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Early cleavage development in the Late Ordovician of northeast Victoria, Australia

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Abstract—A pervasive cleavage, S^*, that subparallels bedding in the Upper Ordovician rocks of northeast Victoria can be related to an incremental strain distribution, in a shear environment, during the establishment of the first set of regional tectonic folds and faults. The cleavage is a strong, preferred orientation of phyllosilicates which overprints sedimentary features, is contemporaneous with early-formed extension fractures and postdates the formation of clastic dykes. The cleavage is attributed to tectonic and metamorphic processes rather than a static mimetic recrystallization of clay minerals during burial metamorphism. There is little evidence to suggest that this is an early deformation originating during imbricate stacking of an Ordovician accretionary prism.

INTRODUCTION

IT HAS been proposed that portions of the Late Ordovician sequence of southeastern Australia, belonging to the Lachlan Fold Belt (Cas 1983), are associated with a forearc basin (Crook 1980) and that deposition was within an accretionary-prism environment (Jenkins *et al.* 1982, Powell 1983a & b). Within these sediments there is evidence to suggest the existence of an early fabric. This fabric, which is folded by the first period of upright mesoscopic folds, was first described by Williams (1970, 1971, 1972a) who attributed it to an inherited sedimentary feature paralleling the primary compositional layering (S_0). Williams termed this bedding-parallel foliation S_1 and S_2 depending on whether it was associated with the first local tectonic folds, B_1, or the later folds, B_2. On the other hand, Powell (1983a) suggested that, in some places, the early fabric cross-cuts bedding at a small angle, and thus formed as a tectonic cleavage. In the Mallacoota Beds of northeast Victoria (Fig. 1) the early bedding-parallel fabric is well developed, and is particularly associated with highly deformed zones. Powell (1983a) attributed such a cleavage, which he defined as $S_{1/2}$ (pronounced S a half), to layer-parallel flattening, possibly produced during imbrication in an accretionary prism. To avoid nomenclature confusion we have followed Powell & Rickard (1985) and use the symbol S^* in referring to this earlier cleavage.

The observations described here are common to most of the Late Ordovician sequence (de Hedouville & Wilson 1983) between Mallacoota and Orbost (Fig. 1). The sequence is composed of turbidites with minor cherts and preserves many primary sedimentary features, as described by Fenton *et al.* (1982) and Fry & Wilson (1982), which indicate a shallow-water depositional environment (Fenton & Wilson in press). Two, and in some places three, obvious upright folding events (Wilson *et al.* 1982) are recognized on the basis of overprinting relationships as well as a set of late kinks. The primary aim of this paper is to describe observations supporting the existence of an earlier cleavage (S^*) which we attribute to a deformation in a shearing environment rather than to an inherited sedimentary feature.

S^* AND ITS RELATIONSHIP TO BEDDING

The bedding considered to represent surfaces of presumably near-horizontal deposition is referred to as bedding *sensu stricto*, S_0 (*ss*), whereas primary depositional features that were not initially horizontal (e.g. slumps, flame structures, cross bedding, etc.) are called bedding *sensu lato*, S_0 (*sl*).

A pervasive preferred orientation of layer silicates, as described by Williams (1972a, pp. 12–16) occurs in all shale and most silty lithologies of the northeast Victorian Upper Ordovician succession (Fig. 2). The main fabric element (S^*) is a series of subparallel fine planes spaced 0.01–0.03 mm apart. The planes are defined largely by an alignment of finely crystallized layered silicates, with scattered larger detrital muscovite or biotite grains, and by a concentration of opaque minerals. X-ray analysis (de Hedouville 1984) shows that the majority of the fine-layered silicates are illite, chlorites (with ratios in the shales of 7 : 3) or interlayered illites and chlorites. On F_1 fold limbs, S^* appears to be a typical 'slaty cleavage' (Wood 1974) defined by a layer-silicate preferred dimensional orientation of (001) without any noticeable com-

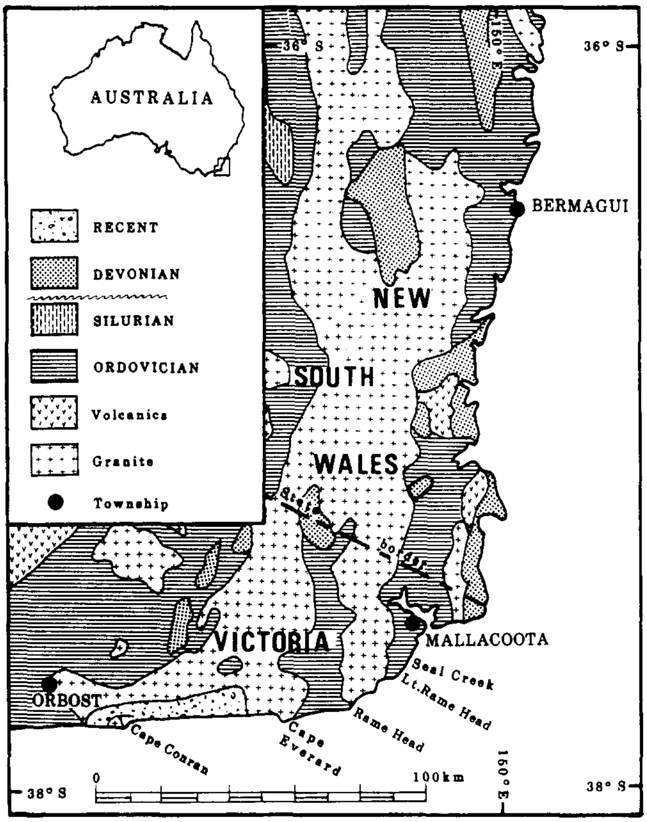


Fig. 1. Locality map.

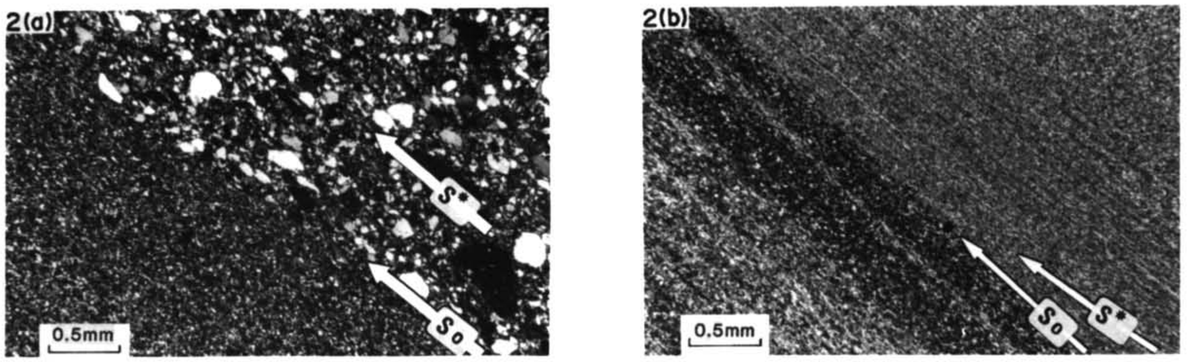
positional layering. The definition of individual mica boundaries is extremely poor at Mallacoota (Fig. 2a) but micas are better defined with distinct shapes and larger grain size in areas deeper in the tectonostratigraphic succession, and of slightly higher regional metamorphic grades, such as at Cape Everard (Fig. 2b). The layer silicates are generally parallel to bedding (Fig. 2a): however, there are some departures of 5–10° (Fig. 2b). In the sandy units, S^* occurs as a preferred orientation of scattered detrital micas and elongate quartz grains and appears to display a weak mica-film fabric (e.g. Means 1975). Mica beards (Williams 1972b) are also recognized where the quartz is recrystallized in the very quartz-rich sandstones.

S^* AND ITS RELATIONSHIP TO FOLDS

In the hinges of the first regionally developed meso- and macroscopic folds, the S^* surface is folded. This folding (F_1) produced a spaced crenulation cleavage (S_1) which may be partly differentiated (Fig. 3a). However, close examination of many fold hinges (Fig. 3) shows the single phase of folding is associated with two inclined cleavages (S_{1a} and S_{1b}). On a mesoscopic scale, cleavage/bedding intersections do not always parallel the F_1 fold axis and many of the tight folds have the characteristics of transected folds (Gray 1981) where the cleavage is discordant to the axial surface. Figure 3(d) illustrates that S_1 development is more complex on compositional boundaries in the hinge than revealed on the limbs (Figs. 3a, c & f) or the middle of a bed. At the compositional boundary illustrated in Fig. 3(d), S_0 parallels S^*. In shale layers away from the compositional boundaries (Figs. 3a & c), S^* is cross-cut by either S_{1a} or S_{1b}. These converge and become indistinguishable further from the compositional boundary where they subparallel the axial surface. However, in the centre of fold hinges (Fig. 3e) and close to an S_0 (*ss*) boundary it is possible to confuse the S_1 cleavage (in Figs. 3a & e) with the S^* cleavage, the distinction being that the S^* micas are folded with S_1 making an acute angle with the bedding, S_0, whereas in the adjacent sandstone S^* is definitely parallel to S_0. The ability to trace S^* around the F_1 folds and the constant vergence between S^* and S_0 in the shales suggest that S^* has to be earlier than the main fold development.

S^* AND ITS RELATIONSHIP TO CROSS-BEDDING, SLUMP FOLDS AND CLASTIC DYKES

Because the mica preferred orientation, S^*, is generally oriented parallel to S_0 (*ss*), it invariably truncates the cross-bedding, S_0 (*sl*) (Fig. 4a). The Mallacoota Beds contain numerous penecontemporaneous deformation features (Fenton *et al.* 1982). In all slump folds (e.g. Fig. 4b), the contorted bedding S_0 (*sl*) is overprinted by a dimensional preferred orientation of layer silicates (S^*) which subparallels bedding S_0 (*ss*) in the undisturbed layers. These relationships indicate that S^* is a post-sedimentary fabric.



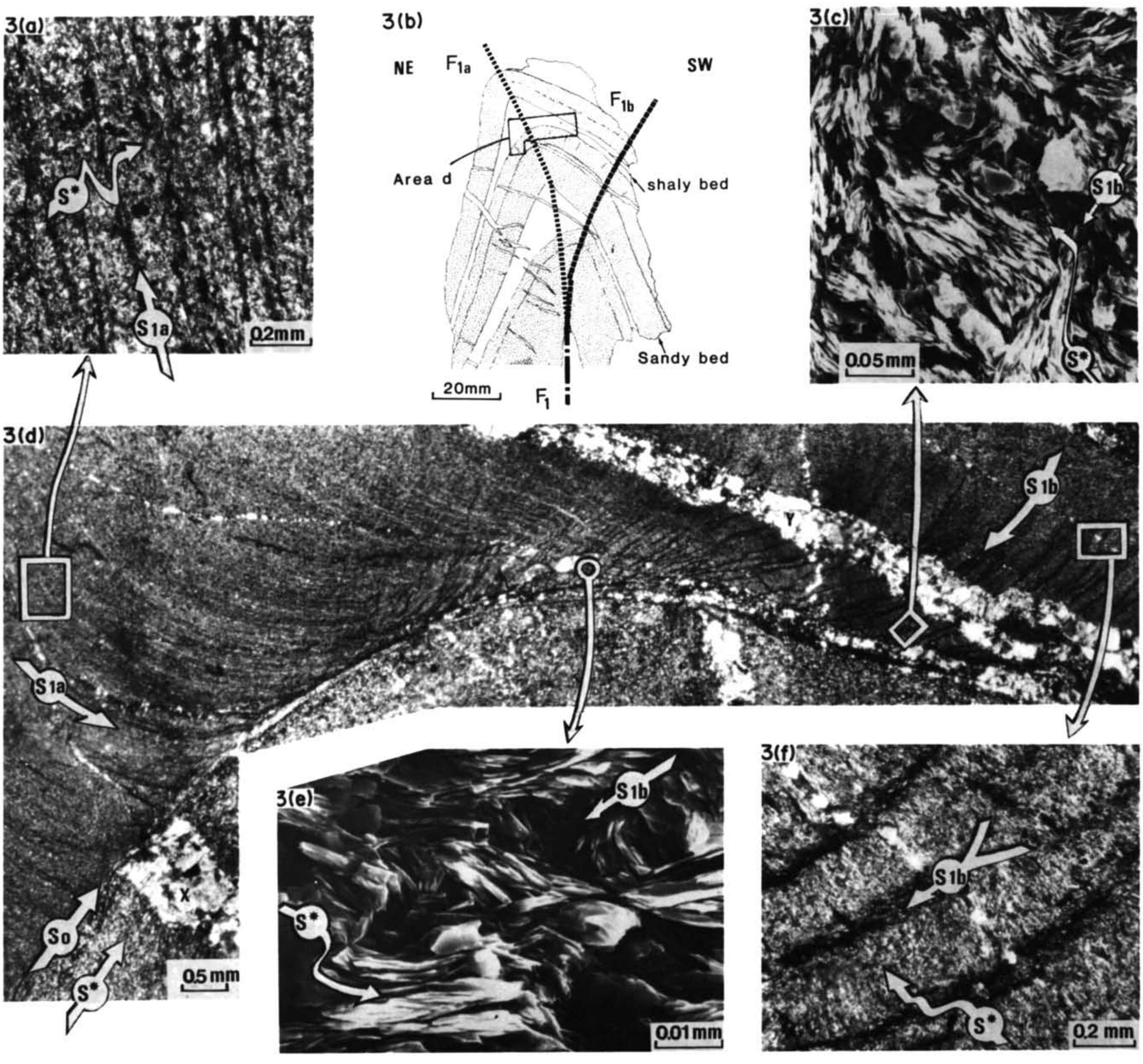
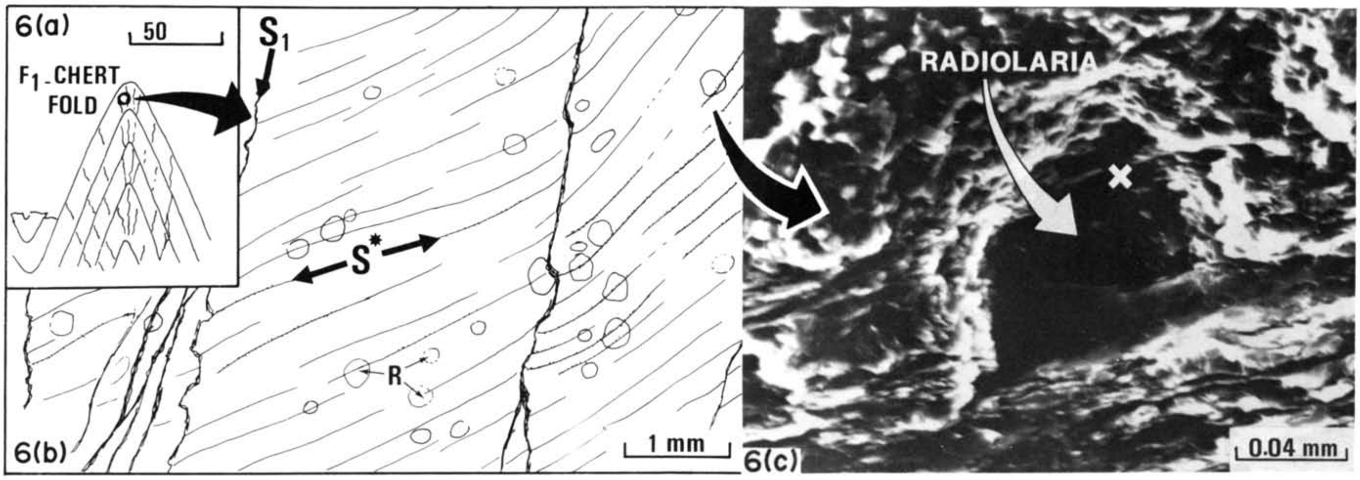


Fig. 2. Photomicrographs illustrating the earliest cleavage, S^*, in siltstone vs shale (a) at Mallacoota and (b) at Cape Everard. S^* is parallel to S_0 (*ss*) in (a) and S^* discordant to S_0 (*ss*) in (b).

Fig. 3. Cleavage structures overprinting S^* and associated with the first regionally important period of folding (F_1). Specimen from S-plunging fold at Seal Creek GR 363277, Mallacoota. (a) S^* is crenulated by a spaced cleavage, S_{1a} with concentration of opaques and zircon along the cleavage zone. (b) the S_1 cleavage is not everywhere parallel to the axial surface but may bifurcate in different parts of the fold and has been labelled S^* and S_1 from local overprinting relationships. (c) A scanning electron microscope (SEM) photograph showing detail of an area in which S_1 overprints the earlier cleavage S^* with the development of mica-rich concentrations along the S_1 cleavage. (d) The hinge area observed in the fold in (b) showing the relationship between S_0, S^* and S_1. On the S_0 compositional planes there is a folded quartz vein, the plane of which contains quartz striae. Two quartz veins, X and Y, are extension veins infilled with fibrous quartz contemporaneous with S^* development (e.g. X) and are folded by S_1. (e) SEM photograph of S^* folded by S_1. (f) Detail of an area dominated by a bifurcating S_1 cleavage superimposed on S^*.



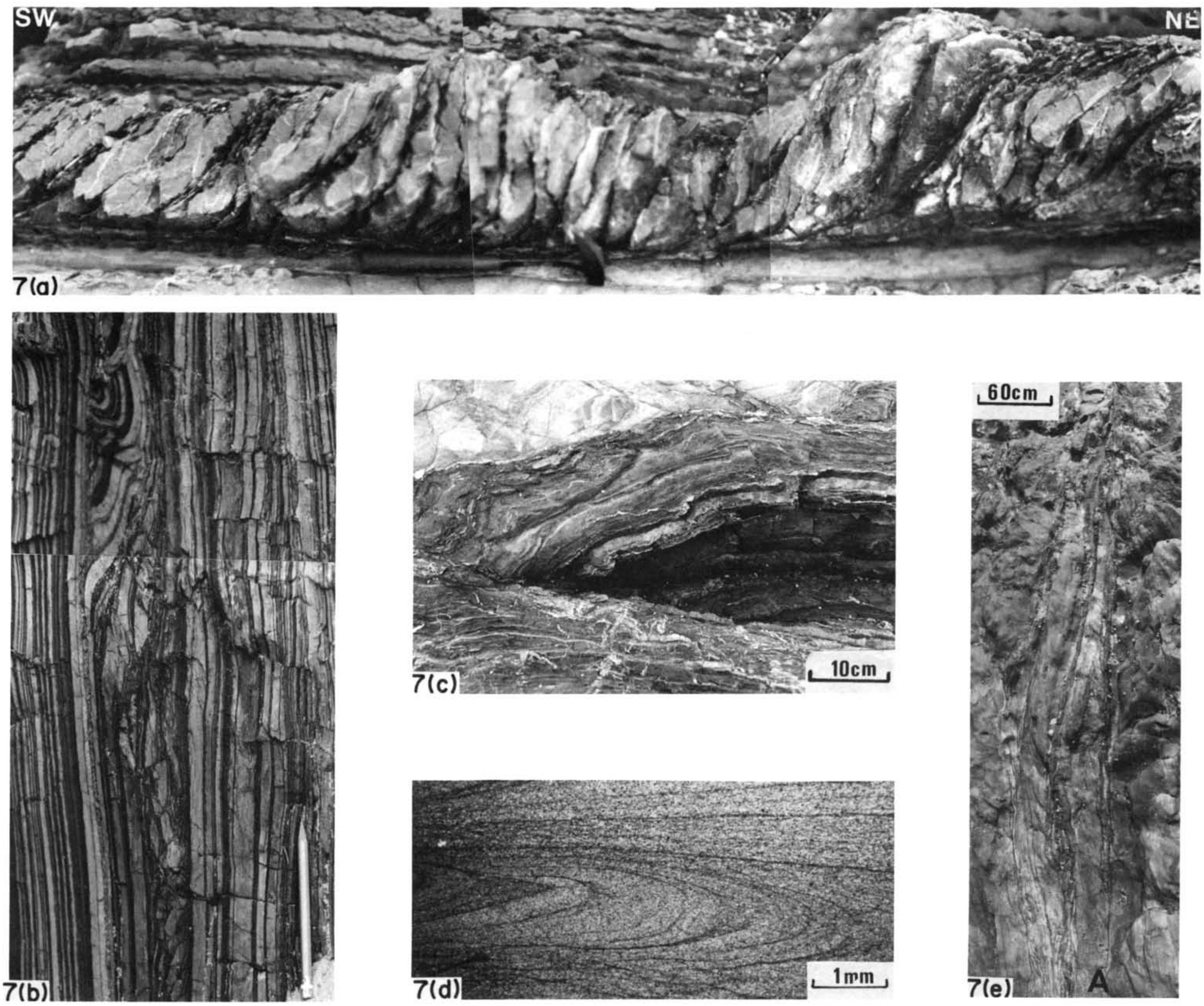


Fig. 6. (a) Folded chert from Seal Creek (GR 371283) showing (b) the relationship between the cleavage S^* and the radiolarians (R) which are overprinted by the cleavage, S_1. (c) SEM photograph illustrating the truncation of the radiolarian by layer silicates at X (specimen R23664).

Fig. 7. Fault-related features observed north of Little Rame Head. (a) Duplex structure in a layer of chert bounded by two fault surfaces within sandstones at GR 358254. The sense of displacement associated with the duplex is to the northeast. (b) Disrupted beds on the W limb of an F_1 fold in interbedded sandstone and shales, GR 363277. (c) Intrafolial fold with bedding disrupted along a décollement surface adjacent to the graptolite locality described by de Hedouville & Wilson (1983), GR 365278. (d) Micrograph of intrafolial fold containing a weak S^* cleavage, GR 365278. (e) A décollement surface (A) along a thin layer of chert at GR 394318. Note the lenticular nature of the bedding.

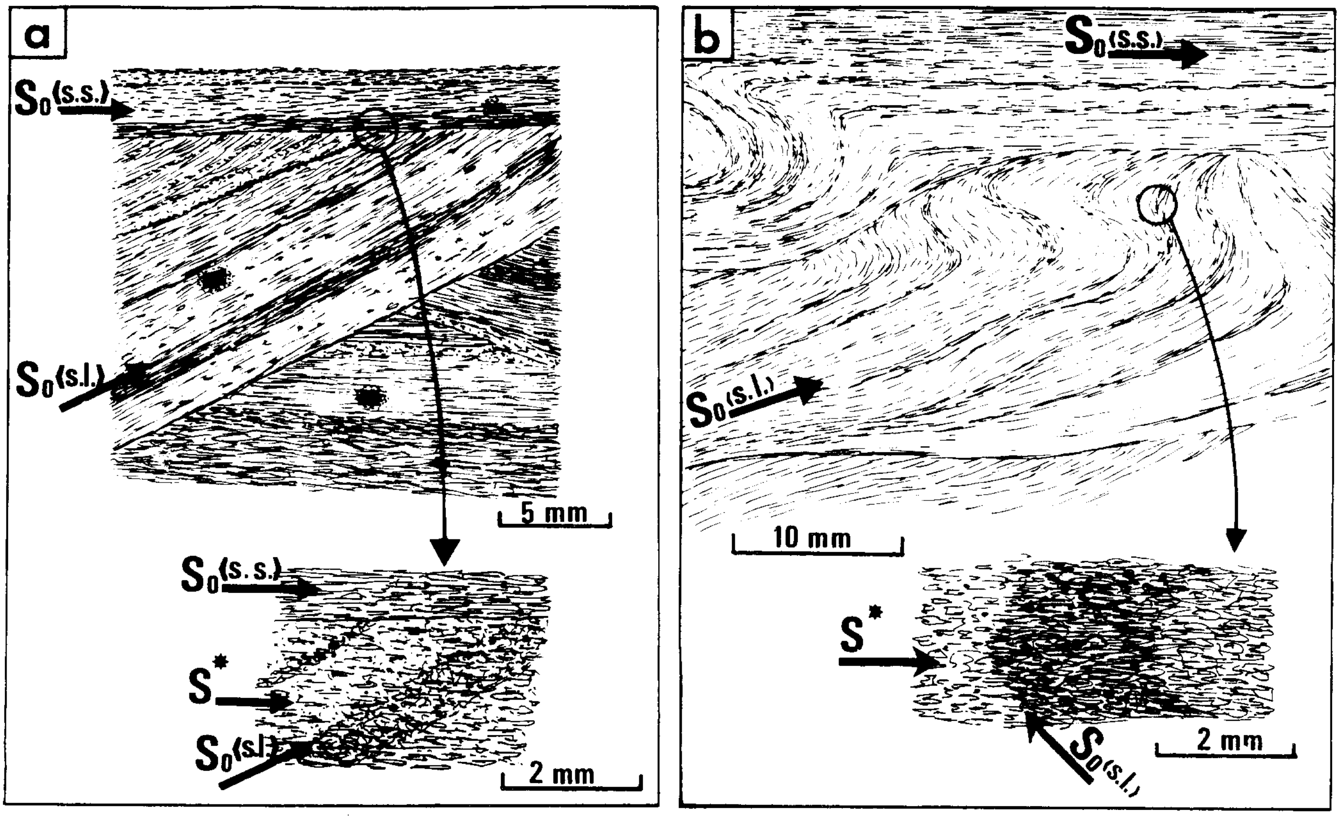


Fig. 4. Sketches from thin-sections illustrating (a) the relationship of S^* to cross-bedding, specimen R23624, and (b) bedding in a slump fold, specimen R23663. Arrows show orientation of bedding [$S_0(ss)$] and primary depositional features [$S_0(sl)$]. The enlarged areas show the dark folia enriched in opaques, illite and chlorite that cross-cut bedding, $S_0(sl)$.

Clastic dykes are uncommon in the Mallacoota Beds and they occur as nearly planar cross-cutting sheets (up to 10 cm wide) or as folded bodies (Fig. 5). The dykes are composed of quartzose sandstones which are cross-cut by a well-defined S^* surface in the adjoining shale beds (Fig. 5): the S^* surface being continuous with the axial surface to the folds in the dykes. Detrital micas and the matrix illite and chlorite (ratio 4:6) in the dykes are poorly aligned. These dykes appear to predate the formation of the S^* cleavage and may represent infillings of tensile fractures probably formed under conditions of abnormally high fluid pressure.

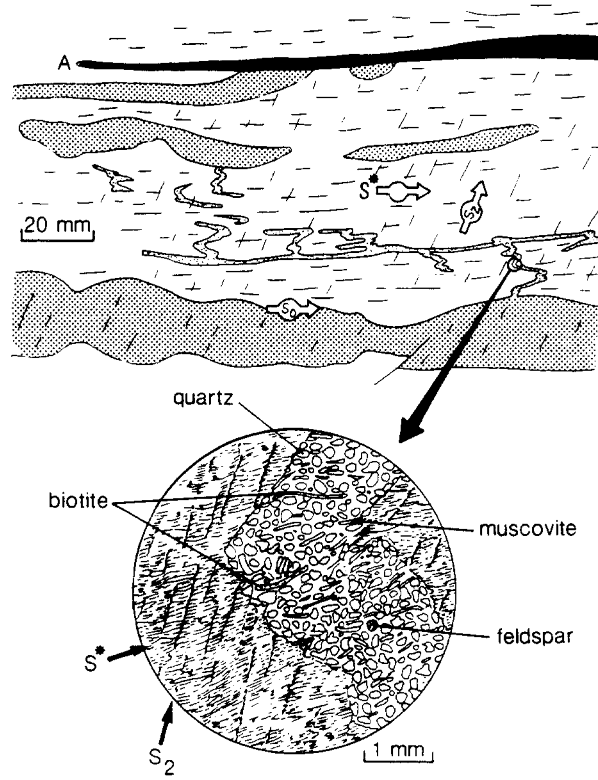


Fig. 5. Clastic sandstone dykes in shale south of Seal Creek near Mallacoota (GR 362270) in a section that is oblique to bedding, S_0, and on the limb of a major F_1 fold structure transected by a later S_1 crenulation cleavage. The dykes are intruded both upward and downward from disrupted beds of sandstone. A–A is a décollement surface within a discontinuous black-shale and chert horizon. The enlargement shows the typical microstructure observed in the host shale and intruding clastic dyke in specimen R23627 (University of Melbourne collection).

S^* IN THE CHERTS

Figure 6(a) illustrates a hinge of an F_1 fold in chert that contains an S^* cleavage subparallel to bedding. The S^* is a dark mica-rich discontinuity that truncates and overprints recrystallized radiolarians (Fig. 6b). The significance of this observation is that S^* is not flattened around the radiolarians, but cuts through them suggesting that a tectonic rather than a sedimentary compactional stress regime existed at the time of S^* formation.

S^* AND ITS RELATIONSHIP TO FAULTS

The limbs of many upright mesoscopic folds (F_1) contain faults, duplexes (Fig. 7a), local duplications of stratigraphic sequences (e.g. as described at Bastion

Point by Wilson *et al.* 1982, fig. 7) and smaller intrafolial folds associated in places with bedding disruption (Fig. 7b). The intrafolial folds occur as isolated hinges or are associated with a detachment surface (Fig. 7c) but everywhere contain a slaty cleavage (Fig. 7d) as the axial surface structure. These tectonic features are particularly noticeable in the incompetent lithologies such as cherts and in the shaly portions of the sequence. Bedding in such areas is commonly lenticular and bounded by a marked décollement surface (Figs. 7d & e). Such décollement surfaces contain evidence of extensive fluid migration, in that they are commonly coated with a veneer of fibrous quartz with metamorphic mica intergrowths. These features are all characteristic of a thrusting environment (Boyer & Elliott 1982) and suggest there may have been significant shearing subparallel to some bedded units.

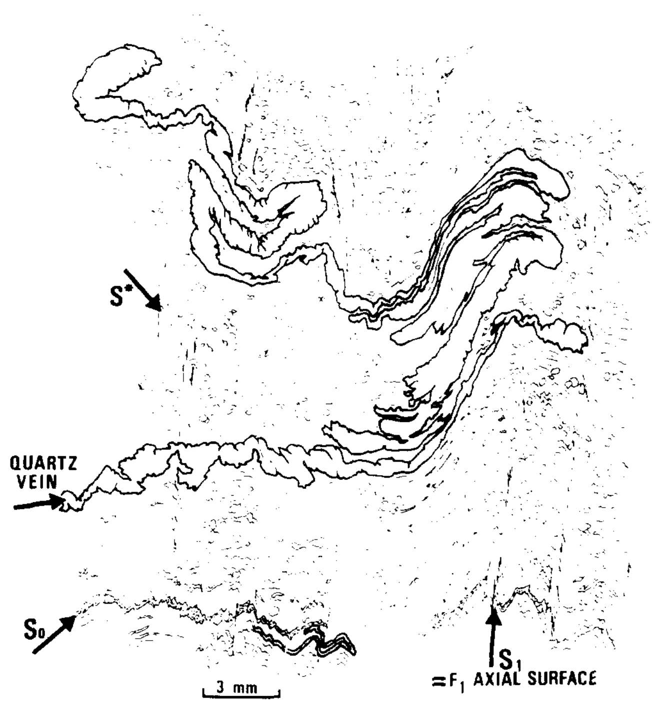


Fig. 8. Early folds in quartz veins with S^* as an axial surface, Cape Conran. The bedded sequence contains a well-developed cleavage that parallels S_0 (*ss*). The bedded sequence is folded by one parallel set of upright folds (F_1) in which the axial-surface structure is everywhere a strongly differentiated crenulation cleavage, S_1. Within a few siltstone beds, but not in the adjacent shale units, there are thin, open to tightly folded quartz veins (1–3 mm thick).

DEFORMED EARLY QUARTZ VEINS

Quartz veins both pre- and postdate the formation of the S^* cleavage. Bedding-parallel veins are commonly recrystallized (Fig. 3d) but retain strong evidence for fibrous growth as described by Boulter (1979). These quartz veins are of undoubted early origin with fibrous quartz attributed to movement along bedding contacts (Wilson *et al.* 1982). Extensional quartz veins (vein X, Fig. 3d) are generally well developed in the sandy units with fibrous growth parallel to S^* but are folded by S_1 (vein Y, Fig. 3d). In extreme cases, the quartz veins may be isoclinally folded with an axial surface that corresponds to S^* (Fig. 8). These early mesoscopic folds have variable plunges that are oblique to F_1 and the marked elongation of individual quartz grains lying within the S_1 axial surface. There are generally no folds in bedding that can be correlated with the early quartz-vein folding. These quartz veins are oblique to bedding and appear to be early infilled fractures developed only in the sandy units and hence represent an early stage of extensional jointing prior to, or during, the formation of S^* cleavage. The curvature of some quartz-vein hinges suggests that they have characteristics of incipient sheath folds (e.g. Minnigh 1979, fig. 11) and hence imply a component of shear strain subparallel to bedding.

DISCUSSION

Origin of S*

The evidence suggesting that tectonic processes, rather than sedimentary compaction, contributed to the development of the S^* fabric is: (1) the phyllosilicate preferred orientation cross-cutting the cross-beds and slump folds (Fig. 4) and clastic dykes (Fig. 5), (2) the radiolarians truncated by S^* (Fig. 6), (3) the presence of early faults (Fig. 7) and (4) the folded quartz veins (Fig. 8). We therefore interpret the strong (001) mica-preferred orientation as a cleavage developed during tectonic processes.

The presence of metamorphic chlorite and the crystallization of distinct illites (Figs. 3c & e) testifies to the significant role of metamorphic processes in the formation of S^*. Such reactions may in part account for the strong development of the layer-silicate preferred orientation. The occurrence of early quartz veins and mica beards also suggests that solution transfer may have occurred during mineral transformations as summarized by Beach (1979).

The above interpretation contrasts with that of Williams (1972a) who argued that the general subparallelism of S^* to S_0 (*ss*) implied a compaction feature. Maltman (1981) has described similar bedding-parallel fabrics in experimental samples and natural rocks and suggests that a phyllosilicate rearrangement by compaction must be produced in the first few metres of burial and advocates some degree of phyllosilicate alignment parallel to bedding. Maltman (1981) argued that a thick sequence of sediments cannot increase the layer-silicate preferred orientation fabric without the intervention of metamorphic or tectonic processes. In the Mallacoota Beds, even if compaction had been the sole factor, the bedding-parallel fabric is stronger (Fig. 2) than those undeformed and unmetamorphosed sediments described by Maltman (1981).

On a regional scale (Fig. 1) there are zones, many of which are disrupted by later granite emplacement and dextral faulting, in which there is a distinct development of a strong vs poor S_1 differentiated layering. These zones correspond, in part, to the inland 'slaty' vs coastal 'stripy' cleavage domains described by Powell (1983a).

The significance of the domains to Powell (1983a) was that the zones of strong S_1 development represent domains where the degree of inherited fabric at the time of the first extensive crustal shortening and development of the major upright structures (F_1) was strongest. Powell (1983a) attributed the strong inherited fabric to imbrication in an accretionary prism. However, as they represent zones of higher strain, internal structural complexities, and commonly higher metamorphic grade within the sedimentary sequence, we believe they are more likely to reflect zones of high shear strain superimposed on a sedimentary sequence well after the period of deposition. The degree of fabric development is significant and there is a lack of stratal disruption or scaly foliation described by Moore *et al.* (1982) from the shallower parts of a modern accretionary prism.

The recognition of early quartz veins is an important consideration constraining the timing and mechanism of S^* cleavage formation. It is apparent that metamorphic processes and a distinct shearing strain contributed to the formation of the S^* cleavage. The folded quartz veins in the coarser-grained rocks indicate a dilatation and extension accompanied the deformation.

Timing and conditions for S^* *formation*

The preferred alignment of early phyllosilicates appears to be regionally extensive (Powell & Rickard 1985) in the Upper Ordovician rocks of southeastern Australia, and not a feature of the overlying Silurian sequences (Bolger 1982). It has also been established that the regional upright folding event during which F_1 formed in the Upper Ordovician sequences (Bolger 1982, Powell 1983a,b) has also affected the Middle and Upper Silurian sequences, which do not possess the early preferred orientation of phyllosilicates. F_1 is attributed to the Bowning (Early Devonian) deformation events (Powell 1983a). Hence S^* may be contemporaneous with the Bowning or the Tabberabberan (Middle Devonian) deformation events.

An early history equivalent to the Benambran deformation (Ordovician–Silurian boundary) would be favoured if imbrication in the sequence was occurring in an accretionary prism, as favoured by Powell (1983a,b). However, this appears unlikely as there is a close genetic relationship with the early imbrication and the evolution of the F_1 upright folds. The F_1 structures have many of the characteristics of a typical foreland fold-and-thrust belt. There is a predominance of early non-planar thrusts or décollement zones on the W-dipping limbs of F_1 folds, there is a consistent NE vergence and sense of transport inferred from the slickenside striae and extension fibres. We believe that F_1 fold initiation commenced during a prebuckling phase of shearing and thrust-faulting (Fig. 9) with a corresponding development of an S^* cleavage. High overpressures associated with the early thrusting have been described in similar foreland thrust belts (Winslow 1983), and cause extensional fracturing as observed in the folded quartz veins and the injection of clastic dykes. The deformation producing the S^* and S_1

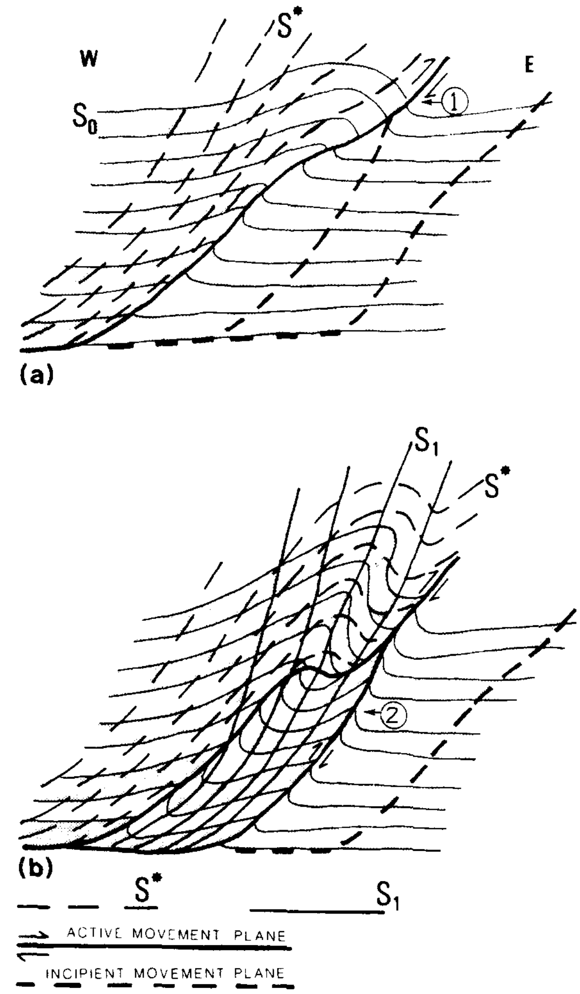


Fig. 9. Stages in the development of S^* and S_1 cleavage. Movement on Fault 1 would occur prior to the initiation of Fault 2, which is lower in the stratigraphic sequence. For details see the text.

cleavages within the sedimentary sequence must be co-eval and related to a possible thrusting event, as has also been suggested by Powell & Rickard (1985). We see the S^* and S_1 cleavages representing increments of deformation related to the development of the F_1 folds and to thrust-faults, as portrayed in Fig. 9 and comparable to the model proposed by Mitra & Elliott (1980). The S^* cleavage and fault initiation would accompany a shearing event with deformation being concentrated in zones, hence the intensity of S^* cleavage development would reflect the variation in finite-strain distribution across the zone. The axial planes of the initial buckles in S_0 and the orientation of S^* would be subparallel to the thrust-faults (Fig. 9a). When movement occurred on later faults there may have been either displacement on the earlier thrust or folding of the earlier fault and its cleavage S^* (Fig. 9b). The thrust-faults must have been initiated lower in the sequence (Boyer & Elliott 1982)—the evidence for such imbrication being the presence of duplexes (Fig. 7). A cleavage, S_1, will also have been initiated with the lower fault and become axial planar to folds that fold the earlier cleavage S^* (Fig. 9b). Hence, we expect that there must be a congruous vergence relationship between S^* and F_1 folds. Where followed downwards, the two cleavages, S^* and S_1, are not recognizably different, and this explains the apparent paradox as to why there are no folds associated with S^*. The model in Fig. 9 for S^* cleavage development also explains the presence of transected folds, together with the abundance and intimate relationship between folding and faulting described in the Late Ordovician of southeastern Australia by Powell & Rickard (1985), Williams (1971) and Wilson *et al.* (1982).

CONCLUSIONS

An early fabric element in the Upper Ordovician sequence of northeastern Victoria is a tectonic cleavage, S^*. This cleavage has previously been thought of as a bedding-parallel feature (Wilson *et al.* 1982). It is equivalent to the bedding-parallel fabric of Williams (1972a), the $S_{1/2}$ cleavage of Powell (1983a) and the S^* of Powell & Rickard (1985). Our observations suggest that this cleavage is associated with folding and a shearing. We suggest that the S^* and the later S_1 cleavages can be attributed to an incremental deformation involving shearing and the development of faults and the F_1 folds. During this coeval deformation the sediments were undergoing low-grade mineral reactions and these are an integral part of the deformation process. Within the sequence, there is a notable absence of evidence indicating that there was imbricate stacking in an accretionary prism, as proposed in the model of Powell (1983a,b). Instead, we believe the deformation and metamorphism (S^*, S_1 and F_1) is post-Silurian in age and must represent a single event that locally may migrate in time and from place to place.

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