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AN EXAMPLE OF THE DEVELOPMENT OF CLEAVAGES

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ABSTRACT

An attempt is made to follow the development of secondary structures in a slate, the Martinsburg formation in Warren County, New Jersey. In part of the area discussed, the structures are of the type common in slate regions with overturned folds, axial-plane flow cleavage, and the development of grain. Grain is believed to result from stretching of quartz grains in *a* rather than from tension normal to *ac* during elongation of the fold axis. Fabric analysis emphasizes the importance of elongation in *a*.

In the southern portion of the area described, other structures have been superimposed as a result of the movement of a thrust fault. The bedding is refolded, the flow cleavage is folded, and fracture cleavage parallels the axial planes. Closer to the thrust, antithetic rotation of the slate along the fracture cleavage has almost destroyed all evidence of the earlier flow cleavage and has caused the fracture cleavage itself closely to approximate flow cleavage in microscopic and megascopic appearance.

INTRODUCTION

The preservation of minute secondary structures is more nearly complete in slates than in almost any other rock. This is especially well illustrated by the highly deformed Ordovician slate belt running from northern Pennsylvania into New Jersey. C. H. Behre, Jr.,[1] has shown that in this area the many megascopic structures make structural interpretation far more complete than is usually possible. This paper summarizes an investigation of the New Jersey slates made by the writer in 1938–40.

GENERAL DESCRIPTION

The Martinsburg formation, of middle and upper Ordovician age, extends northeast across New Jersey from latitude 75° 05′ west to latitude 74° 35′ west, in a belt approximately 7 miles wide. For about two-thirds of that distance a septum of older Kittatinny limestone (Allentown and Beekmantown) divides the belt into two parts. Elsewhere the Martinsburg formation is found only in small areas which have been downfaulted between pre-Cambrian ridges. The region discussed in this paper comprises an area of about 33 square miles south of the limestone band and immediately across the river from the Pennsylvania slate belt (Fig. 1). The thickness of the Martinsburg, where estimated along the Delaware River, ranges from 3000 to 11,000 feet.[2,3]

Three planes of reference can be distinguished in the slates; the bedding, the

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[1] "Slate in Pennsylvania," *Pa. Geol. Surv. Bull.*

[2] G. W. Stose, "Uncomformity at the Base of the Silurian in Southeastern Pennsylvania," *Bull. Geol. Soc. Amer.*, Vol. XLI (1930) p. 634.

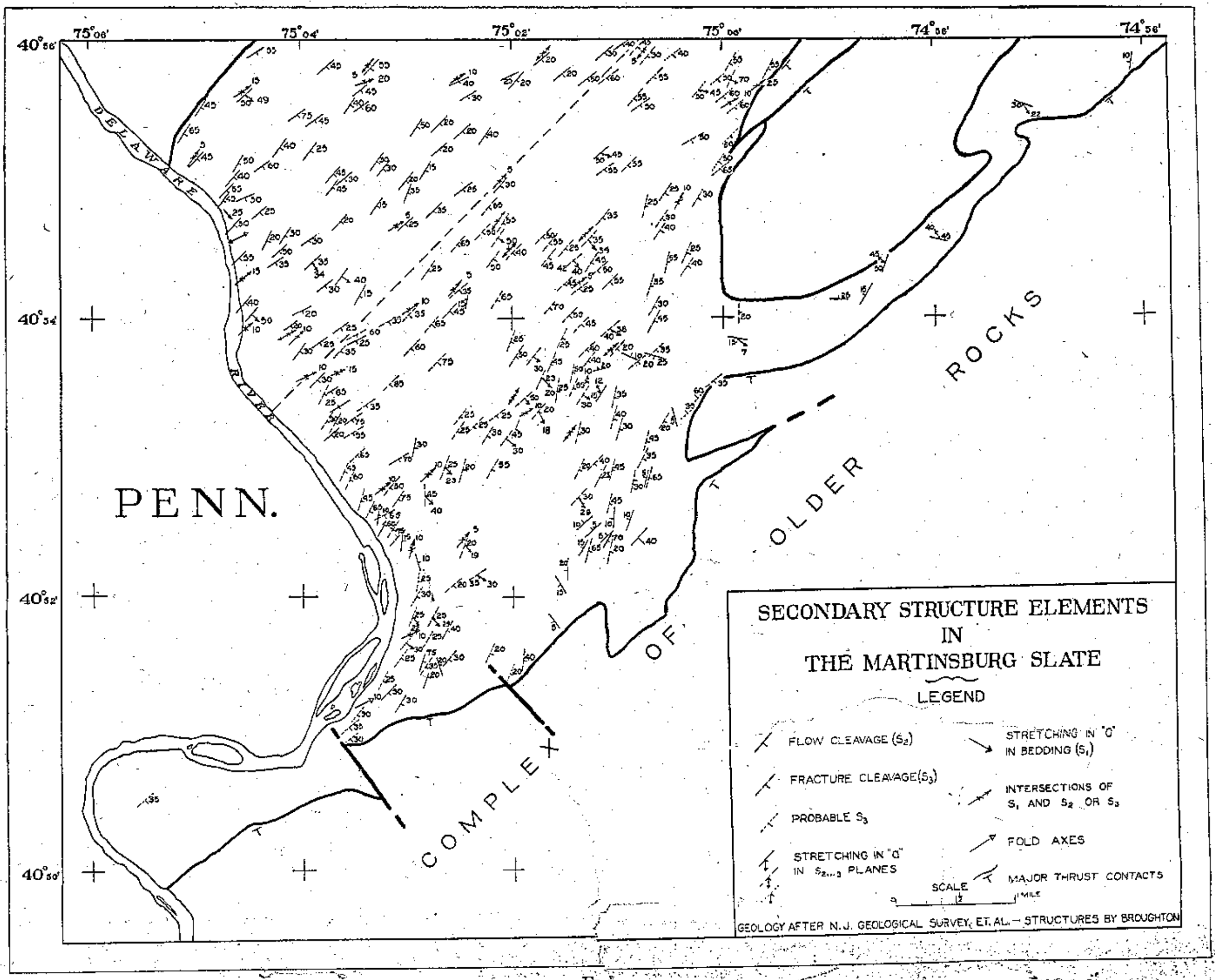
SECONDARY STRUCTURE ELEMENTS
IN
THE MARTINSBURG SLATE
LEGEND
FLOW CLEAVAGE (S_2)
FRACTURE CLEAVAGE(S_3)
PROBABLE S_3
STRETCHING IN "O" IN $S_{2..3}$ PLANES
STRETCHING IN "O" IN BEDDING (S_1)
INTERSECTIONS OF S_1 AND S_2 OR S_3
FOLD AXES
MAJOR THRUST CONTACTS
SCALE
0
½
1 MILE
GEOLOGY AFTER N. J. GEOLOGICAL SURVEY, ET. AL. — STRUCTURES BY BROUGHTON
PENN.
DELAWARE RIVER
OLDER ROCKS OF COMPLEX
75°06'
75°04'
75°02'
75°00'
74°58'
74°56'
40°56'
40°54'
40°52'
40°50'

Fig. 1

flow cleavage, and the fracture cleavage. They will be referred to as S_1, S_2, and S_3, respectively. All structures are described by reference to a triaxial coordinate system. Axis *a* represents the direction of transport, whether it is in a bedding plane, a cleavage, or elsewhere. Axis *b* is normal to it and parallels the fold axes. Axis *c* is normal to the *ab* plane.

Compass directions are referred to a circle of 360° rather than to four quadrants of 90° each.

STRUCTURE

BEDDING (S_1)

The formation has been subdivided lithologically by Behre[4] into a lower, a middle, and an upper part. The lower part is characteristically a banded clay slate, though there are also thin sandstone beds. The middle member contains sandy beds as its most typical facies, though some truly slaty beds are also found in it. The uppermost member is banded like the lower, but there is less sand and the undivided beds are much thicker. The differences between these subdivisions are relative, and in areal mapping the line between them is drawn with difficulty.

A difference of opinion exists as to the actual occurrence of this upper member. Stose[5] believes that it is simply the lower member repeated by folding. Since the question can have little or no bearing on the subject of the slate structures, it will not be discussed further here.

Numerous thin sections of the slate were studied under the microscope. They show that the most common facies of the slate are (1) sericitic slate with carbonaceous matter and a small percentage of quartz and (2) beds made up predominantly of angular quartz grains. The latter beds are seldom more than 2 or 3 feet thick. A very noticeable structure of these sandy beds is an intricate folding, completely contained within the bed and emphasized by contorted films of black, probably carbonaceous, material. These folds seem to bear no regular relation to the axes of deformation and show no parallelism among themselves. It was not possible to collect a satisfactory specimen for petrofabric analysis. W. H. Twenhofel[6] assigns structures of similar appearance to deformation during sedimentation. W. H. Bucher (personal correspondence, 1944) calls this "interstratal flow," differential movement between beds connected with unequal compaction of layers of different mobility.

Carbonate lenses occur locally in the slate. They are very minor features stratigraphically but are important structurally and therefore are discussed in the sections on folds and fold axes.

FOLDS AND FOLD AXES

Throughout the area the bedding has been folded and overturned to the northwest. Behre's areal map (1933, Pl. 24) seems to indicate that these small folds are only minor features. He shows the entire slate belt between the overthrust contact on the south and the limestone band on the north as one major syncline. The whole area can therefore be thought of as a synclinorium.

The fold axes most commonly pitch 5°–20° to the northeast. At a few localities they are horizontal, and rarely pitch to the southwest.

In the highway cut along the Delaware River between Columbia and Delaware, New Jersey, the slate is well exposed. Figure 2, *A*, is a diagram of the poles of bedding planes measured in this

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[4] P. 136 of ftn. 1.

[6] *Principles of Sedimentation* (New York: Mc

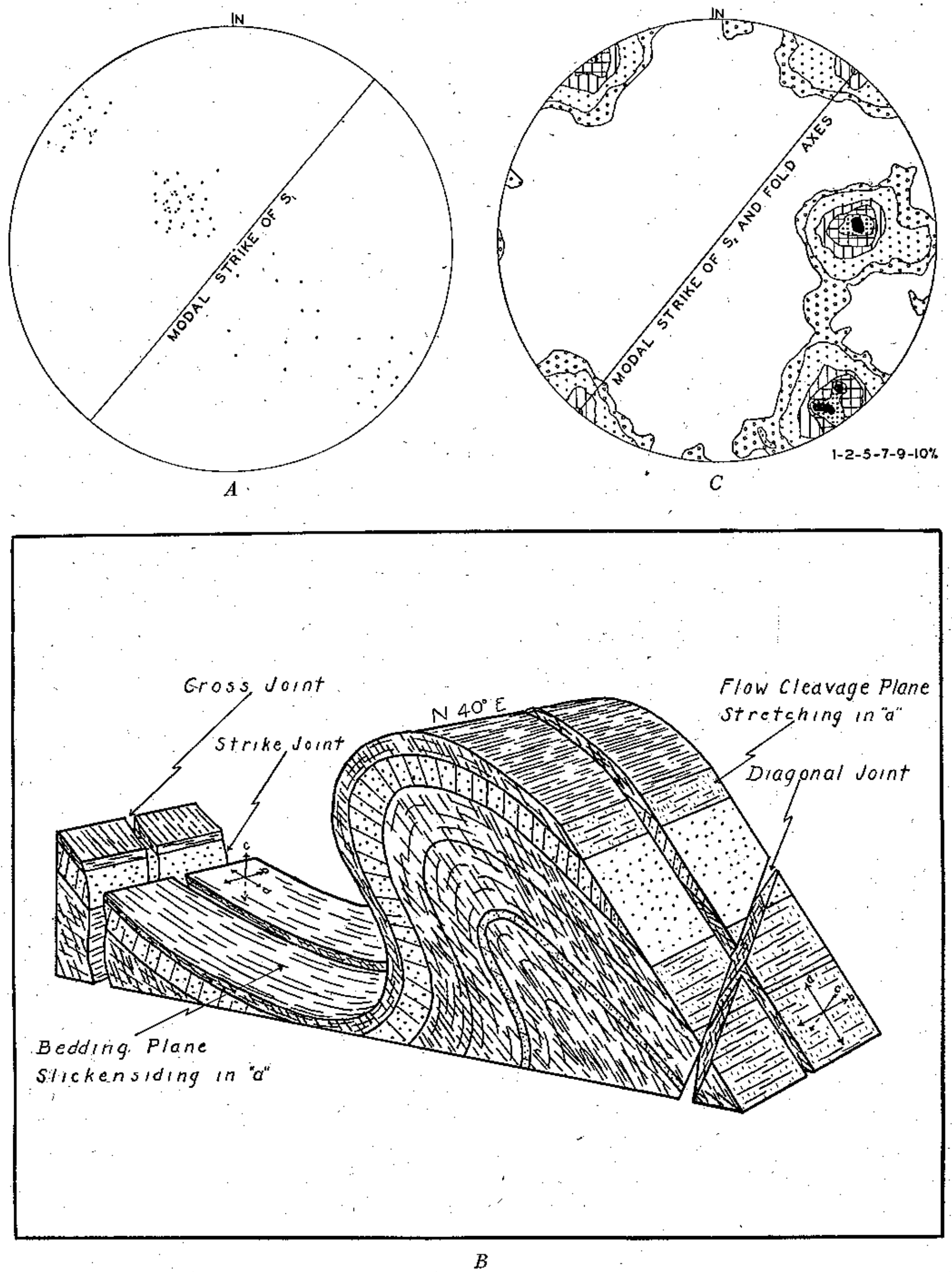

FIG. 2.—Diagrammatic analysis of slate structures (Columbia-Delaware section in northern or "normal" area): *A:* Seventy-five poles of bedding planes. *B:* Schematic diagram of major structural elements. *C:* Two hundred joint poles.

section, projected on a horizontal plane. The most common (modal) strike of the bedding derived from these data is 45°, and the dip is 60°–70° southeast. The axes are horizontal or dip very gently to the northeast. The vertical girdle of points, which passes through the center of the diagram, indicates that the fold axes are ± horizontal. The concentration of points just northwest of the strike line indicates the predominance of overturning, with the gently dipping southeast limbs exposed over a greater area.

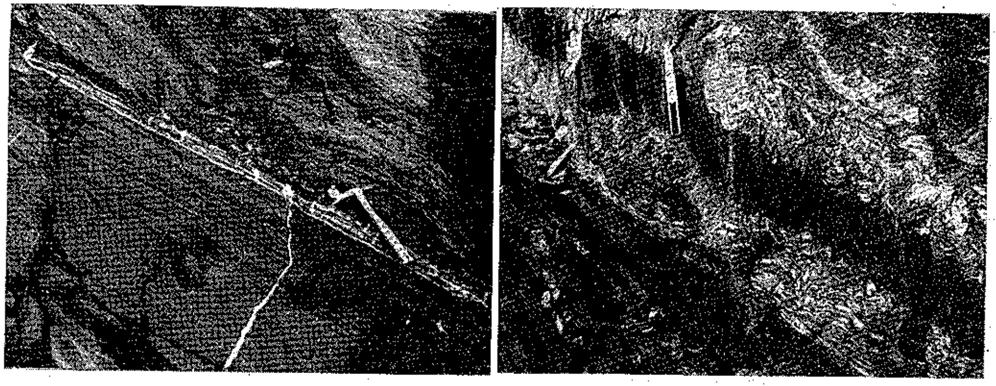
A B

Fig. 3.—*A: bc* tension joints have opened up across calcite horizon ("silver ribbon") and later have been filled with quartz. Columbia-Delaware section. *B:* Shear folding along flow cleavage plane in a wide calcite horizon.

Prior to the development of cleavages, all movements resulting from folding took place along the bedding planes. This movement was in the direction fixed by the intersection of the *ac* plane and the bedding, i.e., in the *a* direction.

The most noticeable result of the folding in the sandy beds is thickening at crests and at troughs of folds. Less common is stretching of a competent horizon on the long limb of a fold so that it becomes attenuated and in some cases has broken across the bed to form a blunt lens. This is an extreme result of stretch-

boudinage structure,[7, 8] which has no recognizable strike and is supposedly dependent for its distinctive barrel-like cross section on both tension and compression.

As mentioned by Behre,[9] horizons of almost pure calcite up to 3 or 4 inches thick are common and are most noticeable on the southeast limbs of the folds. They have evidently been planes of movement, as they are deeply slickensided in the *a* direction. At places these bedding slips break across at a low angle and become true thrust faults. Extensive movement has resulted in the development of wide ribbons with included angular slate fragments. Associated with the movement in *a*, minor tension joints in *bc* have been opened and then filled somewhat later with quartz (Fig. 3).

The bedding is intersected by flow

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[7] P. J. Holmquist, "On the Relations of the 'Boudinage Structure,'" *Geol. fören. i. Stockholm förhandl.*, Vol. LIII, Part II (1931), pp. 193–208.

[8] T. T. Quirke, "Boudinage and Unusual Structural Phenomenon," *Bull. Geol. Soc. Amer.*, Vol. XLVII (1923), pp. 649–60.

cleavage. Because the flow cleavage normally lies in the axial plane of the overturned folds, these intersections may, for all practical purposes, be regarded as parallel to the fold axes (*b*). The pitching of folds results in minor convergences and divergences of the two, but for small angles of pitch these differences are negligible.

South of the dashed line on the map (Fig. 1), fracture cleavage is superimposed on flow cleavage. Here the intersections between bedding and fracture cleavage have been mapped as *b′*. As described below, when viewed in plan, the fracture cleavage cuts all earlier secondary *S* planes at a small angle. For this reason, the intersections with bedding are not so regular as in the northern area.

So far, all folding described has been flexure folding, in which the bedding is the important structural element. As soon as a cleavage develops which renders its active role. From that time on, most movements will take place along the new *S* planes. The bedding is passive. A later stage of the folding illustrates this principle. Shear folding becomes the dominant type immediately upon formation of the cleavage planes. It results from minute movements along the cleavage planes and, in this region at least, simply accentuates the original folds. Such structures have been described by E. Cloos.[10]

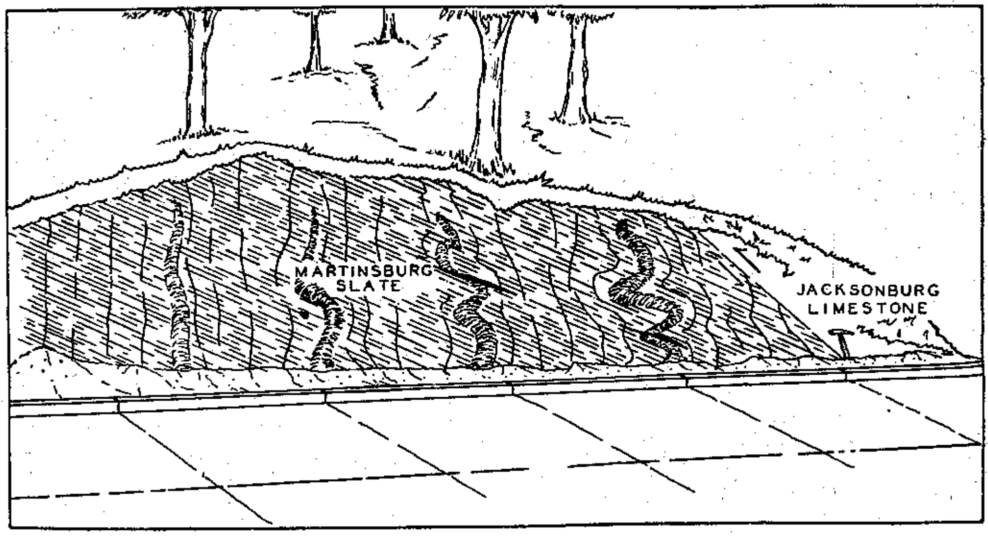

FIG. 4.—Aclinal folding. Sheared S_3 transects bedding and is folded with it. Black bars across folds represent quartz veins.

The latest stage of folding is in the vicinity of the major thrust fault (Fig. 1). The only locality where such folding may be observed is in the road cut on New Jersey Route No. 6 (Belvidere division). Here carbonate lenses have been contorted to a degree of intensity which is inversely proportional to their distance from the major overthrust contact. In this cut the thrust is represented by

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[10] "The Application of Recent Structural Methods in the Crystalline Rocks of Maryland," *Md.*

Jacksonburg limy shale resting on the Martinsburg with 4–6 inches of gouge marking the contact. The bedding of the slate is generally vertical, with strong folding in the immediate vicinity of the lenses. The two lenses which have been most highly deformed are within 10 feet of the thrust; the last of the series is 125 feet from the contact and is the most gently folded. As shown in Figure 4, the cleavage (S_3) has been folded with the bedding. An apparently unavoidable conclusion is that this local folding has been caused by downward compression exerted by the overriding Jacksonburg on the vertical slate beds. It shows most strongly in the limy lenses because of their plastic character. Comparable structures, with similar interpretation, have been given the name "aclinal folds" by Edward Greenly.[11]

FLOW CLEAVAGE (S_2)

In order that a clear picture of the structural elements and their relations may be built up, it is important that flow and fracture cleavage be recognized as distinct features, although genetically there need not be, and probably is not, any difference between the two. By flow cleavage the author means a cleavage which has developed by rotation, flattening, and growth of mineral grains into approximate parallelism. The use of the term "fracture cleavage" is limited in this paper to a cleavage of the type defined by C. K. Leith[12] as "dependent for its existence on the development of incipient parallel fractures which by subsequent welding or cementation remain planes of weakness." In most cases the parallel fractures appear as minute faults associated with crenulations of the particular *S* plane which has been deformed. If this purely formal definition were followed, a cleavage plane would have its classification changed from flow cleavage to fracture cleavage as it passed from a shaly to a sandy bed (R. Balk[13]). A reasonable practice seems to be to use the name "flow cleavage" for the type that dominates at any particular exposure and therefore represents the highest degree of cleavage development at that exposure.

No!

For the sake of clarity the slate area as mapped may be divided into a northern, or "normal," area and a southern area. In the first the structures are as described by Behre in Pennsylvania, while to the south they differ radically. The approximate line of demarcation between the two areas is marked by a broken line on Figure 1.

In the northern area, flow cleavage is the dominant secondary structure. Its attitude is extremely constant, striking 40° and dipping 45° southeast. This cleavage is a true axial-plane cleavage, which permeates the entire rock (Fig. 8, *A*). Bedding as a distinct plane of discontinuity has vanished and, except for the massive sandy beds, may be recognized only by color changes dependent on composition. The angle between the bedding and the cleavage may range between 0° and 90° (Fig. 5). As others have noted elsewhere, the angle at which flow cleavage crosses a bed is dependent on the competency of the bed and is always larger in the sandy members.

X

In the southern part of the slate belt, intricate structures are found involving

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[11] "The Geology of Anglesey," *Mem. Geol. Surv. Great Britain* (London, 1919), p. 190.

[12] "Rock Cleavage," *U.S. Geol. Surv. Bull.* 239

[13] "Structural and Petrological Studies in Dutchess County, New York. I. Geological Structure of Sedimentary Rocks," *Bull. Geol. Soc. Amer.*, Vol.

fracture cleavage, together with folded flow cleavage and refolded bedding. These structures are described below in more detail. However, it should be noted here that, south of the zone bounding the ordinary structures, flow cleavage becomes progressively more subordinate until, near the thrust contact, it has faded to a relict structure. In this belt, bedding and flow cleavage are most commonly parallel or subparallel.

Movement in the direction of *a* may be noted in the flow cleavage, as well as in the bedding. Evidence of this move-

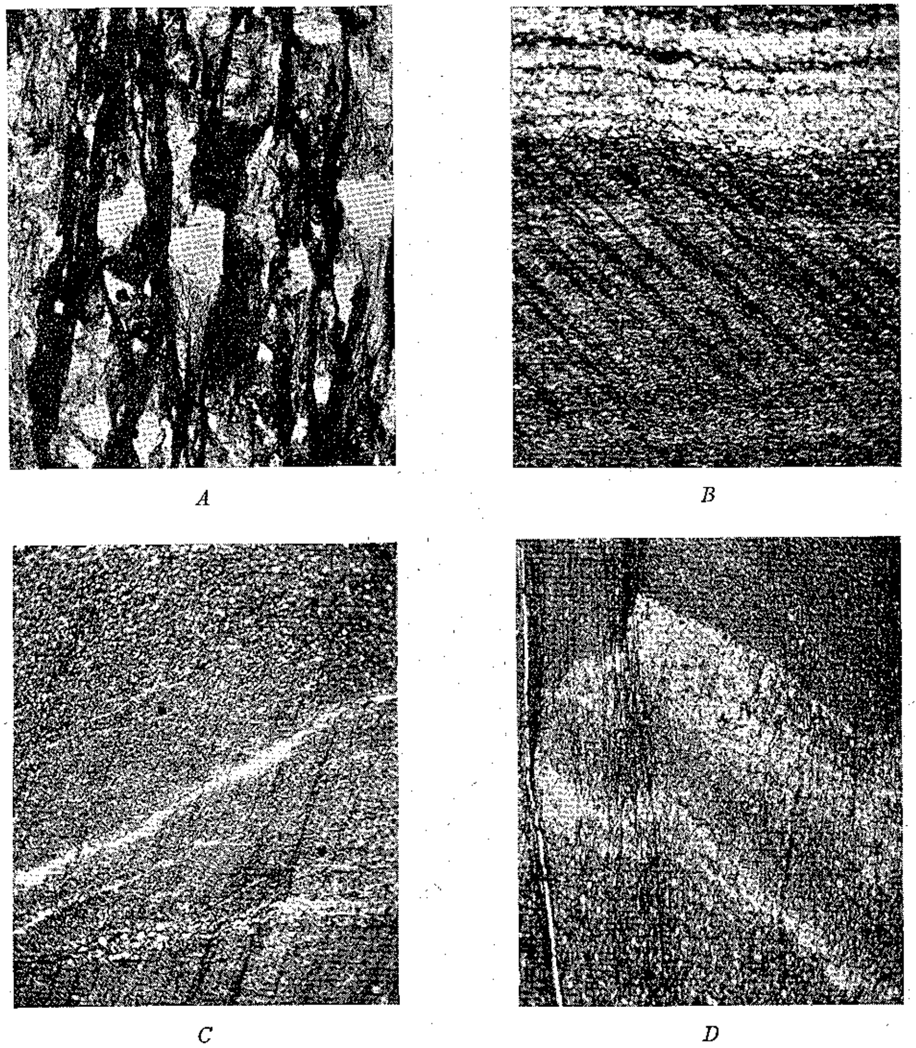

FIG. 5.—*A:* Quartz grains elongated in *a* of flow cleavage. Photomicrograph of Martinsburg slate near Pen Argyl, Pennsylvania, lent by Pennsylvania Geological Survey. *B:* Fracture cleavage dominant. Bedding and flow cleavage essentially parallel. Quartz grains elongated in *a* of flow cleavage. One-quarter mile east of Ramseysburg on road to Hope (sp. 39–65). *C:* Fracture cleavage dipping steeply, flow cleavage gently, to the left. One-half mile southeast of Delaware (sp. 39–78). *D:* Same specimen as Fig. 7, *D*. Relict flow cleav-

ment can be seen very faintly in cleavage planes, expressed by a smearing-out of pyrite flakes into tiny parallel lenses. Other minerals show the same habit but cannot be identified. That this involves true stretching of the rock and not merely slickensiding is borne out by the microscopic evidence, which shows all quartz grains elongated in *a* (Fig. 5, *A*). This direction of elongation is included within the *ac* plane of potential weakness, generally known as the "grain" of slate. The elongation of quartz grains was developed during the formation of the flow cleavage, in the end stages of the folding process. The writer would question recent statements in the literature[14] that elongation of material in the axial plane of a fold normal to the direction of the fold axis is rare or questionable. Grain is a result of this quartz elongation (as well as that of other minerals). Interpretation of this pervasive structure as a tensional effect of the elongation of fold axes fails when it is recognized that the stretching in *a* developed at the same time as the h0l cleavage planes. The capacity of slate to be broken along these *ac* grain surfaces is directly dependent on the development of flow cleavage and the resulting mineral orientation.

FRACTURE CLEAVAGE (S_3)

In the belt of "normal" structures (northern area), fracture cleavage seems to be absent. The structure mapped by Behre as fracture (false) cleavage appears as small jointlike fissures, which give a wavy, crinkled effect to the flow cleavage (Fig. 7, *C*). In appearance it is similar to structures usually identified as fracture cleavage. It strikes parallel to the flow cleavage and dips 90° from it. Since it is found most commonly where thin shale beds are sheared between massive sandy horizons, Behre[15] ascribed its origin to such movement. It is now apparent that the origin is somewhat more complex (Fig. 6, *A* and *B*). The writer believes that the planes were formed originally as a result of tension parallel to *a* in the cleavage planes. Microscopic study shows that they are actually tiny gashes paralleling *bc* which peter out no more than 3 mm. from their surface of origin. The action of the bedding movement (Movement 1, Fig. 6, *B*) was secondary and resulted in slipping and flattening of the flow-cleavage planes (Movement 2, Fig. 6, *B*) by rotation between the massive sandstone layers. This caused an antithetic movement along the *bc* planes, which folded and dragged the flow-cleavage planes (Movement 3, Fig. 6, *B*). This structure has been noted only on the gently dipping southeastern limbs of the folds.

As one proceeds from north to south, one encounters in the vicinity of Delaware a fracture cleavage which is later than the bedding and the flow cleavage of the region as a whole. The dividing zone between the "normal" area and that in which this cleavage predominates parallels the regional strike and is so sharp that it has been represented on the inset map as a broken line. In a few localities this transition zone widens to about half a mile. From here on southward to the major overthrust, the dominant structure is a well-developed fracture cleavage which parallels the axial planes of flow-cleavage folds. This association indicates that it is genetically related to the folding. Locally, especially in the vicinity of quartz reefs, the contortion of S_2 is very strong (Fig. 8, *B*).

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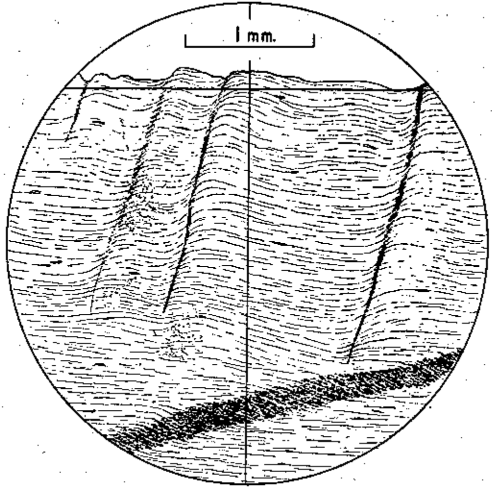
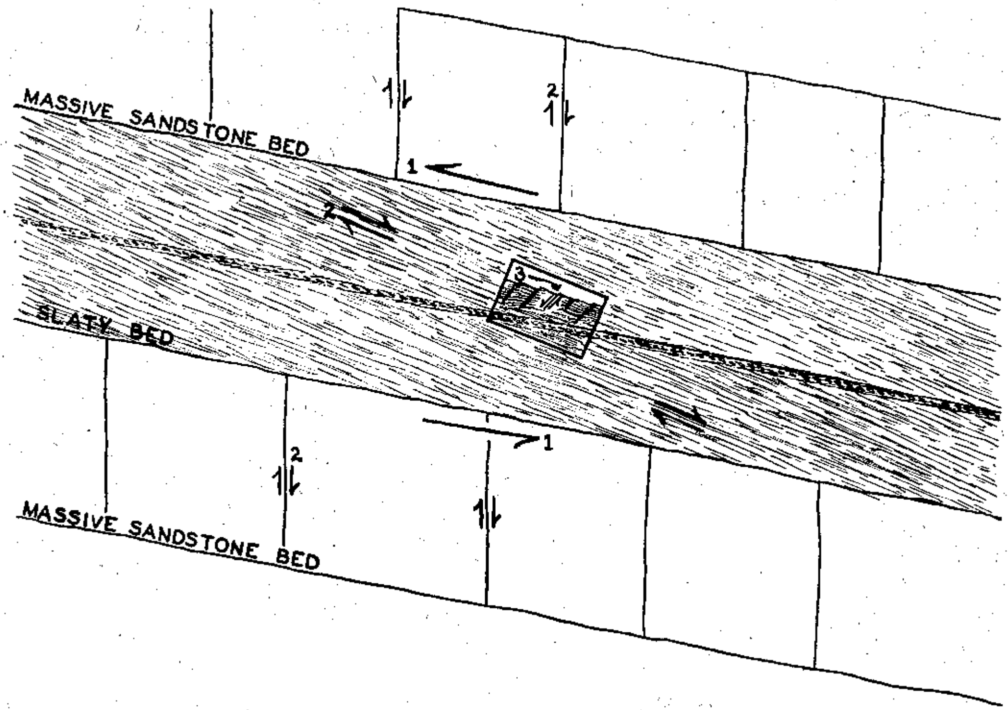
[14] E. B. Knopf, "Structural Petrology," *Geol.*

Elsewhere the flow cleavage is found at a small angle to, or parallel with, the bedding (Figs. 5, *B* and 7, *B*).



A

Relations of the three *S* planes to one another are particularly well exhibited in the Delaware, Lackawanna, and Western Railroad cut at Ramseysburg (Fig. 8, *B*) and a few hundred feet east of that cut on the road to Hope. At the latter exposure, numerous small, steep thrust faults have formed parallel to the fracture cleavage and then have broken through at anticlinal crests. Generally, where this late cleavage was formed, subsequent movement along it or along paralleling faults indicates antithetic rotation[16] to the northwest. Rotation of fracture-cleavage planes is indicated by drag of the earlier *S* planes and suggests flattening of S_3 as a result of continued pressure from the southeast.



B

FIG. 6.—*A*: Camera lucida drawing of rotated *bc* tension joints. *B*: Diagrammatic interpretation of

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[16] "Structure Elements of Domes," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. XX (1936), p. 61.

Slipping of the planes past one another has produced strong slickensiding on every fracture-cleavage surface. It is much more easily visible than the stretching along *a* in the flow cleavage, although it is not so pervasive. Consequently, it has had no effect on the internal structure, except possibly in a few localities where deformation was stronger.

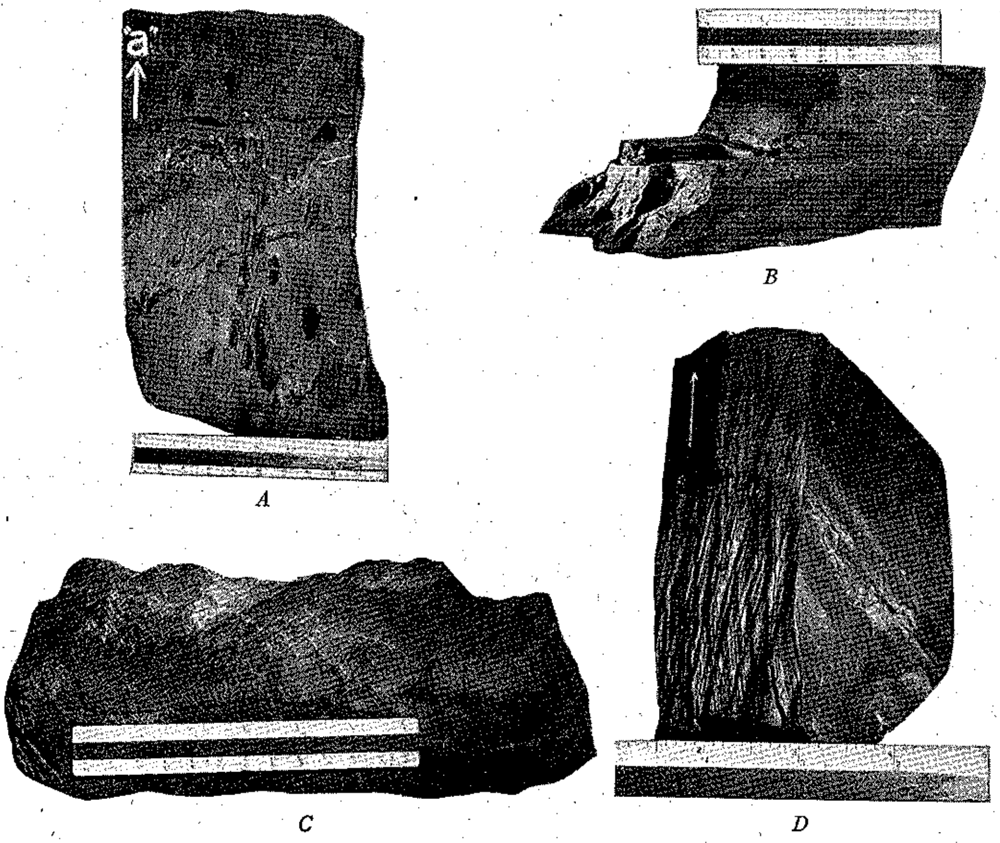
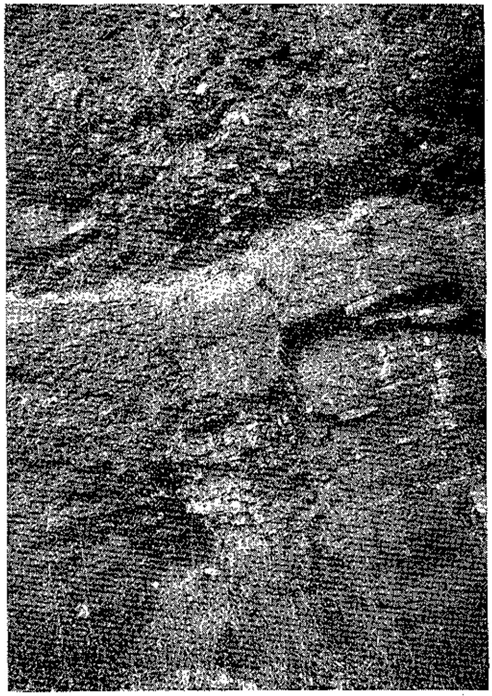


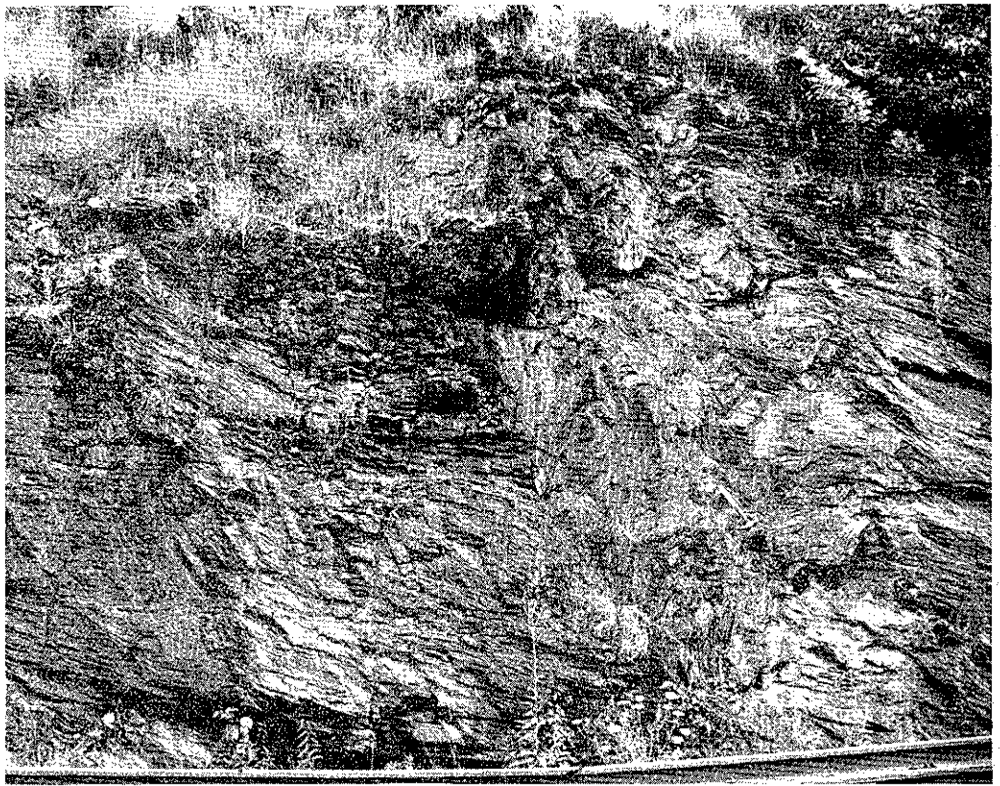
FIG. 7.—*A:* Fossils in Jacksonburg limestone pulled out by movement in *a* along bedding. Rock splits parallel to grain (*ac*). Near thrust contact, ¾ mile south of Swayse's Mills. *B:* Fracture cleavage dominant. Bedding and flow cleavage essentially parallel. One-quarter mile east of Ramseysburg on road to Hope (sp. 39–65). *C: bc* joints developed normal to *a* of flow cleavage. Columbia-Delaware section. *D:* Sheared fracture cleavage. Bedding dips away and to the right of the observer. Relict flow cleavage dips steeply to the left. Pennsylvania R.R. cut—Manunka Chunk (sp. 39–74).

Over most of the area these features of the fracture cleavage persist to the localities marked on the map as "probable S_3," its appearance becomes so similar to normal flow cleavage that it was originally mapped as such (Fig. 8, *C*). Nevertheless, the writer has become convinced that it is the same fracture cleavage but that the slate has undergone intense deformation. As stated above, the original flow cleavage occurs at these exposures as a relict structure. This may be seen in the railroad cut at Manunka Chunk. Figure 7, *D*, is a good example of

A



C



and of the bedding. In thin section (Fig. 5, *D*), flow cleavage is not visible except upon insertion of the gypsum plate, when a faint structure may be seen crossing both fracture cleavage and bedding at an angle. The fracture-cleavage plane has lost its typical microscopic appearance and has developed into a structure which seems to be transitional between fracture cleavage and flow cleavage. The uniform elongation of quartz grains in S_2, observed farther north, has disappeared. The author has interpreted this phase as the result of continued and stronger pressures which have started to develop mineral reorientation and a resultant younger-generation flow cleavage along the fracture-cleavage planes.

Since the field work for this study was completed, a paper by W. J. Mead[17] has appeared, in which he sets up a threefold division for the secondary cleavages. Flow cleavage and fracture cleavage are two of the divisions. The third is "shear cleavage." Of this latter structure Mead says:

> This type of cleavage consists of roughly parallel, closely spaced surfaces of shear displacement on which platy minerals may have developed and into which they may have been dragged .... when the spacing is unusually close, shear cleavage may simulate and be easily confused with flow cleavage.

The writer believes that shear cleavage can be a transitional stage between flow and fracture cleavage. This is discussed below in more detail.

A genetic correlation of this regional fracture cleavage with the major overthrust, of which Jenny Jump Mountain is a part, seems to be an obvious conclusion. The main criteria on which this correlation is based are: (1) the bending of the fracture-cleavage strike opposite that part of the overthrust which seems to have advanced farthest, (2) the gradual increase in intensity of deformation toward the fault, and (3) the fact that the dip of the cleavage progressively flattens from north to south. All suggest the gradual building-up of stress from the southeast with antithetic rotation of the S planes, until, in the final stage, the weaker rocks were overridden by the older gneisses and limestones.

The sharp division between the two structure types in the slate is peculiar. The sudden change from fracture cleavage to flow cleavage northward suggests the possibility of a thrust entirely within the slate, although no such structure was observed. The author has refrained from adding another hypothetical fault to the many that have been postulated in the Appalachian province.

JOINTS

Three well-developed sets of joints cut the slate and its structures throughout the northern, or normal, part of the slate belt. Two hundred joints were measured along the Delaware River between Delaware and Columbia and their poles plotted on an equal-area net (Fig. 2, *C*). Comparison of this diagram with the block diagram (Fig. 2, *B*) illustrates their relation to the axes of deformation.

The submaximum in the first and third quadrants of Figure 2, *C*, represents vertical joints which are exactly at 90° to the strike of the fold axes. They are parallel to the grain of the *ac* direction in the rock and are thus in the proper geometric position for cross-joints. Grain of slate is such a pervasive plane of weakness that in any cut or excavation large vertical faces develop parallel

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[17] "Folding Rocks Flowage and Foliate Structures," *Jour. Geol.*, Vol. XLVIII (1940), pp. 1007–

found constantly throughout the slate area, regardless of the cleavage type which exists. These joints appear most commonly where diagonal joints are rare. The roughhewn character and position of these cross-joints would seem to indicate that they are natural partings along the slate grain. The unevenness of the *ac* joints is explained by the fact that eventual breaking is not along one plane but along many roughly parallel planes, all including and being guided by the direction of quartz elongation (*a*). It is uncertain whether the actual fractures resulted from tension caused by elongation parallel to the *b* axis during folding or by continued pressure in a northwesterly direction after formation of grain. In the latter case, the *ac* joints might be thought of as incipient tear faults.[18]

The sharpest and smoothest joints are inclined to the *b* axis of folding (Fig. 2, *C*) and are probably shear joints. They are commonly coated with calcite films.

Strike joints (Fig. 2, *C*) have a very regular strike. However, it is common for the dip to swing from northwest to southeast or vice versa within a single joint. These surfaces are not so smooth as are the diagonal joints.

All three sets are best developed when their strike and dip are nearest the position indicated by the maximum on the diagrams.

FAULTS

The major fault affecting the slate belt is the thrust fault which bounds it on the south. Bayley and Kümmel[19] have interpreted it as a flat overthrust. The areal map of Northampton County, Pennsylvania,[20] shows no fault extending across the Delaware River into Pennsylvania.

Field evidence indicates that the thrust fault does exist, but it cannot be stated with certainty that it is a flat overthrust.

At the exposure on New Jersey Highway No. 6, from which the folded carbonate lenses are described, Jacksonburg limestone was found resting on Martinsburg slate with a foot or less of gouge between the two. This exposure is only ½ mile east of Northampton County. The fault dips 40° southeast. On the evidence of this exposure, the author has drawn the fault line on his map ¼ mile north of where it appears on the New Jersey State Geological Map (1933).

On the southwest end of Jenny Jump Mountain, Kittatinny limestone was found below pre-Cambrian gneiss. The contact was not seen. However, the limestone has been completely silicified in a zone at least 5 feet thick and has been sheared into flat-lying (5°–15°) folia.

In a new highway cut, ½ mile south of Swayze's Mills (2 miles southwest of Hope), the Jacksonburg cement rock is found in a highly contorted and shattered condition. Folding is intense, and stretching and lensing of sandy beds in *a* are common. A slab of rock taken from this locality shows fossils elongated parallel to *a* on the bedding planes (Fig. 7, *A*). The cement rock appears to be above the slate, but the actual contact was not seen. The author drew the fault line here farther north than it is drawn

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[18] T. S. Lovering, "Field Evidence To Distinguish Overthrusting from Underthrusting," *Jour. Geol.*, Vol. XL (1932), p. 651.

[19] W. S. Bayley, H. B. Kümmel, and R. D. Salisbury, "Raritan Folio," *U.S. Geol. Surv. Folio, 191*

[20] B. L. Miller and D. W. Fraser, "Northampton County, Pennsylvania," *Pa. Geol. Surv. Bull. C48*

on the state map, because of this exposure.

The attitude of fold axes around an outlier serves as a clue as to whether the rock mass is a true klippe or simply an anticlinal core. In the latter case, fold axes pitch outward in the surrounding rock. Not enough observations could be made at this locality. Nevertheless, as far as could be determined, fold axes in the slate pitch inward toward the limestone outlier. Since the limestone is the older rock, this synclinal structure indicates that there must be a fault separating the two.

Faults within the slate belt appear to be confined to renewed movement along zones of earlier fracture, such as the thrusting along fracture-cleavage planes near Ramseysburg. In places, faults have broken across the bedding planes as the dip changes near the crest of a fold. This is simply stronger movement of the same type that caused the common slickensiding in the *a* direction in the bedding planes. It is seen more often where flow cleavage and bedding are nearly parallel. In at least one case, rotation of the intermediate block has occurred between two slightly convergent bedding-plane faults. Feather joints may sometimes be noted branching off from the main plane of movement.

FABRIC

Fabric diagrams of typical specimens of the slate tend to corroborate the separation of the cleavage in the field.

Figure 9, *B*, is a diagram of two hundred quartz axes from a sandy layer in the slate of the "normal" area. This specimen (39–31) was collected along New Jersey Highway No. 8, 3¼ miles south of Columbia. The attitude of the flow-cleavage plane (S_2) has been indi-

age. The concentric circles represent those circles passing through the theoretical quartz tectonite maximums.[21] There is some elongation of the individual quartz grains in *a* of the flow cleavage, but this is not so marked as in the more shaly layers. The quartz grains average 0.05 mm. in diameter.

Coincidence of actual point maximums with those theoretically possible is the exception rather than the rule. However, rotation about *b* is indicated, inasmuch as all the more important maximums and submaximums fall on, or very near, some of the maximum circles. The maximum of 4 per cent at *a* is most easily identified.

It corresponds to Maximum I, which has been interpreted[22] as a result of quartz breaking into needles parallel to its *c* axis and orientation of the needles parallel to fabric axis *a*. A maximum of equal importance lies in the *ac* plane 56° ± from *a*. Lying, as it does, midway between the theoretical Maximums II and V (Fig. 9, *A*), its interpretation is questionable. There is no field evidence to support the hypothesis that it represents Maximum I of another cleavage plane. It will fall roughly on the VI circle if *a* is taken as an axis of rotation; but in this locality there is no evidence whatever to suggest that such was the case. Finally, it may be taken simply as a point maximum falling on the *ac* girdle I-II-V. Whatever the allocation, the author does not feel capable of giving an adequate interpretation.

Submaximums of 3 per cent each lie on the IV, VI, and III circles. The actual

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[21] H. W. Fairbairn, *Structural Petrology of Deformed Rocks* (1942), p. 68.

[22] David Griggs and J. R. Bell, "Experiments Bearing on the Orientation of Quartz in Deformed Rocks," *Bull. Geol. Soc. Amer.*, Vol. XLIX (1938),

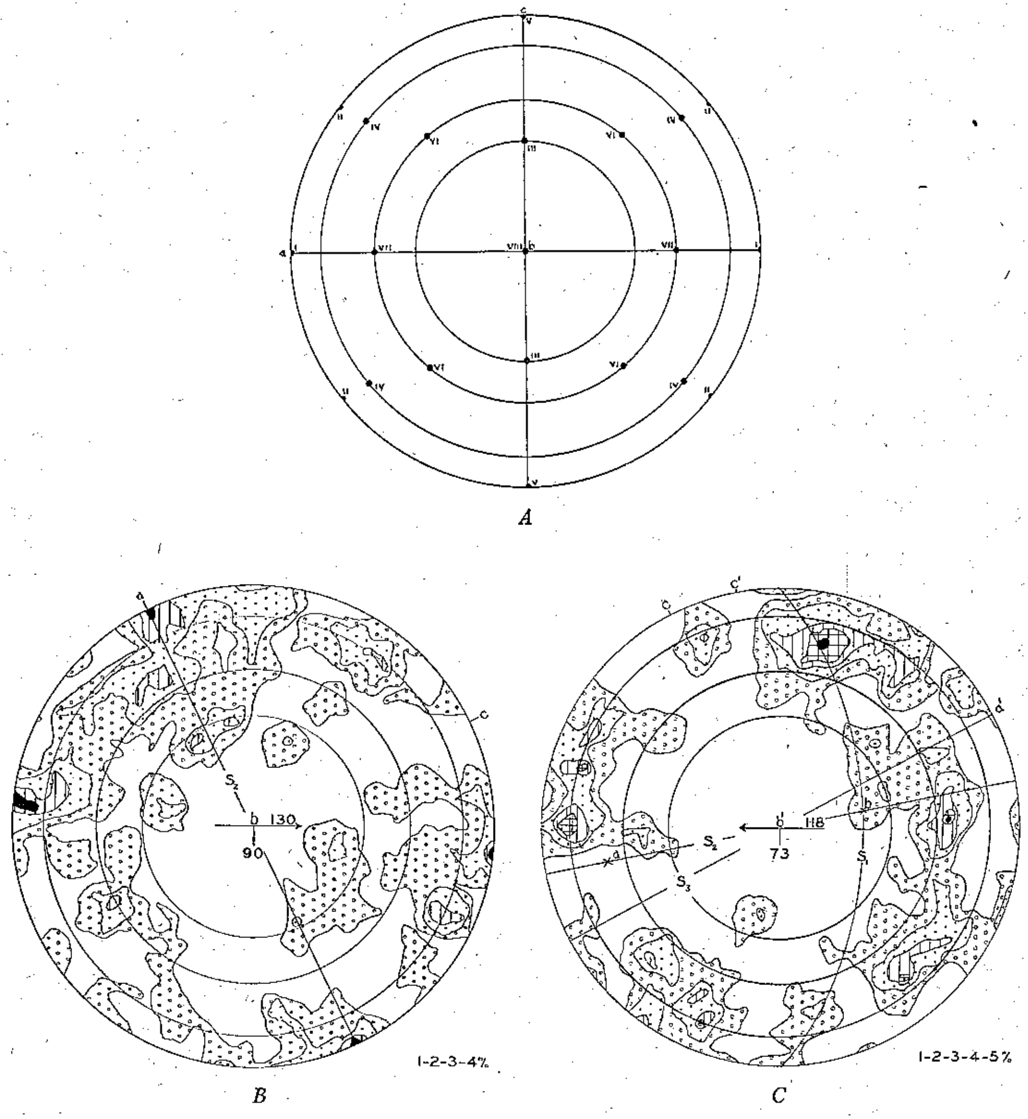

FIG. 9.—*A:* Theoretical quartz tectonite maxima after H. W. Fairbairn in *Structural Petrology of Deformed Rocks* (Cambridge, Mass.: Addison-Wesley, 1942). Drawing reproduced by permission of the author. *B:* Fabric diagram with optic axes of 200 quartz grains in sp. 39–31. *C:* Fabric diagram with optic axes of 200 quartz grains in sp. 39–74.

and theoretical maximums coincide in only one case.

Figure 9, *C* (39–74), is a quartz diagram (two hundred axes) from the slate of the southern area, in which the flow cleavage appears as a relict structure. The specimen was collected along the Belvidere branch of the Pennsylvania Railroad, 1¼ miles south of the junction with the Delaware, Lackawanna, and Western Railroad at Manunka Chunk. All three *S* planes have been drawn into the diagram. S_2 was measured indirectly by determining its intersections with two joint surfaces; *b* was taken as the intersection of S_1 and S_2; and *b′* as the intersection of S_2 and S_3. The braided appearance of the rock in thin section (Fig. 5, *D*) results from the intersection of the two cleavages. The quartz grains average 0.035 mm. in diameter.

A study of the maximums indicates that *b′* has been of greater and more recent importance as an axis of rotation than has *b*. With *b′* as an axis of rotation, all maximums greater than 3 per cent fall either on the IV circle or in the zone between the IV and the VI circles. This type of orientation has been described by H. W. Fairbairn[23] in folded quartzites. If the diagram is rotated so that *b* is at the center, the following arrangement of maximums and submaximums may be seen—six between circles IV and VI and one within circle III. Further, these maximums are not arranged in girdles so completely as in the first case. It is possible that the 4 per cent submaximum nearest fabric axis *a* is the Maximum I already observed as characteristic of the flow cleavage (Fig. 8, *B*).

For these reasons, it appears that the original orientation about *b* has been destroyed and that a later one, developed by slipping and antithetic rotation along S_3, has been superposed. If this type of movement is the same as in the development of S_2, then the process has not gone so far. Further stretching of the fabric in *a′*, just as the rock was originally stretched in *a*, should result in the development of another Maximum I.

SUMMARY AND CONCLUSIONS

The structures of the Paleozoic rocks indicate that they have been subjected to at least two periods of deformation. These structures might well be explained as the result of two peaks in the stress cycle of one period, were it not for the evidence of surrounding areas. Previous investigators (Behre, 1925; Miller, 1926; Stose, 1930) have shown that post-Ordovician, pre-Silurian folding took place. This has been correlated with the Taconic disturbance. The entire region was later affected by the Appalachian Revolution.

The flow cleavage of the Martinsburg formation may be dated as Taconic, since it parallels the axial planes of the folds of that disturbance. The bedding slip which accompanied the earlier stages of folding was superseded by slipping along cleavage surfaces. By this shearing movement, quartz orientation was developed which is believed to be typical Maximum I, in which both the optic axis and the major dimensional axis of quartz grains were aligned in the *a* direction. This pattern is associated with *ac* girdles resulting from folding, in which $b = B$. The external orientation forms the "grain" of the slate quarryman and is shown on the cleavage surfaces as a faint lineation.

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[23] "Hypotheses of Quartz Orientation in Tectonites," *Bull. Geol. Soc. Amer.*, Vol. L (1939), pp.

sented in this region by thrust faults and by a well-developed fracture cleavage. The Cambro-Ordovician and pre-Cambrian rocks exposed on Jenny Jump Mountain are, according to Bayley and Kümmel, underlain by a flat thrust fault. A reverse fault is present, but a flat overthrust is not supported directly by the field relations. At the only point where it could be observed, the fault plane dipped 40° southeast. Elsewhere all the evidence points indirectly to overthrusting. The flatly sheared silicified limestone beneath the gneiss of the Jenny Jump Mountain, the greatly stretched and broken formations of the footwall, and the isolated outlying limestone masses—all are characteristic of a thrust fault of considerable magnitude.

Although thrusting was the culmination of the process, the stresses that preceded it also had a strong effect upon the slate. These stresses, probably acting from the southeast (although with some small deviation from those of the Taconic orogeny), folded the flow cleavage and the bedding with it. Over much of the area, however, flow cleavage now parallels the bedding, which, especially in the massive sandy horizons, appears only slightly disturbed. Very similar relations exist between the two in the Mona complex in Anglesey. Edward Greenly[24] has explained it by isoclinal folding of flow cleavage between the thick uncleaved sandy layers. A secondary effect of the thrusting was the formation of fracture cleavage in the Martinsburg. This is seen up to a maximum distance of 3 miles north of the present fault trace. It bears the same relation to the flow cleavage as that structure bears to the bedding. The writer believes that this secondary cleavage was developed by the thrusting and overriding of the older rocks. Rotating and flattening of the cleavage layers by the same agent is evidenced by progressive flattening of their dip southward, as well as by the gradual change in character of the cleavage. Thus the cleavage was developed by shearing until it was well on the way to becoming a second flow cleavage. The progressive obliteration of the first flow cleavage was a necessary accompaniment. The degree to which the metamorphosis has advanced is clearly shown by the fabric analysis of the slate close to the overthrust, in which it appears that b' (the intersection of S_2 and S_3) = B. However, the flow-cleavage Maximum I has not developed. Evidently, considerable shearing under long-continued stresses is necessary for its formation. Fracture cleavage, commonly considered to be a minor structural feature, often remains unexplained or is lumped together with the other associated phenomena of flow cleavage. It is the contention of this paper that this is an area in which it can be definitely mapped as a regional structure and assigned to a specific cause—major thrust faulting. The opportunity of tracing the development of a cleavage as it is affected by stresses of progressively increasing intensity is of particular interest.

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[24] "Foliation and Its Relation to Folding in the Mona Complex at Rhoscolyn (Anglesey)," *Quart.*