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Pluton emplacement in a strike-slip fault zone: the Doctors Flat Pluton, Victoria, Australia

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Abstract—The Siluro-Devonian Doctors Flat Pluton, Lachlan Fold Belt, Australia, is a hornblende–biotite granite (I-type) that was emplaced into the Early Silurian Omeo Metamorphic Complex. It lies along the Ensay Fault, a major dextral strike-slip fault.

A solid-state foliation is developed in much of the pluton, with the most intense development at the outer parts, grading into massive granite at the centre. This foliation is approximately parallel to trace of the Ensay Fault and to the borders of the pluton. It grades into a mylonitic fabric along the Ensay Fault. In the eastern part of the pluton a second fabric is developed, giving rise to *S–C* fabrics indicating dextral shear.

Some microfabrics in the pluton are typical of relatively high-temperature deformation, consistent with syntectonic emplacement, but lower temperature microstructures overprint them and are dominant. A possible mechanism of intrusion involves the pluton being emplaced into a dilational section of the Ensay Fault when a jog in the fault opened up into a pull-apart structure. As intrusion continued, the northeastern branch of the pull-apart took up all the movement, with later intrusive material being less deformed.

Along the Ensay Fault, lower grade assemblages of chlorite + epidote + albite + sphene and cataclastic textures developed at lower temperatures as fault displacement continued during and after cooling of the pluton.

INTRODUCTION

EMPLACEMENT of plutons occurs in many different tectonic environments and at different times with respect to deformation. Recently several studies have shown the importance of active fault zones in determining the location and style of syntectonic pluton emplacement (e.g. Brun & Pons 1981, Hutton 1982, 1988a,b, Guineberteau *et al.* 1987, Hutton *et al.* 1990). This paper examines an instance where strike-slip faulting has localized the intrusion of a granitic pluton.

GEOLOGICAL SETTING

The Doctors Flat Pluton lies on the southern edge of the Omeo Metamorphic Complex in the Lachlan Fold Belt, southeastern Australia (Fig. 1). This complex consists of Ordovician turbidites which were metamorphosed in the Early Silurian to grades ranging from low-pressure greenschist to amphibolite facies conditions (Morand 1990).

During the Late Silurian to Early Devonian Bowning Orogeny, many I-type plutons were intruded into the metamorphic complex and surrounding areas (Richards & Singleton 1981). A retrogressive regional metamorphic event affected the complex at about this time (Morand 1990) and several large dextral strike-slip faults (Kiewa, Kancoona and Ensay faults) were active (Morand & Gray 1991).

The Doctors Flat Pluton lies along the southwest side of, and partly within, the Ensay fault zone for about 30 km (Fig. 2). To the southwest is a narrow belt of regional metamorphic cordierite zone schists, followed by slate and metagreywacke of the biotite and chlorite zones. On the northeast side of the Ensay Fault are gneiss and migmatite of the regional sillimanite–K-feldspar zone, and several plutons of I-type granite

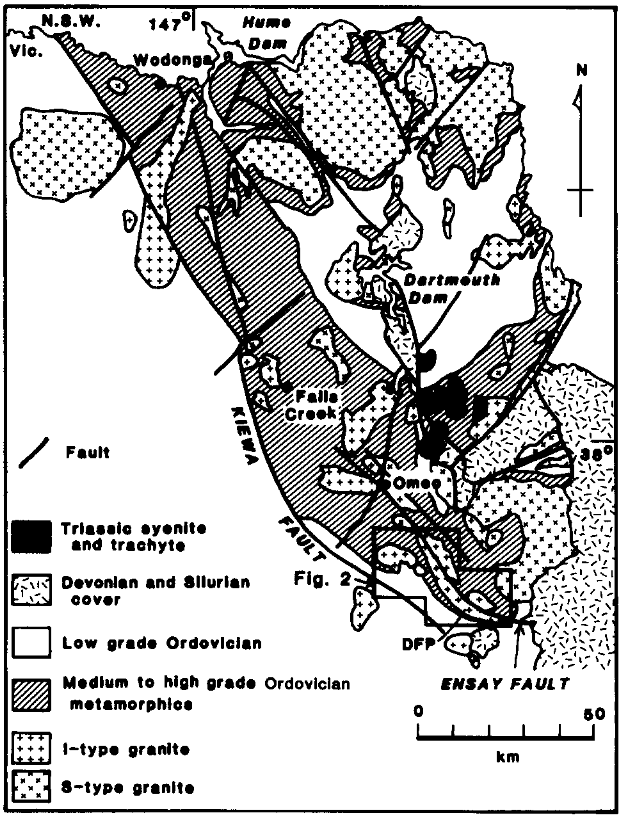

Fig. 1. Location of the Doctors Flat Pluton (DFP) within the Omeo Metamorphic Complex in northeastern Victoria.

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which are petrographically similar to other plutons in the area dated by Richards & Singleton (1981) as Late Silurian to Early Devonian. The Ensay Fault is marked by a belt of mylonite and cataclasite about 1 km wide. Kinematic indicators, mainly *S–C* fabrics (Berthé *et al.* 1979), give a dextral sense of shear (Morand & Gray 1991).

THE DOCTORS FLAT PLUTON

The Doctors Flat Pluton comprises I-type biotite–hornblende granodiorite and tonalite. Although most of the pluton is parallel to the Ensay Fault, a small outlier occurs adjacent to the Swifts Creek Pluton south of Swifts Creek (Fig. 2). This body appears identical to the Doctors Flat Pluton, may be joined to it at a shallow depth, and appears to be intruded by the Swifts Creek Pluton, which has a Rb–Sr age of 405 Ma (Eberz 1987).

The pluton is equigranular and contains quartz, plagioclase and minor K-feldspar in addition to olive coloured biotite and hornblende. A few outcrops contain phenocrysts of hornblende up to 20 mm long. Both normal and oscillatory zoning are common in plagioclase. Accessory minerals include apatite, allanite and zircon. Myrmekite is developed in some rocks, especially the more deformed varieties.

Small rounded microgranitoid enclaves are present in some outcrops. Dykes of aplite are locally common. Some examples of schlieren and igneous layering are present near the southwest boundary of the pluton, where the layering strikes parallel to the boundary and dips steeply southwest. A swarm of mafic dykes intrudes the Doctors Flat Pluton and surrounding rocks. These dykes have been metamorphosed to greenschist facies assemblages but are not cleaved (Morand & Gray 1991).

Two K–Ar ages indicate a Late Silurian to Early Devonian age (412 ± 13 Ma, Richards & Singleton 1981). Both dates are from outcrops with a moderately developed foliation, so this date may be the cooling age of minerals in the foliation. However, it will be shown that emplacement and foliation development were synchronous, and thus the K–Ar ages also approximate the age of intrusion.

A contact aureole, about 500 m wide, is developed on the southwest side of the pluton (Fig. 3). Comparison of Figs. 2 and 3 shows that the contact aureole crosses regional metamorphic isograds. South of Ensay, the aureole extends slightly beyond the regional cordierite isograd, where small contact metamorphic cordierite porphyroblasts post-date the slaty cleavage in biotite

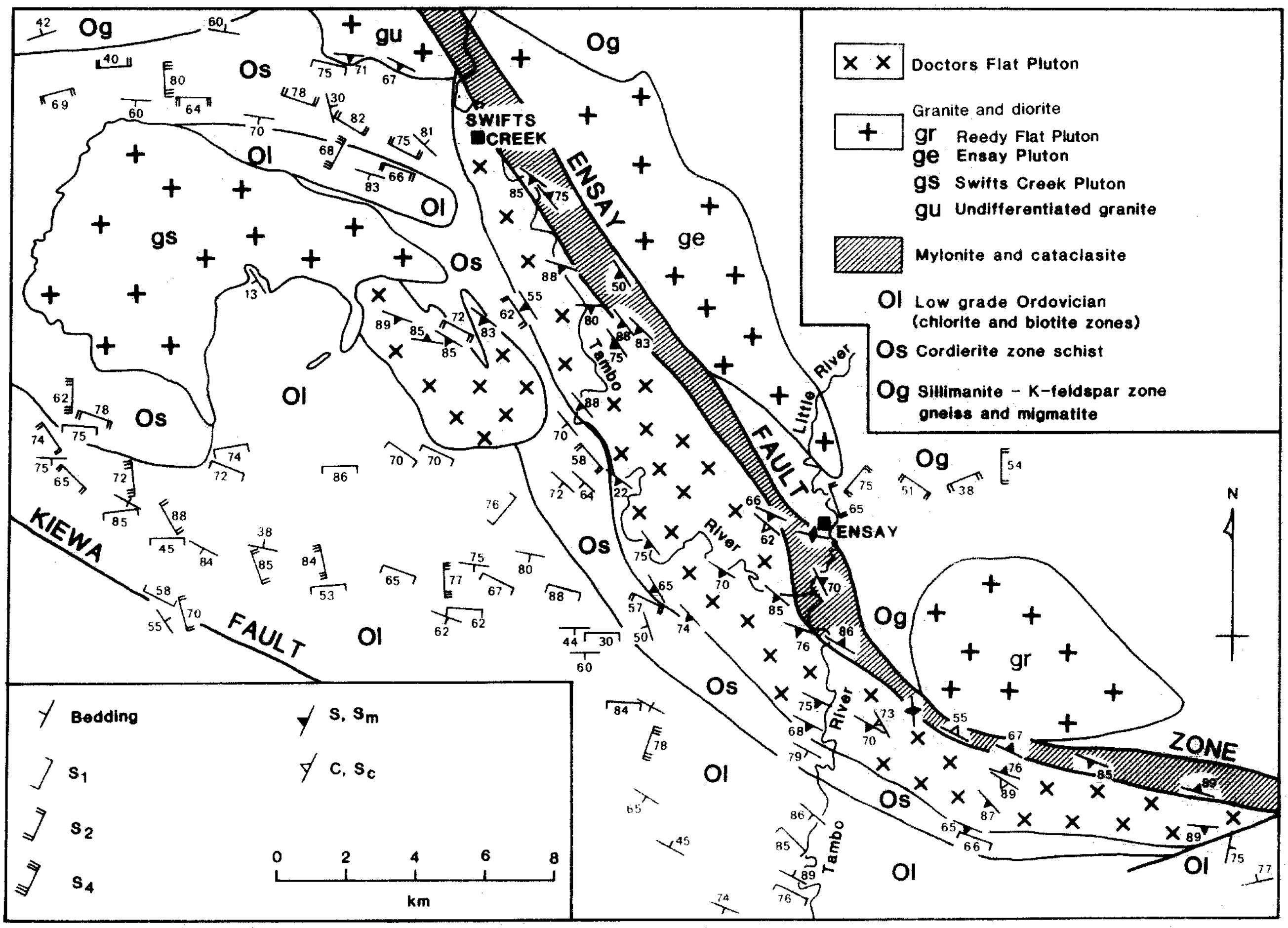

Fig. 2. Geology of the Doctors Flat Pluton and adjacent area. Some structural data from west of Swifts Creek are from MacLennan (1984).

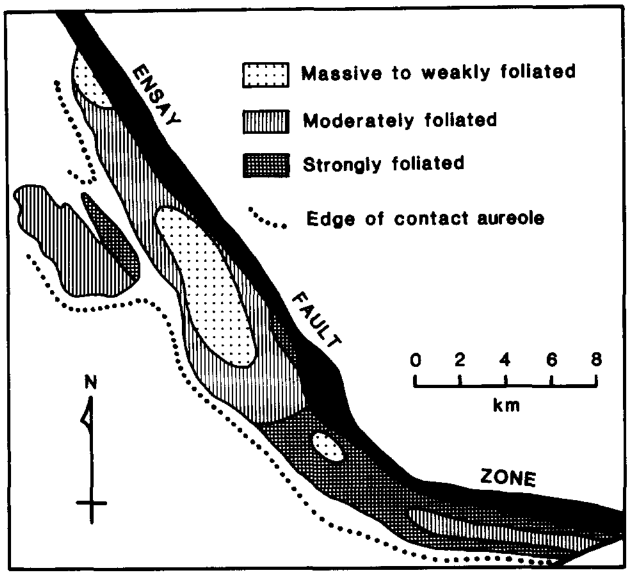

Fig. 3. Map of Doctors Flat Pluton showing intensity of foliation and position of contact aureole.

zone slate. West of Ensay and near Swifts Creek, the aureole lies completely within the regional cordierite zone and no contact metamorphic porphyroblasts are present.

Within much of the contact aureole, cordierite schist is recrystallized and the regional S_2 schistosity is less prominent than outside the aureole. In thin section, mica defining S_2 has been recrystallized into smaller, less well oriented grains. Deformation in the aureole at the southeast end of the pluton is more intense, with porphyroblasts (probably regional cordierite) strongly flattened in a well developed cleavage and retrogressed to biotite and muscovite. Along parts of the contact the granite interleaves with schist, and foliated granite dykes intrude along the regional schistosity, up to about 20 m from the contact. The Ensay Fault marks the northeast edge of the pluton.

STRUCTURE IN THE COUNTRY ROCKS

Metasedimentary rocks southwest of the Doctors Flat Pluton have undergone two episodes of folding. The first folds, F_1, are rare, but S_1 is present as a slaty cleavage in chlorite and biotite zone pelites. Within the regional cordierite zone, S_1 is not obvious in outcrop but occurs as an internal foliation within cordierite porphyroblasts (Morand 1990). The dominant schistosity in the country rocks is S_2, which is a differentiated metamorphic layering axial planar to tight, upright F_2 folds in bedding, which plunge moderately to the southeast and south. S_2 strikes northwest and dips steeply southwest. It wraps around cordierite porphyroblasts and is interpreted as having formed during and after cordierite growth (Morand 1990). In low-grade rocks farther away from the granite, S_1 strikes between west and west-northwest, with a steep dip to the southwest, and S_2 strikes northwest with a subvertical dip (Fig. 2). Structures in the country rocks on the southwest side of the pluton appear to have been dragged toward parallelism with the Doctors Flat Pluton and the Ensay Fault (Fig. 2), and the angle between bedding and cleavage decreases toward the pluton.

In the contact aureole, a sporadically developed cleavage post-dates S_2, and is mainly seen in thin section. It is defined by aligned brown biotite overprinting the differentiated S_2 schistosity at a small angle.

On the northeast side of the Ensay Fault, structure in the gneiss is complex. Several generations of folds are present, with one surface, S_1, being the form surface for all folds. Small-scale, tight F_2 folds are the main structures seen in outcrop. Large folds with wavelengths of a few kilometres and N-striking axial planes, S_3, are the dominant structures north of Ensay. The different axial surfaces in the gneiss cannot be confidently correlated with surfaces in lower grade rocks southwest of the Ensay Fault. Similar structure is seen in high grade rocks well away from the Ensay Fault, so none of the structural surfaces appear to be associated with the fault. Within about 1 km of the Ensay fault zone, the gneiss shows retrogression to greenschist facies assemblages (mainly replacement of biotite by chlorite and sillimanite by muscovite) which may be a contact metamorphic effect of the Doctors Flat Pluton.

A set of N- to NE-striking vertical kinks and ductile shear zones, with sinistral movement, cuts mylonites of the Ensay fault zone and both the Doctors Flat Pluton and its country rocks. This surface becomes a crenulation cleavage, S_4, in rocks to the west and northwest of the Doctors Flat Pluton, and it has been correlated with the Middle Devonian Tabberabberan Orogeny (Morand & Gray 1991). The basis of this correlation is that it is the latest structural surface in the Omeo Metamorphic Complex and it has the same orientation as cleavage in the Tabberabbera area to the west, dated as Middle Devonian by Fergusson & Gray (1989).

STRUCTURE IN THE PLUTON

The main structure in the pluton is a foliation, S, which dips mainly steeply to the southwest and south (Fig. 4). S strikes subparallel to the Ensay Fault, but makes a low angle with the pluton margin (Fig. 2). It varies from strongly developed at the edges of the pluton to weak or absent in the centre (Fig. 3). In some outcrops S is shallowly dipping and weakly developed, and may be a remnant magmatic foliation. However, everywhere else S has many characteristics of a solid-state foliation. In outcrop the foliation is defined by aligned biotite and hornblende, and elongated quartz grains. Enclaves are aligned along S. A stretching lineation, L, is present only in a few outcrops, and it plunges mainly shallowly to the southeast, although some steep plunges have been recorded (Fig. 4).

In thin section, S is defined by elongate, recrystallized quartz grains and the alignment of deformed biotite and hornblende (Figs. 5a & c). Quartz shows undulose extinction, sutured grain boundaries and recrystalliza-

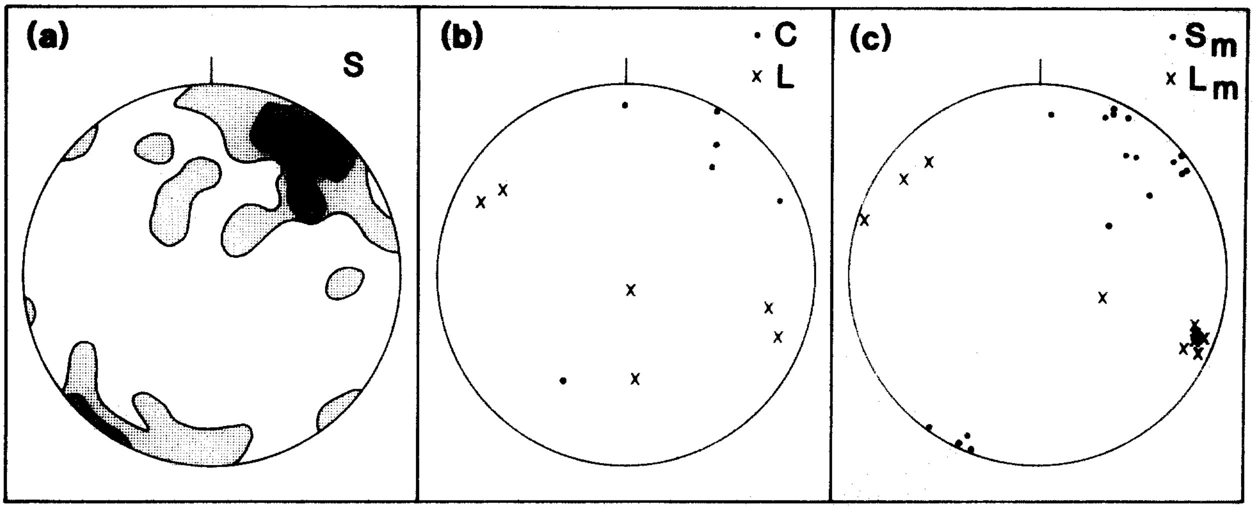

Fig. 4. Equal-area projections, lower-hemispheres, of structural data for the Doctors Flat Pluton and Ensay fault zone. (a) Contoured poles to granite foliation S. Contour values are 1.3, 5 and 10%, $n = 76$. (b) Poles to second granite foliation C ($n = 6$) and stretching lineation L ($n = 6$). (c) Poles to mylonitic layering S_m ($n = 17$) and orientations of stretching lineation L_m ($n = 10$) in the Ensay fault zone.

tion, the degree of which increases with increasing foliation development. In a few weakly foliated specimens quartz contains square subgrains that may result from *c*-slip (Blumenfeld *et al.* 1986) at near solidus temperatures (Paterson *et al.* 1989).

Plagioclase shows few deformation effects in massive to weakly foliated granite (Fig. 5a), but in more strongly foliated rocks it has features such as undulose extinction, flexures, kinks and fractures. In some strongly foliated rocks, tails on plagioclase porphyroclasts indicate dextral shear. Alteration of plagioclase to sericite and epidote, and microfractures filled with albite and epidote, are common in both weakly and strongly deformed granite.

Biotite in massive to weakly foliated granite exhibits undulose extinction and minor kinking (Fig. 5a), and commonly is altered to chlorite, epidote and sphene. In more strongly foliated rocks these features become more common and, in addition, some biotite is recrystallized into small grains aligned along S. Alteration is also more prominent in many strongly foliated rocks, with the newly formed chlorite exhibiting strain effects such as kinks and undulose extinction.

Hornblende is less commonly deformed than biotite, and is not present in many weakly deformed granites. In strongly foliated granite it shows undulose extinction and some recrystallization into smaller grains, as well as alteration to chlorite and epidote.

Veins of albite and epidote are common in foliated granite, and veins of prehnite or prehnite + albite + calcite are less common. All are both parallel and at high angles to S.

In the eastern part of the pluton, a second foliation, C, is present, and the rock has an S–C fabric (Berthé *et al.* 1979). C dips steeply southwest (Fig. 4), striking clockwise from S, and forms small ductile shear zones. The sense of shear on C-surfaces is dextral. Hornblende grains in some of these outcrops have tails which indicate dextral shear. In thin section these hornblende grains are seen to be olive-brown igneous grains that have undulose extinction and small healed fractures in the tails, indicating ductile deformation (Figs. 5c & d). This and the lack of alteration to blue-green metamorphic hornblende or actinolite suggest that the deformation took place at temperatures of the upper amphibolite facies. Joyce (1979) also noted that deformation in the pluton occurred at a higher temperature than that in the Ensay fault zone.

Some outcrops have cataclasite developed along the C-surfaces, indicating that brittle deformation postdated ductile deformation. This is consistent with fault movement continuing with falling temperature.

Foliated granite grades into mylonite along the Ensay fault zone, and within the fault zone mylonitized rocks from both sides of the fault are interlayered on a scale of tens of metres. The mylonitic foliations S_m (mylonitic layering) and S_c (shear bands) appear to be more strongly developed versions of S and C, although S_m can be a modified gneissic layering where gneiss has been incorporated into the mylonite. S_m has a similar orientation to S, and contains a shallow pitching stretching lineation, L_m (Fig. 4). All sense of shear indicators, including shear bands S_c, indicate dextral shear (Morand & Gray 1991). Mylonitized Doctors Flat granite has greenschist facies mineralogy and a strong mylonitic foliation which is typically defined by aligned chlorite and sericite, with finely recrystallized quartz, albite and epidote comprising the rest of the rock. Few remnants of the original igneous mineralogy are left intact.

Cataclasite is developed along parts of the fault zone, mainly in the outer parts. Here the Doctors Flat pluton is fractured into angular, centimetre-sized fragments embedded in a finely crushed, epidote-rich matrix (Fig. 5b). Alteration to albite, chlorite, epidote, sericite and sphene is common. Cataclasis appears to overprint the ductile mylonitic deformation in places, and is interpreted as forming during continuous fault movement as temperatures dropped into the brittle deformation field.

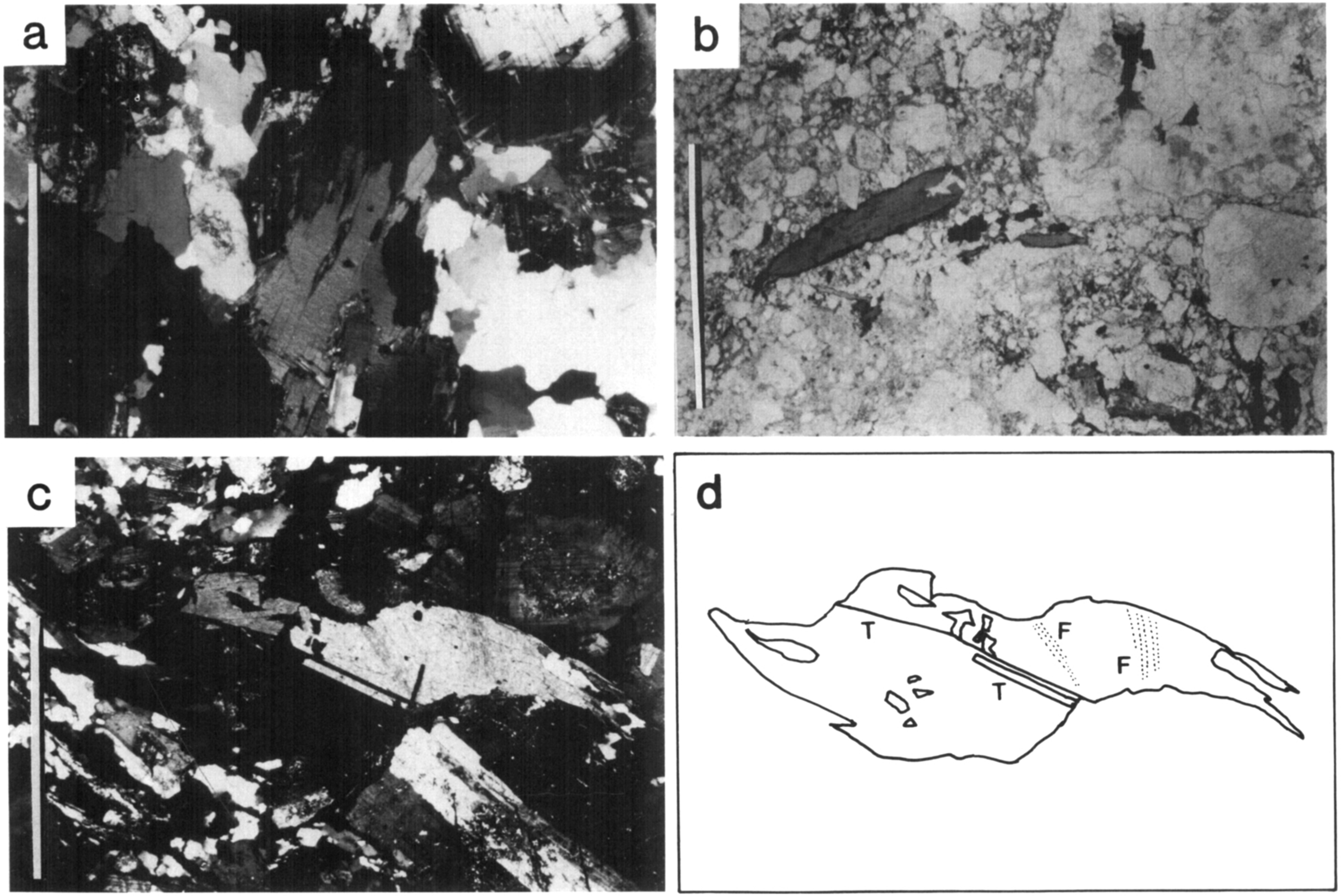

Fig. 5. (a) Thin section of weakly foliated Doctors Flat Pluton showing quartz with undulose extinction and recrystallized grain boundaries, kinked biotite (centre), and undeformed, strongly zoned plagioclase (top left). Crossed polars. Scale bar = 2 mm. (b) Thin section of cataclastic Doctors Flat Pluton from the Ensay fault zone. At upper right is a fragment of deformed granite, surrounded by a matrix of fractured feldspar and quartz grains and fine-grained epidote and chlorite. Above centre is an abraded grain of igneous biotite, rimmed by sphene. Scale bar = 2 mm. Plane polarized light. (c) Hornblende grain with tails drawn out in a dextral fashion parallel to *S*, which trends from bottom right to top left. The horneblende is twinned, with one twin in extinction. Crossed polars. Scale bar = 2 mm. (d) Line drawing of hornblende in (c), showing undeformed twin planes (T), and healed fractures marked by trails of fluid inclusions (F), suggesting relatively high-temperature deformation.

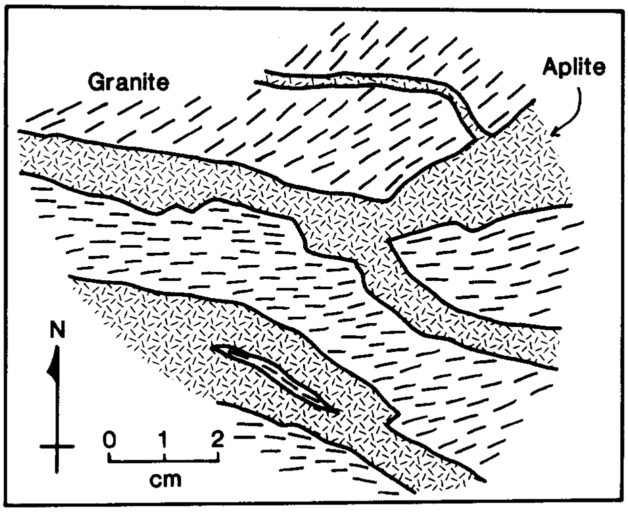

Fig. 6. Sketch of a horizontal outcrop showing dykes of non-foliated aplite cutting across the foliation in the granite, with foliation trends indicated.

TIMING OF EMPLACEMENT

Important points regarding timing of emplacement and foliation development are as follows.

(1) Contact metamorphism on the southwest side of the Doctors Flat Pluton overprints regional metamorphism of the cordierite zone which accompanied S_2 formation, and S_2 is partially obliterated by recrystallization. Biotite in the contact aureole is locally aligned to form a foliation which overprints S_2, but generally foliations associated with granite are restricted to the pluton or the Ensay fault zone, and are not equivalent to any regionally developed foliations.

(2) Some parts of the granite have *S–C* fabrics indicating dextral strike-slip, and these grade into mylonitic fabrics in the Ensay fault zone.

(3) The southwest boundary of the pluton mimics the shape of the northeast boundary against the fault, and is locally faulted (Joyce 1979), and the main body of the pluton closely follows the Ensay Fault, suggesting a possible genetic relationship between the fault and the pluton. If the Ensay Fault post-dated the Doctors Flat Pluton and simply cut it in two, one would expect to find the other part of the pluton on the northeast side of the fault, given that the fault has strike-slip displacement. However, none of the granitic rocks on the northeast side of the Ensay Fault can be matched with the Doctors Flat Pluton.

(4) Foliation in the pluton is subparallel to the Ensay fault zone but west of a jog in the Ensay Fault, near Ensay, it strikes at a low angle to both the fault and the pluton walls. Trends of foliation at the ends of the pluton are unknown because the eastern end is cut by a fault (Fig. 2) and the NW end is covered by alluvium of the Tambo River.

(5) The foliation is locally parallel to igneous layering and schlieren. The schlieren are steeply dipping and hence are likely to result from magmatic flow rather than gravity settling. Some late aplite dykes are massive and cut the foliation (Fig. 6).

(6) Foliation in the pluton generally shows features such as recrystallization of quartz and biotite, flexuring, kinking and fracturing of feldspar, and *S–C* fabrics, which are characteristic of solid-state deformation (Paterson *et al.* 1989). Some deformation is relatively high temperature, with undulose extinction and recrystallization of biotite and hornblende without alteration to lower grade minerals, and possible *c*-slip in quartz, but much of the foliation is defined by greenschist facies alteration products such as chlorite, epidote, sphene and sericite. Thus both relatively high- and low-temperature deformation are evident. Lower temperature microstructures appear to overprint the higher temperature fabrics in the pluton and the fault rocks.

Point (1) indicates that pluton emplacement post-dated regional metamorphism and S_2 formation in the adjacent metamorphics. Points (2) and (4) indicate that foliation development in the pluton was related to fault movement on the Ensay Fault. Point (3) suggests that pluton emplacement was associated with the Ensay Fault. Point (5) suggests that magmatic activity continued locally during and after foliation development. Point (6) indicates that foliation in the pluton and the fault zone continued to develop as the temperature fell. An interpretation consistent with these observations is that the Doctors Flat Pluton was emplaced during active faulting, after the main regional metamorphism and deformation that produced S_2 in the country rocks. The pluton locally raised temperatures in the fault zone, but fault movement continued as the pluton cooled, giving rise to low-temperature, brittle structures.

Few of the features cited by Paterson *et al.* (1989) as indicating magmatic flow are present in the pluton, with the exception of schlieren and local igneous layering. In places this may be a result of strong overprinting by the tectonic foliation after solidification, but the less deformed rocks in the centre of the pluton also show little evidence of deformation in the magmatic state. An emplacement mechanism to account for this is now proposed.

DISCUSSION OF EMPLACEMENT MECHANISM

Several features of this pluton, such as its elongate shape adjacent to a strike-slip fault, steep boundaries, mylonitic margins and higher temperature structures overprinted by lower temperature structures, are similar to the Mortagne Pluton in France, interpreted as having been emplaced into a pull-apart in a strike-slip fault (Guineberteau *et al.* 1987). A similar emplacement mechanism is envisaged for the Doctors Flat Pluton. Figure 7 shows a possible sequence of events during emplacement.

A jog on the Ensay Fault initiated a pull-apart into which granitic magma moved, possibly being drawn into the resultant dilatant zone, as proposed for the Main Donegal granite by Hutton (1982). The strike of the foliation in the pluton west of Ensay, where the initial jog is proposed to have been, is parallel to the direction of extension in the pull-apart. Bedding and cleavage in low- to medium-grade rocks southwest of the pluton were rotated toward the fault in a dextral sense, but in the more rigid high-grade rocks on the northeast of the fault there was little effect of faulting beyond the mylonite zone.

Granitic magma appears to have intruded along the fault zone beyond the initial pull-apart. The earliest magmatic products accumulated the most strain, both in the magmatic and subsolidus states. During this episode the northeast edge of the pull-apart began to take up most of the displacement, so that before emplacement was complete all movement was taking place on this edge of the pluton. Continued intrusion after this stage resulted in emplacement of granite with few deformation or flow features in the centre of the pluton, and late massive aplite dykes. Fault movement continued after solidification of the pluton, with low-grade mylonite and cataclasite forming in the Ensay fault zone along the boundary of the intrusion as it cooled. East of Ensay the fault strike changes to a more easterly orientation, and this may be a result of flexuring, either during the latest stages of fault movement, or perhaps post-dating fault activity.

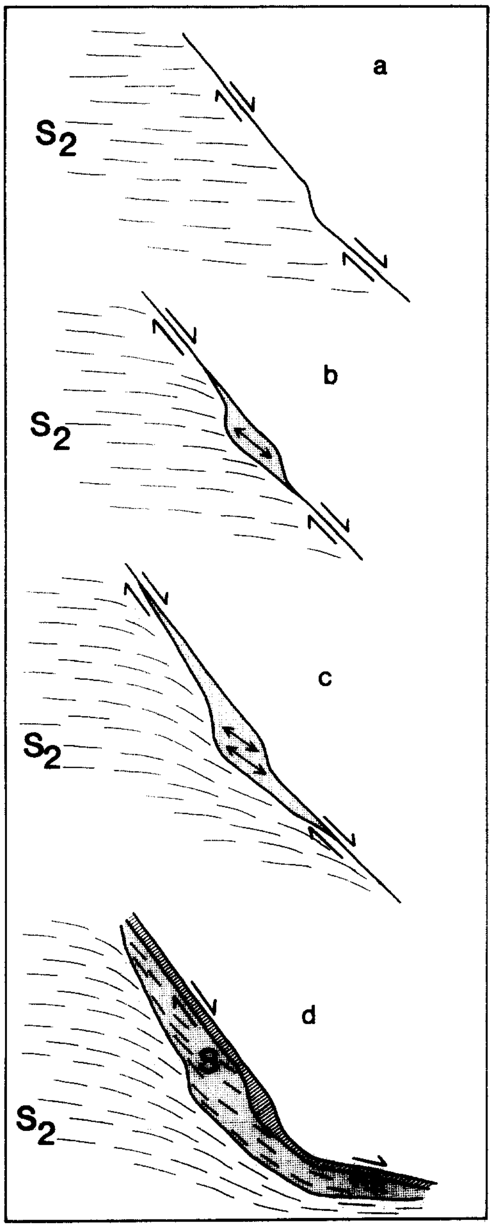

Fig. 7. A possible emplacement mechanism for the Doctors Flat Pluton. (a) A jog is formed on the Ensay Fault, which is undergoing dextral strike-slip. (b) A pull-apart develops on the jog, and begins to fill with granitic magma. The E-trending S_2 foliation on the southwest side of the fault starts to undergo drag into the fault zone. (c) Magma intrudes along the fault zone and a foliation develops parallel to the stretching plane. S_2 undergoes further drag into a southeast trend. (d) All movement is taken up on the northeast side of the pluton, and further intrusion occurs under more static conditions. Fault movement continues as the pluton cools, forming mylonite and cataclasite. The southeast end of the pluton is flexed into an easterly trend, possibly during a deformation post-dating movement on the Ensay Fault.

No compositional zoning has been noted in the Doctors Flat Pluton, apart from the observation that hornblende is rare in the western half of the intrusion, and it appears to have been intruded as one pulse of magma. The Ensay Fault may have cut down into the source region of the I-type magma, which must have underlain the Ordovician metasedimentary pile. Alternatively the rising magma intercepted the fault zone on its ascent.

I-type plutons in the Lachlan Fold Belt do not normally have well developed foliations, even though adjacent S-type granites of the same age are foliated, a cataclastic deformation being more common in I-types (Vernon & Flood 1988). The Doctors Flat Pluton is an exception to this rule because of its emplacement into an active fault zone.

During the Late Silurian to Early Devonian interval many I-type plutons were emplaced into the Omeo Metamorphic Complex and adjacent rocks (Morand 1990), and several of these plutons lie adjacent to NW-striking faults (Fig. 1). Faults of this orientation were active with dextral displacement in the Late Silurian to Early Devonian (Morand & Gray 1991), and it is likely that some of these plutons have a similar emplacement style to the Doctors Flat Pluton.

Elsewhere in the Lachlan Fold Belt, although many granite bodies occur adjacent to major faults (White *et al.* 1976, Vernon *et al.* 1983, Burg & Wilson 1988, Paterson *et al.* 1990), emplacement of plutons within strike-slip fault zones has not been previously documented. Other candidates for this type of emplacement may be found amongst smaller, elongate plutons lying adjacent to fault zones.

CONCLUSIONS

The Late Silurian to Early Devonian Doctors Flat Pluton intrudes rocks of the Omeo Metamorphic Complex but post-dates the main regional metamorphism. It lies along the Ensay Fault, a dextral strike-slip fault, and contains a tectonic foliation which strikes approximately parallel to the fault zone. In places an *S–C* fabric indicates dextral shear in the pluton, and this fabric grades in to mylonitic fabrics in the Ensay fault zone.

Foliations were formed during emplacement and cooling of the granite, with some high-temperature deformation recognized, but most microstructures are typical of subsolidus deformation. The pluton is envisaged as having filled a pull-apart on the Ensay Fault, the foliation forming parallel to the direction of extension. Before emplacement was complete, all fault movement was taken up on the northeast side of the pluton and weakly deformed granite was intruded into its centre. Fault movement continued under falling temperatures after solidification of the pluton.

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