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ORIGIN AND SIGNIFICANCE OF MICROSTRUCTURES IN SANDSTONES OF THE MARTINSBURG FORMATION, MARYLAND

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ABSTRACT. Graywacke in the upper portion of the Martinsburg Formation occupies the core of the Massanutten synclinorium in Maryland. Rough cleavage, the psammitic equivalent of slaty cleavage in pelitic rocks, is well developed in many graywacke beds. It is defined by dark folia of insoluble residue, detrital grains elongated parallel to the folia, and to a lesser degree, oriented phyllosilicates. Pressure solution is believed to have been the dominant mechanism of cleavage formation, but abundant deformation lamellae and bands, undulatory extinction, and subgrain development in detrital quartz grains indicate that intracrystalline deformation may have been important in the modification of detrital grain shapes and hence to the development of cleavage.

Using detrital grain shapes, fibrous minerals, and deformed pre-cleavage veins, it was found that the rough cleavage is subparallel to the λ_1-λ_2 plane of finite strain. Detrital grain shapes indicate that samples with well developed cleavage were shortened 29 to 55.5 percent, depending on how much volume was lost during deformation. Shortening associated with cleavage formation included both extension parallel to the cleavage dip and volume loss.

The cleavage developed during a phase of flattening that followed initial buckle folding. Minor post-cleavage deformational features include bedding-parallel shear zones related to renewed flexural slip and kink folds. Veins, originally extension fractures, are intimately related to all microstructures indicating that pore fluid pressures remained high throughout much of the deformational history.

INTRODUCTION

The origin and dynamic significance of microstructures, especially cleavage, currently is one of the most active topics in structural geology. To date, a large portion of this research has been devoted to fine-grained micaceous rocks with proportionately less reported on sandstones. This paper examines the microstructural evolution of sandstones in the Ordovician Martinsburg Formation and, in particular, the origin and significance of the rough cleavage developed in many samples.

Geologic setting.—The Martinsburg Formation in Maryland is largely shale and siltstone, but interbedded sandstone is common in the uppermost exposed portion. The sandstone is high-rank graywacke consisting of subangular grains in a clay matrix with a framework-matrix ratio of about 1:1. In order of decreasing abundance, the detrital grain types are: quartz, mica, foliated rock fragments, plagioclase, microcline, and recrystallized chert. Sedimentary structures such as flute casts, graded bedding, cross bedding, and slump structures indicate that the upper portion of the Martinsburg was deposited by turbidity currents (McBride, 1962).

No significant metamorphism has affected the area. Clay minerals are abundant and detrital plagioclase does not appear to have lost calcium, indicating that pressures and temperatures were below the chlorite zone of the greenschist facies.

The Martinsburg Formation occupies the Massanutten synclinorium (fig. 1). This fold is asymmetric with the short, or southeast, limb dipping steeply or overturned to the northwest. Faulting and folding are evident on all scales. The contact between the Martinsburg and the underlying Cambro-Ordovician carbonates is faulted in many places (Edwards, 1978). Along strike, across the Pennsylvania border, Stephens and Wright (1981) have mapped folds within the lower portion of the Martinsburg using graptolite zonation to define the stratigraphy. Folds with amplitudes of a few meters and normal and reverse faults with little apparent offset are common in some exposures. Slaty cleavage is well developed in shale beds, but there is little mesoscopic evidence for a penetrative cleavage in graywacke beds. The orientation of the minor

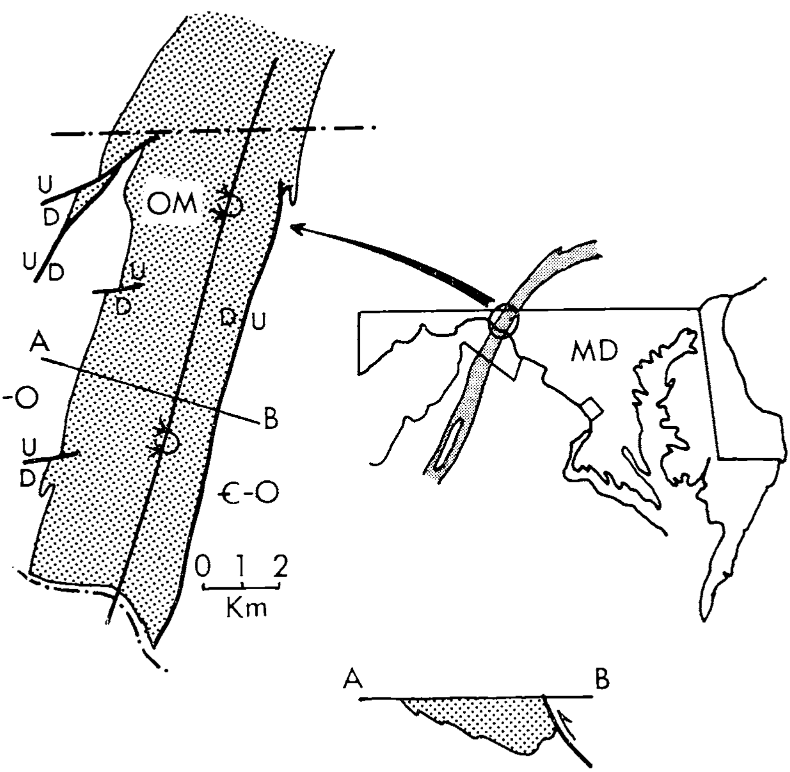


Fig. 1. Location of study area. Dark area on regional map is Martinsburg Formation. Insets show structure in core of Massanutten synclinorium and cross section. OM—Martinsburg; €O—Cambro-Ordovician carbonates.

structural features measured across the entire synclinorium is shown in figure 2.

The observations and data in this paper are based on examination of mesoscopic structures and microstructures in thin sections from 56 samples. Samples were collected from sites equally distributed across the hinge and both limbs of the Massanutten synclinorium. Several minor folds were sampled in detail. Most samples are from graywacke beds, but several shale samples were included.

ROUGH CLEAVAGE

Rough cleavage is the most obvious microstructural feature in the graywacke beds. The term is used here in the same sense as Gray (1978); it is a discontinuous, spaced cleavage characteristic of sandstones defined by differing proportions of dark folia or "seams," elongate detrital grains, and oriented mica and chlorite. Because of the close temporal and spatial relations to slaty cleavage in interbedded shale, Gray proposed that rough cleavage is the morphological equivalent of slaty cleavage.

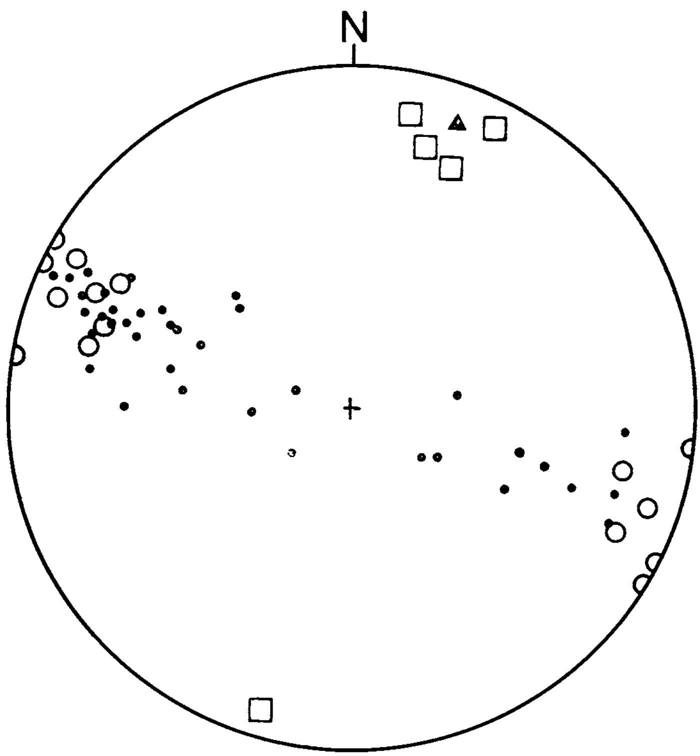


Fig. 2. Equal area plot of bedding and structural features in Martinsburg graywacke. Solid circles are bedding poles; open circles are rough cleavage poles; open squares are minor fold axes; triangle is Pi axis. Rough cleavage orientations were measured from thin sections.

In the Martinsburg graywackes, dark folia are the dominant component of the rough cleavage fabric. In samples with well developed cleavage, these anastomosing folia wrap around and often truncate detrital grains (pl. 1). Individual folia vary in width from 0.01 to 0.05 mm and may extend as little as 0.5 mm or as much as the length of an entire thin section. The folia vary from evenly spaced to highly domainal, often in the distance of a few millimeters.

Except for an uncommon grain of white mica, no specific phases could be identified in the folia. Other workers have shown that dark folia similar to these are concentrations of the relatively insoluble components of the rock such as carbonaceous material, and opaque, clay, and mica minerals (Nickelsen, 1972; Gray, 1978).

In most samples, elongate detrital grains are secondary to the folia in defining the cleavage. Where the cleavage is well developed, detrital grains are elongated parallel to and usually bounded by the cleavage folia. In samples with poorly developed cleavage, the elongation is less pronounced and tends to be parallel to bedding.

Mica and chlorite that have crystallized or recrystallized in beards or mica films are an important component of many rough cleavage fabrics (Williams, 1972; Means, 1975; Gray, 1978). Beards consisting of quartz, chlorite, and sericite which taper off one or both ends of detrital grains in a direction parallel to cleavage are present in limited numbers in several samples (pl. 2). The minerals in most beards are fibrous and aligned with their long axes parallel to cleavage. Despite their presence in several samples, beards or mica films do not constitute an important component of the rough cleavage fabric.

White mica with the (001) parallel to the rough cleavage occurs in some interfolial domains. It usually can be distinguished from detrital mica by its relatively "fresh" look. Even though some samples may contain noticeable amounts of such mica, in general, it does not contribute significantly to the cleavage fabric.

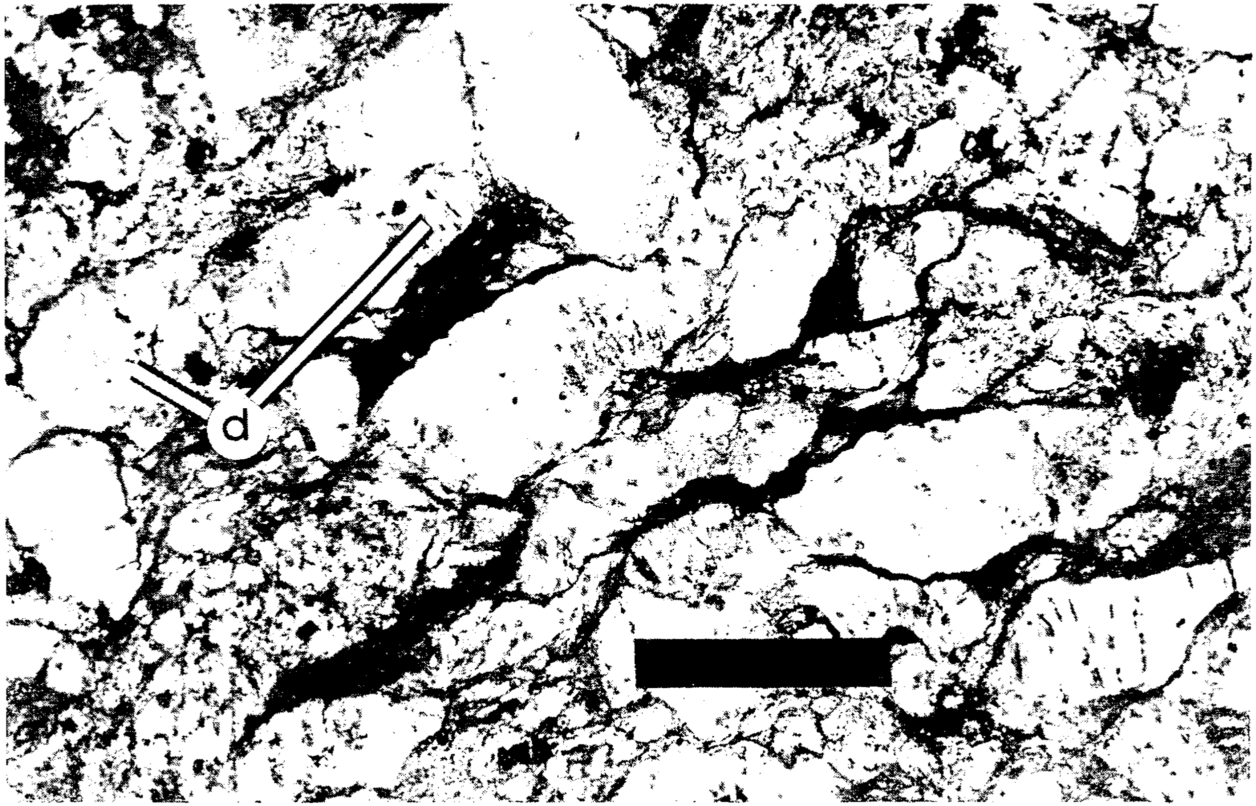
The degree of cleavage development varies from bed to bed and appears to be related to the bed thickness, proximity to shale, and grain size. Thin graywacke beds or those interbedded with shale generally contain better developed cleavage than massive beds or those from thick sandstone sections. In the latter, cleavage is virtually absent. In fine grained beds, cleavage folia are more closely spaced and better developed. Position on a fold, major or minor, has no predictable effect on cleavage development. The orientation of the rough cleavage varies across mesoscopic and macroscopic folds by no more than 20° (see fig. 2). The variation is symmetric about the axial surface defining a weak convergent fan. Refraction of the cleavage from graywacke into shale is generally less than 15°, and often the cleavage in both is subparallel.

The characteristics of the rough cleavage discussed so far cannot all be explained by a single mechanism. Mechanisms that have been suggested by others for one or more of the components of rough cleavage include: brittle deformation (Leith, 1905); intracrystalline deformation (Williams, 1972); pressure solution (Williams, 1972; Means, 1975; Gray,

PLATE 1

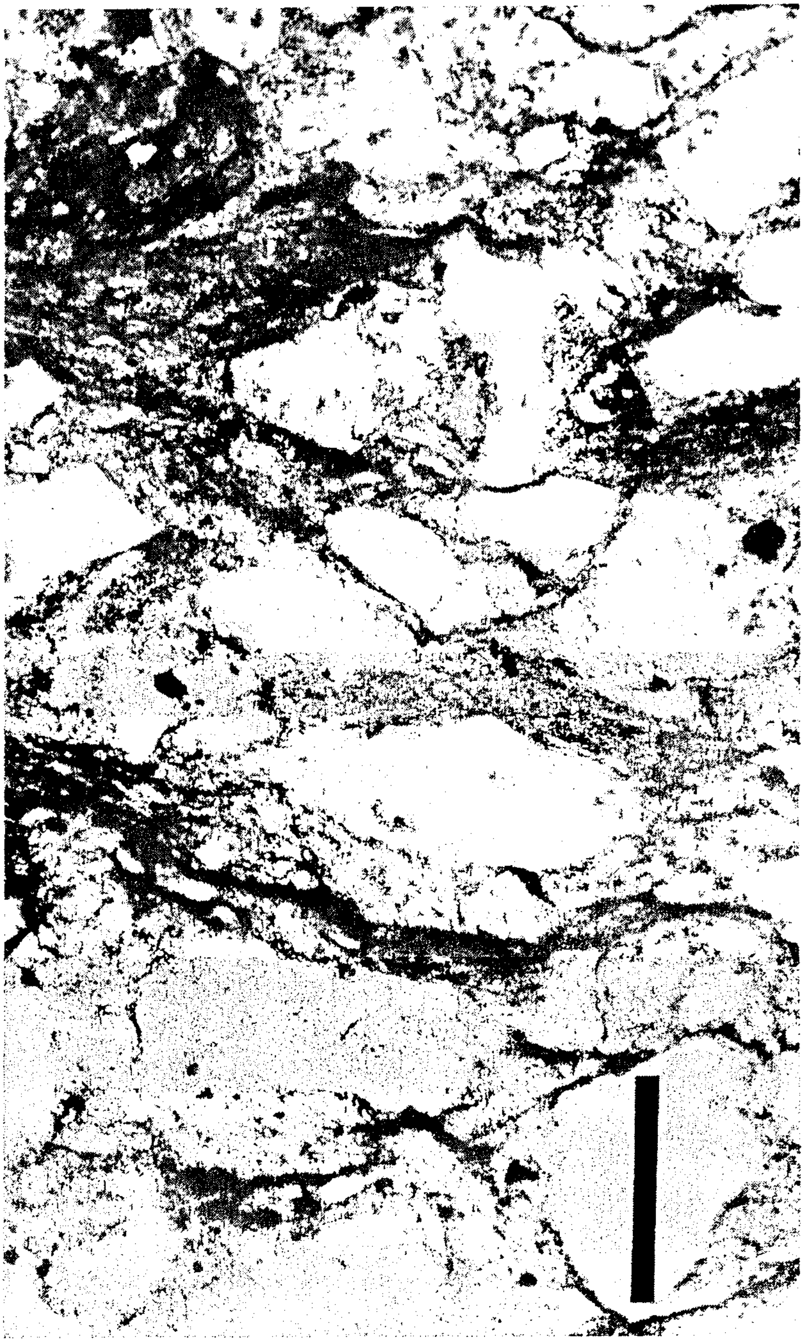
A.

B.



Rough cleavage in Martinsburg graywackes. Both (A) and (B) are from hinge area of Massanutten synclinorium where bedding and cleavage are at high angles. Note deformation lamellae (d) in detrital quartz grains in (B). Cleavage is vertical in (A) and dips to left in (B). Scale bar in both is 0.2 mm. Plane light.

PLATE 2



Quartz-mica beards on detrital grain in center of photo. Cleavage is near-vertical. Note parallelism between fibers in beard and rough cleavage. Scale bar is 0.2 mm. Plane light.

1978); recrystallization (Williams, 1972); and rotation (Williams, 1972; Geiser, 1974). Rough cleavage in the Martinsburg appears to have developed by a combination of pressure solution and intracrystalline deformation. Locally, crystallization and/or recrystallization may have been important.

Many aspects of the cleavage fabric are best explained by pressure solution. Folia composed of concentrations of insoluble residue, sutured grain boundaries, truncation of detrital grains against folia, and offset across folia of suitably oriented veins all argue that pressure solution was an important, if not the dominant mechanism of cleavage formation. The more soluble components such as quartz and calcite were preferentially dissolved from the matrix and margins of grains while the insoluble components were passively concentrated along the folia. Overall, less than 10 percent of the detrital grains have beards or overgrowths. The relative scarcity of these features is an indication that the rock behaved as an open or partially open system during deformation (Durney, 1976). Some material dissolved from the matrix and framework grains may have crystallized in veins, but most must have migrated out of the system.

Although pressure solution appears to have been the dominant mechanism during cleavage formation, there is abundant evidence that intracrystalline deformation may have contributed to the modification of detrital grain shapes and thus to the total strain. Deformation lamellae, deformation bands, undulatory extinction, and subgrain development in quartz; twin lamellae in calcite; and bent twin lamellae in plagioclase are common in samples with well developed cleavage. Contemporaneous development of these features with the cleavage is suggested by the following observations: (1) The abundance of these features is proportional to the development of the cleavage. Samples with the darkest folia and most elongate detrital grains contain the most deformation lamellae, calcite twins, et cetera. Samples with poorly developed cleavage rarely contain such features. (2) The deformation lamellae and the inferred stress orientations derived from their geometry maintain a constant angular relationship with the cleavage. In every sample examined, σ_1 was found to be within 10° of the cleavage pole, regardless of the bedding orientation or position on the fold (Onasch, 1981, 1982, 1983). σ_2 was parallel to the fold axis in most samples, and σ_3 was parallel to the down-dip direction of the cleavage. Had the deformation lamellae developed before the cleavage, during layer-parallel shortening or buckling, they would be related to bedding, not the axial planar cleavage.

Other deformational features that developed at the same time as the cleavage show that the shortening associated with the cleavage could not have occurred entirely by pressure solution. These include kinked mica, buckled rock fragments, and buckled veins.

The partitioning of the strain between pressure solution and intracrystalline deformation during cleavage formation has not been determined. The cleavage folia are probably entirely a product of pressure solution. The elongation of detrital grains, even though they contain structures indicative of intracrystalline deformation such as deformation lamellae, could also be due largely to pressure solution. Deformation lamellae can form before any significant grain elongation occurs (White, 1976). However, the elongation parallel to cleavage of grains that have deformation lamellae but lack bounding folia or sutured contacts would seem to argue for some elongation by intracrystalline deformation.

Crystallization or recrystallization accounts for a relatively small portion of the cleavage fabric. Although modified during deformation, most of the grains are detrital in origin. Mica and chlorite in beards and mica in interfolial domains and films grew during cleavage formation. Some of the white mica, especially in interfolial domains, could have grown from kinked detrital mica deformed during the early stages of cleavage formation. Compared to undeformed mica, kinked mica has a higher internal energy, hence greater tendency to recrystallize (Vernon, 1976). This mechanism has been postulated to explain the preferred orientation of mica parallel to cleavage in slates (Knipe and White, 1977).

FINITE STRAIN

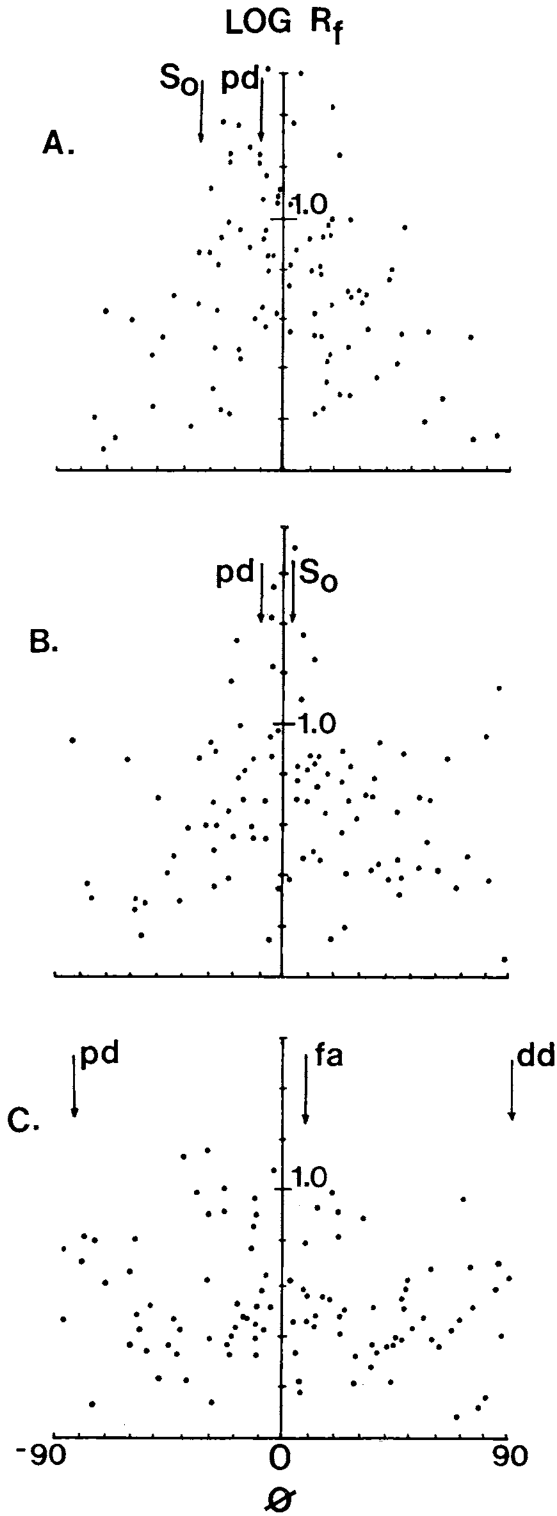
The finite strain in graywacke beds of the Massanutten synclinorium and its relationship to the rough cleavage was investigated by several methods. Principal directions were determined from the geometry of detritial grains and fibrous minerals in beards. Strain ratios and the shortening normal to cleavage were calculated from detrital grain shapes, mesoscopic fold geometry, and deformed pre-cleavage veins.

Principal directions.—Detrital grain shapes were analyzed with the THETA computer program (Peach and Lisle, 1979). Based on the R_f/ϕ technique (Ramsay, 1967; Dunnet, 1969; Lisle, 1977), this program calculates the principal directions and strain ratio from an array of deformed markers. It has an advantage over other R_f/ϕ methods in that it tests, using the χ^2, the assumptions upon which the R_f/ϕ technique is based, namely that the deformation is homogeneous within the grains and matrix and that the undeformed particle orientations were random.

Three mutually perpendicular thin sections were prepared from each sample examined by this technique. The orientations are: parallel to cleavage; normal to cleavage and the fold axis; and normal to cleavage and parallel to the fold axis. These orientations were chosen as a first approximation to the principal planes of finite strain. To illustrate the relationships observed, three samples, one from each limb of the Massanutten synclinorium and one from near the hinge area, were selected (fig. 3,A-G).

In each of the samples examined, the rough cleavage was subparallel to a principal plane of finite strain. In sections normal to the cleavage (fig. 3,A, B, D, E, G, and H), the mode of the R_f/ϕ plot and

Fig. 3. R_f/ϕ plots. R_f is axial ratio of grain; ϕ is angle between long axis and cleavage trace. (A, B, and C) sample 4M from northwest limb of Massanutten synclinorium; (D, E, and F) sample 15M from southeast limb; (G, H, and I) sample 13M from northwest limb, near hinge. (A, D, and G) sections cut normal to cleavage and fold axis. (B, E, and H) sections cut normal to cleavage and parallel to fold axis. (C, F, and I) sections cut parallel to cleavage. S_0—bedding trace; pd—principal direction determined from THETA program; dd—down-dip direction in cleavage plane; fa—fold axis.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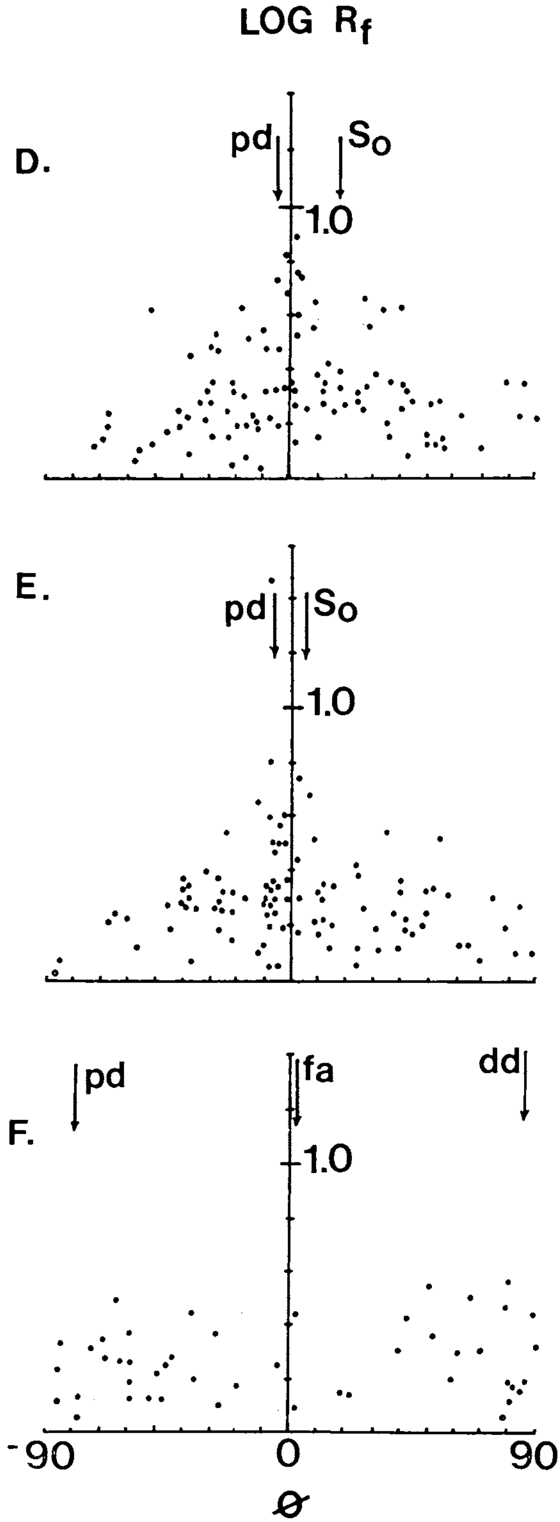
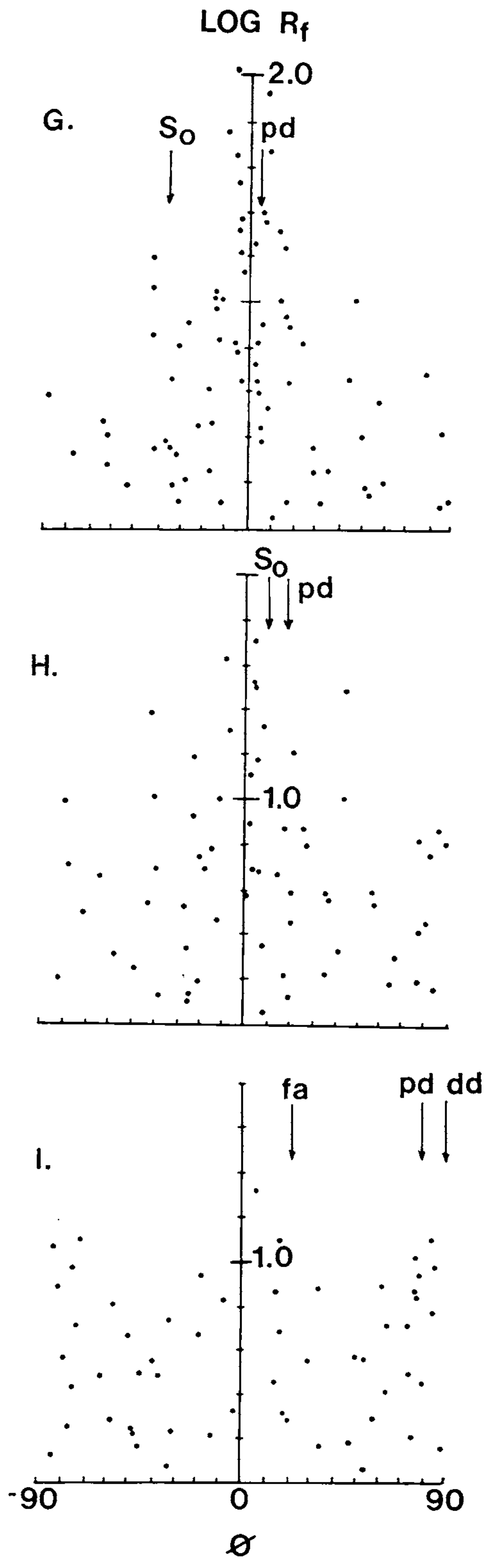


(fig. 3, continued)



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principal direction computed by the THETA program are within 10° of the cleavage trace. In sections parallel to the cleavage (fig. 3,C, F, and I), principal directions are not as well defined on R_f/ϕ plots but are calculated by THETA to be subparallel to the down-dip direction in the cleavage plane.

Mineral fibers in beards and in between segments of pulled-apart grains provide a sensitive record of the strain history. Durney and Ramsay (1973) have shown that fiber long axes are parallel to the extension direction at the time of fiber growth. Straight fibers indicate a coaxial strain history whereas curved fibers record a non-coaxial history.

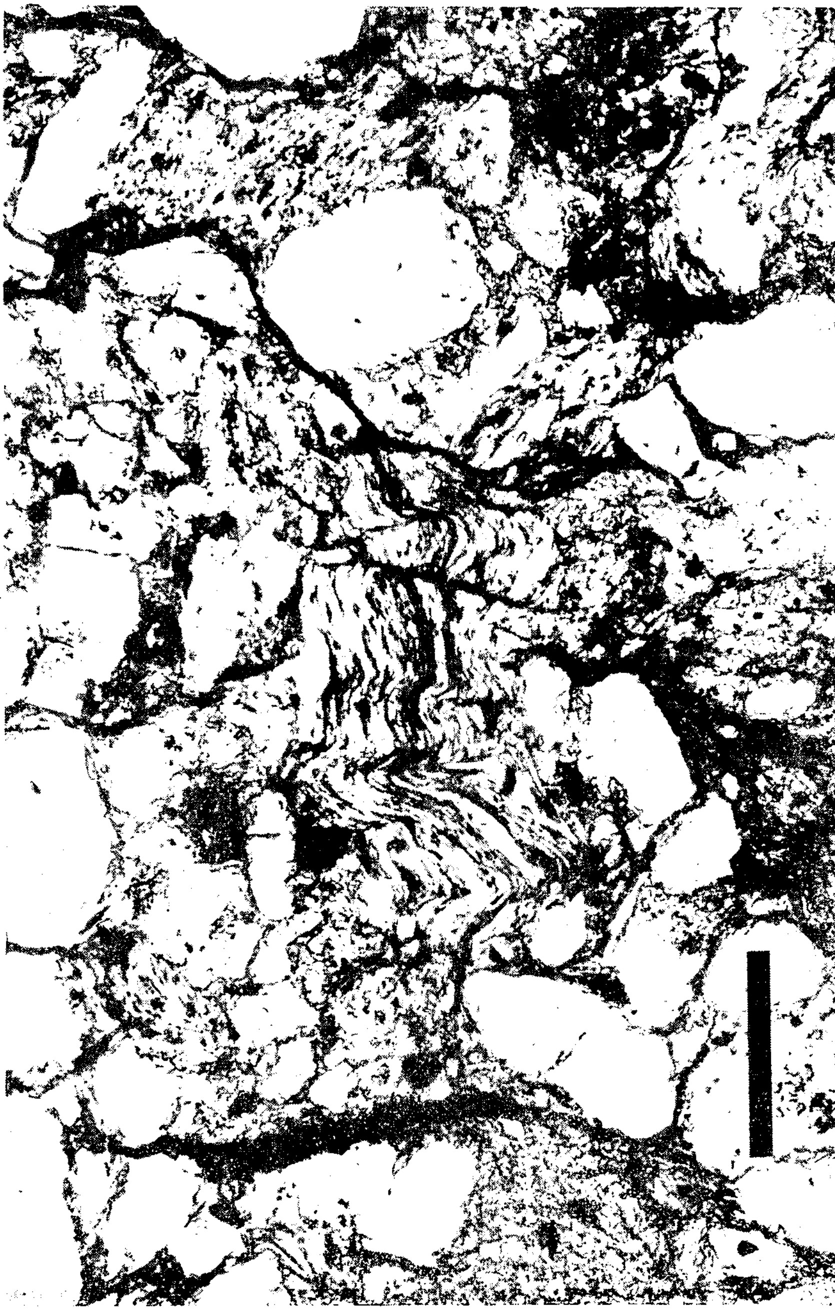
In thin sections normal to cleavage, fibers in beards or in between grain segments are straight and parallel to the cleavage trace (pl. 2). In sections parallel to cleavage, fibers are also straight, but the long axis directions are more variable. In most samples there is a tendency for the long axes to parallel the down-dip direction in the cleavage plane. These relationships show that the cleavage is a principal plane of strain and that the strain history was coaxial during fiber growth and hence, during much of the cleavage formation.

Less sensitive indicators of the principal directions are provided by the geometry of buckled and crenulated rock fragments and pre-cleavage veins. Many foliated rock fragments have been buckled, and some have developed a crenulation cleavage parallel to the rough cleavage in the host graywacke (pl. 3). Pre-cleavage veins have been buckled with the axial surface parallel to the rough cleavage. The geometry of these features is consistent with other strain data and shows that shortening occurred at high angles to the rough cleavage.

Strain ratios.—The amount of shortening normal to cleavage was determined from strain ratios (R_s) calculated by the THETA program. Table 1 shows the strain ratios for the thin sections in figure 3,A to I. Included are the ratios resulting in the lowest χ^2 values along with a range of ratios producing acceptably low χ^2 values at the 90 percent level of significance. In each sample, the highest ratios occur in the sections normal to cleavage and the fold axis. The lowest ratios occur in the sections parallel to cleavage. When the ratios are plotted on a Flinn diagram (Wood, 1974), they fall in the flattening field. The relative magnitude of the strain ratios in the three perpendicular sections, when taken with the fact that these sections approximate the principal planes, shows that the cleavage is subparallel to the λ_1-λ_2 plane of finite strain.

The geometry of mesoscopic folds falls between a parallel and similar style. When measured normal to bedding, the bed thickness is greater in the hinge than on the limbs. Ramsay (1962) attributes the deviation of many folds from a true parallel style to the superposition of homogeneous strain on originally parallel folds. This model appears likely in the Martinsburg, because the rough cleavage is believed to have formed during a phase of homogeneous flattening that followed initial buckle folding. Assuming the folds to be flattened parallel folds and that the flattening was normal to the hinge of the buckle folds, the strain ratio of the flattening can be calculated from the present fold geometry (Ram-

PLATE 3



Rock fragment with crenulation cleavage parallel to rough cleavage (vertical). Scale bar is 0.2 mm. Plane light.

say, 1962). The three folds analyzed yielded ratios of 1.38, 1.59, and 2.50. These values fall within the range of ratios determined from the detrital grain shapes.

Conversion of the strain ratios to percent shortening requires that the amount of volume lost during deformation be known. To illustrate the range of shortening values possible, the strain ratios for sections normal to the cleavage and fold axis were converted to percent shortening for the two limiting cases; where deformation was constant-volume, plane strain and where all deformation was by volume loss. For constant-volume deformation, the shortening values range from 13.5 to 33 percent. For the volume-loss situation, the range is higher and varies from 29 to 55.5 percent. If deformation involved only partial volume loss, the shortening values would fall somewhere in between these two extremes.

Pre-cleavage veins have been buckled and offset along cleavage folia (pl. 4). If it is assumed that the veins were originally planar and that all offset is due to volume loss, the partitioning of shortening between buckling and volume loss can be determined. Twinning strains of the vein calcite were not included but are probably small. All measurements were made in sections perpendicular to the cleavage and fold axis and were normalized to give shortening perpendicular to cleavage where the vein enveloping surfaces were not perpendicular to the cleavage.

Table 2 shows the contributions of buckling and volume loss to the total shortening for seven pre-cleavage veins. With the exception of two veins, shortening due to buckling greatly exceeds that resulting from volume loss. This result is similar to that determined by Gray (1979) who found that the buckling component is 2.5 to 3.8 times that due to volume loss.

The shortening values calculated for the veins are considerably less than those computed from detrital grain shapes, even when deformation of the grains is assumed to have been constant volume. Veins A and B were measured from sample 13M from which the grain shapes were also

TABLE 1

Strain data from R_f/ϕ plots

Sample	R_s (lowest χ^2)	Range of R_s (χ^2 acceptable at 90% significance level)	% Shortening normal to cleavage (using R_s at lowest χ^2) Constant volume	Volume loss
15Ma	1.34	1.15-1.55	13.5	29.0
15Mb	1.26	1.23-1.31		
15Mc	1.20	1.10-1.45		
4Ma	1.95	1.71-2.19	28.0	49.0
4Mb	1.40	1.04-2.03		
4Mc	1.30	none		
13Ma	2.75	1.96-2.89	33.0	55.5
13Mb	2.12	1.92-2.39		
13Mc	1.73	1.67-1.91		

Note: Last letter of sample number corresponds to orientation of section: a — normal to cleavage and fold axis; b — normal to cleavage and parallel to fold axis; c — parallel to cleavage.

analyzed (fig. 3G). Depending on how much volume was lost during deformation, R_f/ϕ data indicate 33 to 55.5 percent shortening whereas the veins yield values of only 15.6 and 16.6 percent. Part of the discrepancy can be explained by the failure to consider twinning strains in vein calcite. Wright and Platt (1982) estimate 10 percent shortening due to twinning in veins from similar settings. The total strain, whether calculated as the sum (Mitra, 1977) or the product (Ramsay, 1967) of the partial strains, would still give a total well below that indicated by R_f/ϕ plots. Apparently, the veins analyzed formed sometime after the onset of deformation and do not record the total shortening.

Volume loss during deformation.—Much recent discussion has centered on the significance of volume loss during deformation (see Ramsay and Wood, 1973; Wright and Platt, 1982). The pelitic portion of the Martinsburg Formation has been the subject of many investigations and opinion on the importance of volume loss during deformation differs greatly. Beutner (1978) proposed that flattening related to the formation of cleavage in Martinsburg slates of the Delaware Water Gap was a constant-volume process. The 62 percent shortening normal to cleavage was accompanied by 163 percent elongation parallel to the cleavage dip. Wright and Platt (1982) argue that shortening associated with the formation of slaty cleavage in Martinsburg shales of central Pennsylvania and further south was accomplished entirely by volume loss. Microstructural evidence in the samples examined indicates that the Martinsburg graywackes falls somewhere between these two extremes; both extension and volume loss accompanied cleavage formation.

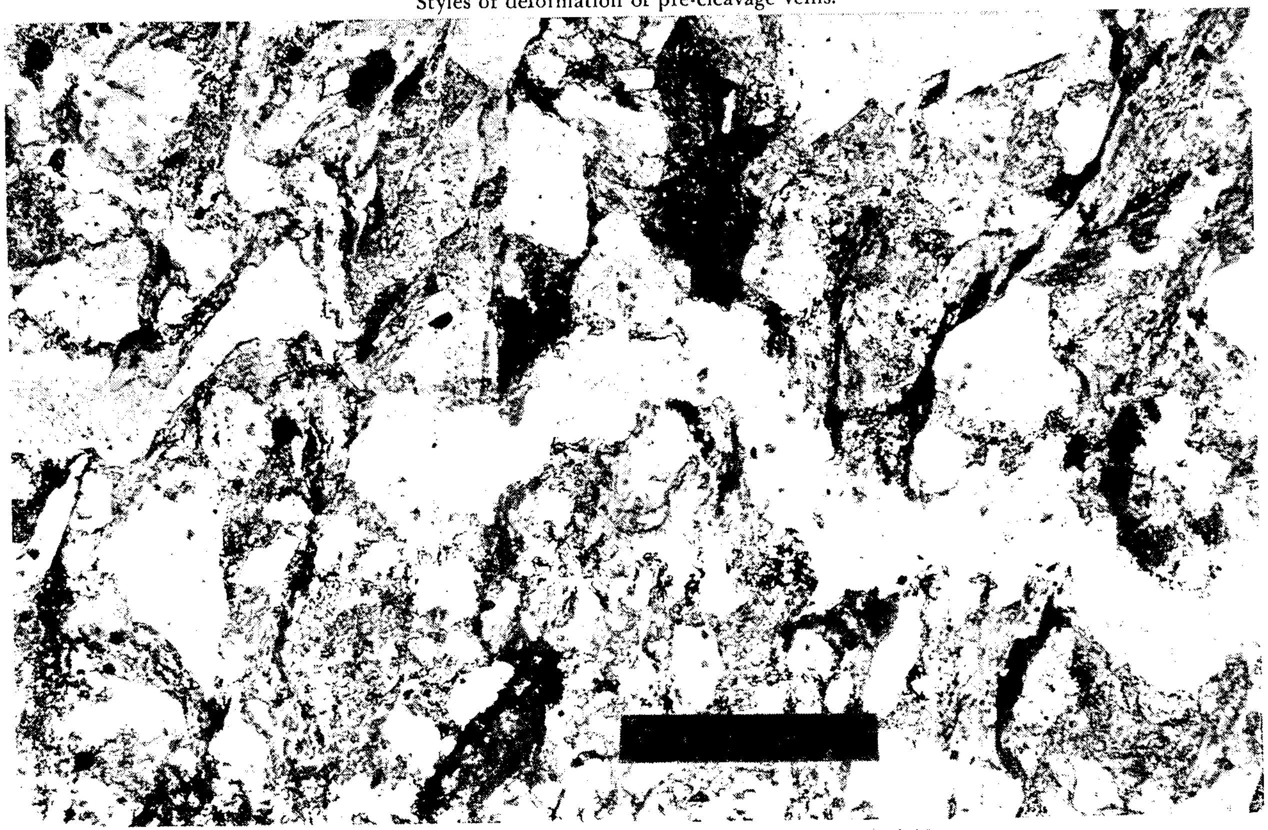
Extension, and hence constant volume deformation, is indicated by pulled-apart detrital grains and fibrous growths in between segments of these grains and in beards. The geometry of the fibers discussed earlier demonstrates that extension occurred mostly parallel to the cleavage dip.

Additional evidence for extension is provided by the geometry of detrital grain shapes and microstructures and by the orientation of syn-cleavage veins. The low χ^2 values computed by the THETA program for most R_f/ϕ plots show that the grains had an initial random orientation and the deformation was homogeneous. Had the deformation been inhomogeneous due to significant volume loss, the χ^2 values would be much higher. The abundant deformation lamellae in detrital quartz grains are a result of intracrystalline deformation, a constant-volume process. Any shape change that occurred by this process would include extension. Finally, syn-cleavage veins which are oriented normal to the cleavage and parallel to the fold axis require extension parallel to cleavage dip.

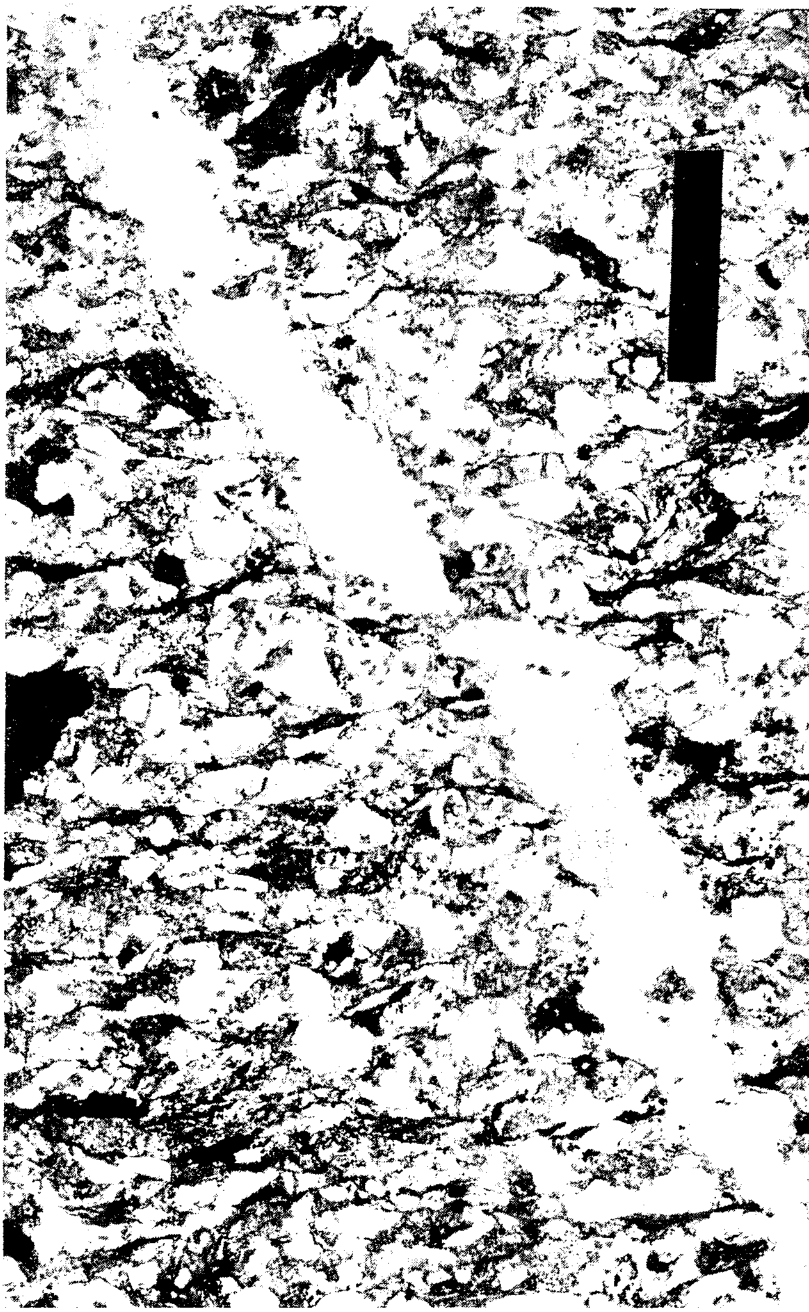
Despite the evidence for extension, some volume must have been lost during deformation. The abundance of features believed to result from pressure solution coupled with the general scarcity of beards and overgrowths indicates that some volume was lost during deformation. Volume loss could also explain the high χ^2 values for some R_f/ϕ plots (see sample 4M, table 1 and fig. 3C). The relationship between the strain ratios in the three principal sections also supports some volume loss. The

PLATE 4

Styles of deformation of pre-cleavage veins.



A. Buckled vein with cleavage parallel to axial surface of folds.



B. Vein offsets along cleavage folia. Sense of offset is consistent with volume loss along cleavage. Scale bar is 0.2 mm in (A) and 0.5 mm in (B). Plane light.

TABLE 2
Shortening values for pre-cleavage veins

	% Shortening normal to cleavage			
Vein	Buckling	Volume loss	Total	Buckling/ volume loss
A	12.6	4.0	16.6	3.15
B	13.6	2.0	15.6	6.80
C	13.7	14.0	27.7	.98
D	19.0	1.5	20.5	12.70
E	14.4	1.6	16.0	9.00
F	13.3	5.2	18.5	2.55
G	6.0	12.3	19.3	.49

Note: Veins A and B are from the same thin section (13 Ma of table 1).

product of the strain ratios in the λ_1-λ_2 and λ_2-λ_3 planes does not equal the ratio in the λ_1-λ_3 plane.

The geometry of deformed pre-cleavage veins provides some insight into the relative importance of volume loss and constant volume processes. With two exceptions, less than a third of the total shortening of the veins in table 2 occurred by volume loss. As far as the deformation of the veins is concerned, constant volume processes are more important than volume loss processes.

VEINS

Veins filled with quartz, calcite, or both are common in many graywacke beds. Cross-cutting relations with other microstructures show that vein formation began before the development of cleavage and continued nearly to the end of penetrative deformation. Based on orientation, type of vein filling, and the age relative to cleavage, three groups were defined: pre-, syn-, and post-cleavage veins.

Veins 0.1 to 0.8 mm thick, filled with strongly twinned calcite characterize the pre-cleavage veins. These veins have diverse orientations (fig. 4) and several show traces of rough cleavage passing through them. Many are buckled and offset along cleavage folia (pl. 4). Where buckled, the cleavage is axial planar to and passes through the vein. Where offset, the sense of offset is consistent with the dissolution origin proposed for the cleavage. Syn-cleavage veins are filled with a combination of quartz and calcite and are oriented normal to the cleavage and parallel to the fold axis (fig. 4 and pl. 5). Compared to the pre-cleavage veins, these veins show relatively minor deformational effects; a few veins are buckled slightly, and the quartz contains only sparse deformation lamellae. Post-cleavage veins cross-cut all other veins along with most other microstructural features. Some post-cleavage veins are nearly parallel to syn-cleavage veins, but most can be differentiated on the basis on orientation (fig. 4). Post-cleavage veins are filled with subhedral to euhedral quartz and calcite that lack any evidence of internal deformation other than some twinning in the calcite. Unlike pre- and syn-cleavage veins, these veins are all planar. The minerals filling veins in each generation have a subhedral to euhedral texture. The grain size generally increases toward the center of the vein.

Pre-cleavage veins developed before most or all of the cleavage and were deformed by shortening associated with continuing cleavage formation. Although this stage of vein formation largely predates the cleavage. shortening data from deformed pre-cleavage veins suggests that some of these veins formed during the initial stages of cleavage development. The viscosity contrast between the veins and the host rock must have been great enough to result in buckling rather than layer-parallel shortening alone. Pressure solution during cleavage formation produced offsets in veins where they crossed the cleavage folia obliquely. Syn-cleavage veins formed during the flattening associated with cleavage. Some formed before all flattening had occurred and were subsequently buckled slightly. Post-cleavage veins cut all other veins, the cleavage, and most other micro-

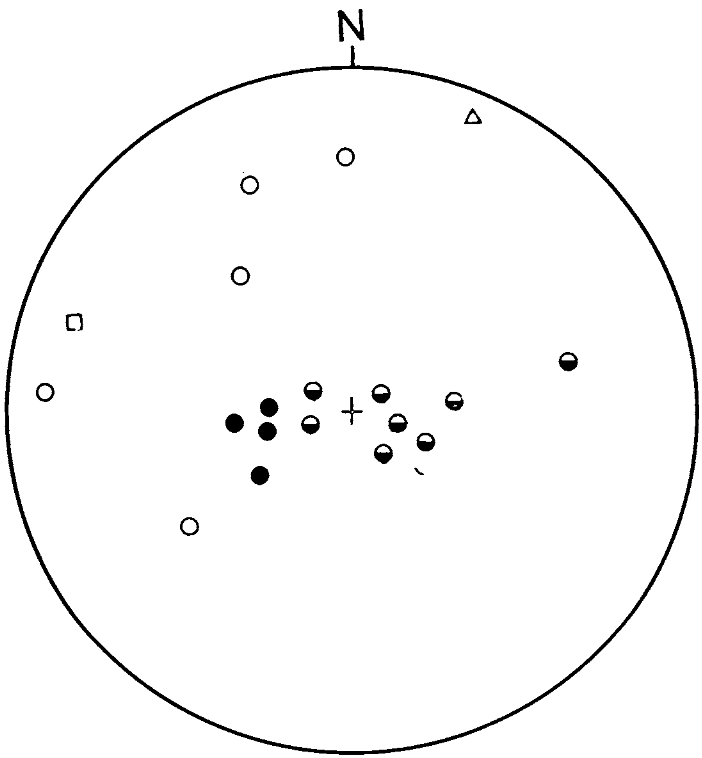
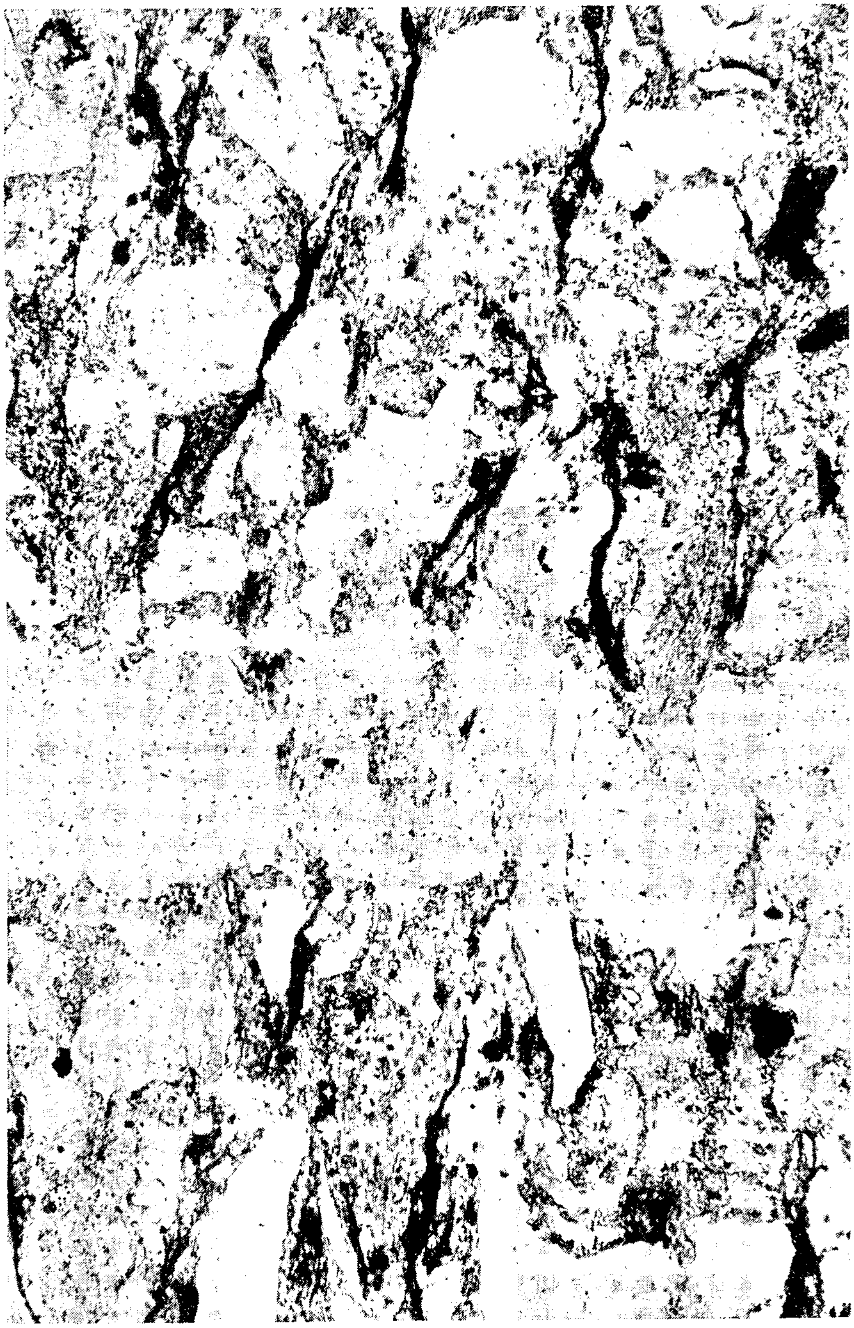


Fig. 4. Equal area plot of vein poles. Open circles are pre-cleavage veins; half-filled circles are syn-cleavage veins; solid circles are post-cleavage veins. Open square is cleavage pole; triangle is Pi axis. Data are from two samples, one from each limb of the Massanutten synclinorium, rotated slightly so that the cleavage in each coincides.

PLATE 5



Syn-cleavage vein. Vein is filled with quartz (clear) and calcite (high relief). Cleavage in wall rock is normal to vein walls. Vein is 0.2 mm wide. Plane light.

structural features. The separation of post- and syn-cleavage veins may be too simple. The similarities in orientation and vein filling suggest that the two may be part of a continuous period of vein formation that began during the development of cleavage and continued nearly to the end of penetrative deformation.

All veins are of dilational origin and are interpreted as filled fractures. The lack of offset across most indicates that extensional fractures were the norm. Extensional fractures are believed to result from hydraulic fracturing (Secor, 1965; Phillips, 1972; Beach, 1977; Ramsay, 1980) indicating that pore fluid pressures remained high throughout much of the deformational history.

The texture of the minerals filling each generation of veins is a product of crystal growth into a fluid-filled cavity during a single increment of dilation (Durney and Ramsay, 1973; Beach, 1977). This differs from the crack-seal mechanism proposed by Ramsay (1980) to explain many if not most extensional veins. The crack-seal mechanism involves filling of the vein by repeated increments of fracturing and sealing with vein minerals. The characteristic fibrous habit of the vein minerals and inclusion trails that result from the crack-seal mechanism were not observed in veins in the Martinsburg graywackes.

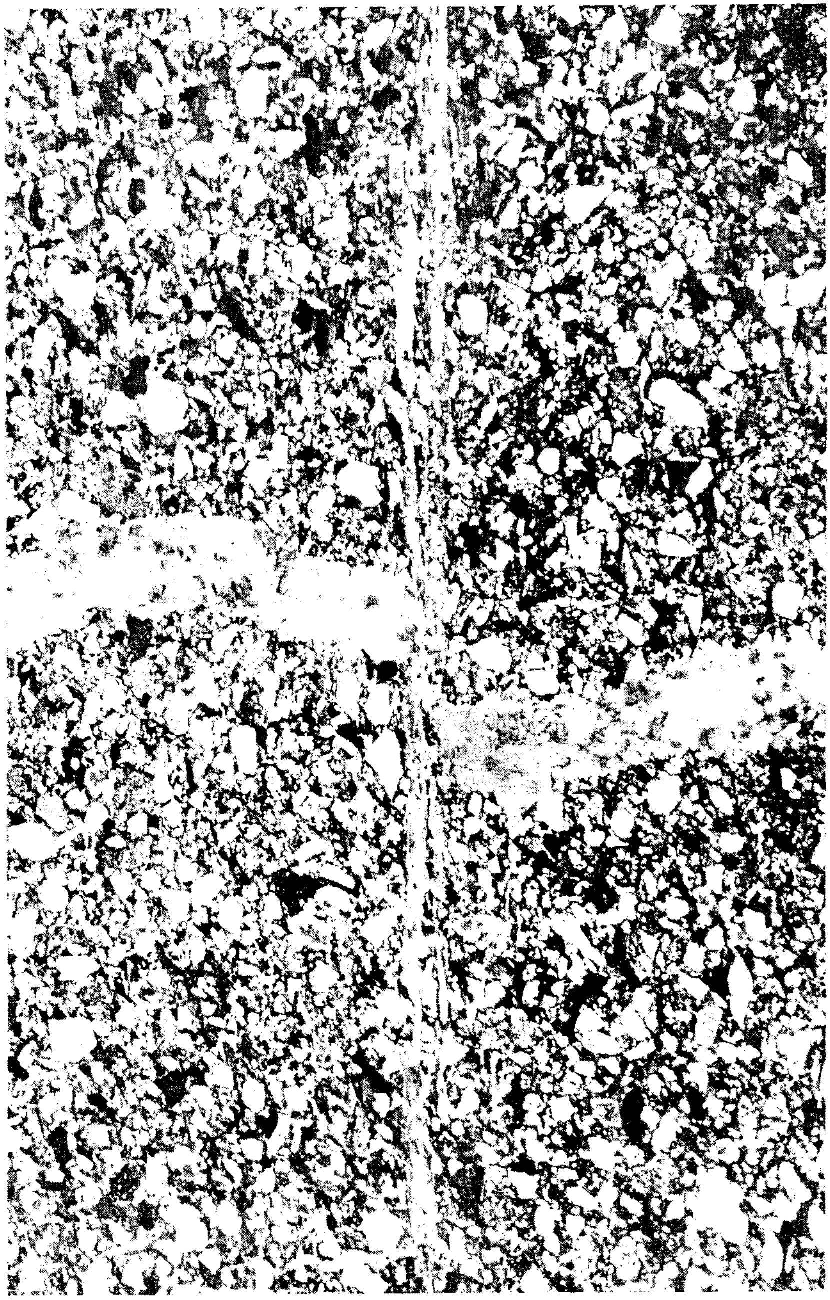
SHEAR ZONES

Planar zones parallel to bedding, 0.5 mm thick, truncate the rough cleavage and offset many veins (pl. 6). These zones have a cataclastic texture consisting of fragments of highly strained detrital grains in a fine grained matrix of polygonal quartz, feldspar, and, less commonly, calcite. The sense of shear determined from the offset of veins reverses from one limb of the Massanutten synclinorium to the other. On both limbs, the rotation sense shows that upper beds moved out of the synclinorium. Observed offset reaches a maximum of about 2 mm on the limbs and decreases progressively toward the hinge.

The cataclastic texture of the minerals in the shear zones and the offset across the zones attest to their origin by shearing. The shearing is believed to result from flexural slip folding. The orientation of the zones parallel to bedding, the reversal of shear sense from one limb to the other, and the general increase in relative motion away from the hinge of the fold attests to this model. The shear zones do not appear to be related to any of the numerous faults in the area for several reasons. (1) The faults have a variety of orientations in any outcrop whereas the shear zones are always parallel to bedding. (2) Both normal and reverse faults can occur in the same outcrop, whereas the sense of shear in the shear zones is predictable by location on the fold. (3) The amount of relative movement across the shear zones is greatest on the limbs of the Massanutten synclinorium. No such relationship was observed for the faults.

Shear strain resulting from flexural slip is often localized within beds rather than on bedding surfaces alone. Kuenen and deSitter (1938) produced discrete shear zones parallel to bedding within thick, homoge-

PLATE 6



Bedding-parallel shear zone offsetting syn-cleavage vein. Shear zone consists of sheared and recrystallized wall rock. Cleavage dips gently to left. At right margin, shear zone is 0.5 mm wide. Plane light.

neous clay slabs during folding experiments. Shear zones remarkably similar to those described here are figured in Ramsay (1967, fig. 7-59). These zones occur in graywacke and offset tension fissures identical in appearance to the syn-cleavage veins of this report. Ramsay attributed the shear zones to intense shear strain during flexural slip.

The deviation of the rough cleavage from a perfect axial planar attitude could be a result of this flexural slip movement. If the cleavage originally formed parallel to the axial plane, additional limb rotation by flexural slip could result in a convergent fan similar to the one defined by the rough cleavage. Although the shear zones were found in many samples and some rotation of the cleavage may have occurred during their formation, these features represent only a minor contribution to the total deformation in the area.

KINK BANDS

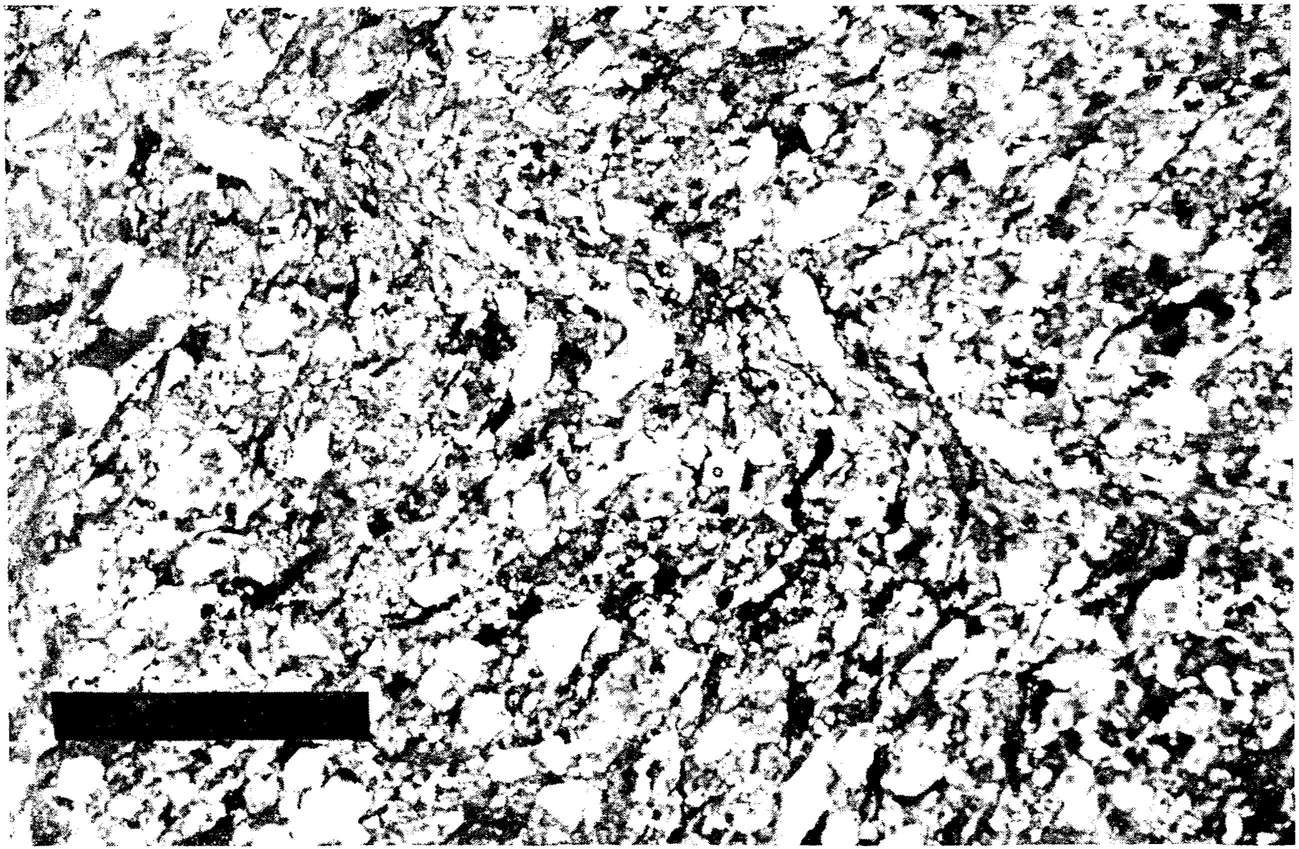
The youngest penetrative microstructural features are kink bands. These are most noticeable in the rough cleavage, but at least one kinked vein was observed. The age of these structures relative to the shear zones must be inferred as the two were never observed to intersect. Whereas some veins cut the shear zones, none were seen to cut the kink bands. Therefore, the kink bands are assumed to be younger than the shear zones.

All but one example of the kink bands occur on the northwest limb of the Massanutten synclinorium. These structures consist of angular folds with interlimb angles of 120° to 150° confined to tabular zones 1 to 3 mm wide, many of which taper to terminations within the area of a thin section (pl. 7). The bands are widely spaced with most thin sections rarely containing more than one. Deformation of detrital grains in the hinge areas often occurs in an abrupt manner. Single grains are fractured, bent, and strongly recrystallized. A weak rough cleavage is developed parallel to some of the wider bands creating a trapezoidal cleavage fabric where it intersects with the primary rough cleavage. Where the kink bands are closely spaced, the fabric resembles crenulations and second generation rough cleavage in psammites from southeast Australia (Gray, 1978).

Kink bands develop in rocks with a well developed layering (Ramsay, 1967). It is surprising to find these structures within homogeneous graywacke beds. In addition, the acute angle between the kink bands and layering (bedding) is difficult to reconcile with the experimental work of Patterson and Weiss (1966) who showed that kink bands generally develop at moderate angles to layering. These problems are overcome if the cleavage, not bedding, provided the anisotropy necessary for kink folding. With this in mind, the gentle southeast dip and the west-over-east rotation sense of the kink bands indicate shortening parallel to the cleavage in a near-vertical direction.

The kink folds have the wrong asymmetry for being minor folds on the northwest limb of the Massanutten synclinorium. This, along with the fact that they deform the cleavage and probably post-date the shear

PLATE 7



Kink fold in rough cleavage. Kink band dips steeply to right diagonally across photo. In polarized light, bent quartz grain in center of photo can be seen to consist of a network of polygonal grains resulting from recrystallization. Scale bar is 5.0 mm. Plane light.

zones indicates that they are unrelated to the earlier folding and flattening. Although kink bands are not a major component of the total strain, they are indicative of polyphase folding in the Martinsburg Formation. This is believed to be the westernmost occurrence of polyphase folding in the central Appalachians.

SUMMARY AND CONCLUSIONS

A four-phase deformational history is proposed to account for the microstructural features present in graywacke beds of the Martinsburg Formation. The separation of this history into phases is for convenience only; these phases are probably all part of a single progressive deformation that occurred during the Appalachian orogeny.

Phase I — buckle folding.—Phase I involved layer-parallel shortening and buckle folding (fig. 5A). This phase was largely responsible for the formation of the Massanutten synclinorium. Tectonic deformation in many folded sedimentary sequences begins with layer-parallel shortening that is followed or accompanied by buckling (Sherwin and Chapple, 1968). The relative importance of each process is a function of the viscosity contrast in the layers being deformed (Hobbs, Means, and Williams, 1976). A high ratio would favor buckling over layer parallel shortening, whereas a low ratio favors shortening. From this, it would appear that the interbedded shale and graywacke in this part of the Martinsburg Formation would lead to a relatively small amount of layer-parallel shortening in the graywacke beds; therefore, this phase is assumed to have been dominated by buckling. The strong mechanical anisotropy would favor folding by flexural slip. Slickensides on bedding surfaces oriented normal to the fold axis may have formed at this time.

Before or during buckling, calcite veins began to develop from fractures. Calcite filling these veins could have been derived from pressure solution in the graywacke and shale beds or from the underlying Cambro-Ordovician carbonates.

Phase II — flattening and cleavage formation.—Phase II was the most important as far as the development of microstructures in the graywacke is concerned. Homogeneous flattening of Phase I buckle folds modified their shape and resulted in the development of rough cleavage parallel to the plane of flattening (fig. 5B). That the cleavage developed after most of the finite amplitude folding is shown by the nearly constant cleavage orientations, coaxial strain history recorded by mineral fibers, and the subparallelism of the cleavage to the λ_1-λ_2 plane of finite strain.

The limited amount of cleavage fanning across folds is difficult to reconcile with cleavage development before much folding, especially in light of the straight mineral fibers in beards and between separated detrital grains. Had the cleavage developed before or during the early stages of folding, it would have been rotated into a strong fan. Rough cleavage in siltstones of the Bloomsburg Formation, 30 km west of the study area, is believed to have formed before folding, during layer-parallel shortening (Geiser, 1974). Now, it is everywhere normal to bedding and defines a strong convergent fan.

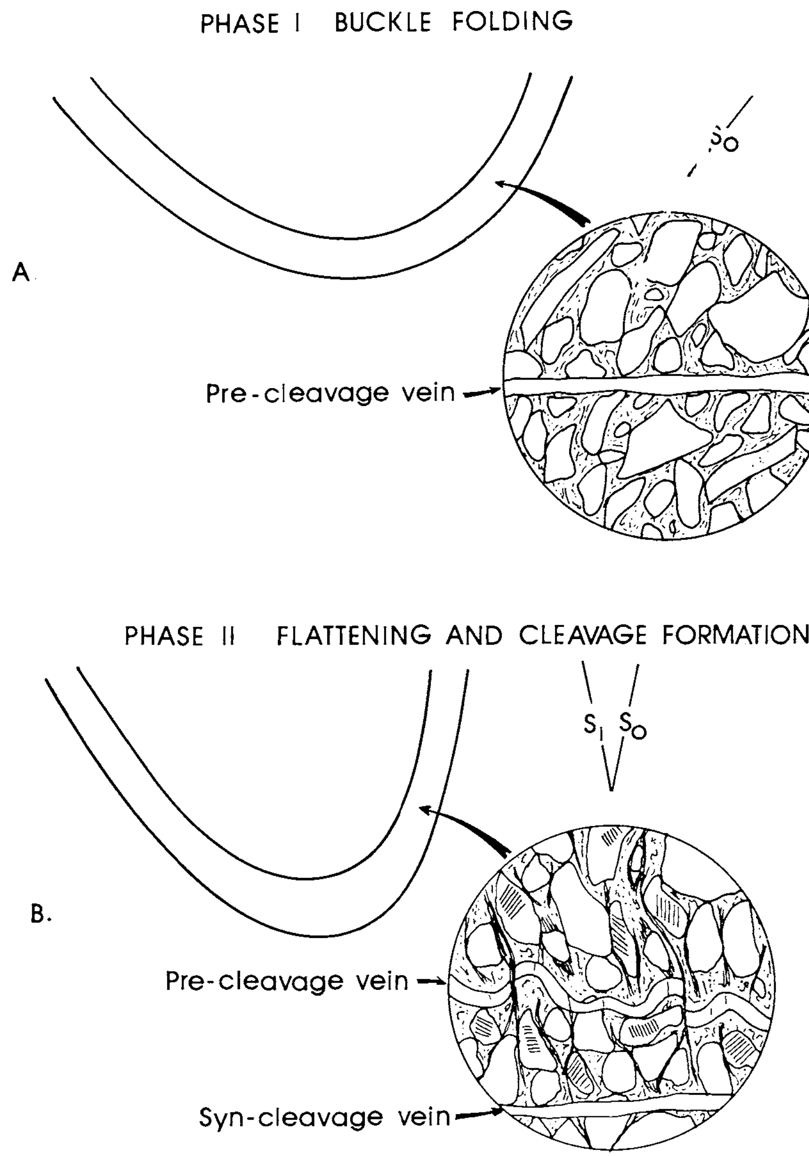
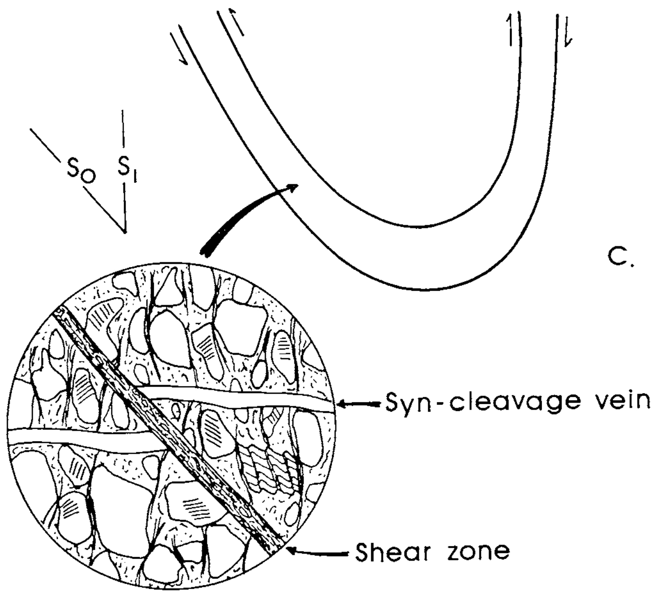


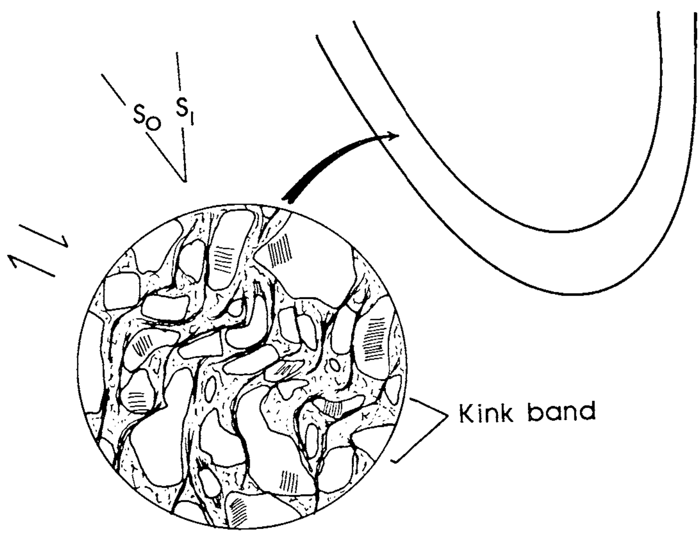
Fig. 5. Deformational history of Martinsburg graywackes based on microstructural features.

PHASE III POST-CLEAVAGE FLEXURAL SLIP



C.

PHASE IV KINK FOLDING



D.

According to Williams (1976), cleavage defined by discontinuities (for example, rough cleavage) will be parallel to the λ_1-λ_2 plane of finite strain in both limb and hinge areas only if it develops entirely during homogeneous flattening that follows buckling. Williams also argues that it is unlikely that cleavage defined by discontinuities would track the λ_1-λ_2 plane through a non-coaxial strain history. As the cleavage in the Martinsburg is subparallel to the λ_1-λ_2 plane and a coaxial strain history is indicated, it would appear then that the rough cleavage developed after folding and during flattening.

Huddleston (1973) pointed out that flattening may be simultaneous with buckling and not separated from it in time. He argued that each process is favored by a different competency contrast between layers and separating the two processes in time would require that the competency contrast change during deformation. Rather than a change in the competency contrast, it is possible that flattening is initiated late in the deformation as a geometrical consequence of the developing folds. Beutner (1978) proposed that the slaty cleavage in the pelitic portion of the Martinsburg developed after folding during flattening. Flattening became the dominant process when limb rotation had progressed to the point where it was necessary to force material out of fold cores.

The flattening during which the rough cleavage developed was accomplished by a combination of pressure solution of the more soluble components, intracrystalline deformation of detrital grains, and a limited amount of crystallization or recrystallization. Both volume loss and extension in the cleavage parallel to dip occurred at this time. Shortening associated with the cleavage formation is estimated to be between 13.5 and 55.5 percent, depending on how much volume was lost. Stress orientations determined from quartz deformation lamellae and twinned calcite in syn-cleavage veins indicate that the cleavage developed normal to the maximum compressive stress (Onasch, 1981, 1982).

In addition to the cleavage, extension fractures, now veins of quartz and calcite, formed normal to the cleavage and parallel to the fold axis. Some of the veins formed early enough during this phase that they were buckled slightly by the waning stages of flattening.

Phase III—Post-cleavage flexural slip.—Cataclastic shear zones parallel to bedding whose rotation sense reverses on opposite fold limbs formed during Phase III as a result of a minor amount of flexural slip folding (fig. 5C). Further tightening of the folds by flexural slip and consequent limb rotation may account for or contribute to the deviation of the rough cleavage from a true axial planar attitude.

The flexural slip is believed to represent the waning stages of the coaxial shortening that began in Phase I. The change in deformational mechanism from flattening the flexural slip could have been brought about by a decrease in pressure or temperature or by an increase in the strain rate.

Extension fractures, now quartz and calcite veins, which began to develop during Phase II, continued to form throughout this phase. Limb rotation or a change in the stress orientations resulted in fractures increasingly discordant with syn-cleavage veins.

Phase IV — kink folding.—The youngest microstructural features are kink bands (fig. 5D). These structures occur primarily on the northwest limb, where they dip to the southeast at angles less than bedding. Their orientation and rotation sense indicates that layering, which probably was the cleavage microlithons rather than bedding, was shortened parallel to itself in a near-vertical direction. Despite the relatively small amount of deformation associated with the kink folds, they deform the rough cleavage and thus indicate the area was affected by polyphase folding.

Structures formed during this phase of the deformational history also appear to represent a major reorientation of the incremental strain geometry. Whereas the first three phases could have all developed in response to a subhorizontal, northwest-southeast shortening, Phase IV indicates a near-vertical shortening. The strain geometry suggests that the kink bands are unrelated to all other structures.

The microstructures in the graywacke beds of the Martinsburg Formation indicate a structural history far more complex than is suggested by the mesoscopic structures. This points out the need for the incorporation of microstructural studies in all structural investigations.

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