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The influence of large ductile shear zones on the emplacement and deformation of the Wyangala Batholith, SE Australia

SCOTT R. PATERSON

Department of Geological Sciences, University of Southern California, Los Angeles, CA 90089, U.S.A.

OTHMAR T. TOBISCH

Earth Science Board, University of California, Santa Cruz, CA 95064, U.S.A.

and

VINCE J. MORAND

Department of Geology, James Cook University, Townsville, Queensland, Australia

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Abstract—The Wyangala batholith consists of many small S- and I-type plutons, most of which are elongate in a N–S direction. Our studies of this batholith indicate that N–S-striking magmatic foliations exist in some of the individual plutons but are not strongly developed. A few individual plutons show evidence of forceful emplacement, but, in general, most do not. Intense post-emplacement deformation occurs in a series of E-directed thrusts that border the eastern edge of individual plutons, or the batholith as a whole. This thrusting formed gneissic layering, mylonites and secondary foliations in the batholith, and complex polyphase folding and cleavage development in the wall rocks. We suggest that the batholith was emplaced as sheet-like bodies, possibly along steep reverse faults. Data presently available indicate that the pre-emplacement deformation of the wall rocks is Middle Silurian, that the batholith was emplaced in the late Silurian, and that post-emplacement thrusting is late Silurian to early Carboniferous. Finally, the close association of batholiths and regions of complex deformation in the Lachlan fold belt suggest to us that these elements may represent shallow-level equivalents of Hollister & Crawford's "surge tectonics" (*Geology* **14**, 558–561, 1986).

INTRODUCTION

BATHOLITHS form a large component of most orogenic belts throughout the world. For example, Chappell & White (1974) estimated that plutons form around 30% of the Lachlan fold belt, Australia, and in the central Sierra Nevada, U.S.A., plutons form from 50 to 70% of the exposed orogen (Bateman *et al.* 1963). Most batholiths form linear belts roughly parallel to the regional trends of structures in the wall rocks. How these batholiths are emplaced, and the role of pluton emplacement in the evolution of orogenic belts, has challenged geologists for many years (Balk 1937, Buddington 1959, Hamilton 1969, Pitcher & Berger 1972, Rickard & Ward 1981).

On closer inspection, most of these linear belts of granitoid rocks are composite bodies, consisting of many smaller plutons or zoned plutonic suites (e.g. Bateman *et al.* 1963, Pitcher *et al.* 1985). Hutton (1988) recently summarized emplacement mechanisms for individual plutons and emphasized that these mechanisms usually reflect complex interactions between regional deformation and the diapiric rise of magma. If we assume that similar processes operate during the emplacement of composite batholiths, then the question of emplacement largely concerns why the individual plutons in batholiths are elongate in shape and emplaced in long linear belts.

Southeastern parts of the Lachlan fold belt, Australia, are dominated by such elongate batholiths with N–S trends parallel to regionally developed folds and cleavages (Rickard & Ward 1981, White & Chappell 1983). Vallance (1969) noted that many of these batholiths are spatially associated with complex deformation in contrast to areas well away from the batholiths, and that they lack well-developed contact aureoles. Recent studies suggest that these batholiths are associated with thrust faults (White *et al.* 1976, Burg & Wilson 1988) or NW-striking sinistral and NE-striking dextral strike-slip faults (White *et al.* 1974, Wyborn 1977, Vernon *et al.* 1983, Powell 1984, Begg *et al.* 1987). Sandiford *et al.* (1988) attempted to integrate these observations by suggesting that Mid-Devonian E–W shortening formed thin-skinned thrust sheets. Batholith emplacement caused the thrust faults to 'lock up', and subsequent shortening occurred by the development of the conjugate strike-slip faults.

In this paper, we will examine the composite Wyangala batholith, one of the elongate batholiths exposed in the Lachlan fold belt west of Sydney, Australia (Fig. 1). Extensive geochemical studies (Fig. 2) and rare

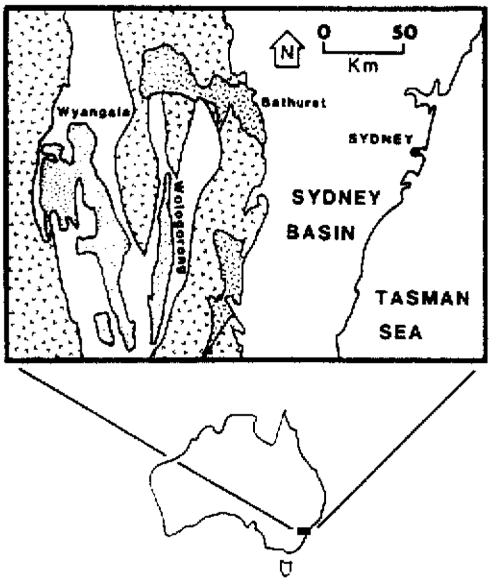

Fig. 1. Location of the Wyangala and Wologorong Batholiths (random dash pattern) in the Lachlan fold belt, southeast Australia. Areas with no pattern are Ordovician metasedimentary rocks near the batholiths, or younger sedimentary rocks in the Sydney Basin. Random 'v' pattern indicates Silurian volcanic rocks.

structural–metamorphic studies (Stevens 1955, Hobbs 1965, Zee *et al.* 1985) have been completed on or near this batholith. We have recently completed detailed structural studies of two regions (Morand 1987, 1988, Tobisch & Paterson 1988) as well as regional studies along three transects across the batholith (Fig. 3). The geochemical studies have considered in some detail the origin of magmas now represented by the plutons in the batholith (see references in Fig. 2). Our intention is to address the following questions regarding this batholith. (1) How was the batholith emplaced? (2) What is the nature of the deformation in and around the batholith? (3) What is the relative timing of batholith emplacement and wall rock deformation? (4) What role did emplacement of the batholith play in the development of structures in the wall rocks? (5) Why was the batholith associated with complex deformation, and why does it lack a well-developed aureole? (6) Are the conclusions of Sandiford *et al.* (1988), in regard to thrusting and batholith emplacement, consistent with observations near the Wyangala Batholith?

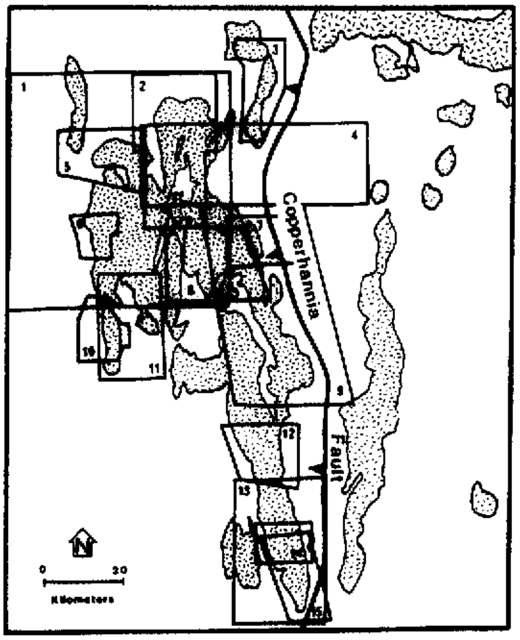

Fig. 2. Areas of previous work in the Wyangala Batholith. Numbered areas are discussed by: (1) Stevens (1955), (2) Close (1978), (3) Berents (1977), (4) Hobbs (1965, 1966), (5) Madsen (1970), (6) Platts (1981), (7) Gibson (1973), (8) Yacopetti (personal communication 1986), (9) Hasan (1956), (10) Cooke (1975), (11) Gibbons (1960), (12) Torr (1968), (13) Wilson (1957), (14) Roberts (1968) and (15) Konecny (1983).

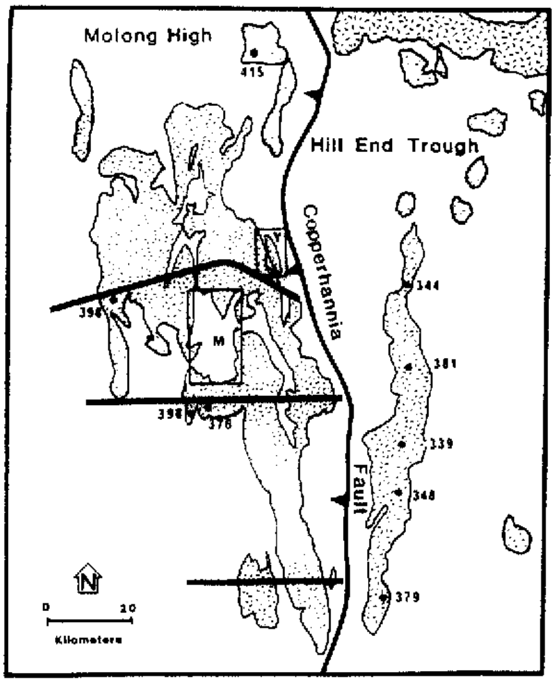

Fig. 3. Distribution of radiometric ages from the Wyangala and Wologorong Batholiths and areas of detailed work by the authors. M = area studied by Morand (1964, 1987, 1988), Y = area around the Yarra pluton studied by Tobisch & Paterson (1988), Paterson *et al.* (1989a) and Tobisch & Paterson (in press). Thick black lines mark locations of regional transects examined by Paterson and Morand. Isotopic ages from Evernden & Richards (1962) and Shaw *et al.* (1982). Ages from the Wyangala Batholith are K–Ar biotite ages, whereas those from the Wologorong Batholith are Rb–Sr whole rock biotite ages. A Rb–Sr whole rock isochron age of 405 Ma is available for the Wologorong Batholith. Finally, Cas *et al.* (1976) note a K–Ar biotite age of 340 Ma from biotite parallel to N–S-striking cleavage immediately to the north of this map in the Hill End Trough (east of the Copperhannia Fault).

DESCRIPTION OF BATHOLITH

General setting and petrology

The Wyangala Batholith is exposed immediately west of the Copperhannia Thrust (Fig. 3), which separates the Molong High and Wyangala Batholith from the Hill End Trough to the east (Hobbs & Hopwood 1969). This

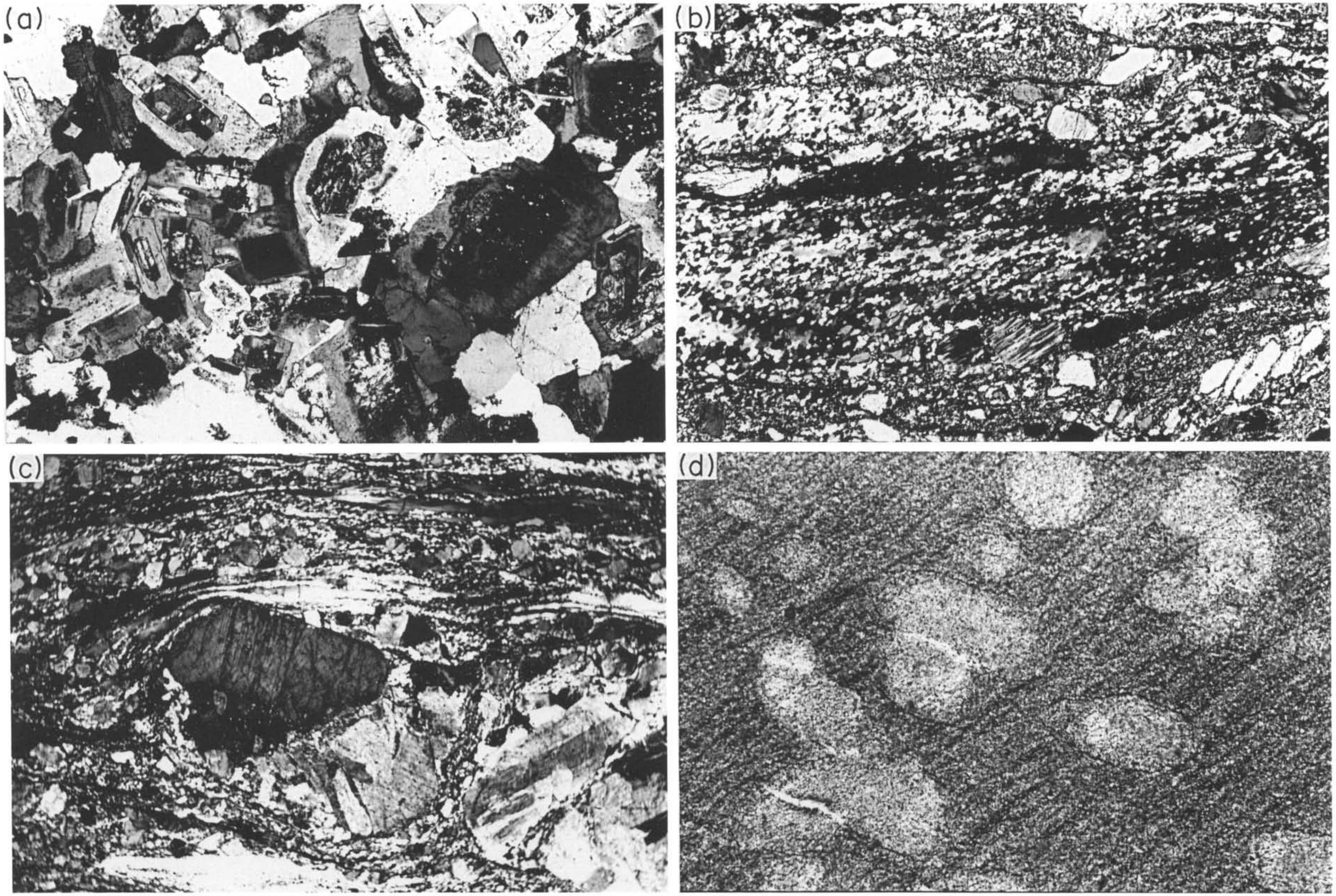

Fig. 4. Photomicrographs of rocks from the Wyangala Batholith. (a) Undeformed plagioclase showing complex zoning; (b) S–C structures in strongly deformed S-type pluton; (c) quartz ribbons surrounding relict igneous feldspars in strongly deformed S-type pluton; (d) porphyroblasts from the middle part of the central regional transect (Fig. 3). Note that the porphyroblasts overprint a regional foliation, but are retrogressed to sericite and folded. All photomicrographs approximately 5 mm across.

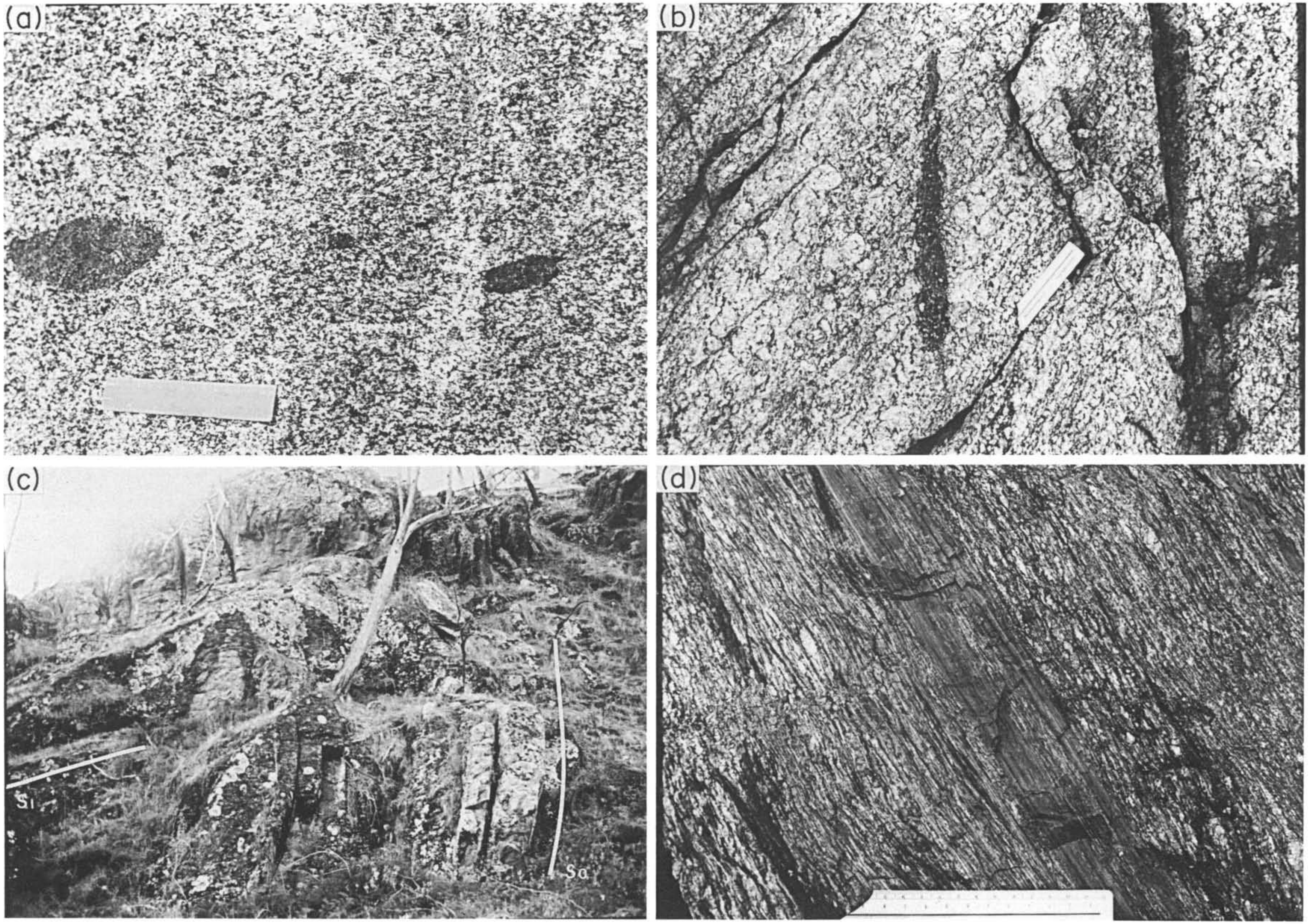

Fig. 5. Photographs of structures in or near the Wyangala Batholith. (a) Magmatic foliation near the southern end of the batholith; (b) *S–C* structures from the Wyangala fault near Wyangala dam; (c) recumbent fold hinge near the Yarra pluton (Y in Fig. 3); and (d) mylonite developed in one of the large ductile shear zones within the batholith.

part of the Lachlan fold belt is dominated by Ordovician sandstones and shales with minor volcanic rocks and Silurian volcanic and sedimentary rocks. The Wyangala Batholith intrudes Ordovician rocks only, but it is considered to be late Silurian to early Devonian (Evernden & Richards 1962, Close 1978). The batholith is approximately 160 km long, 30–50 km wide and consists of over 30 individual plutons (Close 1978). Plutons consist of S-, I- and rare A-type (Yacopetti personal communication 1986) with S-type granites and monzonites twice as common as I-type granodiorites and tonalites (Close 1978). Diorites and gabbros occur locally (e.g. Berents 1977, Close 1978, Platts 1981).

K–Ar biotite ages of 415 ± 2, 398 ± 13, 398 ± 13 and 376 ± 13 Ma have been determined from the batholith (Fig. 3) (Evernden & Richards 1962). All of these dates come from mildly deformed plutons, and thus most likely represent the time of metamorphic cooling and may be significantly younger than emplacement (e.g. Shaw *et al.* 1982).

Magmatic structures

Foliations of strictly magmatic origin are usually not readily identifiable in the Wyangala Batholith. However, where solid-state deformation is weak, aligned igneous minerals (particularly euhedral K-feldspars, but in places plagioclase, hornblende or biotite), microgranitoid enclaves (Fig. 5a), xenoliths and schlieren layering commonly define weakly developed magmatic foliations (Hasan 1956, Wilson 1957, Hobbs & Hopwood 1969, Madsen 1970, Close 1978, Platts 1981, Konecny 1983). These magmatic foliations usually strike N–S and dip steeply east, roughly parallel to the long dimension of the batholith and margins of individual plutons. In rare instances, magmatic foliations are at significant angles to this regional trend (Torr 1968, Paterson & Morand unpublished data) or define concentric patterns in zoned, mafic plutons (Madsen 1970, Berents 1977, Platts 1981). Solid-state foliations usually overprint these foliations (e.g. Hobbs 1965, Torr 1968, Morand 1988), although Platts (1981) noted one instance where the "Cucum adamellite", with a magmatic foliation parallel to its margin, cuts across solid-state foliations in the Wyangala granite. Therefore, magmatic foliations are largely parallel to the margins of plutons, although in rare instances they may define internal lobes.

Solid-state structures

All plutons examined in the Wyangala Batholith show some evidence of solid-state deformation or recrystallization (Hasan 1956, Hobbs 1966, Roberts 1968, Torr 1968, Close 1978, Platts 1981, Konecny 1983, Morand 1988, Tobisch & Paterson in press). Throughout large portions of the batholith, the intensity of solid-state deformation is weak, and foliations do not occur (Figs. 4a–c). In these regions, solid-state deformation consists of undulose extinction in crystals, recrystallization of quartz and the margins of biotite, the inversion of orthoclase to microcline, the fracturing of feldspars, and, particularly in I-type plutons, the breakdown of plagioclase to epidote + sericite (Hasan 1956, Hobbs 1966, Torr 1968, Close 1978, Tobisch & Paterson in press).

Elsewhere, the intensity of solid-state deformation increases forming large zones, hundreds of meters to 5 km wide (Figs. 6 and 7), marked by gneissic layering, *S–C* foliations (Fig. 5b), mylonites (Fig. 5d), and ultramylonites (Hasan 1956, Wilson 1957, Hobbs 1966, Roberts 1968, Close 1978, Morand 1988, Tobisch & Paterson in press). As described in other granitoids (Berthé *et al.* 1979, Vernon *et al.* 1983, Simpson 1985, and others), the transition from non-foliated to foliated portions of the Wyangala Batholith (Figs. 5 and 6) is associated with the following changes: (1) reduction in grain size, largely by recrystallization or neocrystallization, but in part by grain breakage; (2) development of quartz–mica bands, which wrap around resistant feldspars and occasionally resistant quartz clasts; (3) alteration of hornblende to biotite or actinolite, both of which sometimes alter to chlorite; (4) alteration of plagioclase to epidote and sericite, with the epidote and sericite becoming smeared out in bands; (5) development of *S–C* foliations; and (6) in mylonite zones further reduction in grain size and, in I-type plutons, changes in bulk chemistry (e.g. Tobisch *et al.* 1987). The gneissic foliations and mylonite zones show remarkably consistent N–S strikes (Figs. 6 and 8). Dips are always to the west but vary from steep to less than 30° (Fig. 8) (Tobisch & Paterson 1988). Where developed, stretching lineations show pitches near 90°.

C-surfaces (Fig. 5b) are defined by spaced zones rich in micas and fine-grained quartz, strike parallel to the gneissic foliations, but always dip less steeply west (Gibbons 1960, Hobbs 1965, Roberts 1968, Morand, 1988, Tobisch & Paterson in press). Dips of *C*-surfaces vary between 10° and 50° with stretching lineations on *C*-surfaces showing pitches near 90°. As described by Berthé *et al.* (1979) and Lister & Snoke (1984), the gneissic layering bends into *C*-surfaces, indicating that the *C*-surfaces are planes of shear. The sense of shear is west-over-east, consistent with that shown by other kinematic indicators (Paterson *et al.* 1989a). However, *S–C* relationships in the Wyangala Batholith differ from those described previously in several ways: (1) *S*-surfaces are often strongly developed in places without any associated *C*-surfaces (Morand 1988); (2) microgranitoid enclaves, which are transected by *C*-surfaces, are not significantly offset along the *C*-surfaces (Fig. 5b); (3) *S*-surfaces formed during flattening type strain, whereas *C*-surfaces formed during plane strain (Zee *et al.* 1985); and (4) although the angles between *S*- and *C*-surfaces sometimes decrease with increase in intensity of foliation development (e.g. Zee *et al.* 1985), this is not always the case (Tobisch & Paterson in press). We propose that the *C*-surfaces formed late in the development of the *S*-surfaces, due to strain hardening, as *S*-surfaces were increasingly forced to bend around resistant K-feldspar phenocrysts, thus inhibiting further slip on the *S*-surfaces.

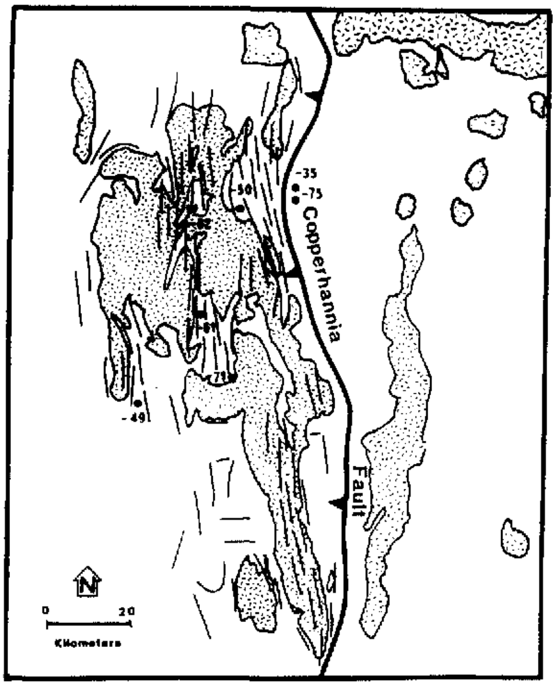

Fig. 6. Map of the Wyangala Batholith showing regional foliation trends. Map is based on previous studies and recent work by authors noted in Figs. 2 and 3. These foliations likely represent S_{c1} outside of ductile shear zones and S_T within these shear zones. Black dots and adjacent numbers represent locations of strain data with the numbers representing average percent shortening along the Z axes of strain. Strain data and references presented in Table 1.

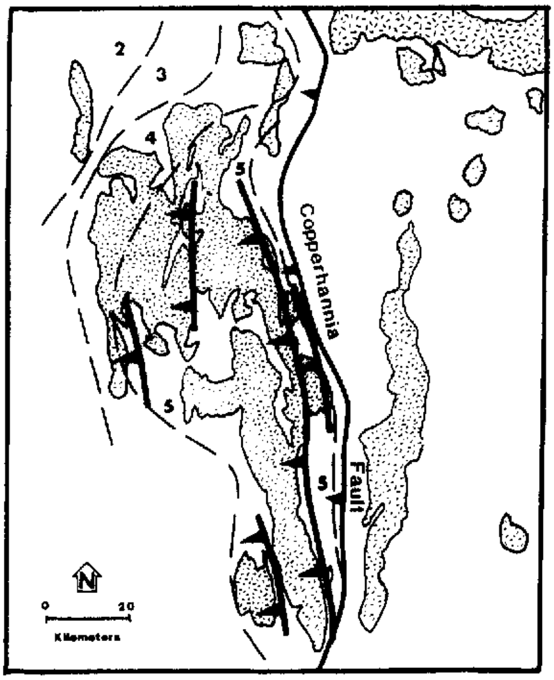

Fig. 7. Map of the Wyangala Batholith showing locations of large ductile shear zones of Paleozoic age and regional metamorphic isograds. Heavy lines mark the position of most intense solid-state foliation development; actual widths of the shear zones are greater than shown. Teeth are on upper plate. Note that these shear zones tend to form along the eastern margins of individual plutons, or of the batholith as a whole. Metamorphic zones near the north end of the Wyangala Batholith adapted from Smith (1969). 5 = biotite zone, 4 = chlorite zone, 3 = prehnite–pumpellyite zones and 2 = prehnite zone. Note that near the batholith, these zones represent assemblages formed after batholith emplacement. See text for discussion.

STRUCTURES IN THE WALL ROCKS

General

In wall rocks well away from the batholith, the traditional view has been that structures in pre-Carboniferous units consist of a single continuous cleavage and associated folds that are locally folded by crenulations or kinks (Packham 1969, Hobbs & Hopwood 1969, Vallance 1969). This cleavage strikes N–S and usually dips steeply west. The associated folds tend to be upright, asymmetrical structures, with N–S-trending axes, and are associated with W-dipping reverse faults (Packham 1969, Hobbs & Hopwood 1969, Vallance 1969, Crook & Powell 1976, Powell *et al.* 1977). Powell and coworkers (Powell *et al.* 1977, 1978) have argued that these structures are late Devonian to early Carboniferous, a suggestion supported by K–Ar age from biotite parallel to the continuous cleavage (Cas *et al.* 1976). However, Rickard (1978) noted that it is difficult to show that all N–S-striking cleavages in this area are of similar age, and that some N–S-striking cleavages may be older. In this regard, Powell & Fergusson (1979) noted that Middle Devonian folding and cleavage development increases to the south in the Lachlan fold belt.

Structures in wall rocks near batholiths in the Lachlan fold belt increase in complexity in comparison with those described above (Vallance 1969). Near the Wyangala Batholith, most workers have noted two widely developed sets of folds and cleavages and locally a third set of kinks or crenulations (Hassan 1956, Wilson 1957, Hobbs 1965, Roberts 1968, Torr 1968, Hobbs & Hopwood 1969, Close 1978, Konecny 1983, Morand 1987). Our recent studies (Tobisch & Paterson 1988, in press, Paterson *et al.* 1989a) indicate that further complexities exist, at least in regions that we interpret to be the continuation of the large ductile shear zones described above. Because of this, we first summarize the structures seen outside of these shear zones, and then examine structures in the more complex zones. In doing so, we will use the nomenclature outlined by Tobisch & Paterson (1988), that is, S_0 for bedding and S_b for bedding-parallel fissilities, S_c for continuous cleavages, S_{cr} for crenulations, S_{cc} for crenulation cleavages and S_T for composite cleavages. Numerical subscripts will be used only when the generation of the foliation can be inferred with reasonable certainty.

A continuous cleavage, S_{c1} and associated folds are everywhere developed in wall rocks near the batholith. S_{c1} strikes N–S and dips steeply west (Figs. 6 and 8) (Wilson 1957, Roberts 1968, Hobbs & Hopwood 1969, Close 1978, Morand 1987, Tobisch & Paterson 1988). Associated folds have quite variable fold-axis orientations and asymmetries; but asymmetries usually indicate a west-over-east or southwest-over-northeast sense of movement. Stretching lineations are not well-developed, but when present have pitches in S_{c1} near 90°.

The above structures are overprinted by less wide-

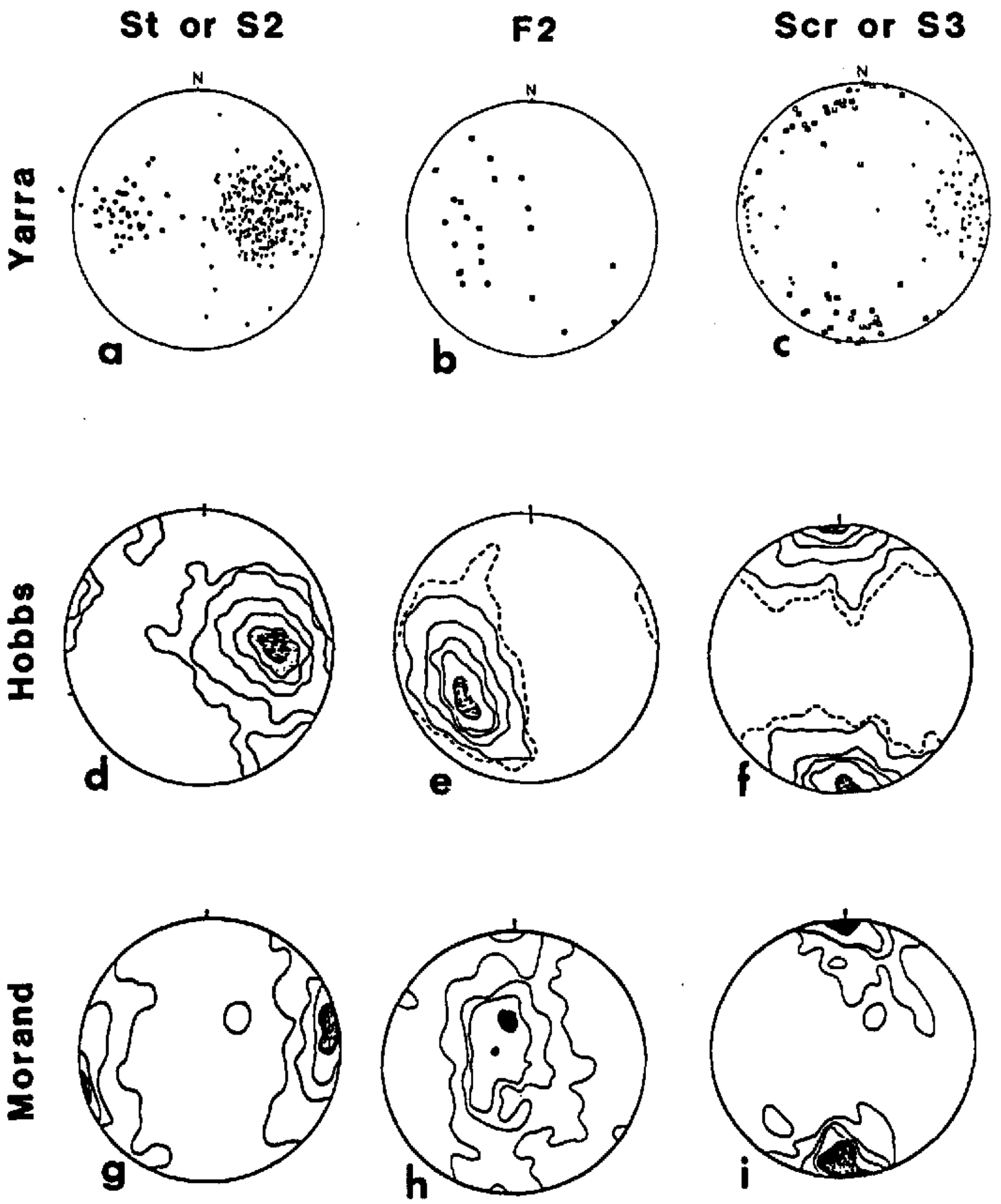

Fig. 8. Selected synoptic equal-area plots of data from different parts of the Wyangala Batholith. Plus symbols = poles to cleavage, filled circles = stretching lineations, boxes = fold axes or bedding–cleavage intersections. Data in row 1 from area marked Y in Fig. 3, data in row 2 from area 4 in Fig. 2, and data in row 3 from area marked M in Fig. 3. See Hobbs (1965), Morand (1987) and text for further discussion.

spread folds and crenulations, and crenulation cleavages, S_{cc2} (Hassan 1956, Torr 1968, Hobbs & Hopwood 1969, Close 1978, Morand 1987, Tobisch & Paterson 1988). These later structures strike N–S and usually dip west (Fig. 8). Fold axes have shallow plunges and fold asymmetries consistently indicate a west-over-east sense of movement (Hasan 1956, Wilson 1957, Torr 1968, Hobbs & Hopwood 1969, Close 1978, Konecny 1983, Zee *et al.* 1985, Tobisch & Paterson in press). Locally developed crenulations and kinks, some of them showing conjugate relationships, fold S_{cc2}, and on a regional scale have variable orientations (Hobbs 1965, Roberts 1968, Torr 1968, Hobbs & Hopwood 1969, Morand 1987, Tobisch & Paterson 1988).

In the ductile shear zones, the oldest structures, S_o and S_{c1}, are overprinted by several generations of coaxial folds and parallel or subparallel cleavages with morphologies varying from S_c to S_T (Tobisch & Paterson 1988). We believe that because of the large amounts of shear in these zones, new folds and cleavages were rapidly rotated and transposed parallel to a composite foliation, S_T (Tobisch & Paterson 1988). Strains were also strongly partitioned into shaly units, and these units commonly show much more complex structures, or more intensely developed foliations, than nearby sandstones. Because of this partitioning, and because of the development of several generations of coaxial structures, it is often difficult to identify which 'generation of structures' are present in a given exposure (Tobisch & Paterson 1988). Instead, we notate these structures as a composite foliation, S_T.

S_T strikes N–S and dips moderately to gently west. Fold asymmetries associated with the development of S_T, along with other kinematic indicators (deflection of foliations, duplex structures, asymmetrical tails around grains) all indicate a west-over-east sense of shear. Stretching lineations tend to plunge down-dip (Tobisch & Paterson in press). S_T and associated folds are overprinted by two sets of folds and crenulations cleavages. The more strongly developed set of folds has axes with gentle plunges and N–S trends, and axial planes that dip steeply west. These fold asymmetries also indicate west-over-east motion. The other set of folds is a locally developed set of E–W-trending crenulations. We have not been able to establish consistent refolding relationships between these two youngest sets of folds, leaving open the possibility that they represent a single set of conjugate structures (cf. Stauffer & Rickard 1966).

These more complex structures are best documented in a zone of intense deformation immediately east of the batholith recently examined by Tobisch & Paterson (1988, in press) (Fig. 3). However, our regional studies indicate that comparable structures exist in all of the ductile shear zones depicted in Fig. 7. Structures equivalent to our S_T and younger folds have been previously described in other areas near the batholith as D1 and D2 structures by Hobbs (1965), Roberts (1968), Torr (1968), and D2 and D3 structures by Morand (1987).

Ductile shear zones

Numerous faults with different styles and ages exist in and around the Wyangala Batholith (e.g. Stevens 1955, Hasan 1956, Noakes 1957, Gibbons 1960, Cleary 1967, Roberts 1968, Torr 1968, Hobbs & Hopwood 1969, Cooke 1975, Close 1978, Zee *et al.* 1985, Morand 1988), some of which may still be active today (Cleary 1967). Here we wish to discuss the evidence for existence of a series of large ductile shear zones of Paleozoic age.

In the batholith, the zones of gneissic layering (Fig. 5b), mylonites, and ultramylonites (Fig. 5d) are developed in N–S-striking narrow zones. Kinematic indicators (*S–C* fabrics, asymmetrical porphyroclasts, quartz fabrics) indicate that shear with a west-over-east sense of motion occurred in these zones. These regions are continuous with zones in the wall rocks that also show intense deformation and an increased structural complexity (e.g. Tobisch & Paterson 1988, Paterson *et al.* 1989a). The consistent asymmetry of folds, local presence of thrust duplexes, transposition of older folds and foliations, and greater intensity of strain (see below) in these narrow zones support the contention that these regions are large ductile shear zones. Fold asymmetries and geometry of transposition in the wall rocks also indicate a west-over-east sense of shear (Paterson *et al.* 1989a, Tobisch & Paterson in press).

As noted earlier, *C*-surfaces in the ductile shear zones in the batholith dip 10–50° W (Zee *et al.* 1985, Morand 1988, Tobisch & Paterson in press) suggesting that the shear zones dip 50° or less to the west (Berthé *et al.* 1979). Foliations in these shear zones have greater dips than nearby *C*-surfaces, but sometimes show progressively decreasing dips with greater strain. These observations indicate that movement on the faults is E-directed along surfaces with *thrust* or moderately dipping reverse fault geometry. With one exception, (Wyangala–Bigga pluton of Close 1978 and Yacopetti personal communication 1986 in Fig. 2), these ductile shear zones occur along the eastern edge of individual plutons and the batholith as a whole (Fig. 7) and, therefore, are comparable to shear zones near the Bega Batholith located further to the south (Burg & Wilson 1988).

Strains

Only a very limited amount of strain data is available from this region (Table 1 and references). The XY principal planes of strain ($X > Y > Z$) are essentially parallel to S_c or S_T and X axes parallel to down-dip stretching lineations. Values of shortening along Z vary from -35 to -79%, whereas values of extension along X vary from 29 to 271% (Table 1, Fig. 6). There is some suggestion that values of shortening of -40 to -50% outside the zones of complex deformation increase to -50 to -70% in these zones. But until a detailed study of how strains vary between rock types, the nature of any regional variations will remain uncertain.

Zee *et al.* (1985) presented the only strains measured to date in the batholith. They noted that large flattening-type strains measured from mafic enclaves were associated with the development of gneissic layering and mylonites (*S*-surfaces) in the Wyangala shear zone (Fig. 7) and that the later *C*-surfaces formed during plane strain. Our initial observations ($S > L$ fabrics are common) suggest that such flattening-type strains are associated with the development of S_c and S_T. A similar relationship has been noted in the Bega Batholith (Begg *et al.* 1987, Burg & Wilson 1988).

Metamorphism

Smith (1969) mapped out five zones of 'progressive burial metamorphism' in northern parts of the Molong High and Hill End Trough (Figs. 3 and 7) ranging from burial conditions to the biotite zone of the greenschist facies. He noted that the grade of metamorphism increased towards the south in the Molong High and eastwards towards the Hill End Trough. These metamorphic zones are cut by the Wyangala Batholith and overprinted in a narrow discontinuous contact aureole ranging in width from 50 to 500 m (Stevens 1955, Hasan 1956, Wilson 1957, Gibbons 1960, Hobbs 1965, Torr 1968, Cooke 1975, Close 1978, Morand 1988). Where this aureole is preserved, metamorphic grade ranges up to hornblende hornfels and textures usually show static overprints on earlier metamorphic fabrics. Estimates of *T–P* conditions during contact metamorphism are 400 and 550°C and 2–3.5 kb (Close 1978, Morand unpublished data).

Continued deformation/metamorphism has overprinted, and in the ductile shear zones, largely wiped out contact metamorphic effects (Vallance 1969, Hobbs 1965, Close 1978, Tobisch & Paterson in press). Meta-

Table 1. Location of strain data shown in Fig. 6. Where multiple samples occurred in one region, strains in Fig. 6 reflect averages. Strains were calculated using R_f/ϕ techniques, except for those measured by Gray & Durney (1979), which were measured using fibers around quartz or pyrite

	Strain data near Wyangala Batholith							
	Axial ratios			Extensions				
Sample No.	*X*	*Y*	*Z*	*X*	*Y*	*Z*	Strain intensity	Lodes parameter
Morand								
62568	3.54	1.05	1	129	−32	−35	1.01	−0.93
62569	4.58	2.02	1	118	−4	−52	1.08	−0.08
62582	7.14	3.14	1	153	11	−65	1.40	0.17
62634	14.29	7.62	1	199	60	−79	2.00	0.53
62592	4.57	2.17	1	112	1	−53	1.07	0.02
62593	9.63	5.19	1	162	41	−73	1.66	0.45
62708	6.90	6.21	1	97	77	−71	1.54	0.89
Paterson & Morand (1988)								
A-87	3.14	2.41	1	60	23	−49	0.85	0.54
Zee *et al.* (1985)								
Ave.	5.25	3.50	1	99	33	−62	−62	0.51
Gray & Durney (1979)								
Greenmantle	3.00	2.70	1	49	34	−50	1.22	0.81
Simpson (1985)								
Tuffs	14.91	4.35	1	271	8	−75	0.86	0.09
Sandstone	1.98	1.84	1	29	20	−35	1.91	0.79

morphic biotite grew during the development of both *S*- and *C*-surfaces in the batholith and with cleavages developed in the wall rocks near the batholith during this later deformation (Hobbs 1965, Close 1978, Morand 1987, Tobisch & Paterson in press). Morand (unpublished data) has suggested that pressures during this latter deformation were around 3–4 kb and that temperatures varied from 350°C well away from the batholith to 550°C in or near the batholith.

Porphyroblast–matrix relationships support the contention that deformation of the wall rocks occurred both before and after emplacement of the batholith. Porphyroblasts of andalusite, cordierite and biotite in the contact aureoles of some individual plutons (Fig. 5d) overgrow a continuous cleavage (S_{c1}), but are in turn recrystallized and folded during later deformation (Stevens 1955, Roberts 1968, Torr 1968, Close 1978, Gray & Durney 1979, Morand 1987, Paterson & Morand unpublished data).

DISCUSSION

Emplacement of the batholith

Most of the individual plutons, and batholith as a whole, have elongate shapes and steep-dipping contacts. As noted previously, magmatic foliations tend to be parallel to the pluton margins and only weakly developed. Wall rock foliations are rarely deflected near pluton margins. Thus our observations indicate that most of the individual plutons are tabular in shape and passively emplaced (cf. Morand 1988). A few exceptions do occur. Foliations (S_{c1}) in the wall rocks are locally deflected near the margins of plutons (Fig. 6) (Madsen 1970, Paterson & Morand unpublished data) and a few plutons are concentrically zoned (e.g. Platts 1981).

Hutton (1988) suggested that even "passively emplaced" plutons commonly occur during active deformation. This raises the question of the tectonic setting during emplacement of the Wyangala Batholith. The sheet-like shape of many of the plutons, and the parallelism of S_{c1} with the pluton margins and magmatic foliations, suggests that pluton emplacement was structurally controlled (see also Stevens 1955, Noakes 1957, Wilson 1957, Torr 1968, Rickard & Ward 1981, Morand 1988). Several observations suggest that faults were present in this region prior to pluton emplacement. In a few cases, steep W-dipping faults are truncated by plutons (Stevens 1955, Gibbons 1960), and Platts (1981) noted that pluton emplacement was still active after the development of solid-state foliations in the batholith. The asymmetrical nature of folds associated with S_{c1} also supports active reverse-faulting prior to pluton emplacement. Therefore, we suggest that plutons in the Wyangala Batholith were emplaced along these W-dipping faults. Space for the tabular bodies was created by deformation of the wall rock by shortening parallel to S_{c1} and faulting.

Alternatively, Wyborn (1977) suggested that many of the batholiths in the Lachlan fold belt were emplaced during Silurian extension, which caused the development of graben structures and emplacement of mafic dikes. Wyborn also suggested that Devonian thrust or reverse faults may have initiated on these graben-bounding normal faults. Morand (1988) noted that N–S-striking mafic dikes are widespread in the Wyangala

Batholith, and therefore suggested that this batholith also was emplaced during Silurian extension. This emplacement mechanism is supported by the weak magmatic foliations and the lack of any evidence that deformation of the wall rocks or plutons occurred during emplacement. Therefore, we cannot completely rule out this possibility, but do note that we have not observed any extensional structures in, or near, the Wyangala Batholith to date. A closer examination of the kinematics and timing of the numerous faults in this region would be useful in this regard.

Timing of emplacement and deformation

A synthesis of structural data provides a consistent picture of the relative timing of deformation and pluton emplacement for the Wyangala Batholith as follows: (1) E–W shortening, which caused the development of reverse faults, asymmetrical folds, and steep W-dipping cleavage under greenschist to sub-greenschist facies conditions; (2) emplacement of the batholith with local contact metamorphism up to hornblende hornfels facies; (3) continued west-over-east movement, which formed large ductile shear zones along the eastern margins of individual plutons, and complex coaxial folding in the wall rocks; and (4) minor folding or kinking. Event (3), and possibly event (4), were accompanied by regional metamorphism under greenschist facies conditions (biotite zone in or near the batholith and chlorite zone away from the batholith).

Some authors have stated or implied that the emplacement of the batholith occurred synchronously with deformation and metamorphism (Noakes 1957, Wilson 1957, Torr 1968, Morand 1988; see also White *et al.* 1974 and Hutton 1988 for more general discussions). However, we have not seen evidence of 'submagmatic flow' or a transition from magmatic to high-temperature solid-state flow (e.g. Paterson *et al.* 1989b). In addition, metamorphic biotite, and not metamorphic hornblende, is associated with the development of foliations in I-type plutons, metamorphic plagioclase is albite, and K-feldspars are not commonly recrystallized, indicating that solid-state deformation occurred well below solidus temperatures, but at higher temperatures than deformation away from the batholith. We suggest that these microstructural observations, and the regional observations indicating that regional deformation did in a broad sense take place during emplacement, can be reconciled if the time required for final emplacement and cooling of individual granitoids was much shorter than time during which regional deformation and faulting were active (e.g. Paterson in press).

In most deformed batholiths in the Lachlan fold belt, K–Ar biotite ages significantly post-date emplacement ages (Evernden & Richards 1962, Williams *et al.* 1975, Roddick & Compston 1976, Richards & Singleton 1981, Shaw *et al.* 1982). K–Ar biotite ages from the deformed Wyangala Batholith range from 415 Ma to 376 Ma suggesting that the Batholith is Silurian. In the Hill End Trough (Fig. 2), K–Ar ages noted by Cas *et al.* (1976) and Shaw *et al.* (1982) indicate that the upright folds and widespread cleavage formed during the early Carboniferous. Hobbs & Hopwood (1969) and Powell *et al.* (1977) proposed that the structures in the Hill End Trough can be correlated with F_1 folds (F_2 of Morand 1987 and our S_T and S_{cr} in the ductile shear zones) near the Wyangala Batholith. Thus, K–Ar dates in the Wyangala Batholith, and the suggestion that deformation occurred during or shortly after emplacement, indicate that the large ductile shear zones are late Silurian to early Devonian, whereas regional correlations indicate that these structures are early Carboniferous.

This discrepancy can be resolved in several ways: (1) the isotopic ages presently available are incorrect or incomplete; (2) the Copperhannia Thrust, the boundary between the Hill End Trough and units around the Wyangala Batholith (Fig. 3), is a major structural discontinuity—deformation east of this fault is early Carboniferous whereas deformation west of the fault is early Devonian or older; (3) deformation continued episodically from Middle Silurian to early Carboniferous, or (4) the batholith remained deeper and hotter than the wall rocks, until moved to its present level by early Carboniferous thrusting.

The presence of thrust faults associated with the batholith indicates that the Wyangala Batholith and enclosed pendants have been brought up from deeper levels relative to the nearby wall rocks. These same faults provided conduits for the migration of hot fluids. Both the thrusting and migration of warm fluids would explain the higher temperatures associated with solid-state deformation in the Wyangala Batholith. If so, we suggest that the K–Ar biotite ages from the batholith date only the cooling of the mildly deformed portions of the batholith (none of the ages are from within the shear zones), and that younger ages would be obtained from within the faults.

In summary, our working hypothesis is that S_{c1} is Middle Silurian, the batholith was emplaced in the late Silurian, and that post-emplacement thrusting could be early Devonian to early Carboniferous. A systematic study of ages of deformed and undeformed parts of the batholith using U–Pb and ^{40}Ar–^{39}Ar would provide much needed data for evaluating this hypothesis.

Role of batholith in development of solid-state structures

Sandiford *et al.* (1988) suggested that the emplacement of batholiths in the Lachlan fold belt may have caused a change from thrusting to strike-slip faulting because the batholiths "locked up" the thrust faults. This is clearly not the case in the Wyangala Batholith (see also Burg & Wilson 1988). Many of the thrust faults deform the batholith and cut completely across plutons or pluton margins, and significant deformation occurred along the faults after solidification of these plutons. In contrast, Hollister & Crawford (1986) suggested that the emplacement of plutons may enhance deformation and cause "tectonic surges" (increased intensity and rate of deformation due to the emplacement of batholiths.

melting of wall rocks and lubrication of shear zones). The association of regions of complex deformation with batholiths in the Lachlan fold belt (Vallance 1969), encouraged us to consider the relevance of Hollister & Crawford's model to the Wyangala Batholith.

The Wyangala Batholith was emplaced at much shallower levels than the plutons discussed by Hollister & Crawford (1986); therefore partial melting of the wall rocks did not occur, and lubrication of faults with magma did not play an important role at the present level of exposure. However, melts probably migrated along the faults at depth, and during final emplacement provided a source of heat and fluids, both of which would facilitate deformation in the wall rocks. Once solidified, the granitoids continued to influence deformation by partitioning deformation into the still hot wall rocks. The localization of ductile shear zones along pluton margins, higher metamorphic grade near the batholith, and complex deformation near the batholith all may reflect this partitioning of deformation into the hot wall rocks. Therefore, we suggest that these batholiths and accompanying complex deformation may reflect shallow-level examples of Hollister & Crawford's "tectonic surges".

CONCLUSIONS

The emplacement of the composite Wyangala Batholith post-dates the development of widespread cleavage and associated folds, but pre-dates subsequent deformation both in the batholith and surrounding wall rocks. Most plutons were passively emplaced, possibly along steep pre-existing reverse faults. The most intense post-emplacement deformation occurs in a series of E-directed thrusts that border the eastern edge of individual plutons, or the batholith as a whole. This thrusting formed gneissic layering, mylonites and *S–C* foliations in the batholith and complex polyphase folding and cleavage development in the wall rocks. Data presently available suggest that the pre-emplacement deformation is Middle Silurian, that the batholith was emplaced in the late Silurian, and that post-emplacement thrusting is late Silurian to early Carboniferous.

The close association of batholiths and regions of complex deformation in the Lachlan fold belt suggests to us that these batholiths and complex deformation may represent shallow-level equivalents of Hollister and Crawford's "surge tectonics". This close association between batholith emplacement and deformation with large ductile shear zones nicely explains why some batholiths in the Lachlan fold belt are associated with complex deformation and lack static metamorphic aureoles (e.g. Vallance 1969).

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