

Dynamic analysis of rough cleavage in the Martinsburg Formation, Maryland

CHARLES M. ONASCH

Department of Geology, University of Maryland, College Park, MD 20742, U.S.A.

(Received 5 April 1981; accepted in revised form 30 September 1982)

Abstract—Deformation lamellae in detrital quartz and twin lamellae in vein calcite are common in greywacke beds in the upper portion of the Martinsburg Formation near Williamsport, Maryland. These features are a product of the same stresses that resulted in the formation of rough cleavage. Dynamic analysis of the deformation lamellae and the calcite twins indicates that the cleavage formed normal to the maximum principal stress. In limb samples, the intermediate principal stress is parallel to the fold axis and the least principal stress plunges steeply in the cleavage plane. In most hinge samples the intermediate and least stress axes could not be differentiated and together define the cleavage plane. The lamellae developed during a period of high differential stress that accompanied flattening of early-formed buckle folds. The abundance of deformation lamellae and their development synchronous with the cleavage, demonstrates that intracrystalline deformation may be an important mechanism in the formation of rough cleavage.

INTRODUCTION

THE RELATIONSHIP between cleavage and the finite strain has been subject to more intense study during the last few years. New techniques and refinements of old ones now allow finite strain to be determined in a variety of rock types and geologic terranes. However, comparatively little is known concerning the orientation of the principal stresses during cleavage formation, owing to the difficulties in finding reliable stress indicators that formed at the same time as the cleavage. The most frequently used paleostress indicators are deformation lamellae in quartz and twin lamellae in calcite. Both have been used successfully for the determination of paleostress orientations in many geologic settings (for example, see Carter & Friedman 1965, Detenbeck & Stanley 1979). Greywacke in the Martinsburg Formation in central Maryland contains detrital quartz with deformation lamellae and twinned vein calcite, along with well-developed rough cleavage. All three can be shown to have formed simultaneously, thus affording the opportunity to determine the principal stress directions during cleavage formation.

Samples for this study are from greywacke beds in the upper portion of the Martinsburg Formation exposed in the core of the Massanutten synclinorium near Williamsport, Maryland. The Massanutten synclinorium is an asymmetric fold with the southeast limb dipping steeply or overturned to the northwest. Bedding in the core of the fold is complicated in places by minor folds and faults, but in general the structure is relatively simple. The geometry of bedding and minor structures is shown in Fig. 1. A total of 15 samples were collected from both limbs and the hinge area of the synclinorium (Fig. 2). Three mutually perpendicular thin sections were prepared from each sample. The orientations are: parallel to cleavage, perpendicular to cleavage and the fold axis, and perpendicular to cleavage and parallel to

the fold axis. These orientations were chosen as a first approximation of the principal planes of finite strain.

ROUGH CLEAVAGE

Rough cleavage, the psammitic equivalent of slaty cleavage in pelitic rocks (Gray 1978), is well developed in many greywacke beds. The cleavage is defined by varying proportions of dark, anastomosing folia and elongate

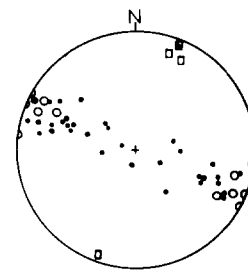


Fig. 1. Equal-area plot of bedding and structural features in sandstones in upper portion of Martinsburg Formation. Solid circles are bedding poles; open circles are rough cleavage poles; open squares are minor fold axes; partially-filled square is P_i axes constructed from bedding poles. Cleavage orientations were determined from thin sections.

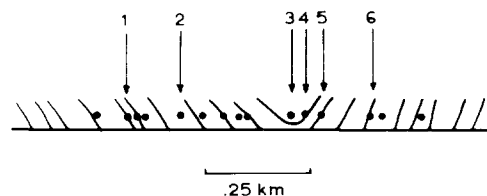


Fig. 2. Schematic cross section of sandstone portion of Martinsburg Formation in core of Massanutten synclinorium showing sample locations (dots). Arrows and numbers are samples and sample numbers in this paper. Minor folds and faults omitted.

detrital grains (Figs. 3 and 4). Detrital grains are usually elongate parallel to the folia and are often bounded by them along one or both edges. The development of folia is domainal; within a single slide, greywacke containing closely spaced, dark folia grades into uncleaved rock. Unlike rough cleavages described elsewhere (for example see Gray 1978), recrystallized mica, either in quartz-mica beards or mica films, is not an important component of the cleavage fabric. Beards such as those in Figs. 3 and 4 are developed only locally and do not make a major contribution to the fabric. Thin beds and those interbedded with shale have the best developed cleavage, but even where obvious in thin section, the cleavage is often difficult to identify in outcrop.

Cleavage orientations define a weakly convergent fan across major and minor folds. Although the dip of bedding varies considerably across the fold, cleavage dips vary no more than 15° from the axial plane attitude (Fig. 1). A poorly developed fracture cleavage or radial jointing is present along with the rough cleavage in some greywacke beds. This surface is distinct from the rough cleavage; it is obvious in outcrop and forms a strongly convergent fan across folds. Slaty cleavage, well developed in shale beds, parallels the axial surface closely.

Both the rough and slaty cleavages developed during the second stage of a four-stage deformational history that is indicated by the microstructural features (Onasch 1981). During this stage, early-formed buckle folds were flattened parallel to their axial surfaces. Although some cleavage may have begun to form during or prior to buckling, the nearly constant orientation of cleavage across the fold requires that it be younger than most folding. Minor tightening of the folds by flexural slip followed by kink folding post-date the cleavage.

DEFORMATION LAMELLAE

Unlike most rocks with rough cleavage (compare Williams 1972, Gray 1978), deformation lamellae in detrital quartz grains are abundant in the samples examined. In many samples, up to 50% of the grains contain at least one set and multiple sets are not uncommon. Deformation lamellae appear to be equally well developed in all three perpendicular sections of each sample. The lamellae occur as subparallel zones of differing birefringence or subparallel planes of brownish fluid inclusions (Fig. 5). The angle between the lamellae pole and c-axis is usually less than 20° indicating that most lamellae are the sub-basal type I of Ave Lallement & Carter (1971).

Before the lamellae can be used for dynamic analysis of the rough cleavage, it must be demonstrated that the two formed synchronously. Three arguments can be made to this point.

(1) The percentage of detrital grains with lamellae is proportional to the degree of cleavage development. Samples with closely spaced folia and strongly elongate detrital grains generally have the highest percentage of

grains with lamellae. Multiple sets are found only in samples with the best developed cleavage. Samples from massive, uncleaved beds are almost devoid of lamellae.

(2) The principal stress directions derived from the lamellae fabrics maintain constant angular relationships with the cleavage, regardless of bedding orientation or position on the fold. Had they developed prior to or early during folding, the lamellae fabrics would be expected to vary with bedding orientation and would show no consistent relationship to the axial-planar cleavage.

(3) Post-cleavage vein quartz contains no lamellae; therefore, the lamellae could not have formed much later than the cleavage.

VEIN CALCITE

Many samples contain veins filled with quartz, calcite or both that formed before, during and after the cleavage. Offset of pre-vein features was not observed across any vein, regardless of relative age; thus, all veins are assumed to be of extensional origin. Syn-cleavage veins used for dynamic analysis of the cleavage can be differentiated from pre- and post-cleavage veins on the basis of orientation, vein mineralogy, extent of vein and vein mineral deformation.

Pre-cleavage veins have highly variable orientations (Fig. 6) and are generally filled with calcite. Most are buckled or offset along the cleavage. Where buckled, the cleavage is parallel to the axial surface. Where offset, the sense of offset is consistent with local volume loss along the cleavage folia. Syn-cleavage veins are oriented normal to the cleavage and parallel to the fold axis (Fig. 6). A few are buckled slightly or show traces of cleavage. Evidence for the deformation of vein minerals is limited to twinning of the sparry calcite and sparse deformation lamellae in the quartz. Post-cleavage veins are inclined at moderate angles to the cleavage (Fig. 6) and show no traces of buckling, cleavage, or intracrystalline deformation of the quartz and calcite vein minerals.

Several observations suggest that the twin lamellae in syn-cleavage veins formed at the same time as the cleavage; therefore, the lamellae can be used for the dynamic analysis of the cleavage.

(1) Cross-cutting relations between syn-cleavage veins and other microstructural features show that the veins are coeval with the cleavage. Syn-cleavage veins cut veins that are offset by the cleavage but are themselves cut by veins, shear zones, and kink folds which are younger than cleavage. In a single sample, some syn-cleavage veins may show traces of cleavage while others truncate cleavage folia.

(2) The fact that the veins formed with cleavage does not prove that twinning of the calcite took place at the same time. However, in the case of extensional veins, Orrell & Onasch (1981) have shown that deformation of vein minerals may occur before the stresses responsible for the initial fracture change orientation. Therefore,

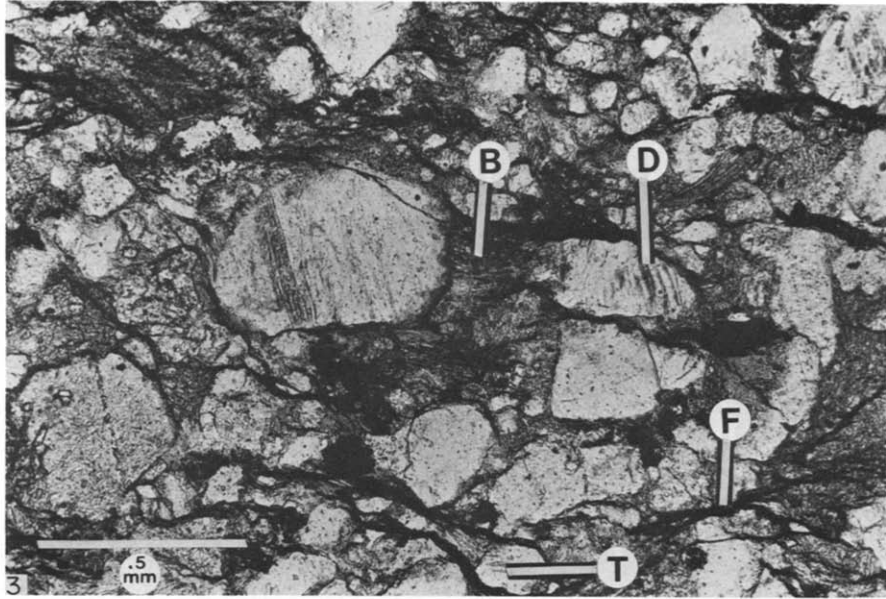


Fig. 3. Rough cleavage in greywacke. F, folia; T, truncated detrital grain; D, deformation lamellae; B, beard. Cleavage is horizontal and bedding dips at a moderate angle to left (SE). Section is normal to cleavage and fold axis. Plane-polarized light.

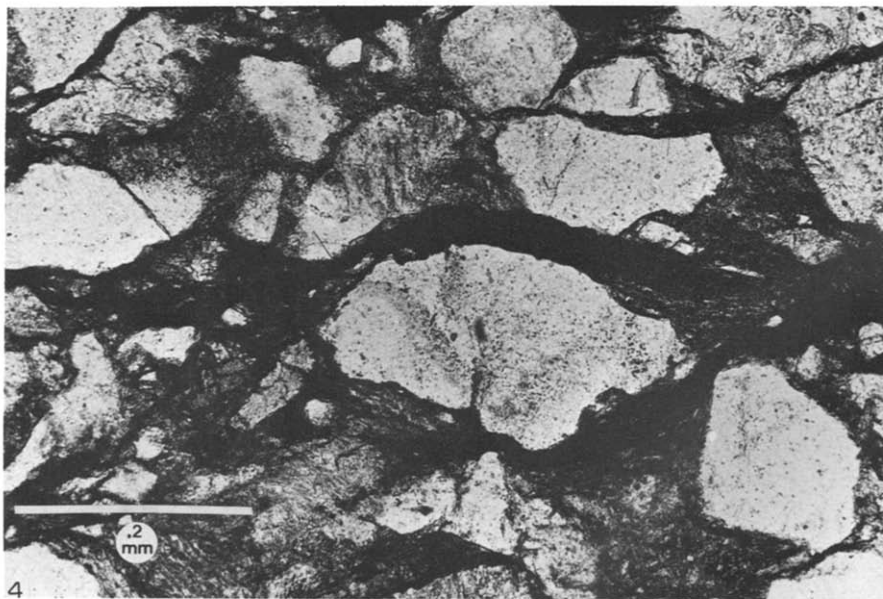


Fig. 4. Rough cleavage with well-developed folia. Note curvature of folia around detrital grains. Cleavage is horizontal and bedding is vertical. Section is normal to cleavage and fold axis. Plane-polarized light.

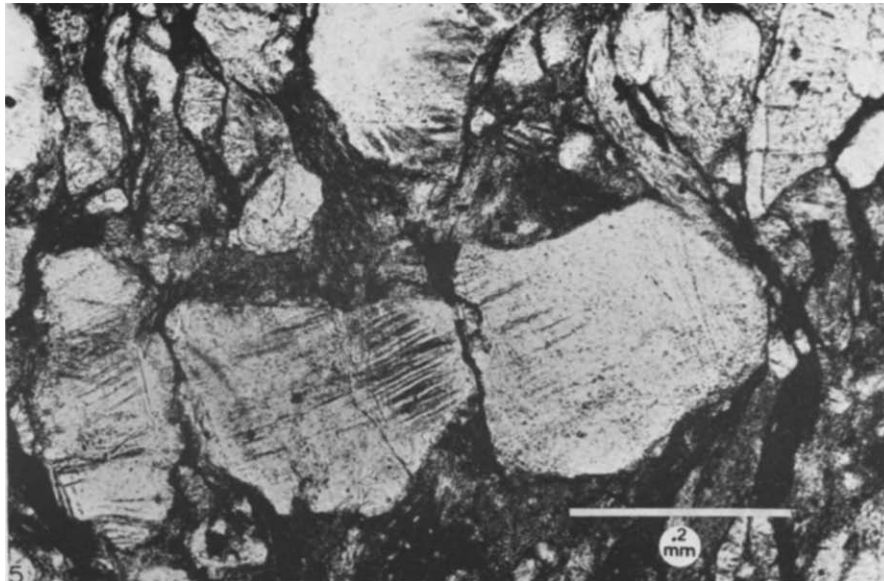


Fig. 5. Deformation lamellae in detrital quartz grains. Cleavage is vertical and bedding is horizontal. Section is normal to cleavage and parallel to the fold axis. Plane-polarized light.

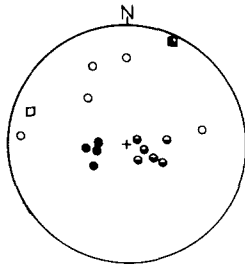


Fig. 6. Equal-area plot of poles to veins. Open circles are pre-cleavage veins; half filled circles are syn-cleavage veins; solid circles are post-cleavage veins. Open square is cleavage pole; half-filled square is P_i axis. Data are from two samples, one from each limb, rotated slightly so that cleavage in each coincides.

twinning of the calcite may reflect the stresses present during vein formation and hence, cleavage formation.

(3) The veins and calcite lamellae fabrics maintain constant angular relations to the cleavage.

DYNAMIC ANALYSIS

Deformation lamellae in detrital quartz and twin lamellae in syn-cleavage vein calcite were used to determine principal stress directions during the formation of rough cleavage. Of the 15 samples studied, two from each limb and two from the hinge area (Fig. 2) are discussed in this paper. These six samples were selected as being representative of the fabrics in other samples from similar structural locations. Orientation data were measured on each of the three perpendicular sections and rotated back to true geographic coordinates.

The interpretation of strain phenomena, such as deformation lamellae in quartz and twin lamellae in calcite, in terms of stress rather than strain, can be made only with some knowledge of the stress-strain relationships. In the experimental deformation of rock, from which the methods for dynamic analysis were developed, stress and strain are usually coaxial. In nature this may not always be true. However, it will be shown later that the deformation and twin lamellae developed late in the deformational history at a time when stress and strain very likely were coaxial; therefore, these microstructures can be interpreted in terms of stress.

Quartz deformation lamellae

Maximum and minimum principal stress directions were determined from deformation lamellae in detrital quartz by c_1 - c_2 and arrow methods, respectively (Carter & Friedman 1965). The c_1 - c_2 method consists of drawing a partial great circle between the c -axis of the most (c_2) and least (c_1) deformed portions of a single grain. The c_2 axis will lie closer to σ_1 than c_1 . Using a number of grains, the orientation of σ_1 is determined by noting where the partial great circles converge. The arrow method consists of drawing a partial great circle between the c -axis (tail) and lamellae pole (arrowhead) for each grain with lamellae. The arrow will point to the average σ_3 orienta-

tion. The best results are obtained when the two methods are used in conjunction with each other.

Figure 7 shows the c -axis and lamellae fabrics, along with the derived stress orientations for each sample. In all six samples, σ_1 was found to lie within 10° of the cleavage pole (Figs. 7g, h, i, p, q & r). In all four limb samples (samples 1, 2, 5 and 6), σ_2 was parallel to the fold axis whereas σ_3 was normal to the fold axis and parallel to the cleavage plane (Figs. 7g, h, q & r). In both hinge samples (samples 3 and 4), σ_2 and σ_3 could not be differentiated and together define the cleavage plane (Figs. 7i & p). The same tendency is also exhibited in sample 5 which comes from a moderately dipping bed on the southeast limb near the hinge (Fig. 2). The arrow diagram for this sample (Fig. 7k) shows several arrows pointing to a great circle parallel to the cleavage plane. In general, the relationship observed in these and other samples is that samples from the limbs, where bedding dips steeply, indicate a general stress field ($\sigma_1 > \sigma_2 > \sigma_3$) whereas those from the hinge area or where bedding dips at low to moderate angles, indicate a triaxial compressive stress field ($\sigma_1 > \sigma_2 = \sigma_3$). The 15 - 20° variation in stress orientations from one limb to the other mimics the change in cleavage orientation associated with fanning.

Vein calcite

Compression and tension axes were determined from twinned vein calcite according to the technique of Turner (1953). Figure 8 shows the compression and tension axis diagrams for samples from each limb. Extension veins were not observed in samples from the hinge area. The lack of veins may be due largely to the comparatively few samples collected from this location.

Both compression and tension axis diagrams show well defined maxima. Compression axis maxima on both limbs are within 20° to the cleavage pole and are nearly parallel to the vein wall. Tension axis maxima on both limbs are within 20° of the pole to the vein wall and are parallel to the cleavage and normal to the fold axis. Compression and tension axes agree well with maximum and minimum stress orientations, respectively, determined from quartz deformation lamellae. This, along with the constant angular relationship of each to the cleavage, further strengthens the contention that the cleavage, calcite twin lamellae in syn-cleavage veins, and quartz deformation lamellae all formed simultaneously in response to the same stresses.

DISCUSSION

The dynamic analysis has shown that the rough cleavage across the Massanutten synclinorium developed normal to σ_1 . This statement, however, must be qualified in terms of scale and the stress-strain relationship during cleavage formation. The statistical nature of the methods used is not sensitive to grain-scale variations in

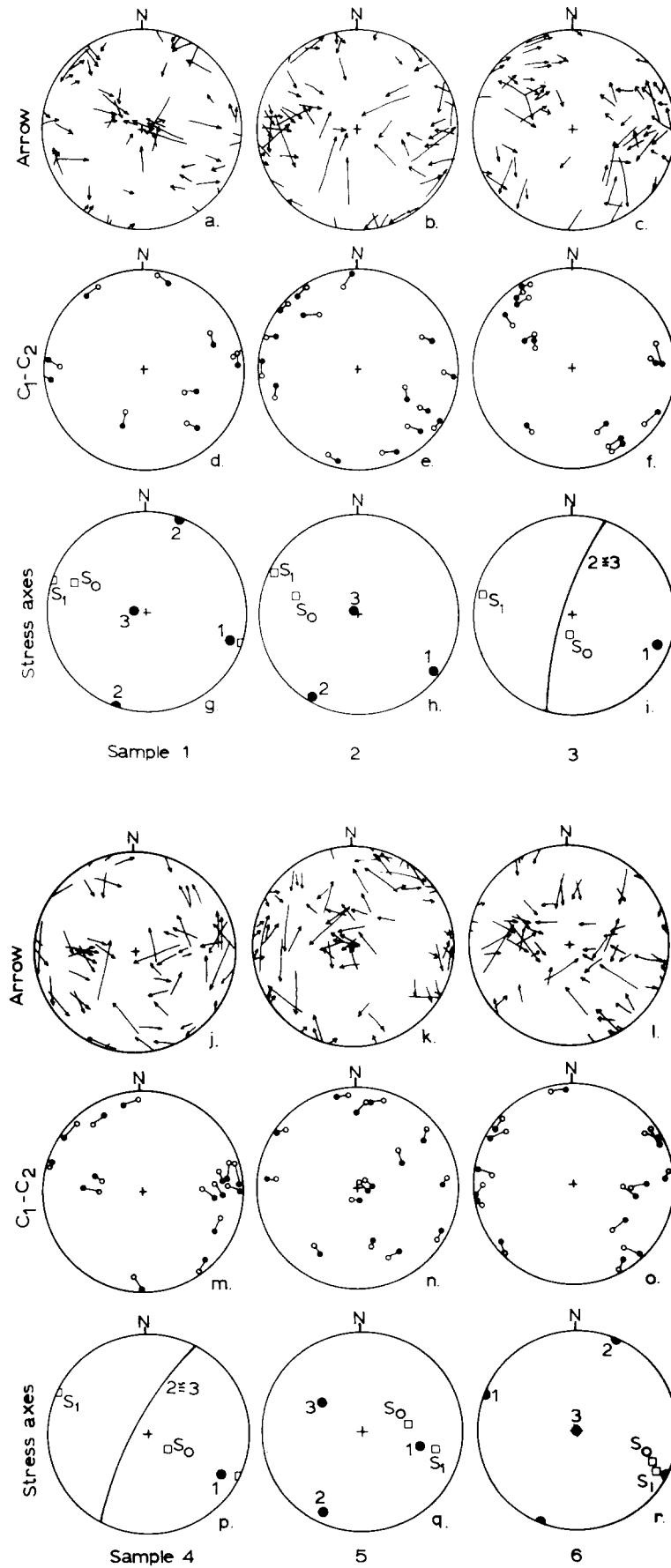


Fig. 7. Fabric diagrams used for dynamic analysis of deformation lamellae in samples 1-6. (a, b, c, j, k & l) arrow diagrams used to locate σ_3 . Lamellae pole is at arrowhead, c-axis at tail. (d, e, f, m, n & o) c_1 - c_2 diagrams used to locate σ_1 . Solid circle is c-axis of more deformed portion of grain, open circle is c-axis of less deformed portion. (g, h, i, p, q & r) principal stress axes derived from previous diagrams. Solid circles are stress axes; open squares are poles to bedding and cleavage. Great circle in i and p contain σ_2 and σ_3 . All plots are lower hemisphere, equal-area projections.

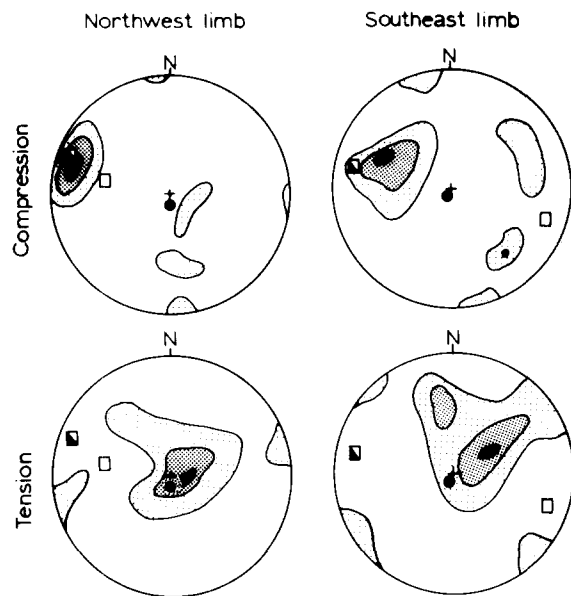


Fig. 8. Compression and tension axis diagrams for calcite in syn-cleavage veins. Solid circle is vein pole; open square is bedding pole; half-filled square is cleavage pole. Contours are at 2, 5 and 8% per 1% area.

stress orientations produced at grain to grain contacts; rather, they yield average orientations for a single thin section. It cannot be stated with certainty that each individual folia formed normal to the local σ_1 direction. Curved folia may result from the deformation of folia by subsequent flattening around a relatively rigid grain, reflect local variation in stress orientations, or show that folia can form at angles to σ_1 other than 90° . It will be argued later that the second explanation is very likely in the samples studied.

The interpretation of deformation and twin lamellae in terms of stress rather than strain has been made with the assumption that stress and strain were coaxial during cleavage formation. This relationship is supported by the geometry of quartz fibres in beards and detrital grains. Fibrous growths have been shown by Durney & Ramsay (1973) to be a sensitive indicator of the strain history. In the samples examined, quartz fibres in all three perpendicular sections are straight and parallel to the cleavage trace. The maximum fibre length is parallel to the cleavage dip direction. These observations indicate that the strain history at the time of fibre growth, hence cleavage formation, was coaxial and that the cleavage developed parallel or subparallel to a principal plane of strain. During this phase of flattening, where the deformation was irrotational, it is reasonable to assume that stress and strain were coaxial.

The relationship between cleavage and lamellae-derived stresses found in the Martinsburg is not unique. Early studies of deformation lamellae in folded sandstones by Fairbairn (1941), Ingerson & Tuttle (1945), Mackie (1947), Riley (1947), Christie & Raleigh (1959) and Hara (1961), all reinterpreted by Carter & Friedman (1965), show that the stress orientations are related to an axial-planar foliation. In each case, σ_1 was

found to be normal to the foliation whereas σ_2 and σ_3 were parallel to it. By contrast, in other folded sandstones, deformation lamellae show that σ_1 maintains a constant angular relationship to bedding, not the axial plane. Hansen & Borg (1962), Scott *et al.* (1965), Carter & Friedman (1965) and Burger & Hamill (1976) found that where stress axes could be determined uniquely, σ_1 is parallel or at low angles to bedding; σ_2 is parallel to the fold axis and σ_3 is normal to bedding. These relationships are independent of bedding orientation and position on the fold.

Computer models of finite amplitude folds yield stress orientations in partial agreement with each of these lamellae fabric relationships. Single-layer models with a high viscosity contrast between layer and matrix shortened 60% predict that σ_1 along the layer midline will be parallel to bedding in the hinge area and at moderate to low angles to bedding on the limbs (Dieterich & Carter 1969). In the limb area, predicted stress orientations differ slightly from natural examples with model stresses at a higher angle to bedding. This difference can be minimized by increasing the viscosity ratio or decreasing the total shortening in the model (Dieterich & Carter 1969). Multilayer models consisting of alternating competent and incompetent layers predict significantly different stress orientations at comparable shortening values (Dieterich 1969). In cases of 60% or greater shortening, σ_1 orientations in both competent and incompetent layers are everywhere nearly normal to the axial plane, regardless of bedding orientation or position on the fold. Dieterich attributes the differences in stress orientations between the two models to the interaction of layers during the later stages of folding.

Whether lamellae fabrics are related to bedding or to the axial plane is determined by the timing of lamellae development. The formation of deformation lamellae requires a certain minimum stress. When, during deformation, this stress is reached determines whether lamellae fabrics will be related to bedding or the axial plane. Lamellae which form during layer-parallel shortening will indicate σ_1 everywhere subparallel to bedding (Hansen & Borg 1962, Scott *et al.* 1965, Burger & Hamill 1976). Computer fold models have shown that compressive stresses can be high during this stage (Dieterich & Carter 1969), hence deformation lamellae often develop at this time. Lamellae which form during buckling will yield stress orientations that vary with location on the fold (Carter & Friedman 1965, Burger & Hamill 1976). Samples from the outer arc of the fold will show σ_1 at high angles to bedding whereas samples from the inner arc will indicate σ_1 subparallel to bedding. Lamellae which develop during flattening, after buckling, as was the case in the Martinsburg greywackes, will yield a σ_1 direction normal to the axial plane, independent of bedding orientation. In summary, the geometrical relationship between the lamellae fabrics and bedding or axial-planar cleavage can be used to determine when, during deformation, the lamellae formed. Lamellae which develop early, during layer-parallel shortening or buckling, will be related to bedding. Lamellae which

form late, during flattening, will be related to the axial plane.

The timing of stresses sufficient for lamellae development appears to be controlled by lithology. Sandstones in which lamellae formed during layer-parallel shortening typically are orthoquartzites (Scott *et al.* 1965) or calcite-cemented quartz sandstones (Hansen & Borg 1962, Carter & Friedman 1965). Sandstones like the Martinsburg greywacke, in which lamellae formed late in the deformation, are usually rich in phyllosilicates.

In the Martinsburg and sandstones of similar composition, stresses in detrital quartz may have been low during layer-parallel shortening and buckling due to the cushioning effect of the clay matrix. During flattening, tectonic compaction and volume loss in the matrix concentrated more stress on the framework grains and deformation lamellae began to form. Abundant syntectonic veins in the samples examined indicate that pore fluid pressures were high during deformation. Initially high pore fluid pressures that decrease progressively during deformation could also produce high framework stresses during only the later stages of deformation. High pore fluid pressures during layer-parallel shortening and buckling would result in low framework stresses. As pore fluid pressure decreases, progressively more stress will be transferred to the framework until eventually, the yield strength of quartz is overcome.

Cleavage appears to be restricted only to those sandstones in which the lamellae developed late in the deformational history. Sandstones in which lamellae developed early are uncleaved. As rocks with axial plane-related fabrics did not experience high stresses until after folding, it appears that they may have folded at lower stress levels than sandstones lacking cleavage.

The contemporaneity of the quartz deformation lamellae and the rough cleavage has important implications with regard to the mechanics of rough cleavage formation. Pressure solution is believed to be the dominant mechanism in the development of rough cleavages (Williams 1972, Means 1975, Gray 1978). In the Martinsburg Formation, folia of insoluble residue, sutured grain boundaries, truncation of detrital grains against folia and offset of properly oriented veins across folia all argue that pressure solution was an important factor during cleavage formation.

The stress orientations during cleavage formation determined from the dynamic analysis are consistent with a pressure solution origin for the cleavage on both macroscopic and grain scales. In a theoretical treatment of the pressure solution process, Durney (1976) predicts that dissolution will occur on grain faces oriented at high angles to σ_1 . Accumulations of the insoluble residue marking the dissolution surfaces would be oriented normal to σ_1 . Thus, on a macroscopic scale, cleavage folia should be oriented normal to σ_1 , as was found across the core of the Massanutten synclinorium. On a grain scale, stress orientations will vary more than is indicated by the dynamic analysis. Irregular grain to grain contacts and ductility differences between grains and matrix will result in curved stress trajectories. Cosgrove (1976) used

the orientation of stress trajectories around rigid objects in a ductile matrix to explain curved pressure solution surfaces. The curvature of cleavage folia around detrital grains depicted in Fig. 4 agrees well with σ_3 trajectory orientations around a rigid object in a ductile matrix (Cosgrove 1976, fig. 17b). The problem of interpreting curved folia discussed earlier can be resolved by considering the folia to be pressure solution surfaces everywhere oriented normal to the σ_1 trajectories.

Despite the direct and indirect evidence emphasizing the role of pressure solution, additional mechanisms must be considered to explain other microstructural features. Abundant deformation lamellae and their development synchronous with the cleavage indicate that intracrystalline deformation may have contributed to the modification of detrital grain shapes and therefore to the total strain. Grains elongate parallel to cleavage, but not bounded by folia or truncated against other grains owe their shape to a mechanism other than pressure solution. Undulose extinction, subgrains and deformation bands in quartz; bent twin lamellae in plagioclase and kinked detrital mica further substantiate the effects of intracrystalline deformation.

The relative contribution of pressure solution and intracrystalline deformation in the Martinsburg greywackes is not known. Pressure solution alone can account for the folia, but the elongation of detrital grains parallel to the folia is probably a product of both mechanisms. Deformation of rutile needles in the few grains which contain them is variable. Some grains have needles that are bent and kinked while in other grains, the needles are undeformed. Although pressure solution may have been the dominant process in the formation of the rough cleavage, its obvious effects tend to bias the observer into underestimating the importance of intracrystalline deformation; the evidence for which is much more subtle.

Acknowledgements—Valuable criticism of various drafts of this manuscript were provided by Edward C. Beutner and Richard H. Groshong, Jr. Suggestions by the referees of the *Journal of Structural Geology* were helpful in improving the final version of this paper.

REFERENCES

- Ave Lallemand, H. G. & Carter, N. L. 1971. Pressure dependence of quartz deformation lamellae orientations. *Am. J. Sci.* **270**, 218–235.
- Burger, H. R. & Hamill, M. N. 1976. Petrofabric analysis of the Dry Creek Ridge anticline, Montana. *Bull. geol. Soc. Am.* **87**, 555–566.
- Carter, N. L. & Friedman, M. 1965. Dynamic analysis of deformed quartz and calcite from the Dry Creek Ridge anticline, Montana. *Am. J. Sci.* **263**, 747–785.
- Christie, J. M. & Raleigh, C. B. 1959. The origin of deformation lamellae in quartz. *Am. J. Sci.* **257**, 385–407.
- Cosgrove, J. W. 1976. The formation of crenulation cleavage. *J. geol. Soc. Lond.* **132**, 155–178.
- Detenbeck, J. C. & Stanley, R. S. 1979. Dolomite and quartz lamellae stress and strain analysis in a multiply-deformed terrane, west-central Vermont. *Bull. geol. Soc. Am.* **90**, 804–805.
- Dieterich, J. H. 1969. Computer experiments on mechanics of finite amplitude folds. *Can. J. Earth Sci.* **7**, 467–476.
- Dieterich, J. H. & Carter, N. L. 1969. Stress-history of folding. *Am. J. Sci.* **267**, 129–154.

- Durney, D. W. 1976. Pressure-solution and crystallization deformation. *Phil. Trans. R. Soc.* **283A**, 229–240.
- Durney, D. W. & Ramsay, J. G. 1973. Incremental strains measured by syntectonic crystal growths. In: *Gravity and Tectonics* (edited by DeJong, K. & Scholten, R.). John Wiley and Sons, New York, 67–96.
- Fairbairn, H. W. 1941. Deformation lamellae in quartz from the Ajbik formation, Michigan. *Bull. geol. Soc. Am.* **52**, 1265–1278.
- Gray, D. R. 1978. Cleavages in deformed psammitic rocks from southeastern Australia; their nature and origin. *Bull. geol. Soc. Am.* **89**, 577–590.
- Hansen, E. & Borg, I. Y. 1962. The dynamic significance of deformation lamellae in quartz of a calcite-cemented sandstone. *Am. J. Sci.* **260**, 321–336.
- Hara, I. 1961. Dynamic interpretation of the simple type of calcite and quartz fabrics in the naturally deformed calcite-quartz vein. *Hiroshima Univ. J. Sci.* **4C**, 35–53.
- Ingerson, E. & Tuttle, O. F. 1945. Relations of lamellae and crystallography of quartz and fabric directions of some deformed rocks. *Trans. Am. geophys. Un.* **26**, 95–105.
- Mackie, J. B. 1947. Petrographic analyses of two quartz-piedmontite schists from northwest Otago. *Trans. R. Soc. New Zealand* **86**, 362–368.
- Means, W. H. 1975. Natural and experimental microstructures in deformed micaceous sandstones. *Bull. geol. Soc. Am.* **86**, 1221–1229.
- Onasch, C. M. 1981. Cleavage and microstructure in sandstones of the Martinsburg Formation, Maryland and Pennsylvania. *Geol. Soc. Am. Abs.* **13**, 169.
- Orrrell, S. A. & Onasch, C. M. 1981. Dynamic analysis of vein calcite in an area of non-coaxial deformation. *Geol. Soc. Am. Abs.* **13**, 523.
- Riley, N. A. 1947. Structural petrology of the Baraboo quartzite. *J. Geol.* **55**, 453–475.
- Scott, W. H., Hansen, E. & Twiss, R. J. 1965. Stress analysis of quartz deformation lamellae in a minor fold. *Am. J. Sci.* **263**, 729–747.
- Turner, F. J. 1953. Nature and dynamic interpretation of deformation lamellae in calcite of three marbles. *Am. J. Sci.* **251**, 276–298.
- Williams, P. F. 1972. Development of metamorphic layering and cleavage in low grade metamorphic rocks at Bergamui, Australia. *Am. J. Sci.* **272**, 1–47.