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Conjugate crenulation cleavages in the Uncompahgre Formation, Needle Mountains, Colorado

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Abstract—Multiply deformed metasediments of the Proterozoic Uncompahgre Formation contain a well-developed conjugate set of crenulation cleavages and related folds. Conjugate character is indicated by the presence of conjugate folds and crenulations, synchronous cleavage development, lack of consistency in sense of overprinting where overprinting exists, and bimodal attitude distribution on πS_2 diagrams. Despite the overall conjugate character of the folds and cleavages, most outcrops exhibit only one of the two possible sets. Attitudes of fold hinges and intersection lineations suggest that these conjugate structures formed late in the second phase of deformation, after extensive D_1 transposition and after D_2 macroscopic folds were well-developed and cut by fold-related thrusts. Although considerable controversy exists regarding whether non-conjugate sets of crenulation cleavages develop parallel to the *XY* plane of the strain ellipsoid or not, it is clear that conjugate crenulation cleavages must develop at an oblique angle to the *XY* plane. Although individual outcrops may develop one member of a conjugate set to the exclusion of the other, mechanical and geometric constraints necessary for conjugate cleavage development appear to be such that it is extremely unlikely that only one member of a conjugate set would develop over an entire region to the total exclusion of its conjugate pair. Although similar in appearance, conjugate and non-conjugate crenulation cleavages appear to be two different species, one forming at a substantial oblique angle to the *XY* plane, the other probably forming parallel or nearly parallel to it.

INTRODUCTION

THE QUESTION of the strain significance of crenulation cleavage has been debated in the literature for many years. A number of researchers have argued that crenulation cleavage, like slaty cleavage, forms parallel or nearly parallel to the *XY* plane of the total finite strain ellipsoid (e.g. Wood 1974, Gray & Durney 1979, Bell 1981). A study of natural crenulation cleavage by Gray & Durney (1979) supports this view, with a careful study of D_2 strain exhibited by deformed porphyroblasts in slates. However, a number of researchers have argued that discontinuities and mechanical anisotropies can play such an important role in secondary deformation that one should not expect all crenulation cleavage to form parallel or nearly parallel to the *XY* plane of either the local or bulk total finite strain ellipsoid (e.g. Cosgrove 1976, Hobbs *et al.* 1982).

With the exception of Cosgrove's (1976) theoretical work, papers concerning the strain significance of crenulation cleavage have concentrated upon the familiar case of a single crenulation cleavage developed during a given phase of deformation. Little has been written concerning the comparatively rare case of conjugate crenulation cleavage. Gray (1979, p. 198), in fact, expresses doubt about the existence of true conjugate cleavages by referring to reports of 'so-called' crenulation cleavage. If a pair of cleavages can be shown to be truly conjugate and not simply sequentially-developed, though, such conjugate cleavages clearly represent a situation in which cleavage formation must have been at a considerably oblique angle to the plane of flattening in the rock. The question then becomes whether a model for the strain significance of conjugate crenulation cleavages can be generalized to simple crenulation cleavages or not; and, if not, why not.

The Uncompahgre Formation in the Needle Mountains of southwestern Colorado exhibits a well-developed set of conjugate structures developed late in a second-phase deformational event. The purpose of this article is to establish the conjugate nature and timing of development of these features and to consider their strain significance.

GENERAL GEOLOGY OF THE UNCOMPAHGRE FORMATION

Folded Proterozoic metasediments of the Uncompahgre Formation are exposed in a gently curved belt approximately 35 km long and a maximum of about 11 km wide, extending from the West Needle Mountains southeastwards across the northern portion of the Needles in southwestern Colorado (Fig. 1). Previous work on the Uncompahgre Formation has focused primarily on lithologic mapping, metamorphic petrology, and mineral assessment (Cross *et al.* 1905, Larsen & Cross 1956, Barker 1969, Burns *et al.* 1980).

Rb/Sr dates on the Eolus Granite, which intrudes deformed and metamorphosed rocks of the Uncompahgre Formation, provide a minimum age of approximately 1.43 Ga for the Formation (Bickford *et al.* 1969). Although a maximum age has not been determined, the Uncompahgre Formation is unlikely to be older than meta-igneous units such as the Twilight Gneiss in the Needle Mountains, dated by Rb/Sr methods at approximately 1.76 Ga (Bickford *et al.* 1969, Tewksbury 1981, Tewksbury 1985). The dates have all been recalculated for current values of λ^{87} (Steiger & Jaeger 1977).

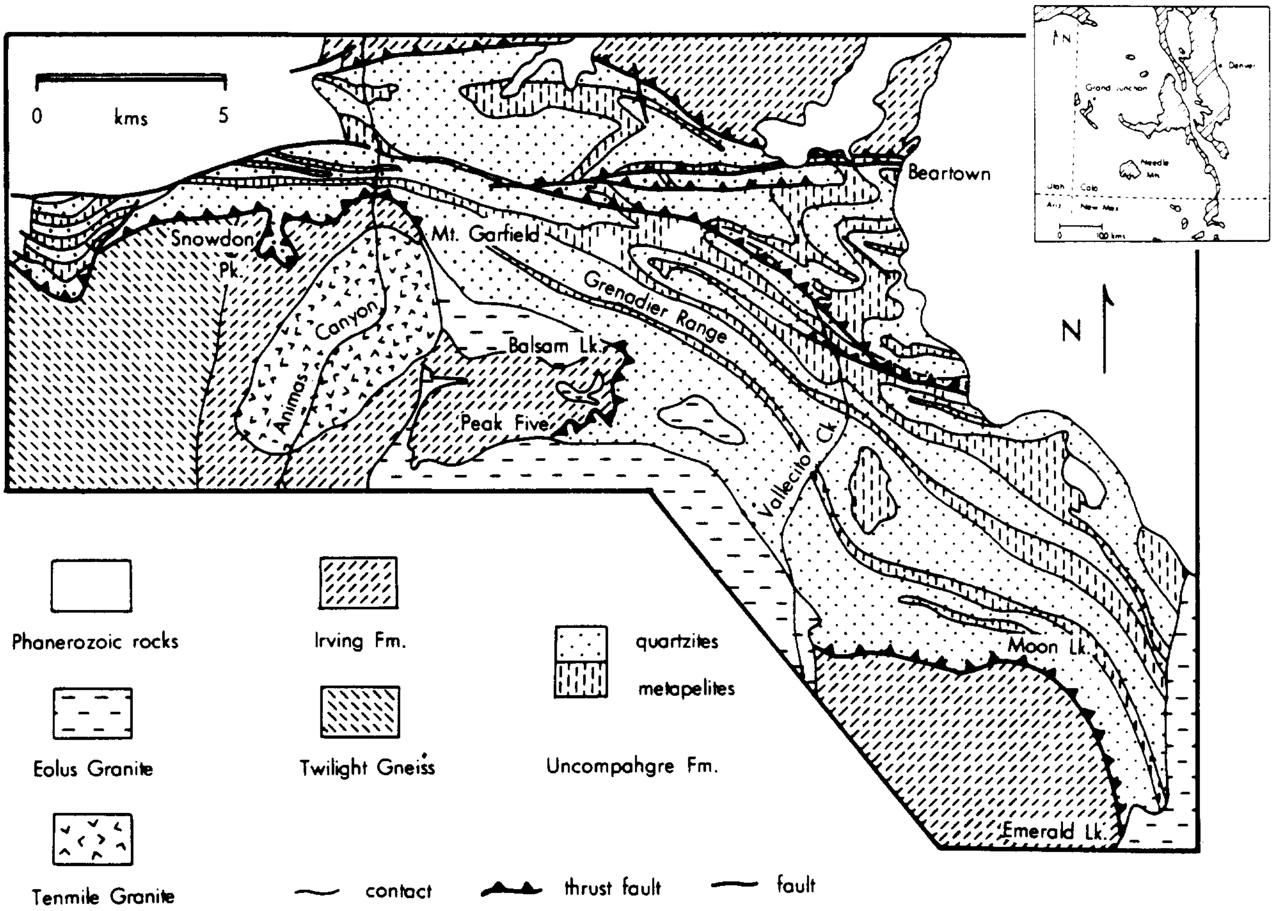

Fig. 1. General geologic map of the Uncompahgre Formation and adjacent units in the Needle Mountains (modified from Barker 1969). Inset shows location in the State of Colorado: diagonal line ornament indicates Precambrian rocks.

Petrology

Division of the Uncompahgre Formation into mappable units of quartzite and metapelite illuminates the geometry of macroscopic folds in the sequence (Fig. 1). Quartzite units range in thickness from 100 m to nearly 1000 m, while metapelite units vary from a few tens to several hundreds of meters in thickness. The quartzite units are dominated by medium-grained, blue-gray or white quartzites, with rare pebbly layers and coarse conglomeratic lenses. Compositional layering (S_0) in the quartzites is defined primarily by subtle grain-size changes, by thin laminae of specular hematite, and by rare, very thin pelitic layers within the quartzites. The quartzite units are rather monotonous, and it is impossible to distinguish one from another on the basis of physical appearance. The pelitic units are neither as monotonous nor as uniform as the quartzites. Pelitic layers alternate with psammitic layers on scales from meters to millimeters, the layering defining S_0. Pelitic layers are predominantly slate and phyllite, some quite quartz-rich; whereas psammitic layers range from fine-grained quartzites to micaceous quartzite and metasiltstone. Contacts between the quartzite and metapelite units are rarely abrupt and are often marked by medium-grained quartzite interlayered with thin pelitic layers over a distance of several meters.

Texture in Uncompahgre metapelites changes from very fine-grained and non-porphyroblastic in the west to medium-grained and coarsely porphyroblastic in the southeast. Strongly foliated fabrics dominate over most of the western and central portion, but granoblastic fabrics appear to the southeast and east. Mineral assemblages syntectonic with respect to D_1 and D_2 are of the lower greenschist facies, most commonly quartz + sericite + carbonaceous material ± chlorite. Appearance of randomly oriented, post-tectonic porphyroblasts accompanies the southeastward change from a foliated to a granoblastic fabric. From west to southeast, this includes the successive appearance of andalusite, chloritoid, biotite, garnet and staurolite. Barker (1969) reports plagioclase, microcline and sillimanite in the most southeasterly portions of the Uncompahgre Formation. Both change in texture and development of porphyroblastic phases are the result of a post-tectonic thermal maximum, perhaps related to intrusion of the Eolus Granite (Fig. 1). Recrystallization during post-tectonic metamorphism obliterated many of the fine features marking polyphase tectonic events. Consequently, the central and western portions of the Uncompahgre Formation preserve the best record of deformation. Data reported here were largely collected from the central portion of the Formation (Fig. 2).

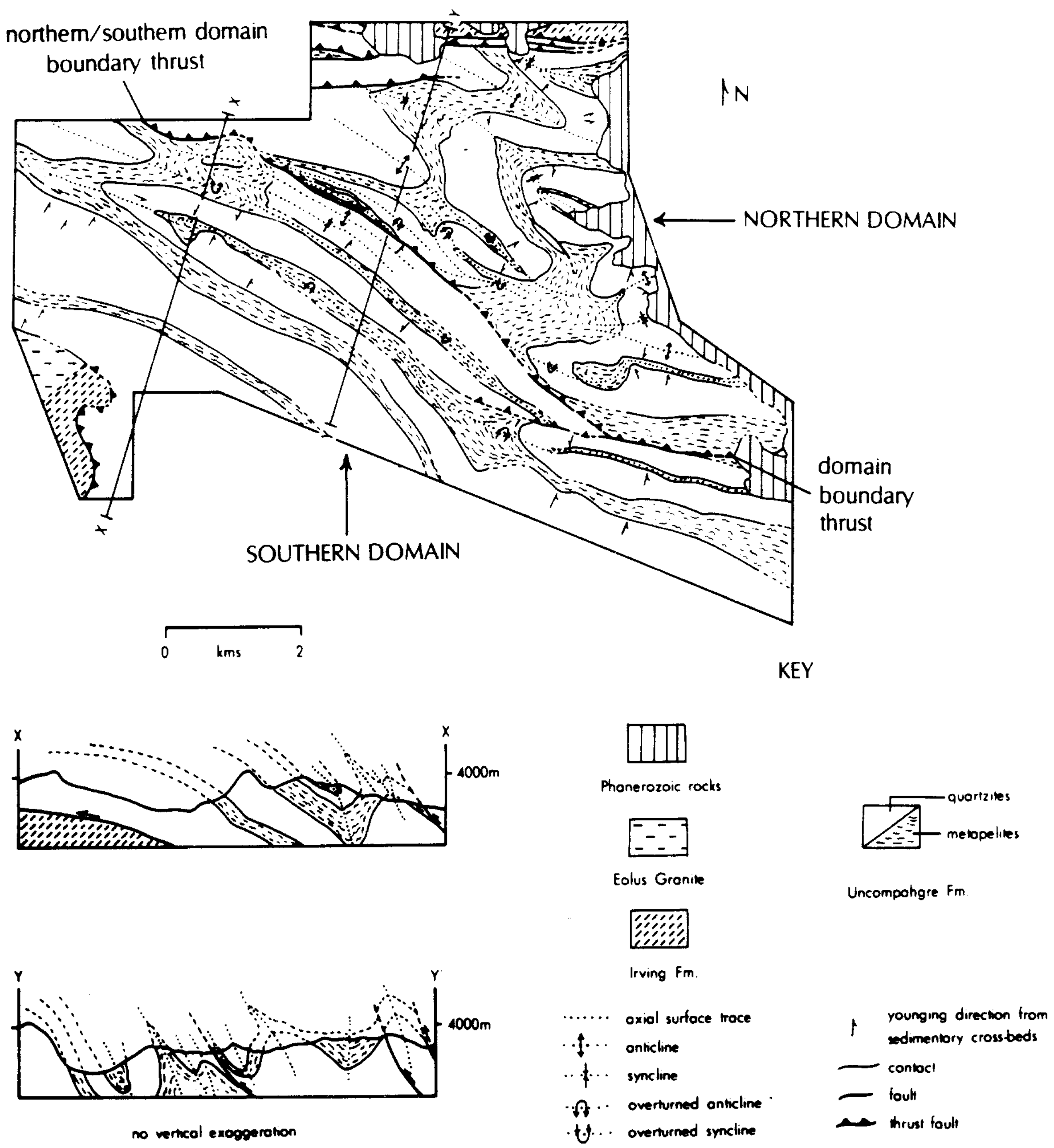

Fig. 2. Geology and structure of the central portion of the Uncompahgre Formation, showing macroscopic folds in S_0, the northern and southern domains, and younging directions in the quartzite units.

Structural domains

The central portion of the Uncompahgre Formation may be divided into two structural domains, a northern domain and a southern domain, separated by a major NE-dipping thrust fault (Fig. 2). This thrust truncates macroscopic folds developed in S_0. The northern domain differs from the southern domain primarily in the plunge of fold axes calculated for macroscopic folds in S_0. πS_0 diagrams in Fig. 3 show that calculated fold axes plunge 30° towards S75°E in the northern domain and 10° towards S75°E in the southern domain. The simplest way to account for this is to postulate a small component of rotation along the boundary thrust between the northern and southern domains. Figure 3 also shows that folds in S_0 are approximately cylindrical.

Stratigraphic sequence

Metapelitic rocks of the Uncompahgre Formation show conspicuous evidence of internal transposition. Intrafolial folds with S_1 axial plane foliations occur at both mesoscopic and microscopic scales (Fig. 4a & b), and S_1 rarely departs from parallelism with S_0 except in the hinge regions of intrafolial folds. In addition, S_1 is parallel to contacts between quartzite and metapelite units. Intensity of intrafolial fold development is zonal within the metapelitic rocks and is particularly prominent near contacts between map units. By contrast, the quartzite units show little evidence of internal transposition. Intrafolial folds are absent except near contacts with the metapelite units. Relict sedimentary structures, including trough cross-bedding and graded bedding,

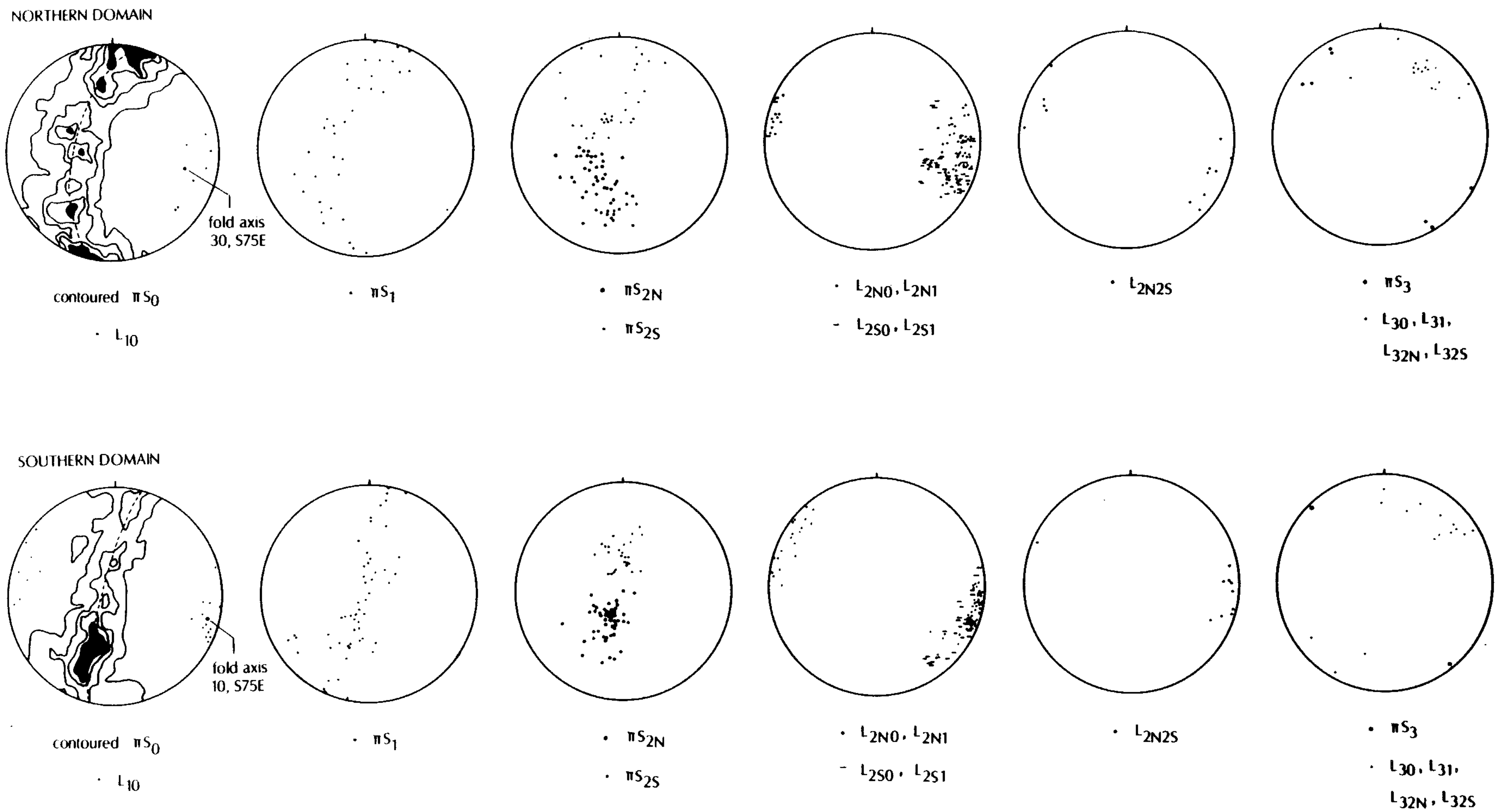

Fig. 3. Equal-area projections of structural data from the Uncompahgre Formation. The top row of diagrams contains data from the northern domain, the bottom row from the southern domain. Tick marks indicate north. πS_0 data from the northern domain (274 points) are contoured at 0.4, 2, 3 and 4% per 1% area; and from the southern domain (175 points) at 0.6, 3, 4.6, and 6% per 1% area. Subscripts for intersection lineations indicate the two intersecting surfaces.

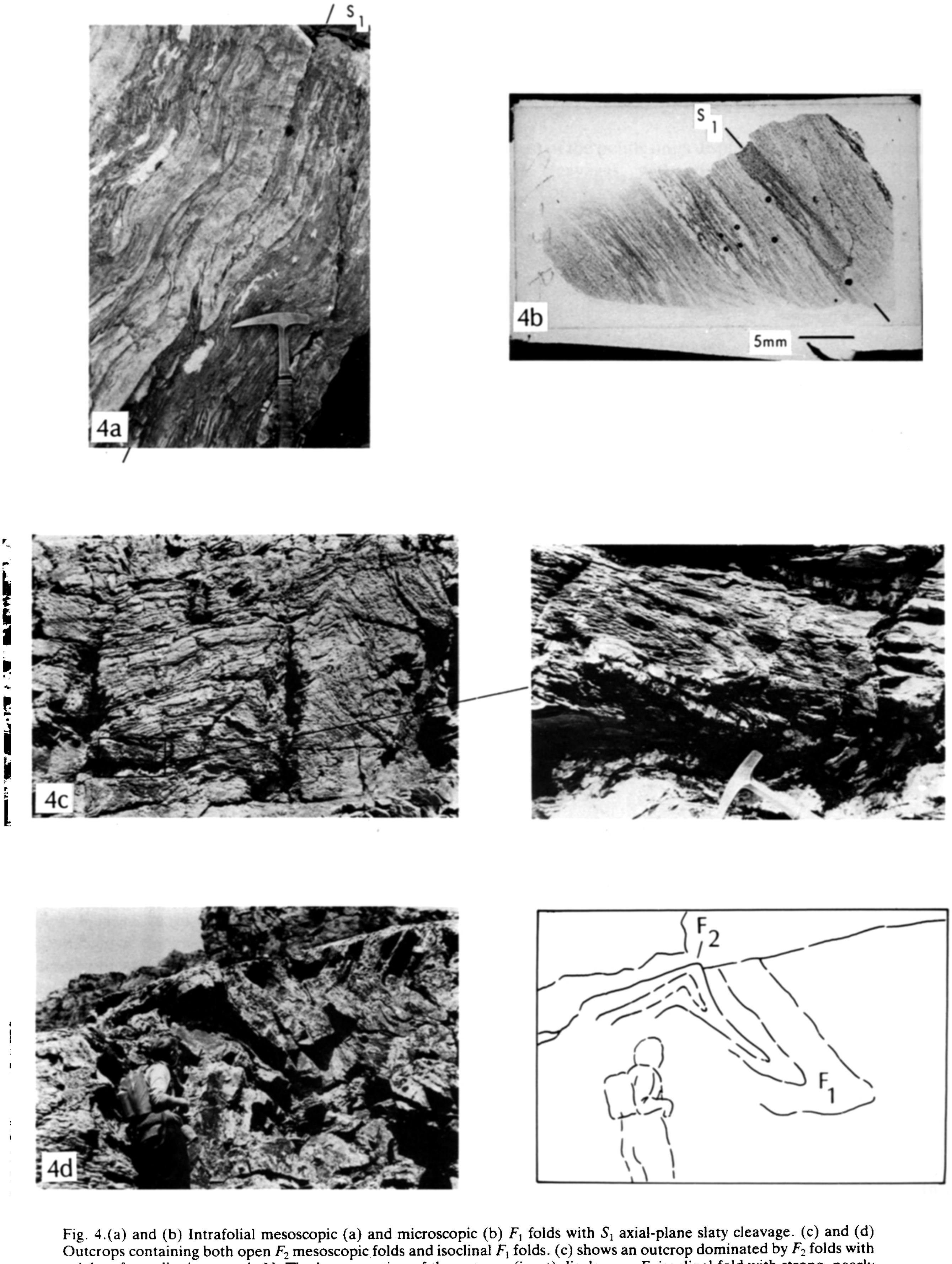

Fig. 4.(a) and (b) Intrafolial mesoscopic (a) and microscopic (b) F_1 folds with S_1 axial-plane slaty cleavage. (c) and (d) Outcrops containing both open F_2 mesoscopic folds and isoclinal F_1 folds. (c) shows an outcrop dominated by F_2 folds with axial surfaces dipping steeply N. The lower portion of the outcrop (inset) displays an F_1 isoclinal fold with strong, nearly horizontal axial-plane S_1 slaty cleavage. Photograph (d) and the accompanying drawing show an F_1 isoclinal fold refolded about an open F_2 fold with N-dipping axial surface.

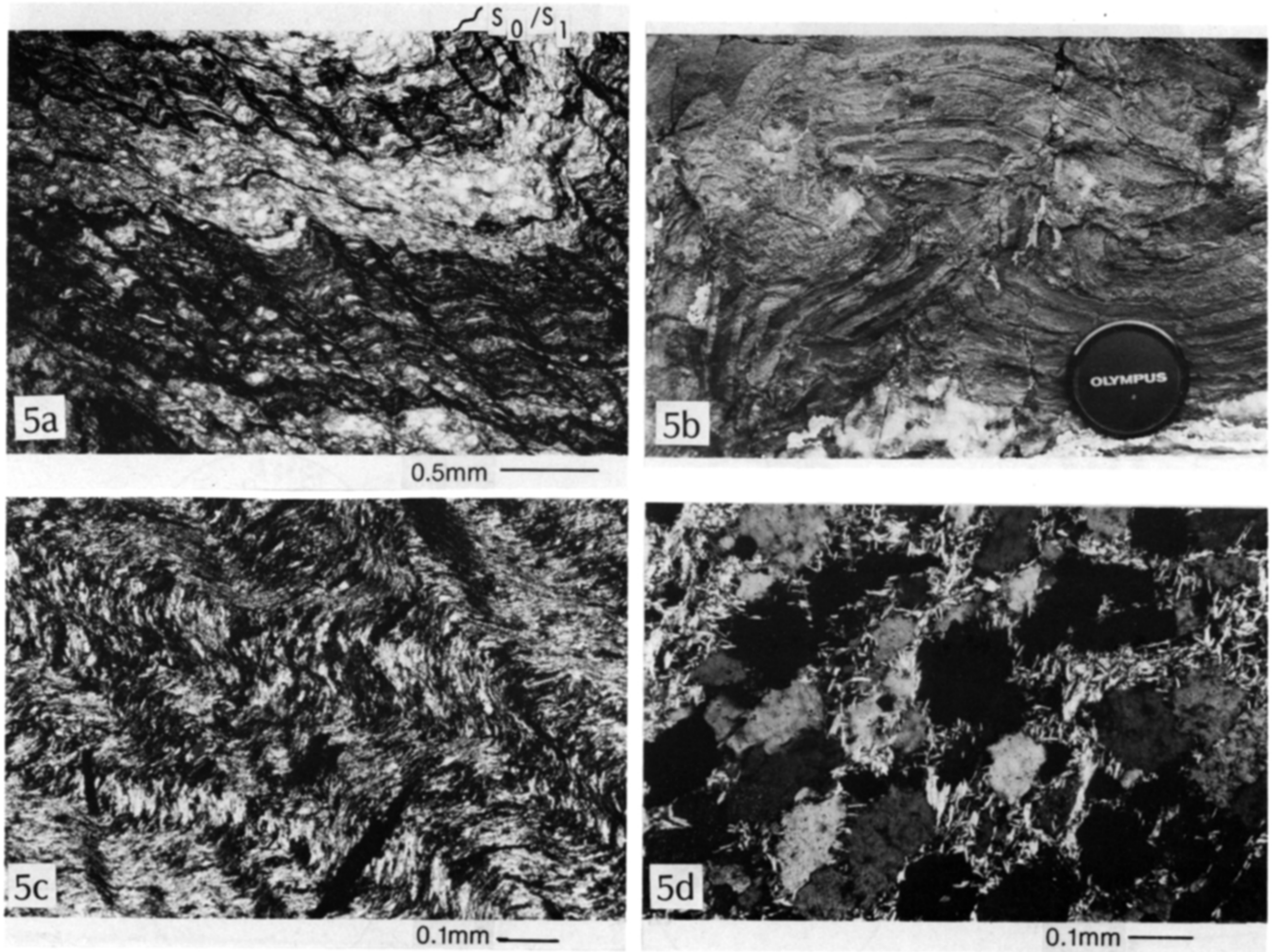

Fig. 5. D_2 conjugate structures. (a) Where only one of the two possible conjugate crenulation cleavages are present, cleavage morphology is indistinguishable from that of non-conjugate crenulation cleavages. (b) Mesoscopic F_2-box fold in S_0/S_1, within the metapelite unit. (c) Conjugate crenulations in a mica-rich layer (crossed polars) (d) Conjugate alignment of sericite in a psammitic layer within the metapelite unit (crossed polars).

show no reversals in younging direction within quartzite units. In addition, younging directions show no apparent reversals from one quartzite unit to the next across the mapped area (Fig. 2).

Although there is extensive internal transposition within the metapelite units, there is no evidence to suggest that the entire package of Uncompahgre metasediments has been transposed by isoclinal folding on a regional scale, with hinges conveniently obscured by erosion or Phanerozoic cover. The apparent absence of large-scale transposition does not rule out the possibility of repetition of the stratigraphic succession by large-scale bedding-plane thrusts.

Deformation structures

Metapelitic rocks in the Uncompahgre Formation record three sets of structural features. The oldest set includes mesoscopic and microscopic F_1 folds and associated S_1 axial-plane slaty cleavage. The second set of structural features includes a set of macroscopic F_2 folds and a conjugate set of mesoscopic and microscopic F_2 folds and crenulations with related S_2 conjugate crenulation cleavages. The youngest set of structural features is of minor importance and includes fine-scale F_3 crenulations and minor open mesoscopic warps.

Establishing the disposition of the macroscopic folds in S_0, shown both in map view and in cross section in Fig. 2, is crucial in determining the deformation history. The absence of fold interference patterns typical of many types of polyphase deformation, the absence of older macroscopic fold closures, the cylindricity of the folds, and the lack of reversals in younging directions within the quartzite units might seem to suggest that these macroscopic folds are F_1 folds. In fact, they are not. In the field, S_1 can clearly be traced around the hinges of the macroscopic folds. In addition, πS_1 diagrams (Fig. 3) show that the S_1 transposition fabric is folded cylindrically about the same axes as S_0 in both the northern and southern domains. The slaty cleavage and related F_1 mesoscopic isoclinal folds clearly predate development of the macroscopic folds.

Mesoscopic folds are ubiquitous in the metapelitic rocks, and most outcrops are dominated by F_2 folds and associated crenulation cleavages. F_2 folds are conspicuously different from F_1 folds in geometry, and Fig. 4(c) illustrates a nearly recumbent F_1 isocline adjacent to an upright, open F_2 fold. In rare outcrops showing interference patterns, mesoscopic F_2 folds clearly overprint F_1 folds (Fig. 4d). Complex interference patterns between F_1 and F_2 folds do not develop, because F_1 and F_2 folds are very nearly coaxial (Fig. 3). Both sets of mesoscopic folds have attitudes similar to those calculated for the macroscopic folds in S_0. Similarities in attitude and style between mesoscopic F_2 folds and the macroscopic folds in the region suggest that the macroscopic folds are the result of D_2 deformation.

D_3 structures are only weakly developed and have attitudes nearly at right angles to both D_1 and D_2 structures. Where measurable, F_3 crenulations have vertical axial surfaces and trend NE–SW, directly across the main structural grain of the belt (Fig. 3).

D_2 CONJUGATE MESOSCOPIC STRUCTURES

Most of the pelitic units display well-developed crenulation cleavages, with spacings ranging from 0.03–0.2 mm. Cleavage domains range from gradational to discrete depending upon intensity of cleavage development. Differentiation is commonly pronounced, with cleavage domains rich in mica, graphite and oxides (Fig. 5a). Some units exhibit very intensely developed crenulation cleavage. Micas aligned parallel to cleavage planes dominate, and, in such samples, the cleavage bears a strong resemblance to slaty cleavage and can easily be mistaken for S_1. The S_2 crenulation cleavages constitute a conjugate set. The presence of conjugate folds, conjugate crenulations, and conjugate mica alignments, and the relative attitudes between the two sets all suggest that these two crenulation cleavages form a conjugate set. Evidence will be presented in the next few paragraphs.

In several outcrops, rare box-shaped folds occur with reverse-kink geometry and oppositely inclined axial-surface crenulation cleavages (Fig. 5b), suggesting contemporaneity of the two cleavages. In these folds, one axial surface dips N and the other S. However, such examples of conjugate geometry are rare. In most outcrops, only one crenulation cleavage is developed, with an attitude similar to one or the other of the axial-surface cleavages in the box folds. The N dipping set is referred to as S_{2N} and the S-dipping set as S_{2S}. Where different sets are developed in close proximity and where folds are associated with both cleavages, it is common for folds to be asymmetric and to show opposite senses of symmetry.

Study of conjugate cleavage systems in other areas (Tobisch & Fiske 1976, Naha & Halyburton 1974, Knill 1959, Johnson 1956) reveals a similar pattern of rare box-shaped folds showing contemporaneity of two cleavage sets, and common outcrops exhibiting only one or the other of the two cleavage sets. Such studies also show that box folds do not necessarily develop in outcrops where both cleavages are formed, and that the two cleavages tend to be unequally common in outcrop. Such is in fact the case in the Uncompahgre Formation, where the ratio of occurrence of S_{2N} to S_{2S} in outcrop is about 2:1.

Thin-section evidence also suggests that S_{2N} and S_{2S} form a conjugate set. A few sections exhibit conjugate crenulations (Fig. 5c). In such sections, neither crenulation cleavage tends to be particularly well-developed, and axial surfaces have somewhat variable attitudes. In all instances, conjugate crenulations show reverse-kink geometry. Many sections show an unusual conjugate arrangement of fine, disseminated mica grains that is best-developed in psammitic rocks (Fig. 5d). These alignments appear to be the analogue in the psammitic layers of a conjugate crenulation cleavage in the pelitic layers.

πS diagrams of S_{2N} and S_{2S} (Fig. 3) show that the two cleavages do form two distinct sets, one N- and one S-dipping. Attitudes are more tightly clustered and define a better bimodal distribution in the southern domain than in the northern domain. πS diagrams such as these are typical of conjugate crenulation cleavages in other areas (Tobisch & Fiske 1976, Naha & Halyburton 1974).

At 29 stations, S_{2N} and S_{2S} occur together. At approximately half these stations, age relationships were clear in the field; for the remaining stations, age relationships were confirmed in thin section. In all cases, S_{2N} is clearly distinguishable from S_{2S} and the two cleavages of each pair have distinctly different attitudes. Invariably, one of the pair dips S and the other N. Age relationships between the two crenulation cleavages show an interesting pattern. Conjugate crenulations, box folds and crenulation cleavages showing ambiguous age relationships suggest that S_{2N} and S_{2S} are contemporaneous at eight of the 28 stations. S_{2N} clearly overprints S_{2S} at seven stations, while S_{2S} overprints S_{2N} at eight stations. At the remaining five stations, the age relationships are uncertain. Where overprinting relationships were observed, S_{2N} overprints S_{2S} at seven out of eight stations in the northern domain. In the southern domain, S_{2S} overprints S_{2N} at seven out of the seven stations where overprinting relationships were observed. Where overprinting occurs, development of both cleavages is unusually intense.

The conjugate nature of a pair of features is often difficult to establish because of the rarity with which conjugate structures occur together in outcrop (e.g. Tobisch & Fiske 1976, Naha & Halyburton 1974). However, in view of the number of features that suggest a conjugate relationship between S_{2N} and S_{2S}, and in spite of local overprinting, it seems pointless to require two separate deformations for development of these foliations in the Uncompahgre Formation. Local overprinting probably resulted when locally intense deformation proceeded preferentially along one of the conjugate cleavages.

TIMING OF CONJUGATE CRENULATION CLEAVAGE DEVELOPMENT DURING D_2

The Uncompahgre Formation is dominated on both macroscopic and mesoscopic scales by folds and foliations developed during D_2. These include both the macroscopic folds in S_0 (Fig. 2) and a set of crenulation cleavages with associated folds. The metapelitic rocks contain a unique set of features illustrating that conjugate mesoscopic structures developed very late in D_2, after macroscopic folding was largely completed. Specifically, comparison of attitudes of S_2 and F_2 conjugate structures in the northern domain with those in the southern domain shows that these structures must largely postdate movement along the boundary thrust between the two domains. Because the boundary thrust truncates D_2 macroscopic folds, conjugate D_2 structures

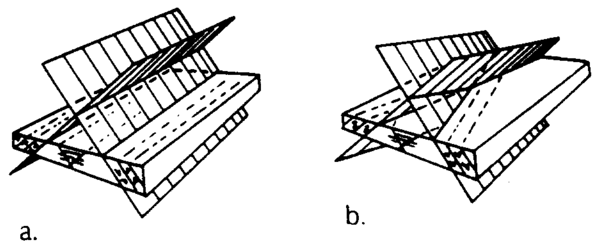

Fig. 6. Block diagrams illustrating geometries of intersection and fold-hinge lineations formed by superimposing a conjugate cleavage set on a layered sequence. (a) Such lineations will be parallel to one another only if the line of intersection between the two conjugate planes is parallel to the surface intersected by the planes. (b) The lineations will not be parallel to one another if the line of intersection between the two conjugate planes is inclined to the surface intersected by the planes (modified from Ramsay 1962).

must therefore largely postdate both D_2 macroscopic folding and thrusting. Evidence for this is the subject of this section.

F_{2N} and F_{2S} mesoscopic folds have similar trends and plunges where occurring together in the southern domain. In the northern domain, on the other hand, attitudes of mesoscopic F_{2N} and F_{2S} are often very different where they occur in close proximity, and plunges may differ by as much as 25°. In addition, composite plots of all intersection lineations between S_2 and S_0 (L_{20}) and between S_2 and S_1 (L_{21}) in Fig. 3 show that both shallow and moderate plunge values occur only in the northern domain. The southern domain exhibits only shallow plunge values.

Ramsay (1962) pointed out that folds of a conjugate pair need not have similar hinge attitudes. From a distinctly geometrical viewpoint, hinge attitudes will be identical only if the line of intersection between the two axial surfaces (or between two conjugate cleavage planes) is contained in the layering being folded (Fig. 6a). If this condition is not met, the conjugate surfaces intersect the folded surface, not in two parallel lines, but in two intersecting lines (Fig. 6b). Similarity in trend and plunge of F_2 fold hinge and intersection lineations in the southern domain where both members of the conjugate set occur in close proximity suggests that the line of intersection between the conjugate planes is commonly contained in the folded surface and that this line of intersection is parallel to the calculated D_2 fold axis in the southern domain. Examination of equal-area plots of L_{2N2S} (Fig. 3) shows that measured and calculated intersection lineations do indeed have a similar attitude to the calculated fold axis for the southern domain. In the northern domain, on the other hand, common differences in trend and plunge of F_2 fold hinges and intersection lineations where both members of the conjugate set occur in close proximity suggests that the line of intersection between conjugate planes is not contained in the folded surface in many cases. The result is a geometry similar to the second hypothetical case illustrated in Fig. 6(b). In this case, the line of intersection is not parallel to the calculated fold axis for the D_2 macroscopic folds in the northern domain. Equal-area plots of L_{2N2S} support this conclusion (Fig. 3). Measured and calculated L_{2N2S} attitudes are few, but all are gently plunging, and none reflect the steeper plunge of the calculated northern domain fold axis. In fact, the plot for this lineation is nearly identical to that for the southern domain.

The most logical explanation of these facts is that the macroscopic folds were nearly completely formed both before faulting and before the conjugate crenulation cleavage and associated features had developed to any great extent. Post-D_1 compression apparently generated macroscopic folds early in D_2. Faulting then displaced and rotated the northern domain with respect to the southern domain. Following faulting, the regional stress maintained its pre-faulting orientation, and the conjugate crenulation cleavage and folds developed, and many macroscopic folds undoubtedly tightened. Because the southern domain had not shifted with respect to the stress field, conjugate features were coaxial with F_2 macroscopic folds in the southern domain. In the northern domain, however, conjugate features were superimposed on units that had shifted orientation, and the intersection between conjugate planes was no longer parallel to northern domain macroscopic fold axes. The result is that L_{2N2S} is similar in both domains, but fold hinge and intersection lineations involving S_0 and S_1 are very different and show much more variability in the northern domain than in the southern domain. In reality, then, the northern domain experienced a D_2 and a D_2' event, while the southern domain experienced only a D_2 event.

There is no reason to suppose that all development of conjugate cleavages and folds took place after faulting or that faulting took place in only one episode. The fact that the cleavages of the southern domain define a more well-defined conjugate set than those of the northern domain may be due to development of conjugate features in the northern domain over a time spanning episodic faulting and periodic changes in attitude of this block within the regional stress field.

STRAIN SIGNIFICANCE OF THE CONJUGATE CRENULATION CLEAVAGE

Boulter (1979) nicely documented the development of two cleavages during one episode of deformation in a sequence of low-grade metasediments from Australia. He suggested that both cleavages developed parallel to the XY plane of the strain ellipsoid, arguing sequential rather than conjugate formation of cleavages as fold limbs rotated and folding mechanisms changed.

The situation in the Uncompahgre Formation is quite different. No sequential pattern exists between the two sets of S_2 cleavages, and evidence for true conjugate character is compelling. Because these crenulation cleavages are conjugate, neither can have formed parallel to the XY plane of the strain ellipsoid.

The orientation of the XY plane during conjugate cleavage development can be estimated from a contoured plot of poles to S_{2N} and S_{2S} (Fig. 7) in the following manner. Average S_{2N} and S_{2S} orientations may be determined from zones of highest concentration on contoured plots for both the northern and southern domains. Acute dihedral angles between average S_{2N} and S_{2S} are 38° in the northern domain and 43° in the southern domain. The intersection between average S_{2N} and S_{2S} defines the Y axis of the strain ellipsoid, while X and Z bisect the dihedral angle between the two average cleavage planes. Trains of F_2 folds and the reverse-kink geometry of conjugate folds and kinks are consistent with horizontal rather than vertical shortening, and are very different from the extensional conjugate structures discussed by Platt and Vissers (1980). The Z axis is therefore the horizontal bisector, and the X axis is the vertical bisector (Fig. 7). The XY plane is oriented N68W, 88SW in the northern domain and N78W, 85NE in the southern domain. Determinations for the southern domain are more reliable than for the northern domain because of greater scatter in data from the northern domain.

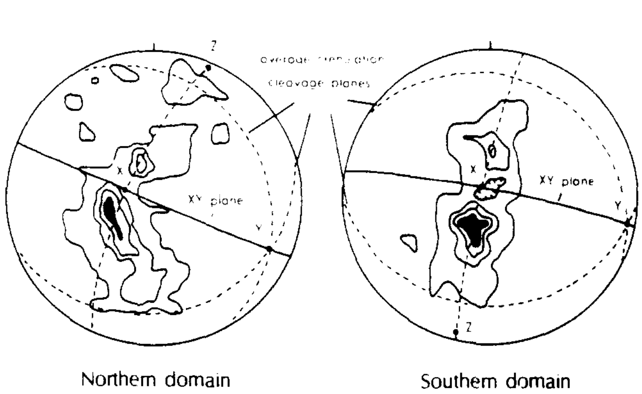

Fig. 7. Contoured πS_{2N} and πS_{2S} diagrams showing the orientations of average axial planes for the conjugate crenulation cleavages, and calculated orientations of the XY plane of the strain ellipsoid during conjugate cleavage formation in both the northern and southern domains. Northern domain 81 points; southern domain 74 points. Contours at 1, 5, 7 and 9% per 1% area.

Deformation apparently only rarely results in conjugate structures, and two factors appear to be significant in development of conjugate features rather than single sets of structures. Theoretical studies by Cosgrove (1976) show that development of conjugate crenulation cleavage is favored by medium to high anisotropy in the deforming rock. Regardless of layer orientation, low anisotropy appears to favor a single cleavage set developed parallel or nearly parallel to the XY plane. Gray (1979) suggests a second contributing factor, namely the ratio between wavelength and thickness of a pelitic layer sandwiched between psammitic layers. Where the ratio is small, a single set of cleavage develops parallel or nearly parallel to the XY plane; where the ratio is larger, conjugate sets oblique to the XY plane may develop. It is difficult to evaluate the relative contributions of the two factors in the case of the Uncompahgre Formation. Intimate interlayering of pelitic and psammitic layers on scales from a fraction of a millimeter to tens of meters certainly suggests high anisotropy, particularly considering the low grade of metamorphism. Whether these rocks have a ratio between fold wavelength and pelitic-layer thickness large enough to encourage development of conjugate structures is unclear.

Cosgrove's (1976) theoretical work also shows that some layering configurations suppress simultaneous development of both members of a conjugate set. Where layering is inclined at a moderate angle to the maximum shortening direction, only one of the two possible sets develops. This single set of folds and cleavages still forms at an angle oblique to the XY plane, even though its conjugate pair is missing. Both members of a conjugate set appear to develop only in sequences with layering oriented at a very high or very low angle to the maximum shortening direction.

Conjugate features in the Uncompahgre Formation developed late in the D_2 event, and much of the macroscopic folding in S_0/S_1 had already been accomplished. As a result, angles between layering and the XY plane were highly variable as conjugate cleavages and related folds began to develop. The XY plane calculated from D_2 conjugate features is nearly vertical and essentially parallel to F_2 macroscopic fold hinges in both domains. When the conjugate structures began to develop, layering would have stood at moderate angles to the maximum shortening direction in the limbs of the macroscopic F_2 folds, at low angles in the hinge regions of the macroscopic folds, and at high angles in the isoclinal or nearly isoclinal macroscopic folds. This suggests that one of the two possible conjugate sets should prevail on moderately dipping macroscopic F_2 fold limbs, and that both sets should occur together most commonly in the F_2 macroscopic fold-hinge regions and steeply dipping fold limbs. In fact, this happens to be the case in both the northern and southern domains.

CONCLUSIONS

Conjugate crenulation cleavages with reverse-kink geometry such as those in the Uncompahgre Formation may be rare, but they do exist. This confirms Cosgrove's (1976) suggestion that, in strongly anisotropic rocks, buckling instabilities that develop axial planes oblique to the XY plane can continue to grow into mesoscopic fold-cleavage systems that persist well after buckling initiates the oblique geometry. Such conjugate systems are not merely tectonic afterthoughts; they are capable of accommodating considerable shortening in a rock sequence, as they did in the Uncompahgre Formation.

In spite of an overall conjugate relationship amongst fold and cleavage sets, most outcrops in the Uncompahgre Formation show only one of the two possible sets of conjugate structures, and this appears to be characteristic of other areas with well-developed conjugate systems. One might ask, then, whether it could ever be possible for a sequence of rocks to develop one of the two possible conjugate sets to the total exclusion of the other. If such a scenario were possible, there would be no evidence that the cleavage developed oblique rather than parallel to the XY plane, because there appears to be little morphological difference between crenulations and crenulation cleavages developed as one member of a conjugate set and those developed as part of a single cleavage set. I would argue that this is unlikely. Cosgrove's (1976) theoretical work suggests that layer orientation relative to the regional stress field is critical to whether conjugate crenulations develop in a given rock volume, or whether one or the other of the two conjugate sets form instead. Formation of one of the two possible conjugate sets to the total exclusion of the other would seem to require that all layering over an entire sequence had approximately the same attitude when the crenulation cleavage and crenulation folds began to develop. This seems unlikely, particularly in multiply deformed rocks. I would argue that sequences showing only one set of crenulation cleavages reflect cleavage formation parallel or nearly parallel to the XY plane of the strain ellipsoid, in rocks whose mechanical properties were inappropriate for conjugate cleavage formation.

The answer to the question 'Do crenulation cleavages form parallel to the XY plane or oblique to the XY plane?' appears to be 'Yes'. Single crenulation cleavage sets developed parallel or nearly parallel to the XY plane appear to be the norm, apparently reflecting a predominance of rocks in which the combinations of geometric and mechanical properties are in the range which suppresses conjugate structure development. Conjugate cleavage sets developed oblique to the XY plane are rare, apparently reflecting the fact that geometric and mechanical properties necessary for conjugate structure development are only rarely combined in an appropriate manner in deforming rocks.

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