. The North Mooney Complex together with the Honeysuckle Beds form a distinct chemical suite with major and trace element data indicating a marginal sea or back-arc setting (Ashley *et al.* 1979). The data are, however, also consistent with the presence of a major crustal suture or thinned continental crust. Other basic igneous complexes of the same age (426 ± 6, Webb 1980), such as the Micalong Swamp Basic Igneous Complex, occur in adjacent but clearly continental settings. The Micalong Swamp Basic Igneous Complex comprises differentiated tholeiitic intrusions along a N-trending belt within the Young Granodiorite about 10–20 km east of the Mooney Mooney Fault System (Owen & Wyborn 1979). Both complexes have sheeted dykes (Wyborn 1977, Brown 1979), similar ages, intrude correlative felsic volcanic units, and are intruded by the subvolcanic Young Granodiorite. The intrusions could be related to a period of crustal extension accompanying upwelling crustal melts which produced the Silurian felsic volcanics and batholiths (Wyborn 1977) and may therefore be unrelated to the Coolac Serpentinite.

With the exclusion of the basaltic and minor sedimentary component (Honeysuckle Beds) and possibly the gabbroic rocks (North Mooney Complex) from the 'Coolac ophiolitic suite', the interpretation of the Coolac Serpentinite as representing a slice of Silurian oceanic crust obducted during closure of the trough is tenuous. The serpentinite is therefore interpreted as an Alpine-type body occupying a major crustal suture. Such bodies can occur as either solid state intrusions of cold serpentinite (Dickinson 1966), magmatic intrusions (Bébien *et al.* 1986) or as tectonic slivers derived from an adjacent ophiolitic terrane (Ray 1986, Donato 1987).

The presence of westward-younging cumulate layering in ultramafic rocks (Ashley *et al.* 1979) is consistent with both the obducted ophiolite and Alpine-type intrusive models. It is unlikely that primary layering would maintain its original horizontal position during the indicated late Silurian and mid-Devonian faulting. A westward rotation caused by drag folding into the Mooney Mooney Fault could be expected considering that the overall sinistral movement also involved some reverse displacement of the ultramafics over the Silurian units to the west (Fig. 5c).

The outlined structural history of the Mooney Mooney Fault System indicates that the Coolac Serpentinite was at its present structural level prior to deformation of the trough sequence. However, as both the serpentinite and early Silurian sequences are intruded by the North Mooney Complex (426 Ma) and the later Silurian Young Granodiorite, the serpentinite must have been emplaced into the upper continental crust by at least late early Silurian. The serpentinite was therefore not emplaced ('obducted') during late Silurian closure (post-granodiorite intrusion) of the trough as suggested by previous workers.

Some serpentinite bodies occurring along high angle faults are thought to have formed by diapiric emplacement of 'cold' serpentinite. These bodies are found in sedimentary sequences structurally overlying ophiolites and were probably formed by hydrolysis of ultramafic rocks and intruded during episodes of extension (Mitchell 1986). Rise of the bodies would be effected by their lower density compared to surrounding rocks, high lateral pressures and the highly faulted nature of the overlying rocks (Dickinson 1966). The Coolac Serpentinite structurally overlies a mafic–ultramafic sequence (the Jindalee Group). However, the mean measured density of 2630 kg m^{-3} and a model density of 2720 kg m^{-3} for the Coolac Serpentinite is higher than that of adjacent Silurian volcanics, sediments and granitic rocks (J. Leven personal communication 1988). In addition, the lack of other features associated with the necessary high pore-fluid pressures (such as mélange diapirs) and the massive nature of the Coolac Serpentinite (mostly partly serpentinized harzburgite) suggests that diapiric emplacement of 'cold' ultramafics in the Mooney Mooney Fault Zone was not a likely mechanism.

An intrusive model for emplacement of the ultramafics is compatible with a genetic link between the Coolac Serpentine and the North Mooney Complex. However, there are few satisfactory analogues for similar ultramafic–mafic intrusions. The innermost Hellenic Ophiolite Belt is an example of an ophiolitic suite emplaced within an ensialic wrench zone during continental extension (Bébien *et al.* 1986). This belt is, however, characterized by contact metamorphism of adjacent rocks and mutually cross-cutting relationships between mafic and felsic intrusions. The observed tectonic contacts and the absence of these features from the Coolac Serpentinite indicate that such an intrusive origin is unlikely.

The most likely mechanism for emplacement of the Coolac Serpentinite in the Mooney Mooney Fault System is that it represents a tectonic slice of basement emplaced in its present position during strike-slip faulting associated with early Silurian extension prior to gabbro intrusion at about 426 Ma. There are numerous examples (e.g. the Himalayas, and the west and east coast of the U.S.A.; Tapponnier *et al.* 1981, Ray 1986) of ultramafic bodies of similar dimensions to the Coolac Serpentinite which form tectonic slivers in major crustal fracture zones and which were derived from structurally underlying or adjacent ophiolitic terranes. Along the Herat Fault (Himalayas) post-collisional strike-slip faults have not only displaced fragments of obducted ophiolitic sequences but have later localized granite intrusion (Tapponnier *et al.* 1981). The localization of the North Mooney Complex intrusions along the Mooney Mooney Fault Zone during early Silurian extension in the Tumut Trough may similarly reflect the lithospheric extent of the fault zone.

A suitable basement, from which the Coolac Serpentinite may have been derived, exists in the Cambrian–Ordovician Jindalee Group. The group, comprising mafic–ultramafic complexes and minor quartz-rich sediments, is interpreted as an oceanic sequence accreted during the Cambrian to early Ordovician (Basden 1986). Although meta-pyroxenite and serpentinized harzburgite have been reported from the group (Basden *et al.* 1978), exposed ultramafic units are strongly serpentinized and smaller than the Coolac Serpentinite. This may be a function of their location within basement high-strain zones which were the focus of tectonism during early Silurian extension (Stuart-Smith in press).

The Coolac Serpentinite may have been emplaced into the upper crust in a similar fashion to allochthonous blocks of metamorphic and ultramafic rocks along strike-slip zones associated with oblique covergent plate boundaries (Karig 1980, Karig *et al.* 1986). Such a model is consistent with strike-slip models for the Tumut Trough (Powell 1983a, Packham 1987) and the Andaman analogue for Lower Palaeozoic development of the Lachlan Fold Belt (Cas *et al.* 1980, Powell 1983a). In the Andaman Sea, major strike-slip faults occur within the volcanic arc about 100 km from the associated trench (Karig 1980) in a similar structural position and orientation to that intperpeted by Cas *et al.* (1980) for the Tumut region during the Lower Palaeozoic.

CONCLUSIONS

Intrusive relationships and the structural history of the Coolac Serpentinite indicate that it was emplaced into the upper crust during early Silurian extension. The concept of a Silurian ophiolitic suite (Ashley *et al.* 1979) incorporating the serpentinite, grabbroic rocks, basalt and minor sediments is rejected. The Honeysuckle Beds, which are supposed to represent the basaltic and sedimentary component of the ophiolitic suite, are the youngest Silurian rocks in the Tumut Trough, conformably overlying the Blowering Formation. Although the Coolac Serpentinite may have originated as part of an ophiolitic suite, it is more appropriately interpreted as an Alpine-type body occupying a major crustal suture. The serpentinite possibly represents either an early Silurian ultramafic intrusion or most likely a tectonic slice derived from the underlying Cambrian–Ordovician Jindalee group.

The Mooney Mooney Fault System, containing the Coolac Serpentinite, is an imbricate strike-slip zone with a complex history or reactivation since at least the early Silurian culminating in large-scale sinistral movement in the mid-Devonian.

(1) The system was in all probability an active strike-slip fault zone during the early Silurian extensional history of the Tumut Trough.

(2) Reverse (east-side-up) movement occurred during deformation of the Silurian trough sequence in the late Silurian. The Jugiong Shear Zone formed at this time.

(3) Mid-Devonian sinistral strike-slip faulting resulted in a total displacement of about 28 km and the formation of the schistose serpentinite margin to the ultramafic belt characterized by *S–C* fabrics. Reverse faulting occurred in localized transpressional areas within the Jugiong Shear Zone.

(4) Conjugate NE-trending dextral strike-slip faults formed in localized transpressional zones during the waning stages of sinistral strike-slip movement.

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