# The Lyon Station–Paulins Kill Nappe—The Frontal Structure of the Musconetcong Nappe System in Eastern Pennsylvania and New Jersey

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*By* AVERY ALA DRAKE, JR.

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*A study of a complex nappe system in the complicated polydeformed terrane of the central Appalachians*

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# TABLE

# THE LYON STATION–PAULINS KILL NAPPE—THE FRONTAL STRUCTURE OF THE MUSCONETCONG NAPPE SYSTEM IN EASTERN PENNSYLVANIA AND NEW JERSEY

By AVERY ALA DRAKE, JR.


ABSTRACT

Geologic and aeromagnetic data show that a major tectonic unit underlies rocks of the Musconetcong nappe in the Great Valley of eastern Pennsylvania and New Jersey. This structure, the Lyon Station–Paulins Kill nappe, can be traced from Lyon Station, Pa., at least to Branchville, N.J., a distance of about 120 km. The nappe has a core of Precambrian crystalline rocks as shown by an aeromagnetic anomaly that has the same signature as the outcropping Precambrian rocks of the Musconetcong nappe. This core extends at least 70 km east from Lyon Station to Bangor, Pa., the eastern limit of the aeromagnetic survey.

Carbonate rocks in the upper limb of the nappe are exposed in the Whitehall window and in an unnamed window near Catasauqua, Pa., and in the Paulins Kill Valley of New Jersey, which is a very large window through the Musconetcong nappe. These carbonate rocks are of a more shoreward facies than the rocks in the Musconetcong nappe, showing that the Lyon Station-Paulins Kill nappe is a frontal as well as tectonically lower structure. The Lyon Station–Paulins Kill nappe has a lower limb, as is proved by three inner windows within the Paulins Kill window in New Jersey. The nappe has no crystalline core this far east.

The Lyon Station–Paulins Kill nappe interfaces with the overlying Musconetcong nappe along the major Portland fault. This fault shears upsection through the Musconetcong nappe, bringing lower-limb rocks of that nappe into contact with the Lyon Station–Paulins Kill nappe in the Whitehall window and bringing upper-limb Musconetcong rocks into contact with the lower nappe in the Paulins Kill window. The Portland fault, though folded, is a late tectonic event and is thought to be a strong imbricate splay from the major décollement that lies just above the basement in the central Appalachians. The Portland fault, therefore, telescoped nappes formed during the Taconic orogeny and was folded with them during the Alleghenian orogeny.

Far-traveled tectonic units within eastern Pennsylvania and New Jersey are recognized to belong to the very complex Musconetcong nappe system. Near Allentown, Pa., this system consists from lowest to highest, of the Lyon Station–Paulins Kill nappe, the Musconetcong nappe (sensu stricto), and the South Mountain nappe. Another structure, the Applebutter thrust sheet, belongs to this system, but its position is unknown. The Musconetcong nappe system is tectonically overlain by the Lebanon Valley nappe system near Reading, Pa., suggesting that all the far-traveled units of these two systems should be included in a Reading Prong nappe megasystem.


## INTRODUCTION

In recent years, a nappe theory has been devised to explain the highly complicated structural relations in the Great Valley and Reading Prong of east-central and eastern Pennsylvania and western New Jersey (fig. 1). Although Stose and Jonas (1935) believed, probably largely intuitively, that the Precambrian rocks of the Reading Prong were in thrust contact with the Paleozoic rocks of the Great Valley, the tectonic concept of far-traveled rocks for this region was not accepted by most geologists. Carlyle Gray and his coworkers of the Pennsylvania Geological Survey (Gray, 1951, 1952, 1959; Field Conf. Pa. Geologists, 1954; Gray and others, 1958; Geyer and others, 1958, 1963) first conceived the relations to be those of a grand Alpine-type nappe in the Lebanon Valley of Lebanon and western Berks Counties, Pa. Their concept has more recently been elaborated and refined by MacLachlan (1964, 1967; MacLachlan and others, 1976; Field Conf. Pa. Geologists, 1966), who also found that in the Harrisburg area, rocks of the Lebanon Valley nappe tectonically overlie autochthonous rocks (Cumberland Valley sequence) that are of similar age but somewhat different facies. This nappe includes all carbonate rocks of Cambrian and Ordovician age of the Lebanon Valley sequence and an indefinite part of the Martinsburg Formation of that sequence.

In 1957, the U.S. Geological Survey began a systematic study of the geology of the Delaware Valley. Large overturned and recumbent folds were soon recognized in the Great Valley and within intermontane valleys of the Reading Prong (Drake

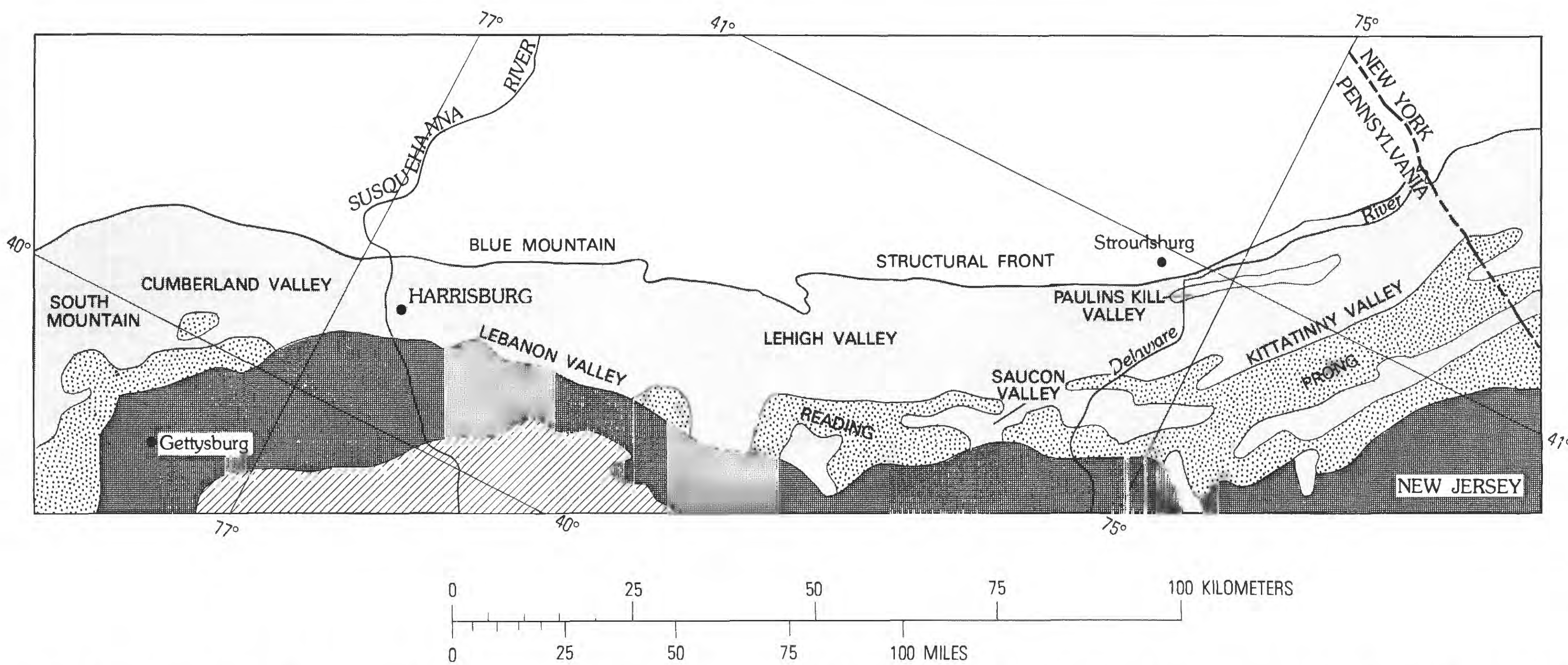



FIGURE 1.—Map showing the divisions of the Great Valley of Pennsylvania and New Jersey and their relations to adjacent geologic terranes. Cambrian and Ordovician rocks of the Great Valley (light shading); Precambrian rocks of the Reading Prong and South Mountain anticlinorium (stippled); Silurian and younger Paleozoic rocks (unshaded); Triassic rocks of the Newark Basin (dark shading); and Precambrian and lower Paleozoic rocks of the Appalachian Piedmont (ruled pattern).

and others, 1960). In addition, we found that thrust faults and overturned folds were more of a factor in the distribution of the Precambrian rocks of the Reading Prong than had been supposed previously and that some Precambrian bodies were probably klippen (Field Conf. Pa. Geologists, 1961). Continued studies culminated in the interpretation that in the Delaware Valley, Precambrian rocks of the Reading Prong and Paleozoic rocks of the Great Valley are all involved in one grand nappe de recouvrement (Drake, *in* U.S. Geol. Survey, 1966; Drake, 1967a, 1967b, 1969, 1970). This structure was called the Musconetcong nappe and was visualized as embracing all lower Paleozoic rocks up to and including the Martinsburg Formation and, in addition, the Precambrian rocks that formed the core.

In addition to the regional nappes described above, Sherwood (1964; Field Conf. Pa. Geologists, 1961) in a topical study of the Jacksonburg Limestone in Northampton and Lehigh Counties, Pa., delineated a large recumbent fold, which he called the Northampton nappe. More recent work has shown that this nappe is the hinge zone of the regional Musconetcong nappe.

The obvious question, therefore, is, what is the relation of the Lebanon Valley nappe to the Musconetcong nappe? Originally, both MacLachlan (oral commun., 1968) and I (Drake, 1969) believed that both our areas were on the same essential structure. At that time, however, no intervening country had been mapped, and in tectonically complicated terrane such as this, anything is possible except a simple solution.

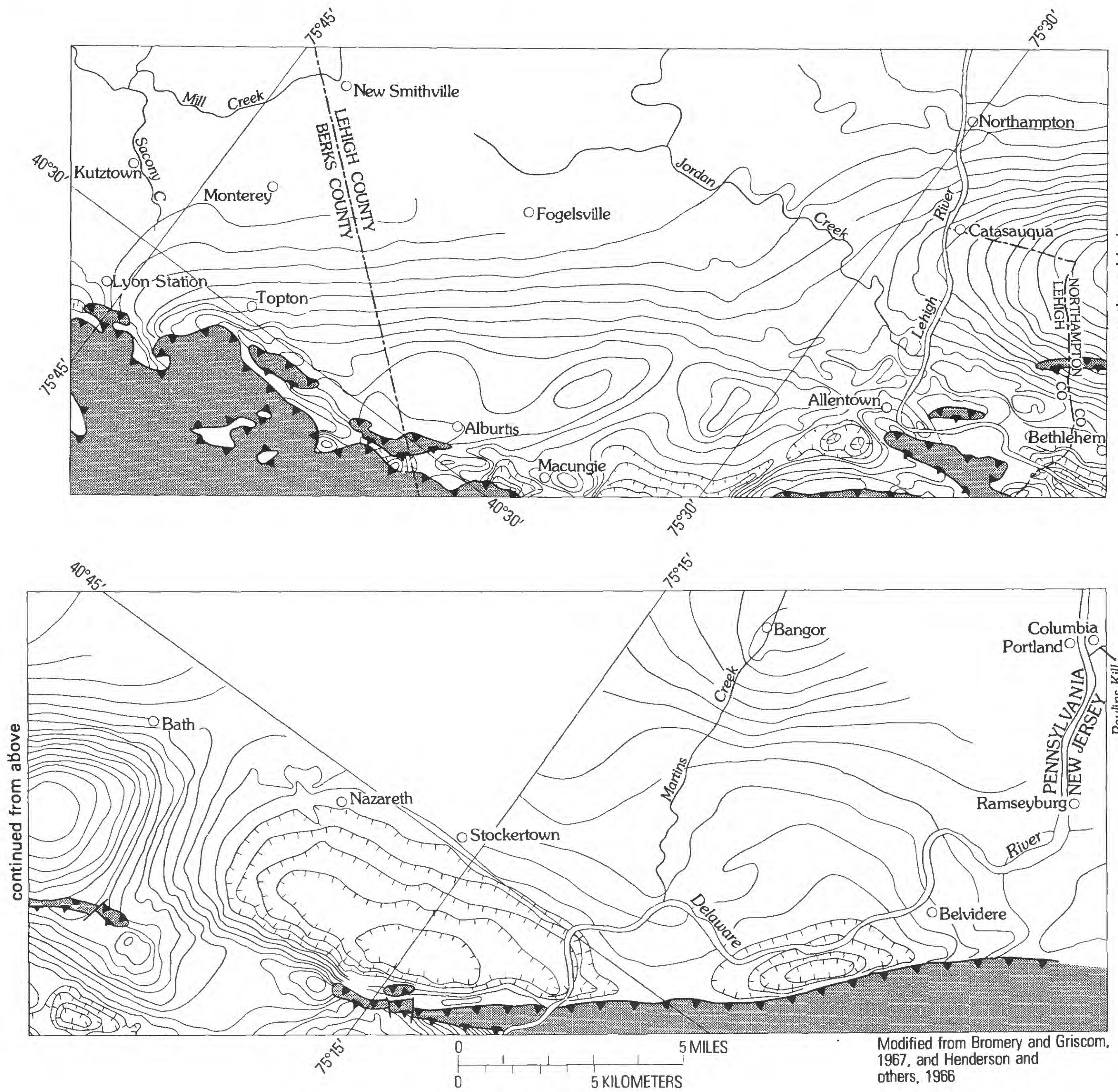
Continued mapping to the east by MacLachlan (MacLachlan and others, 1976) and to the west by me has shown, not too surprisingly, that both the Lebanon Valley and Musconetcong nappes are actually nappe systems, each consisting of several individual structural elements.

Two pieces of evidence suggested to me (Drake, *in* U.S. Geol. Survey, 1969, p. A28) that another nappe of regional extent lies tectonically beneath the Musconetcong nappe in the Lehigh Valley of eastern Pennsylvania and the Kittatinny Valley of New Jersey. The first piece of evidence is a large subsurface aeromagnetic anomaly at a depth of about 1.6 km, centered near Catasauqua, Pa. (fig. 2). This anomaly can be traced northeastward from Lyon Station, Pa., where it emerges from beneath the outcropping Precambrian rocks of the Reading Prong, to the northeast limit of the aeromagnetic survey near Bangor, Pa. The anomaly is like those caused by the outcropping rocks of the Reading Prong, and it seems clear that it is caused by similar rocks. Directly on strike with the anomaly in New Jersey is the carbonate-rock-floored Paulins Kill Valley, which is surrounded by clastic rocks of the Martinsburg Formation (pl. 1*A*). The valley is antiformal, and stratigraphic relations within the carbonate rocks suggest that they are right side up and anticlinal (the Ackerman anticline), but they are bounded on all sides by the Portland fault, a younger-over-older thrust (Drake and others, 1969).

Further reconnaissance in New Jersey turned up lenticular masses of Jacksonburg Limestone (Middle Ordovician) and Epler Formation (upper Lower Ordovician) within Allentown Dolomite (Upper Cambrian) along the axial trace of the Ackerman anticline (Drake, *in* U.S. Geol. Survey, 1971, p. A27). These rocks are severely deformed, and are physically beneath the older Allentown Dolomite. These relations suggest that the rocks have been recumbently folded and that the lower limb has been exposed by later arching and faulting. The Ackerman anticline in the Portland quadrangle (Drake and others, 1969), therefore, is not the relatively simple structure it appears; it rather reflects the arching of the upper limb of the above-defined recumbent fold. The probable Precambrian rocks causing the aeromagnetic anomaly between Bangor and Lyon Station, Pa., were probably from a crystalline core to this recumbent fold, which has been called the Lyon Station–Paulins Kill nappe (Drake, *in* U.S. Geol. Survey, 1971, p. A72). It is apparent that the Precambrian rock core of this structure defined by the aeromagnetic anomaly to the west is not present in this part of New Jersey, and that the entire Paulins Kill Valley is a large window.

Later detailed mapping in the Catasauqua, Pa., area delineated two areas of outcrop of stratigraphically right-side-up Allentown Dolomite within a terrane of generally inverted Epler Formation (Drake, *in* U.S. Geol. Survey, 1972, p. A25). The Allentown is in fault contact with the surrounding rocks, which are in the lower limb of the Musconetcong nappe; it must, therefore, belong to the subjacent Lyon Station–Paulins Kill nappe showing through windows similar to the large Paulins Kill Valley window.

The Lyon Station–Paulins Kill nappe is obviously a major tectonic element in eastern Pennsylvania and New Jersey. The purpose of this paper is to define this frontal and tectonically lowest nappe of the Musconetcong system. This is done by more




Modified from Bromery and Griscom, 1967, and Henderson and others, 1966

**EXPLANATION**

Precambrian rock in core of Musconetcong nappe
*At places includes superjacent Hardyston Quartzite of Early Cambrian age*

Inclined

Overturned

Core-cover interface of Musconetcong nappe

Fault

Magnetic contours
*Contour interval 50 gammas. Hachures show closed areas of lower magnetic intensity*

FIGURE 2.—Aeromagnetic map of part of eastern Pennsylvania.

fully describing the evidence summarized above. In addition, some regional interpretations pointed out by this study are made.

I would like to thank my colleague J. M. Aaron for his work in the Paulins Kill Valley and for his continuing efforts to make me aware of important sedimentological features. Continual prodding by G. H. Wood, Jr., of the U.S. Geological Survey forced me to attempt to relate the Musconetcong nappe system to the major décollement at depth. Free interchange of information through the years with D. B. MacLachlan of the Pennsylvania Geological Survey has been of great help in gaining an understanding of the geology of this highly complicated region.

## REGIONAL STRATIGRAPHY

Rocks pertinent to this study include Precambrian gneisses and granitoids and sedimentary rocks of Cambrian and Ordovician age. The pre-upper Middle Ordovician rocks of the Great Valley belong to the orthoquartzite-carbonate facies and were deposited on the great east-facing bank that was so prominent in the Appalachians at that time. After basin reversal (Zen, 1972), late Middle and lower Upper Ordovician graywacke-shale flysch was deposited. The stratigraphic sequence for the area discussed herein is given in table 1. The thicknesses given were determined at the best exposures in the Delaware and Lehigh Valleys and almost certainly are not valid for the Paulins Kill Valley. (For a complete discussion of this stratigraphy see Drake, 1969.)

In this paper, by necessity, the informal unit Kittatinny carbonate terrane is used for the stratigraphic interval Leithsville Formation through Beekmantown Group in areas where there has been no detailed mapping. In addition, the Martinsburg Formation is undivided where no mapping data are available. Transported sequences of pelitic rocks have been lumped with the Martinsburg Formation in the area west of the Lehigh River, as their presence has no bearing on the theme of this paper.

TABLE 1.—*Rock units in eastern Pennsylvania and New Jersey*

| Formation | Member | Description | Thickness (meters) |
|---|---|---|---|
| Martinsburg Formation (upper Middle and lower Upper Ordovician). | Pen Argyl | Dark-gray to grayish-black, thick- to thin-bedded, evenly bedded slate, rhythmically interlayered with beds of quartzose slate or subgraywacke and carbonaceous slate. Upper contact is unconformable and site of a décollement. Contains mineral assemblage muscovite-chlorite-albite-quartz. | 1,000–2,000 |
| | Ramseyburg | Medium- to dark-gray slate that alternates with beds of light- to medium-gray, thin- to thick-bedded graywacke and graywacke siltstone. Graywacke composes 20–30 percent of unit. Upper contact gradational. Pelitic elements contain mineral assemblage muscovite-chlorite-albite-quartz. | About 930 |
| | Bushkill | Dark- to medium-gray thin-bedded slate containing thin beds of quartzose slate, graywacke siltstone, and carbonaceous slate. Upper contact gradational. Contains mineral assemblage muscovite-chlorite-albite-quartz. | 1,350 |
| Jacksonburg Limestone (Middle Ordovician). | Cement-rock facies | Dark-gray, almost black, fine-grained, thin-bedded argillaceous limestone. Contains beds of crystalline limestone at places. Upper contact gradational. Contains mineral assemblage calcite-chlorite-muscovite-albite-quartz. | 100–330 |
| | Cement-limestone facies. | Light- to medium-gray, medium- to coarse-grained, largely well-bedded calcarenite and fine- to medium-crystalline high-calcium limestone. Upper contact is gradational in main outcrop belt but is apparently unconformable and marked by a conglomerate in the Paulins Kill lowland. Lower contact is marked by a dolomite pebble to boulder conglomerate in main outcrop belt. | 70–130 in main outcrop belt. |
| Ontelaunee Formation (Lower Ordovician). | | Medium-dark gray mostly very finely crystalline dolomite. Unit is cherty at the base and contains beds of medium-gray calcilutite at the top. Upper contact is sharp and unconformable. Unit is only sporadically present east of Northampton, Pa. | 0–200 |
| Epler Formation (Lower Ordovician). | | Interbedded very fine grained to cryptogranular, light- to medium-gray limestone and fine- to medium-grained light-gray to dark-medium-gray dolomite. Upper contact sharp and unconformable except where Ontelaunee is present. At those places it is gradational. | About 270 |

TABLE 1.—*Rock units in eastern Pennsylvania and New Jersey*—Continued

| Formation | Member | Description | Thickness (meters) |
|---|---|---|---|
| Rickenbach Dolomite (Lower Ordovician). | ------------------ | Fine- to coarse-grained, light-medium to medium-dark-gray dololutite, dolarenite, and dolorudite. Lower part characteristically thick bedded, upper part generally thin bedded and laminated. Upper contact gradational. | About 220 |
| Allentown Dolomite (Upper Cambrian). | ------------------ | Very fine to medium-grained, light-gray to medium-dark gray, alternating light- and dark-gray weathering, rhythmically bedded dolomite containing abundant algal stromatolites, oolite beds, and scattered beds and lenses of orthoquartzite. Upper contact gradational. | About 575 |
| Leithsville Formation (uppermost Lower and Middle Cambrian). | ------------------ | Interbedded light-medium-gray to dark-gray, fine- to coarse-grained dolomite and calcitic dolomite, light-gray to tan phyllite, and very thin beds and stringers of quartz and dolomite sandstone. Upper contact is gradational. Phyllite contains mineral assemblage muscovite-chlorite-albite-quartz. | About 350 |
| Hardyston Quartzite (Lower Cambrian). | ------------------ | Gray quartzite, feldspathic quartzite, arkose, quartz pebble conglomerate, and silty shale or phyllite. Upper contact is gradational. Phyllite contains mineral assemblage muscovite-chlorite-albite-quartz. | About 30 |
| | | Quartzo-feldspathic gneiss, granitoids, and amphibolite. Upper contact sharp and unconformable. Rock has been at hornblende granulite facies and is typically retrograded to greenschist facies near tectonic contacts. | |

## CATASAUQUA AEROMAGNETIC ANOMALY

Aeromagnetic mapping of the Allentown, Pa., quadrangle (Bromery and others, 1959) has shown a marked magnetic basement anomaly beneath the Great Valley; this anomaly is centered near Catasauqua, Pa. The anomaly can be traced southwest to Lyon Station, Pa., where it emerges from beneath the outcropping Precambrian rocks (fig. 2). To the east and northeast, the anomaly has two prongs. One passes beneath the outcropping Precambrian rocks near the Delaware River; the other extends toward Bath, Pa. (fig. 2). The anomaly at Bangor (fig. 2) is, almost certainly, an extension of the Bath prong, although the association cannot be verified until the intervening area is mapped aeromagnetically.

The Catasauqua anomaly was originally interpreted as being the reflection of a basement arch associated with an anticline in the outcropping Paleozoic rocks, the basement being about 1.6 km deep (Bromery, 1960). More recent analysis (Bromery and Griscom, 1967) has shown that the gradient associated with the Catasauqua anomaly does not steepen were it intersects the outcropping Precambrian rocks; hence, the magnetic rocks producing the anomaly do not change depth. The outcropping Precambrian rocks, therefore, are tectonically above the buried magnetic rocks. Magnetic rocks apparently occur at two tectonic levels separated by 1.6 km or so of nonmagnetic Paleozoic rock. The question that immediately arises is whether the lower level is basement or possibly another allochthonous nappe core or thrust sheet.

Lithologic boundaries are reasonably well known in the Catasauqua area (pl. 1*B*), and modern stratigraphic and structural studies have clearly demonstrated regional inversion and the presence of a nappe (Sherwood, 1964; Drake, 1969, and unpub. data). Plate 1*B* shows no apparent relation between the trace of the anomaly and the mapped geology; in fact, the anomaly cuts across the geologic grain. The anticline mentioned by Bromery (1960) presumably would be cored by the Allentown Dolomite southwest of Catasauqua (pl. 1*B*). This is not a normal anticline, however, as the Allentown body is bounded on all sides by inverted Epler Formation of the Beekmantown Group, and the contact is a thrust fault.

Southwest of Catasauqua, the trace of the anomaly cuts across the geologic grain at a small angle until it passes beneath the outcropping Precambrian rocks near Lyon Station (pl. 1*B*). Here the anomaly closes and dies out abruptly with only negative anomalies along strike. This pattern is like that within the Reading Prong where anomalies caused by Precambrian ridges abruptly terminate in negative-anomaly basins as the magnetic rocks spoon out (Drake, 1969, 1970). Bromery and Griscom (1967) noted similar relations west of Reading where the prong spoons out. Regional inversion in the Great Valley is shown by the many tectonic windows along this belt that expose antiforms cored with younger rock (pl. 1*B*). The Catasauqua anomaly, therefore, is not caused by basement. If it were, the anomaly would not die out to the west as it does at Lyon Station. Those who would appeal to a masking effect by the outcropping Precambrian rocks must explain why the supposed basement anomaly is not seen west of the outcropping Precambrian rocks.

Northeast of Catasauqua, the trace of the anomaly makes an angle of about 20° with the grain of the geology (pl. 1*B*). At Bangor, it is directly on strike with the Paulins Kill Valley in New Jersey (pl. 1*A*), although, unfortunately, no aeromagnetic data are available farther to the northeast.

I have pointed out (Drake, 1969, 1970) that from north-central New Jersey to Reading, Pa., the Reading Prong and adjacent Great Valley lie dead center on the regional gravity low. The area considered herein is in the deepest part of the gravity trough at depths of 17 to 20 km. Aeromagnetic surveys indicate that basement is deeper than 8.5 km along the Blue Mountain structural front (Blue Mountain décollement of Drake and others, 1969) to the north (Drake, 1969, 1970). In addition, private oil-company seismic surveys (V. E. Gwinn, written commun., 1966) indicate that the first basement reflection is at depths of 12 to 17 km just off the front of the outcropping Precambrian rocks near Lyon Station. All these data make it highly unlikely that basement is the cause of the Catasauqua anomaly; therefore, it must be the result of a blind allochthonous body. One can be confident that this body is similar to the outcropping Precambrian rocks in the Reading Prong, as they have such a characteristic high-intensity magnetic signature. (See Harwood and Zietz, 1974, for a discussion of the differing magnetic signatures of outcropping Precambrian rocks in southeastern New York.)

The configuration of the anomaly, especially the northeast gradient, suggests that the magnetic body, most likely a nappe core, has a diving brow (that is, it has been rotated past the horizontal) and that it has been arched into an antiform. Negative anomalies along its southeast side suggest that it is not connected with another magnetic body in that direction. The strong magnetic peaks about 6 km east of Catasauqua and probably at Bangor are connected with lesser anomalies by a series of saddles; this pattern suggests that the body causing the anomaly porpoises, that is, plunge culminations and depressions vary its depth. Geologic data presented below reinforce this interpretation.

The less well defined southern prong of the anomaly peak at Catasauqua trends east-northeast past Bethlehem, Pa., toward New Jersey and dies out about at the Delaware River (Henderson and others, 1966). This secondary anomaly probably represents a second arch in the nappe core. Geology at the surface supports this interpretation, as the outlying body of Precambrian rock north of Bethlehem (fig. 2 and pl. 1 *B*) is in a synform. A major antiform about coextensive with the anomaly occurs between the synform and the Precambrian rock of the Reading Prong (Drake, 1967a; Aaron, 1975).

Harwood and Zietz (1974) have recently described similar aeromagnetic anomalies from eastern New York and southern New England as resulting from blind bodies of highly magnetic Precambrian rock. They, however, propose a more conservative parautochthonous origin for these bodies in the absence of more firm data on depth to basement. It it interesting to point out that the northeast subsurface continuation of the Reading Prong makes one of these anomalies that passes under the outcropping Berkshire massif, much as the Catasauqua anomaly passes under the outcropping Reading Prong.

## PAULINS KILL VALLEY

The Paulins Kill Valley, a lens-shaped lowland about 50 km long within the Martinsburg terrane of the Kittatinny Valley, is underlain by an outlying mass of carbonate rocks of Late Cambrian to Middle Ordovician age (pl. 1*A*). Most of the lowland is in New Jersey, but about 7 km is in Pennsylvania. Bedrock exposures are sparse throughout the valley because of the heavy glacial cover and are particularly lacking in Pennsylvania, where there is an abominable thickness of gravel in Jacoby Creek kame field. Most of the lowland has not been studied geologically in any detail. Folio mapping (Bayley and others, 1914) covers only a small part of the valley, and only that part nearest the Delaware River has been mapped at large scale (Drake and others, 1969). This, of course, means that geologic interpretation is difficult, as neither detailed stratigraphy nor modern structural data are available.

### STRATIGRAPHY

The Allentown Dolomite, Rickenbach Dolomite, Epler Formation, and Jacksonburg Limestone crop out within the Paulins Kill Valley, which is framed by the Bushkill and Ramseyburg Members of the Martinsburg Formation. Most of the basic stratigraphic information on these carbonate units has been gained to the south in the Musconetcong nappe, the reference section for Allentown through Epler being at Carpentersville, N.J., about 35 km down the Delaware. There are few exposures and no long sections within the part of the Paulins Kill Valley that has been studied in detail. The Allentown Dolomite, however, has more abundant algal stromalite and significantly more oolite and desiccation dolorudite, and much less structureless fine-grained dolomite, suggesting a generally shallower environment than that in which the rocks to the south in the main outcrop belt were deposited. Very little limestone is presented in the Epler Formation, and its absence shows that the dolomitization process has been more complete in this area, again suggesting a generally shallower environment of deposition.

The Jacksonburg Limestone differs greatly from that in the main outcrop belt. The type section of this formation is at Jacksonburg, N.J., within the Paulins Kill Valley. Weller (1903) studied this section in great detail; a trench was dug to expose the formation from its lower contact through a thickness of 40 m. At this point, it was impractical to continue trenching, and Weller estimated that probably 5 to 7 m more Jacksonburg was present; thus the total thickness was determined to be about 46–47 m. Practically all this rock is high-calcium limestone.

Weller (1903) believed that the lower 20 m of this limestone is of Black River age, the remainder being Trenton in age. R. L. Miller (1937) disagreed with the Black River age but agreed that the lower part of the formation was older (Rockland) than the remainder of the unit, which is younger Trenton ("Hull" and "Sherman Falls") age. He called the older part of the Jacksonburg the *Leperditia*-bearing beds.

In the Jacksonburg outcrop belt in New Jersey and eastern Pennsylvania to the Schuylkill River, all authors (Weller, 1903; R. L. Miller, 1937; B. L. Miller and others, 1939, 1941; Sherwood, 1964; Drake, 1965, 1967a, 1967b; Drake and others, 1969) have found the Jacksonburg to be far thicker than at the type section (table 1), and though it contains high-calcium limestone (the cement-limestone facies at the base), far more of the formation is argillaceous limestone (the cement-rock facies). This lithologic change has been visualized (see for instance Prouty, 1959) as occurring at the Delaware River, the implication being that the eastern Pennsylvania sequence is different from the New Jersey sequence. This view is in error, as the Jacksonburg of the main outcrop belt in the Great Valley of New Jersey and within the intermontane valleys of the Reading Prong is essentially the same as that in Northampton, Lehigh, and eastern Berks Counties, Pa., and not at all like that in the Paulins Kill Valley. Moreover, neither Weller (1903) nor R. L. Miller (1937), nor any subsequent worker has found older *Leperditia*-bearing (Black River or Rockland) Jacksonburg outside the Paulins Kill Valley.

Most of the described differences between the Jacksonburg at various places within the main outcrop belt are tectonic rather than stratigraphic, as the bulk of the rock in eastern Pennsylvania is in the inverted limb of the Musconetcong nappe and is extremely deformed, whereas much of the rock at and near the Delaware River is in the brow of the Musconetcong nappe and consequently is less severely deformed. Neither Black River nor oldest Trenton (Rockland) fossils have been found in central or east-central Pennsylvania (Prouty, 1959; Mac Lachlan, 1967). The attempt to relate the rocks west of the Delaware River to the Jacksonburg at the type locality rather than to the rocks east along strike in the main outcrop belt has led to the current difficulties in correlation and nomenclature.

R. L. Miller (1937) interpreted the differences in lithology as resulting from a south-to-north gradational overlap of the argillaceous limestone facies onto the pure limestone facies in New Jersey, combined with a gradual stratigraphic convergence from Pennsylvania into New Jersey. It is certainly true that in the Paulins Kill Valley, presumably nearer shore high-calcium limestone is the dominant facies. The facies difference, however, is between the main Jacksonburg outcrop belt and the Paulins Kill belt. No facies shift was noted in the more than 30-km cross-strike exposure throughout the Reading Prong and Great Valley. I agree with R. L. Miller's (1937) analysis of the sedimentation pattern, but I believe that the present distribution of facies is the result of tectonic telescoping. The Paulins Kill rocks, therefore, are in a separate tectonic unit from the rocks outcropping to the south, which are in the Musconetcong nappe.

## STRUCTURAL GEOLOGY

Classically, the Paulins Kill Valley has been considered to be an anticline largely fault-bounded on the south and partly fault-bounded on the north (Behre, 1927, 1933; Lewis and Kümmel, 1912). The presence or absence of faults apparently was interpreted by the presence or absence of the Jacksonburg Limestone. The northern faults were considered to be thrusts, and the southern fault was presumed to be a high-angle normal fault (pl. 1 *C*). Behre (1927, 1933) in his study of the Pennsylvania slate belt recognized that faults on both the northern and southern borders of the valley had to extend into Pennsylvania. In his mapping, he was faced with the problem of accommodating both sets of faults which had been left dangling in the Martinsburg terrane. In his interpretation, the southern high-angle fault is cut off by the northern thrust faults, which he extended more than 10 km farther into Pennsylvania (Behre, 1927, 1933). The thick gravel in the Jacoby Creek kame field allows almost any interpretation there, but detailed mapping to the southwest in the Stroudsburg and Bangor quadrangles (Epstein, 1973; Davis and others, 1967) clearly shows that Behre's interpretation is not valid and that there is no discontinuity within the Martinsburg terrane that could be the extension of the northern thrust fault. The only logical conclusion, therefore, is that the north and south faults are, in reality, the same fault, which has been called the Portland fault (Drake and others, 1969; Epstein, 1973). This fault has been traced by reconnaissance along both sides of the Paulins Kill Valley. Although complicated by other faults, it closes around the northeast extremity as well, so that the entire lowland is fault-bounded rather than bounded by the hodge-podge of discontinuous faults along the north boundary as is shown by Lewis and Kümmel (1912) (see pl. 1*A*).

As the north and south faults are one and the same, the nature and type of fault must be determined. The distribution of the carbonate rocks within the fault frame suggests an anticline, thereby suggesting that the Portland fault closes upwards over the valley. The concept of far-traveled tectonics within the Great Valley of the central Appalachians, however, necessitates a consideration of the possibility that the carbonate rocks of the Paulins Kill Valley are a large klippe, as the tectonic style changes from windows in the lower limb of the Musconetcong nappe in eastern Pennslyvania to klippen on the upper limb in New Jersey. Numerous klippen of carbonate and Precambrian rock lie on the Martinsburg south of the Paulins Kill Valley between Blairstown, N.J., and Jenny Jump Mountain (pl. 1*A*); Jenny Jump Mountain is itself a klippe. If the carbonate rocks in the valley are a klippe, the carbonate rock would have to be in the trough of a large synform in a thrust similar to the synform shown in section *B–B′* of plate 1*A* for one of the southern klippen. This core would have to spoon out rather than plunge under at its western extremity; that is, the hinge in the Jacoby Creek area should plunge northeast rather than southwest. The westernmost exposures along the axial trace of the lowland structure are a series of outcrops of Allentown Dolomite just east of the Delaware River, which clearly show that there the structure does plunge northeast, as the beds dip in that direction (pl. 1*D*).

## ROCK FABRIC

To better evaluate the possibile structural relations, the tectonic fabric of the rocks must be considered. We have known for some time that the rocks in this general area have been deformed at least twice and have a penetrative slaty cleavage and a less pervasive but locally penetrative strain-slip cleavage (fig. 3) (Drake and others, 1960). Slaty cleavage essentially parallels axial surfaces of first folds in bedding, and strain-slip cleavage parallels axial surfaces of folds in cleavage and some second folds in bedding. The strain-slip cleavage strikes about N. 40° E., dips either northwest or southeast (fig. 4), and forms reversed cleavage fans; that is, the fans converge upwards in antiforms and downwards in synforms. In the southern part of the Portland quadrangle, the strain-slip fabric is dominant. Some late folds have no cleavage, and we do not know whether they formed contemporaneous with the strain-slip fabric or later. Lineations consist of the intersections of these various planar elements and the axes of minor folds. The strain-slip cleavage and folds in slaty cleavage obviously postdate the penetrative slaty cleavage, as do the second folds in bedding. These two fabrics, as well as related joints, have a regional symmetry over more than 286 sq km (fig. 5). Regionally, the first folds plunge rather gently east-northeast, and the second folds plunge gently southwest, although folds in both sets plunge in opposite directions. A third planar element $S_3$(?) is not well understood but is probably cleavage formed during a poorly defined third deformation (see following paragraphs.)

Fabric diagrams have been prepared for the rocks of the Portland quadrangle as well as for several domains within the Paulins Kill Valley and areas immediately adjacent thereto.

Data for the carbonate rocks are shown on figure 6. Small folds plunge erratically, but generally northeast; the statistical fold axis, $\beta$, plunges 4° N. 43° E. These data reflect the sample bias resulting from the lack of outcrop west of the Delaware River but suggest that the geometry results from the second regional deformation.

Fabric data for Martinsburg rocks west of the Delaware River are given in figure 7. Small folds and the statistical fold axis all plunge southwest.



**FIGURE 3.**—Fabric elements in the Martinsburg Formation. *A*. Megascopic isoclinal recumbent fold in bedding with axial-surface slaty cleavage. *B*. Polydeformed slate: Bedding dips moderately to the right, relict slaty cleavage is nearly vertical, and penetrative strain-slip cleavage dips moderately left.

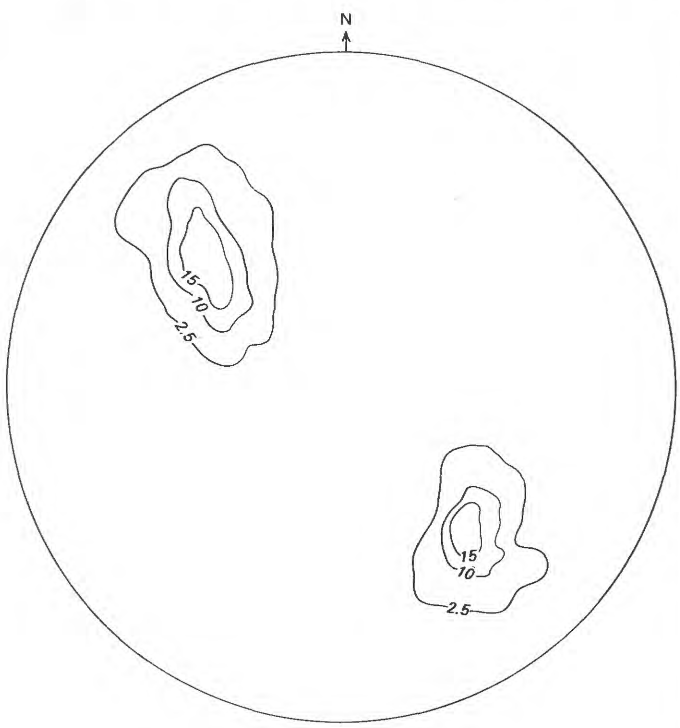



**FIGURE 4.**—Equal-area plot (lower hemisphere) of 40 poles to strain-slip cleavage in the Martinsburg Formation in the Portland quadrangle. Contours at 15, 10, and 2.5 percent per 1-percent area.

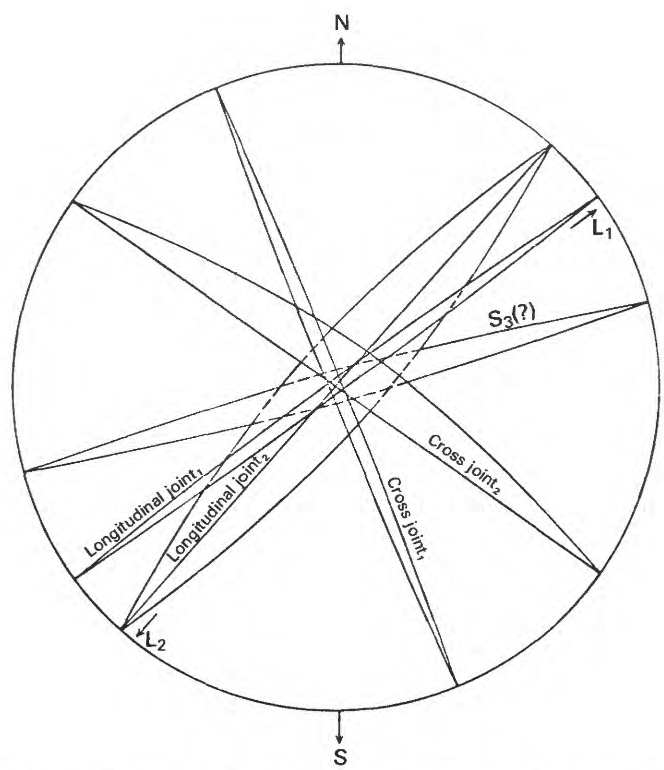



**FIGURE 5.**—Stereographic projection (lower hemisphere) showing double fabric in Martinsburg Formation (from Drake, 1969.)

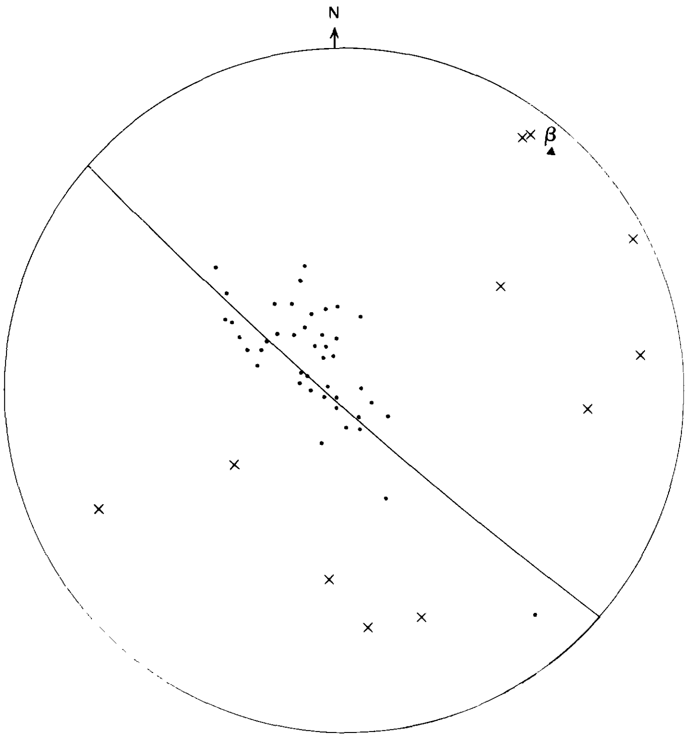



FIGURE 6.—Stereographic plot (lower hemisphere) of 41 poles to bedding (dots) and 11 small fold axes (x) in bedding in carbonate rocks within the Paulins Kill Valley. $\beta$=4° N. 43° E.

Certainly the regional plunge is southwest in this area. Two sets of folds are present in bedding, plunging about S. 60° W. (first) and S. 40° W. (second).

Fabric data for the Martinsburg Formation east of the Delaware River are given in figure 8. Poles to bedding plot in a complicated crossed girdle. Folds in bedding plunge about N. 55° E. with a secondary maximum at about N. 80° E. Identified second folds in bedding and folds in slaty cleavage plunge about 10° S. 40° W. Although the above relations are not completely understood at this time, the data seem to suggest that a third more easterly trending set of folds apparently is present in this area.

Poles to bedding for all outcrops of the Martinsburg Formation in the Portland quadrangle, not too surprisingly, plot in a complicated cross girdle (fig. 9). The bulk of the data, however, define a statistical axis that plunges about N. 45° E., which is more or less parallel to the second folds in bedding defined in all the domains described above as well as to folds in cleavage and recognized second folds. Most of the small folds in bedding plunge about N. 60° E., with another poorly defined maximum at about N. 80° E. These data suggest that there are

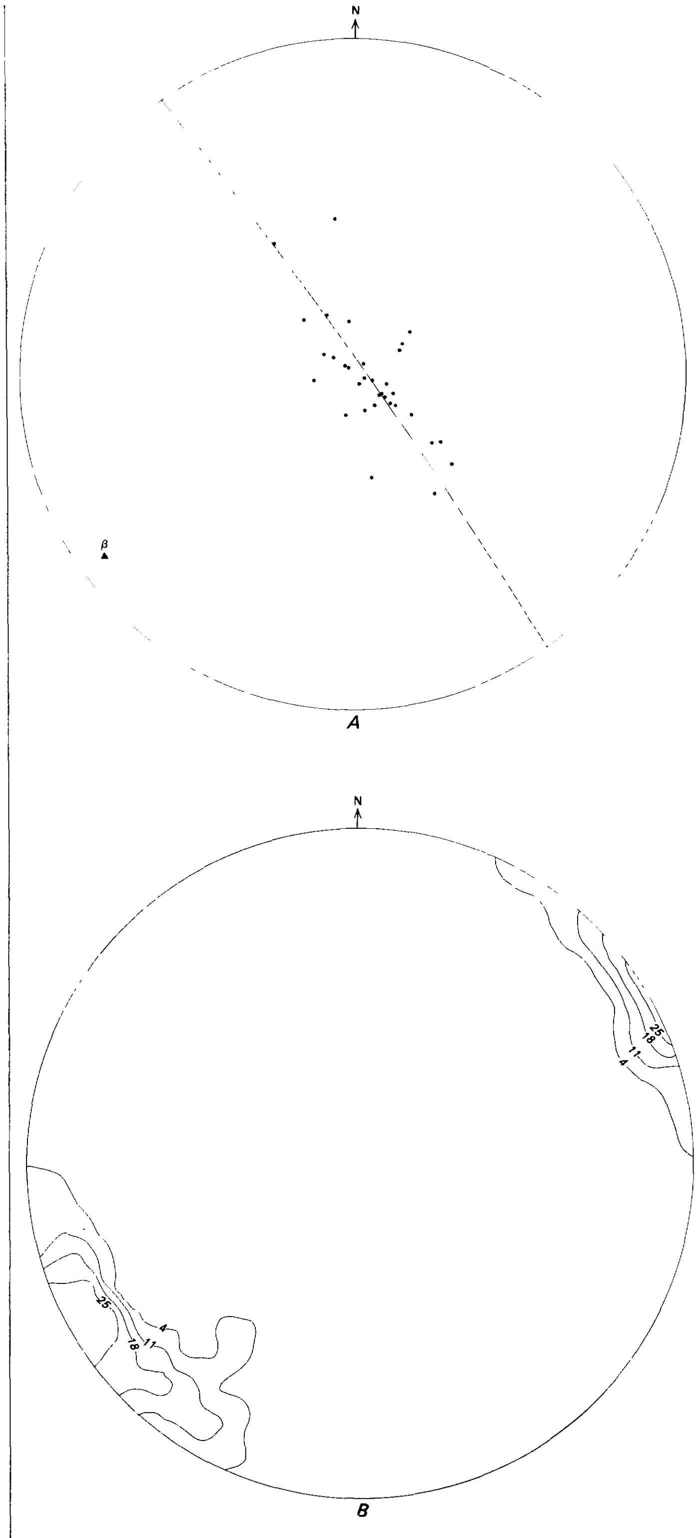
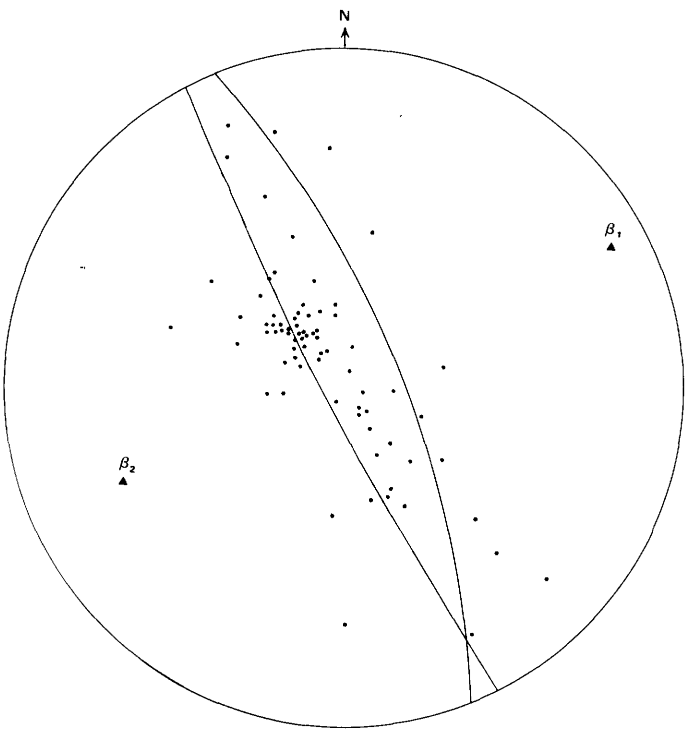


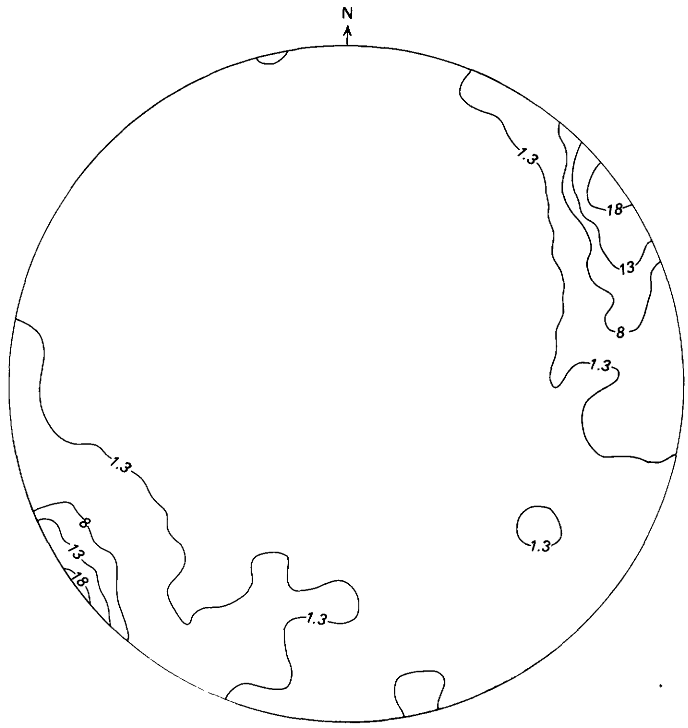

FIGURE 7.—Fabric diagrams of Martinsburg Formation in 1-km strip immediately adjacent to Paulins Kill Valley west of Delaware River. *A*. Stereographic plot (lower hemisphere) of 31 poles to bedding. $\beta$=4° S. 49° W. *B*. Equal-area plot (lower hemisphere) of 28 small fold axes in bedding. Contours at 25, 18, 11, and 4 percent per 1-percent area.

three sets of folds in the area. The same was found true within that part of the Great Valley mapped prior to 1969 (Drake, 1969, p. 105). At that time, the relative ages of the N. 60° E. and N. 80° E. sets of folds were not resolved. A study of the Paulins Kill Valley, however, shows that the N. 60° E. folds are the oldest and the N. 80° E. folds, the youngest, and that a N. 40° E. set intervenes. The configuration of the valley is apparently controlled by both the younger fold sets.

In any case, it has been shown that the Paulins Kill structure is doubly plunging, and though complicated by refolding, the western nose does plunge southwest beneath the Martinsburg cover and is an antiform. This conclusion is supported by the fact that if the carbonate rocks were a klippe, it would require a synform of carbonate rocks to be coextensive in space with an antiform in the Martinsburg, a possible but unlikely relation.




*A*

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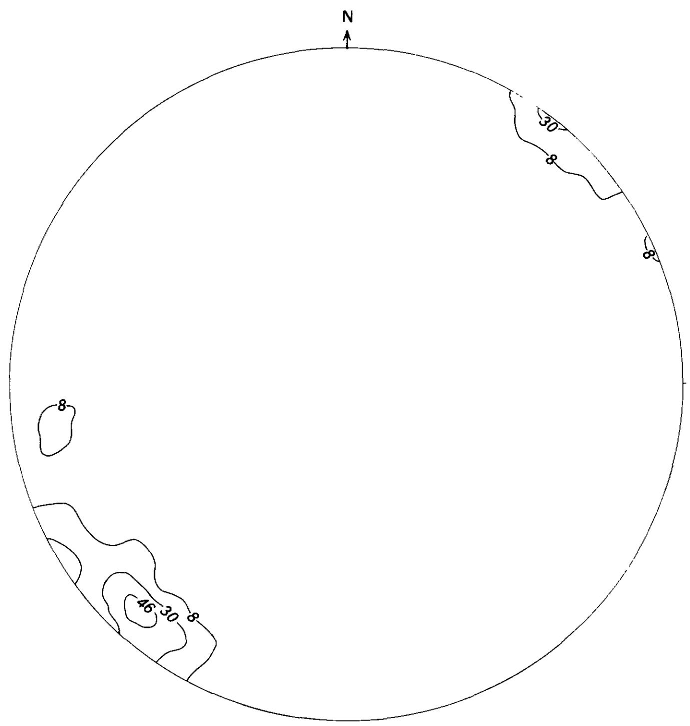
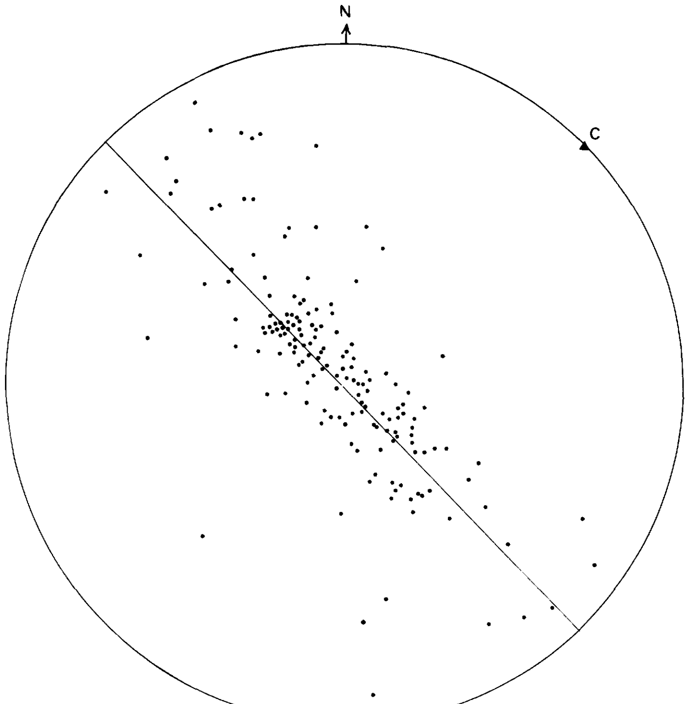



*C*

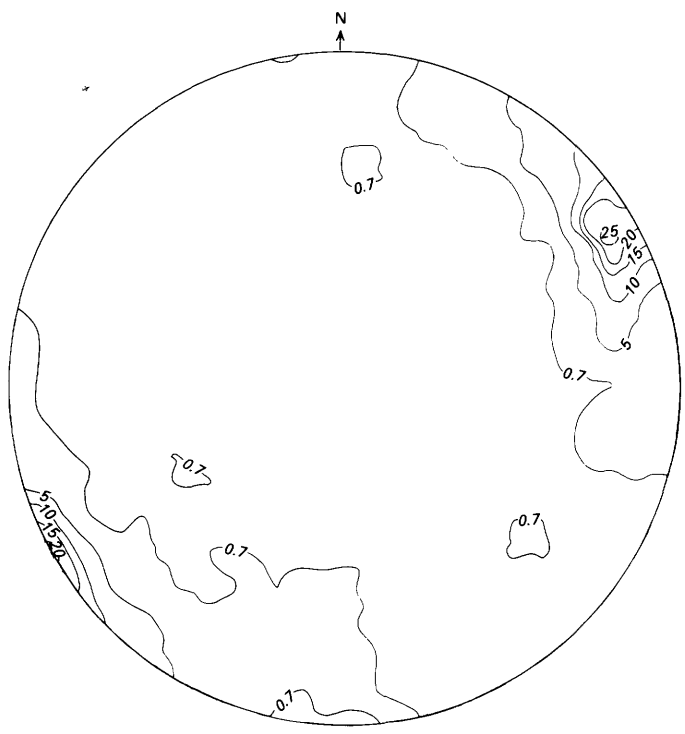
FIGURE 8.—Fabric diagrams of Martinsburg Formation in 1-km strip immediately adjacent to Paulins Kill Valley east of Delaware River. *A*. Stereographic plot (lower hemisphere) of 80 poles to bedding. Crossed girdle with $\beta_1$=6° N. 60° E. and $\beta_2$=10° S. 56° W. *B*. Equal-area plot (lower hemisphere) of 77 small fold axes in bedding. Contours at 18, 13, 8, and 1.3 percent per 1-percent area. *C*. Equal-area plot (lower hemisphere) of 13 axes of folds in slaty cleavage and identified second folds in bedding. Contours at 46, 30, and 8 percent per 1-percent area.

## PORTLAND FAULT

So far, I have shown that the Paulins Kill Valley is framed by one fault, the Portland fault, and that the carbonate rocks of the lowland and the surrounding Martinsburg are antiformal. The Portland fault must therefore be folded into the antiform as well. Field relations (Drake and others, 1969) clearly show that the fault dips north on the north side of the lowland rather than south, as is shown in the older interpretations (pl. 1*C*). The fault is undoubtedly a thrust fault, as "Christmas tree" style minor folds in both overriding and overridden rocks in the north-dipping limb of the fold clearly indicate south-to-north tectonic transport (pl. 1*D*). Minor folds as well as steps on slickensided surfaces clearly indicate south-to-north tectonic transport on the fault on the south side of the lowland and prove that it is not a normal fault as previously interpreted. The fault lies at a small




*A*

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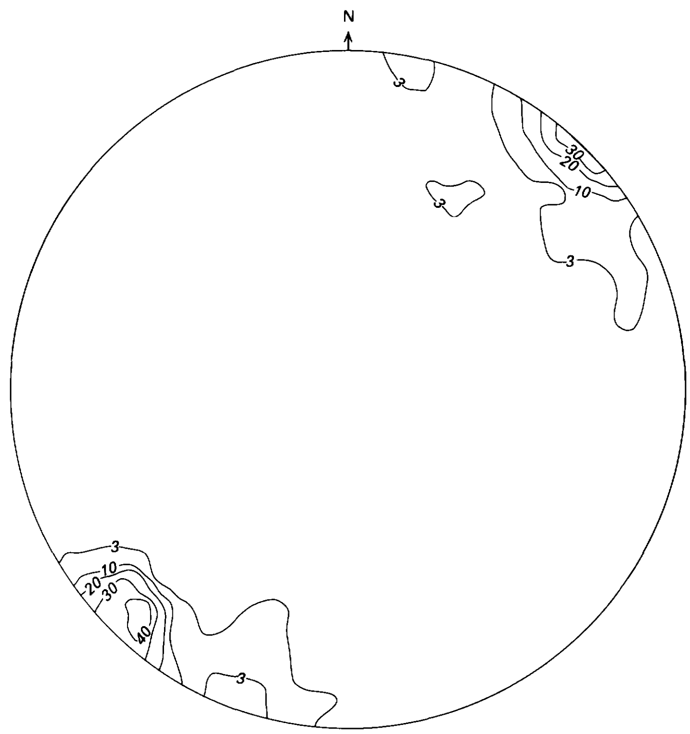



*C*

FIGURE 9.—Fabric diagrams of Martinsburg Formation in the Portland quadrangle. *A*. Stereographic plot (lower hemisphere) of 165 poles to bedding. $\beta$ is about horizontal N. 45° E. with a secondary $\beta$ at 40° S. 48° W. *B*. Equal-area plot (lower hemisphere) of 132 small fold axes in bedding. Contours at 25, 20, 15, 10, 5, and 0.7 percent per 1-percent area. *C*. Equal-area plot (lower hemisphere) of 35 axes of folds in slaty cleavage and recognized second folds in bedding. Contours at 40, 30, 20, 10, and 3 percent per 1-percent area.

angle to the bedding in the Martinsburg and has moved rocks of the upper limb of the Musconetcong nappe an unknown but large distance north. It is extremely difficult, if not impossible, to determine the amount of transport on a fault that brings younger rocks over older rocks. Total displacement on the Portland fault is thought to be several kilometers, although the apparent stratigraphic separations given below mask the true picture.

East of the Delaware River, on the south side of the Paulins Kill Valley, the Martinsburg Formation is in contact with the Epler Formation, only two small slices of Jacksonburg Limestone being present (pl. 1*D*). From a point about 8 km east of the Delaware River, the Portland fault stays at about the same stratigraphic position in the Martinsburg, just above the Bushkill-Ramseyburg contact. Reconnaissance shows that the Epler Formation is north of the fault as far east as Paulina, N.J. North of Marksboro, N.J., Allentown Dolomite is in contact with the Ramseyburg, the entire Beekmantown Group being cut out. Allentown is in contact with Ramseyburg at Swartswood, N.J., east of which I have no stratigraphic information.

Jacksonburg slices are more common and larger along the north border of the valley (pl. 1*A*), and so far as is known, only rocks of the Beekmantown Group abut the fault at other places. Both Epler Formation and Rickenbach Dolomite are present on the north side of the valley as a result of the complicated internal structure of the carbonate rocks. On the north side of the valley, the fault again lies near the Bushkill-Ramseyburg contact. Westward, toward and across the Delaware River, the Portland fault cuts down section into the Bushkill Member (pl. 1*D*).

The minimum possible stratigraphic separation on the Portland fault east of the Delaware River is about 1,550 m, as the Ramseyburg is in contact with the Epler Formation. To the east, near Marksboro, N.J., separation is at least 2,050 m, as Ramseyburg is in contact with Allentown Dolomite. The crude knowledge of the geology of the Kittatinny Valley, however, hinders an interpretation of regional relations. Lewis and Kümmel (1912) believe that there is only about 290 m of Martinsburg between the north border of the Paulins Kill Valley and the Shawangunk Formation (pl. 1*A*, section *B–B′*). Unfortunately, neither the validity of their structural interpretation nor the thickness of rock missing because of erosion along the Taconic unconformity and faulting on the Blue Mountain décollement can be evaluated at this time. Certainly, much of the Martinsburg Formation is absent from this area. In any case, if the thesis of the paper is accepted, measured separations have little meaning, as the fault is an interface between two entirely different tectonic units.

To sum up, the Portland fault is a folded thrust that frames the carbonate rocks in the Paulins Kill Valley; the valley is, then, a very large tectonic window. The fault postdates the $F_1$ fabric in the Martinsburg Formation and appears to be deformed by both N. 40° E. and N. 80° E. sets of folds. Most of the regional configuration of the window probably results from the N. 40° E. deformation, but that part from east of Columbia to about Blairstown (pl. 1*A*), appears to be controlled by the N. 80° E. folding.

### SWARTSWOOD LAKE, STILLWATER, AND WHITE LAKE INNER WINDOWS

Other important evidence bearing on the Lyons Station–Paulins Kill nappe is found in the Swartswood Lake, Stillwater, and White Lake (formerly White's Pond) areas within the Paulins Kill Valley. At these places, fault-bounded bodies of Jacksonburg Limestone occur within the Kittatinny carbonate terrane (pl. 2*A*). These areas of Jacksonburg are all on the crests of upward-closing folds and were considered anticlinal by Kümmel (1901). Kümmel's interpretation (pl. 2*A*, part ***D***) is not very convincing tectonically or mechanically; it requires that a high-angle normal fault form on the crest of an anticline and that the high-angle fault be followed by back-limb thrusting. All the faults are left to dangle in the Kittatinny terrane, and no rational basis is provided for accommodating them. Instead, a reasonable conclusion might be that the Jacksonburg may have been brought to the surface in antiforms and, in fact, may belong to the inverted limb of a recumbent structure. Kümmel's (1901) description of the rocks at these places is consistent with this interpretation, as he found the Jacksonburg to be highly sheared and the fossils therein to be strongly distorted. This tectonite fabric is not present in the stratigraphically right-side-up Jacksonburg along the Paulins Kill Valley boundary, nor is it the fabric one would expect to form during high-angle faulting. Kümmel's data (pl. 2*A*, parts ***A*** and ***D***) allow a refolded nappe interpretation (pl. 2*A*, part ***E***), if the fault bounding the Jacksonburg body on the south is considered to be a folded thrust that was broken by a later thrust. Reconnaissance in the area (pl. 2*B*) supports this interpretation and shows that rocks of the Epler Formation also crop out within this inner window.

That this contact of the Jacksonburg with rocks of the Kittatinny terrane is tectonic is also shown by the relations in plate 2*A*, part ***B***, in which a fold hinge of Jacksonburg is bounded on the south by a fault that joins a sedimentary contact around the closure with no displacement, rather than extending into the Kittatinny terrane. The Jacksonburg would appear to be completely fault bounded. Reconnaissance in the area (pl. 2*C*) shows that the structure is actually an antiform of Jacksonburg Limestone and Epler Formation bounded on all sides by a folded thrust fault.

The structural relations of the Jacksonburg in the White Lake (formerly Whites Pond) area (pl. 2*A*, part ***C***) would appear to be similar to those in the Swartswood Lake area (pl. 2*A*, part *A*), but reconnaissance mapping (pl. 2*D*) clearly shows an antiform of the Jacksonburg and the Epler framed by a folded thrust fault. The dolomite of the Epler has a mylonitic fabric.

The above-cited evidence shows that both right-side-up and inverted rocks are exposed within the frame of the Portland fault and that the inverted rocks are exposed in inner windows within the large Paulins Kill window. These data suggest that the Precambrian core of the Lyon Station–Paulins Kill nappe does not extend very far northeast of Bangor, Pa. (pl. 1*A*), and that the structure in the area of the inner windows is only in sedimentary rocks. The simple-appearing Ackerman anticline of the Portland quadrangle (pl. 1*D*) is actually a much more complicated fold which deforms both limbs of an earlier recumbent fold. The folds in the thrusts that expose the inner windows probably result from the N. 80° E. deformation.

## WHITEHALL WINDOW

A large body of Allentown Dolomite crops out within the Beekmantown terrane along the Lehigh River south of Catasauqua, Pa. (pl. 1*B*). This body has been conventionally interpreted as an anticline (Miller and others, 1941), and as mentioned above, this interpretation was originally accepted by Bromery (1960). Until I did detailed mapping in the area, I interpreted the body as a synform similar to those mapped to the east (Drake, 1967a, b) because of the known regional stratigraphic inversion in the area. Detailed work showed, however, that the Allentown was right-side-up and antiformal and surrounded by inverted Epler Formation and Jacksonburg Limestone (pl. 3*A*). Clearly, the Allentown body is completely fault bounded and underlies the surrounding rocks, which belong to the Musconetcong nappe. The fault-bounded body continues on to the west in the Cementon quadrangle, where mapping has not yet been completed. The Allentown obviously cannot belong to the same tectonic unit that crops out south of the Beekmantown belt. Rocks to the north are also regionally inverted and in places rotated past the horizontal. These rocks extend for at least 17 km and all belong to the Musconetcong nappe. The body of Jacksonburg Limestone north of the fault-bounded Allentown Dolomite (pl. 3*A*) is a back interdigitation within the Musconetcong nappe.

Here again, as in the Paulins Kill Valley, an anticline of Allentown Dolomite shows through a window, the Whitehall window, in a folded thrust fault. This window is also directly above the crest of the Catasauqua aeromagnetic anomaly (fig. 2), and the Allentown is in the upper limb of the Lyon Station–Paulins Kill nappe. The fault-bounded Allentown east of Catasauqua (pl. 1*B*) is also in the upper limb of the Lyon Station–Paulins Kill nappe showing through a window. Detailed mapping shows that this body actually includes some Rickenbach Dolomite and that more of the underlying nappe is exposed. This body is not considered further in this paper, as a description would be largely redundant. I conclude, therefore, that these windows prove the continuity of the structure suggested by the Catasauqua aeromagnetic anomaly.

### ROCK FABRIC

Rocks of the Epler Formation and Jacksonburg Limestone that surround the Whitehall window are inverted and severely deformed. The rocks have a tectonite fabric, and in many exposures, bedding has been transposed and thereby is subparallel to the $S_1$ cleavage (fig. 10). These rocks in most exposures are strongly lineated by a characteristic ruling, which can be seen to result from the intersection of the subparallel bedding and cleavage. The transposed bedding is folded by later stresses, as is the cleavage and bedding in nontransposed rocks. Three sets of fold axes have been recognized (fig. 11*A*): N. 80° E. (strongest), generally southwest, and S. 53° E. The axes S. 53° E. are clearly first folds, as they parallel the strong ruling lineation described above (fig. 11*B*). The southwest-trending fold axes result from the deformation that produced the prominent folds in cleavage (fig. 11*C*) in the Jacksonburg Limestone. These folds characteristically have axial-surface strain-slip cleavage, and strain-slip fabrics are superposed on transposition fabrics in the more incompetent rocks.



FIGURE 10.—Tectonite fabrics in Beekmantown rocks. *A*. Dolomite. *B*. Limestone. Note fold hinge just above coin.

The southwest-trending folds are second folds (note the rotated maximum on fig. 11*A*), and the fold axes trending N. 80° E. are the latest recognized in this area. These folds quite obviously control the configuration of the frame of the Whitehall window as well as the local geologic grain (pl. 3*A*).

The Allentown Dolomite within the window, in contrast to the framing rocks, is not especially deformed, except near the fault frame where it is sheared. This fabric is, of course, in keeping with the upper-limb position of the interwindow rocks.

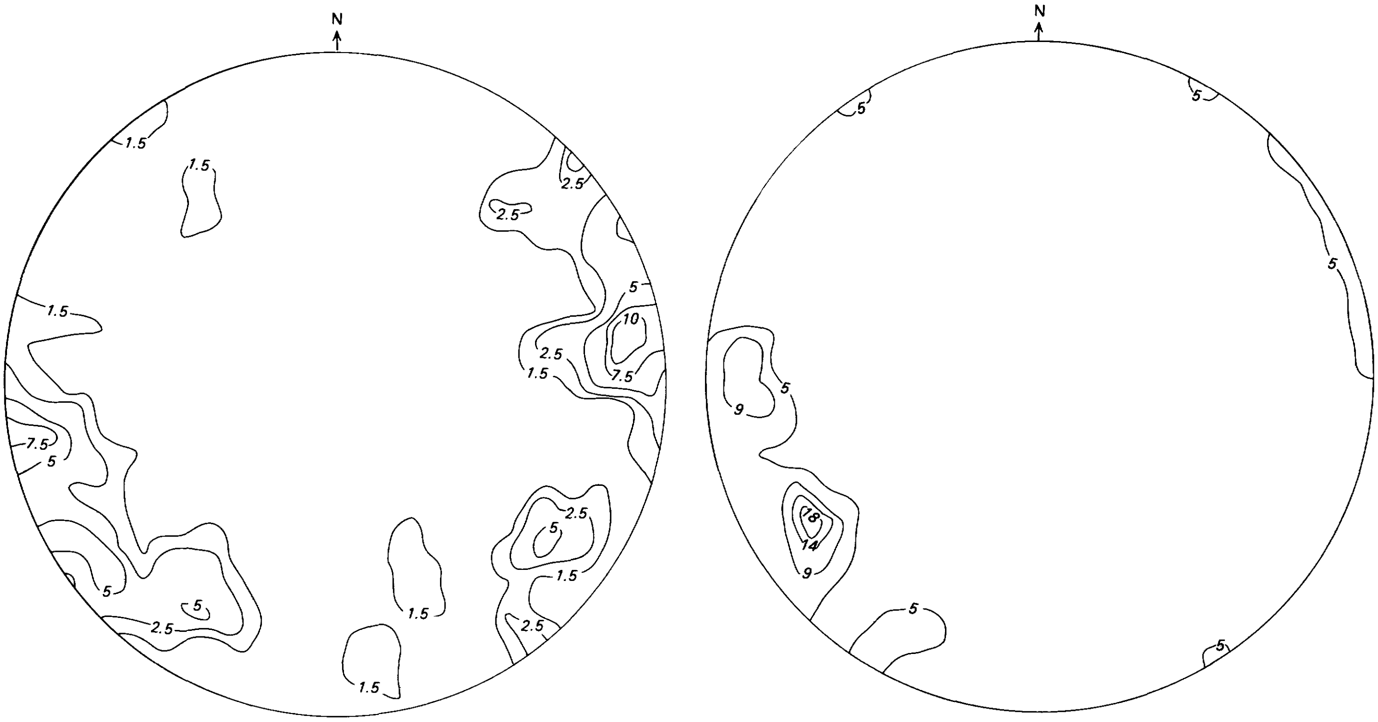
The rocks in the Whitehall window area, like those in the Paulins Kill Valley, have been subjected to at least three periods of folding. The trace of the Catasauqua anomaly, which reflects the antiform in the Lyon Station–Paulins Kill nappe, is controlled by the deformation that produced the southwest-trending fold axes in this area. The configuration of the window, however, is controlled by the later N. 80° E. folding.

### THE FRAMING FAULT

The geologic relations of the Musconetcong nappe, the framing fault, and Lyon Station–Paulins Kill nappe at the Whitehall window are shown in plate 3*B*. These data are from my unpublished maps of the Allentown East and Catasauqua quadrangles, and though somewhat simplified to remove extraneous detail, are geometrically correct. The relations beneath the framing fault are diagrammatic, yet the Precambrian core of the Lyon Station–Paulins Kill nappe is obviously much closer to the surface than was determined geophysically by Bromery (1960). No geologic data are available to support a more complicated configuration than that shown. The thickness of the core is taken as about 600 m. It may be thicker, but it is probably not thinner because of the amplitude of the magnetic anomaly.

The major problem at the Whitehall window is which fault forms the frame. This problem is aggravated by the divergent trend of the outcropping rocks and the subsurface Lyon Station–Paulins Kill nappe (pl. 1*B*). As was shown above, the Portland fault frames the Paulins Kill window. It is by no means certain, however, that the frame of the Whitehall window is the Portland fault, although this fault is the most likely candidate because it is at the same position relative to the Lyon Station–Paulins Kill nappe in both windows.

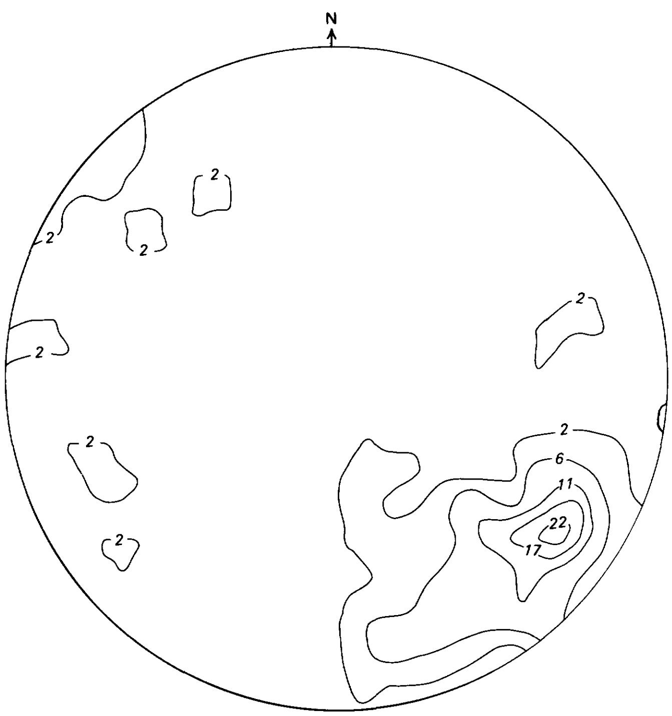
Aside from the Portland fault, only one other thrust fault of regional importance has been recognized in the Delaware and Lehigh Valleys. This fault, the Stockertown fault, is largely blind, but it has been mapped in three quadrangles, where it frames three antiformal windows near Nazareth, Pa. (pl. 1*B*). Although imbricate splays from the fault have been mapped in the Bangor and Wind Gap quadrangles (Davis and others, 1967; J. B. Epstein, unpub. data, 1976), the fault itself has not been recognized in outcrop other than around windows. Especially severe deformation near Manunka Chunk, N.J. (Drake, 1969), suggests that a major fault comes to the surface there, but no such structure could be traced to the west by detailed mapping. However, the fault could easily "hide" within the Martinsburg terrane, especially where glacial deposits are thick. The Stockertown fault can be traced west of the Lehigh River in tectonic windows and intermittent thrust contacts between




A

C

FIGURE 11.—Fabric diagrams of carbonate rocks in the southwestern part of the Catasauqua quadrangle. *A*. Equal-area plot (lower hemisphere) of 85 small fold axes in bedding. Contours at 10, 7.5, 5, 2.5, and 1.5 percent per 1-percent area. *B*. Equal-area plot (lower hemisphere) of 50 ruling lineations. Contours at 22, 17, 11, 6, and 2 percent per 1-percent area. *C*. Equal-area plot (lower hemisphere) of 22 folds in cleavage in Jacksonburg Limestone. Contours at 18, 14, 9, and 5 percent per 1-percent area.




B

carbonate and Martinsburg terranes (pl. 1*B*). The possibility that the Stockertown fault bounded the Whitehall window has been considered, but available data suggest that this is not the case. The Stockertown fault, whenever known, lies along the Jacksonburg-Martinsburg contact in the brow and lower limb of the Musconetcong nappe (pl. 3*C*). Much of the northwestward transport of that nappe is believed to have taken place along this fault, on which the displacement shown on plate 3*C* is rather severely underestimated. If the above interpretation is correct, the Stockertown fault is related to Musconetcong nappe emplacement; I consider it unlikely that the fault is the interface between two major nappes.

When all the available data are considered, one is forced to the conclusion that the fault bounding the Whitehall window is indeed the Portland fault. If this conclusion is correct, then the Portland fault must shear upsection from the inverted limb of the Musconetcong nappe in the Lehigh Valley to the upper limb in the Paulins Kill Valley. That the Portland fault does shear upsection is proved in Paulins Kill Valley, where it passes from the Bushkill Member to the Ramseyburg Member of the Martinsburg Formation (pl. 1*D*). The Portland fault, therefore, is clearly a post-Musconetcong nappe feature that superposes different parts of the structure on the Lyon Station–Paulins Kill nappe. If the fault framing the Whitehall window is not the Portland fault, no interpretation can be made by using currently available data.

## REGIONAL STRUCTURAL RELATIONS

Because the Stockertown fault lies along the Jacksonburg-Martinsburg contact in the brow and inverted limb of the Musconetcong nappe, it is tectonically above the Portland fault and must be cut off by it at depth in the general area of the Whitehall window. Such an arrangement is diagrammed in plate 3*D*, which is a reinterpretation and modification of a section drawn by Sherwood (1964) for an area west of that part of the Whitehall window shown in plate 3*B*. In the construction of this section, the geology beneath the Portland fault was diagrammed as in plate 3*B*. Jacksonburg Limestone is shown to be absent beneath the Stockertown fault, as it is largely absent immediately to the west in both outcrop and in tectonic windows that show Martinsburg Formation through rocks of the Beekmantown Group (pl. 1*B*). Slices of Jacksonburg undoubtedly are present beneath the fault at places, however, as this formation is exposed in discontinuous bodies farther west in the Lehigh Valley (pl. 1*B*). One or more thrust faults are almost certainly present in the lower limb of the Lyon Station–Paulins Kill nappe, but as no data are available to establish their position, they are not shown in plate 3*D*.

### STRUCTURES AT DEPTH

The structure at depth greater than that shown in plate 3*D* is anybody's guess. If one accepts anything approaching the minimum geophysical depth to basement, about 12 km, along the front of the Reading Prong, the structure must be exceedingly complicated, presumably something like that shown by Gray and others (1960, section *A–B*). The structures beneath the Lyon Station–Paulins Kill nappe almost certainly must be confined to the lower Paleozoic sedimentary rocks, as there are no aeromagnetic anomalies suggesting possible Precambrian rock involvement in such structures.

No factual data are available on the behavior of the Portland fault at depth. It has been shown to be a late tectonic feature that cuts across stratigraphic units within the Musconetcong nappe. No Musconetcong rocks have been recognized beneath the Portland fault, so they must be at depth and to the southeast. The Portland fault clearly is a major fault and must be considered a major Alleghenian structure in the Lehigh Valley. This is probably a strong imbricate fault from the major décollement known to occur above the basement interface in the central Appalachians (Gwinn, 1964, 1970; Wood and Bergin, 1970; Root, 1970, 1973). If this interpretation is correct, one must consider the possibility that the Stockertown fault is, in turn, an imbricate from the Portland fault. This is doubtful, however, because the Stockertown seems to be so closely related to the recumbent folding.

### HIGHER TECTONIC UNITS

In the Allentown area, the recently recognized (A. A. Drake, Jr., *in* U.S. Geol. Survey, 1973) South Mountain nappe tectonically overlies the Musconetcong nappe (pl. 3*B*). The South Mountain nappe is not as yet clearly understood, but it is separated from the Musconetcong nappe by the Black River fault (pls. 1*B* and 3*B*). The crystalline core of the Musconetcong nappe consists of the Precambrian rocks east of the trace of this fault (pl. 1*B*), the nappe being represented only by sedimentary rocks in the Allentown area. The Precambrian rocks cropping out in South Mountain and along strike to the west are in the core of the South Mountain nappe. This structure might be the same as the one called the Irish Mountain nappe in the Reading area by MacLachlan and others (1976), but this has not been tested in the field. The position of the interface between the sedimentary rocks of the Musconetcong and South Mountain nappes, that is, the Black River fault, is not known very far west of the west boundary of the Allentown East quadrangle (pl. 1*B*). Problems such as this await further fieldwork.

At least one other tectonic unit is known in the Allentown area. This unit, a thrust sheet of Precambrian rock, the Applebutter thrust sheet (A. A. Drake, Jr., *in* U.S. Geol. Survey 1973), crops out in the Saucon Valley (fig. 1). This thrust sheet and the carbonate rocks beneath it are separated from the South Mountain nappe by a steep major fault, and the relative positions of the two tectonic units are not as yet completely understood. In any case, there is a stack of three nappes in the Allentown area. From lowest to highest, these are the Lyon Station–Paulins Kill, Musconetcong, and South Mountain nappes.

## SUMMARY AND CONCLUSIONS

Geologic and aeromagnetic data show that a major tectonic unit underlies the Musconetcong nappe in the Great Valley of eastern Pennsylvania and New Jersey from Lyon Station, Pa., at least as far as Branchville, N.J., a distance of about 120 km. This structure, the Lyon Station–Paulins Kill nappe, is mostly blind in Pennsylvania but is exposed in the Whitehall window and another unnamed window and is well exposed in a large window in the Paulins Kill Valley of New Jersey. The nappe has a highly magnetic core of Precambrian rock from its western terminus near Lyon Station, Pa., at least to Bangor, Pa., the eastern limit of aeromagnetic surveying, a distance of about 70 km. The core porpoises on plunge culminations and depressions and appears to be nearer the surface in the Whitehall window than was determined geophysically. The eastern part of the structure does not have a crystalline core, as sedimentary rocks of the lower limb are exposed in three inner windows. The carbonate rocks in the Lyon Station–Paulins Kill nappe are of more shoreward facies than those of the Musconetcong nappe, proving that the former nappe is a frontal as well as a tectonically lower structure.

The Lyon Station–Paulins Kill nappe interfaces with the overlying Musconetcong nappe along the Portland fault. This fault shears upsection through the Musconetcong nappe, bringing different parts of that structure into contact with the underlying nappe. The Portland fault is a major structure and is thought to be a strong imbricate splay from the major décollement that lies above the basement in the central Appalachians. The Portland fault is thought to be an Alleghenian structure. If this is correct, nappes of believed Taconic age (Drake, 1969) have been telescoped and folded together during the Alleghenian orogeny.

What was previously thought of as the Musconetcong nappe is now recognized to be a complex nappe system consisting of, from lowest to highest, the Lyon Station–Paulins Kill nappe, the Musconetcong nappe (sensu stricto), and the South Mountain nappe. A fourth tectonic unit, the Applebutter thrust sheet, belongs to the system, but its position is not clear at present. The Musconetcong nappe system is tectonically overlain by the Lebanon Valley system of nappes near Reading, Pa., so it would perhaps be well to think in terms of a Reading Prong megasystem of nappes.

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