F. MARKEWICZ

MR. FRANK J. MARKEWICZ
Route 24, Box 177
Chester, N. J. 07930

Herman

Origin of Slaty and Fracture Cleavage in the Delaware Water Gap Area, New Jersey and Pennsylvania

JOHN C. MAXWELL

Departments of Geology and Geological Engineering, Princeton University, Princeton, N. J.

Reprinted from

Petrologic Studies: A Volume to Honor
A. F. Buddington

Pp. 281–311, November, 1962

PUBLISHED BY THE SOCIETY
1962

Made in the United States of America

PP. 281-311 NOVEMBER 1962

Origin of Slaty and Fracture Cleavage in the Delaware Water Gap Area, New Jersey and Pennsylvania

JOHN C. MAXWELL

Departments of Geology and Geological Engineering, Princeton University, Princeton, N. J.

ABSTRACT

In the Delaware Water Gap area of Pennsylvania and New Jersey a thick sequence of Cambrian to Devonian sedimentary rocks unconformably overlies Precambrian gneiss and marble. A major angular unconformity separates Ordovician and Silurian rocks. Fracture cleavage, locally developed throughout the Paleozoic section, reflects at least two orogenies. Slaty cleavage is restricted to the Ordovician Martinsburg formation and predates overlapping Lower Silurian Tuscarora quartzite. The slaty cleavage is the only indication of metamorphism in the Paleozoic rocks.

The slaty cleavage is a near-perfect axial-plane foliation characterized by a high degree of orientation of constituent minerals, chiefly illite and quartz. Geologic evidence relates the slaty cleavage to folding of a thick, rapidly subsiding, water-bearing pelitic sequence. Rapid application of tectonic stress probably induced abnormally high pore-water pressures, approaching lithostatic pressure. Internal friction was thus drastically reduced, and rotation of mineral grains, accompanied by mass transport parallel to axial planes of developing folds, produced the high degree of preferred mineral orientation that characterizes rocks with slaty cleavage. Escape of pore water at a late stage of deformation, facilitated by parallel mineral orientation, probably aided recrystallization of clay minerals and brought about some redistribution of silica and carbonate.

In the Water Gap area, fracture cleavage has developed in relatively brittle siltstone, limestone, quartzite, dewatered shale, and slate. Two types of fracture cleavage are common—one related to inter-bed shear during folding (bed-delimited fracture cleavage), and another, the false or slip cleavage of the slate belt, apparently related to shearing accompanying a limited differential flowage, essentially the microlithon mechanism of De Sitter.

If the mechanism proposed here is valid, slates form only at one time in an orogenic cycle, *i.e.*, during the initial stages of folding. Furthermore slate is not necessarily an end member of the metamorphic sequence. It may be expected that shales involved in regional metamorphism would be deeply buried and dewatered prior to deformation, hence would pass directly from fracture-cleaved shale to phyllite and schist without passing through a slate stage. If involved in regional metamorphism, slates ordinarily will show a second period of deformation, characterized by development of fracture cleavage.

INTRODUCTION

One has only to read a fraction of the massive literature concerned with the origin of rock cleavage to appreciate the complexity of the phenomena. Each investigator interprets cleavage in the light of his own experience—be it as field geologist, experimentalist, or mathematician. This article is no exception. The area described is unusual, however, in the relative simplicity of its geologic history and corresponding relative lack of ambiguity in relating development of cleavage to larger structures and to geologic history.

Many varieties of secondary-rock cleavage have been described and named. Two major groups are commonly recognized, fracture cleavage and flow cleavage (Leith, 1905). Fracture cleavage is defined as the property of a rock enabling it to part on closely spaced parallel fractures of secondary origin and is not causally related to orientation of minerals within the cleaved rock. Flow cleavage is associated with the parallel orientation of planar or elongated mineral grains so that the rock tends to part along the parallel planes determined by the mineral orientation. The terms slaty cleavage, schistosity, and axial-plane cleavage are generally used more or less synonymously with flow cleavage, or refer to particular types of flow cleavage. It is also commonly assumed that flow cleavage develops only in metamorphic rocks and that a shale undergoing metamorphism progresses through a slate stage to phyllite, schist, and perhaps to gneiss; indeed gneissosity may be included as a form of flow cleavage. For flow cleavage, then, the emphasis is on metamorphism, that is, on the recrystallization and reconstitution of rocks when deformed at elevated temperatures and high confining pressures.

In the Delaware Water Gap area, well-developed slaty cleavage—i.e., flow cleavage—occurs in an environment notably free of other criteria suggesting metamorphism. The obvious conclusion, that slaty cleavage is not necessarily a metamorphic phenomenon related to folding at great depth, will be developed in this paper.

GENERAL GEOLOGY, DELAWARE WATER GAP AREA

The pre-Pleistocene rocks of the Delaware Water Gap area may be differentiated into three "layers of geology," each layer a stratigraphic-structural unit separated from other layers by angular unconformities (Fig. 1). The oldest one, composed of Precambrian gneiss and marble, borders the area on the southeast and is overlain with profound unconformity by lower Paleozoic rocks of the second layer. Locally the Precambrian crystalline rocks have been thrust onto the rocks of the second layer, as at Jenny Jump Mountain.

The second layer, of Cambrian to late Ordovician age, includes the Hardystone sandstone, the Kittatinny Limestone, the Jacksonburg Limestone, and the Martinsburg Shale. Before the end of the Ordovician these rocks were folded in much their present form, asymmetrical to the northwest, and the slaty cleavage was impressed upon the shales of the Martinsburg. A fracture cleavage in the underlying shaly Jacksonburg Limestone may have formed at the same time.

Evidence of age of the folding and development of cleavage may be found in the Water Gap area and vicinity. To the southwest, in the vicinity of Hamburg, Pennsylvania, hundreds of feet of Upper Ordovician conglomerate, sandstone, and shale (Bald Eagle-Juniata) overlie the Martinsburg, possibly unconformably (Woodward, 1957). In the Water Gap area these Upper Ordovician clastic rocks either were not deposited or were eroded, and the Lower Silurian quartzite (Tuscarora or Shawangunk) lies on the Martinsburg slate with marked angular discordance. In northern New Jersey, the Green Pond formation, a conglomeratic quartzite correlated with the Tuscarora, was deposited directly on Precambrian gneiss. Near Lehnertsville, Pennsylvania, folds in the Schochary Sandstone of Martinsburg age can be traced below the unconformable Tuscarora Sandstone of Blue Mountain (Woodward, 1957). In New Jersey, Kümmel (1940) mentions the occurrence of Martinsburg slate in the basal conglomeratic beds of the Shawangunk formation. Such evidence supports the

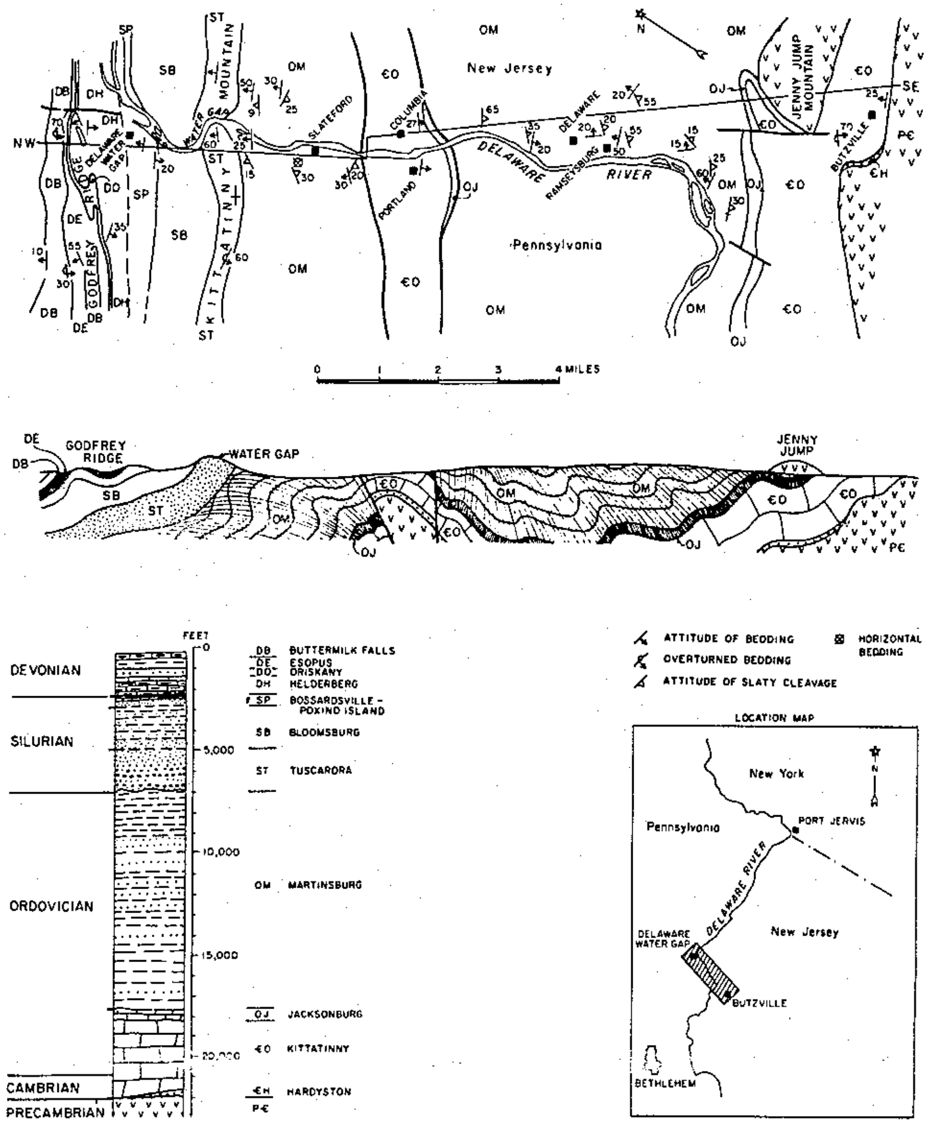


Figure 1. Location of area and summary of geology

conclusion that a period of folding closely followed, and possibly accompanied the latest stages of, the deposition of the Martinsburg Shale, and that the slaty cleavage was impressed on the shale at this time. Behre (1933), in his comprehensive study of the slates of Pennsylvania, arrived at a similar conclusion (Behre, 1933, Pls. 33, 34), although he suggested that the slaty cleavage may have been intensified during a later deformation.

The third layer, the youngest, consists of a thick sequence of Silurian and Devonian clastic rocks with relatively minor amounts of limestone in the middle. The sandstone and conglomerate (Tuscarora or Shawangunk) at the base of this sequence transgressed across the eroded Martinsburg and older rocks during the Early Silurian (Medinan), initiating a cycle of deposition which continued well into latest Devonian and possibly through the Carboniferous. More than 10,000 feet of sedimentary rocks accumulated before this, and the underlying layers were deformed in a post-Devonian "Appalachian" orogeny. Folds in this layer resemble those in the second layer in style, but are of larger amplitude. The silts, shales, and thin-bedded limestones exposed in the Water Gap area are characterized by well-developed fracture cleavage, but slaty cleavage has not been observed.

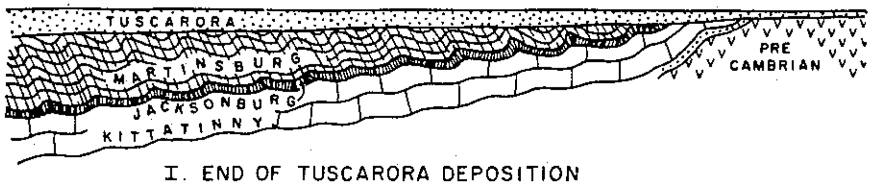
The tectonic history of the Water Gap area, as here interpreted, is illustrated in Figure 2. Folds and slaty cleavage impressed on the second layer by the Late Ordovician orogeny were further deformed in the Appalachian orogeny. Note the arch of slaty cleavage and the overturning of the axial planes of folds past 180° directly beneath the Tuscarora formation at the Water Gap. The overturning developed during the arching of Tuscarora and younger formations into a great anticline, which is asymmetrical and at least locally overturned to the northwest. Thrusting of Precambrian over Paleozoic, here shown as of "Appalachian" age, may actually have occurred during the Late Ordovician orogeny.

DESCRIPTION OF CLEAVAGE

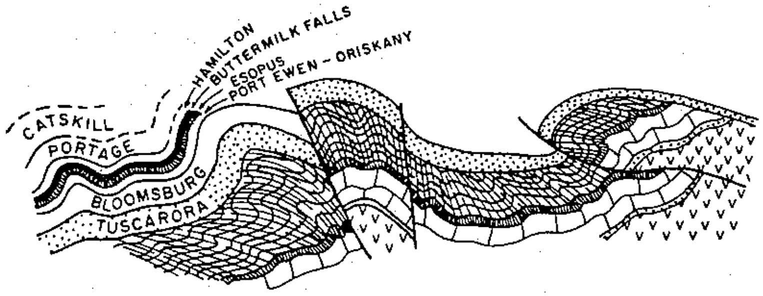
SLATY CLEAVAGE

General statement. It is now widely accepted that slaty cleavage and schistosity are varieties of flow cleavage which, according to Leith's (1905) classic study, is "the cleavage dependent on the parallel arrangement of the mineral constituents of the rock." In the Delaware Water Gap area, although there are many cleaved shales and siltstones, only those of the Martinsburg formation fit the definition of slaty cleavage. These include the commercial slates of the important Lehigh-Northampton district just west of the Delaware River in Pennsylvania.

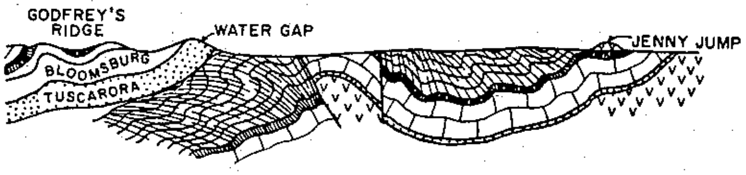
Behre (1933, p. 136–149) gave a detailed description of the Martinsburg shale. He recognized lower, middle, and upper members, the lower including the "hard slate" belt of the Lehigh-Northampton district. The middle member is characterized by sandy shales and fine to coarse impure arkosic sandstones, locally carrying pebbles up to 1 inch in diameter. The middle member has not yielded commercial slate, but slaty cleavage is characteristic of the pelitic zones throughout the formation.



I. END OF TUSCARORA DEPOSITION



II. END OF APPALACHIAN DEFORMATION



III. CROSS-SECTION, DELAWARE WATER GAP AREA
NEW JERSEY - PENNSYLVANIA

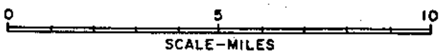



Figure 2. Tectonic history of the Delaware Water Gap area

Stose (1930) recognized only lower shaly and upper sandy members of the Martinsburg. He interpreted the upper shaly zone of Behre as a repetition of the lower shaly zone by folding and attributed the differences to variations in degree of metamorphism. However, Behre's work seems to indicate that the upper zone, characterized by thick beds of "clear" unlayered commercial slate, is lithologically quite different from the thin "ribbon" slates of the lower Martinsburg. The two men differ radically in estimates of thickness of the formation—Stose estimated 3000 feet, and Behre, approximately 11,000 feet. Intense folding and common, although for the most part minor, faulting make an accurate determination of thickness impossible. An estimate from a section taken along the east bank of the Delaware, northward from the base of the Martinsburg to the highest beds exposed in the bottom of a gentle syncline at the town of Delaware, gives a total thickness of 5700 feet. The top 900 feet is distinctly sandy and is probably to be assigned to Behre's middle Martinsburg. The lower

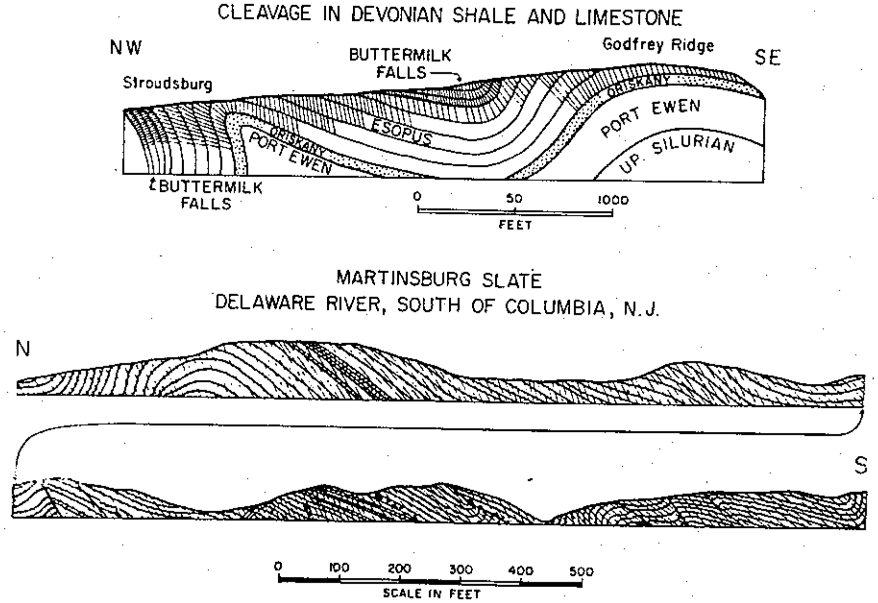


Figure 3. Slaty cleavage in the Martinsburg formation (lower section) and fracture cleavage in Devonian sedimentary rocks (upper section)

Martinsburg would then be about 4800 feet thick, which agrees well with Behre's estimate of 5000 feet. This is a maximum figure, taking into account the large scale folding indicated in Figure 1, but ignoring minor folding and faulting. However, the Martinsburg is thousands of feet thick and is characterized by slaty cleavage throughout.

The slaty cleavage of the Martinsburg is a regional cleavage—that is, the cleavage planes are approximately parallel over large areas although warped and rotated by later folding (Figs. 1, 3). Abrupt discontinuities in attitude of slaty cleavage occur only in conjunction with distinctly younger faults. The slaty cleavage approximately parallels the axial planes of the recognizable folds. Where evidence is available, changes in attitude of slaty cleavage are matched by corresponding changes in the attitude of axial planes of associated folds related to post-cleavage deformation.

The regionally consistent attitude of slaty cleavage, independent of the attitude of bedding, records penetrative strain characteristic of a uniformly plastic body. This implies that the interbedded sandstones were, on the whole, little if any more competent then the associated shales. Fold geometry supports this thesis. Folding is of similar type, showing relative thickening of crests (Behre, 1933, Pl. 5). Slate-sandstone contacts are tightly welded and show no shearing parallel to the contact, and cleavage in the slate is for the most part sharp and undeformed at sandstone contacts, contrary to what would be expected if the sandstones were relatively competent at the time of folding.

Cleavage tends to be absent from the coarser and thicker sandstones, but becomes more obvious with increasing clay content. Typically, the slaty cleavage fades out at the edge of a sandstone bed or is refracted through the bed as a series of vague, widely spaced, undulatory, semi-parallel partings.

One line of evidence suggests that some of the sand beds were actually unconsolidated at the time of formation of slaty cleavage. Small sandstone dikes, branching from sandstone beds along slaty cleavage planes, were found at two places in Martinsburg slate—along U.S. 46, about 2 miles south of Columbia, New Jersey, and in Hudson River black slates and sandstones west of Poughkeepsie, New York, along State Highway 299, 1.8 miles east of the New Paltz exit of the New York Thruway. The first occurrence is particularly interesting because the sand dike was injected downward from the mother sand bed, apparently driven by a jet of water-soaked clay (Fig. 4A). The clay was injected completely through the sand bed. Figure 4B illustrates the occurrence of a

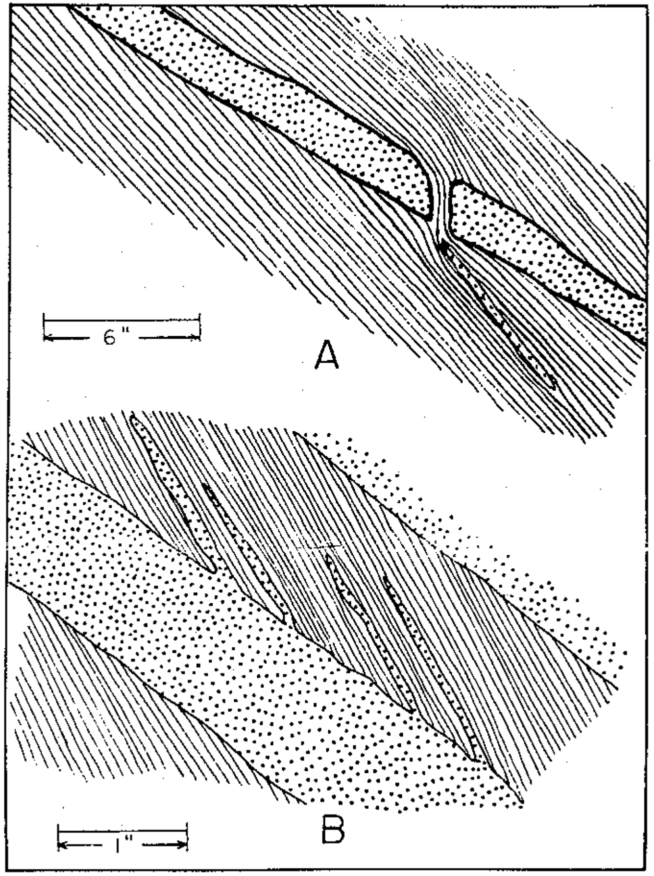


Figure 4. Sandstone dikes parallel to slaty cleavage

A. In Martinsburg formation south of Columbia, New Jersey

B. In Hudson River Group west of Poughkeepsie, New York swarm of thin sandstone dikes in the exposure along Route 299 injected upward from the mother sandstone bed, parallel to the well-developed cleavage. The dikes are interpreted as having formed during the movements that produced the slaty cleavage. In the New Jersey occurrence the sandstone dike seems to diverge a few degrees from the cleavage direction; possibly it was injected in the earliest stages of folding, before the present asymmetry was fully developed.

Slates with interbedded sandstone, apparently unconsolidated at the time of folding and cleavage development, have been described from other slate belts. Dale (1914, Pl. 14) illustrates two examples from Vermont. The plastic behavior of the Dorothea grit of North Wales, described and figured by Morris and Fearnsides (1926), although attributed by the authors to deep-seated deformation related to "slip faults," strongly suggests flowage of an unconsolidated sand during folding.

Mineralogy. The mineralogy and chemistry of slates have been extensively investigated. The early work on which much of our present understanding and interpretation is based is summarized by Dale (1899; Dale *et al.*, 1914), Leith (1905), and Behre (1933). Commercial slates of sedimentary origin are characterized by abundant fine micaceous minerals, commonly with less fine clastic quartz or carbonate grains, and by variable quantities of chlorite, pyrite, carbonaceous granules and flakes, and rutile needles. Other minerals (magnetite, hematite, muscovite, biotite, chalcedonic quartz, zircon, and tourmaline) may also be present (Dale, 1914, p. 21, 188). Of these, only the mica, chlorite (if present), quartz, and carbonate normally are sufficiently abundant to contribute significantly to the structure of the slate.

Mica is primarily responsible for the perfect planar cleavage of the best slates. The mica occurs in minute, flat plates oriented with their largest dimensions parallel to the slaty cleavage; this orientation permits the manufacture of high-grade roofing slates because the slates can be split to any desired thickness, independently of visible parting planes.

The fine mica of slates has commonly been identified as muscovite or sericite. Bates (1947), who investigated the micaceous minerals in the slates of the Lehigh-Northampton slate belt in great detail by petrographic examination, chemical analysis, X-ray diffraction, differential thermal analysis, and electron micrographs, concluded that the dominant micaceous mineral is not sericite or chlorite, but is a member of the illite group. He also found that the illite from the slate differs from the illite of the Fithian (Illinois) Shale used as a standard, in that the Fithian illite occurs as fibrous aggregates, whereas that from the slate forms larger plates similar to sericite. Bates concluded that the illite of the slate formed either by recrystallization of a less well-organized illite like that of the Fithian Shale or by development from other micas and clay minerals; the change in either case was attributed to metamorphism.

Mineral orientation. Sorby (1880) observed that

> "... when a section of fine grained slate cut at right angles to the cleavage is rotated in polarized light it becomes, over nearly the whole surface, very bright and much darker at different azimuths, like a doubly refracting crystal, whereas there is little or no such change in the case of true clay shales of the normal granular type containing much kaolin and very little mica."

This characteristic of strong aggregate polarization is indicative of the high degree of parallel orientation of the mica flakes. Such slates showing strong aggregate polarization are classed as "mica slates" by Dale *et al.* (1914, p. 16), whereas slates with weak aggregate polarization (weak parallel orientation of mica) are designated "clay slates." Gradations between the two are recognized (Dale *et al.*, 1914, p. 17). The slates of the Lehigh-Northampton district of Pennsylvania and adjacent New Jersey show strong parallel orientation of mica and are "mica slates."

In addition to the perfect planar cleavage, slates commonly show a second preferred direction of parting called the grain. The plane of the grain is a wavy and rather irregular surface and apparently depends on the parallel arrangement of the longest axes of elongated mineral grains—mica, quartz, carbonate, and, to a small degree, rutile (Behre, 1933, Pls. 6, 7, 8, p. 32–33)—in the plane of the cleavage and approximately at right angles to the axes of folds. In areas of gently plunging folds the grain may appear as a series of fine striations on cleavage surfaces, approximately parallel to the dip.

The high degree of preferred shape orientation of grains is associated with transport parallel to the cleavage planes. On a scale of millimeters, such movement is well shown in Figure 1 of Plate 1, a photomicrograph taken at right angles to the slaty cleavage and to the axis of a micro "fold." Note that "folding" seems to be a result of transport of material parallel to the trace of the axial planes of the minute "folds" and of the parallel-oriented mineral grains that determine the slaty cleavage. Such small-scale movements tend to occur uniformly over large structural units (Fig. 5).

Locally the visible transport parallel to cleavage can be quite large, as strikingly shown in a road cut, known to many geologists, along U.S. 46, 1½ miles northeast of Belvidere (Figs. 6, 7). The related shortening perpendicular to cleavage is also apparent. A pronounced cleavage dipping 30° SE. dominates the exposure. Crossing the cleavage are rusty brown-weathering beds a few

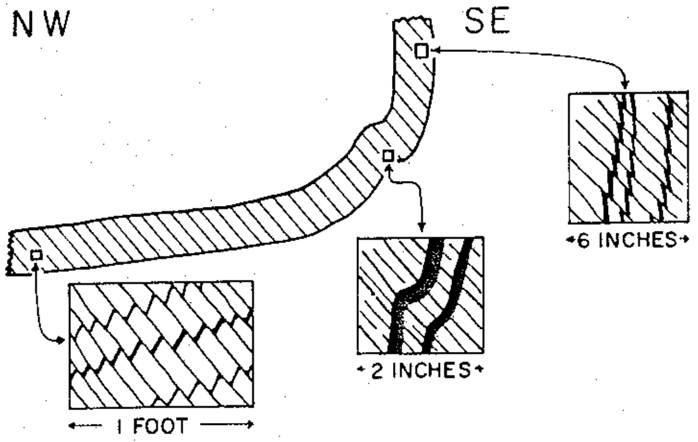


Figure 5. Relation of small and large structures in Martinsburg slate. Length of larger structure approximately 2 miles

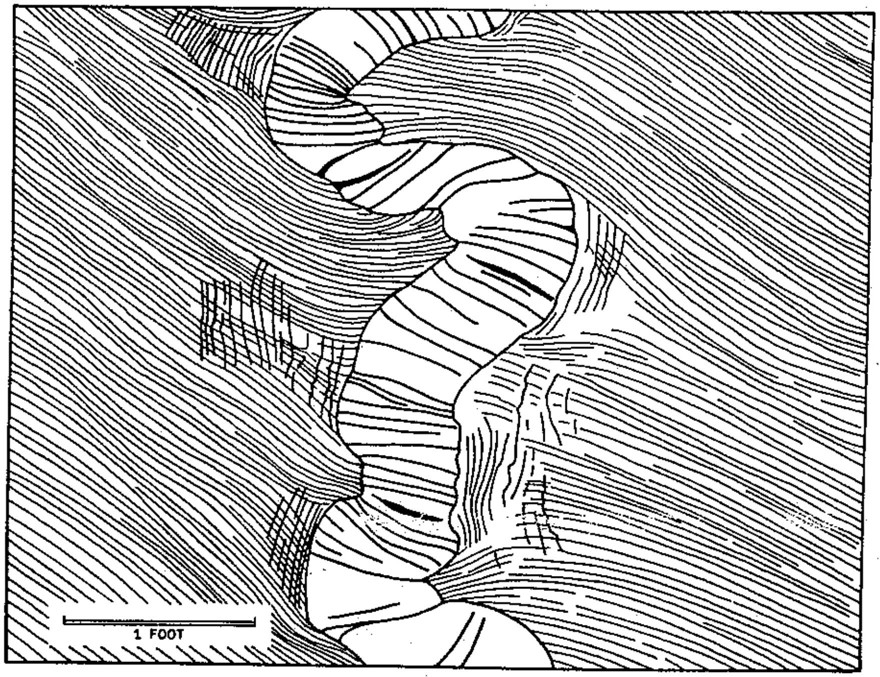


Figure 6. Folding of calcareous silt bed in Martinsburg slate, 1½ miles northwest of Belvidere on U. S. 46

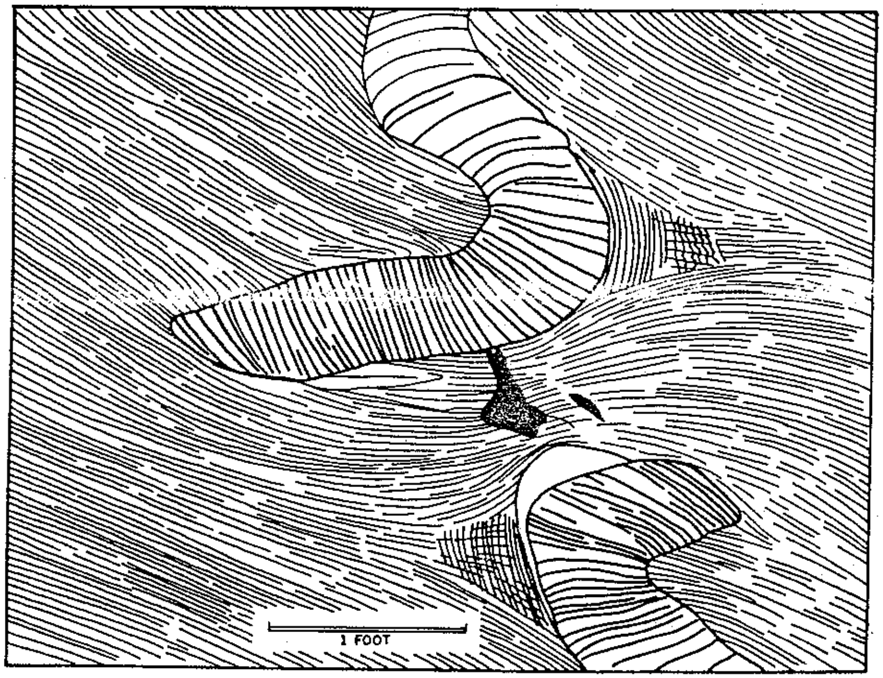


Figure 7. Shearing and transport parallel to slaty cleavage, offsetting calcareous siltstone bed. Same location as Figure 6. Solid black area is quartz-carbonate vein.

inches thick that trend generally vertically but are contorted into serpentinous folds (Fig. 6). The rusty-weathering beds are carbonate-rich, dark-gray siltstones. They are cut by prominent joints, locally spaced closely enough to be called a fracture cleavage; many joints are occupied by veins of calcite and quartz. Apparently the carbonate-rich beds were relatively competent and brittle at the time of deformation. Bedding within the slate is well preserved and scarcely cleaved adjacent to the convex fold surfaces of the carbonate-rich siltstones, whereas intense slaty cleavage has developed in the concave bends with concomitant lateral transport of material and obliteration of bedding. The magnitude of the transport parallel to cleavage which may result is shown by Figure 7 in which a fold in a competent bed has been sheared through and the matching ends of the bed displaced about 3 feet. Measurement of several of the contorted silt beds of this outcrop indicates a vertical shortening of the section of approximately 40 per cent, accomplished at least in part by transport of material parallel to cleavage and probably in part by dewatering of the shales during formation of slaty cleavage.

DEFORMATION OF SLATY CLEAVAGE

Post-cleavage deformation may be observed in almost any sizable outcrop of Martinsburg. The deformation may involve only slight flexing of the cleavage (Behre, 1933, Pl. 6A), or strong folding; it may appear as isolated cleavage shear zones ("hogbacks") or as the imposition of a fracture cleavage ("slip" or "false cleavage"), or it commonly is reflected in thrust faulting and associated zones of brecciation with attendant quartz-calcite veins. The Martinsburg has been involved in large-scale folding of younger sediments with resultant arching of the cleavage, especially evident near the Tuscarora ridge at the Water Gap. In contrast with the uniform and penetrative plastic movements reflected in the formation of the slaty cleavage, the post-cleavage deformation (aside from the broad folding) was local and discontinuous and was brittle rather than plastic.

Cleavage shear zones are isolated narrow zones of cleavage distortion bounded by parallel planes of abrupt bending or fracture of the cleavage (Dale, 1914, Pl. 9; Behre, 1933, Figs. 14, 15). "False" or "slip cleavage" may be associated with the cleavage shear zones (Behre, 1933, Fig. 14) or with minor faulting or folding of the slaty cleavage. In a few places the fracture (slip) cleavage is so strongly developed it dominates and even masks the pre-existing slaty cleavage. A particularly interesting example of fracture cleavage is exposed along tracks of the Lackawanna Railroad, just south of Ramseysburg and about 3½ miles south of Columbia, New Jersey, where the railroad parallels U.S. 46 (Fig. 8). Immediately to the north and south the slaty cleavage is normally developed. In this exposure the slaty cleavage has been folded and faulted, with the development of a prominent secondary fracture (slip) cleavage approximately parallel to the axial plane of the folded cleavage and subparallel to the minor faults. Orientation parallel to the axial plane of secondary folds was also noted by Behre (1933, p. 37).

Near the southern end of the exposure (Fig. 8) the secondary fracture or "slip"

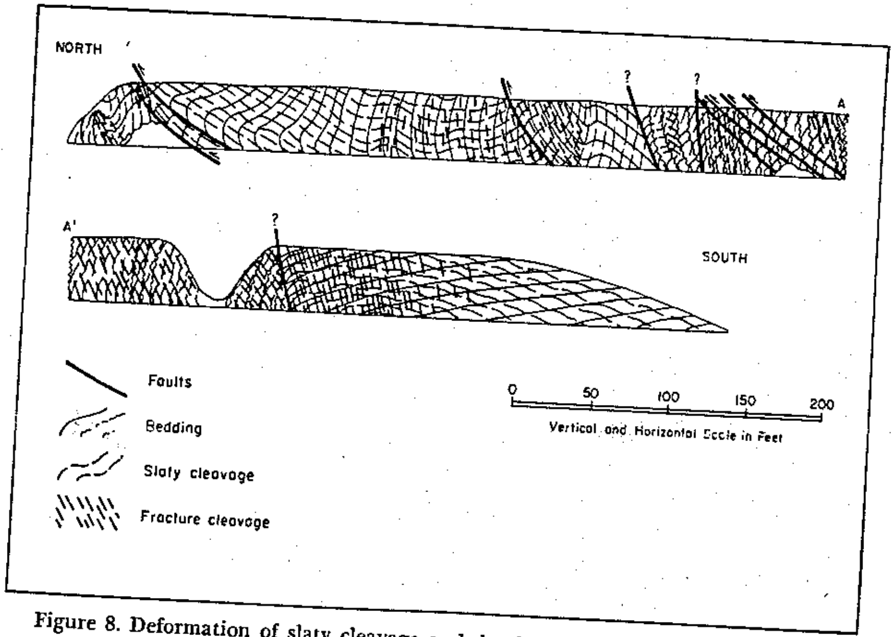


Figure 8. Deformation of slaty cleavage and development of fracture cleavage in Martinsburg formation near Ramseysburg, New Jersey

cleavage is strongly developed as a series of closely spaced, subparallel cracks and microflexures (Pl. 1, fig. 2) approximately at right angles to the slaty cleavage. For some tens of feet the slaty cleavage is almost totally obscured. The fracture cleavage becomes gradually less prominent southward, however, and dies out rather abruptly, and the slaty cleavage assumes its usual prominence. Broughton (1947) suggested that the younger fracture cleavage obliterated the slaty cleavage and replaced it southeastward to the edge of the Martinsburg outcrop. However, it seems certain that slaty cleavage can be traced into and out of the area of maximum development of fracture cleavage, with the same characteristics and attitude on both sides.

FRACTURE CLEAVAGE AND POST-DEVONIAN DEFORMATION

The uppermost "layer of geology" comprising Silurian and Devonian sedimentary rocks has undergone folding similar in intensity to, although on a larger scale than, the underlying Cambrian and Ordovician rocks. Furthermore, these younger rocks are characterized by concentric folding involving conspicuous interbed slip, indicating that the rocks of this "layer" were mostly well consolidated and competent when folded. Fracture cleavage is well developed in the thin-bedded and fine-grained rocks through the sequence.

The Tuscarora quartzite (Shawangunk) is at the base of the upper "layer." The lower part of the Tuscarora is made up of medium- to thick-bedded, coarse gray quartzite, interbedded with conglomerate and with beds of black silty shale a few inches thick. In the upper part, shales are less common, the quartzite

---

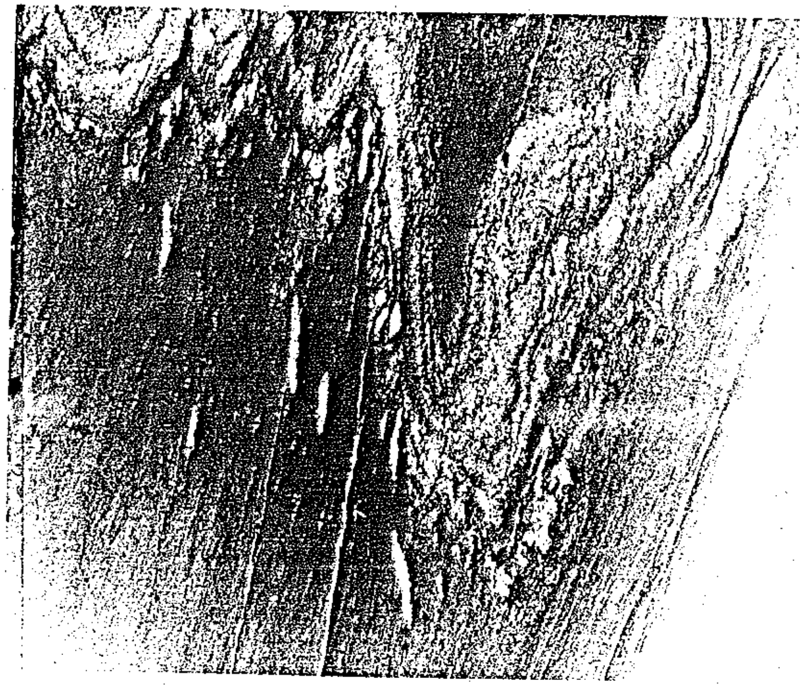


FIGURE 1. Microfold in Martinsburg slate showing transport parallel to slaty cleavage

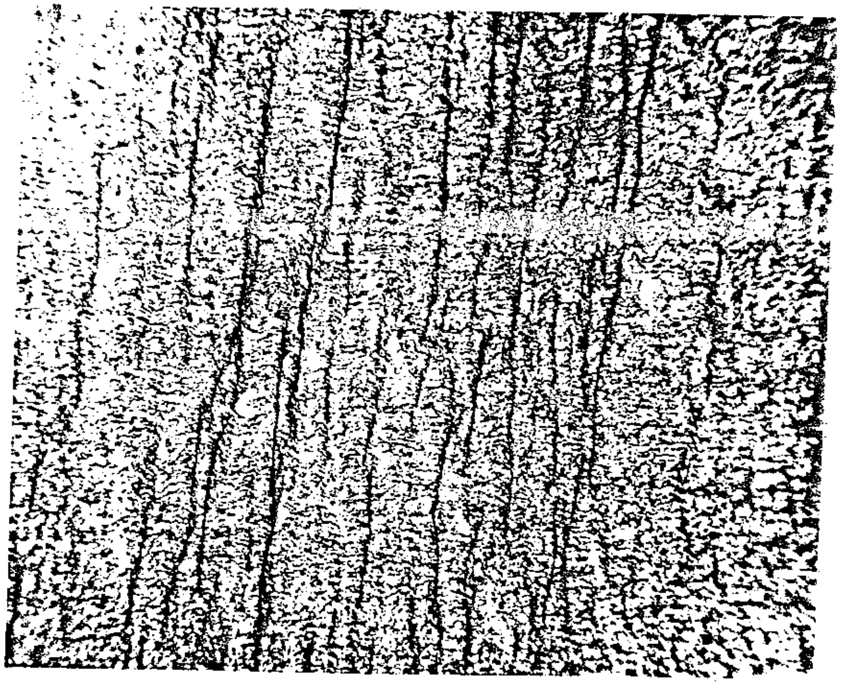


FIGURE 2. Martinsburg slate. Fracture cleavage (vertical discontinuous cracks) cutting and distorting slaty cleavage (horizontal)

becomes thicker-bedded and finer-grained, and the formation grades into the overlying Bloomsburg Redbeds, predominantly red siltstone and fine- to medium-grained quartzite; the Bloomsburg in turn passes into the dark-green and gray sandstones and siltstones of the Poxino Island Formation.

In the thin beds of black silty shale near the base of the Tuscarora, the fracture cleavage consists of closely spaced irregularly planar partings which form an acute angle with the adjacent quartzite beds and indicate pronounced interbed shear between the competent quartzite beds. Higher in the formation, and in the overlying Bloomsburg, the thicker silty beds show a well-developed fracture cleavage, again indicating relative shearing movements between the overlying and underlying competent quartzite beds. The Tuscarora ridge here is the limb of a large syncline, the higher parts of which overturn to the northwest (Fig. 9). The lower limb of this syncline is the gently flexed, flat-lying sequence exposed along U.S. 611 ¾ mile south of the town of Delaware Water Gap. Fracture cleavage on this lower limb is anomalous in that it dips rather uniformly southeast regardless of position on the minor flexures; an example is illustrated by Figure 9, indicating that interbed shear related to the major syncline dominates and obscures that accompanying the much smaller anticlinal flexure.

Cleavage in the Devonian beds is well exposed along U.S. 611 where this highway crosses Godfrey Ridge on the south edge of Stroudsburg, Pennsylvania (Fig. 3). Fracture cleavage may be seen in the calcareous shales of the Port Ewen

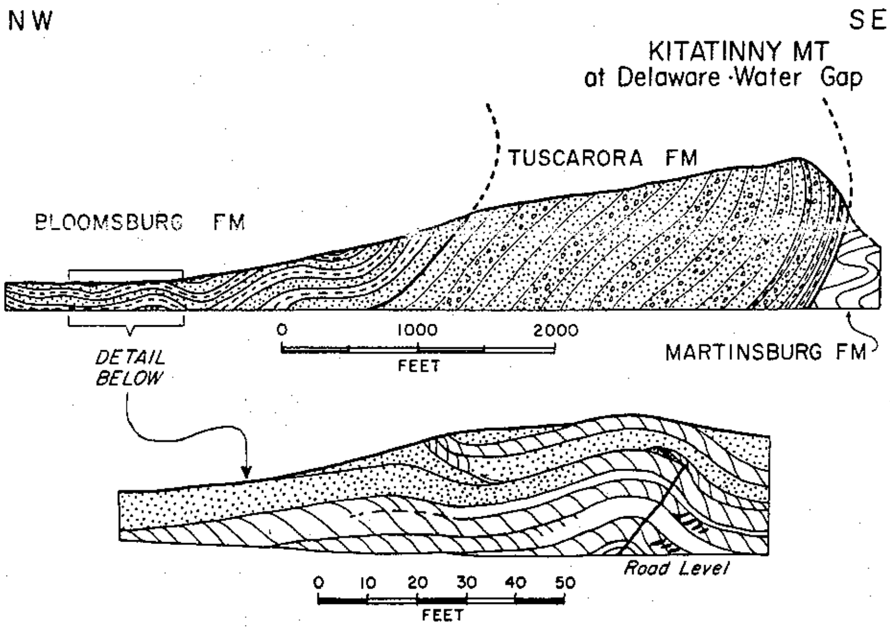


Figure 9. Minor folding and fracture cleavage associated with major syncline north of the Delaware Water Gap

Formation (Helderberg age) and is particularly striking in the Esopus and Buttermilk Falls formations. The Esopus is a very uniform dark-gray siltstone with indistinct bedding. Cleavage is closely spaced and superficially resembles slaty cleavage; it is only slightly planar, however, and consists of irregular, subparallel, discontinuous cracks in a silty matrix. Cleavage surfaces characteristically have a sheen indicating alignment of clay minerals in the cleavage, but the orientation is not apparent between the discrete cleavage cracks. Instead of paralleling the axial plane of associated folds as does slaty cleavage, the cleavage in the Esopus maintains an obtuse angular relationship with the bedding, which causes it to fan across the folds and dip toward the axis of the anticlines. Even though bedding is not readily apparent, interbed slip occurred during folding as shown in disturbed zones of flexed cleavage. Fracture cleavage in the thin-bedded, cherty Buttermilk Falls Limestone somewhat resembles that in the Esopus, but the cleavage characteristically maintains a higher angle to bedding than it does in the Esopus (Fig. 3).

ORIGIN OF CLEAVAGE

GENERAL STATEMENT

This discussion will emphasize the differences in origin of cleavage in order to point out more clearly the particular circumstances that gave rise to the various kinds of cleavage present in the Water Gap area. Three types are recognized: the slaty cleavage of the Martinsburg; the fracture or slip cleavage of the Martinsburg; and the fracture cleavage of formations above and below the Martinsburg, here referred to as bed-delimited fracture cleavage.

ORIGIN OF THE SLATY CLEAVAGE

The following observations bear on the origin of slaty cleavage in the Delaware Water Gap area:

(1) Slaty cleavage is pervasive throughout the pelitic portions of the Martinsburg formation, 3000–11,000 feet thick.

(2) Cleavage is nearly constant in attitude over large areas and is essentially independent of the attitude of beds; abrupt changes in attitude of cleavage seems always to be associated with post-cleavage faulting. Regional changes in cleavage attitude are related to large-scale post-cleavage folding.

(3) The cleavage parallels axial planes of contemporaneous folds, as nearly as can be determined, and is associated with similar folding characterized by thickening of crests of the more highly appressed folds. Both folding and cleavage appear to be the products of uniform and pervasive plastic deformation related to a uniform and pervasive regional compression.

(4) Sandstones interbedded with the slates are typically lenticular, thin-bedded and poorly sorted, with the graded bedding, convolute structure, and bottom markings associated with turbidites (Van Houten, 1954). The sandstones were largely incompetent and water-saturated at the time of folding and cleavage formation. Similar rather than concentric folding, and lack of shearing and cleavage distortion at sandstone–shale contacts indicate incompetent behavior of the sandstones during folding. Further evidence for this is seen in the contemporaneous sandstone dikes and "plastic" behavior of sandstones during folding accompanying cleavage development.

(5) There is abundant evidence of transport of material parallel to slaty cleavage on both microscopic and macroscopic scales. The process apparently involved shear within a plastic material, for in thin section the shear surfaces are indistinct and diffuse, and visible planes of fracture are absent.

(6) Fine white mica is the dominant mineral in most commercial slates. In the Lehigh-Northampton district the mica is illite.

(7) Parallel arrangement of platy micaceous minerals enables the slate to be cleaved into sheets of any desired thinness. Discrete parallel parting surfaces characteristic of fracture cleavage are absent from commercial slate.

(8) The long axes of mineral grains, particularly mica (illite), quartz, carbonate, and perhaps rutile, show parallel orientation in the plane of cleavage and approximately at right angles to fold axes. This orientation is the "grain" of the slate and is responsible for a rough and wavy plane of parting more or less at right angles to cleavage and to fold axes.

(9) In the Delaware Water Gap area the folding and slaty cleavage were impressed upon the Martinsburg formation in the Late Ordovician (Maysville or younger), and uplift and erosion occurred before sedimentation was renewed to the west in latest Ordovician (Juniata) time, although the seas apparently did not reach the Water Gap region until Early Silurian (Medina). If the ages assigned are correct, the folding, uplift, and erosion involved, at most, late Maysville and early Juniata time. It seems improbable that any large thickness of rocks existed above the Martinsburg at the time of deformation. It is therefore quite reasonable to assume that the sands and shales of the Martinsburg were water bearing and poorly consolidated as deformation began.

These observations indicate that the earliest movements associated with deformation of the Martinsburg formation began in Late Ordovician, quite possibly while the formation was still below sea level. The movements produced a pattern of similar folding, asymmetrical to the northwest. A northwest-southeast shortening of the section was accompanied by transport of material obliquely upward parallel to the axial-plane cleavage, and probably by significant compaction associated with expulsion of water. All this occurred at depths of burial probably not exceeding 12,000 feet, hence at no greatly elevated temperature. Under these circumstances water (in clays and sands) was the plasticizing agent—indeed the only one capable of providing the degree of plasticity indicated by the perfect orientation of minerals and by the bulk transport of material parallel to cleavage without formation of discrete planes of shearing or fracture. The shales and sands, dewatered as the movements progressed, became brittle and, in post-Devonian deformation at greater depth of burial, were refolded, fracture-cleaved, thrust-faulted, and brecciated.

This pattern of cleavage formation is counter to the usual assumptions concerning the environment in which slaty cleavage originates, and raises problems of its own. For example, what was the water content of the shales at the beginning of their conversion to slate, and at what depths of burial, or other modifying conditions, was the shale so dewatered and consolidated as to behave as a brittle substance during deformation? By what mechanism is such a high degree of mineral orientation attained, and to what extent and under what conditions do new minerals form and old ones recrystallize? What is the nature of the deformation? Are there similarities in geologic history of slate areas which circumscribe the conditions under which slate may form? And, finally, what is the relation of slaty cleavage to regional metamorphism and to associated schists and gneisses? If it were possible to give unequivocal answers to these questions we would have an excellent understanding of cleavage formation as well as other metamorphic processes. We can at least suggest a few probable answers.

Plasticity and water content of shales. It is commonly accepted that a continuous progression exists from the fluid slurry of newly sedimented clay, through plastic clays which can be worked with the fingers, to compacted shales which break brittlely. However, little is known about the exact behavior of clays and shales under the confining pressure of thousands of feet of overlying sediments. Shales that have been buried not more than a few thousand feet, and which are weak and friable at atmospheric pressure, become ductile when tested in the laboratory at moderate confining pressure; slate on the other hand is brittle at high confining pressures (Handin and Hager, 1957; 1958).

A freshly deposited clay may contain water equal to several times its dry weight, most of which it loses in the first few feet of burial. Dewatering continues with increasing depth, but at a diminishing rate (Emery and Rittenberg, 1952, p. 747, 753). The rate of compaction depends on the rate at which interstitial water can be removed, and is thus a function of time as well as of permeability and weight of overburden. Drainage of water from shales is facilitated if blanket sands or other permeable rocks are interbedded with the shales. Thick shale sequences in which permeable beds are absent or present only as discontinuous lenses may retain abnormally large amounts of water for millions of years. Hubbert and Rubey (1959) and Rubey and Hubbert (1959) point out that thick sequences of relatively young clay rocks, which have been rapidly loaded either by superjacent sedimentation or tectonically, tend to have high pore-water pressures; these may reach the calculated overburden pressure but are generally between this value and the calculated value for normal hydrostatic pressure. Dickinson (1953) has shown that zones of abnormally high formation pressures are associated with lenticular sands in a thick shale section. Fluid pressures in these sands may closely approach values equivalent to the weight of the overburden. The excess above hydrostatic pressure indicates that pore water is bearing much of the weight of the overburden. Because of low permeability in the shales, abnormal pressures are readily measured only in the more permeable sand layers where, through time, water has accumulated from the adjacent shales to maintain equilibrium pressure.

The effect of time (age of formation) is strikingly shown by Dickinson (1953, p. 427). Maximum Miocene shale density measured (from the Gulf Coast) is 2.5, at a depth of about 15,000 feet on Weeks Island; this compares with 2.58 for Eocene Wilcox at a depth of about 8600 feet at Provident City, Texas, and 2.59 for Pennsylvanian shales at a depth of 4500 feet in Oklahoma (Athy, 1930). Estimates of thickness of the Martinsburg range from 3000 to 11,000 feet. From Dickinson's curve (1953, Fig. 14) we can compute that a Miocene shale at a depth of 3000 feet may contain about 30 per cent of water (by volume) whereas at 12,000 feet the water content might be 15–20 per cent. These computations are based on Dickinson's estimate of 2.65 for the mineral density of shale. Slates vary in density between 2.6 and 2.85; Whitehouse and McCarter (1958) list a range of 2.68–2.74 and 2.75–2.86 for the Fithian, Illinois, and Point Chevreuil, Louisiana, illitic clays. The mineral density of illitic shales is therefore higher than 2.65. Assuming a value of 2.75, the calculated water content would then be about 35 per cent by volume at 3000 feet, averaging Dickenson's and Hedberg's (1936) curves, and 20 to 25 per cent at 12,000 feet.

The Martinsburg formation, just prior to deformation, was perhaps hydraulically similar to the abnormally high-pressure zones present at depth in the Louisiana Gulf Coast. Some thousands of feet of pelitic sediment accumulated during Middle and Late Ordovician. Interbedded sandstones are thin, lenticular, and, except in the middle Martinsburg, not quantitatively important. If the Martinsburg shales had a permeability comparable to that of the Miocene clays of coastal Louisiana, even the deepest of them may well have contained 25 per cent or more water, by volume, at the time of deformation. Sandstone dikes (Fig. 4) might readily be formed during the deformation of sedimentary rocks containing pore water at pressures approaching the lithostatic load; hence they would be hydraulically unstable.

More importantly, the physical reorientation of shale minerals would also be greatly facilitated in such an environment, where high pore pressures would reduce friction between the rotating grains. Hubbert and Rubey (1959, p. 147) have shown that the angle down which a block will slide is, on the average, 30° for dry materials, but approaches zero as the pore pressure approaches lithostatic pressure. Terzaghi (1950, p. 92–94) has used this principle in studying low-angle landslides. The shear strength of an uncemented porous material approaches zero as pore pressure values rise toward the lithostatic pressure and the material approaches a fluid in behavior. For intermediate values of pore pressure, a water-bearing clay will possess shear strength, and in general its behavior is plastic rather than fluid; fluid behavior is indicated locally, however, as in the case of the sandstone dike (Fig. 4A).

Although it is possible to guess the order of magnitude of water content which will permit plastic flow and the formation of slate, it is more difficult to estimate the lower limit below which a shale will behave brittlely. As already noted, slates, most of which have a measured porosity of the order of 1 per cent or less, are brittle when deformed experimentally. It may well be that the important controlling factor, above some minimum water saturation, is the presence or absence, during deformation, of pore-water pressure approaching lithostatic pressure. Experimental studies are needed to relate plastic behavior to water content in shales for low values of contained water.

Origin and orientation of minerals in slate. The mineralogical descriptions of commercial slates are monotonously similar. Most workers record the near-perfect planar orientation of mica and chlorite in the cleavage and linear orientation of mica, quartz, and rutile in the direction of the grain. Opinions vary widely, however, on the relative importance of physical reorientation of primary sedimentary minerals versus recrystallization and growth of new minerals during deformation.

The minerals that appear to be significant for a consideration of the origin of slaty cleavage are mica, quartz, calcite, and rutile, although others, including pyrite, carbon, detrital biotite (often chloritized), magnetite (as small grains, commonly included in chlorite), and detrital plagioclase and zircon are present in the Martinsburg slate in minor to moderate abundance (Behre, 1933, p. 181).

"MICA" OF SLATE: Almost all literature on slate identifies the abundant micaceous mineral as muscovite or sericite. If this is correct, the mica for the most part is a product of metamorphism of clay minerals, presumably at high pressure and elevated temperature. The work of Cuthbert (1946) and especially of Bates (1947) shows, however, that the dominant micaceous mineral of the Martinsburg Shale is illite rather than sericite.

Illite may occur either as degraded or as well-crystallized forms in unaltered sedimentary rocks (Smoot, 1960; Nelson, 1956), the form apparently being a sensitive function of degree of exposure of the contained clays to weathering or to circulating meteoric water. Murray's (1954) work on Pennsylvanian shales of Indiana and Illinois indicates a marked enrichment of marine shales in illite as compared to brackish and nonmarine members of a cyclothemic sequence. Nelson (1960) believes that illite becomes more crystalline and that chlorite is newly generated in bottom clays to the Rappahannock River, Virginia, as the waters become more saline toward the mouth. Henin (1956) readily synthesized crystalline micas, including illitic types, at 100° C, and was able to produce some micas at temperatures as low as 20° C, although much less rapidly. There is evidence, therefore, that crystalline illite and chlorite can be generated and preserved in a saline environment, at small pressures and low temperature.

QUARTZ: Silt-sized quartz grains are abundant, both as scattered grains in a clay matrix and as thin beds and lenses. The quartz grains are typically angular, somewhat elongated, and of clastic origin (Dale, 1914, p. 22). Behre (1933, p. 177) points out that the quartz grains are roughly ellipsoidal, the longest and shortest axes lying in the grain plane, with the longest axis parallel and the shortest at right angles to the cleavage. Some exceptionally elongated grains with axial ratios as great as 5:1 Behre attributes to secondary growth. Most grains appear to be clastic, however, and their rather perfect orientation must be attributed to mechanical rotation. Chalcedonic and vein quartz are also locally common in slates.

CALCITE: Carbonate that effervesces readily with dilute hydrochloric acid is abundant. It occurs primarily as minute rhombs elongated with the grain and cleavage (Behre, 1933, p. 178). Dale (1914, p. 22) lists "granular" carbonates (rhombs) among the clastic minerals; Behre (1933, Fig. 55) illustrates quartz grains partly replaced by secondary calcite.

CHLORITE: Chlorite does not appear to be abundant (Bates, 1947, p. 633). It occurs as scattered flakes parallel to cleavage and as larger poorly oriented grains which Behre (1933, p, 179, Pl. 37B) thinks are probably porphyroblasts. Whitehouse and McCarter (1958, p. 112) cite the generation of chlorite plates as a diagenetic modification of montmorillonite clay placed in artificial sea water for 5 years. This observation again emphasizes the conclusion that growth and crystallization of minerals typical of slate may occur readily at small pressures and near-surface temperatures.

RUTILE: Rutile occurs as "... tiny, almost submicroscopic needles, locally well oriented so as to have maximum elongation parallel to grain" (Behre, 1933, p. 181). Behre considers the needles to be probably of secondary origin, but Dale (1914, p. 21) cites a number of workers who report abundant rutile needles in clays. This observation, together with the extremely small size and orientation parallel to grain, suggests that the rutile needles were present in the Martinsburg sediments and were rotated mechanically within the matrix of clay minerals.

MINERALS OF ASSOCIATED ROCKS: In attempting to establish the conditions for generation of slate, the physical and mineralogical character of associated, and particularly of older, rocks is obviously significant. Near Delaware Water Gap the Martinsburg is underlain by the Jacksonburg formation, a dark-gray limestone which is thin-bedded, shaly, and abundantly fossiliferous near the top. Locally the shaly limestones show a well-developed fracture cleavage. The associated fossils, including lacy forms of Bryozoa, may be somewhat flattened but are otherwise well preserved. The Beekmantown Limestone below the Jacksonburg has abundant beds of oölitic and sandy limestone, edgewise conglomerate, and thin layers of black chert, all of which should be sensitive indicators of plastic deformation, recrystallization, or generation of new "metamorphic" minerals. However, none of the 3000 feet of carbonate section below the slate has been converted to anything resembling a marble. As the limestones and carbonates have been folded with the slate, one is forced to conclude that the temperature and confining pressure—that is, the depth—were not great enough during deformation to permit recrystallization, extensive plastic flow, and the formation of new minerals. Ray and Gault (1961) have identified well-crystallized illite, montmorillonite, and chlorite in the Jacksonburg, and suggest that the high degree of crystallinity may be the result of post-diagenetic deformation. Following the reasoning of Turner (1958, p. 215), however, and considering the foregoing discussion on the crystallization of clays, one would conclude that the changes accompanying formation of slate should be considered diagenetic rather than metamorphic, although, as Turner points out, the two have much in common.

MINERAL ORIENTATION: Mechanisms generally advocated to explain orientation of minerals in slate involve either mechanical rotation of existing mineral grains or recrystallization and growth of new minerals with orientation controlled by the direction of maximum pressure within the deforming rocks, or a combination of these processes. It is usually assumed that slaty cleavage is closely related to schistosity in origin. The older studies of these processes are summarized by Leith (1905). Knill (1960) and Gonzalez Bonorino (1958; 1960) give more recent treatments of the problems of origin and classification of cleavage. Few modern writers have been concerned with the origin of slaty cleavage, emphasizing rather the development of cleavage and schistosity in rocks in which there has been, without doubt, extensive recrystallization and growth of new minerals. If the dominant mineral of slate is sericite, then metamorphism probably is a necessary assumption. Behre (1933, p. 50), accepting this assumption, states (p. 55) that the essential change from shale to slate is in the growth of secondary mica. The general lack of deformation in rock constituents, especially mica and chlorite, is cited as evidence against rotation, gliding, and granulation as the principal means of adjustment, although he recognizes (p. 54) that the quartz grains are oriented, at least in part, by rotation.

The mineralogy of the slates of the Martinsburg could well be produced by processes generally ascribed to diagenesis. Metamorphism, in the sense of extensive formation of new minerals under conditions of deep burial and high temperature, is not necessary, nor is it likely to have occurred. The dominant process would seem to be orientation by physical means. Jannettaz (1884) demonstrated that the anisotropy of cleavage and grain could be imposed on a block of freshly quarried clay by compressing the clay while confined on five sides, so that the clay was extruded through the open sixth side. Shackleton (1953, p. 276), impressed by the intense lateral shortening and corresponding extension in the vertical dimension of the Welsh slates, attributes the cleavage primarily to extreme flattening by pure irrotational shear, combined with a slight simple rotational shear on the opposite limbs of the similar folds. This picture of similar folding, with extensive upward transport of plastic material, corresponds with the deformation of the Martinsburg slate in the Delaware Water Gap area. I would emphasize in addition the compaction and possible other effects accompanying the expulsion of perhaps 20–30 volume per cent of water during formation of the cleavage.

In the early stages of compaction a clay may be visualized as an open network of clay plates and fibers with water-filled interstices. As compaction proceeds, water is expelled, and the clay particles rotate, approaching parallelism as more and more water is expelled (Buessem and Nagy, 1954). If the process proceeds slowly and water pressure remains essentially hydrostatic, the load is carried by the clay particles, friction and bearing strength increase, and in later stages compaction occurs only at the expense of considerable deformation of the clay particles. In the process proposed in this paper, it is assumed that a thick sequence of impermeable shaly sediments accumulated just prior to deformation and that escape of pore water was so slow that abnormally high pore pressures characterized the sequence when deformation began. The resulting compression tended to increase the pore-water pressure which may very well have approximated the lithostatic pressure through much of the formation; perhaps even locally lithostatic pressure was exceeded, with resulting instabilities giving rise to fluid flow perpendicular to the maximum pressure. Flowage parallel to cleavage, such as shown in Figures 6 and 7, may well be of this origin, as may be the peculiar downward-injected sandstone dike of Figure 4A.

During deformation, flattening, rotation, and extensive flowage parallel to cleavage resulted in a near-parallel orientation of clay particles. This in turn destroyed the original network of clay particles which held the water so tenaciously; permeability increased in the plane of the cleavage and in the direction of the grain, facilitating the rapid dewatering of the slaty rocks as the last stages of the slaty cleavage episode. Thereafter the rocks were relatively brittle, as indicated by the post-slaty cleavage deformation.

The essence of the process is the extreme plasticity, even fluidity, permitted by relatively large pore-water volumes and high pore pressures. During the late-stage escape of the water, large volumes must have flowed parallel to the cleavage, providing ideal conditions for such diagenetic changes as recrystallization and growth of illite and chlorite crystals, movement of limited amounts of calcite and quartz in solution, and deposition of some chalcedonic quartz and perhaps secondary carbonate. Late-stage quartz-carbonate veins may also have been formed at this time.

The mechanism also explains the common occurrence of shale and mudstone below, as well as above and on strike with, high-quality slate. The relations are such that depth-temperature variations with corresponding variation in metamorphism can hardly be the cause of the distribution of the slate. If the deeper shales had lost all but a few per cent of pore water while overlying shales still contained a larger amount, it is quite possible that slates would be formed from the younger shales while the older and deeper ones were deformed by flexure and generation of fracture cleavage. Examples of this kind of development might include the mudstones below hard slates in the Penrhyn Quarry in North Wales (Smith and George, 1948, Fig. 10) and graptolitic shales, only very locally slaty, more than 2000 feet below the Missouri Mountain Slate in the Arkansas slate belt (Purdue, 1909). Dale (1899, 1914) mentions that Ordovician red slates in many places in the New York-Vermont belt are associated with and probably underlain by black graptolitic shales, and the Lower Cambrian slates of the same area are interbedded with fossiliferous black shale.

Nature of deformation which produced the Martinsburg slate. The slaty cleavage in the Martinsburg is related to similar folding of short wave length; the folding extends about 10 miles across the strike of the slate belt, but individual folds probably lose their identity rather rapidly in a vertical direction. A crumpled carpet on a floor might be a fair analogy of the geometry. Relatively shallow folding, or folding beneath an overriding mass, seems to be indicated. The direct cause of the deformation is unknown, however, as is the degree to which folds in the slate persist in the underlying carbonate rocks. The pattern of broad folds certainly carries downward to, and probably well into, the basement, but these are probably related to post-Devonian folding (Fig. 2). Three possible tectonic mechanisms occur to me: (1) A décollement, moving northwestward under the force of gravity with a detachment plane at the base of the Martinsburg slate or perhaps somewhat lower, within the carbonate sequence; (2) deformation beneath a thrust plate; and (3) regional folding and shortening, involving folding of all the Cambrian and Ordovician rocks and either arching or faulting of the basement.

(1) That a décollement, moving under gravity, may simulate tectonic folding was strikingly demonstrated recently by Korn and Martin (1959). Something

comparable is not unreasonable in the Water Gap area, but to date no detachment plane or zone has been identified.

(2) The strong westward asymmetry and plicated character of folds in the Martinsburg are compatible with an origin related to a major overthrust fault. The Jenny Jump klippe is a remnant of such a fault. In Figure 2, however, the Jenny Jump thrust is shown as originating during Appalachian (post-Devonian) orogeny, as seems to be generally accepted (Kümmel, 1940). Possibly, however, this or a similar thrust originated during the Late Ordovician Taconic orogeny, perhaps to be later rejuvenated.

Deformation beneath an overriding thrust sheet (or gravity slide mass of comparable dimensions) is a doubly attractive hypothesis. It not only accounts for the tectonic style but also provides a mechanism for rapidly loading the water-saturated Martinsburg and thereby producing or accentuating abnormally high pore pressures within the sediments (Rubey and Hubbert, 1959). If an overthrust sheet thousands of feet thick is visualized, the sediments beneath and in front of the advancing thrust mass would be squeezed upward and outward (Bucher, 1956) in a movement pattern similar to that observed in the Martinsburg formation.

(3) Shortening by folding accompanying regional compression possibly occurred in this area as an expression of Taconic orogenic movements. Hubbert and Rubey (1959, p. 153) have indicated that abnormal pore-water pressures may result from horizontal compressive stresses of tectonic origin as well as from loading; hence conditions favorable for formation of slate result from regional compression also. My personal prejudice at present is that a combination of folding and overthrusting is the most likely cause of the northwestwardly asymmetric folding and material transport accompanying formation of the slaty cleavage. The intense flowage illustrated in Figures 6 and 7 was ascribed to deformation beneath the Jenny Jump thrust by Broughton (1947) but considered to be Appalachian, rather than Taconic as here suggested. The type of deformation pictured is much easier to understand if it occurred as a part of the plastic movements accompanying formation of slaty cleavage rather than as an element of the later, more brittle deformation which seems to be associated with "Appalachian" orogeny.

FRACTURE CLEAVAGE IN SLATE

Slaty cleavage is locally deformed by flexing, folding, and thrust faulting, commonly with development of a second "false" of "slip" cleavage. This cleavage may form the crests or limits of sharp linear zones of flexing or chevron folding (the "hogbacks" of Dale, 1914, Pl. VIII; Behre, 1933, Pl. 36B) or may develop subparallel to the axial plane of folded cleavage (Fig. 8, this paper; Behre, 1933, Fig. 14). In any case the cleavage is associated with a shortening of the section, accommodated by folding, thrust faulting, and, on a smaller scale, by microflexures and fractures accompanying slippage on slaty cleavage laminae. Development of fracture cleavage along the crests of microflexures may be seen in Figure 2 of Plate 1 and is especially well illustrated by Behre (1933, Fig. 13).

Fracture or slip cleavage is accompanied by sharp flexing which tends to rotate the platy minerals of the slate toward parallelism with the resulting fractures or incipient fractures. If the mineral parallelism is strong, then the term "strain-slip" cleavage is applied, and this type of cleavage may, with increasing perfection of mineral orientation, grade into a new schistosity (White, 1949).

The precise mechanics of origin of "slip" or "strain-slip" cleavage has been much debated. Knill (1960) distinguishes it from fracture cleavage on the basis that the latter is, by definition, independent of parallel arrangement of mineral constituents. Gonzalez Bonorino (1960) agrees with this distinction but points out that it is not necessarily genetic, since tectonites with well-developed *S* surfaces, when later deformed, will generally form slip cleavage, whereas more massive rocks under identical conditions give fracture cleavage. Formation of fracture rather than slip cleavage is also favored by shallow burial at the time of deformation. The essence of slip and strain-slip cleavage seems to lie in its association with thinly foliated rocks in which compressive deformation can be accomplished by minute crenulations of the laminae, with associated interlaminar slip.

Gonzalez Bonorino (1958; 1960) gives a detailed analysis of the mechanics of development of slip cleavage. He accepts in part the microlithon theory of De Sitter (1956), which assumes that slip takes place on cleavage surfaces by plastic stretching of microlithons between the bounding fracture planes but contends that slip is a minor factor. The process is pictured as one of inhomogeneous plastic deformation accompanying a penetrative stage of deformation following initial flexure folding. So far as the actual mechanics of cleavage formation is concerned there seems to be little fundamental difference between the views of De Sitter and Gonzalez Bonorino. The latter's assertion that De Sitter's microlithons are related to shear folding of the classic type, unaccompanied by lateral shortening, is not borne out by De Sitter's illustrations (1956, p. 96–97). In any case, the mechanism proposed by De Sitter and elaborated by Gonzalez Bonorino seems to explain adequately the fracture or slip cleavage developed in the Martinsburg slate in the Delaware Water Gap area.

FRACTURE CLEAVAGE IN ROCKS ABOVE THE MARTINSBURG SLATE

Much of the well-developed fracture cleavage in younger rocks differs from the slip cleavage in the Martinsburg in being more closely related to interbedding shear than to penetrative deformation in the axial regions of folds or to crosscutting shear zones. One type, the bed-delimited fracture cleavage, consists of parallel, closely spaced fracture planes oriented within a few degrees of the perpendicular to the bedding plane in brittle rocks, but rotated to a more acute angle in shaly facies. Commonly the cleavage is bent and accentuated by interbed shear. In the Tuscarora and Bloomsburg formations, cleavage is better developed on the straight to gently flexed limbs of the major syncline than near its trough (Fig. 9). On Godfrey Ridge, however, fracture cleavage is equally strongly developed on limbs and in the axial region, and it fans markedly around the axis (Fig. 3).

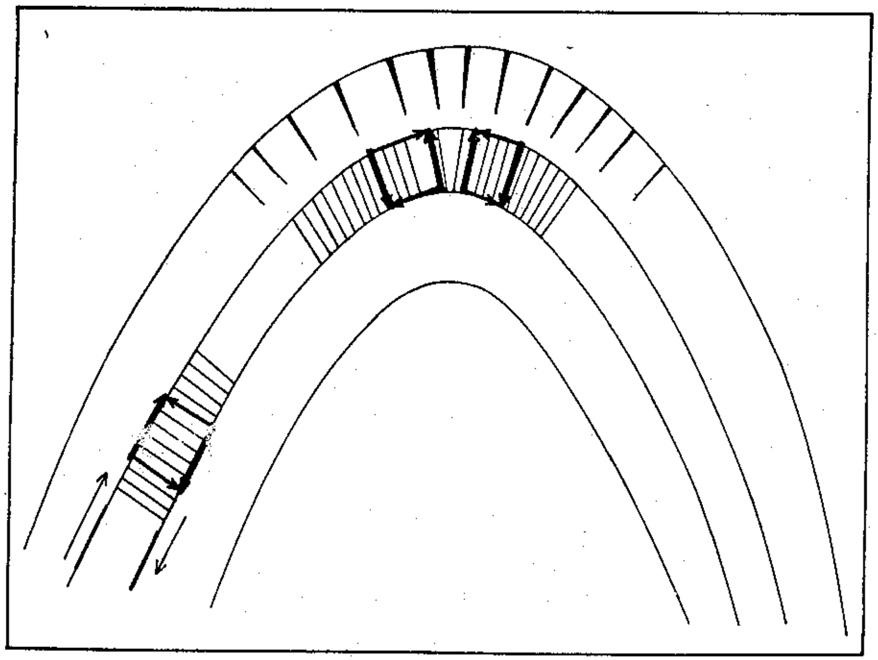


Figure 10. Origin of fracture cleavage on limbs and crests of flexure fold

Various modes of origin have been suggested for what is here termed bed-delimited fracture cleavage. Evidence of interbed shearing like that observed in the Water Gap area is common to other deformed regions; many workers (for example, Wilson, 1946) have suggested that fracture cleavage develops within the beds along shear planes complementary to the shear acting along the bedding planes (Fig. 10). In a simple flexure fold, interbed shear is limited to the limbs, however, and dies out in the axial region, yet fracture cleavage may be equally strongly developed in all parts of a fold. Knill (1960) has therefore suggested that fracture cleavage develops as tensional fractures during earliest stages of bending (crest of fold, Fig. 10). Campbell (1951) proposed also that cleavage may develop at right angles to bedding as a first result of bending, but ascribed it to the action of the vertical shear couple, the horizontal couple being ineffective, (crest, middle bed, Fig. 10). De Sitter (1956, p. 101) thinks that fracture cleavage of this type, along with slaty and flow cleavage, arises "... from simple flattening of the rock in a direction parallel to the largest principal stress, accompanied by differential movement along planes perpendicular to this stress," *i.e.*, the microlithon theory mentioned above in connection with the origin of slip cleavage in the Martinsburg slate.

In the Water Gap area bed-delimited fracture cleavage is particularly well developed in the lower, nearly horizontal limb of the major syncline (Fig. 9). The cleavage is controlled by interbed shear associated with the large syncline, only slightly modified by local flexures. The fracture cleavage probably developed prior to formation of the minor flexures.

This example illustrates a possible mechanism for generating the fracture cleavage found in the axial areas of some folds. A major fold of the type shown in Figure 9, developed in a sequence containing highly competent beds, will generate interbed shearing movements far out on the flank. Continuing or later folding may result in formation of new folds, or intensification of minor flexures on the previously cleaved but otherwise undeformed limb of the major fold. Thus in a sequence of folds only the initial fold might lack pervasive fracture cleavage produced by interbed shear.

The mode of origin of the fracture cleavage on the Godfrey Ridge structure (Fig. 3) is less obvious. In lower silty beds of the Buttermilk Falls Limestone, the fracture cleavage is strongly developed; it maintains a position close to the perpendicular to bedding and shows evidence of interbed slip. It developed in brittle beds, for the cleavage planes in part shear across chert nodules and in part are deflected around them. In the relatively massive and uniform Esopus Formation, a siltstone with interstitial clay and carbonaceous matter, the cleavage appears as closely spaced, subparallel fractures that are quite irregular in detail. The micaceous sheen visible on some cleavage surfaces indicates a degree of orientation of clay minerals in the cleavage; structures such as worm borings between cleavage surfaces are undisturbed, however, and there is no obvious reorientation of fabric.

Evidence bearing on the origin of fracture cleavage on Godfrey Ridge is, therefore, somewhat equivocal. The very close spacing and parallelism of cleavage fractures in the Buttermilk Falls Limestone suggest an origin related to shear, rather than to tension, in the axial areas of folds. Excellent development of the cleavage in rather extensive, almost horizontal parts of the fold does not favor the explanations proposed by Campbell (1951) and De Sitter (1956). Perhaps the cleavage developed by interbed shear related to early folding of the complex Godfrey Ridge anticline, with subsequent generation of minor wrinkles and northwestward overturning. Possibly, therefore, the axes of minor folds do not remain fixed but move along the bedding as folding progresses. Thus, bed-delimited fracture cleavage produced on the limbs of folds by interbed slip may end up in the axial region of a slightly later fold.

This explanation may be adequate for the cleavage in the Esopus also. However, the Esopus cleavage somewhat resembles slip cleavage in the Martinsburg, and some plastic distortion of the siltstone may have occurred during folding and cleavage formation. The microlithon theory of De Sitter (1956) is possibly the best explanation for the origin of this cleavage—modified, however, by interbed slip during folding.

RELATION OF SLATE TO PHYLLITE-SCHIST-GNEISS SEQUENCE

In the Water Gap area, beneath the Martinsburg slate, a sequence of unmetamorphosed sedimentary rocks rests with visible unconformity on old Precambrian gneiss and marble. Within the gneiss terrane, many miles to the southeast and toward the supposed center of the orogen, down-faulted shales and carbonate rocks are folded and fractured but are unmetamorphosed.

About 70 miles northeast of the Delaware Water Gap, along the continuation of the same belt of Cambro-Ordovician carbonate rocks and pelites, is the area of Dutchess County, New York, well known from the work of Balk (1936), Barth (1936), and Balk and Barth (1948). Here the slates, limestones, and dolomites change progressively southeastward into schists, gneisses, and highly deformed marbles. From northwest to southeast the following sequence of structural units is readily observed: slate, and interbedded sandstone and slate (1); similar rocks, modified by post-cleavage folding (2); slightly phyllitic slates (3), cut by shear zones and locally contorted into chevron folds (strong fracture cleavage parallel to axial planes of the folds); highly crumpled, slightly phyllitic slate (4), with beginning of development of biotite porphyroblasts, and initiation of recrystallization of associated carbonates to crystalline marble; rapid increase in degree of metamorphism to biotite-garnet schist (5), with small-scale folding of the schist on subhorizontal axial planes, siliceous layers folded plastically, and no obvious development of new foliation parallel to axial planes; coarse gneiss (6), with large garnet and biotite porphyroblasts (staurolite and sillimanite to the southeast) and strongly developed foliation parallel to the axial planes of poorly defined, tightly appressed folds. Details of these structural zones are given below:

1. The Hudson River Group exposed west of Poughkeepsie, New York, is lithologically similar to the middle Martinsburg. It is predominantly medium- to dark-gray well-bedded sandstone, with graded bedding and contemporaneous slump structures. Slaty cleavage is well developed in interbedded shales, and rather thick slate zones are present locally. This slate-bearing belt is about 10 miles broad and is structurally similar to the Martinsburg belt at the Water Gap. Sandstone dikes parallel to slaty cleavage were found in this belt (Fig. 4B).

2. At the west end of the bridge that crosses the Hudson at Poughkeepsie, the Hudson River rocks are medium- to thick-bedded sandstones with thin beds of slaty-cleaved shale. The rocks are broken by steep reverse faults and the thinner-bedded sandstones and interbedded shales have locally been crumpled into tight folds (Fig. 11A). Slaty cleavage is preserved on one limb of these folds, where its orientation agrees with the fold geometry, and is sheared into rhomboidal fragments on the other limb where it is discordant to the fold geometry. The folding obviously occurred after development of the slaty cleavage.

3. East of Poughkeepsie the slates assume a slight phyllitic sheen. "Shear zones," comparable to those cutting the Martinsburg, are common and locally more intensively developed as zones of chevron folding (Fig. 11B; Balk, 1936, Pls. 3, 4; Balk and Barth, 1948, Stop 1). Fracture cleavage occupying the axial planes of the chevron folds is structurally similar to the fracture cleavage associated with folding of slaty cleavage in the Martinsburg. Chevron folding is most striking in slates that contain thin siliceous beds. The thinner beds tend to be lenticular and to be offset along an early slaty cleavage, although this cleavage and bedding now are nearly parallel.

4. The zone of well-developed chevron folds extends eastward approximately to the biotite isograd which parallels the west edge of Clove Valley (Balk, 1936, Pl. 1). Here the slate becomes increasingly contorted, and fracture cleavage continues to dominate the exposures. Biotite appears first as tiny scattered porphyroblasts; associated carbonate rocks show both flexure and flow folding and well-advanced recrystallization (Balk and Barth, 1948, Stop 2).

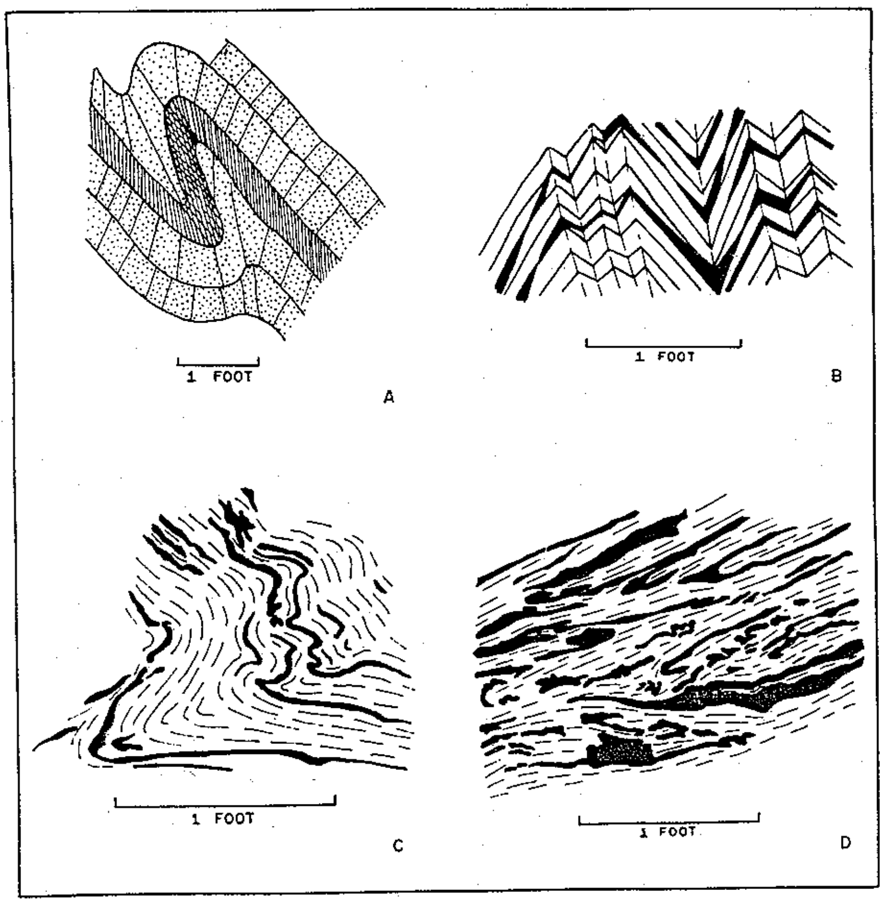


Figure 11. Deformation and progressive regional metamorphism of slate, and of associated siliceous rocks (dots and solid black patterns)

5. East of Clove Valley, biotite and garnet become progressively coarser and more abundant in pelitic rocks. The style of deformation also changes from a dominance of fracture cleavage to a dominance of small-scale plastic folding and wrinkling (Fig. 11C). Fracture cleavage is uncommon; it appears that the slaty and fracture-cleaved rocks change eastward by plastic deformation and mimetic recrystallization into these rocks with folded foliation.

6. For a mile or so eastward the rocks continue to coarsen; muscovite and staurolite porphyroblasts become abundant, and feldspar is common both in the rock and in associated quartz veins. This rock is best described as a well-foliated gneiss (Fig. 11D). Flattening has brought the siliceous layers into near

parallelism; only the apices of folds have been preserved (Balk, 1936, Fig. 13). The foliation that wraps around the apices of folds in Figure 11C is largely superseded by a foliation parallel to the limbs and axial planes of the highly compressed folds (Balk, 1936, p. 712). The new axial-plane foliation, marked by pronounced parallelism of mineral grains, apparently developed by plastic flowage parallel to foliation, accompanied by flattening at right angles to the foliation.

These six structural types are, of course, only samples of an exceedingly complex intergradational sequence. Balk's (1936) descriptions and figures far better capture the range of structural types present. His discussion is somewhat confusing, however, for, although he refers constantly to slate, he uses the term fracture cleavage for all forms of closely spaced parallel cleavage, including slaty and fracture cleavage as used in this paper for the Martinsburg, and phyllitic flow cleavage in Dutchess County.

The relation of slate to phyllite and schist in the Dutchess County area is illustrated in Figure 12. Well-formed axial-plane cleavage, accompanied by a high degree of preferred orientation of platy and elongated minerals, develops only under conditions of intense penetrative plastic flow parallel to the plane of foliation, associated with shortening at right angles to the plane of foliation. These conditions may be realized at two extreme conditions, either while the pelite has a relatively high connate water content and hence behaves plastically, or after deep burial when high temperatures and confining pressure again permit large plastic flow.

The formation of slaty cleavage thus depends on a set of circumstances essentially independent of the deep burial and elevated temperatures responsible for regional metamorphism. A pelite, dewatered before deformation, presumably passes directly to a fracture-cleaved shale which then changes into phyllite without passing through a slate stage. On the other hand, slate, if formed essentially independently of regional metamorphism, would generally show evidence of deformation of the slaty cleavage during movements accompanying initial stages of a later regional metamorphism.

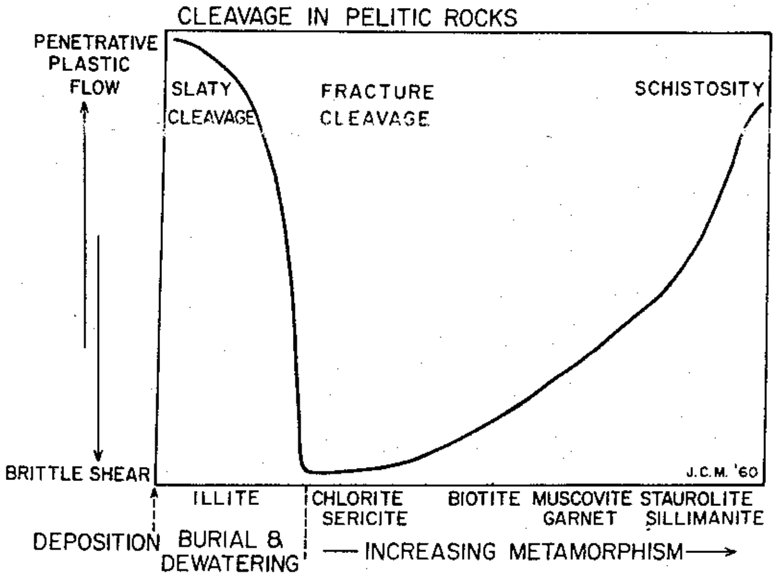


Figure 12. Suggested conditions for development of foliation in pelitic rocks, Dutchess County, New York

ACKNOWLEDGMENTS

During the past decade I have been privileged to visit the Water Gap area with numerous graduate and undergraduate students, faculty colleagues, and other distinguished geologists. The resulting discussions undoubtedly are reflected in this paper. I am particularly indebted to Sheldon Judson whose discovery of sandstone dikes injected parallel to slaty cleavage set off a train of thought, conjecture, and observation which crystallized as the theory of origin of slaty cleavage herein presented. Field trips and discussions with A. G. Fischer, Jean Goguel, J. O. Kalliokoski, Lucian Platt, and John Rodgers were particularly helpful in suggesting desirable modifications and amplifications. I am grateful to A. F. Buddington and A. G. Fischer and to the editors of this volume for criticising the manuscript and for their valiant efforts to improve its readability and effectiveness.

REFERENCES CITED

Ashley, G. H., 1931, A syllabus of Pennsylvanian geology and mineral resources: Pa. Geol. Survey, 4th ser., Bull. G 1, p. 159

Athy, L. F., 1930, Compaction and oil migration: Am. Assoc. Petroleum Geologists Bull., v. 14, p. 25–36

Balk, R., 1936, Structural and petrologic studies in Dutchess County, New York. Part I. Geologic structure of sedimentary rocks: Geol. Soc. America Bull., v. 47, p. 685–774

Balk, R., and Barth, T. F. W., 1948, Metamorphosed rocks, Dutchess County, New York: Geol. Soc. America Guidebook of Excursions, Excursion No 10, p. 95–107

Barth, T. F. W., 1936, Structural and petrological studies in Dutchess County, New York. Part II. Petrology and metamorphism of the Paleozoic rocks: Geol. Soc. America Bull., v. 47, p. 775–850

Bates, T. F., 1947, Investigation of the micaceous minerals in slate: Am. Mineralogist, v. 32, p. 625–636

Behre, C. H., Jr., 1933, Slate in Pennsylvania: Pa. Geol. Survey, 4th ser., Bull. M 16, 400 p.

Broughton, J. G., 1947, An example of the development of cleavage: Jour. Geology, v. 54, p. 1–18.

Bucher, W. H., 1956, Role of gravity in orogenesis: Geol. Soc. America Bull., v. 67, p. 1295–1318

Buessem, W. R., and Nagy, B., 1954, The mechanism of the deformation of clay: Clay and Clay Minerals, Natl. Acad. Sci., Natl. Research Council, Pub. 327, p. 480–491

Campbell, J. D., 1951, Some aspects of rock folding by shearing deformation: Am. Jour. Sci., v. 249, p. 625–639

Cuthbert, F. L., 1946, Differential thermal analysis of New Jersey clays: N. J. Dept. Conserv., Miss. Geol. Paper, 20 p.

Dale, T. N., 1899, The slate belt of eastern New York and western Vermont: U. S. Geol. Survey 19th Ann. Rept., pt. 3, p. 153–300

Dale, T. N., *et al.*, 1914, Slate in the United States: U.S. Geol. Survey Bull. 586, 220 p.

De Sitter, L. U., 1956, Structural geology: New York, McGraw-Hill Book Co., Inc., 522 p.

Dickinson, G., 1953, Reservoir pressures in Gulf Coast Louisiana: Am. Assoc. Petroleum Geologists Bull., v. 37, p. 410–432

Emery, K. O., and Rittenberg, S. C., 1952, Early diagenesis of California basin sediments in relation to origin of oil: Am. Assoc. Petroleum Geologists Bull., v. 36, p. 735–806

Gonzalez Bonorino, F., 1958, El origin mecanico de la esquistosidad: Fac. Cienc., Contr. cient. S. Geol., Univ. Buenos Aires, v. 2, p. 29–94

——— 1960, The mechanical factor in the formation of schistosity: 21st Internat. Geol. Cong. Proc., pt. 18, p. 303–316

Handin, J., and Hager, R. V., Jr., 1957, Experimental deformation of sedimentary rocks under confining pressure: tests at room temperature on dry samples: Am. Assoc. Petroleum Geologists Bull., v. 41, p. 1–50

——— 1958, Experimental deformation of sedimentary rocks under confining pressure: tests at high temperature: Am. Assoc. Petroleum Geologists Bull., v. 42, p. 2892–2934

Hedberg, H. D., 1936, Gravitational compaction of clays and shales: Am. Jour. Sci., 5th ser., v. 31, p. 241–287

Henin, S., 1956, Synthesis of clay minerals at low temperatures: Clays and clay minerals, Natl. Acad. Sci., Natl. Research Council, Pub. 456, p. 54–60

Hubbert, M. K., and Rubey, W. W., 1959, Mechanics of fluid-filled porous solids and its application to overthrust faulting: Geol. Soc. America Bull., v. 70, p. 115–166

Jannettaz E., 1884, Memoire sur les clivages des roches (schistosité, longrain) et sur leur reproduction: Bull. Soc. Géol. de France, 3rd ser., v. 12, p. 211–236

Knill, J. L., 1960, A classification of cleavages, with special reference to the Craignish District of the Scottish Highlands: 21st Internat. Geol. Cong. Proc., pt. 18, p. 317–325

Korn, H., and Martin, H., 1959, Gravity tectonics in the Naukluft Mountains of South West Africa: Geol. Soc. America Bull., v. 70, p. 1047–1078

Kümmel, H. B., 1940, The geology of New Jersey: N. J. Dept. Conserv. and Devel., Bull. 50, p. 203

Leith, C. K., 1905, Rock cleavage: U. S. Geol. Survey Bull. 239, p. 216

Morris, T. O., and Fearnsides, W. G., 1926, The stratigraphy and structure of the Cambrian slate belt of Nantle (Carnarvonshire): Geol. Soc. London Quart. Jour., v. 82, p. 250–299

Murray, H. H., 1954, Genesis of clay minerals in some Pennsylvanian shales of Indiana and Illinois. Clays and clay minerals, Natl. Acad. Sci., Natl. Research Council, Pub. 327, p. 47–67

Nelson, B. W., 1956, The illites from some northern Ohio shales: Clays and clay minerals, Natl. Acad. Sci., Natl. Research Council, Pub. 456, p. 116–124

——— 1960, Clay mineralogy of the bottom sediments, Rappahannock River, Virginia: Clays and clay minerals, Mon. 5, Earth Science ser., New York, Pergamon Press, p. 135–147

Purdue, A. H., 1909, The slates of Arkansas: Ark. Geol. Survey, p. 1–95

Ray, S., and Gault, H. R., 1961, Mineralogy of Jacksonburg (Middle Ordovician) formation in eastern Pennsylvania and western New Jersey: Am. Assoc. Petroleum Geologists Bull., v. 45, p. 39–50

Rubey, W. W., and Hubbert, M. K., 1959, Overthrust belt in geosynclinal area of western Wyoming in light of fluid-pressure hypothesis: Geol. Soc. America Bull., v. 70, p. 167–206

Shackleton, R. M., 1953, The structural evolution of North Wales: Liverpool and Manchester Geol. Jour., v. 1, p. 261–297

Smith, B., and George, T. N., 1948, North Wales (2nd ed.): British Regional Geology, Geol. Survey and Museum, 89 p.

Smoot, T. W., 1960, Clay mineralogy of pre-Pennsylvanian sandstones and shales of the Illinois Basin: Part I. Relation of permeability to clay mineral suites: Ill. Geol. Survey Circ. 286, 20 p.

Sorby, H. C., 1880, On the structure and origin of non-calcareous stratified rocks: Geol. Soc. London Quart. Jour., v. 36, 76 p.

Stose, G. W., 1930, Unconformity at the base of the Silurian in southeastern Pennsylvania: Geol. Soc. America Bull., v. 41, p. 629–657

Terzaghi, K., 1950, Mechanism of landslides, p. 83–123, *in* Paige, Sidney, Chairman, Application of geology to engineering practice: Geol. Soc. America, Berkey Volume, 327 p.

Turner, F. J., 1958, p. 215 *in* Fyfe, Turner and Verhoogen, Metamorphic reactions and metamorphic facies: Geol. Soc. America Mem. 73, 259 p.

Van Houten, F. B., 1954, Sedimentary features of Martinsburg slate, northwestern New Jersey: Geol. Soc. America Bull., v. 65, p. 813–818

White, W. S., 1949, Cleavage in east-central Vermont: Am. Geophys. Union Trans., v. 30, p. 587–594

Whitehouse, U. G., and McCarter, R. S., 1958, Diagenetic modification of clay mineral types in artificial sea water: Clays and clay minerals, Natl. Acad. Sci., Natl. Research Council, Pub. 566, p. 81–119

Wilson, G., 1946, The relationship of slaty cleavage and kindred structures to tectonics: Geol. Assoc. Proc., v. 57, p. 263–302

Woodward, H. P., 1957, Chronology of Appalachian folding: Am. Assoc. Petroleum Geologists Bull., v. 41, p. 2312–2327