AGSO Journal of Australian Geology & Geophysics, 15 (3), 257–295

A field classification and intensity scale for first-generation cleavages

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The chief morphological characteristics and lithological associations of naturally occurring cleavage fabrics are reviewed with the aim of differentiating qualities that represent fabric type from those that represent fabric intensity, and incidental partings from the cleavage fabric itself. This leads to field-based descriptive classifications for types and intensity of rock cleavage which unify diverse previous observations and allow a more formal approach to the description of cleavage. Particular attention is given to first-generation cleavage and incipient cleavage in clastic rocks of low to very low metamorphic grade, although all cleavage types are considered.

Two main divisions of cleavage type are recognised: (a) *penetrative* and (b) *non-penetrative*, according to the spacing of cleavage domains (where present) with respect to the width of dominant clastic (or detrital) grains. Each division includes three types, each of which is closely related to the lithology and texture of the parent rock (*type 1, clay* and *slaty* penetrative types; *spaced, crenulation* and *scaly* non-penetrative types). Each of the six cleavage types may display one (or less commonly both) of two kinds of intensity modulation at the mesoscale: *shear zones* and *'stripes'*.

Fissility, defined as the small-scale crack-structure which develops along planes of bedding- and cleavage-fabric anisotropy in weathered mudrocks, is proposed as an index property reflecting the relative intensity of cleavage, bedding and intersection fabrics in these lithologies. Fissility-ratios can be quantified in the field by measurements of dimensional ratios of fissility-fragments. The ratios are given named class intervals and are quantitatively discussed with the aid of a logarithmic 3-axis diagram. A reference field-example illustrates a full progression of relative cleavage-fissility intensity from none, through incipient, to strong, in relation to a natural strain gradient. The influences of rock type, initial bedding anisotropy, strain and style of tectonic deformation on fissility-ratios are also discussed. Fissility-ratios provide a rapid means of evaluating the effects of regional variations of total fabric and deformation intensity in a given rock type in low- to very low-grade metamorphic environments; they also represent a new tool that may assist in the study of weak deformations, incipient cleavage, sensitivity of different rock types to cleavage development, deformational or tectonic regimes (as reflected by fissility-fragment shape fields) and fabrics in undeformed mudrocks.

Introduction

Different terms have been used to describe rock cleavages. Various descriptions place emphasis on different factors, such as scale of observation or genesis, which make comparisons difficult. Qualifiers like "weak" and "strong", "continuous" and "spaced" have different meanings to different workers, and are mostly not uniquely defined. A more formal approach to nomenclature would, therefore, assist documentation of cleavage phenomena and investigation of their significance in relation to geological factors and mechanisms of formation.

In the course of a study of the relationship between the stage of development of incipient slaty cleavage and the degree of very low-grade metamorphism (Kisch 1989, 1991), it was found that the published characterisations of the fabric—in areas on which data on very low-grade metamorphism are available—can be correlated with a standard cleavage scale only in a very crude way.

Many descriptions merely give very general indications of the fabric, without indicating the—presumably mesoscopic—scale of observation, and distinguish areas of "weak", "moderate" or "strong" fabric (Kemp et al. 1985; Merriman & Roberts 1985) or "non-planar and non-penetrative" and "planar and penetrative" schistosity (Fieremans & Bosmans 1982; after Richert 1974), which are not clearly defined and have different meanings to different workers. Sometimes, observations are given on features such as "development of micaceous sheen on cleavage surfaces", fissility of associated sandstones, and development of segregation lamellae (Turner 1935; Hutton & Turner 1936). Other papers give the percentage of flattening without further textural details other than "fracture cleavage" and "slaty cleavage" (Siddans 1977) or details of spacing of cleavage lamellae (Beutner 1978; Beutner & Diegel 1985). Still others give some details on the characteristics of the microfabric, including spacing of cleavage domains, degree of fabric in the microlithons, and percentage of the rock affected (e.g. Piqué et al. 1984; Piqué 1975, 1982), referring to some standard terminology of microfabric characteristics, such as Powell (1979; see also Borradaile et al. 1982). In some cases, the nature of the microfabric could be clarified by reference to photomicrographs in either the original papers or other papers dealing with cleavage in the same areas, but generally the characterisations are too variable to allow accurate establishment of the stages of cleavage development and, therefore, of their relationship to the degree of very low-grade metamorphism.

Some of the criteria presently used for cleavage description depend on lithology rather than intensity of cleavage development. Thus, a primary parameter in the classification of Powell (1979), the spacing of cleavage domains, appears to be conditioned by pre-existing heterogeneity in clastic rocks, particularly the predominant size of clastic grains of competent minerals, such as quartz, rather than by the intensity of cleavage development—at least until very advanced cleavage development. For instance, during the progressive development of cleavage in the Rheinische Schiefergebirge (Weber 1976, 1981) and the Damara orogen of Namibia (Ahrendt et al. 1977), marked by increasing phyllosilicate recrystallisation in cleavage planes, the cleavage domain spacing remains constant.

If the equivalence of cleavage types in different lithologies at the same degree of regional deformation were known in sufficient detail, we should, ideally, be able to predict the cleavage to be expected in other rock types. However, since this equivalence is known only in very general terms, it is important that descriptions of cleavage contain at least some description of cleavage morphology in one or two common rock types, which can then be used as a standard for comparison; these rock types should include a mudstone (without very pronounced primary bedding-parallel fissility) or clay-rich siltstone and, preferably, a wacke.

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Since most published descriptions of slaty cleavage are—and are likely to remain—field descriptions, and since an essential attribute of cleavage is the ability of the rock to split along preferred directions on the hand-specimen scale, it is both convenient and justified that classification of cleavage should be primarily based on field observation. Further correlation should then be attempted between these field categories and characteristics of the microfabric or other factors, such as strain.

Surprisingly, no accepted field classification of the stages of cleavage development in clastic rocks exists. Such a classification is needed to facilitate comparison and correlation of rock deformation fabrics with other geological variables, such as strain and relation to tectonic features, as well as degree of metamorphism. The scheme should, as far as possible, be internally consistent, with attributes logically grouped according to kind and not overlapping or having ambivalent meanings. One example of this type of approach is the classification of fold geometry by Fleuty (1964). To preserve objectivity in the classification, a clear distinction needs to be made between observation and interpretation. This is best done if the names given to classes or attributes are descriptive and morphological (Dennis 1972; Powell 1979) rather than genetic. The resulting classification will then provide an independent observational framework that should assist in developing ideas about relationships and origins. To serve in this way, the class categories should take into account natural groupings or associations of natural forms. One of these is the extensive variation which can occur as a result of differing lithologies, and another is the effect of varying intensity of any one fabric type. Finally, a classification scheme should be practical to implement. Therefore, it should incorporate concepts and terms that have been widely accepted and should not deviate appreciably from these except where consistency is at risk or where some new attribute is needed to complete a set of descriptors.

The need to encompass incipient cleavage

Cleavage structure proper is generally regarded as planar (e.g. Dennis 1972), and considerable attention has been given to the well-developed planar forms, both mesoscopically in relation to strain (e.g. Wood 1974) and microscopically (e.g. Powell 1979; Borradaile et al. 1982).

One of the purposes of proposing the present classification of cleavage is to recognise and encompass the incipient stages of cleavage formation prior to the development of an overall planar fabric. It is a curious and long-standing paradox that cleavage appears to be closely related to tectonic strain and yet only appears (as a planar structure) above some finite strain threshold: ~35% total strain (including compaction) for slaty cleavage in pelites (Wood 1974); ~25–30% tectonic strain for cleavage in arenites (Clendenen et al. 1988); and ~25% total strain in quartz pebbles (Norris & Bishop 1990). This raises the question as to whether the fabric is suddenly created at some strain threshold or builds up gradually from the earliest stages of deformation, as suggested by Kligfield et al. (1983) and Ramsay & Huber (1983, p.185), and has simply escaped notice in the field. To address questions such as this, it is necessary to have a framework for objective description of incipient cleavage intensity. A similar need arises in attempts to understand the relationship between cleavage fabric initiation and metamorphism (Kisch 1991); a meaningful comparison cannot be made without including the weakest members of the cleavage series.

Two structures which reflect very incipient cleavages are (1) pencil structure (Fig. 2a) and (2) 'pre-pencil structure'.

(1) *Pencil structure*. The pencil structure (Cloos 1946, p.8) produced upon weathering of weakly deformed mudrock reflects a linear bedding/cleavage intersection fabric, which may be associated with either (a) stretching normal to bedding or (b) stretching parallel to the pencils.

For the first type of pencil structure, Reks & Gray (1982) have shown that its development requires two independent fabric anisotropies approximately equal in magnitude and that this condition is met only in a certain range of strain values, where the minimum principal strain (Z) ranges between 9 and 26% shortening; the long axes of the "pencils" are parallel to the bedding/cleavage intersection and the inferred Y-axis of the tectonic deformation ellipsoid. With increasing strain within this range, microfabric changes in the mudrock include lengthening of cleavage-domain traces and reduction in the degree of anastomosing as cleavage-domain traces tend towards planarity; these changes produce pencils with higher length/width ratios.

Pencils of the second type found in the Wildhorn nappe of the Swiss Alps (Ramsay 1981) are elongate parallel to the X-direction of both total strain (Ramsay 1981, fig. 10a; also Ramsay & Huber 1983, fig. 10.26) and tectonic strain (Ramsay 1981, fig. 9, Wildhorn), which here coincides with the bedding/cleavage intersection direction. Pressure-shadow extensions in this region are intersection-parallel (Durney & Ramsay 1973, fig. 22; Dietrich 1989, fig. 6, or Dietrich & Casey 1989, fig. 7) and, therefore, these pencils owe at least part of their elongation to mechanical elongation. However, since the pencils described by Reks & Gray (1982) were tectonically extended normal to the intersection direction, their examples cannot be explained by this means.

As far as is known at present, pencil structure is restricted to areas with very low degrees of metamorphism, with illite 'crystallinity' values of $>0.35°\Delta2\Theta$ (Kisch 1991) indicative of low anchimetamorphic and "diagenetic" grades. For the area they studied, Reks & Gray (1982) gave the temperatures inferred from conodont colour alteration (Epstein et al. 1977) as 250–350°C; i.e. a CAI of 4–5. In the Paleozoic of the Yass area, New South Wales, pencil structure occurs in rocks with illite "crystallinity" values of $0.44–0.54°\Delta2\Theta$.

(2) *'Pre-pencil' structure or embryonic cleavage*. Incipient cleavage-fissility so weak that it is subordinate to bedding-fissility—what may be called the 'pre-pencil' or embryonic type—is commonly overlooked in structural field investigations. It has been alluded to in some studies, mainly under the name of "fracture cleavage" (e.g. Siddans 1977; Price & Cosgrove 1990, p.447), also "pencil cleavage" (Engelder & Geiser 1979), but has otherwise been largely neglected as a serious structural entity. However, it displays a consistent geometrical relation to folds and is accompanied by weak fabric modification (Oertel et al. 1989; Weaver 1984, p.14) and layer-parallel shortening (Engelder & Geiser 1979). Limited regional study carried out for this paper suggests that it is much more widespread than is generally realised.

The need to consider cleavage types

Part of the difficulty, up to now, in defining a workable intensity scale for cleavage fabrics has been uncertainty about whether some variables are functions of deformation, or are characteristic of different kinds of cleavage, or depend only on the lithology of the rock. Consequently, it is not possible to erect an intensity scheme without first distinguishing the factors that define different kinds of cleavage from those that define cleavage intensity. Even the question of what is, and what is not, a cleavage has to be settled before further progress can be made; especially, whether or not "fracture cleavage" is a real cleavage and/or a real fracture. Factors such as spacing of domains, composition and texture of the parent rock, and how fractures fit into the picture must all be addressed.

Accordingly, the first part of this paper reviews observations that previous workers have made about cleavage characteristics and their relationships, and uses this information as a basis for identifying morphological groupings of cleavage types. The chief considerations here are, first, logical consistency of the proposed scheme and, second, divisions that will be practical to use in the field.

In the second part of the paper we use the related concept of mechanical anisotropy—expressed as natural breakage phenomena—to develop a new, field-based, intensity scale, especially for slaty cleavages and related kinds in clastic sedimentary rocks.

Aims and restrictions of the classification

(1) The classification is restricted to rock cleavages; i.e. planar tectonic fabric elements (Dennis 1967), excluding fracture phenomena.

An important aim is to distinguish between the fabric (cleavage) and the ability of the rock to subsequently fracture along fabric planes (fissility). The former constitutes a basis for defining cleavage types, while the latter, especially cracking caused by weathering, provides a useful criterion for field assessment of cleavage intensity.

(2) The classification is intended primarily for application to first-generation penetrative cleavages in low-grade and very low-grade metamorphic clastic rocks. All types of cleavage are, however, considered.

(3) There is no restriction on rock type, but emphasis is mainly on clastic sedimentary rocks.

(4) The primary classification is based on descriptive characteristics which are observable in the field.

(5) The class attributes are:

(a) *type of cleavage* (penetrativeness and lithological dependance), and

(b) intensity (degree of preferred orientation of fissility-cracks).

(6) As far as possible, natural cleavage groupings are preserved (such as slaty cleavage in mudrocks), and existing descriptive terms and concepts are used whenever possible.

Rock type nomenclature

In naming the clastic sedimentary rocks that have been affected by cleavage development, we follow mainly Folk's (1980) sedimentological nomenclature (as far as can be determined from published information and field observations), especially at the lower grades of metamorphism, to emphasise the nature of the parent rocks. Examples are *mudrock* (comprising *claystone*, *mudstone*, *siltstone* or other varieties composed of clay and silt-size particles) and *sandstone* (dominated by sand-size particles of quartz, feldspar, mica and/or lithic fragments). Terms with particular textural significance are *wacke* (poorly sorted, muddy or matrix-rich sandstone) and *shale* (as opposed to mudstone, for a mudrock with pronounced bedding-fabric or lamination). In the latter part of the paper we use *"argillite"* for a dark, indurated lithic-composition mudrock (a laminated lithic siltstone) which can be distinguished in outcrop from more easily weathered "mudstone" and "shale". Where only a grain-size connotation is intended, irrespective of clast composition and roundness, we use *arenite* and *rudite*. To denote mudrocks and sandstones whose grain-size and mineralogy may have been significantly altered by regional or burial metamorphism, we use *pelite* and *psammite*, respectively.

Main cleavage type groupings

Some observations from previous work: a basis for main groupings

A number of important observations have been made about cleavage morphology over the last twenty years or so, which should be taken into account in any cleavage-nomenclature scheme.

(1) "Rock cleavage"

The definition of "rock cleavage" proposed by Dennis (1972, p.179; 1987b, p.172) is that it comprises "secondary planar fabric elements which impart mechanical anisotropy to the rock without apparent loss of cohesion". A consequence of this definition is that the existence of a cleavage can always be verified by the hammer test: an initially coherent sample will tend to split or "cleave" in a preferred direction, usually transverse to bedding. Nevertheless, Dennis emphasised that the planar fabric elements are planes of "potential parting" as opposed to planes which have been, or are now, actual partings (see also Dennis 1967, 1987a, b). The key distinction here is that rock cleavage results from a coherent rearrangement and realignment of the constituent minerals and is therefore essentially ductile rather than brittle in origin. This is supported by a wealth of modern microscopic and geometric observations. In particular, cleavage fabrics do not show the microstructural characteristics of brittle deformation mechanisms, such as split-and-displaced grains and open-space mineral precipitation (though cracks may occur either at a high angle to the fabric within constituent grains or incidentally parallel to the fabric, owing to subsequent cracking). Cleavage planes are also, for the most part, oriented normal to, or at a high angle to, the direction of maximum shortening strain and are, therefore, incorrectly oriented for extensional or brittle shear failure at the time of their development (for example, Dennis 1972; Siddans 1972; Groshong 1975a; Alvarez et al. 1978; Gray 1979; Gray & Durney 1979; Cosgrove 1989). Terms which imply a brittle origin, such as "fracture cleavage" (Leith 1905) and "close-joints cleavage" (Sorby 1857), which are still used in some structural textbooks are consequently inappropriate and should be abandoned (e.g. Dennis 1987b, p.182). It is necessary to carefully distinguish incidental partings and cracks which follow a pre-existing planar fabric—for example, partings brought about by weathering—from the fabric or "cleavage" itself. These features can be important field indicators of cleavage, as will be discussed below under the heading of "fissility", but they do not constitute the actual cleavage, which is here understood to mean the internal rock fabric.

(2) Domainal character of common cleavages

The majority of cleavages, if observed at sufficiently small scale, are *domainal* in character (Williams 1972; Hobbs et al. 1976; Powell 1979; Borradaille et al. 1982). That is, the new alignment of minerals is most pronounced in regions called "cleavage domains" that are interwoven with parts of the rock having a weaker new alignment or remnants of an earlier fabric, called "microlithons" at the microscale and 'lithons' at the mesoscale. The cleavage domains are thin subplanar regions which are also sites of secondary concentration of platy minerals, so that rocks having this fabric tend to split readily along those domains. This is the chief cause of cleavage as a mechanical anisotropy in deformed sedimentary rocks and includes many cases in which the domainal character is observable only at the microscale; for example, common forms of slaty cleavage.

(3) Cleavages in mudrocks and clay-bearing sandstones/calcarenites

Cleavages in mudstones and marls and in clay-bearing sandstones and calcarenites (including poorly sorted varieties or wackes)—the "slaty" and "rough" cleavages, respectively, of Dennis (1972, 1987b)—represent a coherent group of cleavage types showing close spatial associations, micro-morphological similarities and complete transitions with one another (Bakewell 1815 *in* Siddans 1972, p.207; Powell 1969; Dennis 1972, 1987b; Means 1975; Gray 1978; Gibson & Gray 1985]. Both types typically display microscale cleavage domains, called "folia", "mica films", "seams", "cleavage laminae" or "cleavage lamellae", which run around and between the coarser clastic grains. A corollary of this behaviour, noted by Yoshida (1969) and measured by Gray (1978, fig. 17) and Reks & Gray (1982, fig. 11), is that the spacing of the cleavage domains is directly related to the width of the larger clastic grains. This has been further confirmed by Norris & Rupke (1986), who showed that the stratigraphically downward increase in slaty-cleavage intensity in a 200 m thick mudstone—as evident from a closer spacing (decreasing from ca. 250 to 20 μm) and increased continuity and coarsening of the initially anastomosing cleavage domains—correlates with a decrease in the mean grain size, average bed thickness, and quartz/mica ratio.

(4) Role of lithology and initial fabric

Cleavage development is strongly dependent on lithology and initial fabric, both with regard to the type of cleavage developed and its intensity. For example, "slaty" cleavage tends to occur in mudrocks, whereas mesoscopic "spaced" types are most common in impure limestones (e.g. Mitra & Yonkee 1985). These two types of cleavage are also most often developed in rocks with a low initial- or earlier-fabric anisotropy. When the rock has a strong previous fabric, such as an earlier slaty cleavage, the distinctive "crenulation"-cleavage type is usually the one which develops (Cosgrove 1976; Gray 1977c).

Within the pelitic to psammitic group of rocks, it has long been known that cleavage at any one locality is stronger in the pelitic than in the psammitic layers, a feature which is obvious in strata that have graded bedding. Fine argillaceous matrix also has an important influence on the type and strength of cleavage in psammites. In a study of low-grade psammitic (sandy) rocks from southeastern Australia, Gray (1978, p.580 and fig. 6) found that S_1 rough cleavage in silty sandstones (Type A, 50–80% matrix) is typically weak and irregular, due to short, discontinuous cleavage seams around random to weakly oriented grains, whereas in wackes (Type B, 80–90% matrix) it is stronger and more regular, due to continuous cleavage seams around S_1-oriented detrital grains.

The development of spaced cleavage in carbonate rocks of low to very low metamorphic grade appears also to be strongly influenced by clay content: for example, penetrative cleavage in pure limestone, but spaced cleavage in impure dolomite (Tapp & Wickham 1987), and isolated tectonic stylolites in pure limestone, but widespread cleavage only in limestones with more than 10% clay–quartz matrix (Marshak & Engelder 1985). In addition, Schweizer & Simpson (1986, p.781) found both a decrease in the spacing of cleavage domains and a change in their shape from planar to anastomosing with increasing clay content in dolomite; in limestone, domain spacing is similarly affected, but the domain shape in this rock changes from stylolitic to planar with increasing clay content (Alvarez et al. 1978).

(5) Cleavage zones or 'stripes'

Cleavage domains are commonly concentrated in roughly planar 'super-domains'. These structures are generally visible at the mesoscale and are marked by variation in both composition and fabric intensity: usually a concentration of platy minerals and dark opaque matter, together with a stronger cleavage fabric, in the more cleaved zones as compared with the less-cleaved zones. Descriptions which emphasise the compositional variation include "metamorphic layering", "metamorphic differentiation" or "differentiated layering" (Talbot & Hobbs 1968; Williams 1972; Cosgrove 1976), "litages tectoniques" (Soula & Debat 1976), "striping" (Beach 1974), "Pseudoschichtung" (Langheinrich 1977), "mica bands" (Boulter 1979; Boyer 1984), "P and Q domains" (Stephens et al. 1979; Waldron & Sandiford 1988), and "M and Q domains" (Gregg 1985). Those that emphasise the fabric enhancement include "cleavage zones" (Nickelsen 1972), "alignment zones" (Geiser 1974), "cleavage bands" (Means 1975), "isolated cleavage zones" (Gray 1978, p.580), "pressure solution cleavage", "cleavage stripes" or "pressure solution stripes" (Beach 1979; Siddans 1979), "compound tectonic fabrics" or "coplanar spaced cleavage" (Gray 1981), and "spaced cleavage zones" (Clifford et al. 1987).

These zones most commonly occur in impure psammites. A similar effect occurs in pelites—"layering parallel to cleavage" (Talbot & Hobbs 1968), "cleavage bundles" (Southwick 1987), "splaying" (Murphy 1990) or "coalesced slaty cleavage" (Erslev & Ward 1994)—although these are often special cases that are spatially tied to competence variations such as multilayer folds (Cosgrove 1976; Langheinrich 1977), contacts between coarser and finer lithologies (Talbot & Hobbs 1968, pl. 1; Nickelsen 1972; Langheinrich 1977; Southwick 1987), and margins of competent objects (Durney 1972a, 1976a; Cosgrove 1976; Gray 1981; Gratier 1979; Prior 1987). Cases which more closely resemble the free-ranging stripes in psammites include mesoscopic stripy zones in laminated low-grade pelites composed of mudstone, siltstone and very fine sandstone laminae (Soula & Debat 1976; Cox et al. 1991; Gray & Willman 1991). Limestones may also display this effect as a clustering of fine anastomosing spaced cleavage domains called “diffuse-”, “compound-” (Geiser & Sansone 1981, fig. 9) or “wispy-” (Koepnick 1985, fig. 1) “seams”.

The phenomenon is not a purely mechanical “transposition of bedding”, as proposed by Turner & Weiss (1963) and Bishop (1972, figs. 1 and 7), since it involves a pervasive loss or gain of selected minerals superimposed on previous layering. Indeed, the mesoscopic “differentiation” or segregration of minerals can occur in rocks, such as coarse wackes, that lack a primary internal layering. We also distinguish it from crenulation-cleavage differentiation (Cosgrove 1976; Gray 1977b) or metamorphic layering associated with crenulations (Glen 1982a), which is restricted to a fundamental domainal structure. It is essentially a modulation or “second order” (Durney 1972b, 1976b) variation of smaller scale, cleavage domain, differentiation and not strictly a separate type of cleavage in its own right. Although it is often called “spaced cleavage” (Gray 1981; Roberts 1989) or “disjunctive cleavage” (Murphy 1990), these are terms used for single-domain structures (Dennis 1972, p.180; Powell 1979). The zones referred to here comprise groupings of many individual cleavage domains, and the intervening zones also usually include some cleavage domains (Gray 1978, p.580). Extreme cases can arise where the concentration of cleavage domains is so great that they merge to form a single wide cleavage domain (Gray 1981; Murphy 1990, fig. 7). But even these cases typically display at least a weak cleavage throughout the rock, as shown by its ability to split parallel to cleavage anywhere in the specimen.

The difference between cleavage and cleavage zones (or bundles, differentiated bands, etc.) is perhaps clearest where the two are at an angle to each other (Boulter 1979; Boyer 1984; Powell & Rickard 1985, fig. 2; Murphy 1990). In this case, the rock splits oblique to the compositional layering, demonstrating that the latter is not *the* cleavage. In this paper, we distinguish *cleavage* (cleavage domains), as elementary-domain structures, from many-domain *cleavage zones.* The cleavage-type divisions which follow are based on the cleavage domains, if present. Cleavage zone development is considered to be a modification of the basic cleavage type.

(6) Shear zones

The previously described “cleavage zones” or “stripes” should be distinguished from heterogeneous zonal structures dominated by shearing rather than by loss of non-flaky minerals: namely, “shear zones” or “ductile shear zones” (e.g. Carreras et al. 1980; Simpson 1986; Lloyd et al. 1992) (see fig. 1B). The appearance and kinematics of these structures are very different from the “cleavage zones” of the preceding section. And, although they may contain domainal cleavages (Nickelsen 1986; Casas & Sàbat 1987), the type of cleavage or fabric within them is often different as well. The chief characteristics of shear zone fabrics in metamorphic rocks and their differences from cleavage zone fabrics are as follows:

(a) In constrast with domainal cleavage and cleavage zones, which are confined mainly to fine phyllosilicate-bearing rock types, shear zones are not restricted as to rock type and frequently occur in medium to coarse-grained, medium to high metamorphic grade or igneous parent rocks that lack fine phyllosilicates, especially schists, gneisses, granulites, granites, metadolerites, quartzites, coarsely crystalline vein quartz and so forth. At very low metamorphic grades, they may occur in relatively pure and fine-grained limestones.

(b) There is usually a reduction in grain size of all minerals in shear zones, leading to the formation of fine recrystallised “mylonite” and “mylonitic foliation” (Bell & Etheridge 1973; White et al. 1980), whereas grain size in domainly cleaved rock shows little or no variation between domains except for reductions in width of specific minerals, such as quartz, related to the local associated compositional variations.

(c) Initially coarse-grained quartz and mica, if present, becomes involved in the deformation of shear zones, whereas deformation in domainly cleaved low-grade sedimentary rocks appears to be concentrated in cleavage domains and, sometimes, beard structures, which run around and between the larger detrital grains of quartz and mica.

(d) Grain alignment in shear zones is commonly oblique to the zone, indicating shear parallel to the zones (Ramsay & Graham 1970), whereas in cleavage zones it is commonly parallel to the zone, indicating shortening normal to the zones (Gray 1981).

(e) A special type of meso- to microscale domainal structure is known only or mainly in shear zones: “S and C structure” (Berthé et al. 1979; Lister & Snoke 1984), and similar structures described as “extensional crenulation cleavage” (Platt & Vissers 1980), “shear bands” (Harris & Cobbold 1985) and “normal kink-bands” (Cosgrove 1989). It is characterised by very planar “C” or “C′” (“cissaillement” or “shear”) bands, with a strong asymptotic fabric, that alternate with “S” (“schistosité” or “foliation”) bands that contain a weaker, oblique and often sigmoidal fabric. Composition is usually about the same and can be identical in the two types of band or domain. This is in sharp contrast to the wavy, phyllosilicate-rich and sometimes ‘conjunctive’ (p. 265) domains that make up most types of domainal cleavage.

(f) Bulk compositional change may or may not (Beach 1980; Kerrich et. al. 1980) accompany shear zone fabric development. When present, it commonly involves both inward and outward migration of different chemical components in varying proportions with little apparent systematic pattern (Tobisch et al. 1991, table 3) and may occur in zones up to tens of kilometres wide (hydrated shear zones described by Grocott & Watterson 1980). In contrast, compositional variation always accompanies cleavage zone development; it consistently involves a relative loss of specific components such as carbonate (Gratier 1979) and silica (Clifford et al. 1987; Waldron & Sandiford 1988; Erslev & Ward 1994) from the cleavage zones; there is no obvious variation in degree of hydration of minerals; and cleavage zone widths fall within a restricted range of up to about 10 mm (e.g. Soula & Debat 1976; Waldron & Sandiford 1988).

Thus, it is clear that there are often fundamental differences between the fabrics developed in these two types of zonal structure. These differences involve considerations of deformation mechanisms and deformation environments which are beyond the scope of this paper (cf. Groshong 1988, for an extensive review of those topics) and which may be difficult to resolve in some cases (e.g. Burg & Iglesias Ponce de Leon 1985). From an observational point of view, however, their respective occurrences are evidently conditioned to a large extent by lithology, especially by grain size, grain-size distribution and presence or absence of fine phyllosilicates, and by the ability of the rock to undergo mass transfer at the cleavage-domain scale. The nature of the parent lithology and type of zonal structure, therefore, provide clues to the existence of two distinct natural groups of penetrative cleavage. One displays a compositionally differentiated domainal fabric, while the other shows a more throughgoing deformation and alignment of the grains, with little or no domain-scale differentiation.

Proposed divisions of cleavage type: penetrative and non-penetrative

Our principal divisions of mesoscale cleavage types are what we term *penetrative* and *non-penetrative*, based on the known or inferrable relationship of the cleavage fabric to the size of the coarser constituent particles (see Fig. 1A).

"Penetrative", as ordinarily understood and as used here, is not equivalent to "uniform" (Oertel 1962, p.326); nor is it exactly equivalent to "continuous" as *defined* by Dennis (1972, after Chidester 1962), though it includes both of these as particular cases. It is the quality of 'permeating' or 'passing through' something to a fairly intimate level in the way that water, for instance, may pass through a porous rock. Thus, we define *penetrative cleavage* as a mineral alignment which 'penetrates' or 'passes through' the rock, down to the dominant grain or clast size. The mineral alignment may occur in all grains of the rock or, as more commonly happens, it may occur especially within domains which pass around and between the larger grains or clasts of the rock. It therefore includes the "slaty" and "rough" types referred to in (3) above as two particular examples ("continuous" as *used* by Dennis 1972). From the field observational point of view, the rock appears capable of splitting in the plane of cleavage anywhere between the coarser competent grains (such as quartz grains). In the case of a mudrock, the rock literally appears able to split anywhere. *Non-penetrative cleavage*, on the other hand, is defined as that in which domains of mineral alignment occur at intervals significantly greater than the size of the dominant grains or clasts.

Ideally, the penetrative/non-penetrative division depends on the relationship of cleavage spacing to grain size and does not occur at any particular cleavage domain spacing. But for practical reasons, a lower limit of 1.0–0.5 mm spacing must apply to the recognition of the non-penetrative type as a field-based term. Fortunately, the majority of these cleavages do appear to be spaced at intervals greater than 1.0–0.5 mm and can be readily identified in the field (e.g. the mesoscopic spaced cleavages of Alvarez et al. 1978).

Conversely, some "penetrative cleavages", according to the definition above, can be spaced at considerably more than the 1.0–0.5 mm field resolution limit (e.g. cleavage seams which weave between limestone pebbles and cobbles at spacings of more than 10 mm in Ramsay & Huber 1983, fig. 7.24B). These cases are morphologically analogous to "rough" cleavages in impure sandstones and calcarenites and therefore belong naturally within the penetrative group. The only difference is that cleavage domains in the conglomeratic type are clearly visible in the field, whereas, in the finer-grained varieties, they are inferred to exist from the way the rock splits.

Types of penetrative cleavage

As most "penetrative cleavages" are not further resolvable by direct observation in the field, and also because these cleavages tend to show close natural associations with particular lithologies (point 3 above), our major subdivision of this group is based on lithology. Accordingly, we recognise

(1) *penetrative type 1* cleavage fabrics in relatively fine-phyllosilicate-poor and usually well-sorted clastic and chemical sediments, and most igneous rock types; and

(2) *penetrative type 2* cleavage fabrics in clastic rocks containing significant proportions of fine phyllosilicate or other platy minerals (Fig. 1A).

We assign the numbers "1" and "2" to these types on the basis of relative fabric complexity. Type 1 fabrics are simpler in that they are typically undifferentiated uniform grain-shape fabrics. Except in cases where they are well developed, they impart little or even no capacity for directional splitting. Type 2 fabrics are more complex, in that they are typically, though not universally, domainal at the microscale. Rocks with type 2 fabric thus tend to split easily; the cleavage domains offer paths of easy parting through the rock.

(1) *Penetrative 1 or grain cleavage* occurs in rocks with little or no fine platy mineral fraction: relatively 'pure' and often well-sorted calcareous and siliceous sediments, many igneous rocks, and recrystallised metamorphic rocks with a medium to coarse-grained platy mineral fraction (schists, gneisses: see "schist fabric" of Gray 1977c). Fissility may occur anywhere within the rock, but is generally much harder to induce than in mudrocks and some poorly sorted arenites; in some cases, fissility may be lacking, although a poor fabric is present. Fissility in this type of cleavage is due to an alignment of all or most of the minerals present, whether of fine or coarse overall grain size (e.g. Dietrich & Song 1984).

    Penetrative 1 cleavage may be heterogeneously developed in mesoscale shear zones (Fig. 1B). "Differentiation" or "striping", as seen in mudrocks and wackes, is generally absent except in some schists and gneisses.

(2) *Penetrative 2 cleavage* is pervasive in the sense that it penetrates at least part of the matrix of the rock between the coarser clastic grains, which means that the cleavage domains, if present, are spaced at about the width of the coarse grains: the rock splits anywhere except through the coarser competent clastic grains. Microscopically, the platy mineral orientation in the microlithons between cleavage domains may be largely unrelated to the cleavage domains (disjunctive in the terminology of Powell 1979) or it may be largely oriented parallel to the cleavage domains, what we propose to call a "conjunctive" or simply

"parallel" relationship.

Two principal divisions of penetrative 2 cleavage are recognised, according to the degree of lithification and metamorphism of the rock:

(a) *Clay type*—an undifferentiated preferred orientation of clay flakes known to occur in some unlithified and unmetamorphosed clay-rich fault gouges ("P-foliation" of Rutter et al. 1986; "clay foliation" of Chester & Logan 1987).

"Clay type" penetrative 2 cleavage is commonly accompanied by scaly cleavage, with which it forms a small angle, analogous to S-structure in ductile shear zones (Chester & Logan 1987) (Fig. 1B).

(b) *Slaty type*—which is by far the more common, including slaty cleavage and its incipient forms and related fabric types in poorly sorted coarser clastic rocks. The slaty type occurs in lithified fine-platy-mineral-bearing rocks of very low to low metamorphic

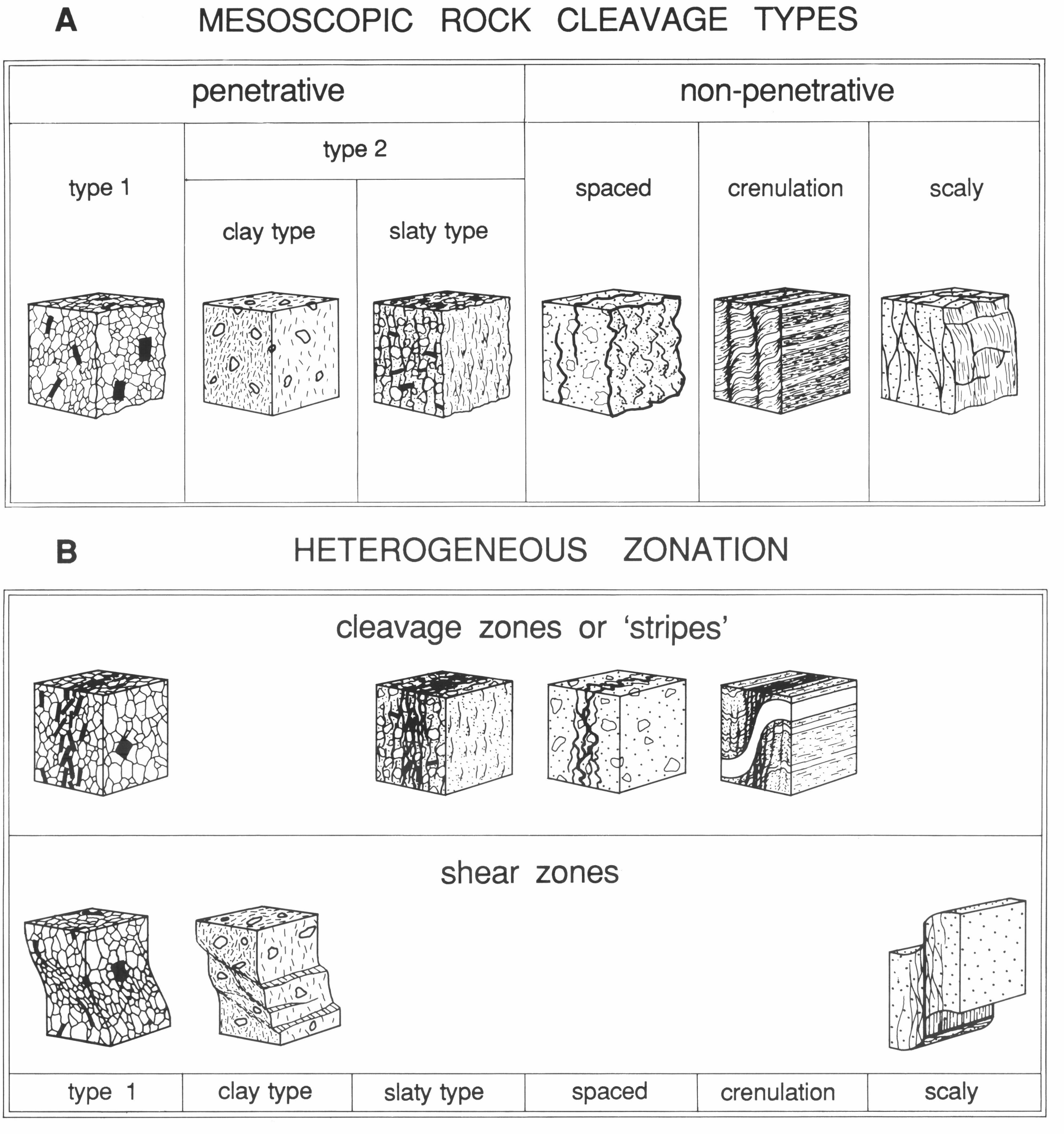


Figure 1. A—Schematic representation of *cleavage types* observable in the field. *Penetrative:* mineral alignment down to the dominant grain or clast size, comprising non-domainal fine-phyllosilicate poor (*type 1*) and domainal and non-domainal fine-phyllosilicate rich (*type 2*) types. *Non-Penetrative:* domainal mineral alignment spaced wider than the dominant grain or clast size, usually mesoscopic.

B—Schematic varieties of mesoscale zonation of the six cleavage types. *Cleavage zones:* Compositional differentiation into bands of greater and lesser concentration of cleavage domains and immobile minerals. *Shear zones:* Fabric intensification in bands of high shear strain without necessary compositional differentiation.

grade. Mineralogically differentiated domainal structure is typically present at the microscale (or, in rudaceous rocks, at the mesoscale).

"Slaty type" penetrative 2 cleavage domains may be heterogeneously developed at the mesoscale in usually gradational and cleavage-parallel zones of greater and lesser cleavage intensity (Fig. 1B). These are commonly marked by darker and lighter appearances, respectively, as a result of differences in mineral composition—differentiated "stripes" and mesoscopic "cleavage zones". In the more weakly developed stages, the enhanced cleavage may be restricted to isolated zones. Zonation may occur both in impure psammites or wackes (e.g. Gray 1978) and in pelites (e.g. the cleavage bundles of Southwick 1987). The dominant fabric orientation in the less-cleaved zones may be either disjunctive or conjunctive, as in microscale microlithons.

Two sub-types of "slaty type" penetrative 2 cleavage can be distinguished on the basis of clastic grain size (Dennis 1987b). The terms are derived from Powell (1979, p.34) and Dennis (1987b, p. 172) and are applied as field names to the major grain-size divisions of slaty type penetrative 2 fabrics in low and very low-grade metamorphic rocks (at higher grades of metamorphism, the fabric tends towards penetrative 1 type):

(i) *Smooth*—fissility has a smooth or smoothish feel. It occurs in rocks up to about coarse silt size and includes *slaty cleavage* and its incipient forms.

(ii) *Rough*—fissility has a rough feel, owing to wrapping of cleavage around coarse clastic grains. It occurs in coarser grained rocks with a predominance of sand sizes, including arenites and rudites with a notable phyllosilicate mineral fraction and wackes.

Types of non-penetrative cleavage

Non-penetrative cleavages are subdivided into three distinctive types (Fig. 1A):

(1) *spaced cleavage*—tectonic stylolites and more planar equivalents in initially isotropic to weakly anisotropic rocks (Davis 1984, p.407; Engelder & Marshak 1985);

(2) *crenulation cleavage*—fold-limb-related types in harmonically folded, initially strongly anisotropic, rocks (Rickard 1961; Cosgrove 1976; Gray 1977a); and

(3) *scaly cleavage*, otherwise known as "scaly foliation" and "scaly clay fabric" (Moore et al. 1986), "phacoidal cleavage" (e.g. Bosworth 1984), "microscopic shear bands" (Chester & Logan 1987), and "hydroplastic microfaults" (Guiraud & Séguret 1987), comprising a mineralogically poorly differentiated to undifferentiated, slickensided, phenomenon in a group on its own (this paper).

(1) *Spaced cleavage.* Differentiated cleavage domains, and portions of uncleaved rock with many clasts or grains which we call "lithons", can be distinguished in hand-specimen (Engelder & Marshak 1985, p.327). Cleavage is generally restricted to relatively narrow and distinct cleavage domains showing concentration of dark or phyllosilicate minerals; exposed cleavage surfaces generally show dark coatings with a sheen due to very strong platy mineral alignment. Domain spacing may range from about 1 mm to decimetres and may be regular (Fig. 1A) or clustered (Fig. 1B). The intervening rock is generally little changed. This type corresponds to mesoscopic "discrete" and "disjunctive" cleavage.

Spaced cleavage occurs mainly in rocks with a minor proportion of fine platy minerals and a major proportion of other fine mineral grains, such as carbonates, quartz, and feldspar. The morphology of the cleavage surfaces may range from subplanar through wavy to dentate or stylolitic forms. The surfaces are commonly axial planar (Alvaro & Capote 1973) and symmetrical with respect to extension veins and minor faults (Arthaud & Mattauer 1969), but may be striated due to oblique convergence (Ramsay & Huber 1987, pp.648–658).

(2) *Crenulation cleavage.* For crenulation cleavage, we use the morphological definition of Gray (1977a)—"zones of mineral differentiation coincident with the limbs of microfolds in crenulated rock fabrics"—which follows essentially the earlier definition of Rickard (1961, his section II, iii). Essential features are its strict dependence on "crenulations" or harmonic microfolds, its restriction to microfold limbs and its constitution as axial planar cleavage domains marked by a concentration of dark or platy minerals. Thus, it differs from, for example, stripy differentiated slaty cleavage in folded laminated mudrocks (Hills 1965, his fig. VIII–29; Cox et al. 1991 fig. 9a; Gray & Willman 1991 fig. 6c) in not existing in the related microfold hinges and always being coincident with fold limbs.

Although sometimes visible only under the microscope, the crenulations commonly range from "a fraction of an inch (~1 mm?) up to about 1 inch (25 mm) across" (Rickard 1961, p.325; see also Dennis' 1972 examples). Hence there is usually little difficulty in distinguishing them in the field.

Mesoscale concentration of cleavage domains, similar to that associated with slaty cleavage, is common in the vicinity of competency contrasts and larger mesoscopic folds (Fig. 1B).

(3) Scaly cleavage. Scaly cleavage is a distinctive structure with smooth and highly polished/slickensided discrete surfaces which intersect or merge with one another to yield lensoid flakes, scales or chips (Fig. 2b). The fresh rock is coherent, but breaks with extreme ease along the scaly cleavage surfaces. The cleavage occurs in rocks with a high proportion of weak or platy minerals, such as claystones, mudstones, marls, carbonaceous rocks, serpentinites and talcstones. An analogous structure called "web structure" (Cowan 1982; Witschard & Dolan 1990) has been found in sandstones and consists of polished, striated and discoloured intersecting seams of cataclasis. In highly argillaceous rocks, such as clay-rich fault gouges, a penetrative clay-mineral alignment is sometimes present in the domains between the surfaces of scaly cleavage (Rutter et al. 1986; Chester & Logan 1987). In marls, similar structures may be accompanied by a sigmoidally distorted, smooth to stylolitic, spaced cleavage (Casas & Sàbat 1987).

Scaly cleavage appears to result chiefly from slip along the surfaces; the surfaces are spaced, but usually lack obvious mineral differentiation or new mineral concentration in hand specimen. Unlike other cleavages, it is essentially a shearing phenomenon rather than a flattening phenomenon or axial-planar cleavage. Its orientation relative to the axial planes of folds is variable, ranging from "subparallel" in some cases (Witschard & Dolan 1990, p.801) to grossly discordant in others (Fig. 2c). It typically forms a small angle with any other associated cleavage, often in obtuse angle sets displaying conjugate shear motion symmetrical with respect to the associated cleavage (Casas & Sàbat 1987). It is often associated with fault movement, particularly thrust faults, and may be concentrated within fault zones (Bosworth 1984; Behrmann et al. 1988; Maltman et al. 1993) or "scaly deformation bands" (Labaume et al. 1991) (Fig. 1B). A similar structure, marked by films of strong particle alignment, has been produced by engineering shear tests and surficial landslip movement in unlithified clays (Skempton 1964; Morgenstern & Tchalenko 1967a, b) and in laboratory analogue materials (Williams & Price 1990; Wilson & Will 1990), all in relation to known shear displacements. The fact that dilational features and cataclasis are often scarce or absent, whereas thin, gently curved films of highly oriented platy minerals with undoubted shear displacement are present, suggests that it is not, in the main, brittle in origin, but a true fabric rearrangement analogous to C-surfaces of ductile shear zones (Moore et al. 1986; Chester & Logan 1987 p.631; cf. p. 261).

As far as known, the occurrence of scaly cleavage in argillaceous rocks is restricted to "soft" (Guiraud & Séguret 1987) and "partially lithified" (Behrmann et al. 1988; Maltman et al. 1993) sediments, and to lithified mudstones and greywackes with low ('diagenetic') degrees of very low-grade metamorphism (cf. Kisch 1989, p.181). Because it does not appear to develop into a penetrative slaty cleavage, it cannot be considered an intermediate stage in the development of slaty cleavage, but represents a variety of non-penetrative cleavage in a class of its own.

Relationships to earlier cleavage classifications

Our penetrative and non-penetrative groups correspond directly to Dennis' (1972, 1987b) *usage,* in practice, of the terms "continuous" and "spaced". Dennis (1972 after Chidester 1962; Dennis 1967, p.19 and 22) *defined* these terms as applying to both mesoscale and microscale observations: "continuous"—"dimensional parallelism of all platy minerals present" (Dennis 1972, p.179;1987b, p.172); and "spaced"—"all types of cleavage which by visual or microscopic examination reveal discretely spaced surfaces of discontinuity, but do not affect intervening spaces" (Dennis 1972, p.180). However, the examples that he described (Dennis 1972, figs 9–1 to 9–5) seemed to be best distinguished on the basis of visual examination: "slaty" and "rough" "continuous" types (with domainal character at the microscale) and "crenulation" "spaced" types (with domain spacings of a few millimetres).

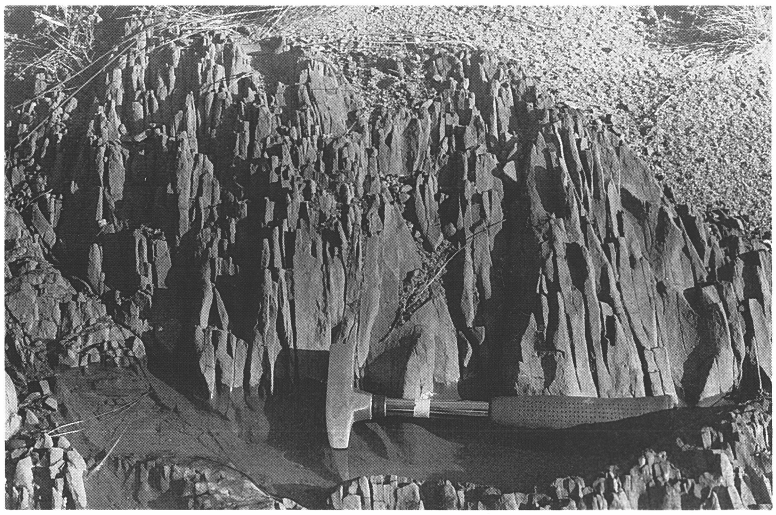
In terms of usage, Dennis' major divisions correspond to the older divisions of "flow" and "fracture" cleavage proposed by Leith (1905), which, though now rightly discredited, were at least eminently practical for application in the field. The attraction of Dennis' terms, however, is that they are purely descriptive.

A problem with Dennis' (1972) definition of "continuous" is that it stipulates a platy mineral alignment which is not always present, or not always present in the same direction as cleavage, in the microscopic domains between cleavage domains in slaty and rough cleavages. This point was recognised in the classification of Powell (1979), who suggested, in fact, that all slaty and rough cleavages show a discordant or "disjunctive" relationship between microlithon and cleavage domain platy mineral fabrics. Dennis (1987a, b) later revised the usage of his classification to reflect this to some degree, recognising cases of disjunctive relationship as "spaced". Both parallel and disjunctive types of platy mineral relationship are, however, known to exist in these cleavages: for example, microlithons with cleavage-parallel "mica beards" in some rough cleavages (Means 1975) and microlithons with clearly discordant mica fabric in some slates (Weber 1982). Consequently, neither of the two categories, "continuous" or "disjunctive", or for that matter "continuous" or "spaced", appears applicable by definition to all slaty and rough cleavages. If they were to be applied strictly, they would introduce a major division within this important and naturally associated group of fabrics (e.g. Dennis 1987b, p.172, with reference to slaty cleavage). It has also never been very clear exactly how one distinguishes between "continuous" and "spaced", in Dennis' definitions, in a rock with domainal cleavage and a parallel microlithon fabric. Chidester (1962, figs 8,9,10, p.21), in describing domainal slate fabrics of this kind from Vermont, stated that "the sericite flakes between surfaces of spaced schistosity have a continuous schistosity", clearly indicating that he intended these terms as descriptors of fabric attributes which could coexist within the one fabric. Therefore, it may be that "continuous" and "spaced" were never entirely appropriate as a basis for defining mutually exclusive cleavage types.

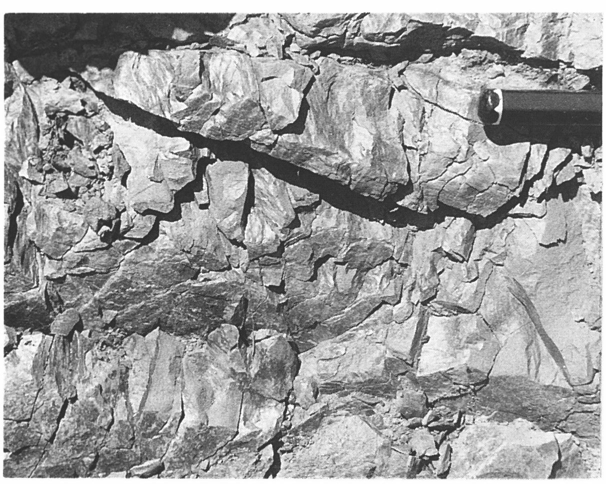
For these reasons, we suggest the simple term "penetrative" (as defined here) for the members of the slaty cleavage and rough cleavage group. Because "penetrative" is not defined in terms of absolute dimensions, this usage also avoids, on the whole, description conflicts which arise from the scale-dependence inherent in the Chidester–Dennis–Powell classifications, as in 'continuous' at the mesoscale, but 'disjunctive' at the microscale. Any need to convey grain-scale heterogeneity of the fabric should be covered adequately by the now common and self-explanatory term "domainal".

Powell (1979, p.29) applied the term "disjunctive" to what he called "spaced cleavages" which "lack sense of continuity or relationship between the pre-existing rock fabric and the new fabric in the cleavage domains". "Disjunctive" therefore describes a type of interdomainal relationship in a domainal fabric. Since our "penetrative type 2" and "non-penetrative" groups are domainal, we adopt and extend the use of the term "disjunctive" for these groups. For rocks showing largely parallel orientation of platy minerals in the microlithon domains, we use the term parallel or *conjunctive* (the opposite of "disjunctive"). "Conjunctive" is equivalent to a "continuous" (as defined by Dennis 1972, p.179; 1987b, p.172) domainal fabric. But we prefer not to use that term in view of the divergent use made of it by Powell (1979) and Borradaile et al. (1982: "continuous 1"), who used it as the opposite of "spaced", and by Borradaile et al. (1982: "continuous 2"), who modified Dennis' (1972, p.179) and Chidester's (1962) "continuous" by adding the stipulation that "cleavage domains do not exist in the sample" (p. 5, and p. 34ff).

The classification scheme suggested by Borradaile et al. (1982) follows, to some extent, the earlier scheme of Powell (1979). Unfortunately, this new scheme incorporates wholesale re-definitions of previously well-established terms ("continuous", "spaced", "rough", "zonal", "foliation", "schistosity") as well as some resurrected terms of genetic or very doubtful connotation ("cracks", "crack-like", "slices", "conjugate" and "differentiated"—as a 'variety' of "mineral concentration"), and has not been widely adopted in the literature. Nevertheless, our type 1 and type 2 penetrative cleavages correspond approximately with their "continuous 2" and "continuous 1"



a. pencil structure



b. scaly cleavage c.

d. weathering

fissility and jointing e.

types, respectively.

The term "spaced" which was used by Dennis (1972) has found a place as an umbrella for 'non-continuous' (or non-penetrative) types in many idealised classification schemes, including Dennis' own scheme. But it is rarely used in such a broad sense in practice. For example, most writers refer to "crenulation cleavage" as just that and apparently do not find a need for the more formal 'crenulation spaced cleavage'. Also, many writers in recent times have referred to stylolites and more planar mesoscopic equivalents simply as "spaced cleavages" or alternatively as "disjunctive cleavage", rather than the more formal 'stepped (spaced) cleavage' and '(quasi-stylolitic?/mesoscopic?) disjunctive (spaced) cleavage'. Some writers have suggested "solution cleavage" or "pressure solution cleavage" for these (Alvarez et al. 1978; Cosgrove 1976; Geiser & Sansone 1981; Ramsay 1981). But this introduces the dimension of genesis into what should be an objective descriptor and suggests, perhaps not correctly, that microscopic domainal cleavages and non-domainal cleavages have a different origin. Groshong (1975b), Geiser & Sansone (1981) and Guzzetta (1984) have suggested including the more planar, unsutured varieties under the name "stylolite", but this is not consistent with the etymology and usually accepted meaning of "stylolite" as a "columnar" (Stockdale 1922) or at least "very uneven" (Park & Schot 1968, p.175) structure.

There is clearly a need to identify the natural fabric group of stylolites and more planar equivalents with a simple, non-genetic, term. Current usage of "spaced" (Alvarez et al. 1976; Durney 1984, p.A2; Engelder & Marshak 1985; Mitra & Yonkee 1985) seems to satisfy this requirement. The alternative term disjunctive" has been used in a wider sense to include slaty cleavages and, therefore, seems less distinctive. So we adopt the usage of "spaced" suggested for this group by Engelder & Marshak (1985).

Where we differ from the Engelder & Marshak (1985) scheme is in the primary division into penetrative and non-penetrative. We believe that a primary division based solely on spacing is arbitrary and unnatural, just as a division between joints and spaced cleavages on the basis of spacing is arbitrary and unnatural [cf. the "jointes stylolitiques" of Arthaud & Mattauer (1969) or "joints with stylolites" of Ramsay & Huber (1987) of the central European Jura Mountains, in which some stylolites are considered to have a joint-like character and vice versa]. Our primary division is based on the relation of cleavage to grain size, acknowledging that there will be some overlap in the domain spacing of the two main divisions.

We have also not adopted an intensity scale for cleavage based on domain spacing, though it may be a useful technique for spaced cleavages in certain types of limestones (Alvarez et al. 1978). Our reservations in this regard stem from the known grain-size dependence of domain spacing in penetrative type 2 cleavages (Gray 1978) and the influence of rock composition on the spacing of some spaced cleavages in carbonate rocks (Alvarez et al. 1978; Schweizer & Simpson 1986; Ferrill & Dunne 1989, p. 427). Considering the highly variable nature of spaced cleavages, intensity estimates for these structures may require measurements of relative thickness (Simon & Gray 1982) and continuity (length) of cleavage domains, as well as domain spacing, and should probably be considered unique for each lithology in which the spaced cleavage occurs. An alternative that might circumvent some of the problems associated with lithological variation would be to use a cleavage/bedding ratio-scale based on the relative spacing of bedding and cleavage clay seams. Later in this paper, this type of approach will be adopted in a different way, using cracks rather than domains, to establish an intensity-scale for penetrative cleavages.

Some authors have suggested that fabrics in many slates, particularly in the early stages of development, are in fact varieties of crenulation cleavage (Knipe & White 1977; White & Johnson 1981; Weber 1982). Whether or not the fabrics described are true "crenulations" in the sense of Rickard (1961) is perhaps a matter for debate. But the different naming of the fabric on microscopic grounds presents a nomenclatural problem that requires special attention, particularly where a potential for conflict of terms exists. The present scheme can include first-generation cleavages in strongly oriented primary fabrics under the "crenulation cleavage" grouping. But because of its field-based nature, the scheme only allows this as a mesoscopically recognisable form distinct from slaty cleavage (c.f. penetrative/non-penetrative division, p. 262). If a first-generation crenulation fabric occurs in a slate or an embryonic equivalent, it will be recognised only under the microscope and will not alter the primary naming of the rock as a "slate" nor of the cleavage as a "slaty cleavage". If required, we suggest that microstructural observations could be incorporated in the naming of the cleavage by means of qualifying adjectives to clarify cases of possible ambiguity, as in "crenulation pencil cleavage" (Ferrill 1989) and "domainal slaty cleavage".

Cleavage field intensity divisions based on fissility

Relationships of fissility to cleavage

Many writers have referred to the fact that tectonically deformed rocks, particularly low to very low-grade metamorphosed mudrocks, tend to occur in a naturally cracked or fractured state in outcrop, with cracks spaced a few centimetres or less and aligned parallel either to an obvious plane of cleavage or to directions which behave geometrically as though they were cleavages in relation to strain indicators and the axial planes of folds. The effect has been noted particularly in weakly deformed mudrocks: "pencil cleavage" or "pencil structure"

Figure 2. a—Pencil structure, view normal to bedding. Upper Silurian Booroo Ponds Gp, Bowning Creek, Bowning, New South Wales (NSW). b—Detail of fault-related scaly cleavage surfaces showing polish and striations. Lower Devonian Elmsdale Fm. mudstone, Black Range Rd, Yass, NSW. c—Scaly cleavage in steep limb of a kink fold, view parallel to cleavage and fold axis. The cleavage is mostly confined to, and subparallel to bedding in, the steep limb (right), and runs for a short distance discordantly over the hinge plane (dipping left). Upper Silurian Cowridge Siltstone mudstone, Boorowa Rd, Bowning, NSW. d—Disaggregation of a roadside block into pencils by modern weathering processes. Lower Devonian Kirawin Shale, Wee Jasper Rd, Wee Jasper, NSW. e—Fissility-cracks (close, discontinuous cracks running from 'top to bottom' of photo) contrasted with joints (widely spaced, planar, continuous factures in three oblique sets). View normal to bedding. Termination of fissility-cracks at joints shows that the cracks post-date regional stress relief and uplift associated with jointing. Upper Devonian Noumea Beds mudstone, Byrnes Gap Rd, Manilla, NSW.

(Engelder & Geiser 1979; Reks & Gray 1982; Wilson with Cosgrove 1982; Ramsay & Huber 1983, p.185–188; Nickelsen 1986), "reticulate cleavage" (Crook 1964; 1982), examples of "cleavage fracture" (Weiss 1972, plates 1 to 5), and so-called "fracture cleavage" in mudrocks (Price & Hancock 1972; Siddans 1977; Price & Cosgrove 1990). Also, the degree of alignment of the cracks is generally understood to increase towards the more deformed parts of fold belts, suggesting a probable correlation with either strain or strength of internal fabric. At outcrop scale, the relationship has been demonstrated qualitatively by Nickelsen (1986, figs. 10 & 11) and Price & Cosgrove (1990, p. 447–448) as a continuous change of the structure from bedding-parallel cracks to a cleavage-parallel platy structure in relation to expected strain gradients around concretions and folds.

As is evident from the names given to these structures, they have often been regarded as actual cleavages (especially "fracture cleavage"). However, none of them is, properly speaking, a cleavage in the sense of Dennis (see discussion p. 259), since the described feature is an incidental pattern of cracks and not the cleavage fabric itself. This is confirmed by recent microscopic observations showing that the structure is a form of natural open cracking which approximately follows the internal tectonic and bedding-parallel fabrics of the rock (Durney 1982; Reks & Gray 1982; Ferrill 1989). The cracks are actual separations, usually with no cementation, and there is no evidence of tangential movement on them. Thus, although they are directionally analogous to a cleavage, they are morphologically quite unlike any of the cleavage types reviewed earlier in this work. Accordingly, the crack patterns should be referred to as "structures", not "cleavages"—especially *pencil structure* (Reks & Gray 1982; Ramsay & Huber 1983) for elongate, subuniaxial, crack clusters and *reticulate structure* (renamed here after Crook 1964) for the more stubby, subuniaxial, crack clusters (see also pp. 281–282 for further discussion).

Crook (1964, p.527) noted that incipient forms of the structure in mudstone are "barely distinguishable from the irregular fracture that results from weathering". The irregular variety referred to by Crook is typical of undeformed mudstones and has been acknowledged to be a weathering product in engineering studies of weathering: viz. centimetrically spaced and randomly oriented "stress relief fissures" transverse to bedding, regarded as an indicator of the first stage of weathering in the mudstone-weathering-zone classification of Hawkins & Pinches (1992).

We suggest that all of these forms—random, incipient, and the more closely spaced planar cracks which follow an obvious slaty fabric—are products of weathering in the surface environment. Evidence for this is:

(a) the similarities in surface morphology (curviplanar), spacing, parent rock and mode of occurrence of all types, with complete gradations between them, suggesting a common origin, and differing only in degree of alignment of the cracks and strength of tectonic fabric;

(b) the general absence or very much greater rarity of the structure in fresh surface excavations, fresh drill-core specimens and underground exposures;

(c) greatest intensity of crack development at the weathered surface, decreasing rapidly with a depth of only a few centimetres below the surface (e.g. relatively uncracked bedding beneath a highly cracked veneer, Fig. 2e);

(d) instances where road development work or quarrying has mechanically dumped large blocks of mudrock, which are now pervaded by a delicate network of the structure and could not conceivably have been transported in that condition (Fig. 2d): in other words, development in a matter of years on exposure to the atmosphere; and

(e) a structural timing for the structures post-dating jointing (Fig. 2e).

A general name to describe this effect is *fissility* (Wilson with Cosgrove 1982 pp. 35, 37). "Fissility" is a word commonly used to describe bedding-parallel partings in mudrocks and has served as a field criterion for distinguishing shale ("fissile") from mudstone (considered as "massive") (Pettijohn 1975, p. 261). The effect of bedding anisotropy is physically similar to that of a tectonic fabric in mudrocks; the splitting is parallel to, and depends on the degree of alignment of, clay particles, organic matter and lamination (Ingram 1953; Curtis et al. 1980). Like the transverse cracks discussed in (c) above, bedding-parallel fissility is also restricted to surface environments (Lewan 1978, p. 748) and for this reason has been called a "weathering phenomenon" (Lundegard & Samuels 1980, p. 781).

Thus, the term "fissility" is applicable to both bedding and cleavage structures: *bedding-fissility* for partings guided by bedding fabric, and *cleavage-fissility* for partings guided by tectonic fabric. This meaning is consistent with a literal interpretation of Van Hise's (1896, p. 450) definition for fissility as "a structure in some rocks by virtue of which they are already separated in parallel laminae in a state of nature", as distinct from "cleavage proper" which he regarded as a "capacity to part" rather than an actual parting. A similar definition was given in a related paper by Hoskins (1896, p. 872): "actual separation of the rock along certain planes".

The definition of "fissility" given by Van Hise (1896) was subsequently confused by many writers, including Van Hise himself (1896), Leith (1905), Knopf & Ingerson (1938), and Shaw (1957), who included under this term cleavages that were believed to form by fracturing ("fracture cleavage") or even a "capacity to part". However, there is a practical need to distinguish the two things. With the decline in use of the term "fracture cleavage" in modern writings, there is no longer a reason to confuse "fissility" or "actual separation ..." with "cleavage" as a fabric element having "a potential to part" (Dennis 1972) and Van Hise's "cleavage proper". So, we suggest using the term "fissility" in this sense as an incidental parting that follows a pre-existing tectonic fabric. This conforms with the way that the term is currently applied to undeformed mudrocks by sedimentary petrologists: partings that follow a bedding fabric or lamination (e.g. Pettijohn 1975).

Because it is the same phenomenon in slates as in shales, we propose an expanded role for the term fissility as a *fabric-dependent parting* that predominantly follows a tectonic fabric, or a bedding fabric, or both. Fissility, then, is a form of present-day open-crack structure that is guided by internal anisotropy and occurs naturally in surface outcrops as a result of, or through enhancement by, weathering. Cleavage, on the other hand, represents a potential for the rock to part on certain planes, as manifest, for example, when the rock is struck by a hammer.

Distinction between fissility and jointing

Joints may display a surface texture similar to fissility-cracks and, like them, some joints may be closely spaced (Priest & Hudson 1976), i.e. "extremely close" or < 2 cm in engineering parlance (Brown 1981, p. 18). Fissility-cracks nevertheless appear to originate in quite a different way and are distinct from joints in several respects.

(a) Fissility-cracks are less regular than joints, being characterised by curviplanar surfaces and seemingly unsystematic T-intersections in a 3D-network, producing a generally flat or elongate pattern of interlocking, irregular polygonoids. In contrast, joints in all rock types, including mudrocks, are usually very planar and parallel. (See Hancock 1982 for an analogous distinction between jointing and cracked spaced cleavage; also Siddans 1977; Price & Cosgrove 1990, fig. 9.31, and Figs. 2E and 14B here, for illustrations of joints in mudrocks.) Joints therefore appear in distinct orientational sets and tend to produce flat-sided angular blocks, often parallelepipeds and prisms.

Crack irregularity and crack length (discussed in the next point) are probably the most useful criteria for distinguishing the two types of fracture when the fragments are similar in size and shape. For example, the small parallelepipeds in Foster & Hudleston (1986, fig ??) are clearly joint-controlled, whereas the irregular chips and discontinuous cracks in our Figure 10 are fissility structures.

(b) Joints are much more continuous ("persistent"— Brown 1981, p. 19) in length, being commonly decimetric (Engelder 1987, fig. 2.15) to kilometric (Zhao & Johnson 1992, fig. 2), as opposed to the centimetric lengths that are typical of fissility-cracks. Thus, joints tend to traverse minor lithological junctions without interruption or deflection (Fig. 14b) and commonly produce boulder-size blocks, long slivers (e.g. Ramsay & Huber 1987, fig. 27.3) or long chains of blocks (e.g. Rawnsley et al. 1992). These properties presumably reflect relatively regular stress fields during the formation of many joints, particularly systematic joints, as would occur when a pre-existing regional tectonic stress is modified by removal of overburden pressure (Price & Cosgrove 1990), though local perturbations may occur (Rawnsley et al. 1992). In contrast, the stresses responsible for fissility-cracks are evidently more disordered, considering their small-scale variability. (It is possible that they are of internal origin associated with heterogeneous hydration and oxidation reactions during weathering.)

(c) Statistically, fissility-cracks develop parallel to tectonic and sedimentary fabric anisotropy planes, as observed microscopically (Durney 1982; Hancock 1982), mesoscopically, or by directions of preferred splitting on impact of a hammer. Joints, on the other hand, enjoy no such exclusive relationship, except that they may preferentially develop orthogonal to bedding (Hancock 1985) or cleavage (Siddans 1977, fig. 4).

(d) The frequency of fissility-cracks decreases very rapidly with depth below the earth"s surface, whereas joints, except for exfoliation structure and sheeting joints (Suppe 1985), persist well into the subsurface.

Fissility as a field basis for interpretation of cleavage intensity

Since fissility is the prominent attribute of cleavage on a mesoscopic scale, the scale of cleavage-intensity proposed here, at least as applied to penetrative-cleavage types, is based on fissility.

Fissility is a property which lends itself to quantitative description, because the degree of fissility in any one plane can be gauged from the spacing of the cracks. However, earlier attempts to define fissility scales on the basis of 1-dimensional spacing of bedding-plane partings (Lewan 1978, table 3; Potter et al. 1980, table 1.3; and, in part, Ingram 1953, p. 871) are limited by the fact that absolute spacing of the cracks depends on degree of weathering (see Lewan, 1978, for bedding-fissility, and p. 268 here, for tectonic fissility) and on rock and clay-mineral composition (Pettijohn 1975, p. 263–264; Blatt et al. 1980, p. 398) as well as on internal fabric and lamination.

The fundamental property that we seek a relationship to is the anisotropy of the parent-rock fabric. So it is more meaningful for this purpose to consider the anisotropy of fissility. The 3-dimensionally connected nature of fissility-cracks means that connecting cracks exist across the dominant fabric-plane as well as cracks along this plane. Hence the total network of cracks defines a statistical orientation-density tensor capable of possessing anisotropy: i.e. form, symmetry and orientation. It is easy to estimate all three attributes of the fissility-tensor in the field from the shapes and orientation of the split pieces of rock. Thus, different degrees of one fissility (say, a bedding fissility) in different directions can be judged from the width-to-thickness ratio of the platy fragments. Or two different fissilities in the same specimen can be compared from the cross-sectional shapes of the fragments.

Here, we use the latter property to define a relative-intensity scale for slaty cleavage and related structures compared with bedding. The assumption is that the shapes of the fragments reflect the relative strengths of the two fabrics. Hence, in any one rock type with a uniform initial bedding fabric, the shapes should represent an absolute strength of the cleavage fabric.

An advantage of this method is that it can be applied almost instantly in the field and does not require sophisticated microscopic or analytical procedures. It is furthermore unique in being a clearly observable and estimable index of fabric development over the entire range of fabric intensities and grain scales, and it is especially sensitive in precisely those areas where direct observation of fabric so often fails: in mudrocks and in the low-intensity fabric ranges.

Cleavage/bedding fissility ratio or relative cleavage-fissility scale

The intensity scale that we propose for cleavage-fissility is the relative intensity of tectonic-fissility compared with bedding-fissility in the same sample. We call this the *cleavage/bedding fissility ratio* or *relative cleavage-fissility*.

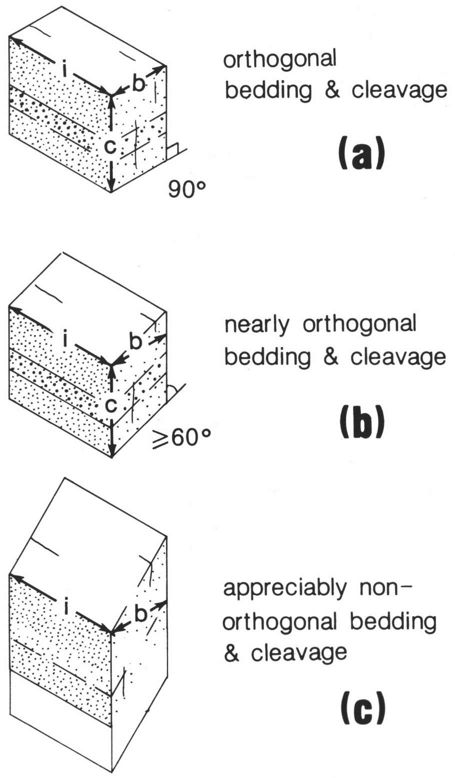


Figure 3. Fissility-fragment dimension measurements. Cleavage is vertical and trends '10 o'clock'; bedding is horizontal and shown by top surface and stippled band.
(a) & (b)—*orthogonal and nearly orthogonal cracks:* *c*, *b* and *i* may be measured as fragment lengths and widths parallel to 'cleavage', 'bedding' and 'intersection' directions, respectively.
(c)—*appreciably non-orthogonal cracks:* *c*, *b* and *i* are normal spacings of bedding, cleavage and transverse cracks, respectively.

To be recognisable as such, the fracture that we call "cleavage-fissility" should display a detectable, though not always strong, preferred direction transverse to bedding. It follows that cleavage-fissility cannot be directly distinguished when cleavage coincides with bedding; for purposes of measuring cleavage/bedding fissility ratios, the cleavage should be at a moderate to high angle to bedding (for example, near the hinges of folds).

A suitable index for this scale is the relative spatial frequency of cleavage-fissility cracks and bedding-fissility cracks, c/*b*, in the plane normal to the bedding/cleavage intersection. *c*/*b* may be measured simply as the aspect ratio of the fissility-fragments in the cleavage direction relative to the bedding direction in this plane (see Fig. 3 and further explanation in Appendix A). The order of the ratio (i.e. *c*/*b* rather than *b*/*c*) is significant; therefore it is necessary to know the directions of cleavage and bedding in the samples, preferably from observations of in-situ material. Where only a bedding-fissility exists, an analogous parameter to *c*/*b* is the thickness-to-width ratio of the fragments (c_0/b_0 or $b\perp/b$). This represents the inverse of bedding-fissility anisotropy (see eqn. 2, p. 275, and **Lithology effects— shaliness**, p. 280 for further discussion).

Being dimensionless, the quantity c/*b* may be applied to rocks with different absolute crack spacings and different weathering histories. In practice, we have found it to be consistent among fragments of different size; that is, smaller fragments preserve similar *c*/*b* ratios to larger ones, and larger fragments break up into smaller fragments of approximately similar shape.

In any one statistically homogeneous outcrop, the shape ratios of individual fragments nevertheless vary within a certain range. For measurements reported below, we estimated mean fissility-ratios by visual selection of mean-shape and extreme-shape fragments from representative samples comprising many fragments. Where greater precision is required, the mean of several such estimates has been taken. In all cases, we assume logarithmic mean values for "fissility-ratios" discussed here.

Cleavage/bedding fissility ratio or relative slaty-cleavage fissility categories

Fissility-fragments with predominant bedding-fissility and subordinate cleavage-fissility (*c*/*b* < 1) and those with intersection pencil structure (*c*/*b* 1), represent incipient forms of cleavage development. Fragments with predominant cleavage-fissility (*c*/*b* > 1) are manifestations of true cleavage in the sense that they reflect a planar tectonic direction of potential rupture of the rock (Dennis 1972).

These broad divisions may be further subdivided into a series of quantitative categories based on approximately binary logarithmic divisions of the *c*/*b* ratio (Fig. 4), thereby permitting greater descriptive precision than was possible previously when formal divisions did not exist. In earlier writings, it was common to call all obvious incipient forms of slaty cleavage, and some barely developed true slaty cleavages, "pencil cleavage" or "pencil structure". The categories presented below allow this broad field to be separated into more truly equidimensional cross-section "pencils" (0.7 to 1.4 aspect ratio), and structures having varying degrees of relative cleavage-fissility both stronger and weaker than this. In this way, the scheme extends and refines earlier ideas that originated from the study of pencil structure (esp. Ramsay 1982 or Ramsay & Huber 1983, p. 185–188; Reks & Gray 1982).

(a) *Cleavage-fissility absent* (*c*/*b* generally small)—rock does not split in any preferred direction transverse to

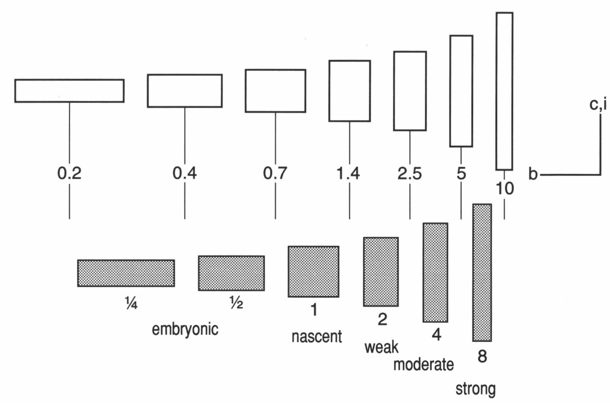


Figure 4. Fissility-crack ratio categories. *Open rectangles:* decimal divisions corresponding to a nearly binary progression. *Shaded rectangles:* approximate median values of categories. Ranges are: 0 < *c*/*b* < ∞ and 0.7 < *i*/*b* < ∞.

bedding. Bedding-fissility, ordered sets of subplanar joints, and (in mudrocks) irregular polygonal transverse cracks are the only fractures present. In some cases, the rock is known to be tectonically deformed from field relations or deformation of primary structures, but no preferred fissility can be found. This case is mainly of interest for penetrative 1 "grain" cleavage types.

(b) *Embryonic cleavage-fissility* (c/b < 0.7)—rock splits with comparative difficulty in the tectonic direction: bedding-plane fissility is dominant, though may be widely spaced in arenites. Mudrocks yield a bedding-parallel 'platy', 'blade' or 'matchbox' structure, though with a recognisable elongation in the tectonic direction; the fracture is often curviplanar, subconchoidal or ragged; oval corestone or spheroidal weathering may occur in mudrocks in weathered environments: *pre-pencil structure* (especially when markedly elongate in the intersection direction) and *pre-reticulate structure* (weakly to moderately elongate).

(c) *Nascent cleavage-fissility* (c/b 0.7–1.4)—rock splits roughly equally in bedding and tectonic directions. Mudroks yield irregular polygonal to rhomboidal cross-section, curviplanar, prismatic fragments elongate in the intersection direction: bedding-parallel *pencil structure* (when strongly to very strongly elongate) and *reticulate structure* (when weakly to moderately elongate).

Well-sorted arenites show a distinct though weak grain flattening.

(d) *Weak cleavage-fissility* (c/b 1.4–2.5)—the first appearance of true cleavage structure: the rock splits more readily, though weakly, in the tectonic direction; matchbox-like and slightly flattened prisms elongate in the intersection direction are typical ("intersection pencil structure" of Ramsay & Huber 1983, p. 186).

(e) *Moderate cleavage-fissility* (c/b 2.5–5)—rock splits readily and preferentially in the tectonic direction; bedding-fissility is subordinate, but usually distinct. The tectonic fissility tends to be somewhat curviplanar and disconnected. Mudrocks normally yield truncated lensoid fragments.

Poorly sorted arenites mainly show weak grain flattening and grain impingement; well-sorted arenites show clear grain flattening.

(f) *Strong cleavage-fissility* (c/b 5–10)—rock splits almost invariably in the tectonic direction; bedding fracture is uncommon except at lithological junctions. Cleavage fracture tends to be planar and closely spaced. Yields sharply ended flakes and sheets; an intersection lineation may be observed on the cleavage surface, but general alignment of the minerals on this surface is not obvious, except possibly in arenites.

Poorly sorted arenites display distinct grain flattening, while well-sorted arenites show strong flattening and elongation.

(g) *Very strong cleavage-fissility* (c/b 10–20)—rock splits in a manner similar to strong fissility, but cleavage flakes are more highly planar, and all lithologies may display a distinct elongation of constituent minerals or of cleavage flakes on the cleavage surface: a mineral lineation. This lineation may be expressed as an elongation of coarser grains, of augen or beard structures around coarser grains, of corrugations or of cleavage flakes; to be clearly recognisable as a mineral lineation it should usually be observed at an angle to the intersection lineation or to the known direction of the bedding/cleavage intersection lineation.

Poorly sorted arenites display strong flattening of grains parallel to cleavage.

(h) *Extremely strong cleavage-fissility* (c/b > 20)—a further development beyond category (g), c/b = 40 being a probable practical upper limit for cleavage/bedding fissility measurements because of a tendency for interference from later structures in highly deformed material.

Effect of lithology

For comparable results, cleavage/bedding fissility observations should be restricted to a particular lithology, since lithology will affect the strength of the initial bedding fabric (Spears 1980) and hence the stage of deformation at which a planar cleavage fabric first begins to appear. For example, a shale with "nascent relative cleavage-fissility" (pencil structure) is likely to possess a stronger tectonic fabric than a mudstone with "nascent relative cleavage-fissility" (reticulate structure), since it balances a stronger bedding fabric. Similarly, in mudstones with only weakly developed bedding-fissility, 'absolute' cleavage-fissilities similar to those formed in associated shales (with a strong bedding-fissility) should result in much higher c/b ratios.

The cleavage/bedding fissility scale is intended primarily for rocks with poor initial bedding anisotropy, such as mudstones, marls and wackes. It may also be applied to shales and other rocks with strong initial bedding fabric, such as finely laminated shale–siltstone composites and sandstones with closely spaced carbonaceous partings. But, in this case, no direct equivalence with mudrock fissility can be assumed. Therefore, it is advisable to supplement the observations with measurements of fissility-fragment aspect ratio in the bedding plane to define more fully the respective influence of bedding and cleavage fabrics.

Relative intersection fissility scale

In order to incorporate the effect of lithology in the relative slaty-cleavage-fissility scale, and to indicate the extent of tectonic fabric development in rocks of different initial bedding anisotropy, the relative length of the fissility-fragments measured in the direction of the cleavage/bedding intersection lineation (i) has to be considered.

This can be done using the i/b ratio of fissility-fragments in the bedding plane: the length (i) of fissility of fragments in the cleavage/bedding intersection direction over their width (b) normal to i in the bedding. This ratio, which we call the *intersection fissility-ratio*, is similar to the l/w shape factor used by Reks & Gray (1982, p. 163) to describe pencil shapes, except that i is taken as the actual length of the fragments, whereas l is the projected taper length. An alternative procedure, which is convenient for rocks with a strong cleavage, is to measure the ratio of the length of cleavage fractures in the intersection direction over their height, i/c (Fig. 3), and to compute i/b from this and from c/b .

As noted for the "cleavage-fissility absent" category in the relative slaty-cleavage-fissility scale, cases where a tectonic fabric appears to be absent are represented by equidimensional polygonal fragment shapes in the bedding plane, or i/b = 1. Increasing unidirectional or planar tectonic fabric development should therefore produce fissility-fragments of increasing slenderness in the intersection direction, or $i/b > 1$. This should occur in both shales and massive lithologies. Thus, whereas c/b measures degree of cleavage development, i/b represents an index for degree of directional tectonic fabric development which begins at the most incipient stages. For this reason, it should be closely related to the degree of tectonic deformation and is necessary for interpreting deformation as against just cleavage development.

However, because fissility-ratios are only secondarily related to fabric and strain, they may be (and are) both numerically different from tectonic stretch-ratios and capable of bearing different relationships to stretch-ratio in different rock types. Also, the proviso of a unidirectional (or plane) tectonic fabric modification is necessary for tectonic intensity interpretations of i/b, because two or more weak tectonic fabrics transverse to bedding may combine to produce what we call "transverse pencil structure" and "transverse reticulate structure" with i/b 1, but $c/b > 1$. This case may show little or even no anisotropy in the bedding plane, but may nevertheless have a distinct linear fabric at an angle to bedding, signifying a significant deformation. A similar effect could be produced by a single, well-developed "stretching" deformation (Cloos 1946, p. 18) or "grain" (Wilson with Cosgrove 1982, p. 63–64) oblique to bedding. The simple interpretation of i/b as a tectonic index thus requires observations to be restricted to regions with single- (first-) generation structures with a single axis of tectonic shortening—for example, a system of straight horizontal folds—as well as to a single rock type and deformational regime.

Three-dimensional fissility-fragment shape

Combined measurements of i/b and c/b define a 3-dimensional (3D) fissility-fragment shape, which can be shown on a 3-axis diagram similar to that adopted for 3D natural strains by Owens (1974) after Hsu (1966). This diagram shows deviation in shape of an object, say a rectangular parallelepiped, from an equant body of the same volume (a cube), along three fixed principal axes. The axes have a logarithmic scale with zero at their common origin. Each shape plots as a single point on this diagram, with cubes at the origin and increasingly slender shapes farther out. Points on the diagram can be visualised physically as approximately the offset positions of the upper front corner of rectangular objects relative to the lower rear corner, when viewed in isometric projection (compare dot positions on objects and plot in Fig. 5). In addition to representing invariant shape, the diagram also shows which of the three reference axes the object"s longest and shortest axes are aligned with.

Special features of the fissility-ratio system and the way it represents shapes are described here. As reference axes, we choose directions C, B and I of the cleavage, bedding and intersection fissility dimensions c, b and i (Fig. 3), respectively. The C-axis is drawn in a 'vertical' position to represent the reference bedding orientation as a 'horizontal' plane (tilted slightly towards the observer). Axes C and I contain the plane of dominant cleavage, which has a 'vertical' reference orientation striking '10 o'clock'

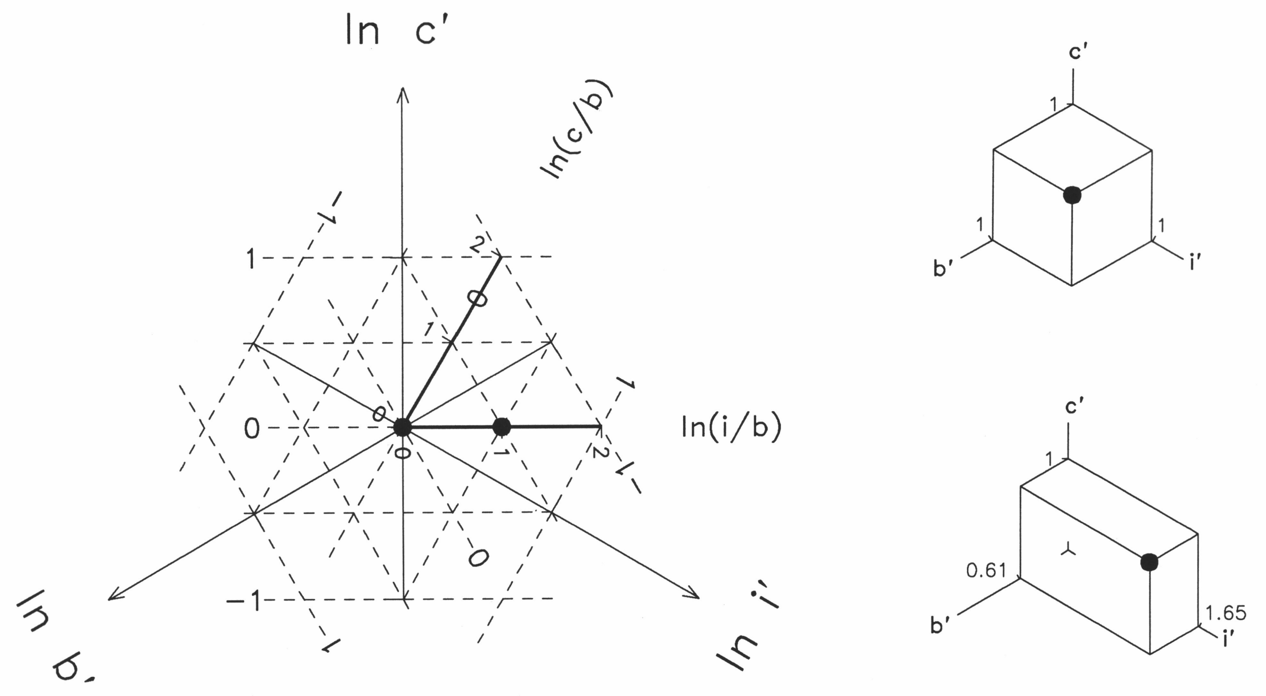


Figure 5. Relationship of axes on a logarithmic 3-axis shape/orientation diagram. Principal axes (ln c', ln b' and ln i') define prolateness of axisymmetric shapes in fixed directions C, B and I respectively. Axial ratio axes (ln(c/b) and ln(i/b)) define 2D shapes seen on specific principal planes. Slenderness of shapes increases outwards from the centre of the plot while shape type and orientation varies with polar direction. At each point, ln c' + ln b' + ln i' = 0, ln(c/b) = ln c' − ln b' and ln(i/b) = ln i' − ln b.' The example cube (upper right) plots at the centre of the diagram. The example blade (lower right) plots at the point ln c' = 0, ln i' =½, ln b' =−½, and hence at ln(i/b) = 1. (See text for further explanation.)

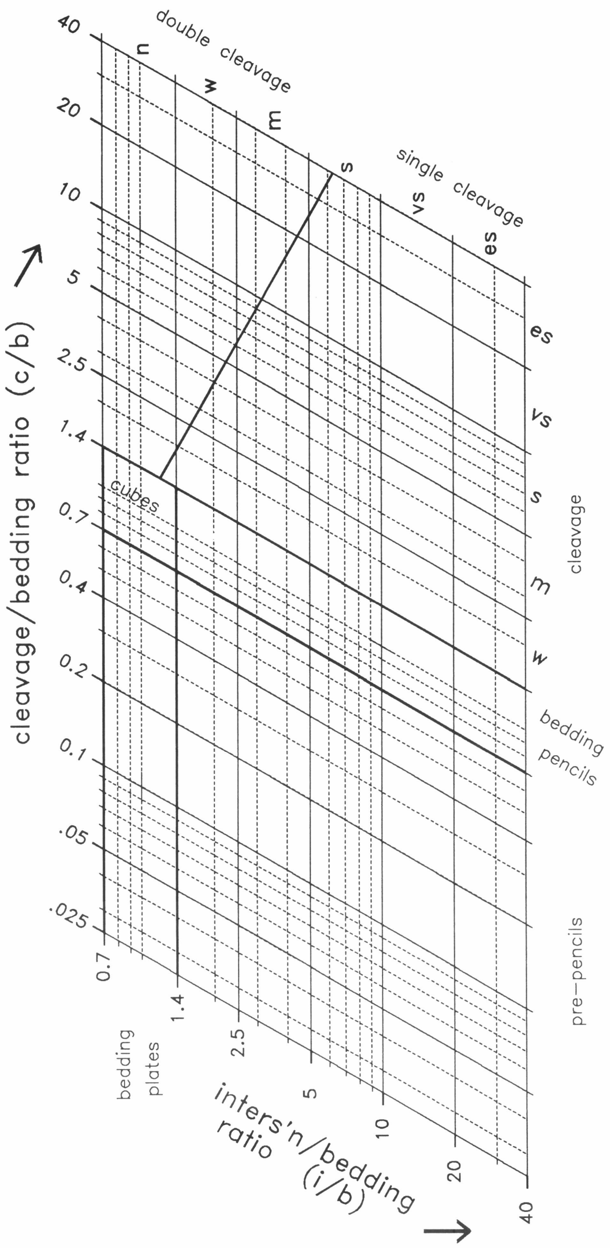


Figure 6. Logarithmic 3-axis grid for plotting *c*/*b* and *i*/*b* fissility-ratios or categories. Category divisions are shown by solid lines. The suggested relative strength categories are: *n* ('absent'), *w* ('weak'), *m* ('moderate'), *s* ('strong'), *vs* ('very strong') and *es* ('extremely strong'). Only the right hand field is shown, corresponding to one dominant cleavage and increasing *i*/*b* values.

to '4 o'clock'. Principal axis dimensions are ln c', ln b′ and ln i′, respectively, where c′, b′ and i′ are the measured fissility dimensions normalised against the cube root of their product (c′ ≡ $c/(cbi)^{1/3}$, etc.).

The fissility-ratios c/b and i/b are shown as natural logarithms, $\ln c/b = \ln c' - \ln b'$ and $\ln i/b = \ln i' - \ln b'$, along a pair of subsidiary axes 30° from the C (ln c') and I (ln i') axes, respectively. Contour lines drawn normal to any principal axis or subsidiary axis show the value of the logarithmic quantity along that axis. However, the subsidiary axes, derived vectorially from the principal axes by the above equations, have a different scale, as shown in Figure 5. Contours and descriptive categories for direct plotting of c/b and i/b ratios in logarithmic 3-axis format are shown in Figure 6. If normalised principal values are required, they can be obtained from ratios most conveniently by expressions of the type: $i' \equiv i/(cbi)^{1/3} = [(i/b)^2/(c/b)]^{1/3}$.

Assuming there is only one dominant cleavage direction, all shapes can be represented in one half of the 3-axis diagram, as shown in Figure 7. Distance from the centre represents degree of slenderness, while angular position around the centre shows the type of shape and its orientation in the *C*, *B* and *I* coordinate directions. Thus, *bedding plates* and *cleavage plates* lie in the –*C* and –*B* directions, respectively, whereas *pencil structures* may be elongate either in the +*I* (*bedding*) or in the +*C* (*transverse*) direction. Intermediate polyaxial shapes are called *laths* or *blades*, with a distinction between *broad* and *narrow* forms according to whether they lie closer in shape to plates or pencils, respectively. Blades that are halfway between plates and pencils (with intermediate normalised dimension equal to 1) are called *biaxial*. The three possible orientations of blades are distinguished according to the dominant plane (*bedding* or *cleavage*) and, in the case of cleavage blades, the long-axis direction (*bedding-elongate* or *transversely elongate*): for example, "biaxial bedding-elongate cleavage blades" along the *I–B* (ln *i*/*b*) axis.

From a structural point of view, the most meaningful divisions are between:

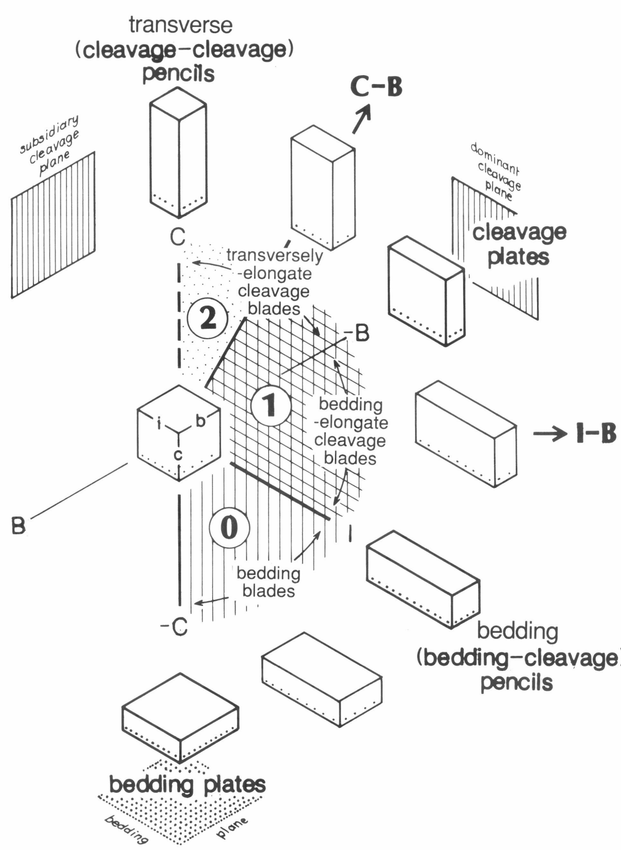


Figure 7. 3D fissility-fragment *shape fields* on a 3-axis diagram. Dimensions and orientations are shown relative to fixed fabric principal directions: *C*, *B* and *I*, as shown in Fig. 3. *Field 0:* bedding-dominant. *Field 1:* single-cleavage dominant. *Field 2:* multiple- or linear-cleavage dominant.

- bedding-dominant structures—*Field 0*: c/b <1;
- single-cleavage dominant structures—*Field 1*: c/b >1 and $i > \sqrt{(c'b')}$; and
- multiple transverse cleavage structures—Field 2: $i' < \sqrt{(c'b')}$ (see Fig. 7).

For practical purposes, we recognise bedding plates, bedding pencils and cubes as distinct groups of structures with finite c/b and i/b ranges (see Fig. 6). Therefore, these groups, in effect, represent transitions between Field 0 and adjoining fields. The basis for the Field 1 to 2 division is discussed further in connection with multiple deformation at the end of the paper.

The 3-axis fissility diagram shows most directly the shapes of orthorhombic fragments. Moderately monoclinic and triclinic shapes can be plotted and classified in the same way, insofar as c, b and i are independent quantities (Appendix A) and thus algebraically orthogonal. However, the axes on the plot do not then correspond physically to axes of oblique-fissility samples, and predictions based on orthogonally superposed fabrics (outlined in the next section) probably will not apply in precisely the same way.

Models of fissility intensity and style on a 3-axis diagram

It is useful to consider ways in which a tectonic fabric might be superimposed on an initial bedding fabric and how this would be expressed in the resulting fissility-fragment shapes.

In the absence of a suitable theory for oblique-coaxial superposition of fabrics, we consider combinations of orthogonal-coaxial superposition. In particular, we explore the consequences of assuming that:

(1) fissility-fragment shape is directly related to total fabric;
(2) the total fabric comprises an initial bedding-parallel oblate part and an orthogonal coaxially superposed tectonic part;
(3) the tectonic part of the total fabric is directly related to tectonic deformation; and
(4) relations between the sets of principal ratios for fissility, fabric and deformation are of a power-law type and are unique for each rock type and each pair of ratio sets; e.g.

$$c/b = p\ (s_c/s_b)^n; \qquad (1a)$$

$$i/b = q\ (s_i/s_b)^n; \qquad (1b)$$

for relations between fissility and deformation, where the s parameters are stretches parallel to fissility axes and p, q and n are constants).

It can be shown that fissility-fragment shapes that vary in a regular way in one rock type would then fall on a locus in the same relative positions and with the same gradient on a logarithmic plot as the relative positions and loci of fabric variation and deformation variation in that rock, though all three loci would generally be different in length and different from loci in other rocks. (The *loci*, or *fields* if they occupy areas on a logarithmic plot, refer here to variations of final states through space.) These correspondences would therefore allow deductions to be drawn about the *relative intensities* (relative plot positions) and *style* (plot gradient) of fabric and total deformation variations in a region from the relative intensities and style of the fissility variations.

An important property of the logarithmic 3-axis diagram is that multiples of the same shape transformation, applied coaxially in the same way to any initial shape, plot as equally spaced points on a *straight line* locus. This results from the logarithmic conversion of shape multiples to simple vector sums. The direction of the line indicates the type of shape change, while the starting point represents the initial shape. On a natural strain plot (Hsu 1966), such lines would correspond to loci of increasing distortional strain of a particular 3D type superimposed on some initial object shape. On a fissility-fragment shape plot, the lines represent increasing degrees of tectonic fissility intensity of a particular type superimposed in a particular way on a notional initial bedding-fissility anisotropy. Quantitatively, this is expressed by a relation between fissility ratios:

$$\ln c/b = \ln A + B \ln i/b, \text{ or} \qquad (2a)$$

$$c/b = A\ (i/b)^B, \qquad (2b)$$

where A is the intercept of c/b for the undeformed state (i/b = 1), equal to the inverse of bedding-fissility anisotropy ratio, and B is the gradient:

$$\Delta \ln (c/b)\ /\ \Delta \ln (i/b)$$

of the line on a ln c/b versus ln i/b plot, representing the local deformational style (tectonic axial ratio type

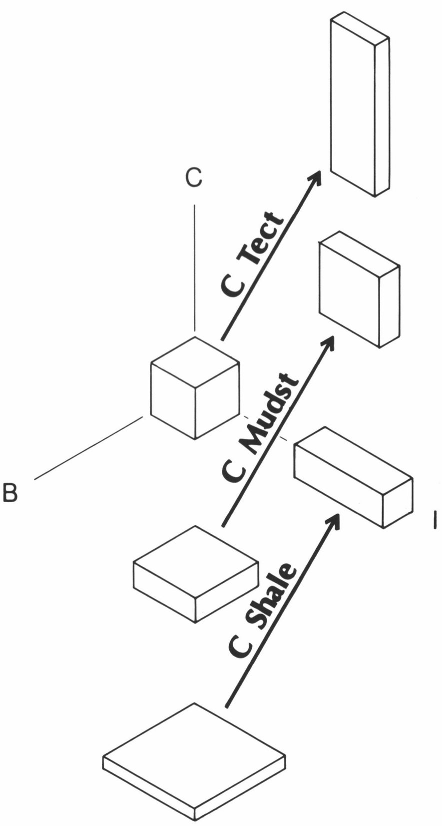


Figure 8A. Effect of *bedding-fissility strength* on fissility-fragment shape locus in a single tectonic regime. Cleavage-fissility in this example is assumed to be directly related to a biaxial, layer-parallel shortening and layer-normal extension (a contraction locus). *C Tect:* no bedding-fissility. *C Mudst:* notionally 'moderate' bedding-fissility, as in a mudstone. *C Shale:* notionally 'strong' bedding bedding-fissility, as in a shale.

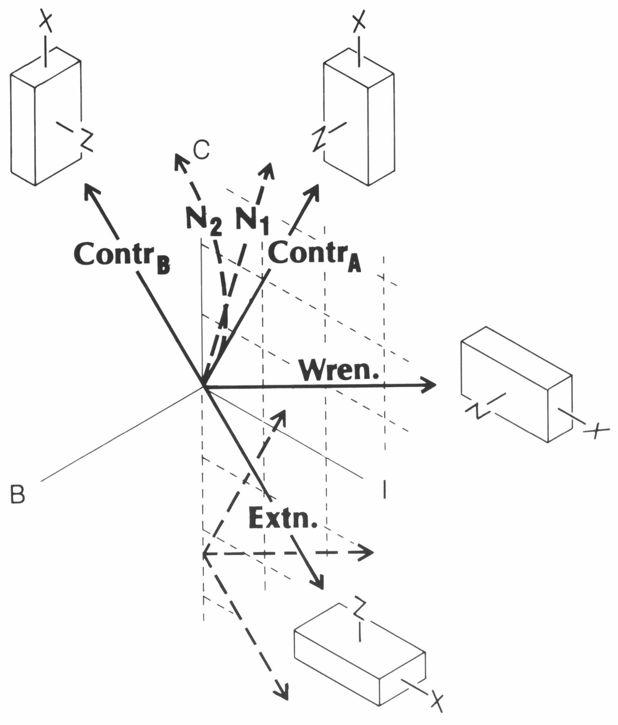


Figure 8B. Effect of *tectonic deformation style* on fissility-fragment shape locus, beginning with an isotropic (unbedded) material. *Contr, Wren* and *Extn* are biaxial fissility-fragment shape loci assumed to correspond to biaxial, bedding-parallel, 'contraction-', 'wrench-' and 'extension-' tectonic deformations, respectively. Principal directions of tectonic elongation (X) and shortening (Z) with respect to bedding (IB plane) as shown. N_1 and N_2 are non-plane loci. N_1 has a constant style and N_2 a changing style. $Contr_B$ shows a locus which is horizontally orthogonal to (the mirror of) $Contr_A$.

and its orientation with respect to bedding).

Figure 8A illustrates this idea for one type of fissility locus superimposed on three materials of different initial anisotropy. The loci start at different positions on the $-C$ axis, because of differing initial bedding platiness, and they trend upwards at the same angle for the same distance, as a result of experiencing identical tectonic fissility modifications. The locus for the initially isotropic material is not influenced by the initial state and so shows the tectonic changes directly. The initially anisotropic materials, however, show complex shape series resulting from interplay of the two factors. Also, the more anisotropic the starting material (e.g. a 'shale' compared with 'mudstone': Fig. 8A), the greater is the change in fissility intensity required to reach a shape of any particular type, say, pencils.

The kinds of alternatives expected when different types of locus or tectonic modification are superimposed on any one material are shown in Figure 8B. The straight lines are loci of constant shape-change type, whereas curved lines are loci of varying shape-change type.

Three biaxial straight-line loci (loci for which there is no change in the intermediate normalised fissility dimension) are of special interest as analogues of constant-volume plane-strain deformation on a deformation plot. We call these *contraction-*, *wrench-*, and *extension-loci* by geometric analogy with the "contraction" and "extension" fault kinematic categories proposed by Norris in relation to bedding (Hancock 1985, p. 440; Hatcher 1990, p. 213). They represent three different ways of coaxially superimposing an ideal plano-linear cleavage fabric on a planar bedding fabric. In the contraction type (B = 2), cleavage is superposed normal to bedding, while the beds undergo shortening and thickening. In the wrench type (B = ½), cleavage is also normal to bedding, but there is elongation in the plane of bedding instead of thickening of the beds. In the extension type (B = –1), cleavage is bedding-parallel and accompanied by thinning of the beds and extension in one direction in the plane of bedding.

These three loci concern local cleavage/bedding relations in the field. Because the way that strains are superposed on bedding varies according to position within folds (Mazzoli & Carnemolla 1993), the corresponding fissility states will generally vary from one part of a fold to another, particularly between the limbs and hinges of open to tight folds (Mazzoli & Carnemolla 1993, figs 14–17). Hence, to investigate variations of fissility state on a regional scale, it is necessary to select measurement sites with comparable deformation histories and comparable positions within folds, such as in the middle of incompetent layers in fold hinge zones.

If, after allowing for local variation within folds, there is a consistent linear locus of fissility across a region, it suggests there is probably a corresponding consistent deformation style at the regional scale. To distinguish these regional styles or "tectonic regimes" from the *cbi* bed-related loci discussed above, the three simplest biaxial regimes will be called *contraction-tectonic*, *wrench-tectonic* and *extension-tectonic*, according to whether the particular section of crust under study has been shortened and thickened, shortened and orthogonally extended, or thinned and extended, respectively. These categories are equivalent to the "thrust", "wrench" and "gravity" regimes, respectively, of Harland & Bayly (1958), except that they are expressed here in terms of deformation rather than stress. When bedding is subhorizontal (as in the hinges of upright folds), the *c*, *b* and *i* fissility coordinates may correspond to the *V*, *H* and *L* tectonic coordinates of Harland & Bayly (1958), in which case the fissility data may be interpreted directly in terms of the regional tectonic regime.

Our final section discusses some field examples illustrating the use of the fissility-ratio technique and applications of the concepts that have been outlined in this section.

Field examples of relative fissility intensity

The following sections illustrate applications of the two scales of relative fissility to quantification of cleavage and tectonic fabric intensity in the field.

The *c*/*b* (cleavage/bedding) ratio and, especially, the *i*/*b* (fissility-ratio in the plane of bedding) ratio, provide sensitive indicators for the early stages of fabric development. A simple way of describing a progression of cleavage development states is to measure the *c*/*b* fissility-ratio in a fixed rock type. Our first set of examples shows such a progression of *c*/*b* in mudstones, from undeformed bedding-fissility to a well-developed slaty cleavage. However, for a more complete picture it is necessary to include also measurements of *i*/*b* at the same outcrops. We have therefore included illustrations of *i*/*b* in this series. The photographs and ratio data for this series thus form a reference set which serves as a guide to the way we envisage the method can be applied in the field.

Subsequent examples deal with several further and also little-investigated effects: effects of lithology (grain size, initial anisotropy, and ability to crack) and effects resulting from the apparent superposition of two cleavage fabrics at a high angle to each other. Both of these can have a significant influence on fissility-ratios and on the interpretation of these ratios in terms of tectonic deformation and structural evolution. To infer a particular style of deformation from fissility measurements, it is necessary to isolate the possible influence of variable initial bedding anisotropy and, if possible, to conduct measurements in regions which have just a single cleavage fabric. To do this, measurements of both *c*/*b* and *i*/*b* are required. In addition, these ratios can be used to identify regions where cryptic multiple deformation occurs; we give an example of this little-documented, but fairly widespread phenomenon, from the Lachlan Fold Belt of New South Wales (NSW).

Progression of relative cleavage-fissility and intersection-fissility, Manilla district of the Tamworth Belt, NSW

The Tamworth Belt (Fig. 9A) is a west-verging fold-and-thrust belt belonging to the western margin of the Late Permian–Triassic New England Fold Belt in northern NSW (Korsch 1977). It is an essentially linear belt, some 60 km wide, comprising Devonian to Permian arc-derived volcaniclastics, volcanics and minor limestones, that is affected by colinear, NNW-trending, gentle to tight upright folding and is bounded by major thrust faults (Pedder 1967; Chesnut et al. 1973; Leitch 1974; Leitch et al. 1988, p. 12–15; Liang 1991; Brown et al. 1992). Some thrusting or reverse faulting also occurs within the belt.

A dominant lithology over much of the region is a turbiditic grey-green mudstone, having a litharenite composition with a mainly andesitic volcanic provenance (Morris 1988; Chappell 1968). It occurs in four main formations: the Noumea Beds, Lowana Formation and Mandowa Mudstone (all Upper Devonian), and the Namoi Formation (Lower Carboniferous) (Brown et al. 1992). These formations include arenaceous and rudaceous members and are capped by a thick succession of fluvial sediments and volcanics deposited in partly glacigene conditions.

"Reticulate cleavage" (reticulate structure) was first described by Crook (1964, 1982) from mudstones of this fold belt in a region south of Tamworth in the Goonoo Goonoo Mudstone, a unit equivalent to the Mandowa Mudstone and Namoi Formation farther north. Packham & Crook (1960) also described several stages of incipient metamorphism in the Tamworth Belt, interpreted as a burial metamorphism.

A reconnaissance study at about the latitude of Manilla, some 50 km north of Tamworth, indicates the presence of incipient reticulate structure over the gently folded western three-quarters of the Belt (Fig. 9B). Near the eastern boundary of the Fold Belt it rapidly increases in intensity and locally becomes a strong slaty cleavage associated with tight upright folds (Fig. 9C). For most of the region, up to a few kilometres from the Peel Fault, the trace of the fissility on bedding is concordant with the NNW-trending regional folds and thrusts. As shown by the photographs, the optimum material for study is *in-situ* material that has been strongly disaggregated, but not significantly disoriented, by weathering processes.

No examples of completely undeformed mudstone were found in the western section of the belt, but one is present in the centre of the Manilla Syncline (Voisey 1957), where it is presumed to have been protected by underlying arenite members of the Lowana Formation (Fig. 9C). This example, sample 1 of the series, is shown in Figures 10a and b. The *c*/*b* ratio at this location is estimated to be about 0.3 (Fig. 10a). As in other examples of this series, this ratio was estimated visually in the following manner: identification of the most slender fragments, identification of the least slender fragments, then estimation of the mean or most common dimensional ratio as the cited figure. Typically, the extreme values vary by a factor of one category interval (x2 to x½) from the mean. Fissility on the bedding plane (Fig. 10b) is a completely random network of polygonal cracks, having no preferred direction, apart from locally in the neighbourhood of transecting joints, and no visible relation to the known fold-axis direction, which here runs upwards across the photograph.

Sample 2 of the series is a typical "embryonic cleavage-fissility" or "pre-reticulate" structure from the western half of the fold belt near Keepit Dam (Fig. 10c, d). S_0 (bedding) fissility is dominant in most of the outcrop. However, the view parallel to fold axis (horizontal, Fig. 10c) shows a weak but distinct preferred orientation of steep S_1 (embryonic cleavage) fissility-cracks in the approximate orientation expected for the axial plane of major folding at this location. The existence of a tectonic fabric anisotropy in the mudstone is confirmed by a clear alignment of fissility-cracks on the bedding surface (Fig. 10d) with *i*/*b* about 2.5.

Examples of roughly equidimensional *c*/*b* "reticulate structure" in mudstone are found in a major anticline immediately east of the Manilla Syncline (sample 3 in Figure 10e, f). *i*/*b* here is noticably greater than the previous example—around 3 to 4—consistent with it having a stronger tectonic imprint (Fig. 10f). Although pencil-like in form, the structure is too short to be called pencil-structure; therefore, we use the term reticulate structure to describe these. (This is a slightly more restricted usage than Crook's (1964) original, which he applied to examples with a marginally dominant S_1 fissility.)

The first stage of true, planar, cleavage-fissility (sample 4) is observed on the eastern limb of the previously mentioned anticline. (Crook 1964, plate 1, shows a similar example from a locality south of Tamworth.) Figure 11a shows this fissility in profile with a reasonably good planar preferred orientation of S_1 cracks at 40° to bedding. This case is closely related to the previous example of reticulate structure *sensu stricto*, but has a noticably more pronounced development of S_1 fissility over S_0 fissility, which we call "post-reticulate structure" or "weak slaty cleavage-fissility". As the bedding/cleavage angle is less than 60°, the observed length/orthogonal width ratio in profile ($c/c\perp = 2.5$, where $c\perp$ is normal to c) requires a downward adjustment by sin 40° to give a true crack-spacing ratio of $c/b = 1.6$ (cf. Fig. 3). The *i*/*b* ratio (4) is viewed down-cleavage in Figure 11b and so shows the true crack spacings. These ratios define "narrow bedding-elongate cleavage blades" (Fig. 7), typical of the beginning stages of a true cleavage in many fold belts (e.g. Ramsay & Huber 1983, fig. 10.27).

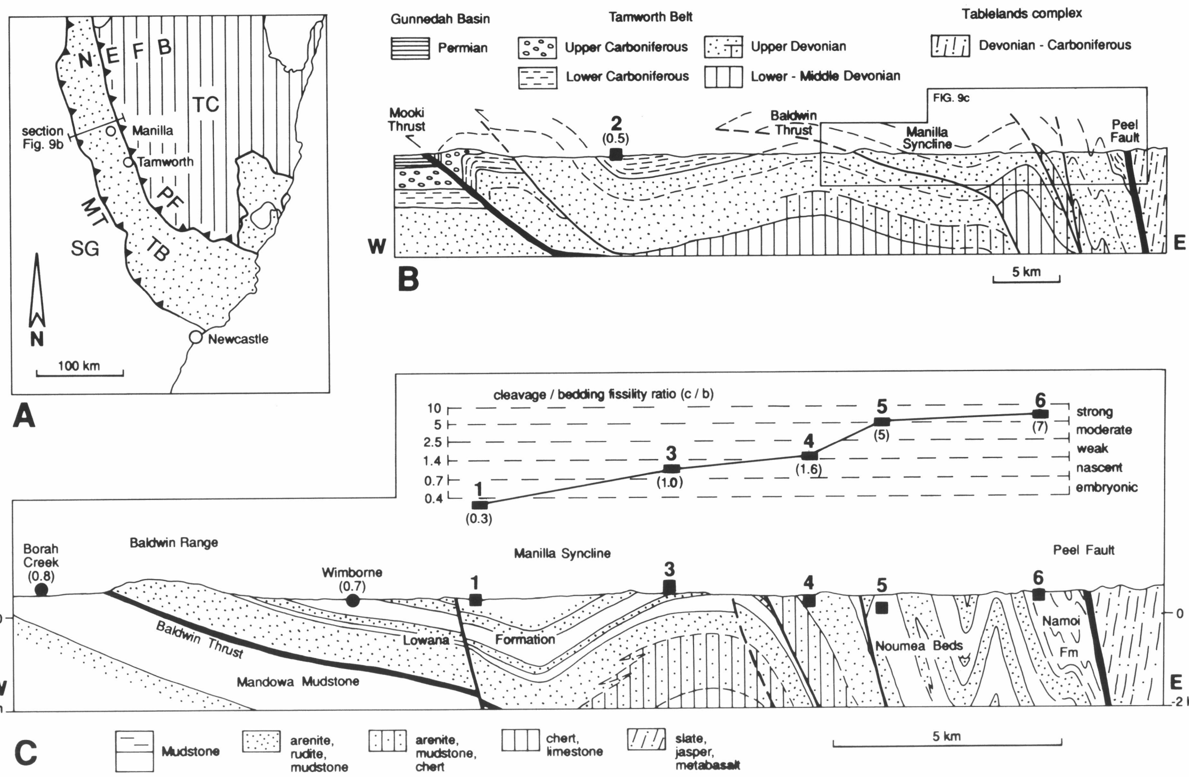


Figure 9. Location of mudstone fissility progression samples, Manilla, NSW, shown in Figs 10 & 11. A—Location of area. *MF*: Mooki Fault. *NEFB*: New England Fold Belt. *PF*: Peel Fault. *SG:* Sydney–Gunnedah Basin. *TB*: Tamworth Belt. *TC*. Tablelands Complex. B—Section through Tamworth Belt, Keepit to Manilla (modified after Liang 1991). Includes location of sample 2. C—Section and *c*/*b* fissility-ratio profile through eastern margin of Tamworth Belt along Namoi River, Manilla, NSW (based on field studies by D.Durney, P.Conaghan and students) showing sample locations 1 and 3–6. Section coordinates (AMG): 669045 (W), 807075, 848092, 921117 (E).

The remaining two examples are from the region of close to tight folds in the far eastern part of the Tamworth Belt.

Sample 5 (Fig. 11c, d) we categorise as having a "moderate to strong" slaty cleavage-fissility. Although not what most observers would call a "slate", it displays a clear and dominant S_1 fissility in profile. The *i*/*b* ratio here is similar to *c*/*b* (5), defining an oblate "cleavage plate" morphology in 3D.

Sample 6 (Fig. 10e, f) shows the strongest planar cleavage observed in this Belt, about 1 km from the bounding Peel Fault. It is definitely a "strong" slaty-cleavage-fissility, and approaches oblate "cleavage plate" morphology, though still with a greater length in the intersection direction and no sign of stretching lineation on the cleavage surfaces.

3D interpretation of Manilla mudstone fissility series

The 3D fissility-fragment shapes of the preceding cleavage-fissility series are plotted on a 3-axis logarithmic ratio diagram in Figure 12. We refer to the field of points in Figure 12 as the *Manilla mudstone field* (see Table 1, Appendix B, for sample descriptions).

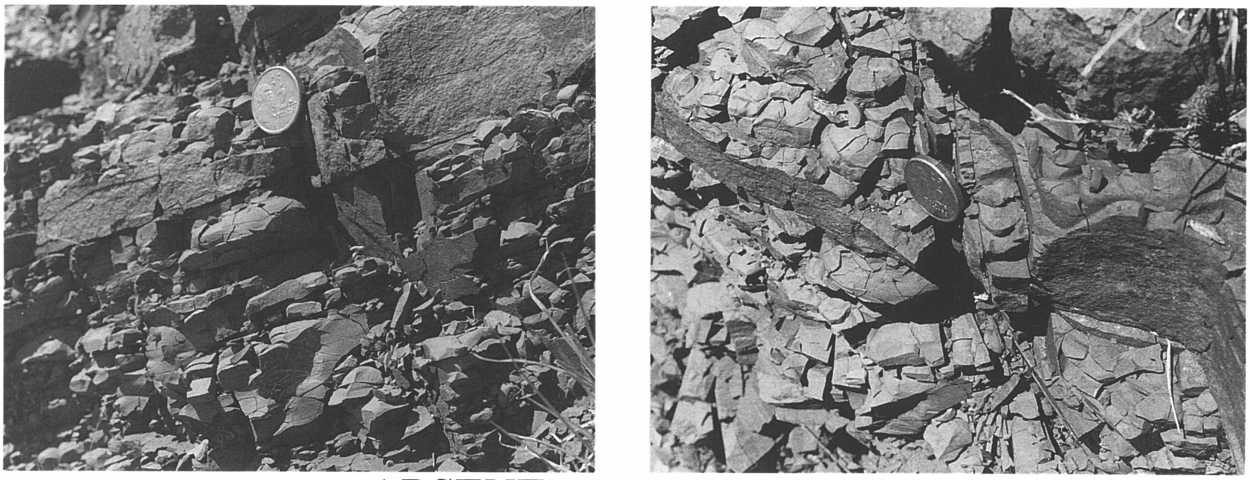
The most striking feature of this distribution is its confinement to an *I*-constant band parallel to the *c*/*b* axis. *c*/*b* ratios correlate well with *i*/*b* according to a mean relation represented by

$$c/b = A\ (i/b)^B,$$

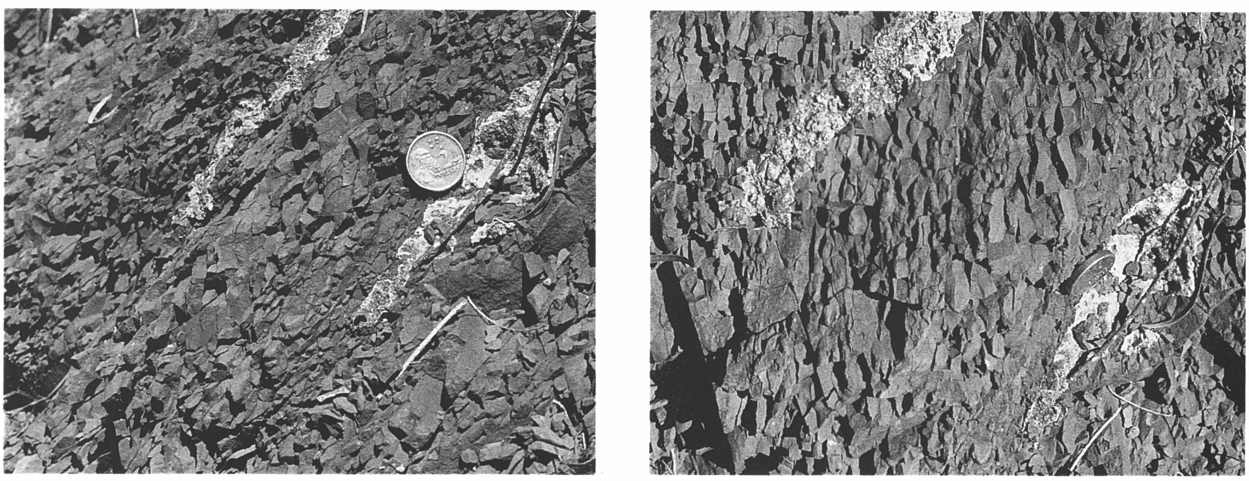
(eqn. 2b) where $A = 0.16$ and $B = 1.86$. The constant A is the mean initial cleavage/bedding fissility ratio, where the projected mean trend of the distribution intersects the $i/b = 1$ axis. From A we may calculate $i' = (1/A)^{1/3} = 1.84$.

With minor variations, and despite increasing tectonic modification, other samples from this series show similar values of i'. Since the samples are all of similar mudstone lithology, it seems reasonable to conclude that initial bedding fabric is responsible for this feature and has been preserved in the uniform i' values. Consequently, the inverse of A (or $b_0/c_0 = 1/A$, the projected bedding/cleavage fissility ratio) represents a measure of this initial anisotropy. It has a value of 6.3 or is "strong" according to the category divisions of Figure 4.

At the same time, the distribution runs very close to the expected fabric modification locus for increasing plane "contractional" fabric modification, having a value for B equal to 1.86 compared with 2 for the model locus 'C–Mudst' in Figure 8A. This type of data field and deformation style has been demonstrated previously for 3D total strain measurements in other areas; e.g. the Sudbury Basin of Canada (Clendenen et al. 1988) and the Alpine foreland of Southern France (Siddans et al. 1984; Hanna & Graham 1988). In the Tamworth Belt, supporting evidence is found in associated structural patterns—upright folds with reverse faults, and consistently oriented, fold belt parallel, fold axes and bedding/cleavage intersection lineations—suggesting simple horizontal contraction with vertical extension on a regional scale.



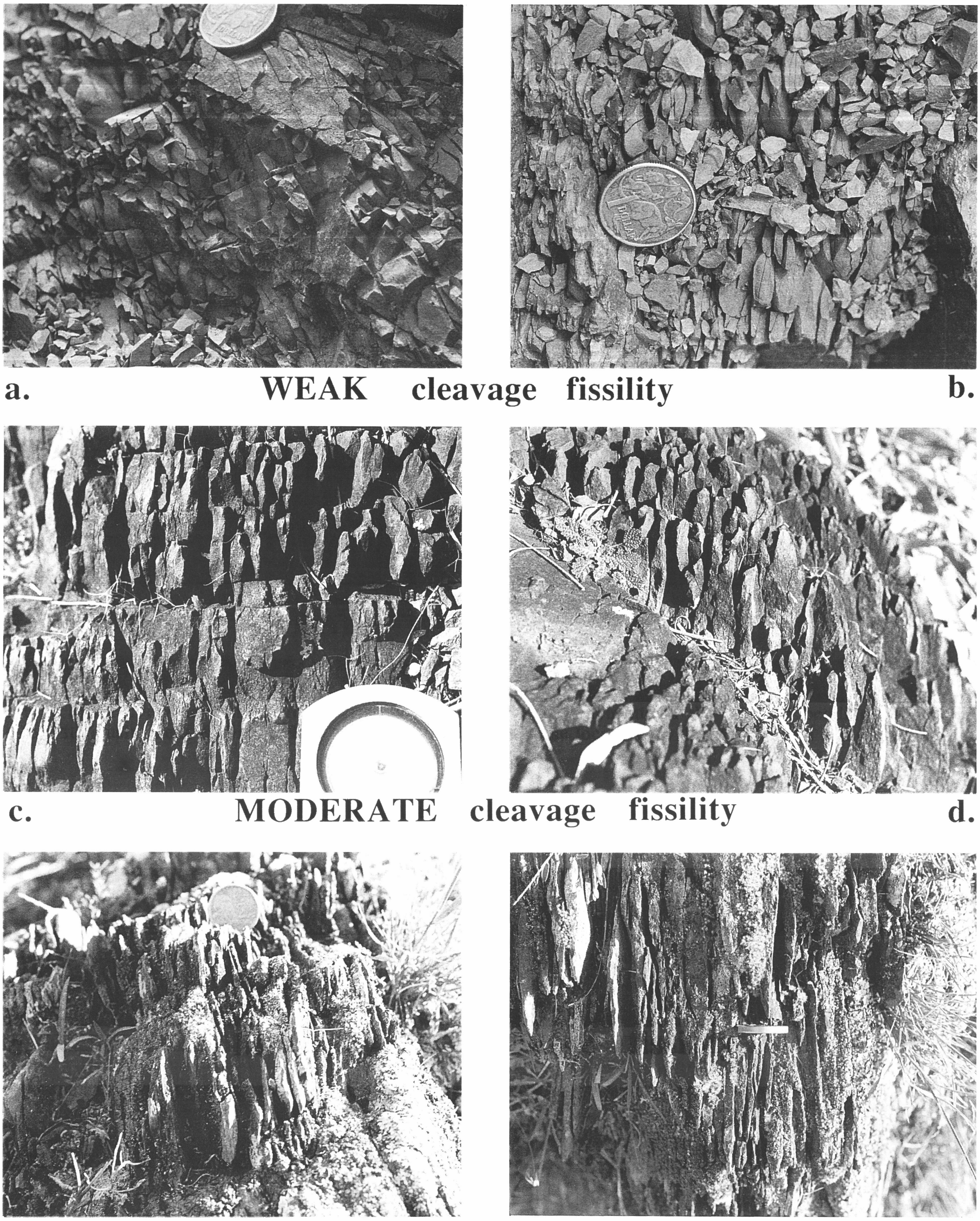
a. ABSENT cleavage fissility b.



c. EMBRYONIC cleavage fissility d.

e. NASCENT (reticulate) cleavage fissility f.

Figures 10 and 11. Progression of cleavage-fissility states in slaty-type penetrative 2 cleaved mudstone, Manilla, NSW. Left hand photos (a, c & e) view the outcrops looking along the bedding/cleavage intersection direction and show cleavage cracks and bedding cracks (*c*/*b* ratios). Right hand photos (b, d & f) view the same outcrops looking down cleavage onto bedding planes and show cleavage cracks in the intersection direction and linking cracks (*i*/*b* ratios). Cleavage traces run 'top to bottom'; bedding traces and linking cracks run approximately 'left to right'. Figure 10 a & b: Sample 1, uncleaved. c–f: Samples 2 & 3, incipiently cleaved. Figure 11 a–f: Samples 4 to 6, weakly to strongly cleaved.



a. **WEAK cleavage fissility** b.

c. **MODERATE cleavage fissility** d.

e. **STRONG cleavage fissility** f.

Strain in incipiently cleaved Manilla mudstones

Ideally, 3D measurements of both fissility-ratio and strain should be combined to establish the precise relationship between these two variables. In the previous section, we showed how the type of imposed tectonic deformation can be qualitatively determined from a fissility progression. Previously, Reks & Gray (1982) reported measurements demonstrating that there is also a quantitative relation to strain in the case of nascent cleavage-fissility in shaly rock. In this section, we present some initial measurements for embryonic cleavage-fissility in mudstones from Manilla which support this view.

2D measurements in the plane of bedding are possible at some locations in the Manilla area using specimens of the deformed plant fossil *Leptophloeum australe* (Gould 1975 fig. 2f; previously *"Lepidodendron australe"*, David & Browne 1950, pl.26d). This lycopod stem displays a bilaterally symmetric pattern of diamond-shaped leaf cushions which can be analysed for distortional strain by Breddin"s method (Ramsay & Huber 1983) (Fig. 13A, B, C). In single specimens, the stretch-ratio on bedding, $R(S_0)$, is found assuming the trace of cleavage to be a principal axis of strain. Multiple specimens yield, in addition, independent confirmation that the principal axis of strain, $\phi(S_0)$, is close to the trace of cleavage, plus some information on statistical uncertainty.

Table 2 (Appendix B) summarises the results, together with fissility measurements and structural data for the three localities. These data show an increase in i/b with increase of $R(S_0)$, as foreseen previously on p. 271(Relative intersection fissility scale), although i/b increases more rapidly than $R(S_0)$. The limited data available could fit either a power function (like that proposed in eqn. 1b and as proposed for magnetic anisotropy ratio/stretch-ratio correlation by Rathore & Henry 1982, eqn. 1):

$$i/b = R^n(S_0), \qquad (3)$$

where $n = 2.4$ (Fig. 13D), or the linear approximation to equation (3)

$$i/b - 1 = m\ (R(S_0) - 1), \qquad (4)$$

where $m = 3.3$ (Fig. 13E).

Lithology effects — sandstone vs. mudstone

From the point of view of cleavage-fissility development, sandstones fall into two distinct categories: (1) muddy sandstones or wackes and (2) well-sorted sandstones (also, well-sorted siltstones) (Gray 1978, fig. 1).

Our observations at a number of different localities generally indicate that the c/b and i/b fissility-ratios for rough penetrative cleavage in thin beds of wacke are similar to, or lower than, those of interbedded mudstones (Fig. 14a).

The situation in thickly bedded and especially well-sorted sandstones is very different, however; these lithologies tend to be dominated by diagonal joints and display no evidence whatever of any fissility at low associated mudstone i/b values (Fig. 14b). Only when moderately strained do they begin to display a crude form of fissility, and even then it is subordinate to jointing (e.g. deformed micro cross-lamination in fine quartz sandstone, and moderate to strong S_1 cleavage in associated mudstone, observed in the Lower Devonian Majurgong Formation, Taemas Synclinorium, near Yass, NSW).

Lithology effects—shaliness

To illustrate how fissility-ratios vary as a function of bedding anisotropy, we examined a location in the Lachlan Fold Belt of NSW where two muddy lithologies of contrasting initial anisotropy have undergone the same amount of strain. For these examples, we use the same numerical ratio categories to describe strength of the initial anisotropy as for the relative cleavage-fissility scale: "weak" anisotropy (b_0/c_0 1.4–2.5), "moderate" anisotropy (b_0/c_0 2.5–5), and so on.

The area referred to is the uniformly dipping eastern limb of the Yass Syncline at Derringullen Creek, Yass, in NSW, where Upper Silurian shaly limestone and dark-grey calcareous mudstone lie in close proximity to each other (Fig. 14c & d). The structure here is uncomplicated; the beds dip gently, there are no faults or bedding-plane detachments in the vicinity, and incipient cleavage lies at a high (60°–70°) angle to bedding. Therefore the two rock units would have experienced the same layer-parallel shortening and similar layer-parallel shear strain. The fissility-ratios in the mudstone are typical of those found in the Manilla mudstones, notwithstanding the contrasting compositions and tectonic histories of these two rock units (see Yass mudstone in Fig. 15). The shaly rock, however, is distinguished from the mudstone by having a much smaller c/b ratio while having nearly the same i/b (Yass shaly limestone in Fig. 15). If these samples are projected back to the $-C$ axis along a contractional fabric locus, the mudstone shows a "strong" initial bedding anisotropy (b_0/c_0), while the shaly limestone shows a "very strong" to "extremely strong" anisotropy. This confirms the previous observation that c/b is strongly bedding-dependent. It also shows that i/b is relatively independent of the initial bedding anisotropy in these rocks.

An example of bedding anisotropy in undeformed shale is shown by Upper Ordovician black paper shale (Llanffawr Mudstone) at Llandrindod Wells in central Wales, UK. The beds here directly display the initial bedding anisotropy: $b_0/c_0 = 30$ to 50, which is at the limit of our "extremely strong" category. This is similar to the 50:1 ratio for various undeformed "flaggy shales" studied by Ingram (1953). Thus the Yass shaly limestone and undeformed shales suggest a grouping for some rocks at significantly higher bedding anisotropies than mudstone (Fig. 15). We call this group the *shale field* (in accordance with the meaning of "shale" as used by Pettijohn 1975).

With increasing tectonic modification of the fabric, lithologies belonging to the "shale" group should lie increasingly distant from the bedding-dominant group shown at the bottom of Figure 15. If the fabric locus is contractional, c/b and i/b ratios should both increase in a locus parallel to the Manilla mudstones, but below this field, and will eventually reach and continue beyond the category of structures we have called "bedding/cleavage (or bedding) pencil structure" (that is, fragments which are equidimensional in c/b but strongly elongate in i/b).

Most published examples of 'pencil' structure (*sensu lato*) in fact lie approximately in this position (Fig. 15). They lie in a higher i' (or I) band than mudstone and occupy the same i' range as undeformed and weakly deformed "shales". These facts are consistent with these pencils having been derived from shaly lithologies by a contractional tectonic locus. But further evidence is required to corroborate this conclusion.

Some 'pencils' from the Appalachian fold and thrust belt of the USA (Reks & Gray 1982; Ferrill & Dunne 1989) appear to fit this interpretation well; they commonly have a "black shale" or "shale" parent lithology, and pressure-shadow fibres show extensional strain normal to bedding signifying a contractional tectonic deformation.

Pencil structure observed in thin section in grey mudrock of the Booroo Ponds Group on the west limb of the Yass Syncline in NSW (e.g. Figs 2A and 15) shows relict bedding-parallel differentiated microdomains, similar to slaty cleavage domains, and/or a higher than usual detrital mica content (silt-size flakes of clear white mica sert in a dark illitic matrix of very low metamorphic grade: cf. p. 258 "Pencil structure"). The S_1 cleavage microdomains themselves are moderately well-developed, suggesting that they would have been capable of forming a weak to moderate slaty-cleavage-fissility had they been present in a mudstone. Small chlorite pressure-shadows on pyrite grains are oriented at a high angle to bedding in the plane of cleavage and thus indicate a true contractional deformation. In addition, fissility-fragments from the same horizon exposed on the limb of a gentle cleavage-congruent fold have a form which is intermediate between that of the pencils and bedding plates of the "shale field": namely, "strong bedding blades" ("blades" on Fig. 15).

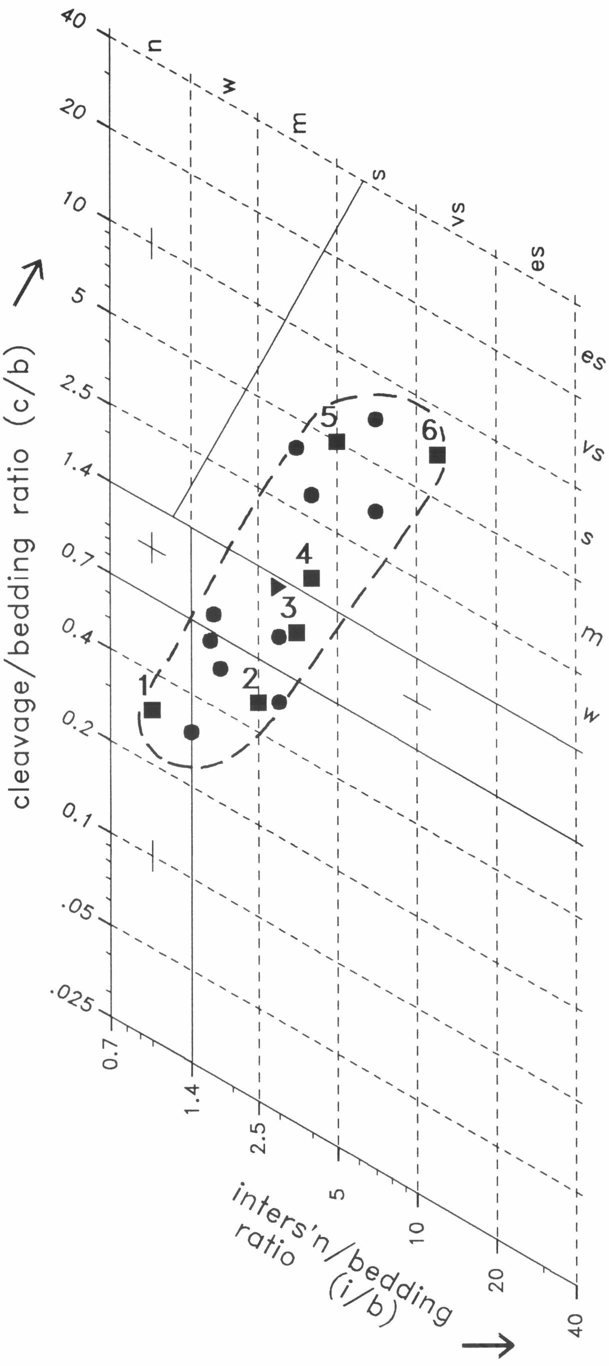


Figure 12. 3-axis plot of 3D fissility-ratio measurements for mudstones of the Manilla area, NSW. ***Squares:*** **progression series samples illustrated in Figures 10 & 11.** ***Dots:*** **other locations in the Manilla area.** ***Triangle:*** **Tamworth Council Quarry sample.**

Our interpretation of this example is therefore twofold. First, the initial bedding anisotropy in these pencils is stronger than that of mudstones; in other words, these rocks are more shaly in character than ordinary mudstones. This is further confirmed by the contractional type of deformation locus by which the pencils would have been reached, and by the observed intermediate fissility forms. Second, the degree of tectonic fabric modification required to balance the initial bedding anisotropy in the pencils is greater than that required for mudstones.

These examples suggest that the shale field and what we call the "para-pencil field", on Figure 15, may be linked to form an important second lithological grouping on 3-axis plots having a boundary with the Manilla mudstone field at approximately i′ = *2.7,* b_0/c_0 = 20 or *i/b* (true pencil/reticule division) = 5. Observations that the more stubby fissility forms from "mudstones" (Crook 1964; Engelder & Geiser 1979) fall within our mudstone fissility field (Fig. 15) further support this interpretation. On the other hand, the pencil structure described by Ramsay (1981) is associated with a "wrench" deformation (see p.258) and hence more logically derived from a mudstone parent fabric than from a shale (cf. "Wren" path in Fig. 8B). So, although the fields outlined in Figure 15 may be common, they are dependent on the style of deformation and, consequently, are by no means unique for particular lithologies.

The conclusion we reached concerning a greater fabric modification in pencils than in mudstone reticules suggests that *c/b* ratios are probably not a reliable guide to intensity of tectonic strain. For a given deformation style, the *i/b* ratio should be a more appropriate deformation index in view of its independence of bedding anisotropy. However, as the next example demonstrates, *i/b* is not totally independent of lithology and in fact may display considerable variation in its response to strain in different rock types.

Lithology effects—sensitivity to strain

At the Borah Creek strain measurement location at Manilla, NSW, three distinct rock types are interbedded with one another in the same outcrop of uniformly and gently dipping beds: a mudstone, a fine to medium muddy sandstone (both slightly weathered) and an argillite of fresh, very dark green to black, splintery, appearance. Figures 14E and F show contrasting development of intersection fissility, *i/b*, in the argillite and sandstone seen on bedding planes: a "moderate to strong" *i/b* ratio in the argillite but only "nascent to weak" in the mudstone and sandstone. The *c/b* ratio is also higher for the argillite than the sandstone (Table 3, Appendix B, and Fig. 17); however, the mudstone is comparable to the sandstone in both *c/b* and *i/b*.

These differences cannot be explained by variable deformation, because layer-parallel shortening strain should be identical in the three lithologies and the cleavage/bedding angle (related to layer-parallel shear strain) in the argillite is similar to that of the sandstone. The reason for the difference in behaviour is not clear, other than that it is a function of lithology. We call it simply the *sensitivity* of cleavage-fissility development to tectonic strain: high in argillite, and moderate in mudstone and sandstone. The consequences for fissility-ratio measurements are

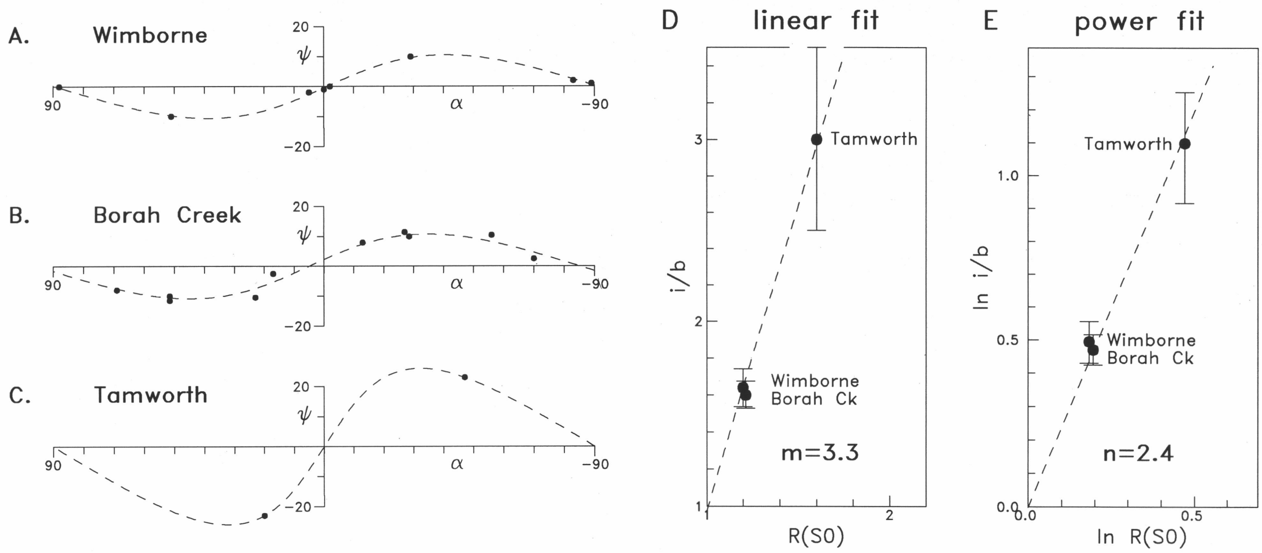


Figure 13. Stretch-ratios in the Manilla–Tamworth area from deformed *Leptophloeum* plant stems. A–C: Breddin plots (angular shear strain, ψ, vs. line orientation, α) and best-fit curves; see Table 1 for results. Angle conventions are as described in Ramsay & Huber (1983). The angles are measured in the plane of bedding, viewed downwards, relative to the average trace of cleavage on bedding at each location. D & E: Intersection-fissility ratio vs. stretch-ratio plots for the above localities; vertical error-bars are standard errors on *i/b* means. D—linear-law interpretation; E—power-law interpretation.

nevertheless clear. Neither *c/b* nor *i/b* may be assumed to be universal indicators of deformation intensity in all rock types; the value of these measurements lies chiefly in their use for characterising deformation and fabric intensity in a single lithology. For any one lithology, whether mudstone, shale, sandstone or argillite, we predict that an ordered relationship will exist between the fissility anisotropy, initial bedding anisotropy and tectonic strain, but that the relationships will be different for the different lithologies.

Figure 16 summarises the currently available data for sensitivity in three rock types in contractional deformation environments: Manilla-Tamworth mudstone, Borah Creek argillite and Appalachian "shale". We use the exponent *n* in equation 3, the *sensitivity exponent*, as a quantitative measure of sensitivity in these examples. Reks & Gray"s (1982, fig. 14) pencil data are plotted as *i/b* ratios using the conversion given in our Table 4 (Appendix B). Their *Y/Z* (intermediate to least principal tectonic stretch-ratio) is taken to mean effectively the same as our $R(S_0)$ (bedding plane stretch-ratio, where cleavage is at a high angle to bedding).

The Reks and Gray 'pencils', which we believe represent the behaviour of a "shale", clearly show the greatest sensitivity of tectonic fissility development to deformation: $n = 11$, or a power 8.6 greater than that of the Manilla–Tamworth mudstones ($n = 2.4$). The single measurement for argillite lies intermediate between these two rock types with an *n* value 6 powers greater than mudstone. Thinly bedded muddy sandstone (Table 3) appears to have a sensitivity similar to or slightly lower than that of mudstone.

These results demonstrate:

(1) very much greater numerical values of *i/b* compared with stretch-ratios and hence their appreciable sensitivity for registering small variations of deformation;

(2) widely varying fissility sensitivities to deformation in some rock types, ranging over 8.6 powers of $R(S_0)$; and

(3) considerably greater fabric modification, for a given amount of tectonic strain, in shales compared with mudstones and sandstones. Note that property (3) has the effect of balancing, to some extent, the opposed influence of high bedding anisotropy on *c/b* ratios in shales.

Effects of multiple deformation?: transverse blades

The samples that we have discussed so far all lie below the *c/b* or *C–B* axis on the 3-axis diagram (Figs 12 and 15); that is, within Fields 0 and 1 of Figure 7. This is the behaviour expected when a single, plano-linear, tectonic fabric is superimposed on an initial bedding-parallel fabric. As shown in Figure 8B, all initially isotropic and bedding-parallel anisotropic materials will fall on or below the *c/b* axis if modified by any of the three straight biaxial loci. The *c/b* axis therefore defines the theoretical upper limit of samples that are dominated by a single, planar, cleavage. The small sector above the *c/b* axis represents constrictional or linear, non-plane, fissility-fragment shapes at a high angle to bedding called "transverse pencils" and "narrow, transversely elongate, cleavage blades" (Fig. 7). This distinctive group is defined as Field 2. Using the correspondence principles (1) to (4) postulated on p.274, the style of tectonic fabric and total deformation required to produce Field 2 fissility would also be constrictional non-plane.

Fissility-fragment shapes which belong to Field 2 have only rarely and very briefly been reported in the literature; e.g. "forma astillosa" (splinters) due to "two cleavages almost perpendicular to bedding" (translated from Meléndez & Fúster 1978, fig. 19-4), and perhaps pencils that are due to "intersection of two cleavages" (translated from Mattauer 1973, fig. 5.48). However, we have found them at several places in the Lachlan Fold Belt of NSW, where Devonian strata have been affected by NW to NNE-trending upright folds and reverse faults of the Early

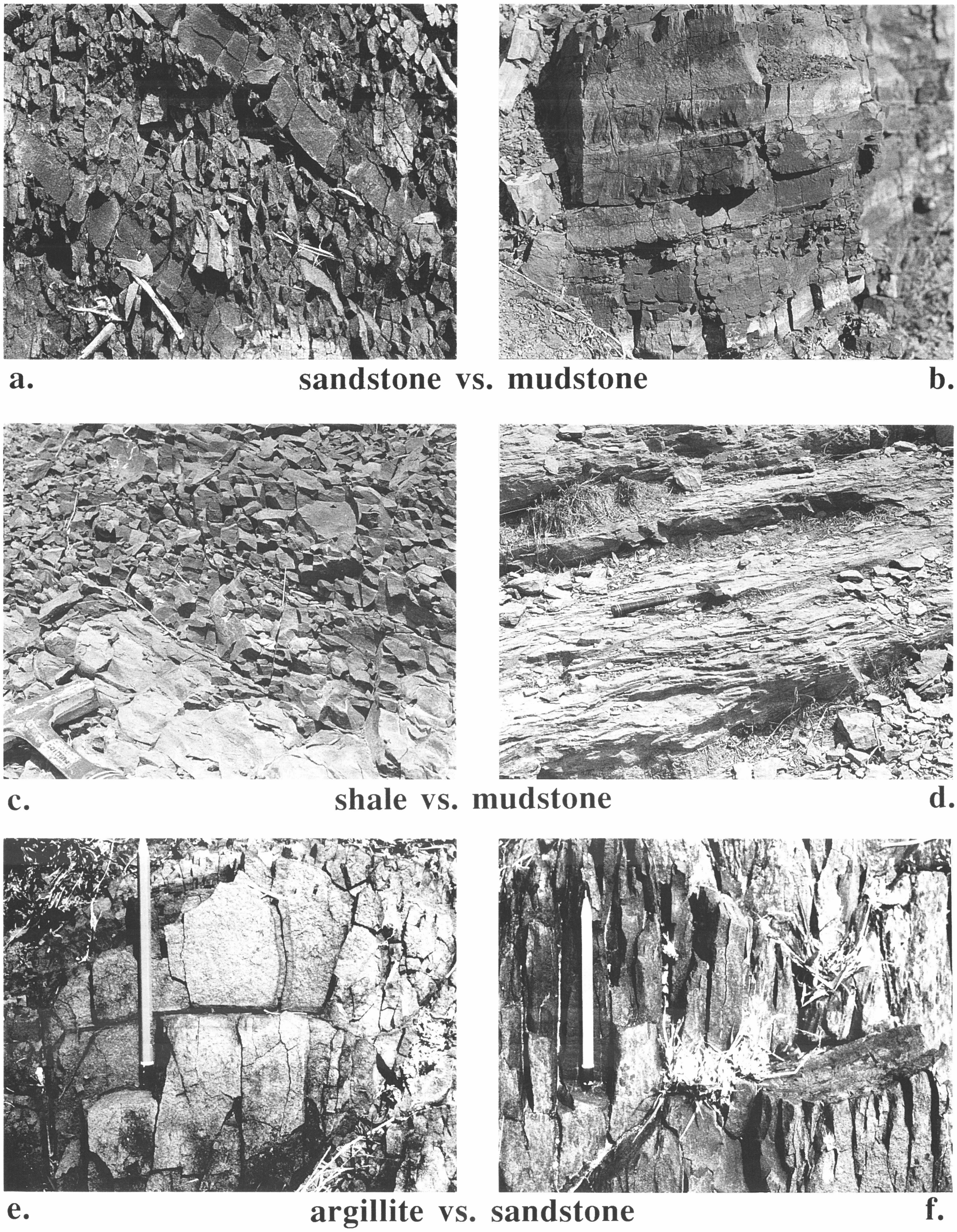


Figure 14. Effects of lithology on fissility. a & b: Contrasting *fracture types in sandstone,* viewed parallel to bedding/cleavage intersection. a—Nascent cleavage-fissility in deformed litharenite sandstone and weak cleavage-fissility in associated mudstone layers (Lower Carboniferous Namoi Fm, Glamorgan homestead, Manilla, NSW). b—Joint-dominated fracture in weakly deformed litharenite sandstone (Upper Devonian Mandowa Mudstone, with nascent relative cleavage in associated mudstone layers, Tamworth Council Quarry, NSW). c & d: Contrasting *strength of bedding-fissility* in two Upper Silurian muddy calcareous rocks, 100 m apart in uniformly dipping strata, viewed parallel to bedding: Derringullen Creek, Yass, NSW. c—Grey calcareous mudstone (Booroo Ponds Gp) with absent to weak bedding-fissility (b_0/c_0 = 1.4). d—shaly limestone (Silverdale Fm) with strong to very strong bedding-fissility (b_0/c_0 = 10). e & f: Contrasting *cleavage intersection fissility* at one location in Upper Devonian Mandowa Mudstone, Borah Creek, NSW. View normal to bedding. Beds dip gently and uniformly; relative cleavage-fissility in associated mudstone layers is nascent. e—Absent to weak intersection fissilty in tuffaceous sandstone layers (i/b = 1.5). f—moderate to strong intersection fissility in siliceous argillite (i/b = 5).

Carboniferous Kanimblan Orogeny (Powell et al. 1976; Glen 1982b). Below we describe an example from the Merimbula area on the South Coast of NSW where Rixon et al. (1983) first noted the related phenomenon of prismatic cleavage lithons transverse to bedding.

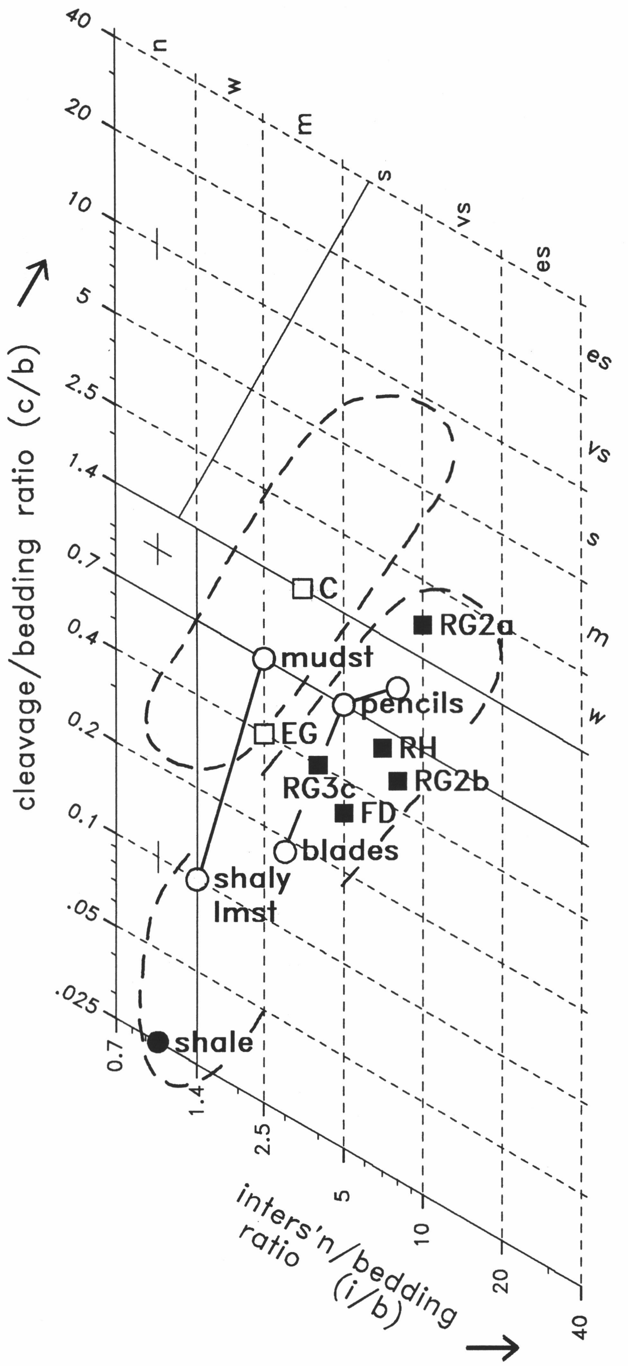


Figure 15. Comparison of bedding-anisotropy fissility effects in shaly rocks and Manilla mudstones (upper outlined field); 3-axis plot. *Solid squares*—para-pencil and deformed shale fissility-ratios measured from published illustrations: *FD* (Ferrill & Dunne 1989, fig. 7b, "pencil cleavage"), *RG* (Reks & Gray 1982, figs 2a, 2b & 3c, "pencil structure"), *RH* (Ramsay & Huber 1983, fig. 10.26, "pencil structure"). *Open squares*—mudstone fissility-ratios measured from published illustrations: *C* (Crook 1964, pl.1, "reticulate cleavage"), *EG* (Engelder & Geiser 1979, figs 3 & 4, "pencil cleavage"), *Circles*—Yass mudrocks: mudstone and shaly limestone, Derringullen Creek (Figs 14c, d); pencils (Fig. 2a); bedding blades, Bowning Creek, NSW. *Dot*—Paper shale, Llandrindod Wells, Wales.

At Merimbula Point, a strong slaty-type cleavage is locally developed in Upper Devonian Worange Point Formation fluvial red mudrocks in the steep limb of a horizontal monocline. Fissility in the cleaved mudrocks shows a distinctive "narrow transversely elongate blade" morphology (Fig. 17) characteristic of Field 2 (cf. Fig. 7). The blades display a well-defined steep plunge at 40° to 60° to bedding, but the strike of fissility cracks fluctuates up to 30° about the fold-axis direction, defining fragments that are crudely rhombic in horizontal section. The structure thus displays properties of both a single cleavage (the mean fabric plane) and two or more intersecting cleavages (the tendency to split at angles to the mean direction).

The associated fabric could be explained in one of two ways:

(1) The fabric is a single plano-linear cleavage of an anastomosing nature (Rixon et al. 1983; M. Rickard pers. comm. 1993), possibly produced by a continuous constrictional, non-plane deformation (straight path in Fig. 17).

(2) It is a compound fabric resulting from discretely or progressively superposed contractional biaxial deformations acting in different or changing directions with time in the plane of bedding (kinked and curved paths, respectively, in Fig. 17).

There is a singular lack of obvious overprinting relation between the different cleavage and fold trends that are

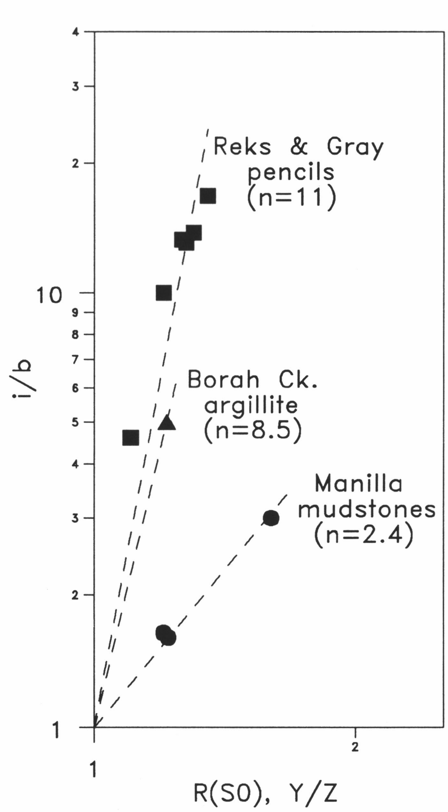


Figure 16. Comparison of *i/b* vs. stretch-ratio relations for Reks & Gray pencils (Table 4) and Manilla mudstones and argillite (Tables 2 & 3). Log-log plot with reduced ordinate scale; gradients of best-fit lines through (1,1) give sensitivity exponents (*n*).

present in the area; therefore the question cannot be easily resolved by conventional structural means.

Observations which suggest that the fissility morphology and related cleavage morhology here are not typical of single-generation structures are:

(a) Transverse-blade structure is unknown in regions where there is a single fold direction, such as the Tamworth Belt (cf. 'mudstone field' in Fig. 12).

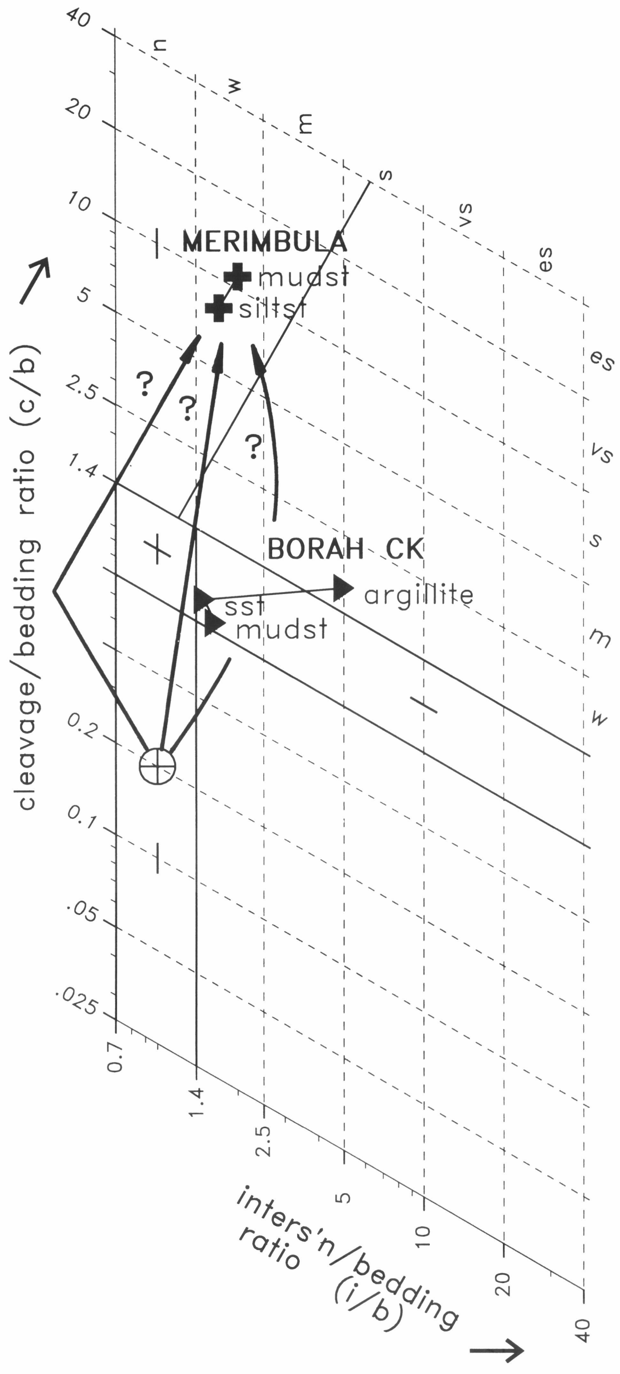


Figure 17. 3-axis plot illustrating sensitivity and cryptic multiple deformation effects. ***Triangles*—Comparative sensitivity of Borah Creek lithologies, NSW: mudstone, sandstone (Fig. 14E) and argillite (Fig. 14F). See Table 3 for data.** ***Crosses*—Transverse cleavage blades, Merimbula Point, NSW: mudstone and siltstone.** ***Arrowed paths*—some possible deformation paths that may give rise to Merimbula transverse blades: 2-stage contraction (left); constant non-plane (centre) and changing non-plane (right).** ***Circle with cross*—presumed initial anisotropy of Merimbula sediments.**

(b) The circa 60° azimuth range of weak cleavage-stripe intersection traces on bedding in flat-lying sandstones (Rixon et al. 1983, fig. 6) is much larger than the norm for such cleavages in other areas (see outcrop illustrations of stripy and spaced cleavage in Borradaile et al. 1982: plates 53 (Granath), 65 (Alvarez & Engelder), 71 (Hancock), 89 (Cook), 91 (Sansone), 92 (Pfiffner), 97–98 (Beach) and 229 (Williams)).

(c) At low strain, a greater fluctuation of cleavage traces across bedding than in the bedding-plane would be expected as a result of lithological variation across the beds, but the situation at Merimbula is opposite to this (compare Rixon et al. 1983, figs 6 & 11).

(d) Contractional-style *en echelon* vein arrays and locally associated cleavage stripes in nearby sandstones show gently plunging σ_1 axes ranging over 80° in azimuth (Powell 1983, fig. 44; Rixon et al. 1983, fig. 18b) suggesting non-coaxial layer-parallel shortening during at least part of the cleavage-forming history.

The lack of clear overprinting in the cleavage might be due to an insensitivity of the fabric to changing directions of strain at low strain; i.e. a *cryptic multiple or non-coaxial deformation* where early stages of the fabric are insufficiently advanced to respond to later oblique increments by crenulation. Field 2 fissility structures may, therefore, warrant further investigation as indicators of polydeformation and cleavage-strain behaviour in weakly deformed rocks.

Conclusions

(1) Characteristic fabric attributes which distinguish or relate different varieties of cleavage are reviewed and lead to a revised morphological classification for first-generation cleavages based on field characteristics. The classification applies mainly to clastic sedimentary rocks, where the cleavage is at a moderate to high angle to bedding, and encompasses rocks showing evidence of incipient slaty cleavage, such as pencil structure. Structures formed by purely brittle deformation processes are not included as categories within this *cleavage-type scheme*.

The primary field division is into *penetrative* and *non-penetrative* cleavages, penetrative being defined on the basis of grain size as a mineral alignment penetrating the rock down to the dominant grain or clast size; this distinction corresponds to Dennis' (1972) usage (rather than his definition) of the terms "continuous" and "discontinuous". A practical lower limit of 0.5 mm spacing applies to the mesoscopic recognition of the non-penetrative type.

Two types of "penetrative" cleavages are distinguished:

- *penetrative type 1*, a non-domainal or grain cleavage in relatively phyllosilicate-poor and relatively well-sorted clastic and chemical sediments and most igneous and coarse-grained metamorphic rocks; and
- *penetrative type 2*, a commonly though not exclusively differentiated domainal type typified by *slaty type* cleavage in lithified clastic rocks with significant

proportions of phyllosilicate or other platy minerals.

The *non-penetrative* cleavages, which are all domainal, are divided into three kinds:

- *spaced cleavage*, tectonic stylolites and more planar differentiated domainal non-penetrative cleavage in initially isotropic to weakly anisotropic rocks);
- *crenulation cleavage*, microfold-dependent differentiated domainal cleavage in initially strongly anisotropic rocks; and
- *scaly cleavage*, a largely non-differentiated slip phenomenon consisting of microscopic C-surfaces analogous to ductile shear zones.

Two kinds of heterogeneous mesoscopic intensity banding of the basic cleavage types are recognised:

- differentiated *cleavage zones* or *stripes*, and
- largely mechanical ductile *shear zones* in type 1 penetrative and scaly cleaved rocks.

(2) The main attribute of cleavage on a mesoscopic scale being fissility, we propose a *cleavage-intensity scale* based on this property. *Fissility* is distinguished as an actual parting (Dennis' 1972 "incidental partings") guided by the mechanical anisotropy of an existing cleavage or bedding fabric, especially small-scale fissility-cracks produced by present-day weathering processes in type 2 penetrative cleavage and bedding fabrics.

The intensity scale uses two aspect ratios of fissility-fragments:

- the *cleavage/bedding fissility ratio c/b* in the plane normal to the bedding/cleavage intersection, defining the *relative slaty-cleavage fissility scale*; the *c/b* ratio incorporates effects due to initial bedding anisotropy and shows the relative degree of cleavage development compared with bedding fabric; and
- the relative fissility in the cleavage/bedding intersection and bedding direction *i/b*, defining the *relative intersection fissility scale*; the *i/b* ratio indicates the extent of tectonic fabric development in any one lithology and structural/tectonic regime.

Class names are given to these ratios using approximately binary divisions of the *c/b* and *i/b* scales: *weak* (1.4–2.5), *moderate* (2.5–5), and so on. The categories cover a complete range of usefully measurable forms, from very incipient pre-pencil types to rocks with strongly developed slaty cleavage. The divisions thus lead to more precise definitions of cleavage-fragment shape, one of the consequences of which is a more restricted usage of the terms "cleavage structure" and "pencil structure".

Undeformed *bedding-fissility anisotropy* is also describable under this scheme, using the width-to-thickness ratio (b_0/c_0) of morphologically platy bedding-parallel fragments and the same class intervals as *c/b* and *i/b* ratios.

(3) The two fissility-ratios are shown on a 3-axis diagram in bedding–cleavage–intersection coordinate space, with the natural logarithms of b', c' and i' [b, *c* and *i* normalised against $(ibc)^{1/3}$] as axes; this diagram gives contours of both the *c/b* and the *i/b* ratio for plotting and description purposes. The diagram displays:

- the type of *fissility-fragment shape* or *structure* ("plate" or "blade" or "pencil", with qualifications "narrow", "biaxial" and "broad" for blades);
- its *orientation* with respect to the bedding and cleavage axes (cleavage-parallel or bedding-parallel for planes of flatness, and "bedding-elongate" or "transversely elongate" with respect to bedding for long axes); and
- its *slenderness*.

Three structural groups of are distinguished according to whether the dominant fissility is:

- bedding (*Field 0*), or
- a single cleavage at high angle to bedding (*Field 1*), or
- a constrictional or intersecting dual cleavage fabric at a high angle to bedding (*Field 2*).

(4) Methods for interpreting data fields on the logarithmic 3-axis diagram are outlined in terms of *initial bedding anisotropy* and its modification by spatially variable coaxial *tectonic deformations* ("fissility loci"). These methods include a new general relation for constant shape-type (straight line) loci:

$$c/b = A\ (i/b)B,$$

where A is inverse initial bedding anisotropy ratio (intercept) and B defines the type of shape locus or style of tectonic deformation with respect to bedding (slope). Three kinds of biaxial fissility locus are distinguished:

- $B = 2$ or *contractional*, involving shortening and thickening of beds,
- $B = 1/2$ or *wrench*, involving shortening and orthogonal elongation in the plane of bedding, and
- $B = -1$ or *extensional*, involving thinning and elongation of beds.

(5) Possible *applications of the fissility intensity scales* to problems of cleavage development and regional deformation in the field are illustrated with examples of penetrative type 2 cleavage fabrics from New South Wales (NSW), Australia, and the Northern Hemisphere.

- A *series of mudstones* showing progressively increasing cleavage-fissility intensity from the Tamworth Belt, NSW ('Manilla mudstones') is presented as a kind of standard for comparison of other cases. A complete progression is recorded, from apparently undeformed samples to samples which possess a strong slaty cleavage. These changes define a linear spread with mean slope $B = 1.86$ on the 3-axis diagram and are related to a regionally increasing, single-generation, contractional-tectonic, episode of folding and reverse faulting. A persistent influence of generally "moderate to strong" initial bedding anisotropy is also noted and characterises the *c/b* to *i/b* relationship as being of a "mudstone" type. Mudstones from other areas mostly fall within this fissility field. Deformed plant remains in the same samples indicate a relationship between the *i/b* fissility-ratio and the bedding plane tectonic stretch-ratio in the order of 3.3:1.
- Fissility-ratios in muddy sandstones or *wackes* are comparable to those in the mudstones; no fissility

observations could be made on deformed, well sorted sandstone due to its poor development and a dominating influence of joints.

- Undeformed to weakly deformed *shaly rocks* define part of a separate lithological field on the 3-axis diagram, called the "shale" field, characterised by "very strong" to "extremely strong" initial bedding anisotropy. Many of the structures from the Appalachian fold-and-thrust belt, USA, described in the literature as 'pencils', and pencils from Upper Silurian shallow-marine sediments in the Yass area, Australia, define a linear contractional spread of data, called the "para-pencil" field, which appears to be contiguous with the shale field.

- *Cleavage/bedding pencils* of the 'Ramsay'-type (Ramsay 1981), formed from mudstone in a wrench deformational setting, may be morphologically indistinguishable from 'Reks & Gray'-type pencils (Reks & Gray 1982), formed from shale in a contractional setting. Structural indicators of tectonic elongation direction are required to differentiate these two types.

- Differing responses of relative cleavage-fissility (c/b) and relative intersection fissility (i/b) to uniform layer-parallel deformation in different rock types are attributed to a property that we call the *sensitivity* of fissility development to tectonic strain. Available correlations of i/b with bedding plane stretch-ratio show shale and argillite to be highly sensitive, whereas mudstone and muddy sandstone are significantly less sensitive.

- A *new kind of pencil and narrow blade structure*, with steep plunge at a high angle to bedding and a slaty-type cleavage or incipient cleavage, is recognised as a probable product of multiple tectonic deformation. Cryptic cleavage-cleavage intersection structures of this kind plot in field 2 of the fissility 3-axis diagram and represent the type of response expected from weak, non-coaxially superimposed, contractional (layer-parallel shortening) events.

(6) In view of the dependence of fissility-ratios on bedding anisotropy, sensitivity and orientation of the imposed deformation, their use as indicators of cleavage development and tectonic strain is best restricted to a specified rock type and structural setting, such as mudstone in a mudstone-dominant formation near hinges of folds.

Acknowledgements

Fieldwork in Australia was supported by Research Grants from Macquarie University and a Travel Grant from Ben Gurion University of the Negev (1989 and 1990). D.W.D. also acknowledges assistance from organisers of The John Ramsay Meeting, Zürich, 1991, which enabled a summary of the work to be presented there, and facilities at Barcelona University (1993), where part of the manuscript preparation was carried out.

An article of this nature inevitably draws upon the work of many individuals over a period of time, to whom we are indebted for information and stimulus. In particular, reviews by Pat Conaghan, John Cosgrove, Keith Crook, Mike Rickard, Brinley Roberts, Ron Vernon, Karl Wolf and two anonymous reviewers led to improvements in the manuscript. We also thank David Gray and Xingnan Cao for discussion; Brinley Roberts and Dick Merriman for comments on the fissility-ratio technique during a field trial in Wales; and structural staff of the Department of Dynamic Geology, University of Barcelona, and CISC Institute, Barcelona, for comments during a similar trial in the Eastern Pyrenees. Students and staff in the Macquarie University field unit 'Field Geology' contributed information which assisted preparation of the cross-section (Fig. 9C). We thank Ken Rousell for preparing Figure 9.

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Appendix A: Fissility dimension/crack -frequency relations

Because physical dimensions of fissility fragments are more directly measured and conceptualised than crack frequencies, we have adopted dimension as the preferred basis for describing fissility-ratios in this paper. However, in certain cases, such as where cleavage and bedding are oblique to one another, it is necessary to appreciate that the intensity of a particular set (parallel group) of cracks is more fundamentally described by its spatial frequency, a parameter which increases with increasing numbers of cracks of a particular set in a given volume of material. When two or more distinct sets of fractures exist, it is assumed that intensity measurements based on crack frequency of each set are independent of the intensity of other crack sets in the rock. Two other parameters related directly or indirectly to crack frequency are: (1) crack spacing and (2) fragment edge length. Of these two, crack spacing is the more fundamental and forms the basis of the *c-b-i* dimension system. This appendix presents notation for and relations between the different measurement systems so that conversions may freely be made one to the other, especially when the fissility planes are oblique to each other, as shown in Figure 3c.

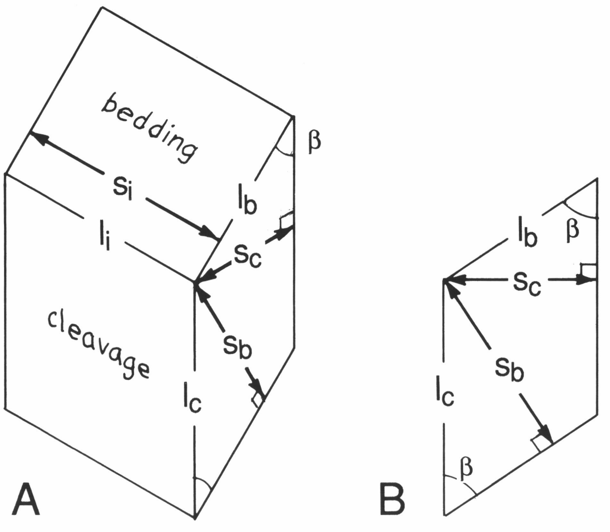

Figure A1. A—Edge lengths (*l*) and crack normal spacings (*s*) for a monoclinic fissility-fragment of bedding/cleavage angle β. B—Relationships between *l* and *s* in the plane normal to the bedding/cleavage intersection.

Let the *frequency* (*f*) of a set of subparallel cracks be the number of cracks of that set per unit distance normal to the cracks over some representative distance interval. Then the average *normal spacing* (*s*) of consecutive cracks over the same interval is the inverse of the crack frequency: $s = 1/f$.

Consider now a notional monoclinic parallelepiped bounded by pairs of cracks belonging to three crack sets where the crack pairs have normal spacings equal to the average normal spacings of the respective sets. In a physical sense, this solid represents the average three-dimensional morphology of fissility fragments in a particular outcrop. The three crack sets considered are:

(1) cleavage plane cracks (denoted by subscript c),

(2) bedding plane cracks (denoted by subscript b), and

(3) cross cracks normal to the cleavage-bedding intersection (subscript i), as shown in Figure A1A. Then

$$f_c = 1/s_{c,},\quad fb = 1/s_b,\quad f_i = 1/s_i. \tag{A1}$$

Let the *edge lengths* (*l*) of the parallelepiped normal to the cleavage-bedding intersection be *lc* and l_b in the cleavage and bedding planes, respectively, and let l_i be the edge length in the intersection direction. The edge lengths are related to normal spacings as shown in Figures A1A and B and by the relations:

$$s_c = l_b \sin\beta,\quad s_b = l_c \sin\beta,\quad s_i = l_i, \tag{A2}$$

where β is the angle between the bedding and cleavage planes.

Defining relative crack frequency (*R*) as the fundamental measure of relative crack intensity, the relative *crack frequency ratios* of the three crack systems are

$R_{cb} \equiv f_c / f_b$, (cleavage/bedding frequency ratio)

$R_{ci} \equiv f_c / f_i$, (cleavage/cross-intersection frequency ratio)

$R_{bi} \equiv f_b / f_i$.
(bedding/cross-intersection frequency ratio) (A3)

We introduce the following simplified notation for measurement purposes:

$$c \equiv s_b,\quad b \equiv s_c,\quad i \equiv s_i, \tag{A4}$$

the ratios of which are the *fissility dimension-ratios* referred to in the paper. Combining A1 to A4 yields equivalencies for these ratios as follows:

$c/b = Rcb = sb / s_c = l_c / l_b$, (cleavage/bedding dimension-ratio)

$i/b = R_{ci} = s_i / s_c = l_i / l_b \sin\beta$, (intersection/bedding dimension-ratio)

$i/c = R_{bi} \quad s_i / s_b = l_i / l_c \sin\beta$. (intersection/cleavage dimension-ratio) (A5)

Hence, *c/b* can be measured directly as the ratio of edge lengths in the cleavage and bedding directions. *i/b* and *i/c*, however, require either trigonometrically adjusted edge lengths or projections of edge lengths as seen when the fragment is viewed in the direction of the third edge. An example of projected edge length ratio would be the ratio (*i/b*) of the edges seen when simultaneously looking down the cleavage and cross crack planes; the resulting measurement is equivalent to the ratio of the normal spacings of the cross cracks and cleavage cracks.

When the angle β in Figure A1A is 90°, the dimension-ratios (A5) are reduced to

$$c/b = l_c / l_b,\quad i/b = l_i / l_b,\quad i/c = l_i / l_c, \tag{A6}$$

as shown in Figure 3a.

When 60° < β < 90°, (A6) may be assumed as approximations since the trigonometric adjustments are then no more 13%.

When 0° < β < 30° approximately, the bedding and cleavage fabrics may no longer be independent and so interpretation becomes problematical.

Finally, when β = 0°, cleavage no longer exists as a fabric separate from bedding; therefore *c* does not exist and fragment shape must be represented with the aid of edge length normal to bedding instead of *c*.

Appendix B: Tables

Table 1. Data for "Manilla mudstone field" fissility samples in Figure 12.

Series				*Rock*	*Fissility*	*Ratios*	*Structure*[3]		
no.	*Sample*	*Grid ref.*[1]	*Formation*	*type*[2]	*c/b*	*i/b*	S_0	I_1	S_0^S_1
Progression series samples (Figs. 10, 11)									
1	K89–19	2763566126	Lowana	M	0.3	1	160 15W	—	—
2	K89–10.2	2578 65867	Namoi	Z	0.5	2.5	150 45E	338 8	60
3	M90–12.1	2815 66077	Lowana	M	1	3.5	025 8E	178 3	90
4	M90–20.2	2840 66090	Noumea	M	1.6	4	130 42E	000 40	40
5	M90–17.7	2857566093	Noumea	mfS	5	5	102 62N	345 60	85
6	K89–26.2	2903566081	Namoi	Z	7	12	085 70S	218 65	70
Strain samples (Table 2)									
Wim.	M91–14	2742 66070	Lowana	M	0.7	1.6	042 6E	166 2	85
Bor.	M90–1	2691 66100	Mandowa	M	0.8	1.6	025 15E	163 10	65
Tam.	K89–2	2965 65560	Mandowa	Z	1.3	3	140 12E	340 4	75
Other samples									
	K89–10.1	2578 65867	Namoi	M	0.3	1.4	150 40E	350 16	—
	K89–5.1a	2668 65740	Namoi	M	0.6	1.8	160 13W	160 0	70
	K89–5.1b	,,	,,	,,	0.9	3	,,	,,	,,
	K89–20	2732566197	Noumea	Z/M	0.6	3	000 12E	165 4	88
	K89–21a	2849 66123	Noumea	mS	3	4	015 40E	162 25	50
	K89–24	2859 66065	Lowana	Z	4	3.5	145 60E	338 25	45
	K89–26.1	2902566080	Namoi	Z	3.5	7	095 53S	193 52	66
	K89–22	2848 66149	Noumea	sM	7	7	170 20E	150 10	40

[1] Australian Map Grid, Zone 56J.

[2] Field-identified rock types: M — mudstone, Z — siltstone, S — sandstone, m — muddy, s — sandy, fs — fine sandy (c.f. Folk, 1980, p.25–28).

[3] Structural data (degrees): S_0 — bedding (strike, dip), I_1 — bedding/cleavage intersection (azimuth, inclination), S_1 — cleavage, ^ — "angle from" (in mudstone).

Table 2. Correlation of mudstone fissility-ratios and stretch-ratios in the plane of bedding, Manilla–Tamworth district, NSW. Stretch-ratios determined by Breddin method from *Leptophloeum australe.*

Location: *sample:*		*"Wimborne"* *M91–14*		*Borah Creek* *M90–1*		*Tamworth Council Quarry* *K89–2*	
Fissility–ratios							
c/b ± s.e.	(n)	0.66 ± 0.01	(2)	0.79 ± 0.13	(2)	1.3 ± 0.27	(2)
i/b ± s.e.	(n)	1.64 ± 0.23	(5)	1.60 ± 0.16	(5)	3.0 ± 0.68	(5)
Stretch–ratios							
$R(S_0)$ ± s.e.	(n)	1.20	(1)	1.21 ± 0.03	(5)	1.6	(4)
$\phi(S_0)$^I_1		+1° ± 2°		+5° ± 5°		assumed 0°	

I_1: bedding/cleavage intersection. $R(S_0)$: stretch-ratio on bedding. $\phi(S_0)$: major principal strain axis on bedding, measured anticlockwise positive relative to locality average cleavage trace. n: number of mean estimates (of fissillity-ratio) or specimens (for stretch-ratio). s.e.: standard error. ^: "angle from". (See Table 1 for further information.)

Table 3. Comparison of fissility-ratios in three rock types, Borah Creek, Manilla, NSW. (See Table 2 for symbols.)

		Mudstone		*Muddy sandstone*		*Argillite*	
c/b ± s.e.	(n)	0.79 ± 0.13	(2)	0.85 ± 0.17	(4)	1.69 ± 0.21	(5)
i/b ± s.e.	(n)	1.60 ± 0.16	(5)	1.52 ± 0.33	(5)	5.0 ± 0.8	(6)
S_0^S_1		65°		85°		75°–90°	

Table 4. Correlation of fissility-ratios with dimensional ratio and stretch-ratio data for "pencil structure" in Reks & Gray (1982, Figs 2, 3 & 14).

Reks & Gray data				*Our estimates*		*R & G.*
Figure	*View*	*Locality*	*l/w ratio*	*i./b*	*c/b*	*Y/Z*
i/b — l/w correlation from outcrop photographs						
2a	↑↑ I_1	158	15.6	10	2	
2b	⊥ S_0	17 (2)	13.4	7.5	0.5 ?	
2c	⊥ S_0	21	19.8	12		
3a	loose	21	19.8	15		
3b	loose	17 (2)	13.4	10		
3c	⊥ S_0	57	10.4	4	0.4 ?	
	(linear best-fit correlation: i/b = 0.92 *l/w* — 4.4, corr. coeff. = 0.92)					
i/b — Y/Z correlation from best-fit relation						
14		66	9.8	4.6		1.10
14		158	15.6	10.0		1.20
14		35	19.0	13.1		1.27
14		36 (2)	19.2	13.3		1.26
14		21	19.8	13.8		1.30
14		53	23.0	16.8		1.35

I_1: intersection lineation direction. S_0: bedding. *l/w*: Reks & Gray projected intersection length/width parameter. *i/b:* Durney & Kisch intersection/bedding parameter. *Y/Z*: intermediate/least principal stretch-ratio, approx. parallel to bedding (inferred from pressure-shadow extension strains normal to bedding).

Editorial invitation: Supporting comments or counter-arguments relating to the above paper would be welcome for publication as *Discussion*.