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STRAIN AND PRESSURE SOLUTION IN THE MARTINSBURG SLATE, DELAWARE WATER GAP, NEW JERSEY

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ABSTRACT. The cleavage in a silty sample of the Martinsburg slate from the Delaware Water Gap consists of micaceous cleavage laminae with quartz-rich zones between the laminae. Quartz grains adjacent to the cleavage laminae show abrupt truncations, interpreted to be the result of pressure solution, whereas quartz grains between the laminae remain relatively equant. Pressure shadows indicate the mobility of the quartz and local redeposition. The cleavage laminae are interpreted to be the low mobility components of the rock remaining after pressure solution of the quartz. The orientations of the well-known sandstone dikes, which are approximately parallel to the cleavage plane, can be interpreted as owing their orientation to strain rather than to soft-state injection parallel to the cleavage. The compressive strain normal to the cleavage has been estimated from the shortening of nearby minor folds to be within the range of —40 to —75 percent. The strain required to deform a sandstone dike from an original orientation normal to bedding to its present orientation nearly parallel to the cleavage is —63 percent by either simple shear parallel to bedding or by pure shear with compression normal to cleavage. Both strain models give virtually the same principal axis directions. Thus the strain independently estimated from the folds is sufficient to deform the sandstone dike into its present orientation. Strain and pressure solution together can explain the microscopic fabric and the cleavage-sandstone dike-bedding geometric relationships within the Martinsburg slate.

INTRODUCTION

The hypothesis of Maxwell (1962) that the cleavage in the Martinsburg slate is the result of soft-state deformation has stimulated a considerable body of discussion. Carson (1968) and Alterman (1973) have supported Maxwell in subsequent studies of the Martinsburg slate, and a number of others have adopted this theory, in some cases with modifications, as the explanation for the origin of the slates in other areas (Moench, 1966, 1970; Powell, 1969, 1972a, b, 1973; Braddock, 1970; Clark, 1970; Ross and Barnes, 1975; Davies and Cave, 1976). Others have questioned the hypothesis (Epstein and Epstein, 1969; Williams, 1972; Epstein, 1974; Boulter, 1974; Geiser, 1975; Holeywell and Tullis, 1975). Deformation during soft-state dewatering cannot be a general explanation for slaty cleavage, because, as pointed out by Wood (1974), distorted but originally relatively rigid fossils are common and because cleavage is present in igneous and retrograde metamorphic rocks as well.

It has also been suggested that the cleavage in the Martinsburg slate is principally the result of aligned grain growth during metamorphism (Epstein and Epstein, 1969). The most recent analyses of the mineralogy (Epstein, 1974; Holeywell and Tullis, 1975) show scattered chlorite crystals with muscovite as the dominant mica. Holeywell and Tullis (1975) indicate that recrystallization, perhaps associated with pressure solution, could account for the grain fabric. The conodont alteration color indicates that the rock has been heated to about 200°C (Epstein, 1974;

Epstein, Epstein, and Harris, 1975). Farther north, in the Hudson River Valley, whole rock K-Ar ages of the equivalent Hudson River Pelite suggest temperatures high enough for argon loss but too low for visible metamorphism (Long, 1962).

Bulk strain that is penetrative to the scale of the individual grain has been postulated as the cause of grain orientations in many slates (Wood, 1974). The grains rotate during the deformation such that their long dimensions become oriented perpendicular to the maximum shortening direction. This mechanism can produce a mineral orientation in either hard-rock or soft-state deformation. However, Holeywell and Tullis (1975) have shown that this mechanism alone cannot explain the mineral orientation in the Martinsburg slate at Lehigh Gap because the muscovite and chlorite were not affected equally.

This paper investigates the hypothesis that the geometric effects of the bulk strain, together with pressure solution as one of the deformation mechanisms, can explain the fabric of the Martinsburg slate. The near-parallelism of sandstone dikes and cleavage in the Water Gap, often cited as evidence for soft-state cleavage formation (following Maxwell, 1962) can be explained quantitatively in terms of the bulk strain measured previously in the same area. Insofar as this strain is penetrative on the grain scale, it must also cause grain rotations. A brief literature review reveals that fissility in shale is the result of planar grain alignment and is commonly interpreted as being caused by grain rotation during the bulk strain associated with compaction. Evidently grain rotations associated with bulk strain need not result in a rock described as slate. Evidence is presented to show the importance of pressure solution in the formation of the Martinsburg slate. Perhaps solution (or diffusion) and redeposition is the mechanism that makes the difference between fissile shale and slate.

STRAIN

It is now well-known that the cleavage planes in many slates are essentially perpendicular to ε_1, the maximum principal compressive strain axis (Wood, 1974). The available evidence suggests that this may also be true for the Martinsburg slate in the Delaware Water Gap area. The shape of a deformed trilobite (fig. 1) is consistent with shortening perpendicular to the cleavage. The fossil is from the Hamilton Group, stratigraphically above the Martinsburg, but within the same belt of slaty rocks. The well-known minor folds in the Water Gap near Belvidere, about 7 km south of Columbia (Maxwell, 1962, p. 290), have axial surfaces nearly parallel to the cleavage and indicate shortening perpendicular to the cleavage. The strain normal to cleavage (Maxwell, 1962, p. 291), computed by comparing the curved-bed length of the folded layers to the straight-line length, is about −40 percent (compression is negative). This value assumes that there was no volume change or layer-parallel shortening in the folded layers. If the layer-parallel shortening strain predicted for the buckling of a linearly viscous layer is included, the strain normal

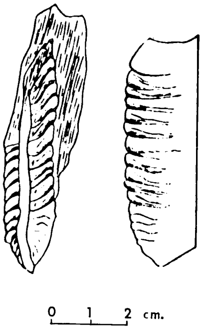


Fig. 1. Two views of a trilobite (*Phacops* sp.) from the Carbon County slate district of Pennsylvania, distorted by the compression that developed the cleavage (from Behre, 1933: used with permission of Pennsylvania Geol. Survey). The trace of cleavage on bedding is represented by the short lines nearly parallel to the long dimension of the fossil in the plan view.

to cleavage is −75 percent (Sherwin and Chapple, 1968, p. 177). Both the folds and the sandstone dike used in later strain calculations are exposed in sections normal to strike.

The range of −40 to −75 percent strain is considered to be a reasonable estimate of the minimum and maximum values of ε_1. The maximum strain in any direction is ε_1, so that if the enveloping surfaces (Ramsay, 1967) of the folded layer were not precisely parallel to ε_1, the given values would underestimate the strain. If the rheology of the folded layer were nonlinear, the layer-parallel shortening could be much smaller (Fletcher, 1974), thereby reducing the maximum value but not affecting the minimum estimate. If the folded layer suffered a volume loss, then both the given values would underestimate ε_1. Ramsay and Wood (1973) have shown that homogeneous strain including volume loss changes the strain magnitudes normal to ε_1. However, the probable volume loss normal to cleavage in the slate should be accommodated mainly by buckle shortening in the folded layer, so volume loss in the slate should not affect the estimate of ε_1 from the folded layer.

STRAIN AND CLASTIC DIKE ORIENTATION

The Martinsburg slate in the Delaware Water Gap contains sandstone dikes that are approximately parallel to the cleavage. The hypothesis to be examined here is that the dikes owe their present orientation to the strain. Nearly any given set of original angular relationships between bedding, sandstone dikes, and cleavage can be deformed into the present configuration by a wide variety of strain paths. In this section, a geologically reasonable original orientation for the angle between the sandstone dikes and bedding is chosen. Two mechanically reasonable models of the strain are selected, and the strain required to deform the original dike-bedding angle into the observed angle is computed. The computed strain is found to be within the range of the observed strain described in the previous section.

For the purpose of argument and for an order-of-magnitude strain calculation, it is adequate to assume that the clastic dikes were originally perpendicular to bedding. Although this orientation is certainly not universal in nature, it is common in many of the published examples of less deformed rocks (Shrock, 1948; Dzulynski and Radomski, 1956; Conybeare and Crook, 1968; Truswell and Ryan, 1969; Truswell, 1972; Thomson, 1973; Dionne and Shilts, 1974) and is mechanically expected in nearly horizontal sediments in which σ_1, the maximum compressive stress, is vertical and caused by the weight of the overburden. It is recognized that the strain computed using this original configuration may not be a perfectly accurate representation of the true strain, even if the assumed nature of the deformation is correct, but it should be accurate enough to assess the hypothesis that the angles between the dikes, cleavage, and bedding could be caused by the observed strain.

Folds in the Delaware Water Gap area show a regular relationship between wavelength and layer thickness, a feature characteristic of buckle folding produced by loading approximately parallel to the layering. The sandstones of the Martinsburg appear to be more competent (stiffer) than the shale (now slate) that surrounds the sandstone dikes. Considered here are two strain models that are consistent with the strain developed in pliant (incompetent) layers during buckle folding. The first is simple shear parallel to bedding, and the second is pure shear with ε_1 perpendicular to the final cleavage orientation. Simple shear parallel to bedding should approximate the strain in the pliant layers of a multilayer sequence (for example, Dieterich, 1970, p. 476). Pure shear with ε_1 perpendicular to the (axial plane) cleavage approximates the deformation within any of the layers, if material property contrasts are small (for example, Dieterich, 1970, p. 474). The two strain models are viewed as end member possibilities in the buckle fold context but are, of course, only two of an infinite number of possibilities. The other possibilities are likely to be more complex but, if stated explicitly, could also be used for computations. The pure shear model has been used by Borradaile and Johnson (1973) for somewhat similar strain calculations, and Boulter (1974) has demonstrated the effect of pure shear on the angle between inclined dikes and cleavage.

The example of a sandstone dike from the Delaware Water Gap illustrated by Maxwell (1962, his fig. 4A) was measured directly on the figure to obtain the angles needed in the computations to follow. The dip of bedding is 30°, cleavage dips 20° more steeply than bedding, and the sandstone dike dips 3° more steeply than cleavage. Slight differences in these angles will generally not greatly affect the computations with the exception that the computed simple shear is quite sensitive to the angle between the dike and cleavage.

Simple shear parallel to bedding.—If an original marker perpendicular to bedding is deformed by simple shear parallel to bedding, the finite shear strain, γ, is

$$\gamma = \tan \psi \tag{1}$$

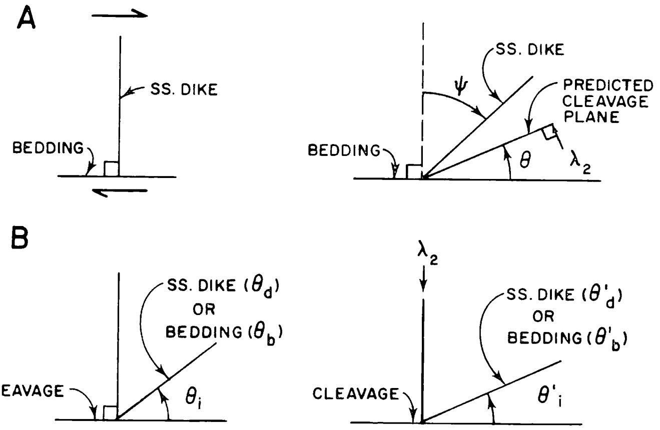


Fig. 2. Geometric elements for strain calculations, undeformed on left, deformed on right. A. Simple shear strain parallel to bedding. The short straight arrow is λ_2. B. Pure shear strain with maximum compressive strain perpendicular to cleavage.

where ψ is the angle of shear (fig. 2A; and Ramsay, 1967, p. 53). The principal quadratic elongations associated with this shear strain are

$$\lambda_1 \text{ or } \lambda_2 = \frac{\gamma^2 + 2 \pm \gamma(\gamma^2 + 4)^{1/2}}{2} , \tag{2}$$

where λ_1 is the maximum extension (>1.0) and λ_2 is the maximum shortening (<1.0) following Ramsay (1967, p. 85). Note that as defined in this paper the ε_1 axis is parallel to λ_2. The angle between the normal to λ_2 and the plane of shear (θ in fig. 2A) is found from

$$\tan \theta = \frac{\gamma}{1 + \gamma^2 - 1/\lambda_1} \tag{3}$$

(Ramsay, 1967, p. 87).

For the sandstone dike example from the Delaware Water Gap cited by Maxwell, the angle ψ is 67° which leads to $\lambda_1 = 7.42$, $\lambda_2 = 0.13$, and $\theta = 20.17°$. Using the relationship between the quadratic elongation and the strain ε_1, figured as the change in length divided by the original length (Ramsay, 1967, p. 52), ε_1 is −63 percent (fig. 3A). This value is corrected from that given in a preliminary report of results (Groshong, 1974). In Maxwell's example the cleavage is 20° from the bedding. Thus, the computed cleavage direction differs from the observed direction by less than two-tenths of a degree.

Pure shear perpendicular to cleavage.—From an equation given by Ramsay (1967, p. 67) for pure shear strain

$$\tan \theta'_i = \tan \theta_i \, (\lambda_2/\lambda_1)^{1/2} \tag{4}$$

where θ_i is the angle between the λ_1 axis and the plane of interest before

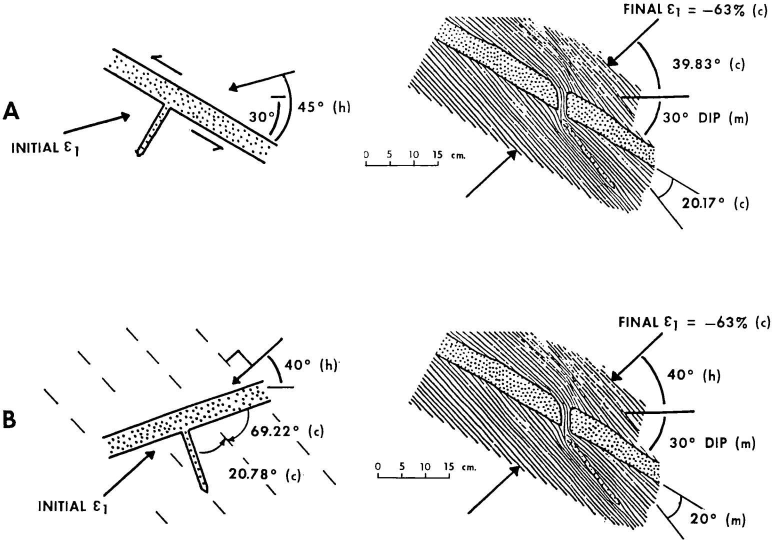


Fig. 3. Possible strain histories producing 23° bedding to sandstone dike angle from an original right angle: undeformed state on left, deformed state on right. The right-side figures are after Maxwell (1962, his fig. 4A). The symbol (c) represents a computed value, (h) an hypothetical value, and (m) a measured value. A. Simple shear parallel to bedding. The postulated strain does not alter the dip of bedding from the initial to the final state. B. Pure shear with the maximum compressive strain axis (ε_1) normal to cleavage. The initial configuration is inferred from the assumption of irrotational strain; the cleavage does not rotate, but both bedding and the dike do rotate. This strain model requires the direction of bedding dip to reverse during deformation, considered unlikely.

deformation, and θ'_i is the corresponding angle after deformation (fig. 2B). For zero volume change $\lambda_1 = 1/\lambda_2$ and from (4)

$$\lambda_2 = \frac{\tan \theta'_i}{\tan \theta_i} \tag{5}$$

From the deformed geometry (fig. 2B) and (5) we can write

$$\lambda_{2d} = \frac{\tan \theta'_d}{\tan \theta_d} \text{ and } \lambda_{2b} = \frac{\tan \theta'_b}{\tan \theta_b}$$

where λ_{2d} is the strain associated with the angle change of the sandstone dike, and λ_{2b} is the strain associated with the angle change of bedding.

In this case $\lambda_{2d} = \lambda_{2b}$, hence

$$\frac{\tan \theta'_d}{\tan \theta_d} = \frac{\tan \theta'_b}{\tan \theta_b} \, . \tag{6}$$

If the original angle between the sandstone dike and bedding ($\theta_b + \theta_d$; see undeformed state, fig. 3B) is known, then (6) can be solved for θ_d. For the situation of interest $\theta_b + \theta_d = 90°$: $\tan \theta_d = \tan (90 - \theta_b) = 1/\tan \theta_b$. Substituting this relationship into (6)

$$\tan \theta_d = \left(\frac{\tan \theta'_d}{\tan \theta'_b} \right)^{1/2} \tag{7}$$

For the same example from Maxwell (1962) $\theta'_d = 3°$, $\theta'_b = 20°$. Using (7) we find $\theta_d = 20.78°$, $\theta_b = 69.22°$, and from (5) we find $\lambda_2 = 0.14$, or $\varepsilon_1 =$ 63 percent (fig. 3B). Note that if θ' for either bedding or the sandstone dike were zero, equation 7 could not be solved. This means that irrotational strain alone cannot explain a dike orientation exactly parallel to cleavage unless the dike initially happened to be perpendicular to ε_1.

Discussion.—The fact that the strain computed from the sandstone dike-cleavage-bedding geometry falls within the range inferred from the minor folds is interpreted here as confirmation of the concept that these geometric relationships could be caused by strain. The accuracy of the computed magnitude of the strain (63 percent) depends upon whether the sandstone dike was originally exactly perpendicular to bedding. Small variations in the original angle will, however, cause only small variations in the final result.

The agreement between the observed cleavage direction and the simple shear prediction is geologically significant, although at large strains the probability is great that the simple shear model will at least approximately predict the cleavage orientation regardless of whether the model is correct. Given that the cleavage plane is within the acute angle between the bedding and the dike and the assumption that the cleavage is perpendicular to ε_1, then at large strains (small bedding-dike angles) the range of possible orientations for the cleavage is small, and the simple shear model will approximately predict the orientation. Any simple shear strain is equivalent to a pure shear plus rotation so that if the simple shear model fits the observations, the magnitude of the pure shear strain will be the same. This explains the agreement between the results of the two calculations. At small strains the simple shear model is unlikely to predict the cleavage orientation, unless it is, in fact, the correct model. The pure shear model will always fit the bedding-dike-cleavage angular relationships, because the computation is based upon these relationships.

Clastic dikes that are not parallel to cleavage are observed in the Martinsburg and other slates. Geiser (1975) has measured the angles between poles to clastic dikes and cleavage in the Martinsburg slate near New Paltz, N.Y. He found that the difference averaged 14°. Wood (1974) points out that the sandstone dikes in the Siamo slates of Michigan deviate up to 50° from the slaty cleavage. This lack of parallelism can also be understood in the context of the strain. If the strain is small or if the dike has the proper original orientation, it need not end the deformation parallel to cleavage.

Thus, a variety of strain histories can explain clastic dikes that are parallel (or not parallel) to the cleavage. The parallelism of clastic dikes and cleavage is not sufficient evidence to conclude that the cleavage and the dikes were both caused by soft-state deformation. Regardless of how the cleavage was formed, the large strain suffered by the rock and the effect of this strain upon the angles between cleavage, dikes, and bedding must be included in a complete explanation of the origin of the cleavage.

SOFT-STATE DIKE INJECTION, GRAIN ROTATION AND RELATION TO CLEAVAGE

On the basis of their characteristic sedimentary structures, the sandstone beds in the Martinsburg have been interpreted as turbidites (Van Houten, 1954; McBride, 1962). Clastic dikes produced by soft-state injection are known in other turbidite sequences as well. It is instructive to examine the relationships between cleavage and sandstone dikes in some of these occurrences. Thomson (1973) reports sandstone dikes in the Tesnus Formation of west Texas, a unit that, to judge from his photographs, does not have a cleavage. Sandstone dikes from the lower Ecca Group of South Africa have been illustrated (Truswell and Ryan, 1969; Truswell, 1972). A bedding-plane foliation, which may be the early stage of a cleavage, is developed in the shales. Some of the sandstone dikes are perpendicular to bedding and are folded with axial surfaces parallel to the bedding foliation. Dzulynski and Radomski (1956) show photographs of a number of sandstone dikes in the Carpathian flysch. Here again the only cleavage-like feature is the bedding foliation in the shale, and many of the dikes are perpendicular to bedding. The dikes at a high angle to bedding are also commonly folded with axial surfaces approximately parallel to the bedding foliation. All the writers cited interpret the sandstone dikes as soft-state deformation features. Quite obviously the occurrence of slaty cleavage parallel to sandstone dikes in rocks like the Martinsburg is not universal. Thus, injection of the dikes does not necessarily cause a cleavage, nor is the presence of a cleavage required prior to injection.

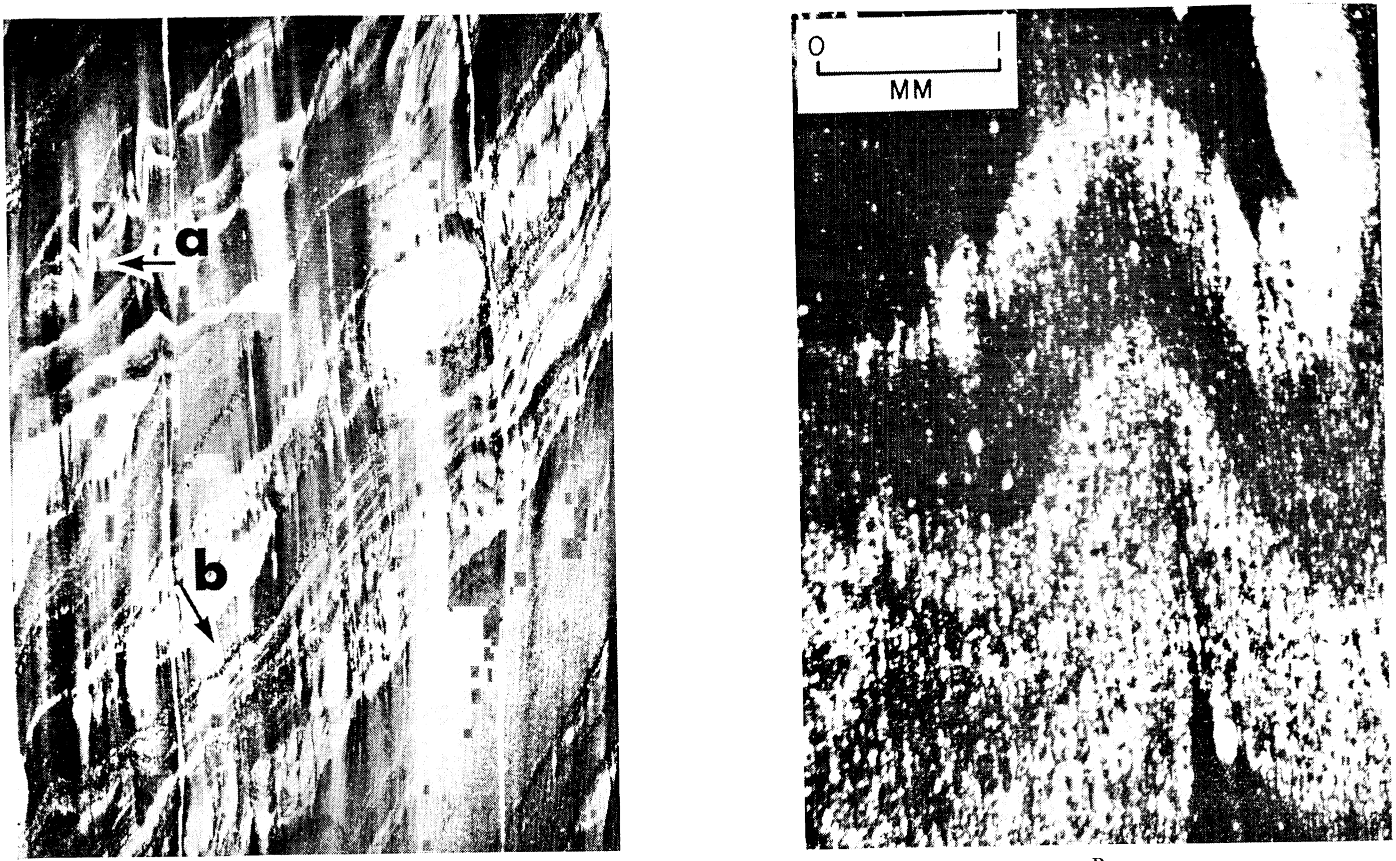
In terms of stress-strain relationships, the dewatering of clay-rich sediments whether by tectonic stress or by the weight of overburden should be very similar, at least through the stage of expulsion of free water, and probably through the mechanical deformation stage (Hedberg, 1936; Heling, 1970). Thus, it is significant to compare the fabric of dewatered shale and mudstone with that of the Martinsburg slate. Although the compaction of sediments under the weight of overburden need not be caused by a differential stress, the occurrences of clastic dikes cited above suggest that a differential stress may occur at least locally in turbidite deposits. (This statement is not intended to imply that sandstone dikes occur only in turbidites; see review by Dionne and Shilts, 1974, for other occurrences). In addition, because the compaction of sediments appears to involve vertical shortening without significant horizontal length changes, it is reasonable to infer that a differential stress existed with σ_1 vertical. With the possible exception of the orientations of the principal stresses, no fundamental difference is required between tectonic- and overburden-induced compaction.

It is generally agreed that fissility in shale, the property of splitting along approximately parallel surfaces (Ingram, 1953), is the result of the parallel alignment of platy minerals. This has been demonstrated by observations with the petrographic microscope (Ingram, 1953; Byers, 1974), the scanning electron microscope (O'Brien, 1970), and X-ray orientation analysis (Odom, 1967; Oertel and Curtis, 1972). The lack of fissility, which leads to the irregular fracture of mudstone, is shown by the same workers to be the result of a lack of alignment of the platy minerals. Fissile shales and mudstones are known to occur in very close vertical association (Odom, 1967) and to be laterally gradational within the same unit (Byers, 1974). From these data two conclusions that affect the interpretation that slate forms by tectonic dewatering are drawn. (1) Dewatering alone does not necessarily produce a good alignment of platy minerals; additional factors are important. (2) Fissile shales are generally not described as slates, suggesting that parallel mineral alignment alone is not sufficient to produce a slate as the term is used for hand specimens.

On the other hand, the grain orientation approximately parallel to the axial planes in the soft-state fold examples cited by Williams, Collins, and Wiltshire (1969) and Moore and Geigle (1974) are reasonably attributed by them to grain rotation during dewatering with σ_1 approximately parallel to bedding. The important question about the Martinsburg slate is not whether grain rotation during dewatering is possible, but whether the rotation alone produces a cleavage like that in the Delaware Water Gap.

Dike injection contemporaneous with grain rotation and parallel to the plane of grain alignment seems unlikely but is not impossible. Dike injection in an isotropic material will occur normal to σ_3, the least compressive principal stress (Anderson, 1972; Jaeger and Cook, 1969). Inasmuch as in an isotropic material the maximum compressive stress and strain axes will be nearly parallel except in certain portions of folds (Dieterich, 1969), and because the plane of grain alignment will be normal to ε_1, dike injection normal to σ_3 should occur at right angles to the plane of grain alignment not parallel to the alignment. The exception, as pointed out by Alterman (1973), occurs if the grain orientation introduces an important planar anisotropy. The most favorable case for dike injection is if the material has zero tensile strength normal to the plane of grain alignment and some finite tensile strength in all other directions. In this case dike injection can occur even if σ_1 is normal to the cleavage as long as the effective stress (total stress minus hydrostatic stress) in that direction is zero or tensile. However, if σ_1 is tensile, all the other effective stresses must be tensile. Thus the explanation proposed by Alterman requires that all three principal effective stresses be zero or tensile. The important question here is not whether the dike injection is possible, but whether it is probable and an integral part of the cleavage-forming process. Alternative explanations for the fabrics interpreted by Alterman (1973) as resulting from dewatering will be mentioned after the evidence for pressure solution is discussed.

PLATE 1

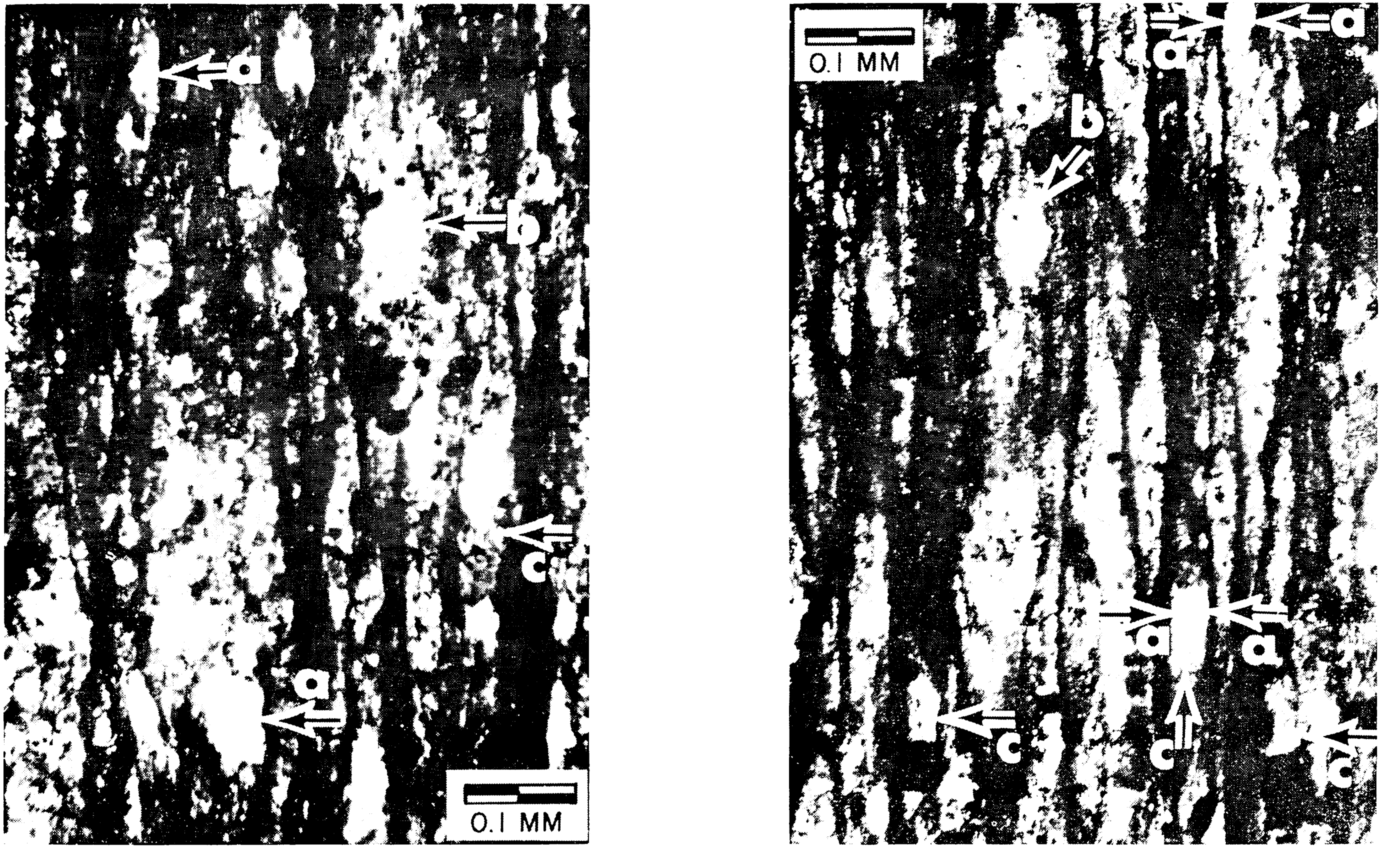


A.

B.

A. Photograph of a large thin section of the Martinsburg slate. The long dimension of the photo is 7.5 cm. The diagonal light-colored bands are silt beds; cleavage is parallel to the long dimension of the photo. Area of (B) indicated by (a); bed from which plate 2 was photographed indicated by (b). B. Photomicrograph of folded silt beds in the Martinsburg slate.

PLATE 2



A.

B.

A. Photomicrograph of (a) grains truncated on one side, (b) normal (equant) grains, and (c) pressure shadows.
B. Photomicrograph of (a) grains truncated on two sides, (b) normal (equant) grains, and (c) pressure shadows.

MICROSCOPIC EVIDENCE FOR PRESSURE SOLUTION

The traditional evidence for pressure solution is (1) fabric elements truncated by removal, not offset, and (2) truncated fabric elements abutting narrow zones of the relatively insoluble components of the rock. These criteria have been applied by Stockdale (1922) to demonstrate the pressure solution origin of stylolites. The same criteria have been applied to demonstrate the pressure solution origin of certain cleavages by Plessman (1965), Schamel (1969), Durney (1972), Nickelson (1972), Williams (1972), and Groshong (1975a). The resulting fabric is a spaced cleavage (Dennis, 1967), seen as thin sub-parallel cleavage laminae that are separated by domains of different composition and lesser (or different) grain alignment. As pointed out by Williams (1972), this is a common fabric in many rocks defined in hand-specimen as slate but is different from a truly penetrative slaty cleavage in which essentially all minerals show the preferred orientation.

The specimen of the Martinsburg slate described here was collected in the Delaware Water Gap along U.S. 46 about 1.6 km south of Columbia, N.J. In that area bedding dips south 8° to 18°, and cleavage dips south about 45° (Behre, 1933). In thin section the cleavage consists of thin dark lines cutting across the light, quartz-rich beds (pl. 1-A). The more closely spaced the cleavage laminae, the darker that portion of the thin section. Close examination reveals the cleavage laminae to be spaced about 0.05 to 0.10 mm apart where they cut the quartz-rich beds and less than 0.05 mm apart in the intervening beds (pl. 1-B). The quartz grains are relatively equant when not in contact with the cleavage laminae, with diameters on the order of 0.05 mm (pl. 2). Where in contact with the cleavage laminae, the grains show planar sides; just one side is planar in some grains (pl. 2-A), whereas two sides are planar in others (pl. 2-B). Many of the opaque grains have fibrous tails (pressure shadows) extending parallel to the cleavage (pl. 2-B) and, less obviously, so do many of the quartz grains (pl. 2). Particularly good photographs of quartz grains having pressure shadows are shown by Elliott (1973).

The planar grain boundaries terminating against the cleavage laminae are here interpreted as satisfying the conventional criteria for pressure solution. The abnormal truncations of the grains are interpreted to be the result of pressure solution, and the cleavage laminae are interpreted as insoluble residue. At least some and perhaps all of the quartz removed from grain faces parallel to cleavage is redeposited in pressure shadows. This appears to be the reason that many grain outlines are not sharply defined. The quartz-filled pressure shadows provide additional evidence of quartz mobility during deformation. Similar fabrics have been so interpreted by Elliott (1973).

It might be argued that the shape of the quartz grains is caused by ductile deformation of the grain. The grains truncated on two sides have a roughly elliptical shape, but that shape is not caused by ductile strain of the grain. The round and half-round grains indicate the lack of penetrative strain within the grains. In addition, the outlines of the remaining portions of doubly-truncated grains (especially pl. 2-B) are not greatly elliptical (see also Elliott, 1973).

Pressure solution and the development of the cleavage laminae is a deformation mechanism of major importance in the Martinsburg slate but probably not the only deformation mechanism. Grain alignment between the laminae is suggested optically (Maxwell, 1962) and by X-ray studies (Holeywell and Tullis, 1975). This implies that either grain rotation or oriented grain growth also occurs.

CONCLUSIONS

Bulk strain has caused the sandstone dikes in the Martinsburg slate at the Delaware Water Gap to lie in or near the cleavage plane. The strain normal to cleavage inferred from the shortening of minor folds is sufficient to produce the observed angular relationships by either of two mechanically plausible strain models.

Pressure solution plays an important role in the formation of the cleavage. Evidence for pressure solution is seen in detrital quartz grains truncated against the cleavage laminae. Grains not in contact with cleavage laminae are unaffected. Pressure shadows give additional evidence of quartz mobility. The cleavage laminae, along which the rock breaks, are interpreted to be the relatively insoluble residue (low mobility components).

Most of the features of the Martinsburg slate that have been associated with the cleavage can, I believe, be interpreted to be the result of (1) pre-cleavage, soft-state deformation, (2) bulk strain, and (3) pressure solution. The sandstone dikes themselves and the isolated silt "clumps" and "tongues" (Alterman, 1973) are common features in turbidites with or without cleavage and are best attributed to pre-cleavage, soft-state deformation that is probably associated with dewatering. The various "clay trails" of Alterman (1973) can be interpreted as the insoluble residue remaining after pressure solution. The offset or apparent thinning of the beds where crossed by the "clay trails" can be the result of the removal of material by pressure solution (Groshong, 1975a). Other fabrics attributed to dewatering have been interpreted in terms of pressure solution by Williams (1972).

Another aspect of the slate that can be explained by pressure solution is its strength relative to fissile shale. All well-compacted shales have presumably suffered complete dewatering and attendant grain rotation, yet they do not all have slaty cleavage and are not all suitable for use as roofing slate. I believe that much of the material removed by pressure solution is redeposited nearby in a slate, thus increasing the consolidation and strength of the rock relative to a compacted shale. Carson (1974) has recently suggested that pressure solution and redeposition caused "overconsolidation" in a Pleistocene subduction-zone deposit.

Several different mechanisms have been established as possible causes of slaty cleavage. In penetrative-cleavage slates the planar grain alignments may be due to grain rotation caused by the bulk strain (Oertel and Phakey, 1972; Tullis and Wood, 1975) or by metamorphic grain growth without significant strain (Etheridge and Lee, 1975). Planar grain alignments can also be caused by rotation within the solution-residual zones of spaced-cleavage slates (Williams, 1972). Grain rotation alone, however, does not necessarily produce slate; a fissile shale may equally result. Diffusion in either a fluid medium or the solid state evidently is a factor in all slaty rocks and perhaps in all cleavage-bearing rocks.

The spaced-cleavage slates appear to form a continuous spectrum in both physical appearance and deformation mechanism (pressure solution-diffusion) with the more widely-spaced cleavages commonly called "false" cleavage or "fracture" cleavage (Schamel, 1969). The transition from the widely-spaced cleavage that is common in sedimentary rocks (Nickelsen, 1972; Groshong, 1975a, b) to the closely-spaced cleavage of slates like the Martinsburg may be a function of increasing temperature but evidently occurs at temperatures below those usually characterized as metamorphic. Increasing penetrative strain also seems to characterize the transition.

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