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# Shear-zone deformation in the Yackandandah Granite, northeast Victoria

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The Early Devonian Yackandandah Granite in northeast Victoria was emplaced along the western boundary of the Omeo Metamorphic Complex. Deformation of probable mid-Devonian age resulted in the formation of a ductile shear zone in the granite, termed the Kiewa shear zone. Displacement of granite boundaries and shear-zone fabrics, including excellently developed S–C fabrics, indicate that the shear zone accommodated ~7 km of sinistral strike-slip displacement, with no evidence for thrusting as suggested in previous studies. Detailed mapping of fabrics across the shear zone suggest that ~70% of strain was accommodated by the formation of the finite strain foliation (S-planes), with the remaining strain accommodated by discrete slip along C-planes parallel to the shear-zone boundary.

**Key words: deformation, S–C fabrics, shear zone, Yackandandah Granite.**

## INTRODUCTION

The western boundary of the Omeo Metamorphic Belt in northeastern Victoria forms one of the major structural discontinuities of southeastern Australia (Fig. 1). Our present understanding of this boundary is based largely on the work of Beavis (1960, 1961, 1962) who recognized that the boundary was a zone of intense deformation, which we term the Kiewa shear zone. Recently, Scheibner (1985) suggested that this boundary may be a suture separating terranes with fundamentally different geological histories. Consequently, the interpretation of the Kiewa shear zone is of considerable significance to models for the Palaeozoic evolution of the Lachlan Fold Belt. Mapping by the Victorian Mines Department indicates that the Kiewa shear zone deforms the Yackandandah Granite (Fig. 1), a porphyritic granite cropping out in the Yackandandah–Mudgegonga region (Leggo 1964). Numerous studies have shown that porphyritic granites preserve an excellent record of shear-zone deformations (e.g. Burg & Laurent 1978; Berthe *et al* 1979). In this paper, the structures in the deformed Yackandandah Granite are described in order to elucidate the movement history of the Kiewa shear zone where it crosses the Yackandandah Granite.

## REGIONAL SETTING OF THE KIEWA SHEAR ZONE

The Kiewa shear zone is a northwest-trending structure cropping out between Swifts Creek (37°22′S, 147°41′E) and Barnawatha (36°07′S, 146°41′E) in northeastern Victoria. The shear zone is 2–5 km wide and defines a prominent discontinuity in metamorphic grade between, to the west, a greenschist facies Ordovician turbidite sequence known as the Tabberabberan terrane, and, to the east, a schist and gneiss terrane termed the Omeo Metamorphic Complex (Gregory 1902; Beavis 1960; VandenBerg 1978). Since the work of Beavis (1961, 1962, 1976), the Kiewa shear zone has been regarded as a thrust resulting from the westward-directed transport of the Omeo Metamorphic Complex over the Tabberabberan terrane. Beavis (1973, p. 23) described the character of fault-related mylonites south of Tawonga as follows '. . . the foliation of the mylonites dips 70–80°E with a strike NE 15–20°. Foliation planes are strongly lineated, the lineation plunging gently north'.

At Yackandandah, the contact between the Omeo Metamorphic Complex and the Tabberabberan terrane has been intruded by the Yackandandah Granite, a coarse grained megacrystic granite (Fig. 2) of Early Devonian age

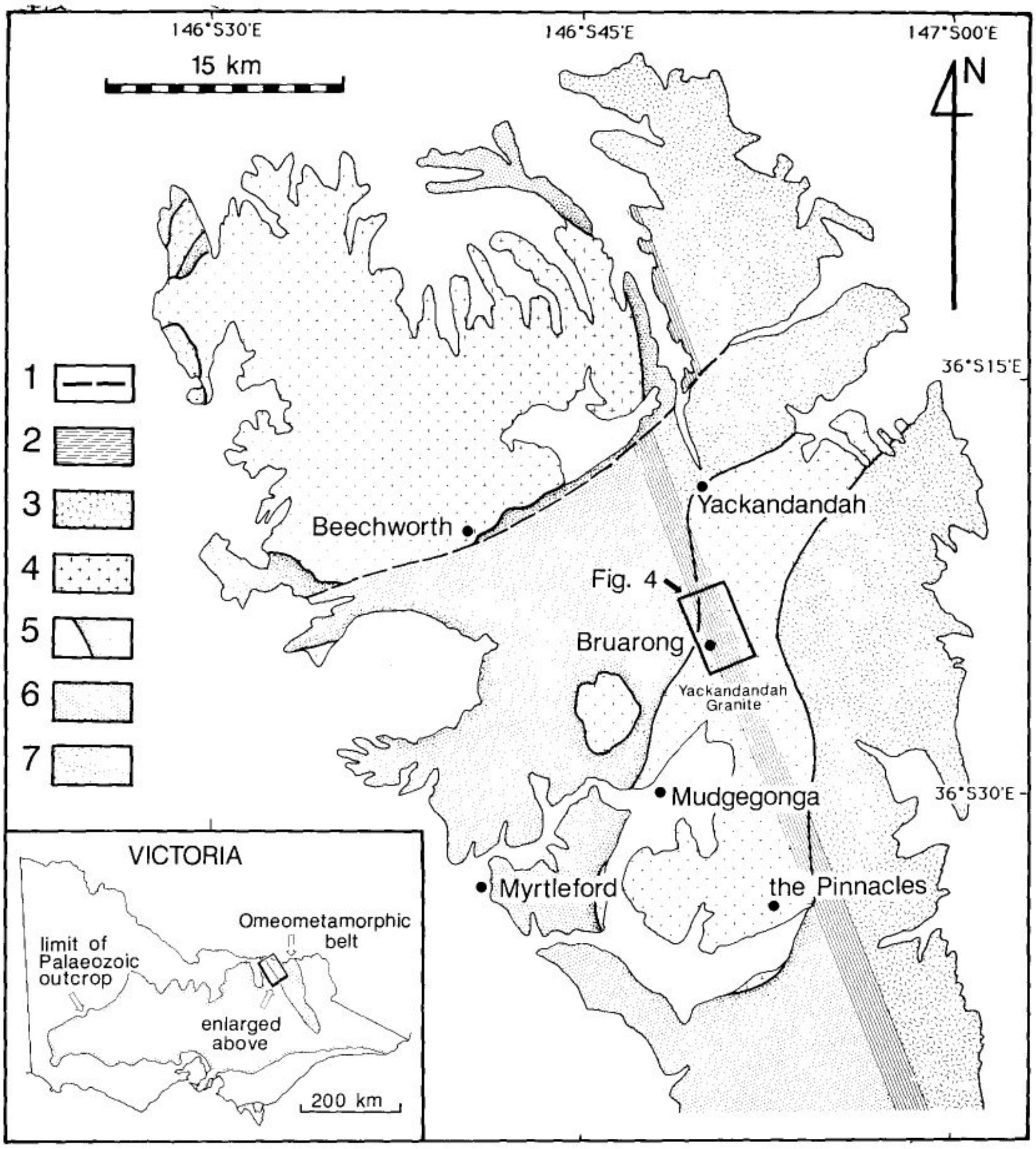


**Fig. 1** Geology of the Yackandandah–Mudgegonga region. 1, Fault; 2, Kiewa shear zone; 3, Permian sediments; 4, Devonian granitoids; 5, contact aureole; 6, Tabberabberan terrane; 7, Omeo Metamorphic Complex. Inset indicates the area covered by Fig. 4.

(Richards & Singleton 1981; McKenzie *et al* 1983). Along its western boundary, the Yackandandah Granite is surrounded by a contact aureole between 100 and 300 m wide characterized by the development of coarse grained biotite, muscovite and poikiloblasts of cordierite and/or andalusite. Quartz and muscovite inclusion trails within these (now retrogressed) poikiloblasts define an internal foliation at a high angle to the external foliation, which, in turn, is defined by contact metamorphic muscovite and biotite. This external foliation is axial to a series of upright, tight folds with southeast-plunging axes. The folds can be traced westwards, grading down beyond the contact aureole towards Beechworth with no apparent change in

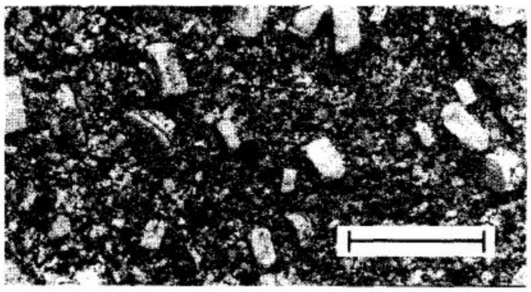

Fig. 2 Undeformed Yackandandah Granite, showing K-feldspar megacrysts. Bar scale is 10 cm.

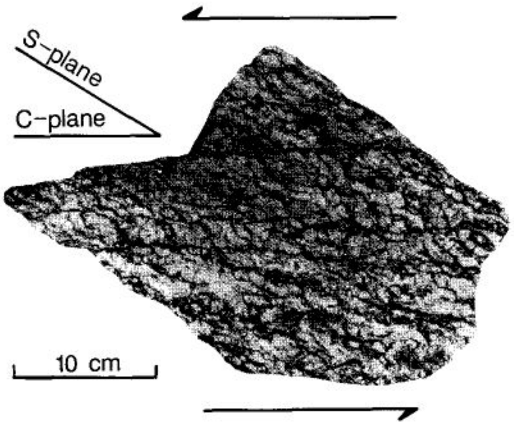


Fig. 3 S–C fabric in deformed Yackandandah Granite. The surface is the X–Z plane with $S\hat{}C = 30°$.

morphology, and imply that the emplacement of granite and development of the contact aureole accompanied a regional deformation. The relationships along the eastern margin of the granite with the Omeo Metamorphic Complex are less clearly understood because of poor exposure. However, the strong discordance between the granite and the northwest-trending foliation in the metamorphics implies that emplacement of the granite postdates the strain associated with foliation formation.

In general, the Yackandandah Granite preserves igneous textures, often megacrystic (Fig. 2), and has a weak meridonal alignment of xenoliths. The granite is strongly, but variably, deformed along the Kiewa shear zone in a northwest-trending zone approximately 3.5 km wide (Fig. 1).

## SHEAR ZONE DEFORMATION IN THE YACKANDANDAH GRANITE

### Macroscopic and mesoscopic structures

The shear zone in the Yackandandah Granite extends from Yackandandah in the north to the Pinnacles in the south (Fig. 1). At Bruarong, the granite obliquely intersects the northeastern boundary of the shear zone approximately 7.5 km northwest of the equivalent boundary on the southwestern side of the shear zone, with the subhorizontal sinistral displacement due to the shearing estimated at ~7 km.

Within the shear zone, the granite exhibits excellent S–C fabrics (Berthe *et al* 1979). The C-planes are well-defined planar discontinuities with a marked offset of the finite strain foliation (S-planes) defined by preferred dimensional elongation of the component minerals including deformed K-feldspar aggregates, quartz ribbons and micas, as well as by the elongation of the microgranitoid enclaves (Fig. 3). Both C- and S-planes are subvertical and contain horizontal to shallow (<5°) northwest-plunging lineations defined by mineral elongation.

Throughout the shear zone, the C-plane orientation is relatively constant, with a distinct strike maxima between 310° and 320°, parallel to the boundary of the shear zone (Fig. 5a). In contrast, the S-plane orientation varies systematically across the shear zone, having a trend of approximately true north near the boundaries of the shear zone and ranging to 315–330° near the centre of the zone (Figs 4, 5b). The angle between C- and S-planes ($S\hat{}C$) varies from 40–45° near the margins of the shear zone to as little as 12° near the centre of the zone (Fig. 4). A plot of $S\hat{}C$ versus distance from the margin of the shear zone (Fig. 6) indicates that there is little variation in the angular relationship between C- and S-planes along lines parallel to the boundary of the shear zone and that the shear zone shows a marked symmetry.

### Microstructure

Outside the bounds of the shear zone, the essentially undeformed Yackandandah Granite exhibits a modified igneous fabric containing alkali feldspar megacrysts, oscillatory zoned plagioclase, quartz, biotite and hornblende as the

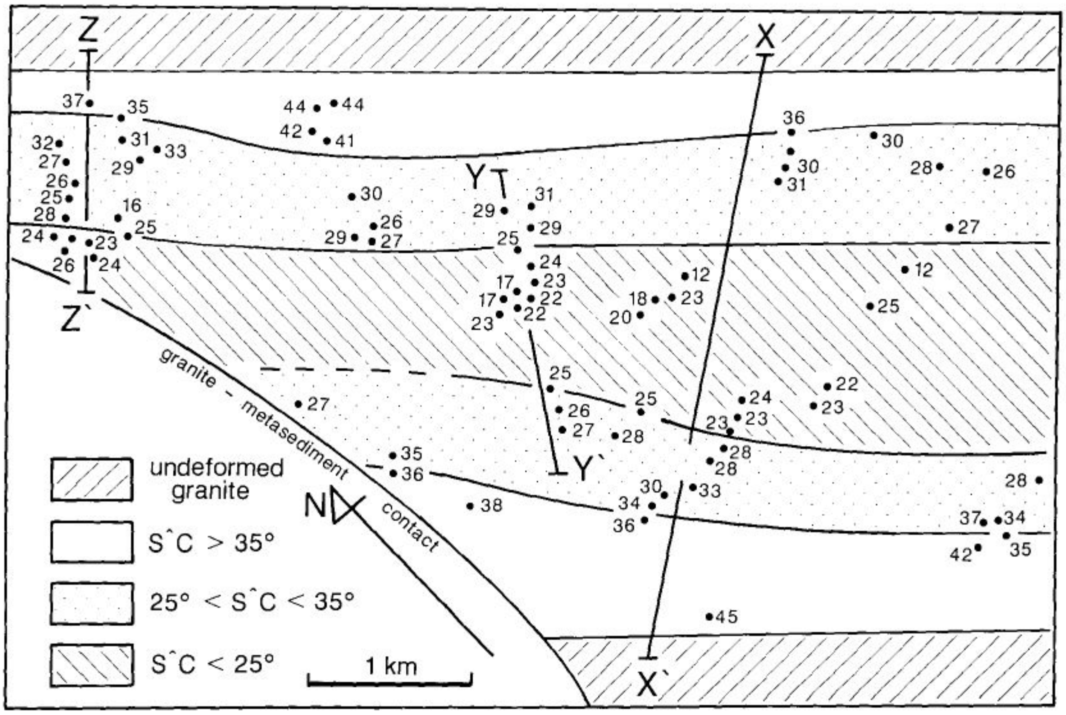


**Fig. 4** Map showing the angular relationship between C- and S-planes in XZ (S^C) in the Bruarong area (the location of the area is marked by the rectangle inset in Fig. 1). The boundary of the shear zone is approximately parallel to the contours of S^C, indicating a relatively simple shear-zone geometry. Position of shear-zone profiles used in Fig. 6 are indicated by X–X′, Y–Y′ and Z–Z′.

principal components. Sphene and apatite are present as accessory phases, mostly as inclusions in biotite and hornblende. Quartz typically exhibits some undulose extinction and quartz grain boundaries are typically serrated, testifying that mild deformation has affected the whole pluton.

The igneous fabrics have been substantially modified within the shear zone, with the microstructures exhibiting a pronounced asymmetry and a progression of changes with increasing strain. At low shear strains near the boundary of the shear zone (S^C = 40–45°), microstructural modification has been limited to subgrain development within quartz and recrystallization of quartz–quartz grain boundaries. At shear strains of ~1.2 (S^C = 30°), deformation has been accommodated by extensive recrystallization of quartz, recrystallization and disaggregation of biotite to produce mica 'fish', and fracture in feldspars. Quartz typically forms polygonal aggregates with an average grain size of 0.1 mm, although relics of coarser grained quartz persist. At shear strains greater than 2.4 (S^C < 20), the deformation has produced a layered fabric consisting of quartz- and biotite-rich selvages, which wrap around the fragmented remains of feldspar porphyroblasts elongated in the S-foliation because of extensive micro-boudinage. Individual quartz selvages are typically 0.2–1.2 mm wide. The internal microstructure of such selvages varies considerably: some contain polygonal aggregates with a grain size of <0.1 mm, while in others somewhat coarser quartz grains (0.5 mm) have serrated grain boundaries and a preferred dimensional elongation oblique (~20–30°) to the S-plane. The latter microstructure is attributed to resetting of the finite strain clock within individual quartz domains (Lister & Snoke 1984). The field trend of the oblique quartz fabric is close to true north. Grain size in the biotite selvages is generally very fine (0.05 mm) but coarser grained mica 'fish' are common. Minor recrystallization of alkali feldspar within fine grained (<0.03 mm) elongate selvage had taken place but the

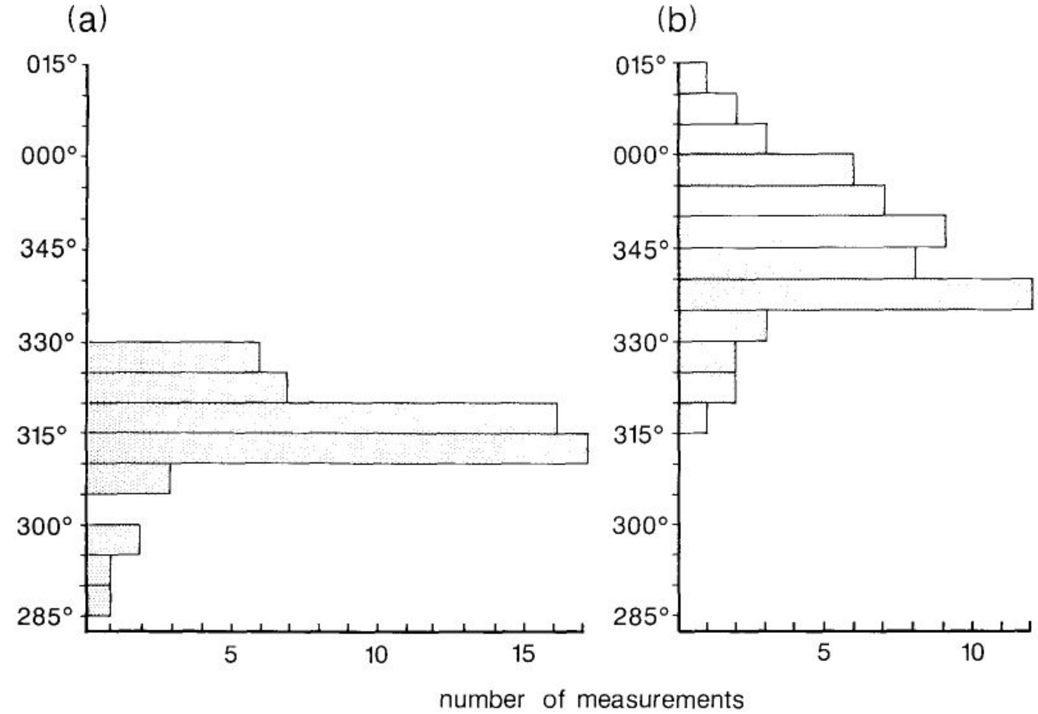


**Fig. 5** Histograms showing measured (a) C-plane strikes and (b) S-plane strikes in the Kiewa shear zone in the Bruarong region.

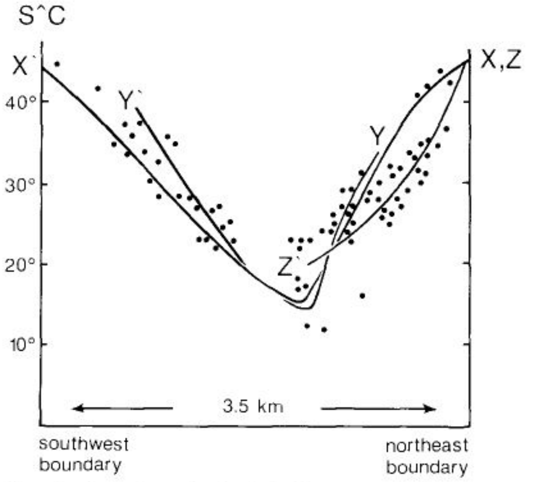


**Fig. 6** Angular relationship between C-planes and S-planes (S^C) plotted as a function of distance across the Kiewa shear zone. Selected profiles as shown in Fig. 4.

dominant mechanism in feldspars was brittle fracture.

The sense of asymmetry of mica 'fish' and feldspar microboudinage and the obliquity of reset quartz fabrics within quartz-rich selvages are consistent with sinistral strike-slip deformation throughout the shear zone and thus concur with field observation cited in the preceding section.

**Movement history and strain partitioning**

The relatively constant orientation of C-planes and stretching lineations, the angular relationship between C- and S-planes, and the constant sense of the microstructural shear criteria imply that the Yackandandah Granite was deformed in simple shear during a northwest sinistral strike-slip displacement of the Kiewa shear zone. A finite displacement of ~ 7 km is indicated by field relationships at the northern boundary of the granite where the shear zone displaces the contact between the Yackandandah Granite and the Tabberabberan terrane.

Except for outcrops within the Yackandandah Granite, outcrop of the Kiewa shear zone is extremely poor in the Yackandandah district. Consequently, it has proved difficult to confirm the shear sense deduced from the deformed granite with fault rocks within the bounding metasediments. A sinistral strike-slip fault motion is supported by S–C fabrics and asymmetrical microstructures preserved in an outcrop of sheared chlorite-bearing metasediments 6 km north-northwest of Yackandandah on the Beechworth–Wodonga road. In contrast to the evidence for sinistral strike-slip motion in the Yackandandah area, the southerly continuation of the Kiewa shear zone, south of Mt Beauty (36°41′S, 147°9′E), preserves abundant evidence of a dextral strike-slip motion (Scott 1985; M. Sandiford, S. F. Martin, E. M. Lohe pers. obs.). In this region, we have been unable to find evidence for the sinistral strike-slip motion recorded at Yackandandah and the relative significance of dextral and sinistral movement episodes on the Kiewa shear zone remains poorly constrained. The absence of evidence for dextral shear sense criteria in the Yackandandah Granite, despite very good exposure, suggests that any episode of dextral movement on the Kiewa shear zone must have predated the emplacement of this granite.

For shear zones with S–C fabrics, the finite displacement is the sum of two distinct strain components: (1) the displacement due to the strain accommodated in the formation of the finite strain foliation or S-plane ($\varepsilon_S$); and (2) the displacement due to the strain accommodated in the formation of the C-plane fabric ($\varepsilon_C$). The shear zone within the Yackandandah Granite provides an excellent natural laboratory for investigating relative strain partitioning in S–C fabric development because: (1) the finite displacement across the shear zone is known from field relationships; (2) the shear zone has a relatively simple geometry without abrupt strain discontinuities; and (3) S–C fabrics are well developed throughout.

The finite displacement due to strain accommodated in the formation of the S-planes has been calculated according to the method of Ramsay and Graham (1970), in which the shear strain ($\gamma$) is given by: $\gamma = 2/\tan 2\theta$, where $\theta$ is the angle between the finite strain foliation and the shear-zone boundary and for S–C fabrics is equivalent to $S\hat{\ }C$. The small scatter in $S\hat{\ }C$ parallel to the boundary of the shear zone (Figs 4, 6) precludes the calculation of a unique value of $\varepsilon_S$ for the Yackandandah shear zone. The calculated displacements for the upper and lower bounds of all points shown in Fig. 6 are 3.5 and 6.5 km, respectively, and represent absolute minima and maxima for $\varepsilon_S$. The best estimate of $\varepsilon_S$ may be calculated from the profile X–X′ in Figs 4 and 6, which represents the best constrained shear-zone profile. The calculated displacement due to $\varepsilon_S$ for X–X′ is 4.8 km or ~70% of the total displacement across the shear zone determined from field criteria.

## DISCUSSION

Deformation in the Yackandandah Granite implies that post-Early Devonian movement of the Kiewa shear zone included sinistral strike-slip motion with a finite displacement of ~7 km. The shear zone preserves no evidence of the previously postulated thrusting associated with this structure (Beavis 1961, 1973) and while we cannot unequivocally dismiss an early (pre-Early Devonian) thrust motion on the basis of the results of this study, two lines of evidence suggest that such an early thrust motion is unlikely. First, fault rocks elsewhere along the Kiewa shear zone are characterized by subhorizontal stretching lineations (Beavis 1961; M. Sandiford, S. F. Martin, E. M. Lohe pers. obs.) and no down dip lineations have been documented from the fault zone. Second, while the terranes on either side of the shear zone indicate substantially different metamorphic grade, they probably do not represent significantly different levels of exposure. The Omeo Metamorphic Complex is characterized by the presence of andalusite, sillimanite and cordierite, and therefore is similar to the low-pressure metamorphic terrane at Cooma (Joplin 1942; Flood & Vernon 1978), which may be regarded as a regional scale, penetratively deformed, contact aureole. At Cooma, the gradation from chlorite to sillimanite–K–feldspar zones takes place over approximately 6 km, without any substantial evidence for different levels of erosion. In light of these considerations, as well as the general similarity of lithotypes in both the low- and high-grade zones, we believe there is no necessity to postulate the existence of a thrust boundary or a major crustal discontinuity between the Omeo Metamorphic Complex and the Tabberabberan terrane. The observed regional tectonic relationships are equally consistent with the Kiewa shear zone being a small discontinuity imposed along the boundary of a high T–low P Cooma-style metamorphic belt.

The age of sinistral strike movement along the west Kiewa shear zone is constrained to be younger than Early Devonian, the emplacement age of the Yackandandah Granite. North-northwest-trending sinistral strike–slip faults are relatively common in the eastern part of Victoria and in southwestern NSW where they are conjugate to northeast-trending dextral strike–slip faults such as the Burrogate and Fiddlers Creek Faults (White *et al* 1976; Powell 1983; Begg *et al* 1987). The movement on these conjugate fault systems in eastern Victoria has been shown to predate the deposition of Late Devonian sedimentary sequences and is therefore regarded as Middle Devonian in age (J. A. Webb & S. C. Twyerould unpubl. data). We suggest that the Kiewa shear zone formed part of this conjugate mid-Devonian fault system, developed in response to east–west compression. Evidence for a possible earlier dextral movement episode along the Kiewa shear zone (Scott 1985) suggests that this mid-Devonian sinistral movement represents the reactivation of an older structure.

The intrusive relationships at Yackandandah suggest that the granite was emplaced into an actively deforming crust in which east–west shortening was accommodated initially by folding. Similar interpretations have been proposed for the Early Devonian Cape Conran Granite in eastern Victoria, where Burg and Wilson (1988) have documented a transition from thrust and fold-accommodated shortening during granite emplacement to strike–slip fault-accommodated shortening during the Middle Devonian. The similarity in structural development of the Yackandandah and Cape Conran Granites suggests that the transition from fold-accommodated to strike–slip fault-accommodated latitudinal shortening may be a general feature of the Early to Middle Devonian of the Lachlan Fold Belt, temporally related to the emplacement of granites. Because folding in this belt has been accompanied by the development of thin-skinned detachment zones or decollements (Cox *et al* 1983; Sandiford & Keays 1986), this transition in deformation style must have been produced by the locking of the decollement surfaces, possibly because of the 'stitching' effect of granite emplacement.

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