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Multiply deformed terrains—problems of correlation

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Abstract—The best tools available for carrying out a structural analysis in a complex area are overprinting, style and patterns of orientation. Unfortunately, all have limitations which are reviewed briefly and discussed.

In areas of continuous, unfaulted outcrop the deformational history can be established purely on the basis of overprinting, but even in such areas there can be problems since not all overprinting relationships are unambiguous. Most fold interference patterns are reliable. Overprinting relationships based on foliations, however, are commonly unreliable, and various examples are cited and discussed.

Even in areas where the sequence of deformational events can be established, their temporal significance is unclear, since the methods applied only determine local relative timing, and absolute relationships must vary in space and time across an orogen.

INTRODUCTION

THE WRITER was asked to examine critically the problem of correlation in complex, multiply deformed areas and general methods therefore, are briefly reviewed. However, since many of the general problems are already extensively dealt with in text books (e.g. Turner & Weiss 1963, Hobbs *et al.* 1976) this paper is mainly concerned with the less well-treated problems inherent in the use of foliations in correlation. As our knowledge of deformed rocks improves, there is a tendency for the number of possible interpretations, for a given situation, to increase. There is thus a continual need to question the validity of the methods that we use to analyse multiply deformed areas, and to consider which of these methods are most reliable.

When the geological history of an area has been determined it is often possible in retrospect to find a single mesoscopic specimen or outcrop that demonstrates the total deformational history of that area (see Turner & Weiss 1963). However, the history has to be known first, since it cannot be assumed that the history recognized in any one outcrop or hand specimen, represents the total history of the area—it is necessary to look at the area as a whole and to build the total picture in a piecemeal fashion. In order to do so we must correlate the structures seen throughout the area. Such correlation is always necessary, even in areas of continuous outcrop, where it is comparatively simple. It is most difficult in complex areas where outcrop is poor.

The importance of correlation in the interpretation of geological history is fundamental; without correlation there can be no ordering of deformational structures. Its importance is less obvious, but no less significant, in the interpretation of the geometry of areas containing macroscopic structures. Wherever the geometry has to be interpreted rather than observed, knowledge of the relative age of various structures places limitations on the possible interpretations (e.g. Fig. 1). Thus correlation is important at all stages in the study of the deformation of complex areas.

METHODS OF CORRELATION

Various features have been used as a basis for correlation. In the early days of modern structural analysis, Weiss and McIntyre made extensive use of 'style' (Weiss & McIntyre 1957, Turner & Weiss 1963) to organize folds into groups that were dated relative to one another by use of overprinting criteria.

The assumption is that, in a given area, structures belonging to each generation have a characteristic style. That is to say that, within arbitrary limits, they display the same morphology (see Turner & Weiss 1963, p. 79). The folds are grouped first on the basis of style, and generations are then established on the basis of overprinting. If, in the area in question, style is a valid way of grouping the folds (that is 'valid' in the sense that it allows grouping of folds that belong in the same niche in the deformational history) then this approach gives the relative ages of the various structures at any point, in the area under consideration. It does not give any information on the absolute ages of the structures (see e.g. Hobbs *et al.* 1976, p. 351 & following). For this reason the term generation is particularly apt; in any outcrop a structure belonging to, say F_2, will be younger than one

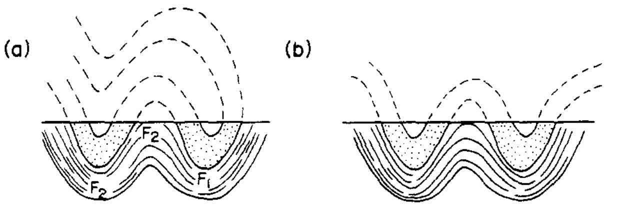

Fig. 1.(a) Interpretation of an area in which the folds can be ascribed to specific generations. (b) A more reasonable interpretation of the same area where the folds cannot be ascribed to specific generations.

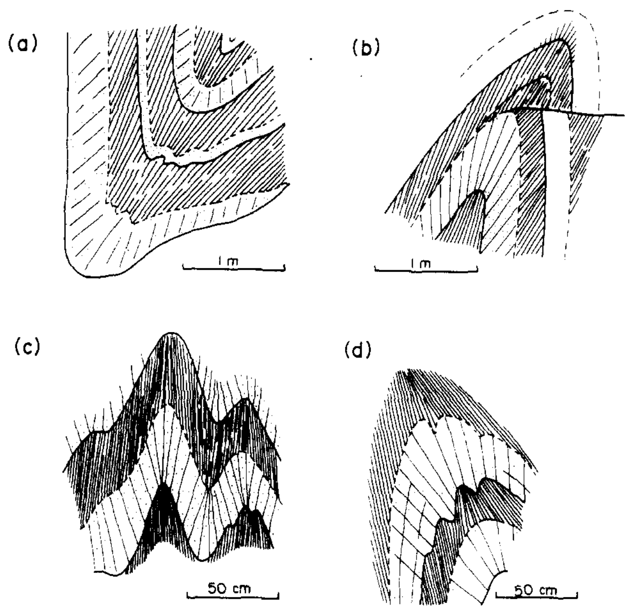

Fig. 2. Fold profiles from Bermagui, Australia, showing the overlap in style of F_1 and F_2. (a) and (b) are F_1 and (c) and (d) are F_2.

belonging to F_1. As with human generations, how much younger is not specified and just as a man may be older than his uncle, so an F_2 fold may be older than an F_1 fold elsewhere in the same area (see Hobbs *et al.* 1976, pp. 354 & 355). The sequence is the same everywhere, but the absolute timing of the sequence may vary from point to point.

The style of a structure of a given generation is dependent in part on rock type (e.g. Ramsay 1967, chap. 7, Platt *et al.* 1983) and this must be taken into account when establishing style groups. This is not generally a problem in areas of good outcrop, but can be, where outcrop is sparse. The greatest problem in using style is that in some areas (see Fig. 2) more than one generation of structure has the same style or overlapping ranges of varying style (Park 1969, Williams 1970, Passchier *et al.* 1981, Williams & Compagnoni 1983). To recognize this problem it is generally necessary to have sufficient continuity of outcrop to see overprinting relationships between folds of the same style, and thus in areas of poor outcrop the problem may exist but may go undetected.

Despite this limitation, style is probably still the best single characteristic for meaningful grouping or correlation of structures and there are areas where it does seem to work.

Orientation is considered by some writers to be a component of style (e.g. Whitten 1966, p. 37) but most writers treat it as a separate entity. It is generally considered unreliable for correlation purposes (Hobbs *et al.* 1976, p. 354) and if used, must certainly be used with care. There are areas however, where it is useful. For example, in the Bard area of the Sesia Lanzo (Passchier *t al.* 1981, Williams & Compagnoni 1983), F_5 and F_6 ave overlapping styles and cannot be distinguished in e field by their appearance. However, having estabhed, in areas of continuous outcrop, the existence and ntation pattern of both, it is possible to recognize members of each group, in less exposed areas, by their orientation.

Structures can sometimes be grouped on the basis of their relationship to metamorphic minerals and assemblages. In general, such grouping is not precise enough to allocate the folds to single generations but it can be helpful in separating some generations. For example, in the Little Broken Hill area south of Broken Hill, Australia, F_2 and F_3 folds have very similar styles but whereas the F_2 folds have an axial-plane foliation and axial lineation defined by high-grade minerals, including biotite and sillimanite, the F_3 folds have corresponding structures defined by low-grade minerals, namely muscovite and chlorite.

Another example of the use of metamorphic criteria is to be found in the Sesia Lanzo zone of the Alps (Williams & Compagnoni 1983). There, three generations of kink folds (F_4, F_5 and F_6) have overlapping styles, differing only in that, although all three show the same range of interlimb angles, the average interlimb angle for each generation becomes smaller in going from the youngest to the oldest generation. All three generations kink large individual micas and mica aggregates and, for kinks of equal interlimb angle, serrated boundaries are best developed in F_4 folds, weakly developed in F_5 folds and only very rarely seen in the tightest F_6 folds. Similarly, F_4 and F_5 microfolds are overgrown by albite II whereas albite II is deformed by F_6 microfolds.

A disadvantage of this method is that some of the microstructural criteria used to determine the relative ages of deformation and metamorphism are ambiguous and this problem is illustrated below. The method does have one important advantage however, in that we can put limits on the time required for significant changes in metamorphic conditions and can thus learn more about the timing of deformation, than is possible from purely geometrical methods (e.g. Rickard 1965, Tobisch *et al.* 1970, Black *et al.* 1979, Williams & Compagnoni 1983).

In some areas ubiquitous foliations have been used as datum markers for purposes of correlation; thus, for example, in the Seve Köli nappe complex of Sweden (Williams & Zwart 1977) folds have been grouped into pre- or syn-transposition foliation and post-transposition foliation. A similar procedure has been adopted in the Sesia Lanzo area of the Alps (Williams & Compagnoni 1983). There are, however, potential dangers in this approach and these are discussed in more detail below.

USE OF FOLIATIONS IN CORRELATION

Foliations are used for correlation, in complex areas, in three ways. They are used to establish overprinting relationships, for relating deformation and metamorphism and as datum structures. These different uses are discussed.

Foliations and overprinting

Foliations are commonly used to recognize overprinting relationships but the more we learn the more suspect some of the criteria become. For example, in

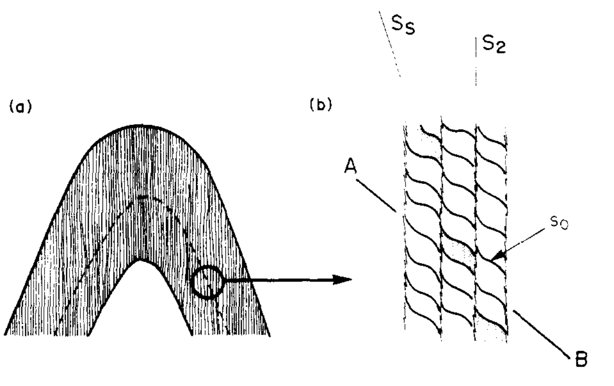

Fig. 3. See text for explanation.

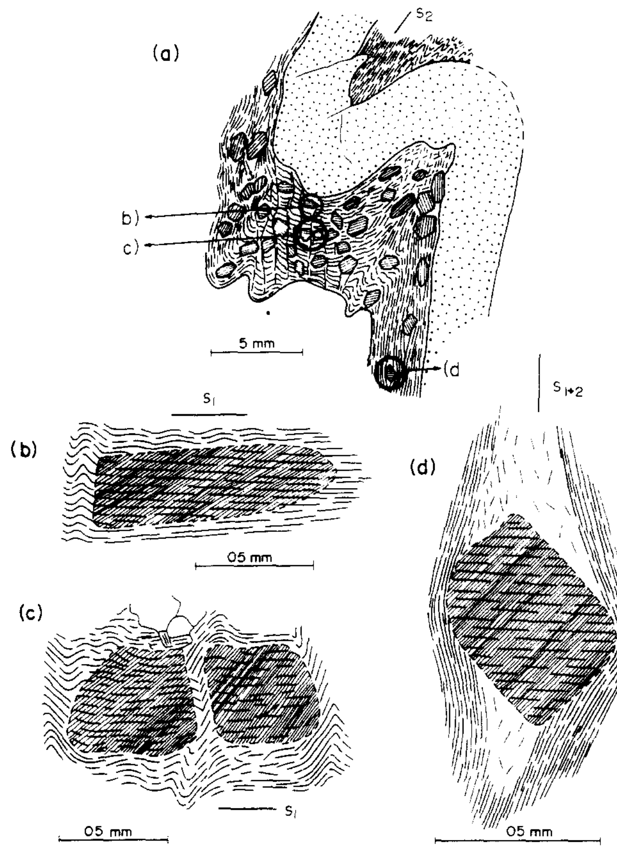

Fig. 4. See text for explanation.

many areas the earliest recognized folds fold a foliation defined by mica preferred orientation as well as a compositional layering parallel to it. Many writers have interpreted such mica foliations as a product of an early deformation which has transposed layering into the cleavage orientation. The folds are thus interpreted as F_2 and the lack of F_1 folds is attributed to the completeness of the transposition (e.g. Trouw 1973). There are cases where this approach has proven correct; for example Rao Irrinki (1979) interpreted the existence of such F_1 structures in the Bathurst area (Canada) and such folds have since been found (van Staal & Williams 1984). In general, however, this approach is not valid because bedding-parallel mica preferred orientations are a feature of many if not most sediments (e.g. Hobbs *et al.* 1976, p. 153, Siddans 1976).

If the folded mica foliation is consistently inclined to layering a much better case can be made for its tectonic origin. Imbrication of detrital grains is not uncommon in sediments but is not normally developed in micas, of all beds, in such a regular fashion as a tectonic foliation. Care must be exercised, however, in determining that the early cleavage is truly inclined to layering and was inclined prior to modification of the foliation by later deformation.

If the folds overprinting the early mica foliation have an axial-plane foliation it may be difficult or impossible to determine the relationship between the early foliation and layering. The point is demonstrated in Fig. 3. Bedding, defined by lithologic layering (*Ss*) and a mica preferred orientation (S_0), is folded by F_1 which has an axial-plane crenulation cleavage. In the right-hand limb of the fold the crenulated foliation (S_0) seems to be inclined to bedding (*Ss*) such that it dips less steeply (parallel to the line A–B). This apparent difference in orientation is an optical illusion. We equate the dominant visible orientation of S_0 in the microlithons, with the orientation of S_0 on a larger scale, but since we cannot follow a single surface through the repetition of microlithons and septae, we are not seeing the true orientation of S_0 (=*Ss*). This is a common feature of F_1 folds at Bermagui but in that area there are occasionally marker surfaces* in the pelites that make it possible to trace a single surface, which is then seen to be parallel to the larger-scale bedding surfaces separating pelite and sandstone (Fig. 3). A clue to the existence of the problem is given by the symmetrical appearance of the two limbs, that is S_0 in the pelite appears to dip more gently than *Ss* on both limbs. However, this observation is not diagnostic since the same geometry can result from folding of two non-parallel surfaces.

It might be argued that the difference in orientation between *Ss* and S_0 should be recognizable within the microlithons if they are broad enough, but even that may be difficult. In experiments with layered foliated specimens made of mixtures of salt and mica (Williams *et al.* 1977) we found that an incompetent mica-rich layer adjacent to a competent salt layer crenulated in such a way that crenulations persist right up to the 'bedding plane' where they die out immediately. The result is that whereas the micas were originally parallel to bedding they may now appear inclined, even within a microlithon, right up to the bedding plane. Thus the original relationship has been modified by later deformation but it is not always easy, or even possible, to recognize that the modification has occurred.

A similar problem of late modification commonly occurs with respect to porphyroblasts. Zwart (1960) proposed a number of criteria for determining the relative age of a porphyroblast and a foliation in the surrounding rock. One of these criteria indicates that a porphyroblast is at least older than the late stages of foliation development if the foliation bends around the porphyroblast (e.g. Fig. 4d) and this is especially true if

*One such surface is marked by coarse detrital biotites in a finer-grained rock in which the layer silicate is mainly white mica. Others are marked by very thin silt layers in otherwise finer-grained rocks.

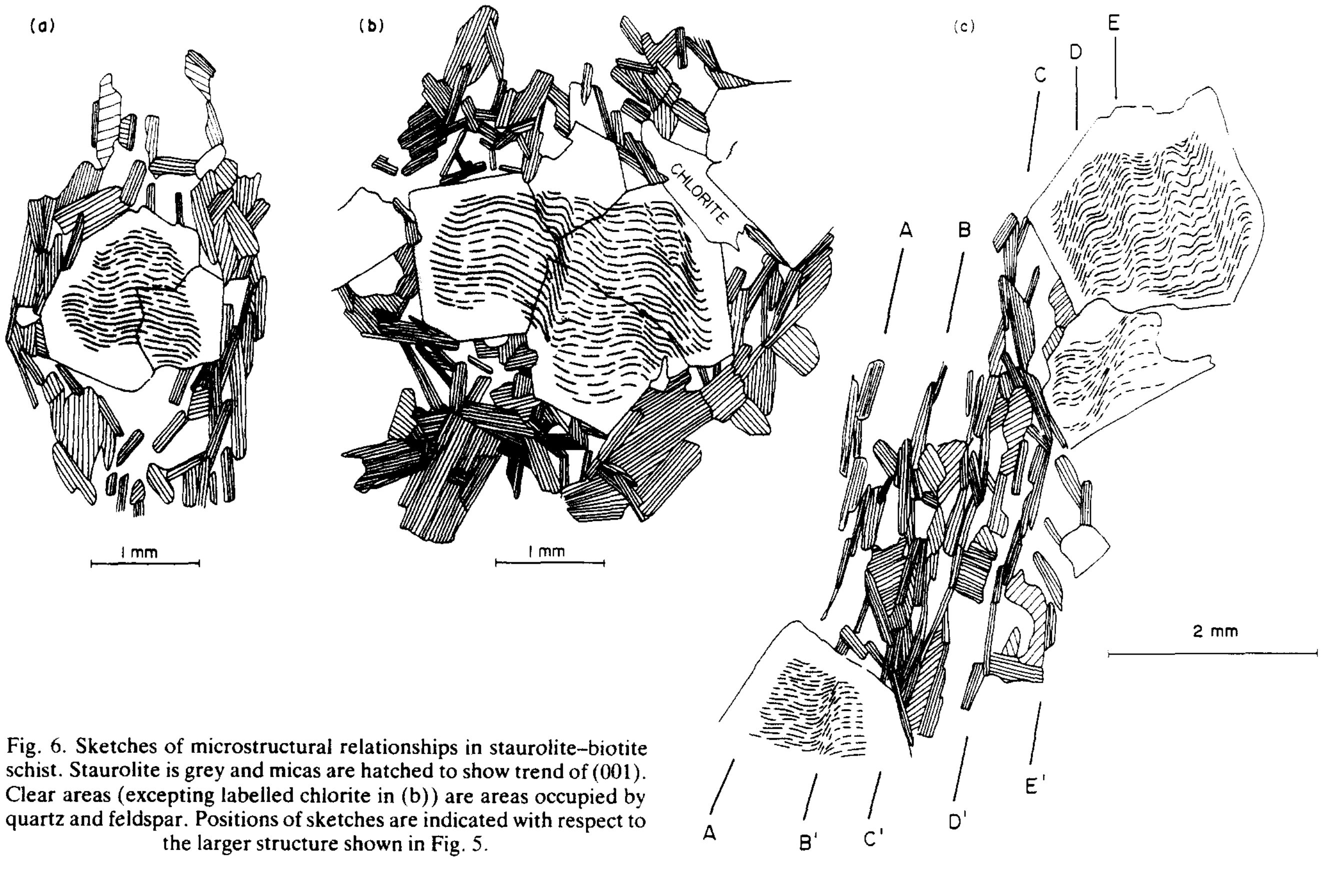

Fig. 6. Sketches of microstructural relationships in staurolite-biotite schist. Staurolite is grey and micas are hatched to show trend of (001). Clear areas (excepting labelled chlorite in (b)) are areas occupied by quartz and feldspar. Positions of sketches are indicated with respect to the larger structure shown in Fig. 5.

the porphyroblast has an *Se* that is discontinuous with the *Si*. Figure 4, however, shows an example from Woody Island, Newfoundland, in which this criterion for overprinting breaks down. Two folds (F_2) in a competent layer fold a foliation (S_1) defined by penetrative preferred orientation of mica. In the left-hand fold, on the convex side of the competent layer, S_1 can be traced as inclusion trails through several porphyroblasts (Figs. 4a–c). Outside of the porphyroblasts, S_1 is crenulated but crenulations are only slightly overgrown by the porphyroblasts (Figs. 4b & c). The relationships are clear, the porphyroblasts grew after the development of the foliation, possibly late during its development but not before it. The foliation was then folded by F_2 during the final stages of porphyroblast growth. On the limb of the F_2 fold, however, the foliation is bent around a porphyroblast and *Se* and *Si* are not continuous (Fig. 4d). The porphyroblast, as noted above, therefore appears to be older than the foliation. There are two possible explanations. (1) The porphyroblasts may not all be the same age. (2) The porphyroblasts are all post-S_1 but the microstructure has been modified on the limb of the fold by flattening associated with the folding. Observation of other folds from the same area shows that these microstructures are repeated, and because it is unlikely that the 'old' and 'young' porphyroblasts would have all grown in what were to become the limbs and hinges, respectively, of later folds, we can assume that the second interpretation is the correct one.

We are only able to recognize the true relationship in this example because of continuity of the specimen and considerable variation in strain magnitudes, parallel and perpendicular to the foliation, between hinge and limb. Despite the differences in strain there is no obvious difference in the morphology of S_1. Even if there were a lesser degree of preferred orientation in the hinge, it could be attributed to the localized development of the younger crenulations. Obviously any correlation based on what is observed in the fold limb in this example would be incorrect unless it were assumed that the foliation was forced aside by growth of the crystal. The last possibility has been discussed by Ferguson & Harvey (1972) and further adds to the problem of interpreting such relationships. Yet another problem could arise if the hinge and limb relationships were seen in isolated outcrops. S_1 would then most likely be interpreted as two foliations or the growth of staurolite would be extended over a longer period of time. Examples of this type of problem are common.

A similar problem is illustrated in Figs. 5 and 6, where a schistosity is defined by coarse-grained biotite and muscovite. It might be argued, as is commonly done (Tobisch *et al.* 1970, Dallmeyer *et al.* 1983, and Brown & Read 1983, who used the same argument for a lineation), that the foliation is defined by these minerals and must therefore have developed during their metamorphic growth. However, in this particular rock the bimodal orientation pattern and, locally, the spatial distribution (see Fig. 6c) indicate that the schistosity grew from a crenulation cleavage, and this cleavage is in fact preserved as inclusion trails in staurolite porphyroblasts. The *Si* crenulation cleavage is well developed and

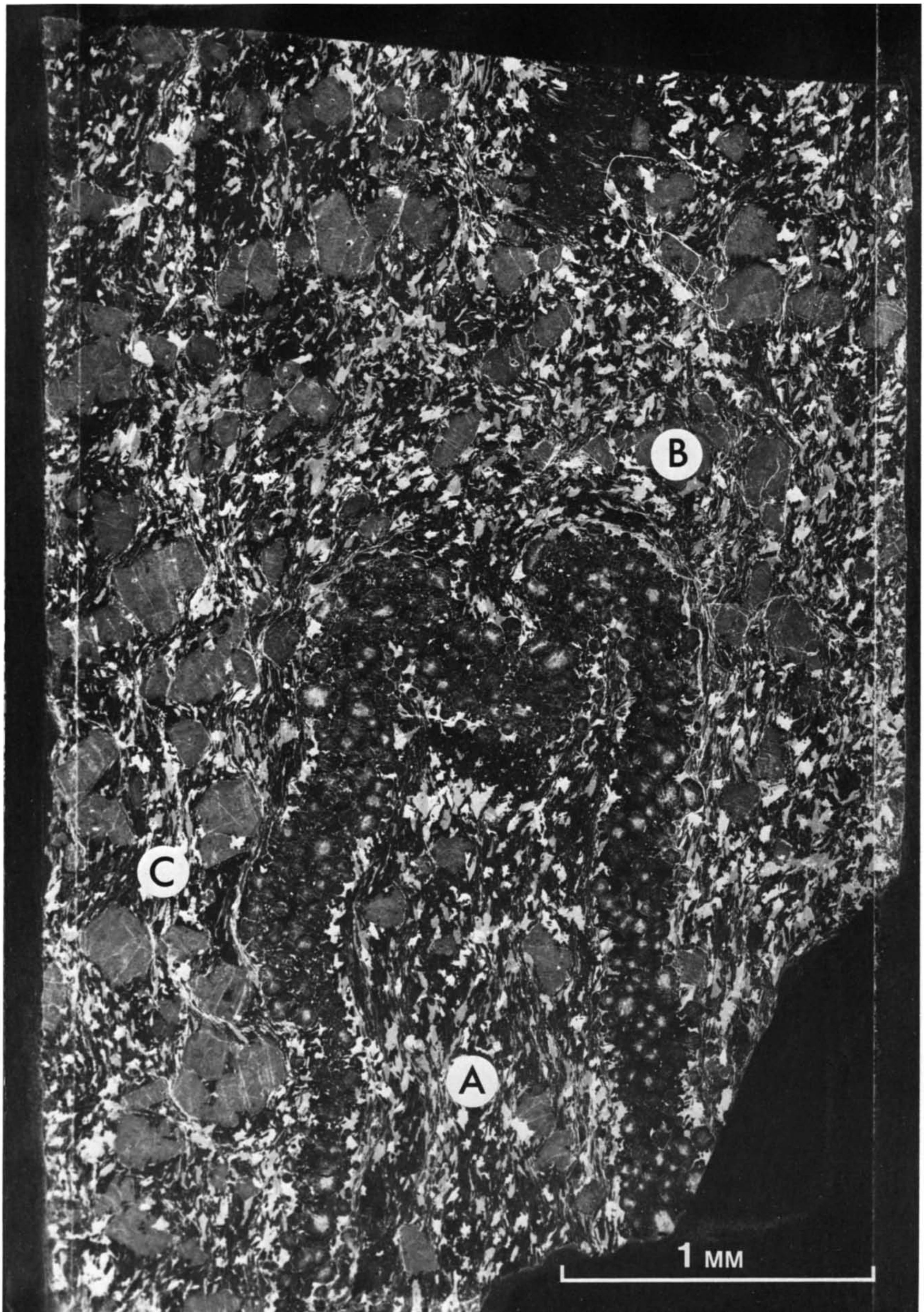

Fig. 5. Folded cuticule layer in staurolite–biotite schist. Letters indicate positions of areas represented by sketches in Fig. 6.

consistently has an asymmetry and orientation that is compatible with the larger fold (Fig. 5), indicating that it is related to the development of the fold. It is in fact, a convergent, axial-plane crenulation cleavage that has largely been obliterated in the matrix by subsequent mica growth.

The helicitic occurrence of the crenulation cleavage in the staurolite, indicates that the staurolite developed later than the cleavage. Furthermore, since the finer details of the cleavage are much better preserved in the staurolite than in the matrix, the helicitic part of the porphyroblasts, at least, must be earlier than much of the coarsening of the mica, which at the time of porphyroblastesis had to be fine grained enough to preserve the smooth curves of the crenulations. The smaller staurolites and the outer rims of the larger ones are inclusion free and may be contemporary with the main mica coarsening.

Despite the considerable mica coarsening, the crenulation cleavage can still be recognized in the matrix, where it is well developed in the staurolite. Additionally, the width of the septa/microlithon pairs is the same for *Si* and *Se* (Fig. 6c) and these two facts indicate that there has been little, if any, deformation since staurolite growth. Thus the cleavage appears to have developed at the time of folding and presumably developed in lower grade rocks. During the very final stages of folding, or at any later date, static mineral growth gave rise to the present metamorphic assemblages. The mineral growth has been interpreted in part as a product of contact metamorphism (Pickerill *et al.* 1978) and the age of the folding is unknown so that the interpretation presented here is not incompatible with the regional story. The important point, however, is that close study of the microstructures demonstrates the danger of correlation based on the assumption that a foliation is coeval with the metamorphism responsible for the minerals defining the foliation. This problem extends also to radiometric dating since the age of the biotite gives the age of that stage in the metamorphism, but not necessarily the age of the deformation.

Overprinting of folds and foliations by later folds and foliations seems at first sight an unambiguous situation but in fact can also be complex. Three examples are given here; each would lead to problems of correlation if misinterpreted.

Figure 7 represents cleavage-fold relationships seen in some F_1 and F_2 folds at Bermagui. It is a composite diagram that shows all the foliations believed to be related to folds of a single generation (F_1 or F_2), that is if the fold is F_1, the foliations are F_1 related, if the fold is F_2 the foliations are F_2 related. The morphology is the same for both generations and they are therefore described as a single morphological group.

The earliest foliation is parallel to bedding and the author believes is generally of primary origin. Locally, however, a differentiated layering, that must be of secondary origin, occurs within the Bouma A units (Fig. 7a). This foliation is only found on the fold limbs and dies out towards the hinge. Its symmetrical relationship to the

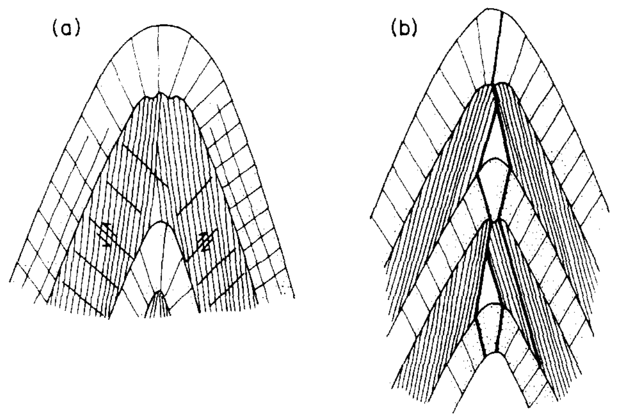

Fig. 7. Diagrammatic representation of foliations associated with both F_1 and F_2 folds at Bermagui. See text for additional discussion.

folds suggests that it is a product of the deformation that produced the folds, and it is interpreted as a slip surface related to a flexural-slip mode of deformation, in the early stages of folding (Williams 1972).

The second structure is a strongly refracted axial-plane cleavage that in some pelitic layers (usually only one in any one fold) appears, in the fold-hinge, as two separate cleavages with one intersecting the other. The writer has interpreted (Williams 1972) these two surfaces as a single axial-plane cleavage in the sense that they are thought to be formed during the one folding event. The reasons for this are as follows. (1) The cleavage is generally divergent in the pelitic beds so that the geometry is not very different between folds where the cleavage planes intersect and folds where they do not. (2) Cleavage planes of both orientations intersect bedding in a line parallel to the fold axis. (3) Where the foliations converge there is no evidence of one being folded by the other, that is no real evidence of overprinting. (4) Individual foliation septa can be traced, in large thin sections, through adjacent coarser beds into the next pelitic layer on either side, where they do not intersect. (5) In one outcrop intersecting relationships exist in two adjacent pelitic beds, and there, in one bed, the foliation from the right-hand limb cuts off the foliation from the left-hand limb. In the succeeding pelitic bed the relationship reverses as shown diagrammatically in Fig. 7(b).

In Newfoundland, the writer and colleagues are faced with a similar situation in folded turbidites where the intersecting relationship depicted in Fig. 7(a) is much more common, and locally occurs in every pelitic bed. Further, in a given fold the cleavage from one limb consistently cuts off the cleavage from the other limb. It is not clear whether we should treat this as an overprinting relationship or as a single axial-plane cleavage as at Bermagui.

A further feature of the Bermagui structure is that both F_1 and F_2 folds are overprinted by conjugate pairs of crenulation cleavage (Fig. 7a). These foliations certainly overprint the earlier folds and axial-plane cleavage. However, because of (1) their symmetrical relationship to the folds, (2) their sense of shear and (3) the fact

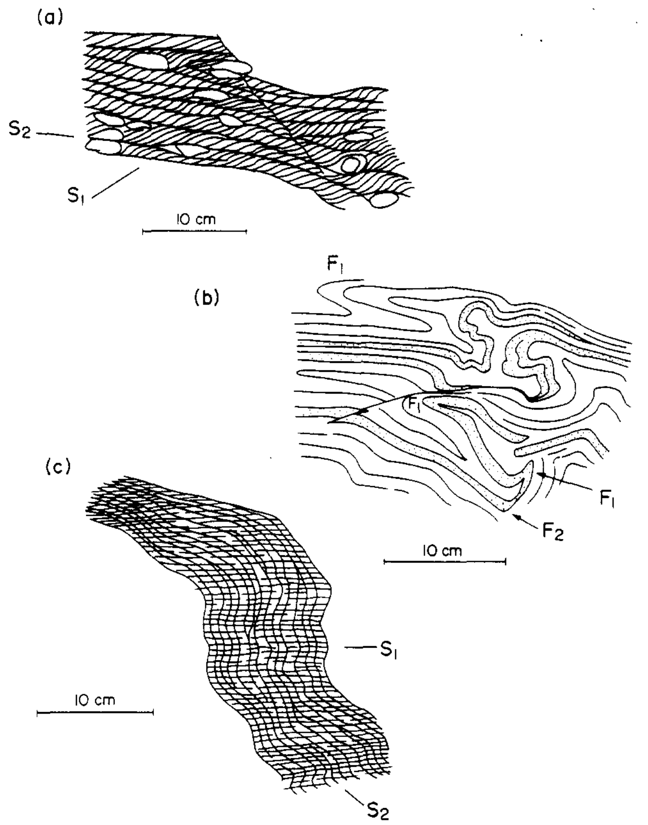

Fig. 8. Overprinting relationship in quartz–feldspar porphyry, banded ironstone and fine-grained quartz–feldspar porphyry. See text for discussion. All diagrams have the same orientation.

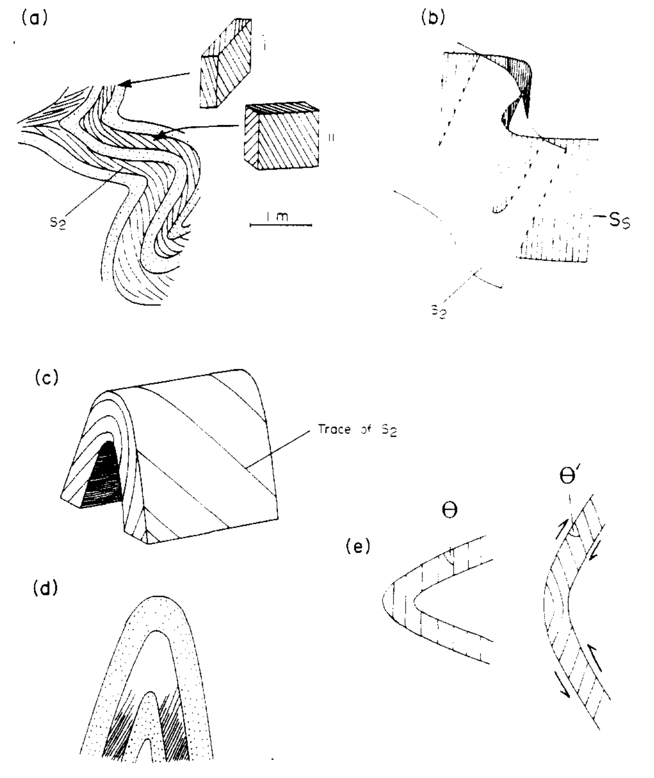

Fig. 9. Folds in bedding and early cleavage. (a) Sketch of outcrop with inset blocks showing bedding/cleavage relationship in three-dimensions. (b) Diagrammatic representation of three-dimensional form of folded *Ss* (bedding) and cleavage (S_2). Note: with respect to (a) the folds are being viewed from the top of the page. For additional explanation and details of (c)–(e) see text.

that they are not axial planar to any folds, the writer has interpreted them as a product of the late stages of the deformations responsible for the folds with which they are spatially associated (Williams 1979). Such a foliation is commonly produced in folding experiments (Hobbs *et al.* 1982) and is, in that situation, shown to develop late in the folding history, as the last step in a progressive deformation.

Generally, both in the experimental folds and at Bermagui, only one orientation of a conjugate pair occurs in a given fold limb and intersections of the pairs are found only in fold hinges (Fig. 7a). In addition, the foliation is generally restricted to the more pelitic beds. However, in the limbs of some folds at Bermagui the late conjugate cleavage reactivated the suitably oriented convergent, axial-plane cleavage (S_1 or S_2) in the coarse, competent layers and crenulated the same axial-plane cleavage (S_1 or S_2) where it forms part of a divergent fan, in the pelitic layers.

These complex cleavage patterns with more than one surface associated with a single deformation have the potential for problems of correlation if one relies on cleavage for recognizing deformation generations.

Figure 8(a) shows an overprinting relationship between two foliations (S_1 and S_2) at Brunswick No. 6 Mine, New Brunswick, Canada. A closely spaced layering is crenulated and the limbs of the crenulation are differentiated, defining a coarser layering that apparently overprints the finer one. For several years these foliations were correlated respectively, with F_1 and F_2 structures, elsewhere in the area, on the basis of this apparent overprinting. However, in less well-foliated layers (intercalations of iron formation) in these rocks, there are folds with axial-planes orientated parallel to 'S_1' and 'S_2' (Fig. 8b) but the folds show the opposite overprinting relationship (i.e. the folds with axial planes parallel to 'S_1' overprint folds with axial planes parallel to 'S_2'). There are also rare folds in which the 'S_2' layering is folded with 'S_1' as an axial-plane cleavage (Fig. 8c) and other equally rare folds that have 'S_2' as axial-plane cleavage and are overprinted by 'S_1' (Cees van Staal pers. comm. 1984). Thus the 'S_1' foliation is the younger of the two and it is refracted as it passes through the 'S_2' layers, rather than folded by a later 'S_2'-related deformation. It is not even possible to recognize the true relationship in thin sections of material such as that illustrated in Fig. 8(a). The refraction is so strong and the microstructure so complicated by other crenulations that occur within the S_1 and S_2 mica-rich layers, that the overprinting relationship cannot be determined with any certainty. Recent work (Cees van Staal pers. comm. 1984) has revealed that the strong refraction, reported here, occurs on the limbs of large, true F_2 folds. In the hinges of these folds the refraction is much weaker and the correct overprinting relationship between the foliations is recognizable both in the field (as in Fig. 8c) and in thin section.

A second example of this type of problem is shown in Fig. 9. In Fig. 9(a) folds are seen that are cut, in the pelitic layers, by a foliation. This foliation was in-

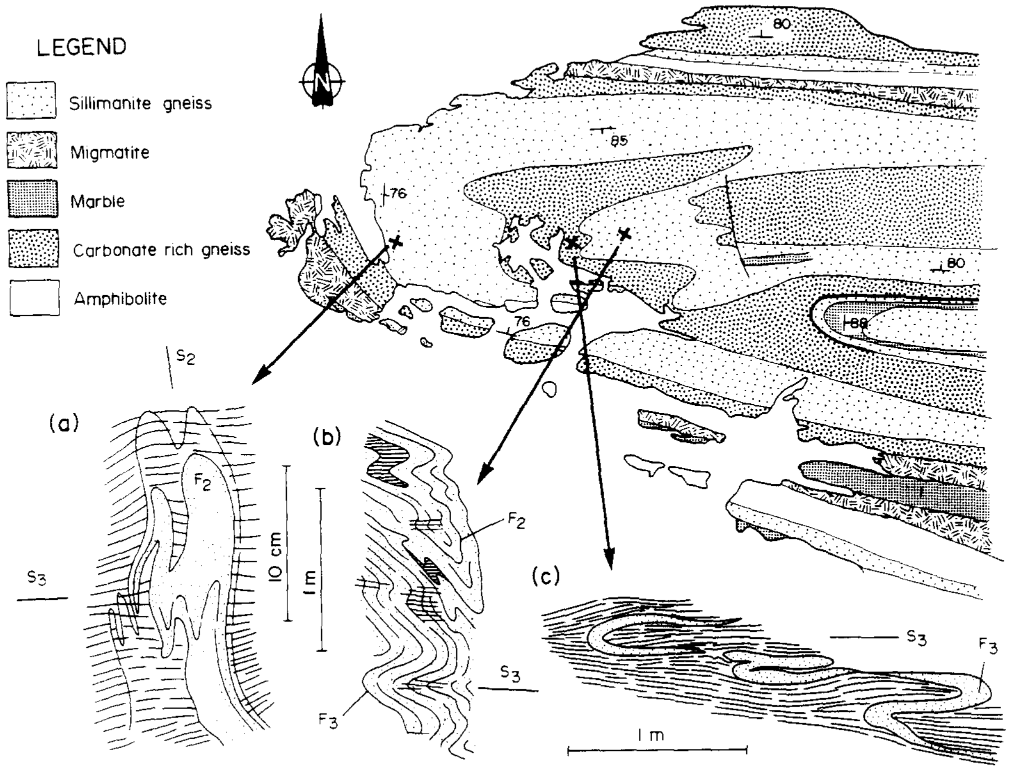

Fig. 10. Map of Vågaholmen, Norway after Kuipers (1982). Insets (a), (b) and (c) show details of the mesoscopic structure; all three are oriented with respect to the map. For further discussion see text.

terpreted by a group of geologists, on an I.G.C.P. field excursion, as younger than the fold. The bending of the foliation was attributed to refraction and this interpretation was initially accepted by the writer. It is difficult, however, to understand how refraction could produce the observed pattern. If it is assumed that refraction is due to heterogeneity of layer-parallel shear during deformation (cf. Bayly 1965) and if the cleavage is assumed to be approximately perpendicular to the bulk shortening direction, then the earlier folds would be unfolding during the cleavage development (Fig. 9e). Such a deformation would give rise to layer-parallel shear in the pelitic layers as shown in Fig. 8e), and while the shear rotates the foliation in the right direction to produce the observed geometry (i.e. θ is reduced) the bulk rotation of the limbs has the opposite effect, so that the expected result would be as shown in Fig. 9(e). It could be argued that this model for refraction is incorrect and it may be possible to find a more appropriate model. However, other evidence indicates that the cleavage is in fact older than the fold. The first clue comes from samples collected from the fold, that allow the three-dimensional geometry to be determined (see Fig. 9a, detail blocks i & ii). It can be seen that the cleavage/bedding intersection curves around the folds in a way that permits the structure to be interpreted as mutually inclined bedding and cleavage folded together about axes perpendicular to the general trend of the bedding/cleavage intersection. This interpretation is confirmed by observation of a larger area, because there is a transition in continuous coastal outcrop from the situation depicted in Figs. 9(a) and (b) to a situation where the fold axes are no longer perpendicular to the cleavage–bedding intersection and the cleavage is in some cases obviously folded (Fig. 9c). The difficulty of recognizing the true relationship is compounded, however, by the fact that the cleavage, which is rarely easy to see, is completely obscured in most of the fold closures (as in Fig. 9d) so that the fold seems to be overprinted obliquely by the cleavage. The transition between the situation illustrated in Figs. 9(c) and (d) can be seen, however, and the lineation relationships in Fig. 9(d)-type folds is the same as in Fig. 9(c). Before the true relationship was recognized the folds shown in Fig. 9(a) and similar ones throughout the region were labelled F_1 and the cleavage S_2. The folds are now labelled F_3 and the cleavage S_2 and the regional structure makes much better sense.

Use of datum structures

As mentioned above, common use has been made of ubiquitous foliations as datum markers in the deformational sequence (e.g. Zwart 1979, Platt *et al.* 1983), and in some examples the foliation used is a transposition foliation (e.g. Williams & Zwart 1977, Williams & Compagnoni 1983). This may be a reasonable approach in many areas but there are dangers in using transposition foliations due to heterogeneity of the transposition. This point is demonstrated in the Vågaholmen Peninsula in northern Norway.

The peninsula (Fig. 10) comprises an isoclinal fold related to the regional transposition (Williams 1983) and outcrop is continuous around the coast and sufficiently good inland that the entire structure can be observed rather than interpreted. Along the west coast of the peninsula, Anschutz (1977) and van der Stijl (1977) recorded a transposition foliation (S_2) folded by open F_3 folds (Fig. 10a) which have an axial-plane crenulation cleavage (S_3). The same structure can be seen at another outcrop, in the same competent layer (Fig. 10b), in the core of the fold, but F_3 is now better developed. In an incompetent layer between the other two outcrops (Fig. 10c) there is a transposition foliation that differs from the S_2 foliation only in ways that can be attributed to difference in lithology. There is no reason not to correlate these foliations, except that, due to the continuity of outcrop, the foliation in the core of the fold can be seen to be the S_3 of Anschutz (1977) and van der Stijl (1977). Given more normal discontinuity of outcrop it is likely that an erroneous correlation would be made based on the use of two transposition foliations as a single datum surface.

Cleavage-transected folds

Cleavage-transected folds constitute a considerable dilemma. First there is the difficulty of proving their existence and second, if they exist, they pose a potential problem for correlation based on foliations.

There is little doubt that minor deviations from parallelism between fold axial surface and related cleavage do occur. Because of fanning, most cleavage planes are inclined to the axial surface, but if fanning is the only reason for non-parallelism then the cleavage plane passing through a fold hinge will contain the fold axis and will pass through successive hinges. However, even that plane may deviate from parallelism with the axial surface and/or the axis, that is in the terminology of Borradaile (1978) both Δ and d may have small non-zero values. The difficulty is more with large deviations; if they exist, they constitute a potential problem for correlation and in the writer's opinion also pose problems with respect to cleavage development. However, contemporaneity of folds and cleavages said to transect them, with large values of Δ and/or d has not been proven and it is difficult to conceive a situation whereby it could be proven. What has been demonstrated by a number of writers is that the earliest recognizable cleavage in a given area transects the earliest folds (Powell 1974, Stringer 1975, Borradaile 1978, Stringer & Treagus 1980). This does not prove contemporaneity of the two structures, however, and more detailed work by the writer in one of the type areas (Bathurst, Canada) has in fact shown the transecting cleavage to be related to a later set of folds (Fig. 11) which were not recognized previously. The same situation may exist in other areas.

If it is assumed, however, that large values of Δ and d are possible, the existence of transected folds is a potential source of error in correlation. The problem is that in assuming a transected-fold relationship, according to the theory of transected folds (Borradaile 1978), we are implying that fold and cleavage are a product of the same progressive deformation, whereas if this interpretation is incorrect the cleavage could belong to a much later and

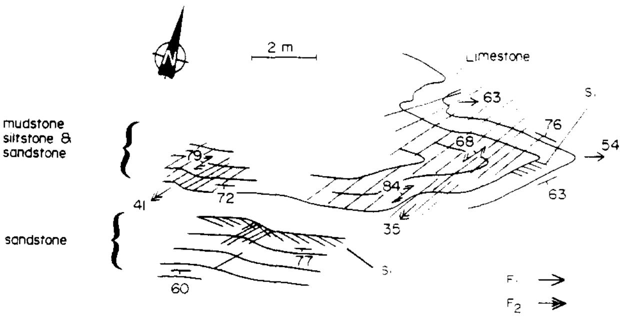

Fig. 11. 'Transected fold' New Brunswick, Canada. The northeast-trending cleavage and the large fold have been interpreted as coeval. However, an earlier cleavage (S_1) can be recognized locally and there are small folds (F_2) associated with the 'transecting' cleavage.

completely separate deformation. The problem does not arise, however, if we treat the situation as a normal overprinting relationship, since then both the possibility of the structures being either a product of continuous deformation or a product of two discrete deformations is left open. This is consistent with the explanations for transected folds, subscribed to by most authors, which rely on progressive deformation, with the foliation developing after the initiation of the fold. The same relationship is possible for any pair of consecutive generations of structures where there is no independent evidence, such as association with different metamorphic assemblages, for a distinct time gap between the two. Gray (1981), however, has suggested that in rocks from Virginia the transecting foliation was initiated before folding, and the transected appearance is due to migration of the fold hinges. In these folds, however, values of Δ and d are small and there is no overprinting relationship between folds and cleavage.

DISCUSSION AND CONCLUSION

Correlation of structures, microstructures and metamorphic assemblages in complex multiply deformed areas is of fundamental importance from the point of view of understanding structural geometry and deformational and metamorphic history. The style and orientation of structures have been criticized as correlation criteria in the past and in this paper I have attempted to indicate some of the problems inherent in the use of foliations in correlation. Perhaps the single most important feature of foliations from this point of view is that many foliations are susceptible to modifications that may be difficult or impossible to recognize except under exceptional circumstances. Occasionally we recognize the composite nature of a foliation as in Fig. 4 (see also Meneilly 1983), but there may be many other situations where the long history of modification that a given foliation has experienced is not recognized.

For this reason, foliations are particularly suspect for purposes of correlation. Further, they are also difficult and sometimes impossible to use as a means of recognizing overprinting relationships. For example in the area depicted in Figs. 9(a) and (b), without the relationships seen elsewhere in the outcrop (Fig. 9c), there are two possible interpretations; namely the foliation is either younger or older than the fold. Yet another possibility, not discussed above, would be that the foliation is an arcuate cleavage and contemporary with folding (see Roberts & Strömgaard 1972, Savage 1965).

With respect to correlation between foliations and metamorphism, it has been shown that it is insufficient to demonstrate that a foliation is defined by a given metamorphic assemblage in order to confirm contemporaneity of deformation and metamorphism. Positive evidence is needed. If a mineral is deformed by the foliation or a foliation is clearly overgrown by a mineral (as the staurolite in Figs. 5 and 6) we have positive relationships indicating relative timing. The foliation development is, at least in part, post- and pre-mineral growth, respectively. Positive relationships of this type, and of the type found where one fold is refolded by another, are probably the most informative structures for the interpretation of deformation history, so long as the limitations of overprinting are kept in mind. The principal limitation of the method is that it gives only a local, relative sequence of events and not an absolute dating, nor even a relative dating from place to place. For this reason we have to be extra careful about interpretation of the timing of deformation responsible for correlated structures over a large area. We cannot, for example, say, on the basis of overprinting and correlation, that all D_1 thrusts in a large area are of the same age. Nor would we expect it from the concept of piggy-back thrusting (Dahlstrom 1970, Elliott & Johnson 1980).

It seems clear that there is no single factor that can be used for correlation with confidence in all situations. It would appear that there is the need for very detailed studies in which correlation is based on as many factors as possible. This may seem obvious but it is noticeable that there is a marked tendency to analyse areas which are so large that it is impossible to examine them in the necessary detail. On the other hand, regional studies may reveal significant evidence that would never be recognized in one small part of the area, so that perhaps the ideal approach is a combination of regional mapping and detailed studies in selected parts of the region.

One point that emerges from detailed studies is the importance of continuity of outcrop. In view of this, it is suggested that where the purpose of an analysis is to understand the principles of deformation and/or the development of deformation structures, the analysis should be restricted to areas or samples in which there is good continuity of exposure, that is as good an approximation to a mesoscopic domain (Turner & Weiss 1963, p. 15) as possible. Where the goal is simply to determine the structure of an area for whatever reason, we have to make do with what is available, and use as many criteria for correlation as possible, and aim for internal consistency.

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