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Back-rotation during crenulation cleavage development: implications for structural facing and cleavage-forming processes

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Abstract

Structural facing can be a useful tool for understanding macroscale structural geometries, particularly where poor outcrop inhibits the mapping of fold closures. However, in some situations facing must be determined with considerable care. In graded metaturbidites, where bedding and a near-parallel foliation have been overprinted by a crenulation cleavage, the earlier foliation in the metapelitic layers can be substantially 'back-rotated' in the hinges of the overprinting crenulation cleavage. Thus, the rotation in the crenulation hinges is opposite to the rotation in the crenulation limbs. When viewed in the metapelitic layers, relative to a bedding surface, back-rotation can cause an apparent reversal in the structural facing (and vergence) on the rotated foliation. To avoid such misinterpretation, structural facing on the earlier foliation should be determined in the metapsammitic layers, where the effects of the overprinting crenulation cleavage are minimal. Because foliations that intersect bedding at a low angle are commonly hard to identify in metapsammitic outcrops, microstructural analysis may be required. The back-rotation process provides important constraints on mechanisms and kinematics of crenulation cleavage development, and may also have important implications for porphyroblast rotation, folding mechanisms and issues of strain compatibility in compositionally interlayered rocks. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

In 1957, Shackleton extended the concept of 'facing' from strata to structures. Where a foliation and bedding intersect, the structural facing on the foliation is defined as *the direction of younging along the foliation of interest, measured in a direction perpendicular to the foliation/bedding intersection lineation* (Fig. 1a). When defined in this way, structural facing can be very useful for determining the positions of fold-hinge lines or crestal traces, particularly where poor outcrop or monotonous stratigraphy inhibits the tracing of rock units around folds (Shackleton, 1957; Bell, 1981). If the foliation of interest is axial-surface to folds, structural facing becomes the same as the fold facing. This tool can also be used to determine the positions of early fold axial-surface traces that predate the foliation of interest, as well as later ones that postdate the foliation (Fig. 1b). In areas of poor outcrop, the method outlined in Fig. 1(b) may be the only way to determine the positions of late folds that do not have axial-surface foliations. Finally, combining structural facing information from two or more foliations in an area can aid greatly in clarifying the macroscale structural geometry (Fig. 1b), and can add useful additional information to more conventional geometrical analyses.

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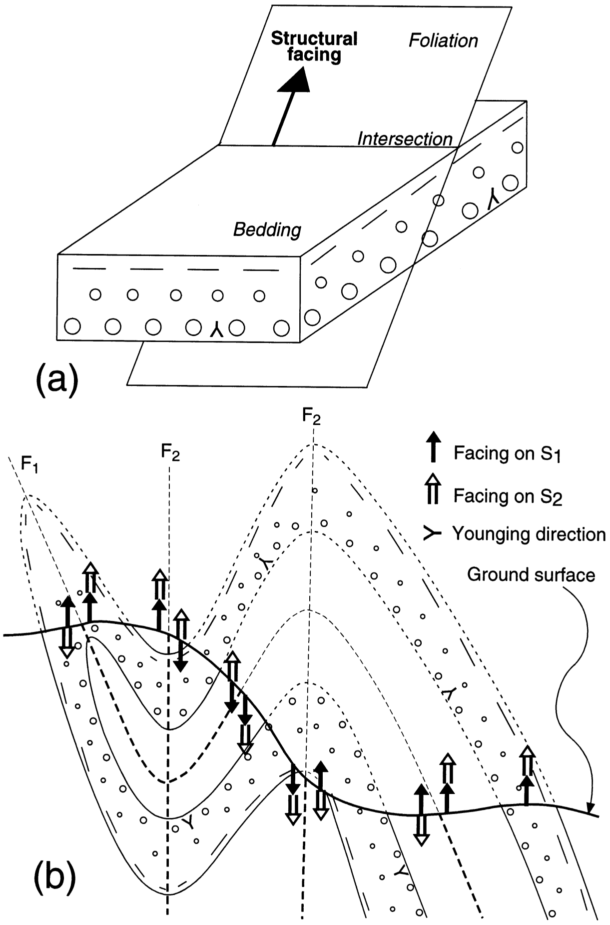

Fig. 1. (a) Diagrammatic definition of structural facing on a foliation. (b) Diagram illustrating how structural facing on two axial-surface foliations can be used to find fold traces of each generation, and elucidate the overall macroscale geometry. Facing is shown as either up or down, and so in the case of S_1 it is not drawn parallel to the foliation.

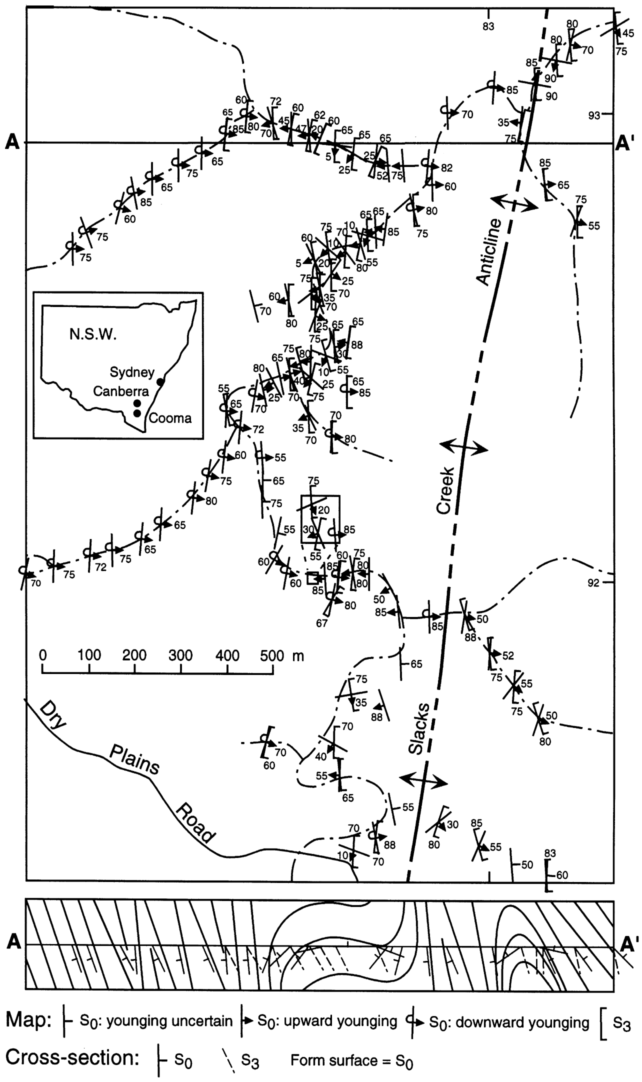

Fig. 2. Map of Slacks Creek area in the Cooma Complex (inset shows location of Cooma) showing strikes and dips of S_0 and S_3, crestal trace of the Slacks Creek Anticline, and cross-section along the line A–A′.

Although structural facing is a useful tool, and the points outlined here are simple enough, determination of structural facing must be made with considerable care in particular situations. For example, in areas of graded metaturbidites, where bedding and the foliation of interest intersect at a low angle and have been overprinted by a later crenulation cleavage, structural facing can potentially be misinterpreted. This situation occurs in the Cooma Complex, Australia, which provides a good example of an area where structural facing must be determined with care.

2. The situation at Cooma

The Cooma Complex is a low-pressure, high-temperature metamorphic complex in the Lachlan Fold Belt of southeastern Australia (Fig. 2), and has been the focus of numerous structural/microstruc-

Fig. 3. Intensely developed, near-vertical S_3 overprinted by the S_4 crenulation cleavage. Younging is to the right (west), and the sandy base of a metaturbidite couplet fills the right side of the photograph. S_3 is marked by small lines in S_4 crenulation hinges in the metapelitic layer, where it dips in the opposite direction to overturned S_0. View looks south. Diameter of coin 2 cm.

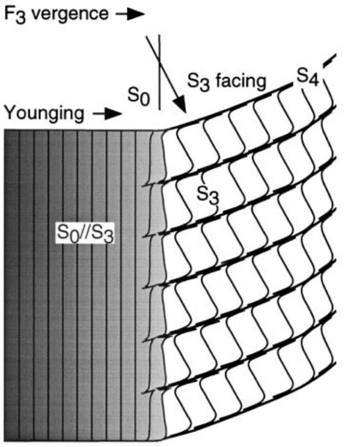

Fig. 4. Sketch illustrating mesoscale relationships commonly seen on the overturned limb of the Slacks Creek Anticline. A metapsammite–metapelite couplet grades to the right (west). S_3 and S_4 are obvious in the metapelitic portion, but the only foliation in the metapsammitic base (shaded) is apparently bedding-parallel. If the very consistent orientation of S_3 in the metapelitic portion reflects its original vergence relative to S_0, downward structural facing on S_3 is indicated. The photograph in Fig. 3 illustrates this relationship.

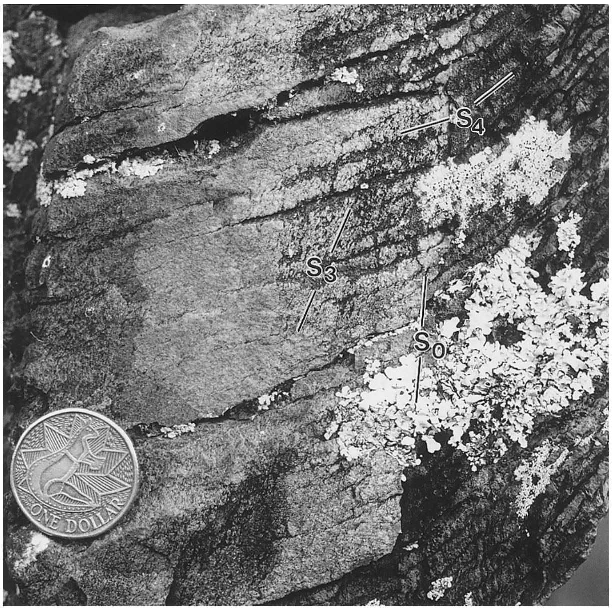

Fig. 5. Outcrop showing graded S_0 slightly overturned and younging to the right (west). S_3 in the metapsammitic layer dips to the east less steeply than the overturned S_0, and both are overprinted by the gently-dipping S_4 crenulation cleavage. View looks south. Diameter of coin 2.5 cm.

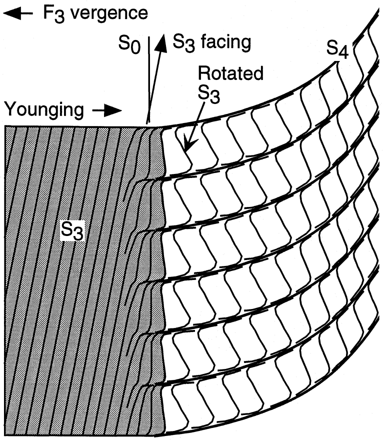

Fig. 6. Drawing illustrating mesoscale relationships rarely seen on the overturned limb of the Slacks Creek Anticline. A metapsammite–metapelite couplet is shown grading to the right (west). S_3 and S_4 are obvious in the metapelitic portion, and, as in Fig. 5, S_3 is also present in the metapsammitic portion (shaded), where it dips less steeply than S_0. These relationships demonstrate that structural facing on S_3 is upward, and that the dip of S_3 relative to bedding in the metapelite is misleading.

Fig. 7. Photomicrograph of sample collected directly below the outcrop shown in Fig. 5, illustrating the relationships shown in Figs. 5 and 6. Graded S_0 youngs to the right (west). Complete continuity exists between S_3 in the metapsammite and back-rotated S_3 in the metapelite. Lines in the central crenulation show the progressive change in S_3 orientation, which rotated a maximum of approximately 80° through the thin section-scale trace of S_0. Note that the porphyroblast long axes and inclusion trails in the metapelitic layer are parallel to the foliation in the crenulation hinges. Vertical thin section looking south. Partially crossed polars; long axis 35 mm.

tural studies (e.g. Hopwood, 1976; Granath, 1980; Vernon, 1988; Johnson et al., 1994; Johnson and Vernon, 1995; see Johnson, 1999 for extensive reference list).

Fig. 2 shows the macroscale structural geometry of part of the Slacks Creek area at Cooma. Event D_3 of Johnson and Vernon (1995) produced tight, upright to gently overturned, variably-plunging macroscale F_3 folds that control the macroscale geometry at Cooma (Johnson, in press). Throughout the overturned western limb of the Slacks Creek Anticline, bedding and S_3 generally intersect at a small angle, and both have been overprinted by the S_4 crenulation cleavage (Fig. 3). S_3 and S_4 are readily visible in the metapelitic tops of the layers, but in the metapsammitic bases S_4 is poorly developed, and S_3 generally intersects S_0 at such a small angle that it cannot be clearly recognized at most outcrops. Therefore, field determinations of structural facing on S_3 at these locations can only be attempted on the basis of its orientation in the metapelitic layers relative to nearby S_0 (Fig. 4). Although individual S_3 surfaces cannot be traced through the S_4 crenulations in the metapelites, and thus an S_3 form-surface cannot be determined, the remarkably consistent orientation of S_3 in the S_4 crenulation hinges appears to provide a reliable indicator of its orientation relative to S_0 (e.g. Figs. 3 and 4). On this basis, the structural facing on S_3 in Figs. 3 and 4 would be interpreted as downward, which, if correct, would require that the rocks were overturned prior to D_3. Additionally, vergence on S_3 in Figs. 3 and 4 would be to the right, or west, on the basis of foliation–bedding intersection angles.

Although this interpretation seemed reasonable on the basis of initial field observations, detailed microstructural work, combined with more careful field observations at key localities, demonstrated that it was incorrect. At several localities on the western limb of the Slacks Creek Anticline, S_3 in the metapsammites is clearly oblique to S_0 at the mesoscale (Fig. 5), and the relationship between S_3 and S_0 indicates upward structural facing on S_3, with F_3 vergence to the left, or east (Fig. 6). Because the metapsammites have generally not been strongly affected by the S_4 crenulation cleavage, I consider the S_3 orientation relative to S_0 in the metapsammites to be reliable, whereas the orien-

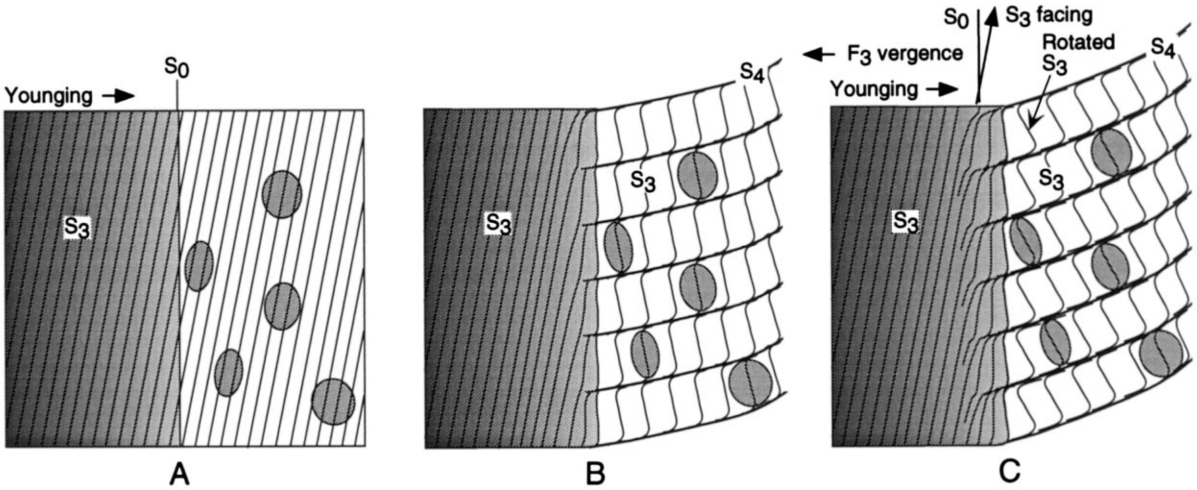

Fig. 8. Diagram showing a three-stage sequence leading to the relationships shown in Fig. 6. This sequence illustrates that back-rotation of S_3 in the hinge-zones of the S_4 crenulation cleavage is responsible for the misleading dip of S_3 in the metapelites relative to S_0. Several porphyroblasts are shown in the metapelitic layer, where they back-rotate with the crenulation hinges. Metapsammitic portion of metaturbidite couplet shaded. S_4 dip increases from (B) to (C) owing to foliation refraction during folding.

tation in the metapelites is unreliable. Where S_3 in metapsammites is oblique to S_0, S_3 in the adjacent metapelites dips in the *opposite* direction relative to S_0 (Fig. 6). This relationship cannot be attributed to refraction of S_3, because it would require refraction either: (a) through greater than 90° and through the normal to bedding, or (b) through the bedding surface. Additionally, S_3 can be traced continuously across metapsammite–metapelite transitions in thin sections (Fig. 7), and so it is demonstrably the same foliation in the two rock-types.

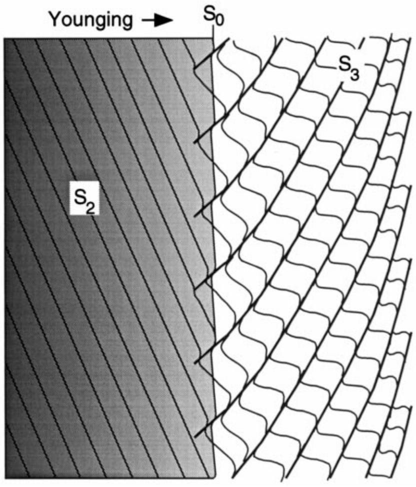

Fig. 9. The overprinting relationships shown in Henderson (1997, fig. 4a). Although the situation is similar to that in the Slacks Creek area, important differences are discussed in the text. Metapsammitic portion of metaturbidite couplet shaded.

On the basis of microstructural investigations of metapsammite–metapelite transitions, I conclude that rotation of S_3 in the hinges (or short limbs) of S_4 crenulations occurred in the opposite direction to rotation of S_3 in the crenulation long limbs (Fig. 8). This back-rotation has led to apparent S_3 dips in the metapelites that are *opposite* to those in the metapsammites that are largely unaffected by S_4. Recognition of this process dictated that the geometrical relationships between S_0 and S_3 in these rocks be determined only in metapsammites that had not been crenulated by S_4. Because such relationships in metapsammitic rocks are commonly difficult to determine, owing to the small angle between S_3 and S_0 at most outcrops, structural facing determinations were made at numerous locations from thin sections (e.g. Fig. 7). All samples examined indicated the same relationships as those shown in Fig. 6, demonstrating that structural facing on S_3 is upward over the entire area, and that F_3 vergence is consistent with the macroscale geometry defined by folded S_0 (Fig. 2).

3. Chevron cleavage pattern—an alternative geometry

Structural relationships similar to those in the Slacks Creek area were described in the Slave structural province, Canada, by Henderson (1997). There, an earlier, pervasively-developed foliation (S_2) in graded metaturbidites was also overprinted by a crenulation cleavage (S_3) that is well-developed in the metapelitic portions of the beds, and absent from the metapsammitic bases (Fig. 9). The earlier foliation is also back-rotated in the crenulation hinges, but this foliation and the overprinting crenulation cleavage initially had opposite vergence relative to S_0, whereas at Cooma they had the same vergence. Thus, after back-rotation, the earlier foliation in the crenulation hinges has the same vergence relative to S_0 as it does in the metapsammitic bases (Fig. 9), rather than the opposite as at Cooma (Fig. 6). The earlier foliation in the metapsammites, and overprinting crenulation cleavage in the metapelites, together form the chevron cleavage pattern common in the Northwest Territories of Canada (e.g. Henderson, 1997, and references therein).

4. Discussion and concluding remarks

The process of back-rotation discussed earlier was only apparent because two conditions were met in these rocks: (1) a marked gradient in crenulation cleavage development occurred across layers of different composition; and (2) the crenulated foliation was well-developed in all rocks, allowing a comparison of its orientation relative to bedding across the crenulation gradient. Without these conditions, there would be no way to demonstrate the back-rotation of the crenulation hinges. Microstructural work played an essential role in this study.

I am intrigued by the tendency for foliations in crenulation hinges to back-rotate towards orthogonality with the developing crenulation cleavage (e.g. Figs. 3 and 7), even though in many instances the *initial* overprinting angles between the two are as low as 45° (e.g. Fig. 7), or even lower. This tendency has the following implications; (1) porphyroblasts commonly appear to grow during crenulation-cleavage development. If the crenulation hinges back-rotated, the syn-deformational porphyroblasts in the hinges must also have rotated with the hinges (Figs. 7 and 8), which may account for the near-orthogonal relationships commonly preserved between inclusion trails and the overprinting cleavage; (2) back-rotation of hinges can promote gaping between individual foliation surfaces parallel to the developing cleavage, providing low-pressure sites for quartz deposition. Thus, at least some of the quartz dissolved from the developing cleavage seams can theoretically be readily redeposited in the hinges. Back-rotating past orthogonality with the cleavage seams would no longer favour this process, which may partly explain the near-orthogonality commonly (but by no means exclusively) observed. (3) back-rotation towards orthogonality can serve to minimize overall shortening perpendicular to the developing cleavage for a given amount of shortening in the cleavage seams. This effect is maximized at the point of orthogonality, and may aid in maintaining strain compatibility across compositional layers.

After orthogonality is reached, deformation must proceed by one or more different processes that progressively shorten the crenulation hinges, and sometimes completely destroy them to form a new pervasive foliation.

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