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Geologic Map of the Allentown East Quadrangle Lehigh, Northampton, and Bucks Counties, Pennsylvania

By
Avery Ala Drake, Jr.[1]

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[1]Reston, Va.

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GEOLOGIC MAP OF THE ALLENTOWN EAST QUADRANGLE LEHIGH, NORTHAMPTON, AND BUCKS COUNTIES, PENNSYLVANIA

Introduction

The Allentown East quadrangle, in eastern Pennsylvania, lies across the contact of Mesoproterozoic (Plumb, 1991) crystalline rocks of the Durham and Reading Hills segment of the Reading Prong, a major external basement massif in the central Appalachians (Drake and others, 1988), with lower Paleozoic rocks of the Lehigh Valley segment of the Great Appalachian Valley and Mesozoic rocks of the Newark basin. These rocks are covered and obscured through much of the quadrangle by glacial deposits of pre-Illinoian age.

The rocks exposed in this quadrangle have been studied elsewhere in eastern Pennsylvania and the reader is referred to Buckwalter (1959, 1962), Drake (1969, 1984, in press a), and MacLachlan (1979, 1983) for descriptions of the Mesoproterozoic rocks, to Drake (1965, 1969), Drake and Epstein (1967), MacLachlan (1967, 1979, 1983), and MacLachlan and others (1975) for descriptions of the lower Paleozoic rocks, and Drake and others (1961), MacLachlan (1967), MacLachlan and others (1975) and McLaughlin (in Willard and others, 1959) for descriptions of the Mesozoic rocks. Regionally, the quadrangle is within the complex tectonic terrane termed the Taconides by Drake (1980), which was described in detail by Drake and others (1989). Here the Mesoproterozoic rocks were first deformed during the Grenville orogeny (Rankin and others, 1993), and were again deformed with the lower Paleozoic rocks during the Ordovician Taconic orogeny (Drake, 1980). These structures were later overprinted by those formed during the late Paleozoic Alleghanian orogeny. The latest structural event was Mesozoic extension related to the opening of the Atlantic Ocean (Manspeizer and others, 1989). Geologic structure in this quadrangle is dominated by emergent thrust faults.

Stratigraphy

The Allentown East quadrangle is underlain by gneisses and foliated granitoid rocks of Mesoproterozoic age, which are cut by a few Neoproterozoic dikes, and are overlain by sedimentary rocks of Cambrian and Ordovician age, and sedimentary and intrusive rocks of Mesozoic age. The pre-Middle Ordovician rocks were deposited on the great east-facing (present direction) shelf of the Laurentian craton after the opening of the Iapetus Ocean (Rankin and others, 1989). At the beginning of the Taconic orogeny, the shelf foundered forming the Martinsburg foreland basin, which was filled by Middle and lower Upper Ordovician flysch deposits (Drake and others, 1989). In Triassic time, the Newark basin was formed by extension related to the opening of the Atlantic Ocean.

Mesoproterozoic Rocks

Mesoproterozoic rocks are abundant in the Allentown East quadrangle. The oldest unit is quartz-oligoclase gneiss (Y^2lo) of the Losee Metamorphic Suite that was interpreted to be basement to other rocks in the Reading Prong (Offield, 1967; Drake, 1984). Recently, an unconformity was mapped in New Jersey between Losee rocks and the overlying metasedimentary sequence (Volkert and Drake, in press). On the basis of chemistry, the quartz-oligoclase gneiss has been interpreted to be a sequence of volcanic-volcaniclastic quartz keratophyre and dacite (Drake, 1984; Puffer and Volkert, 1991). Isotopic dating of the Losee is not complete, but similar rocks in the Green Mountain massif in Vermont have a U-Pb upper intercept age of about 1350 Ma (Aleinikoff and others, 1990). The Losee, therefore, is Ectasian (Plumb,

1991) in age. Quartz-oligoclase gneiss is not abundant in the Allentown East quadrangle. It can be best seen in an abandoned quarry on the south slope of South Mountain near the west border of the quadrangle. It also crops out in University Heights on South Mountain near the eastern border of the quadrangle.

The quartz-oligoclase gneiss is unconformably overlain by a sequence of calcareous, quartzofeldspathic, and quartzose metasedimentary rocks and amphibolite. Calcareous rocks are sparse and consist of marble (Y^2mr) and its metasomatic products, hornblende skarn (Y^2sk) and phlogopite-talc schist (Y^2pt). Marble and phlogopite-talc schist can be seen in an abandoned quarry on the north slope of South Mountain about 1700 feet south of Summer Camp. Hornblende skarn (Y^2sk) crops out on the northwest slope of Applebutter Hill just west of Chestnut Hill Road.

Quartzofeldspathic gneiss in the Allentown East quadrangle consists of biotite-quartz-feldspar gneiss (Y^2b), potassic feldspar gneiss (Y^2k), and sillimanite-bearing gneiss (Y^2s). Biotite-quartz-feldspar gneiss is highly variable in both composition and texture (see modes in Drake, 1969, 1984) and is not abundant in this quadrangle. It is characterized by conspicuous biotite and prominant compositional layering. The unit was interpreted to be metamorphosed graywacke (Drake, 1984). It can be best seen on the south slope of South Mountain between North Mountain Drive and Seidersville Road near the east boundary of the quadrangle. A body was also mapped on Limeport Hill near the southwest corner of the quadrangle.

Potassic feldspar gneiss (Y^2k) is abundant in the Allentown East quadrangle and is characterized by its high content of potassic feldspar and quartz and a paucity of plagioclase (see modes and chemical analyses in Drake, 1969, 1984). Much of the unit is heterogeneous, and some phases are feldspathic quartzite (Y^2q). Much of the rock resembles meta-arkose, whereas some parts are iron-rich and resemble metamorphosed iron-formation (taconite). Such rocks were interpreted by Drake (1990) to contain an exhalative component. In some places, such as along Route 309 on the north slope and summit of South Mountain the potassic feldspar gneiss contains small sheets, veins, lenses, and blotches of anatectic granitoid.

Sillimanite-bearing gneiss (Y^2s) is restricted to a thick layer on the north slope of South Mountain both north and south of Seidersville Road. As elsewhere in the Reading Prong, it is strongly migmatitic. The unit is thought to be a more aluminous phase of potassic feldspar gneiss (Y^2k).

Graphite bearing quartzite (Y^2qq) does not crop out in the quadrangle. Three bodies, however, were mapped on Limeport Hill on the basis of float.

Amphibolite (Y^2a) is abundant in the Allentown East quadrangle, as it is throughout the Reading Prong. It has been found to have had more than one origin. Some is closely interlayered with metasedimentary rocks and likely has a metasedimentary origin. In New Jersey, relict pillow structures in amphibolite have been described and illustrated by Hague and others (1956) and Drake (1990). Elsewhere is New Jersey, enclaves of undeformed gabbro have been described by Baker and Buddington (1970) and Hull and others (1986), and described and illustrated by Drake (1990). The protolith or protoliths of amphibolite in this quadrangle cannot be determined.

At places, such as west of Summit Lawn and east of Bauer Rock, amphibolite has been migmatized to arterite (Y^3ma). In these stromatic migmatites, microperthite alaskite forms the leucosome and amphibolite the paleosome. At places, migmatization has progressed to the point that the rocks could be described as hornblende granite. Similar reactions have been described by Buckwalter (1958), Drake and others (1961), and Drake (1993).

The supracrustal metasedimentary sequence described in this quadrangle occurs throughout the Reading Prong, and similar rocks crop out in the Honey Brook Upland to the south in Pennsylvania and the Berkshire and Green Mountain massifs in New England (Rankin and others, 1993). In the Reading Prong, these rocks have been interpreted to have been deposited in a rift setting (Drake, 1990; Volkert and Drake, in press). They are probably Ectasian (Plumb, 1991) in age because they are intruded by rocks of Stenian age (Plumb, 1991).

The Losee Metamorphic Suite, the metasedimentary rocks and amphibolite have been intruded by rocks of the Byram Intrusive Suite (Drake, 1984). In this quadrangle, the Byram Intrusive Suite consists of microperthite alaskite (Y^3ba), hornblende granite (Y^3bh) and biotite granite (Y^3bb).

Microperthite alaskite is abundant in this quadrangle, and is best exposured on South Mountain and Lehigh Mountain. Hornblende granite is equally abundant and is also well exposed on South Mountain and Lehigh Mountain. Biotite granite was mapped on the basis of float on Limeport Hill in the southwest corner of the quadrangle. Modes and chemical analyses of Byram rocks are given in Drake (1969, 1984) and Drake and others (1991a). The Byram chemistry is similar to that of supposed, intraplate, anorogenic granites (Volkert and Drake, in press), however, the rocks, which have a Stenian U-Pb age of about 1090 Ma (Drake and others, 1991a), were emplaced synkinematically during the Grenville orogeny (Drake, 1969, 1984, 1990, in press a; Rankin and others, 1993). The Byram magma was interpreted to have been generated within an intraplate rift zone (Volkert and Drake, in press).

Neoproterozoic Dikes

Altered diabase (Zd) was mapped on the basis of float on South Mountain about 1200 ft north of University Heights and about 2800 ft S. 63°W. of the intersection of Vera Cruz and Chestnut Hill Roads, on Dutch Hill about 3200 ft N.70°E. of the Allentown Hospital, and on Limeport Hill near the southwestern corner of the quadrangle. These rocks are interpreted to be Neoproterozoic in age because they have been metamorphosed in greenschist facies and have intruded only Mesoproterozoic rocks. Similar metadiabase in New Jersey has chemistry like that of known Neoproterozoic rocks elsewhere in the Appalachians (Puffer and others, 1991; Volkert and Puffer, 1995). If the above interpretation is correct, the dikes were emplaced during the rifting event related to the opening of the Iapetus Ocean.

Lower Paleozoic Rocks

MacLachlan (1967, 1983) divided the carbonate rocks of the Great Appalachian Valley of Pennsylvania into four somewhat different stratigraphic sequences; from west to east these are: the Cumberland Valley, the Lebanon Valley, the Schuylkill, and the Lehigh Valley sequences. These sequences result from deposition on different parts of the Laurentian passive margin. The Beekmantown Group and older rocks thicken and increasingly contain more limestone from the Lehigh Valley in the east to the Lebanon Valley in the west. The overlying post-Beekmantown carbonate units contain more terrigenous material related to beginning foreland basin sedimentation (Drake and others, 1989). This suggests that the Lebanon Valley sequence originated on a more outboard part of the passive margin, the Schuylkill sequence (a transition facies) from an intermediate position, and the Lehigh Valley sequence from a more inboard position. Only the Schuylkill and Lehigh Valley sequences crop out in this quadrangle.

Lehigh Valley Sequence

Rocks of the Lehigh Valley sequence occur in the footwall of the Black River thrust fault and constitute the cover rocks of the Musconetcong nappe (MacLachland, 1979, 1983; Drake, 1993, in press b). Lehigh Valley rocks in this quadrangle include the Hardyston Quartzite (Ꞓh), Leithsville Formation (Ꞓl), Allentown Dolomite (OꞒa), Stonehenge Formation (Os), Richenbach Dolomite (Or), and Epler Formation (Oe). Prior to the work of Drake and Lyttle (1985) and Karklins and Repetski (1989) in New Jersey, the Stonehenge Formation was not recognized at the base of the Beekmantown Group, and was mismapped as either Rickenbach Dolomite or Epler Formation.

Good outcrops of Hardyston Quartzite can be seen on both Lehigh Mountain and Dutch Hill. The Leithsville Formation crops out on both the west and east slopes of Lehigh Mountain and Dutch Hill. There are abundant outcrops of Allentown Dolomite in the north part of the quadrangle. The Stonehenge Formation, Rickenbach Dolomite, and Epler Formation crop out in an overturned section along Jordan Creek in the northwestern corner of the quadrangle.

Schuylkill Sequence

Rocks of the Schuylkill sequence occur in the hanging wall of the Black River thrust fault and constitute the cover sequence of the Irish Mountain nappe (MacLachlan, 1979, 1983; Drake, 1993, in press b). Schuylkill rocks in this quadrangle include the Hardyston Quartzite (Ꞓh), Leithsville Formation (Ꞓl), the Tuckerton (Ꞓat), and Muhlenberg Members (Ꞓam) of the Allentown Dolomite, Stonehenge Formation (Os), Rickenbach Dolomite (Or), Epler Formation (Oe), Jacksonburg Limestone (Oj), and Bushkill Member of the Martinsburg Formation (Omb). The Hardyston Quartzite can be best seen on the north slope of South Mountain, on the north slope of Saucon Hill, and north of Vera Cruz. The Leithsville Formation crops out just east of the Emmans thrust fault in the western part of the quadrangle. The Tuckerton Member of the Allentown Dolomite does not crop out, whereas the Muhlenberg Member crops out at several places along the western boundary of the quadrangle. It is likely that much of the undifferentiated Allentown Dolomite in the Saucon Valley is Muhlenberg Member because it contains scattered limonite mines. The Stonehenge Formation can be best seen in the sharp reentrant in the Applebutter thrust fault in the eastern part of the quadrangle. The best exposures of Rickenbach Dolomite are in the Friedensville area, where there are also good outcrops of Epler Formation. Excellent outcrops of Epler Formation can also be seen in the ridge north of Saucon Creek about 5000 ft southwest of Lanark. The Jacksonburg Limestone can be best seen east of Route 309 south of Summit Lawn. The Bushkill Member of the Martinsburg Formation can be seen in an abandoned quarry about 3500 feet west-southwest of Lanark. Here the slate of the Bushkill is quite calcareous (sample 1, table 1), contains thin interbeds of graded graywacke siltstone, float off which litters the surrounding area.

Mesozoic Rocks

Bedded rocks of the Passaic Formation, which as a maximum thickness in the Newark Basin of 11475 ft (Olsen, 1980), are exposed in the southeastern corner of the quadrangle. Claystone and mudstone (Ꞧp) form scattered outcrops in the Coopersburg area. Sandstone (Ꞧps) can be best seen in outcrops along Passer Road. An outcrop of limestone fanglomerate (Ꞧpl) could be seen in 1969 about 500 ft north of the intersection of Passer Road and Main Street, but may have been destroyed by highway construction in recent years. Quartzite fanglomerate (TRpq) does not crop out but underlies Chestnut Hill on the basis of float. Diabase (Jd) and its hornfels collar (TRph) can be seen in outcrops along the railroad near the Lehigh-Bucks County line. An analyses of diabase is given in table 1.

Structural Geology

The Mesoproterozoic rocks were first deformed during the Mesoproterozoic Grenville orogeny. They were later deformed with their early Paleozoic cover during the Ordovician Taconic and late Paleozoic Alleghanian orogenies. The Mesoproterozoic rocks were the "rigid basement plunger" during the Paleozoic deformations and, therefore, constitute the newly defined raetide tectonic facies of Hsü (1995). The early Paleozoic rocks are characterized by thin-skinned deformation and, therefore, constitute the alemanide tectonic facies of Hsü (1995).

Mesoproterozoic Deformation

The metamorphosed Mesoproterozoic sedimentary and volcanic-volcaniclastic rocks are both compositionally layered and foliated. These planar elements are nearly parallel at most places, but in some outcrops, foliation that roughly parallels layering on the limbs of small early folds, passes through the fold hinges rather than wrapping around them. This evidence, as well as the lens-shaped map units, suggests regional transposition of layering into the foliation. All mapped folds deform both layering and foliation, so none are first phase folds.

F_2 folds are abundant on South Mountain. Most trend about west-northwest and are overturned to the west, although some are upright. These folds are refolded by both northeast and east-northeast-trending folds. Both later fold phases are considered to be F_3, but the east-northeast trending folds may have resulted from a distinct F_4 phase. No northeast-trending axis, however, was seen to be refolded by an east-northeast trending axis in the field.

F_2 folds on Applebutter and Limeport Hills trend east-northeast. These folds are either upright or are overturned to the north. They are refolded by west-northwest-trending upright F_3 folds. These folded rocks are in a different thrust sheet than those underlying South Mountain.

On Lehigh Mountain, F_2 folds are strongly refolded by northwest- to nearly north-trending F_3 folds that are either upright or are overturned to the west. F_2 and F_3 folds have similar attitudes on Dutch Hill.

Rocks of the Byram Intrusive Suite were emplaced during the F_2 folding event, so the Grenville orogeny was in process at 1,090 Ma (Drake and others, 1991a). That orogeny was apparently complete by 1,020 Ma based on the age of the post-kinematic Mount Eve Granite in the New Jersey Highlands (Drake and others, 1991b).

Paleozoic Deformation

Pre-Silurian rocks in eastern Pennsylvania structurally constitute the Reading Prong nappe megasystem (Drake, 1973, 1978, 1991). At least five major nappes are known, from west to east and highest to lowest, they are the Lebanon Valley, the Applebutter, the Irish Mountain, the Musconetcong, and the Lyons Station. These nappes constitute a crystalline duplex, which is probably the northeastern extremity of a crustal duplex beneath the Newark basin and the Piedmont (Drake, 1991, in press b).

Rocks of the Applebutter, Irish Mountain, and Musconetcong nappes crop out in the Allentown East quadrangle. The Lyons Station nappe is present in the subsurface in the northwestern corner of the quadrangle (Drake, 1978). The Applebutter is separated from the Irish Mountain by the Applebutter thrust fault, the Irish Mountain from the Musconetcong by the Black River thrust fault, and the Musconetcong from the Lyons Station by the Fullerton thrust fault.

Thrust Faults

Thirteen northwest-directed thrust faults were mapped in the Allentown East quadrangle. In addition, two other thrust faults were projected into the subsurface from the north.

The highest thrust fault, which is unnamed, has placed Epler Formation on Mesoproterozoic rocks and Hardyston Quartzite of the Applebutter nappe north of Coopersburg. On May 26, 1970, the sole of this thrust could be seen in a new cut for Route 309 about 2,100 ft north of Passer Road. The sole was marked by carbonate mylonite above mylonitic microperthite alaskite. The mylonitic foliation had an attitude of N.20°E. 38SE, and was marked by a strong down-dip stretching lineation. In September 1993, only mylonitic microperthite alaskite was exposed at this site. The Applebutter thrust fault has placed Mesoproterozoic rocks and, in places, Hardyston Quartzite on Allentown Dolomite and Stonehenge Formation. In September 1993, the sole of this thrust fault was exposed about 2,300 ft S.20°W. from the intersection of Spring Drive and Lanark Road. The sole was marked by north-dipping hornblende granite mylonite above carbonate mylonite that had a very strong, down-dip stretching lineation. The Mesoproterozoic rocks in the hanging wall of the Applebutter thrust fault constitute the Applebutter nappe (Drake, 1973, 1993, in press b; Smith and Barnes, in press). Rocks of the Applebutter nappe contain a much higher content of radioactive minerals than the other crystalline rocks of the Durham and Reading Hills (Smith and Barnes, in press). Water well data here (W-2, W-5, W-9,W-10, table 2), in the Allentown West quadrangle (Drake, 1993), and farther southwest (D.B. MacLachlan, Pennsylvania Geological Survey, written commun., 1980) confirm that carbonate rocks underlie the Applebutter nappe. Wells W-1, W-3, and W-4 (table 2) confirm that Hardyston Quartzite underlies Mesoproterozoic rocks.

A klippe of Bushkill Member of the Martinsburg Formation sits on Allentown Dolomite of the Irish Mountain nappe just north of Limeport. The thrust fault is well exposed in a large dolomite quarry. The sole can be seen in the southeast corner, the southwest corner, and the center of the quarry. The movement surface is nearly horizontal and is essentially parallel to the slaty cleavage in the Bushkill. The dolomite has a mylonitic fabric roughly parallel to bedding. The cleavage rolls around in the thrust zone and is rucked by a strong crenulation cleavage. There has been late, brittle movement along the thrust surface, which at places, is marked by 2 to 3 inches of gouge. The thrust must be rooted somewhere beneath the Newark basin.

The Saucon thrust fault disrupts major folds in the lower Paleozoic rocks in the Saucon Valley. It has rocks as young as Epler Formation in its hanging wall, and as young as Bushkill Member in its footwall. It is not exposed, but has been proved by core drilling (Callahan, 1968). Its trace to the east and west of the Friedensville-Lanark area is poorly constrained, but it is clearly cut off by the Colesville fault west of Lanark.

An unnamed thrust fault disrupts the hinge of the Lanark syncline about 4000 feet west of Lanark, and has placed Bushkill Member of the Martinsburg Formation and Jacksonburg Limestone above Epler Formation. It is poorly understood because there are no available structural data.

The Colesville fault was interpreted to be a normal fault by Miller and others (1941) and Callahan (1968) because core drilling proved that it stands steep, and that it has brought younger rocks onto older rocks. It was interpreted to be a steep thrust fault by Drake (1969). Such an interpretation is supported by recent work in New Jersey (Drake and others, 1995) where such thrust faults are abundant. The Colesville fault was interpreted to be an out-of-sequence thrust fault that has broken previously deformed rocks (Drake, 1993). The fault is not exposed. It has formed a duplex within lower Paleozoic rocks along its eastern reach (see section A-A' and B-B').

The Emmaus thrust fault is totally obscured in this quadrangle by surficial deposits. Data from the adjacent Allentown West quadrangle (Drake, 1993) and scattered exposures show that it has placed Leithsville Formation on the Tuckerton and Muhlenberg Members of the Allentown Dolomite of the Schuylkill sequence. The Emmaus thrust fault joins the Applebutter thrust fault north of Wilbur and to the west in the Allentown West quadrangle (Drake, 1993) capturing a large horse of Leithsville Formation.

The Black River thrust fault has brought rocks of the Schuylkill sequence onto those of the Lehigh Valley sequence, and is the bounding fault between the Irish Mountain and Musconetcong nappes. Most of its trace in this quadrangle is obscured by glacial deposits. On the west border of the quadrangle, inverted rocks of the Muhlenburg Member of the Allentown Dolomite are in contact with right-side-up Allentown Dolomite of the Lehigh Valley sequence. At the west nose of Lehigh Mountain, the Black River thrust fault cuts across the basement-cover contact, Hardyston-Leithsville contact, and the Leithsville-Allentown contact. In the eastern part of the quadrangle, it has placed Mesoproterozoic rocks and Hardystown Quartzite on Leithsville Formation.

The Lehigh Mountain thrust fault is the footwall of an "orphan" (Lewis and Bartholomew, 1989), that is, an exotic detached duplex of Mesoproterozoic rock and lesser Hardyston Quartzite and Leithsville Formation, which has the Black River thrust fault as its hanging wall.

The Fountain Hill thrust fault forms the hanging wall of another duplex of Mesoproterozoic rocks, Hardyston Quartzite, and Leithsville Formation that has the Rittersville thrust fault as its footwall. The East Allentown thrust fault forms the hanging wall of yet another orphan of Mesoproterozoic rocks, Hardyston Quartzite, and Leithsville Formation. The Rittersville thrust fault is the footwall of this orphan, and has Allentown Dolomite in its footwall.

The Jordan Creek thrust has placed upright Allentown Dolomite onto an overturned sequence of Beekmantown Group. This relation is well exposed to the north and was previously described by Miller and others (1941), Sherwood (1964), and Drake (1978). The Jordan Creek is a major thrust fault in the area northeast of the Allentown East quadrangle (A.A. Drake, Jr., unpublished data, 1970-93).

The subsurface Fullerton thrust fault has placed inverted Epler Formation on right-side up Allentown Dolomite (Drake, 1978), and is the contact between the Musconetcong and Lyon Station nappes. To the north, this relation is shown by the Whitehall, Mechanicsville, and Schoenersville tectonic windows (Drake, 1978, unpublished data, 1970-71). Rocks of the Epler Formation have a mylonitic fabric and a strong down-dip stretching lineation (Drake, 1978). Core drilling in Allentown Dolomite within the Whitehall window encountered a thrust fault and Epler Formation at a depth of 385.5 ft (M.M. Azmeh, P.E. LaMoreaux and Associates, written commun., April 27, 1992). Conodonts from the core were typical of those of the lower third of the Epler Formation at its type locality (J.E. Repetski, U.S. Geological Survey, written commun., 1992). The results of this drilling shows the complexity of the geology of eastern Pennsylvania.

Folds

Three folds were mapped in the lower Paleozoic rocks in the Saucon Valley, the Lanark syncline, which is overturned to the northwest, the Friedensville anticline, which is upright to slightly overturned to the northwest, and a doubly plunging syncline in the hanging wall of the Saucon thrust fault, which is overturned to the northwest. The klippen of Mesoproterozoic rocks and the reentrants in the Applebutter thrust fault also define folds, but these axes were not drawn so as to avoid additional clutter. The folded lower Paleozoic rocks have an axial surface cleavage and their general overturned nature suggest that they belong to the Irish Mountain fold phase of Drake (1993) Irish Mountain folds were the earliest in this part of eastern Pennsylvania.

Numerous east- to east-northeast-trending, small amplitude folds were mapped in the Allentown Dolomite in the northwestern part of the quadrangle. Similar folds in the adjacent Allentown West quadrangle were interpreted to be second phase Iron Run folds (Drake, 1993). They may, however, be Stone Church folds of Drake and Lyttle (1985). If so, they would belong to the youngest fold phase recognized in eastern Pennsylvania and New Jersey. The abundance and style of these folds suggest that the anticlines might be tip anticlines, that is, anticlines above blind thrust faults. That interpretation, however, is not shown in the cross sections.

Normal Faults

Three normal faults, the 7-17, Nason, and Cemetery were mapped in the Friedensville area. This would have been impossible without the detailed data kindly supplied by the New Jersey Zinc Company (W.H. Callahan, written commun., 1969). According to Callahan, none of these faults were impressive where observed underground.

Time of Deformation

Time of deformation is a major concern in Appalachian geology. Most geologists think that the regional nappes formed during the Taconic orogeny (Drake and others, 1989). If this is correct, the Irish Mountain fold phase is Taconic. Lash (1982, 1987) presented evidence that the first fold phase in the Hamburg quadrangle to the west, which I correlate with the Irish Mountain folds, predates deposition of Upper Ordovician molasse. In New Jersey, slaty-cleaved Martinsburg Formation occurs as xenoliths in Late Ordovician intrusive rocks (Rowlands, 1980; Ratcliffe, 1981; Drake and Monteverde, 1992) showing that the cleavage in the Martinsburg surely must be Taconic. Other geologists, such as Epstein and Epstein (1969) present evidence suggesting that cleavage in their areas to the north formed during the Alleghanian orogeny. Recently, mica from cleavage surfaces in the Pen Argyl Member of the Martinsburg Formation at Lehigh Gap, Pa., about 16 miles to the north, was interpreted to be Permian in age (Wintsch and Kunk, 1992). Is all the slaty cleavage the same age, or does it become younger in a progression of deformation fronts (Gray and Mitra, 1990)? Until this question is answered, one can only speculate on the time of deformation.

The Applebutter thrust appears to be early, and therefore Taconic in age. This interpretation is supported by the fact that it is folded by Irish Mountain folds. Most, if not all, the other thrust faults are probably Alleghanian in age. Certainly those that have brought younger rocks onto older rocks, such as the Colesville, must be Alleghanian. The Saucon thrust fault cuts probable Taconic folds so is also a likely candidate for an Alleghanian structure. If the low amplitude folds in the northwestern part of the quadrangle are tip anticlines, they are likely Alleghanian and belong to the Stone Church phase.

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Table 1. Chemical analyses of some rocks from the Allentown East quadrangle (weight percent)

	1	2
SiO_2	19.9	52.6
Al_2O_3	6.6	17.4
Fe_2O_3	0.8	2.3
FeO	1.5	6.4
MgO	2.1	4.9
CaO	35.5	9.9
Na_2O	0.6	2.2
K_2O	1.5	1.1
H_2O+	1.6	1.4
H_2O-	0.1	0.3
TiO_2	0.3	1.1
P_2O_5	0.2	0.2
MnO	0.1	0.2
CO_2	29.0	---
Total	99.8	100.0

Rapid rock analyses by chemists of the U.S. Geological Survey

Description of Samples

1. Sample AE-E-3-9 very calcareous slate from the Bushkill Member of the Martinsburg Formation containing very thin intervals of graywacke siltstone from outcrop in Saucon Valley about 3200 feet S.62°W. from the Carmelite Monastery in Lanark at lat. 40°32'53"N. and long. 76°26'43"W.

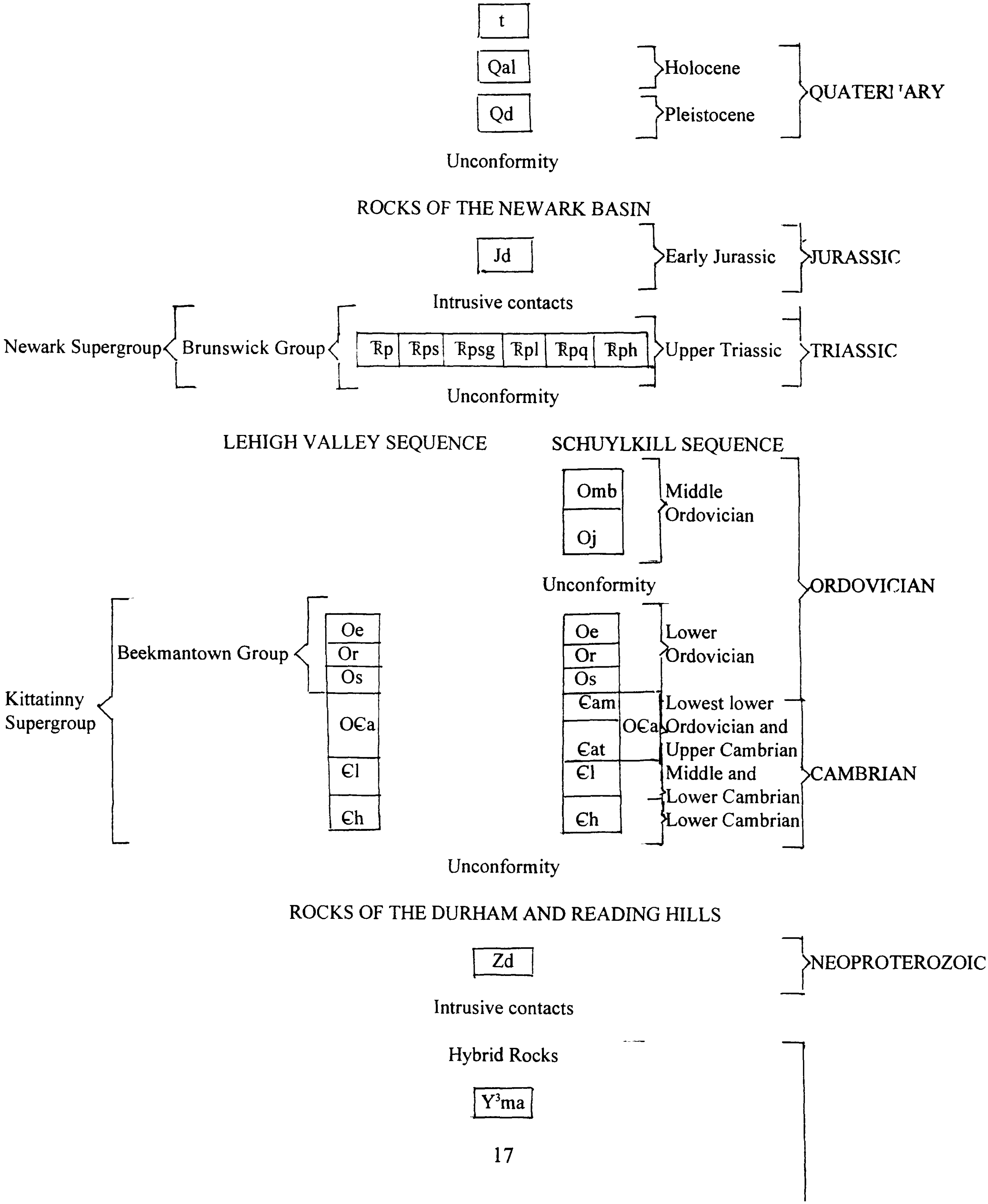
2. Sample AE-H-6-3 of Jurassic diabase from Shelly Intrusion from outcrop along Reading Railroad about 600 ft south of Lehigh-Bucks County line at lat. 40°30'06"N. and long. 75°23'10"W.

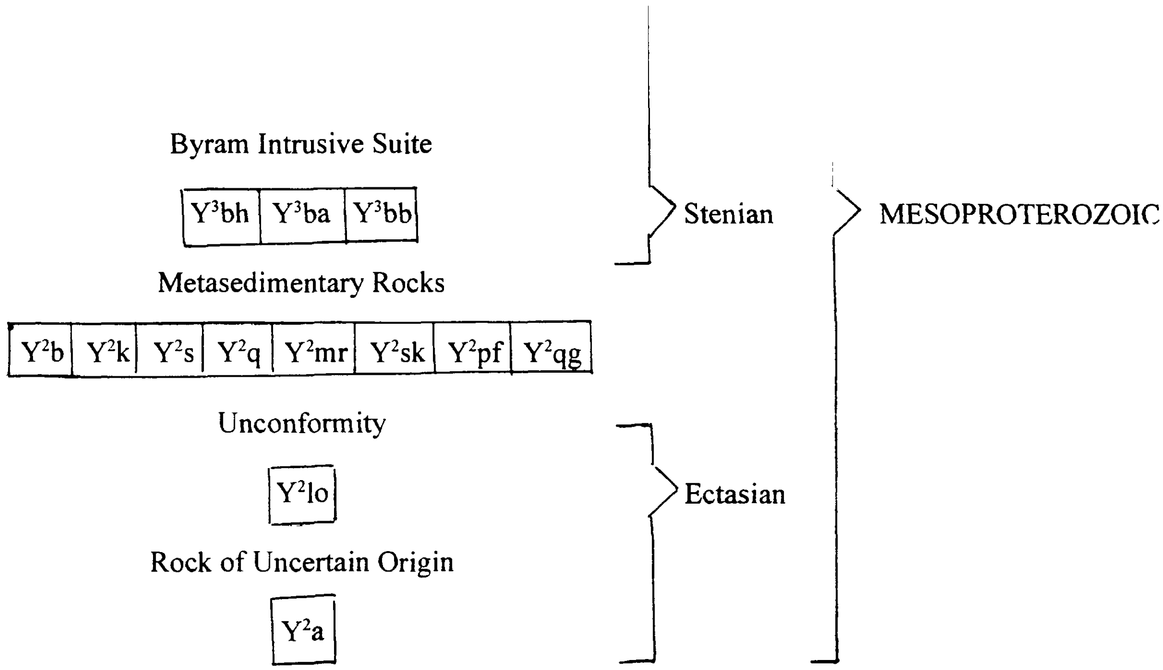
Table 2. Selected Water Wells in the Allentown East Quadrangle
[Data from Wood and others (1972)]

Well Number	Bottom of well	Depth (ft)
W-1	Hardyston Quartzite	131
W-2	Carbonate rock	127
W-3	Hardyston Quartzite	288
W-4	Hardyston Quartzite	220
W-5	Carbonate rock	96
W-6	Carbonate rock	183
W-7	Carbonate rock	105
W-8	Carbonate rock	173
W-9	Carbonate rock	308
W-10	Carbonate rock	268

CORRELATION OF MAP UNITS[1]

color designations, in parentheses, are from Goddard and others (1948)




Byram Intrusive Suite
Y³bh Y³ba Y³bb
Metasedimentary Rocks
Y²b Y²k Y²s Y²q Y²mr Y²sk Y²pf Y²qg
Unconformity
Y²lo
Rock of Uncertain Origin
Y²a
Stenian
Ectasian
MESOPROTEROZOIC

DESCRIPTION OF MAP UNITS[1]

t Mill tailings

Qal Alluvium and flood-plain deposits (Holocene)--Deposits of clay, silt, and lesser sand and pebbles in stream beds and adjacent flat valley floors. Mostly less than 20 ft thick

Qd Terrace deposits and till (Pleistocene, pre-Illinoian)--Moderate-brown (5 YR 4/4) to moderate-yellowish-brown (10 YR 5/4) clays silt and medium to coarse sand in terraces above the Lehigh River and poorly sorted, unstratified and unconsolidated grayish-orange (10 YR 7/4) to light-reddish-brown (3 YR 5/6) till

ROCKS OF THE NEWARK BASIN

Jd Diabase (Early Jurassic)--Medium- to coarse-grained, dark-gray (N3) to grayish-black diabase that has a typical diabasic texture, and is composed largely of grayish-green calcic plagioclase and green augite

Passaic Formation (Upper Triassic) (Olsen, 1980)

TRp Moderate-red (5 R 4/6) to dark-reddish-brown (10 R 3/4) to grayish-red (5 R 4/2) claystone, mudstone, and lesser siltstone

TRps Dark-reddish-brown (10 R 3/4) to grayish-red (5 R 4/2), fine- to medium-grained sandstone and lesser siltstone. Grades into and interfingers with TRp, TRpl, and TRpq

TRpsg Medium-gray (N5) to greenish-gray (5 GY 6/1), fine-grained sandstone and siltstone

TRpl Dark-reddish-brown (10 R 3/4) to grayish-red (5 R 4/2) limestone fanglomerate consisting of limestone clasts as much as 2 in in diameter set in a sandstone matrix. Also contains scattered clasts of Mesoproterozoic rocks

TRpq Dark-reddish-brown (10 R 3/4) to grayish-red (5 R 4/2) quartzite fanglomerate consisting of pebbles and cobbles of quartzite set in a sandstone matrix

TRph Grayish-green (5 G 5/2) to very-dusky-purple (5 P 2/2) hornfels

ROCKS OF THE LEHIGH VALLEY SEQUENCE

Oe Epler Formation of the Beekmantown Group (Lower Ordovician) (Hobson, 1957)--Medium- (N5) to medium-dark-gray, thin- to thick-bedded, finely crystalline and much less medium crystalline silty limestone interbedded with thin- to thick-bedded, light (N7) to medium-dark (N4) gray, cryptocrystalline to medium-crystalline dolomite. Contains a North American Midcontinent Province Conodont Fauna low D through E, so is of Ibexian (Tremadocian to Arenigian) age. Grades down into the Rickenbach Dolomite (Or). Thickness cannot be determined in this quadrangle, but is about 800 ft in the Delaware Valley (Drake, 1969)

Or Rickenbach Dolomite of Beekmantown Group (Lower Ordovician) (Hobson, 1957)--Medium- (N5) to medium-dark-gray (N4), medium- to coarse-crystalline dolomite containing rosettes of light-gray (N7) chert and medium-light- (N6) to medium-gray (N5), finely crystalline, laminated dolomite containing dark-gray (N3) chert nodules, lenses, and beds. Contains a North American Midcontinent Province Conodont Fauna high C through low D so is of Ibexian (Tremadocian) age. Grades down into Stonehenge Formation (Os). Thickness is probably about 600 ft

Os Stonehenge Formation of Beekmantown Group (Lower Ordovician) (Stose, 1908; Drake and Lyttle, 1985)--Thin-bedded, medium-dark-gray (N4), very fine-grained dolomite, fine- to medium-grained, silt-ribbed, laminated dolomite and limestone; earthy limestone; and solution-collapse breccia. Contains conodonts of the <u>Rossodus manitouensis</u> Biozone so is of early Ibexian (Tremadocian) age. Elsewhere grades down in Allentown Dolomite (OꞒa) the base being marked by thin-bedded, medium-dark (N4) to dark (N3) gray dolomite or limestone that has thin shale partings, the Evans Marker of the New Jersey Zinc Company (Callahan, 1968). Thickness cannot be determined in the quadrangle. Elsewhere, it is as much as 700 ft thick

OꞒa Allentown Dolomite (lowest Lower Ordovician and Upper Cambrian) (Wherry, 1909)--Light- (N7) to dark- (N3) gray, fine- to medium-grained, thin- to medium-bedded, massive to laminated, rhythmically bedded dolomite that typically weathers to light (N7) and dark (N3) gray. Nodular and bedded chert and orthoquartzite are common. Unit is characterized by oolite, algal stromatolites, intraformational conglomerate, ripple marks, and mud cracks. Shelly fauna collected from near the bottom and top of the formation in New Jersey and the Buckingham Valley to the south are of, respectively, Dresbachian and Trempealeauan age (Howell, 1945; Howell and others, 1950). Grades down into the Leithsville Formation (Ꞓl). In the Delaware Valley and northwestern New Jersey is about 1,900 ft thick

Ꞓl Leithsville Formation (Middle and Lower Cambrian) (Wherry, 1909)--Thick-bedded, medium- (N5) to medium- (N4) gray, finely crystalline dolomite cyclically interbedded with platy- and shaly-bedded dolomite. In New Jersey, the unit contains archaeocyathids in its lowest part suggesting an intraformational disconformity separating rocks of Middle Cambrian age from those of Early Cambrian age (Palmer and Rozanov, 1976). Unit grades down into the Hardyston Quartzite (Ꞓh). It appears to be about 1000 ft thick

Ꞓh Hardyston Quartzite (Lower Cambrian) (Wolff and Brooks, 1898)--Light-gray (N7), to moderate-reddish-brown (10 R 4/6) thin- to medium-bedded quartzite, arkosic sandstone, and quartz-pebble conglomerate. Early Cambrian trilobites have been found in the unit in the Reading area to the west (Walcott, 1896) and in New Jersey (Drake and others, 1994). Unit may be as much as 200 ft thick at places

ROCKS OF THE SCHUYLKILL SEQUENCE

Omb Bushkill Member of the Martinsburg Formation (Middle Ordovician) (Drake and Epstein, 1967)--Medium- (N5) to dark-gray (N3) slate containing thin beds of graywacke siltstone. Some rock is quite calcareous (table 1). Unit has been difficult to date because of its sparse graptolite fauna that represents a very restricted and extreme biofacies. On the basis of graptolites collected from the Great Valley of Pennsylvania and New Jersey it ranges from Kirkfieldian (Caradocian) to Edenian in age (Ross and others, 1982). Grades down into the Jacksonburg Limestone by a decrease of pelitic material and an increase in carbonate. Thickness in the Saucon Valley cannot be determined

Oj Jacksonburg Limestone (Middle Ordovician) (Spencer and others, 1908; Miller, 1937)--Dark-gray (N3) to black (N1), shaly limestone, lesser fine-grained, laminated to medium-bedded, argillaceus limestone, and much lesser crystalline limestone. In New Jersey, unit contains a North American Midcontinent Province Fauna 9, so it is of Kirkfieldian (Caradocian) age. It unconformably overlies rocks of the Beekmantown Group. Thickness in the Saucon Valley cannot be determined

Oe Epler Formation of the Beekmantown Group (Lower Ordovician) (Hobson, 1957)--Medium- (N5) to medium-dark-gray, thin- to thick-bedded, finely crystalline and much less medium crystalline silty limestone interbedded with thin- to thick-bedded, light (N7) to medium-dark (N4) gray, cryptocrystalline to medium-crystalline dolomite. Contains a North American Midcontinent Province Conodont Fauna low D through E, so is of Ibexian (Tremadocian to Arenigian) age. Grades down into the Rickenbach Dolomite (Or). Thickness cannot be determined in this quadrangle, but is about 800 ft in the Delaware Valley (Drake, 1969)

Or Rickenbach Dolomite of Beekmantown Group (Lower Ordovician) (Hobson, 1957)--Medium- (N5) to medium-dark-gray (N4), medium- to coarse-crystalline dolomite containing rosettes of light-gray (N7) chert and medium-light- (N6) to medium-gray (N5), finely crystalline, laminated dolomite containing dark-gray (N3) chert nodules, lenses, and beds. Contains a North American Midcontinent Province Conodont Fauna high C through low D so is of Ibexian (Tremadocian) age. Grades down into Stonehenge Formation (Os). Thickness is probably about 600 ft

Os Stonehenge Formation of Beekmantown Group (Lower Ordovician) (Stose, 1908; Drake and Lyttle, 1985)--Thin-bedded, medium-dark-gray (N4), very fine-grained dolomite, fine- to medium-grained, silt-ribbed, laminated dolomite and limestone; earthy limestone; and solution-collapse breccia. Contains conodonts of the Rossodus manitouensis Biozone so is of early Ibexian (Tremadocian) age. Grades down in Allentown Dolomite (O€a) the base being marked by thin-bedded, medium-dark (N4) to dark (N3) gray dolomite or limestone that has thin shale partings, the Evans Marker of the New Jersey Zinc Company (Callahan, 1968). Thickness cannot be determined in the quadrangle. Elsewhere, it is as much as 700 ft thick

Allentown Dolomite (lowest Lower Ordovician and Upper Cambrian) (Wherry, 1909)

O€a Allentown Dolomite undivided

€am Muhlenberg Member (Upper Cambrian) (MacLachlan, 1979)--Medium- (N5) to medium-light (N6) gray, thick-bedded dolomite and magnesium limestone. Contains interbedded calcareous sandstone that serves as host rock for stratabound limonite deposits, which were widely exploited in areas to the west (Drake, 1993). Its age within the Late Cambrian is not known. Grades down into the Tuckerton Member (€at). Unit appears to be 850 ft thick in the adjacent Allentown West quadrangle (Drake, 1993)

€at Tuckerton Member (Upper Cambrian) (MacLachlan, 1979)--Medium- to thick-bedded dolomite and magnesium limestone. Grades down into the Leithsville Formation (€l). Does not crop out in this quadrangle

€l Leithsville Formation (Middle and Lower Cambrian) (Wherry, 1909)--Unit essentially identical to Leithsville Formation in the Lehigh Valley sequence, see above. Grades down into Hardyston Quartzite (€h)

€h	Hardyston Quartzite (Lower Cambrian) (Wolff and Brooks, 1898)--Differs from the Hardyston Quartzite in the Lehigh Valley sequence (see above) in that it contains abundant jasper in the Vera Cruz area. Unconformably overlies Mesoproterozoic rocks

ROCKS OF THE DURHAM AND READING HILLS

Zd	Diabase (Neoproterozoic)--Medium-dark (N4) to dark-gray (N3), fine-grained to aphanitic, highly altered dikes metamorphosed in greenschist facies

Hybrid Rocks

Y^3ma	Arterite (Stenian)--Medium-gray (N5) stromatic migmatite (Mehnert, 1971) consisting of microperthite alaskite (Y^3ba) leucosome in amphibolite (Y^2a) paleosome

Byram Intrusive Suite (Drake, 1984)

Y^3bh	Hornblende granite (Stenian)--Medium- to coarse-grained, grayish-pink (5 R 8/2) to light-gray (N7) to light brownish-gray (5 YR 6/1) gneissoid to indistinctly foliated granite and sparse granite gneiss composed principally of microcline microperthite, quartz, oligoclase, and hornblende. Contains unmapped bodies of pegmatite and amphibolite. Unit has an upper intercept U-Pb age of 1090 Ma (Drake and others, 1991a)
Y^3ba	Microperthite alaskite (Stenian)--Medium- to coarse-grained, grayish-pink (5 R 8/2) to light-brownish-gray (5 YR 6/1), gneissoid to indistinctly foliated alaskite composed principally of microcline microperthite, quartz, and oligoclase. Contains unmapped bodies of amphibolite
Y^3bb	Biotite granite (Stenian)--Medium- to medium-coarse-grained, grayish-pink (5 R 8/2) to pale-yellowish-brown (10 YR 6/2), moderately foliated gneissoid granite composed of microcline microperthite, quartz, oligoclase, and biotite. Unit contains many layers and discontinuous bodies of biotite-quartz-feldspar gneiss (Y^2b). It is interpreted to result from the assimilation of biotite-quartz-feldspar gneiss (Y^2b) by microperthite alaskite (Y^3ba) magma

Metasedimentary Rocks

Y^2b	Biotite-quartz-feldspar gneiss (Ectasian)--fine- to medium-grained, light- (N7) to medium-dark-gray (N4) to pale-yellowish-brown (10 YR 6/2), well-layered gneiss of variable composition, but containing conspicuous biotite. Some phases contain garnet, magnetite, and sulfide
Y^2k	Potassic feldspar gneiss (Ectasian)--Fine- to medium-grained, grayish-pink (5 R 8/2), pinkish-gray (5 YR 8/1), light-gray (N7), or light-brownish-gray (5 YR 6/1) gneiss and lesser granofels that have a poor to fair foliation and are composed largely of quartz and potassic feldspar and minor amounts of biotite and (or) magnetite and more rarely garnet and (or) clinopyroxene. Parts of the unit are magnetite-rich and resemble metamorphosed iron-formation and may have an exhalative component (Drake, 1990). In places, unit has been mobilized to form sheets and irregular bodies of alkali-feldspar granite or quartz-rich granitoid
Y^2s	Sillimanite-bearing gneiss (Ectasian)--Medium-grained, light-gray (N7) to light-greenish-gray (5 GY 8/1) to pinkish-gray (5 YR 8/1), well-foliated gneiss characterized by the presence of sillimanite. Other minerals include quartz, microcline microperthite, monoclinic potassic feldspar, and strongly sericitized oligoclase

Y^2q Feldspathic quartzite (Ectasian)--Light-gray (N7) feldspathic quartzite contains some quartz-pebble conglomerate. Is associated with potassic feldspar gneiss (Y^2k) and sillimanite-bearing gneiss (Y^2s)

Y^2mr Marble (Ectasian)--Medium-grained, medium-gray (N5), silicated, impure dolomite marble

Y^2sk Hornblende-skarn (Ectasian)--Dusky-green (5 G 3/2) to black (N1), coarse-grained, inequigranular, heterogeneous skarn composed largely of hornblende; contains some diopsidic pyroxene and minor amounts of biotite, calcite, and magnetite. Probably a metasomatic alteration product of calcite marble

Y^2pt Phlogopite-talc schist (Ectasian)--Light-gray (N7) medium-grained, phlogopite-talc schist that contains some serpentine. A metasomatic alteration product of dolomite marble (Y^2mr)

Y^2qg Graphite-bearing quartzite (Ectasian)--Grayish-blue feldspathized quartzite containing as much as 10 percent graphite

Losee Metamorphic Suite (Drake, 1984)

Y^2lo Quartz-oligoclase gneiss (Ectasian)--Grayish-green (5 G 5/2), white-weathering, medium- to medium-coarse-grained, moderately well-layered, foliated, gneiss composed of quartz and oligoclase and local chloritized biotite and (or) clinopyroxene and magnetite

Rocks of Uncertain Origin

Y^2a Amphibolite (Ectasian)--Dusky-green (5 G 3/2) to grayish-black (N2), medium-grained rock composed of largely of hornblende and andesine. Some phases contain biotite, clinopyroxene, orthopyroxene, or magnetite

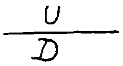
[1] The term "Neoproterozoic" follows the usage of Plumb (1991) and applies to rocks ranging in age from 1000 Ma to ~544 Ma (base of Cambrian following Bowring and others, 1993; and Landing, 1994). The terms "Mesoproterozoic," "Stenian," and "Ectasian" also follow the usage of Plumb (1991). Mesoproterozoic applies to rocks ranging in age from 1600 Ma to 1000 Ma, "Ectasian" to rocks ranging in age from 1400 Ma to 1200 Ma, and "Stenian" to rocks ranging in age from 1200 Ma to 1000 Ma.

EXPLANATION OF MAP SYMBOLS

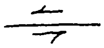

Contact--Distribution and concentration of structural symbols indicates accuracy of placement

Dotted where concealed. Queried where contact must be present, but precise location is uncertain

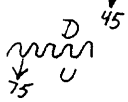
Faults--Dotted where concealed. Queried where fault must be present, but precise location is uncertain



High-angle fault--U, upthrown side; D, downthrown side


Tear fault--Showing relative horizontal movement

Thrust fault--Sawteeth on upper plate. Dip shown where known

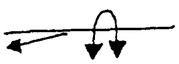


Fault seen in outcrop--Showing dip and relative motion where known

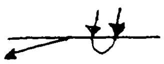
FOLDS

Folds of Proterozoic age in Proterozoic rocks--Folds of both layering and foliation can be no older than F_2. At least one phase of earlier folds can be recognized in outcrop. Folds are designated from oldest to youngest as F_2, F_3

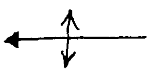

Antiform--Showing trace of crestline and direction of plunge

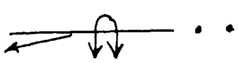

Overturned antiform--Showing trace of axial surface, direction of dip of limbs, and direction of plunge where known

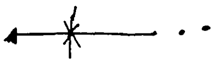

Synform--Showing trace of trough line and direction of plunge

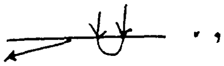

Overturned synform--Showing trace of axial surface, direction of dip of limbs, and direction of plunge where known

Folds of Paleozoic age--Fold phases are named for geographic localities where well displayed or for prominant major folds of that phase. Initials indicate phase, from oldest to youngest: Irish Mountain (IM); Iron Run (IR)

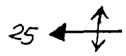

Anticline--Showing trace of crest line and direction of plunge, where known


Overturned anticline--Showing trace of axial surface, direction of dip of limbs, and direction of plunge. Dotted where concealed


Syncline--Showing trace of trough line, direction of dip of limbs, and direction of plunge where known. Dotted where concealed


Overturned syncline--Showing trace of axial surface, direction of dip of limbs, and direction of plunge. Dotted where concealed

MINOR FOLDS



Minor anticline or antiform, showing plunge

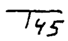
Minor asymmetric fold of bedding--Showing bearing and plunge of axis and rotation sense viewed down plunge

Minor fold of cleavage--Showing plunge

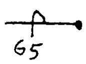
PLANAR FEATURES

(May be combined with linear features)

Strike and dip of beds--Ball indicates top known from sedimentary structures

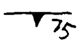


Inclined



Overturned

Strike and dip of crystallization foliation



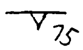
Inclined


Vertical

Strike and dip of mylonitic foliation

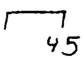
Inclined


Vertical



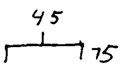
Strike and dip of transportation foliation--Bedding rotated into parallelism with slaty cleavage

Strike and dip of slaty cleavage

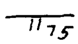


Inclined

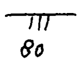

Vertical



Strike and dip of slaty cleavage and bedding parallel in strike but divergent in dip



Strike and dip of crenulation cleavage



Strike and dip of spaced cleavage

LINEAR FEATURES
(May be combined with planar features)

35	Mineral lineation
	Bearing and plunge of intersection of bedding and slaty cleavages
10	Inclined
	Horizontal
25	Bearing and plunge of crenulations
10	Bearing and plunge of intersection of slaty cleavage and spaced cleavage
e cs	Bearing and plunge of elongation lineation
	Bearing and plunge of striations

OTHER FEATURES

F	Fossil (conodont) locality
	Mine, quarry, or pit--l, limonite; m, magnetite; zn, zinc; gn, gneiss; q, quartzite; d, dolomite
	Water well (see table 1)
	Location of chemically analyzed samples
	Mesoproterozoic rocks (Drake, 1984)
	AE-D-3-33, analysis 1, table 5
	AE-G-1-4, analysis 1, table 6
	AE-D-5-16, analysis 5, table 10
	Bushkill Member of Martinsburg Formation (reported herein). See table 2
	Diabase (reported herein). See table 2

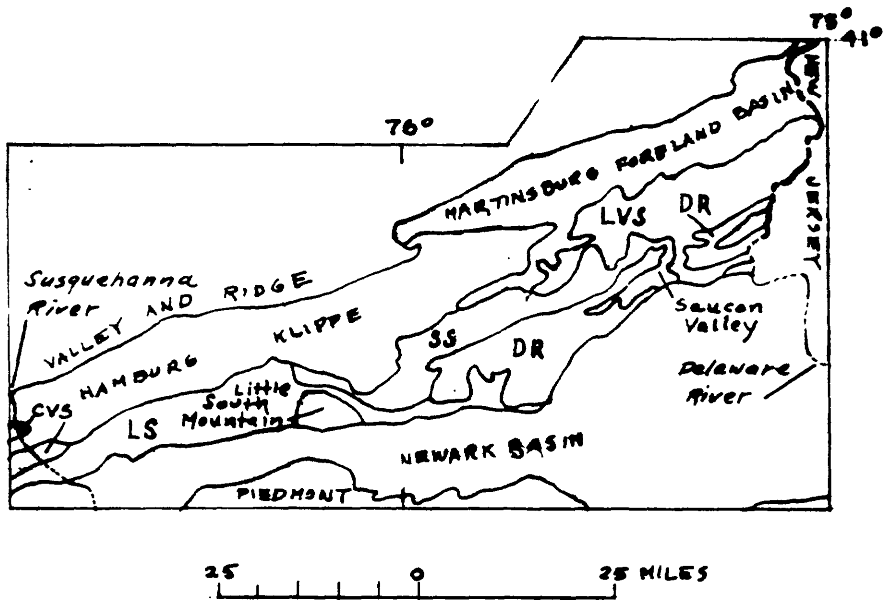


Figure 1. Sketch map showing major lithotectonic units in eastern Pennsylvania. LVS, carbonate rocks of Lehigh Valley sequence: SS, carbonate rocks of Schuylkill sequence; LS, carbonate rocks of Lebanon Valley sequence; CVS, carbonate rocks of Cumberland Valley sequence; DR, Mesoproterozoic rocks of the Durham and Reading Hills.