U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Geologic Map of the Nazareth Quadrangle, Northampton County, Pennsylvania

By

John M. Aaron and Avery Ala Drake, Jr.[1]

Open-File Report 97-33

[1]Reston, Va.

1997

GEOLOGIC MAP OF THE NAZARETH QUADRANGLE,
NORTHAMPTON COUNTY, PENNSYLVANIA

By John M. Aaron and Avery Ala Drake, Jr.

INTRODUCTION

The Nazareth quadrangle, in eastern Pennsylvania, lies across the contact between Mesoproterozoic 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, 198), and lower Paleozoic rocks of the Lehigh Valley segment of the Great Appalachian Valley. These rocks are obscured throughout much of the quadrangle by glacial deposits of pre-Wisconsinan (Illinoian?) Age.

The rocks exposed in this quadrangle have been studied elsewhere in Pennsylvania, and the reader is referred to Buckwalter (1959, 1962), Drake (1969a, 1984, in press a), and MacLachlan (1979, 1983) for descriptions of the Mesoproterozoic rocks, and to Drake (1965, 1969), Drake and Epstein (1967), MacLachlan (1967, 1979, 1983), and MacLachlan and others (1975) for descriptions of the lower Paleozoic rocks. Regionally, the quadrangle is within the complex tectonic terrane termed the Taconides by Drake (1980) described in detail by Drake and others (1989). The Mesoproterozoic rocks were first deformed during the Grenville orogeny (Rankin and others, 1993), and were subsequently deformed along with the lower Paleozoic rocks during the Ordovician Taconic orogeny (Drake, 1980). This Taconic fabric was later overprinted by structures formed during the late Paleozoic Alleghanian orogeny (Drake, 1980). The Paleozoic structure is dominated by emergent and blind thrust faults and complex folds.

The Nazareth quadrangle was mapped by Aaron as part of the requirements for the Ph.D. at the Pennsylvania State University (Aaron, 1971). At the time of this work, the Stonehenge Formation was not recognized at the base of the Beekmantown Group and was mapped as either Rickenbach Dolomite or Epler Formation. This led to severe structural misinterpretations. Work by Drake and Lyttle (1985) and Karkins and Repetski (1989) in New Jersey corrected this stratigraphic misconception and Drake remapped the area underlain by rocks of the Beekmantown Group, reinterpreted the structural geology of the quadrangle and wrote this text.

PHYSIOGRAPHY

The area is part of the Appalachian Highlands and includes the Durham and Reading Hills of the Reading Prong section of the New England province, and the Great Valley section, known locally as the Lehigh Valley, of the Ridge and Valley province.

The topography ranges from flat or gently rolling in the Great Valley to moderately hilly in the Durham and Reading Hills. Altitude of the divides in the Great Valley is about 400 feet where the bedrock is limestone or dolomite, but as much as 700 feet where the bedrock is slate. Summit altitudes along the Durham and Reading Hills in this area range from 670 to 1016 feet. The maximum relief in the Nazareth quadrangle, from the highst point on top of Gaffney Hill in the southeasternmost part of the area to the lowest point along the Lehigh River, is 826 feet.

Pleistocene glaciers, thought to be pre-Wisconsian in age (Miller and others, 1939), covered most of the area north of the Lehigh River. However, aside from the very flat topography developed on patches of drift, there are no topographic forms in the area that can be recognized as being intrinsically glacial. The principal effect of glaciation was to subdue and soften the profile of the preglacial topography.

STRATIGRAPHY

The oldest rocks in the Nazareth quadrangle are gneiss, serpentinized marble, and foliated granitoid rocks of Mesoproterozoic age. The pre-Middle Ordovician sedimentary rocks were deposited on the great east-facing (present direction) shelf on 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).

Mesoproterozoic Rocks

Mesoproterozoic rocks crop out in the southern part of the Hellertown quadrangle and as the Pine Top and Chestnut Hill "orphans" (Lewis and Bartholomew, 1989). The oldest of these rocks are hornblende-clinopyroxene-quartz-plagioclase gneiss (Y^2hc), epidote-clinopyroxene-hornblende-plagioclase gneiss (Y^2he), and quartz-garnet-clinopyroxene granofels (Y^2hg) of the Hexenkopf Complex (Drake, 1984). Chemical analyses of the gneisses were presented by Drake (1984, table 12 and 1996a, table 1). Composition ranges from basalt to dacite. The gneisses of the Hexenkopf complex were interpreted to be a metamorphosed and severely altered sequence of plutonic rocks ranging in composition from pyroxenite to mafic diorite. Alternatively, the complex could consist of metamorphosed volcanic rocks. The granofels was interpreted to be a metamorphosed and altered impure chert, which lay above the mafic complex. The more silicic rocks are probably the result of later alteration.

Quartz-oligoclase gneiss (Y^2lo) of the Losee Metamorphic Suite unconformably overlies the Hexenkopf Complex in the southwestern corner of the quadrangle. Elsewhere in the Reading Prong, the Losee Metamorphic Suite was interpreted to be basement to other rocks (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 quartz keratophyre and dacite (Drake, 1984; Puffer and Volkert, 1991).

Most of the Losee rocks are well layered, but some parts are granitoid or pegmatitic in aspect and were mapped as albite-oligoclase gneiss (Y^2la). The origin of these rocks has been controversial, but field evidence (Drake, 1969, fig. 4; Drake, 1984, fig. 11) and geochemistry (Puffer and Volkert, 1991) show that these rocks have been generated in situ by anatexis.

Isotopic dating of the Losee Metamorphic Suite is incomplete, but similar rocks in the Green Mountain massif in Vermont have an U-Pb upper intercept age of about 1350 Ma (Aleinikoff and others, 1990). The Losee and the underlying Hexenkoff complex by analogy are Ectasian (Plumb, 1991) in age.

The Losee Metamorphic Suite is unconformably overlain by a supracrustal sequence of quartzofeldspathic gneiss, carbonate rocks, and amphibolite. Quartzofeldspathic gneiss in this 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 and chemical analyses in Drake, 1969, 1984). It is characterized by conspicuous biotite and a prominent compositional layering. The unit was interpreted to be metamorphosed graywacke (Drake, 1984).

Potassic feldspar gneiss (Y^2k) is abundant in the Nazareth quadrangle. It is characterized by a 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. Much of the rock resembles meta-arkose, whereas some is iron-rich and resembles metamorphosed iron-formation (taconite). Such rocks in the Franklin-Sterling Hill district, New Jersey, were interpreted by Drake (1990) to contain an exhalative component. In some places, potassic feldspar gneiss contains small sheets, veins, lenses, and blotches of granitoid resulting from local anatexis. Particularly good exposures of potassic feldspar gneiss can be seen on Chestnut Hill.

Sillimanite-bearing gneiss (Y^2s) is not abundant in the Nazareth quadrangle. The unit has been interpreted to be a more aluminous phase of potassic feldspar gneiss (Y^2k) (Drake, 1969, 1984).

Carbonate rock in this quadrangle consists of serpentinized marble and talc schist in a klippe north of Chestnut Hill. There is only a minor amount of amphibolite (Y^2a) in the Nazareth quadrangle. Amphibolite has been found to have had more than one origin in the Reading Prong. Some is closely interlayered with rocks that are clearly metasedimentary and likely has a metasedimentary or perhaps volcaniclastic origin. In New Jersey, however, relict pillow structures in amphibolite have been described and illustrated by Hague and others (1956) and Drake (1990). This amphibolite had a submarine volcanic origin. 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 of protoliths of amphibolite in this quadrangle cannot be determined.

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 in the Berkshire and Green Mountain massifs in New England (Rankin and others, 1993). In the Reading Prong, these rocks were interpreted to have been deposited in a rift setting (Drake, 1990; Volkert and Drake, in press). They are interpreted to be Ectasian in age because they are intruded by rocks of the Byram Intrusive Suite of Stenian (Plumb, 1991) age.

Microperthite alaskite (Y^3ba) of the Byram Intrusive Suite crops out in small bodies in the Nazareth quadrangle. Modes and chemical analyses of Byram rocks are given in Drake (1969, 1984) and Drake and others (1991a). The Byram chemistry is mildly anorogenic (Volkert and Drake, in press). The rocks, which have a Stenian U-Pb age of about 1090 Ma (Drake and others, 1991a), were clearly 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).

Lower Paleozoic Rocks

The Lower Ordovician and older sedimentary rocks in this quadrangle belong to the Sauk sequence (Sloss, 1963) and constitute the Kittatinny Supergroup of Drake and Lyttle (1980). The overlying Jacksonburg Limestone and Martinsburg Formation belong to the lower part of the Tippecanoe sequence of Sloss (1963). All these rocks constitute the Lehigh Valley sequence of MacLachlan (1967) and Drake (1969).

The oldest unit in the Kittatinny Supergroup is the Hardyston Quartzite (Ꞓh). The Hardyston is not well exposed in the quadrangle, but can be seen along the mountain front east of Steel City and in the Pine Top "orphan." The Hardyston typically has arkosic conglomerate at the base and passes up into arkosic sandstone, orthoquartzite, carbonate-cemented sandstone, and silty shale and jasper. This sequence is repeated several times suggesting numerous intraformational unconformities. It is likely that the Hardyston represents the feather-edge of the rift-drift transition on the Laurentian margin (Drake, in press a).

The Cambrian carbonate rocks in the Kittatinny Supergroup were deposited in a series of different cycles (Aaron, 1971). The lowest carbonate unit, the Leithsville Formation (Ꞓl) is well exposed along the mountain front south of the Lehigh River in the Redington area. A characteristic Leithsville cycle started with the deposition of a thin (usually very thin) bed of quartz and (or) dolomite sand followed by sandy shale, calcareous shale, platy bedded planar laminated dolomite, and finally by thick-bedded, commonly planar-laminated dolomite.

The Leithsville Formation grades up into the Allentown Dolomite (O€a) by a change of depositional cycles. The Allentown occupies a wide outcrop belt but good outcrops are largely restricted to the north bank of the Lehigh River. Cyclic deposition of the Allentown was first described by Zadnik (1960) who studied two sections, bed by bed, along the Delaware River. Zodiak proposed an ideal cycle beginning with dololutite followed by dolarenite, oolitic dolarenite, dolorudite, algal stromalolites, and finally flat-pebble dolorudite. These rock types indicated a shallowing-upward sequence. Aaron (1971), using Zaduck's data, suggested that an ideal cycle started with flat-pebble dolorudite rather than dololutite. Later, Aaron (1979) reinterpreted Zadnik's data using the Markav (stochastic process), which indicated the likely transitions would be dololutite, dolarenite, oolitic dolarenite, dolorudite, algal stromalotites, flat-pebble dolorudite, and finally oolitic dolarenite or dolarenite. In any case, these studies all indicate deposition in a shallowing-upward, regressive, cycle.

The Stonehenge Formation (Os) was not recognized when the Nazareth quadrangle was originally mapped and was called either Rickenbach Dolomite or Epler Formation. There are many outcrops of Stonehenge in the quadrangle, but it can be best seen along Shoreneck Creek and at the quarry of the Industrial Limestone Company (II) near Steuben. There are also many outcrops of Rickenbach dolomite (Or) in the quadrangle. Good exposures can be seen along Shoeneck and Bushkill Creeks and at the interchange of Routes 22 and 191.

The Epler Formation (Oe) is lithically similar to the Stonehenge Formation (Os), so at places, a characteristic conodont assemblage is necessary for correct identification. Conodont identification by J.E. Repetski of the U.S. Geological Survey (written commun., 1994) were of immense help in correctly identifying these units in the Nazareth quadrangle. Strata-bound limonite deposits are common in the Epler Formation, a fact first recognized by geologists of the New Jersey Zinc Company. These geologists used that relation to prospect for zinc deposits because sphalerite is stratabound in the underlying Beekmantown section (W.H. Callahan, New Jersey Zinc Company, written commun., 1968). There are numerous outcrops of Epler Formation in the quadrangle, but it can best be seen in the Trumbaurer Crushed Stone quarry (VIII) where its contact with the cement limestone facies of the Jacksonburg Limestone is exposed.

The cement limestone facies of the Jacksonburg Limestone (Ojl) is well exposed in quarries near Nazareth. Otherwise, there are few outcrops.

The cement rock facies of the Jacksonburg Limestone (Ojr) in well exposed in the quarries near Nazareth and forms scattered outcrops throughout the quadrangle. It contains a lower crystalline limestone interval (Ojrl) that can be seen in the quarries near Nazareth and can be traced throughout the quadrangle. It also contains an upper crystalline limestone interval (Ojru) that can be seen along the north border of the quadrangle both east and west of Broad Street. It was not found elsewhere.

There are abundant outcrops of the Bushkill Member of the Martinsburg Formation in all the drainages in the northwestern part of the quadrangle. It also crops out in the Gracedale window.

Surficial Deposits

Glacial Deposits

Patches of glacial drift cap bedrock throughout the Nazareth quadrangle north of the Lehigh River. These deposits consist of dark yellowish orange, moderate yellowish brown, and grayish orange pebbly to bouldery silty clay and clayey silt. They are poorly consolidated, poorly sorted, deeply weathered, and lack stratification. Angular to round pebbles and boulders up to 20 inches in diameter are abundant throughout the deposits and are common on the surface as float. Most boulders are weathered, iron-stained sandstones, siltstones and quartzites that are similar to rocks of the Silurian Shawangunk Conglomerate and Bloomsburg Red Beds that crop out eight miles north of the quadrangle boundary and from which the pebbles and boulders presumably were derived.

Topographic relations indicate that glacial drift is a maximum of 50 feet thick in the Nazareth quadrangle, but mostly much less. Topography on drift deposits typically is flat to gently rolling, and is not particularly distinctive as a mapping tool. No distinctive constructional topographic forms (eskers, kames, etc.) that are typically associated with glacial deposits were seen.

The deposits described above occur sporadically for several miles south of the terminal moraine and other well-developed glacial features associated with the Wisconsian ice sheet in Pennsylvania and New Jersey, and presumably pre-date those features. These deposits of older drift south of the Wisconsian terminal moraine have long been recognized (Salisbury, 1892, 1902; Leverett, 1934). Leverett (1934) thought that most of these extra-morainic deposits resulted from the Illinoian glacial advance and that some may date from the Kansan advance. The deposits in the Nazareth quadrangle would be included in what Leverett (1934) and others workers considered to be Illinoian in age.

The deposits of glacial drift in the Nazareth quadrangle are considered herein as pre-Wisconsian, Illinoian(?) in age.

Alluvium

Alluvial deposits occur in and along the Lehigh River and in some smaller streams in the area. The deposits generally are small and thin. They are largely composed of unconsolidated silt, sand, and much lesser gravel.

STRUCTURAL GEOLOGY

The Mesoproterozoic rocks in the Durham and Reading Hills, of which Pine Top and Chestnut Hill are the northernmost exposures, were first deformed during the Mesoproterozoic (about 1.1 Ga) 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" or "bulldozer" (Hsü, 1995) of 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 mesoscopic folds, passes through the fold hinges rather than wrapping around them. This evidence, as well as the lens-shaped map units, suggests regional transposition. All mapped folds deform both layering and foliation, so none are first phase folds.

Both upright and overturned F_2 folds were mapped on the mountain south of the Lehigh River. Those south of the Colesville fault plunge north-northeast or north-northwest, whereas those north of the Colesville fault plunge either east-northeast or south-southwest. No folds were mapped in either the Pine Top or Chestnut Hill "orphans."

Rocks of the Byram Intrusive Suite were emplaced during the F_2 folding event, so the Grenville orogeny was in progress at 1,090 Ma (Drake and others, 1991a). That orogeny was apparently completed 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, in press b). 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 Lyon Station. These nappes have a fault-propagation fold aspect and were defined largely by their cover sequences. West from the Delaware River, the depth of autochthonous basement increases (Drake, 1991). Concomitant with this increase in depth, deformation becomes more intense and complex in the cover rocks. In this quadrangle, this progression is shown by the change from upright folds in the east to overturned folds in the west. The crystalline rocks in the nappe were not folded, but accommodated themselves to the form surfaces by movement on zones of ductile and brittle deformation at about the ductile-brittle transition because the temperatures in the cover rocks were at least as high as 300°C based on conodont color alteration (J.E. Repetski, U.S. Geological Survey, written commun., 1991, 1992, 1994).

These nappes constitute a crystalline duplex, which is probably the northeasternmost exposure of a crustal duplex that lies beneath the Newark basin and the Piedmont (Drake, 1991, in press b).

The outcropping rocks in the Nazareth quadrangle belong to the Musconetcong nappe. The Lyon Station nappe is in the subsurface.

Musconetcong Nappe

The Musconetcong nappe, or nappe system, comprises the basement massifs and their cover in eastern Pennsylvania beneath the Black River thrust fault (see Drake, 1993, 1996a, 1996b) and continue on into New Jersey (Drake and others, 1996). The Musconetcong nappe overlies the Lyon Station nappe on the Fullerton thrust fault.

Lyon Station Nappe

The Lyon Station nappe occurs largely in the subsurface and was defined by Drake (1978) on the basis of aeromagnetic data (Bromery, 1960; Bromery and Griscom, 1967) and the mapping of cover rocks in the Whitehall window and the western part of what is now called the Schoenersville window (Drake, 1996c). These studies suggested that a magnetic body, presumably Mesoproterozoic rocks, occurs at a depth of about 1 mile in the Catasauqua area (Drake, 1978, 1996c). Their analyses showed that the gradient associated with the Catasauqua anomaly does not steepen where it intersects outcropping Mesoproterozoic rocks to the southwest; hence, the magnetic rocks causing the anomaly do not change depth. The outcropping Mesoproterozoic rocks, therefore, are tectonically above the buried magnetic rocks and separated from them by an interval of nonmagnetic rocks.

The Catasauqua anomaly was identified much earlier by Ewing and Pentg (1936) on the basis of a ground magnetic survey and Ewing (1936) on the basis of a juxtaposed seismic reflection survey. These studies suggested that the anomaly was centered beneath the Industrial Limestone Company quarry (II) at a depth of about 2.3 miles for the presumed Mesoproterozoic rocks. Construction of cross sections, however, suggests that the buried Mesoproterozoic rocks are at a depth of about 1.3 miles assuming that there are no additional buried thrust faults. This may not be a valid assumption!

Thrust Faults

Ten thrust faults emerge in the Catasauqua quadrangle. In addition, three thrust faults are known or interpreted in the subsurface.

The Colesville is the highest thrust fault in the Nazareth quadrangle. It has been mapped to the southwest in the Hellertown quadrangle (Drake, 1996b), Allentown East quadrangle (Drake, 1996a) and Allentown West (Drake, 1993) quadrangle where it passes beneath rocks of the Mesozoic Newark basin. It was mapped to the east as the Whipoorevill fault in the Easton quadrangle (Drake, 1967) and well into New Jersey (Drake and others, 1996). Here, it has placed Mesoproterozoic rocks on Mesoproterozoic rocks, its trace being marked by sheared rocks.

Hellertown Thrust Fault

In the western part of the Nazareth quadrangle, the Hellertown thrust fault has placed Mesoproterozoic rocks onto Leithsville Formation (Ꞓl), and for a short reach, the Hardyston Quartzite (Ꞓh). As such, it is the major frontal fault of the crystalline massif of this part of the Durham and Reading Hills. Mesoproterozoic rocks are, however, exposed in the Pine Top and Chestnut Hill "orphans." Farther to the east, the Hellertown thrust fault becomes intraformational within the Allentown Dolomite (OꞒa) where it has formed a complex duplex.

Ritterville Thrust Fault

To the west in the Allentown East quadrangle (Drake, 1996a) the Ritterville thrust fault has placed Mesoproterozoic rocks onto Leithsville Formation (Ꞓl). In the Hellertown quadrangle (Drake, 1996b), it has placed Leithsville Formation (Ꞓl) onto Allentown Dolomite (OꞒa) as it has done in the southwest corner of this quadrangle. It then becomes interformational within the Allentown Dolomite (OꞒa). It has formed two mapped duplexes. There are likely more in the area of no exposure as other duplexes were mapped along its trace to the east in the Easton quadrangle (Drake, 1967) and New Jersey (Drake and others, 1996).

Jordan Creek Thrust Fault

The Jordan Creek thrust fault has placed Allentown Dolomite (OꞒa) onto Stonehenge Formation (Os). It was mapped to the west in the Catasauqua (Drake, 1996c), Allentown East (Drake, 1996a), and Allentown West (Drake, 1993) quadrangles where it has placed a variety of older carbonate rocks onto younger carbonate rocks. In this quadrangle, it is intraformational within the Allentown Dolomite (OꞒa) and forms a duplex near the east border. It was mapped but not named in the Easton quadrangle to the east (Drake, 1967). It has been mapped well into New Jersey (Drake and others, 1996).

Harmony Thrust Fault

The Harmony thrust fault has placed Stonehenge Formation (Os) on Mesoproterozoic rocks, and is the upper bounding surface of the large Pine Top "orphan." In the Catasauqua quadrangle to the west (Drake, 1996c) the Harmony thrust fault is cut off by the Jordan Creek thrust fault.

To the east of the Pine Top "orphan,: the Harmony thrust fault has placed Stonehenge Formation (Os) into younger Beekmantown Group rocks forming a complex duplex. Farther east, it has placed Allentown Dolomite (O€a) onto Stonehenge Formation (Os), Allentown Dolomite (O€a) onto Allentown Dolomite (O€a), and Leithsville Formation (€l) onto potassic feldspar gneiss (Y^2k), and is the upper bounding surface of the Chestnut Hill "orphan." The Harmony thrust fault has been mapped well into New Jersey (Drake and others, 1996).

Pine Top Thrust Fault

The Pine Top thrust fault is the lower bounding surface of the Pine Top "orphan" and has placed Mesoproterozoic rocks onto Epler Formation (Oe). It rejoins the Harmony thrust fault in the Catasauqua quadrangle to the west (Drake, 1996c).

Chestnut Hill Thrust Fault

The Chestnut Hill thrust fault has placed potassic feldspar gneiss (Y^2k) into Leithsville Formation (€l), and forms the lower bounding surface of the Chestnut Hill "orphan." It rejoins the Harmony thrust fault in the Easton quadrangle (Drake, 1967) to the east.

Foul Rift Thrust Fault

The Foul Rift thrust fault has placed Epler Formation (Oe) onto cement limestone (Ojl), cement limestone (Ojl) onto cement rock (Ojr), various Beekmantown units onto other Beekmantown units, and finally, Allentown Dolomite (O€a) onto Stonehenge Formation (Os). In the Catasauqua quadrangle (Drake, 1996c) to the west, it is cut off by the Fullerton thrust fault. It has been mapped well into New Jersey (Drake and others, 1996).

Stockertown Thrust Fault

The Stockertown thrust fault crops out as the frame for the Gracedale window that exposes Bushkill Member of the Martinsburg Formation (Omb) beneath the older cement rock of the Jacksonburg Limestone (Ojr). Similar windows were mapped in the Bangor (Davis and others, 1967) and Wind Gap (Epstein, 1990) quadrangles.

The Stockertown thrust fault is part of a major, largely subsurface thrust system that appears to be largely intraformational within the Bushkill Member of the Martinsburg Formation. The thrust faults east of Christian Springs and in the northwestern corner of the quadrangle are probably imbricate splays from the Stockertown thrust fault. Similar splays were interpreted by Davis and others (1967) and Epstein (1990).

The steep thrust fault exposed in the Nazareth Cement Company quarry (VII) has a throw of about 110 ft (Sherwood, 1964). It apparently has no relation to the Stockertown thrust fault.

Blind Thrust Fault

Two blind thrust faults are known in the subsurface. The Fullerton thrust fault crops out in the Catasauqua (Drake, 1996) and Cementon (A.A. Drake, Jr., unpublished data, 1971-77) quadrangles where it forms the frame of several windows. It has placed Epler Formation (Oe) of the Musconetcong nappe onto Allentown Dolomite (O€a) of the Lyon Station nappe (see discussion above).

Core drilling in Allentown Dolomite (O€a) within the Whitehall window int he Cementon quadrangle (A.A. Drake, unpublished data, 1971-77) encountered a thrust fault, the blind thrust fault, and the Epler Formation (Oe) 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).

A blind thrust fault is interpreted to be present beneath the Stockertown thrust fault. This interpretation was made because tectonic windows commonly form on antiformal stacks (Hatcher, 1991).

High Angle Fault

One high angle fault was mapped south of the Christian Springs quarry of the Penn Dixie Cement Corporation (V). The mapping was based on the distribution of rock units.

Folds

Rocks in the Nazareth quadrangle are complexly folded. Long ago, Prime (1883) found that: "Level as the general surface may be, it is the planed-off section of as gnarled and twisted piece of the earths crust as can be found in any country. Although these plications are comparatively small they are of the same nature as the gigantic overthrown anticlinals of the Alps and Appenines." Prime illustrated his concept with a section showing a recumbent nappe in Monte Corchia, Italian Alps.

The complex folds depicted on the cross sections were modeled on natural folds seen in outcrop, particularly in quarries and along the Lehigh River to the west. Such folds can be seen in photographs in Prime (1878), Peck (1911), Miller and others (1939), Miller and others (1941), Sherwood (1964) and Drake (1969). Folding decrease in intensity and complexity from east to west.

Two special types of folds can be seen in the Nazareth quadrangle. One type, called quasiflexural by Donath and Parker (1964), is common to interbedded limestone and dolomite sequences in the Stonehenge (Os) and Epler Formation (Oe) in which dolomite beds have deformed by flexural-slip or flexural-flow and limestone beds have accommodated themselves to the form surface by irregular and contorted flow. Cascade folds (van Bemmelen, 1954) are common in rocks of the Martinsburg Formation (Omb) and in the duplex of Allentown Dolomite (O€a) south of the Lehigh River. The axial surfaces of such folds dip northwest down the regional dip and have a northwest-dipping upright limb and an overturned southeast-dipping limb. These folds did not, however, form under the conditions of gravity tectonics as originally visualized by van Bemmelen (1954) and modeled here by Sherwood (1964).

The map pattern of the rock units within the quadrangle, direct observation of small folds in the field, and fabric studies indicate that the rocks have been affected by at least five distinguishable phases of folds. These phases, following the usage of Tobisch and Fleuty (1969) were named either for geographic localities where they are well displayed or for prominent major folds (Table 1). This was done because regionally all phases may not be present, and a numerical chronology could become confusing.

The oldest fold phase, the Musconetcong (Table 1), was named by Drake and Lyttle (1985) for flattened folds related to Musconetcong nappe emplacement. The cleavage in the carbonate rocks and Martinsburg Formation is almost parallel to the axial surfaces of the Musconetcong folds. Where not appreciably affected by later folding, Musconetcong folds trend east-northeast. Many Musconetcong folds were mapped in rocks of the Martinsburg Formation. Later deformation has largely obliterated these folds in other rocks.

The next fold phase, the Iron Run (Table 1), was named by Drake (1987) for the Iron Run synform in the Topton quadrangle. These folds strongly overprint and obliterate the Musconetcong folds. Many of these folds fold the cleavage and transposition foliation resulting from Musconetcong deformation.

The next youngest fold phase, the Hokendauqua (Table 1), was named by Drake and Lyttle (1985) for Hokendauqua Creek in the northwestern part of the Causauqua quadrangle where folds of this phase were first recognized by Drake (1971). Hohendauqua folds were mapped in rocks of Martinsburg Formation. These folds have a poor to fair spaced cleavage that dips either northeast or southwest. It is best developed in rocks of the Bushkill Member of the Martinsburg Formation. The parallelism of these folds to the direction of tectonic transport suggests that they formed by stretching in a constrictive flow regime as modeled by Cloos (1946) and Johnson (1956).

The next youngest recognized fold phase, the Manunka Chunk (Table 1), was named for the village of Manunka Chunk on the Delaware River in the Belvidere quadrangle, where many folds of this phase deform the slaty cleavage of the Martinsburg Formation (Drake and Lyttle, 1985). These folds are abundant throughout the Great Valley of eastern Pennsylvania and New Jersey and deform bedding, slaty cleavage, and Hokendauqua spaced cleavage. These folds are best developed in rocks of the Jacksonburg Limestone and Martinsburg Formations. An abundant crenulation cleavage in the less competent rocks, such as the Bushkill, is nearly parallel to the axial surface of these folds and is thought to be genetically related to them.

The latest fold phase, the Stone Church, was named by Drake and Lyttle (1985) for the Stone Church syncline in the Bangor (Davis and others, 1967), Portland (Drake and others, 1969, 1985), and Blairstown quadrangles (Drake and Lyttle, 1985). These folds are fairly large to large open structures that have also been mapped to the west by Lash (1982, 1985, 1987). Stone Church phase folds were the cause of the arching that allowed the formation of the Gracedale window. Several Stone Church folds were also mapped in the Allentown Dolomite in the southeastern corner of the quadrangle.

Time of Deformation

Time of deformation is currently a major concern in Appalachian geology and it seems important to attempt to interpret the polyphase relations to this quadrangle, although precise constraints are lacking. It is fair to say that most geologists believe that the regional nappes stem from the Taconic orogeny. If this is true, then the Musconetcong fold phase is Taconic. Lash (1982) presented direct evidence that the first phase folds in the area to the west, which correlate with the Musconetcong folds as used here, pre-date the deposition of Upper Ordovician molasse. In New Jersey, slaty-cleaved Martinsburg Formation occurs as inclusions in Late Ordovician intrusive rocks (Rowlands, 1980; Ratcliffe, 1981; Drake and Monteverde, 1992b) showing that the cleavage in the Martinsburg surely must be Taconic. Recently, however, mica from cleavage surfaces in the Pen Argyl Member of the Martinsburg Formation at Lehigh Gap, about 8 miles to the north, was interpreted to be Permian in age (Wintsch and others, 1996). Is all the slaty cleavage the same age, or, as suggested by Gray and Mitra (1990), does it become younger in a progression of deformation fronts. Manunka Chunk folds have been considered to be Alleghanian in age because they post-date what are believed to be major Alleghanian thrust faults (Drake and Lyttle, 1980, 1985). In the Kutztown and Hamburg quadrangles to the west, Lash (1982) found that his D_3 folds, Manunka Chunk folds as used here, deform both the Silurian and pre-Silurian rocks, and therefore must be of Alleghanian age. It seems nearly certain then, that the Musconetcong folds are Taconian and that the Manunka Chunk folds are Alleghanian.

In New Jersey, Hokendauqua folds have been overridden by what are believed to be major Alleghanian thrust faults and are clearly overprinted by Manunka Chunk structures, and are thus believed to be of Taconic age (Drake and Lyttle, 1985). Here the Hokendauqua structures are also overprinted by

Manunka Chunk structures. Because Hokendauqua folds refold Iron Run folds, it appears that both Iron Run and Hokendauqua folds may be Taconic in age. Regionally, Stone Church folds post-date other structures and in New Jersey, they fold what are thought to be Alleghanian thrust faults. The Stone Church fold phase, therefore, must be Alleghanian in age.

The Hellertown and Ritterville thrust faults are of Taconic age because they have placed older rocks onto younger rocks. The Jordan Creek thrust fault is evidently of Taconic age because it has a fault propagation relation to a Taconic fold and is folded by Iron Run folds to the west (Drake, 1993, 1996a, 1996b). The Pine Top and Chestnut Hill faults are Taconic because they have placed Mesoproterozoic rocks onto carbonate rocks. The Stockertown thrust fault is Taconic in age because in the Allentown West (Drake, 1993), Topton (Drake, 1987) and Cementon (A.A. Drake, Jr., unpublished data, 1971-77) to the west it is folded by Iron Run folds.

The Colesville fault is probably Alleghanian in age because it has placed Cambrian and Ordovician rocks on Mesoproterozoic rocks. The Harmony and Foul Rift thrust faults are probably Alleghanian in age because at places they have brought younger rocks onto older rocks. Such thrust faults are common in New Jersey (Drake and others, 1996).

ECONOMIC GEOLOGY

The Nazareth quadrangle contains deposits of both metallic and nonmetallic minerals. Iron ore is the only metallic deposit to be exploited. The cement rocks have been exploited to a large extent. Limestone and dolomite constitute a source for crushed stone, and in the past, were utilized for agricultural lime. B.L. Miller (1925) presented a report on the mineral resources of the Allentown 15-minute quadrangle of which the Nazareth quadrangle is the northeastern quarter.

Cement

The Jacksonburg Limestone has been exploited for cement since 1825. The cement rock facies (Ojr), when properly treated, is a natural hydraulic cement. Portland cement, much superior in properties to hydraulic cement, was first produced in the Lehigh Valley in 1875 and exploitation soon spread to the Nazareth quadrangle. Portland cement is produced by mixing high-calcium cement limestone facies (Ojl) rocks with cement rock (Ojr) and others ingredients. Many quarries in the Lehigh Valley, such as those near Nazareth, were favorably located to produce Portland cement as the raw stone is composed of the natural constituents for production of the best grade of cement. Currently, the cement industry is not as active as in the past, but several plants are still in operation in the Nazareth area.

Iron

In the past, limonite was actively mined in the Lehigh Valley and Nazareth quadrangle. The improvement of transportation facilities allowed the importation of better ores from elsewhere in the United States and foreign countries and mining ceased in the Lehigh Valley. Limonite deposits in the Nazareth quadrangle are stratabound in the Epler Formation (Oe), apparently in sandy limestone intervals, in a belt between Shoenersville and Hollo. There are likely abundant limonite resources remaining for future exploitation should future conditions demand it.

Stone

Limestone and dolomite, particularly in the Beekmantown Group, have been and are being exploited for crushed stone. There are abundant resources of this material, but is will likely be difficult, if not impossible, to obtain permits for exploitation at this time. In the past, these rocks were locally burned for agricultural limestone.

REFERENCES CITED

Aaron, J.M., 1971, Geology of the Nazareth quadrangle, Northampton County, Pennsylvania: Unpublished Ph.D. thesis, Pennsylvania State University, University Park, Pennsylvania, 353 p.

_____1979, A stochastic approach to definition of cyclicity in the Allentown Dolomite (Upper Cambrian), eastern Pennsylvania and northwestern New Jersey: Geological Society of America Abstracts with Programs, v. 11, no. 1, p. 1.

Aleinikoff, J.N., Ratcliffe, N.M., Burton, W.C., and Karabinos, Paul, 1990, U-Pb ages of Middle Proterozoic igneous and metamorphic events, Green Mountains, Vermont: Geological Society of America Abstracts with Programs, v. 22, p. 1.

Baker, D.R., and Buddington, A.F., 1970, Geology and magnetite deposits of the Franklin and part of the Hamburg quadrangle, New Jersey: U.S. Geological Survey Professional Paper 638, 73 p.

Bemmelen, R.W. van, 1954, Mountain building: Martinus Nijhoff, The Hague, Holland, 208 p.

Bouma, A.H., 1962, Sedimentology of some flysch deposits: Amsterdam, Elsevier, 168 p.

Bromery, R.W., 1960, Preliminary interpretation of aeromagnetic data in the Allentown quadrangle, Pennsylvania: U.S. Geological Survey Professional Paper 400-B, p. B178-B180.

Bromery, R.W., and Griscom, Andrew, 1967, Aeromagnetic and generalized geologic map of southeastern Pennsylvania: U.S. Geological Survey Geophysical Investigation Map GP-577, scale 1:125,000.

Buckwalter, T.V., 1959, Geology of the Precambrian rocks and Hardyston Formation of the Boyertown quadrangle, Pennslvania Geological Survey, 4th series, Geological Atlas 197, 15 p.

_____1962, The Precambrian geology of the Reading 15-minute quadrangle: Pennsylvania Geological Survey, 4th series, Progress Report 161, 49 p.

Callahan, W.H., 1968, Geology of the Friedensville zinc mine, Lehigh county, Pennsylvania, in Ridge, J.D., editor, Ore deposits of the U.S., 1933-1967, the Graton-Sales Volume: New York, American Institute of Mining, Metallurgical and Petroleum Engineers Inc., p. 95-107.

Cloos, Ernst, 1946, Lineation, a critical review and annotated bibliography: Geological Society of America Memoir 18, 122 p.

Davis, R.E., Drake, A.A., Jr., Epstein, J.B., 1967, Geologic map of the Bangor quadrangle, Pennsylvania-New Jersey: U.S. Geological Survey Geologic Quadrangle Map GQ-665, scale 1:24,000.

Donath, F.A., and Parker, R.B., 1964, Folds and folding: Geological Society of America Bulletin, v. 75, p. 45-62.

Drake, A.A., Jr., 1965, Carbonate rocks of Cambrian and Ordovician age, Northampton and Bucks Counties, eastern Pennsylvania and Warren and Hunterdon Counties, western New Jersey: U.S. Geological Survey Bulletin 1194-L, 7 p.

_____1967, Geologic map of the Easton quadrangle, New Jersey-Pennsylvania: U.S. Geological Survey Geologic Quadrangle Map GQ-594, scale 1:24,000.

_____1969, Precambrian and lower Paleozoic geology of the Delaware Valley, New Jersey-Pennsylvania, in Subitzky, Seymour, ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions: New Brunswick, N.J., Rutgers University Press, p. 51-131.

_____1973, Nappes in Allentown area, Pennsylvania, in Geological Survey Research 1973, U.S. Geological Survey Professional Paper 850, p. A36-A37.

_____1978, The Lyon Station-Paulins Kill nappe--the frontal structure of the Musconetcong nappe system in eastern Pennsylvania and New Jersey: U.S. Geological Survey Professional Paper 1023, 20 p.

_____1980, The Taconides, Acadides, and Aleghenides in the central Appalachians, in Wones, D.R., ed., Proceedings, "The Caledonides in the USA." I.G.C.P. Project 27--Caledonides Orogen, 1979 Meeting, Blacksburg, Virginia: Virginia Polytechnic Institute and State University Memoir 2, p. 179-187.

_____1984, The Reading Prong of New Jersey and eastern Pennsylvania--an appraisal of rock relations and chemistry of a major Proterozoic terrane in the Appalachians, in Bartholomew, M.J., ed., The Grenville event in the Appalachians and related topics: Geological Society of America Special Paper 194, p. 75-109.

_____1990, The regional geologic setting of the Franklin-Sterling Hill district, Sussex County, New Jersey, in Character and origin of the Franklin-Sterling Hill orebodies: Bethlehem, Pennsylvania, Lehigh University-Franklin-Ogdensbury Mineralogical Society Symposium Proceeding Volume, p. 14-31.

_____1991, Basement-cover relations in the Durham and Reading Hills--a reappraisal: Geological Society of America Abstracts with Programs, v. 23, p. 23-24.

_____1993, Bedrock geologic map of the Allentown West quadrangle, Lehigh and Berks Counties, Pennsylvania: U.S. Geological Survey Geologic Quadrangle Map GQ-1725, scale 1:24,000.

_____1996a, Geologic map of the Allentown East quadrangle, Lehigh, Northampton, and Bucks Counties, Pennsylvania: U.S. Geological Survey Open-File Report 96-22, scale 1:24,000.

_____1996b, Geologic map of the Hellertown quadrangle, Northampton, Bucks, and Lehigh Counties, Pennsylvania: U.S. Geological Survey Open-File Report 96-547, scale 1:24,000.

_____1996c, Geologic map of the Catasauqua quadrangle, Northampton and Lehigh Counties, Pennsylvania: U.S. Geological Survey Open-File Report 96-700, scale 1:24,000.

_____in press a, Precambrian and lower Paleozoic metamorphic and igneous rocks of South Mountain and the Reading Prong, in Shultz, C.H., ed., The geology of Pennsylvania: Harrisburg, Pennsylvania, Pittsburgh Geological Society.

_____in press b, Structural geology and tectonics of South Mountain and the Reading Prong, in Shultz, C.H., ed., The geology of Pennsylvania: Harrisburg, Pennsylvania, Pittsburgh Geological Society.

Drake, A.A., Jr., Aleinikoff, J.N., and Volkert, R.A., 1991a, The Byram Intrusive Suite of the Reading Prong--age and tectonic environment, in Drake, A.A., Jr., ed., Contributions to New Jersey gelogy: U.S. Geological Survey Bulletin 1952D, p. D1-D14.

_____1991b, The Mount Eve Granite (Middle Proterozoic) of northern New Jersey and southeastern New York, in Drake, A.A., Jr., ed., Contributions to New Jersey geology, U.S. Geological Survey Bulletin 1952C, p. C1-C10.

Drake, A.A., Jr., and Epstein, J.B., 1967, The Martinsburg Formation (Middle and Upper Ordovician) in the Delaware Valley, Pennsylvania-New Jersey: U.S. Geological Survey Bulletin 1244-H, 16 p.

Drake, A.A., Jr., Hall, L.M., and Nelson, A.E., 1988, Basement and basemen-cover relation map of the Appalachian orogen in the United States: U.S. Geological Survey Miscellaneous Investigation Map I-1655, scale 1:1,000,000.

Drake, A.A., Jr., and Lyttle, P.T., 1980, Alleghanian thrust faults in the Kittatinny Valley, New Jersey, in Manspeizer, Warren, ed., Field studies of New Jersey Geology and Guide to field trips: Newark, Rutgers Unversity, p. 91-114.

_____1985, Geologic map of the Blairstown quadrangle, Warren County, New Jersey: U.S. Geological Survey Geologic Quadrangle Map GQ-1585, scale 1:24,000.

Drake, A.A., Jr., and Monteverde, D.H., 1992, Bedrock geologic map of the Branchville quadrangle, Sussex County, New Jersey: U.S. Geological Survey Geologic Quadrangle Map GQ-1701, scale 1:24,000.

Drake, A.A., Jr., Sinha, A.K., Laird, Jo, and Guy, R.E., 1989, The Taconic orogen, in Hatcher, R.D., Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, The Geology of North America, v. F-2, p. 101-177.

Drake, A.A., Jr., Volkert, R.A., Monteverde, D.H., Herman, G.C., Houghton, H.F., Parker, R.A., and Dalton, R.F., 1996, Bedrock geologic map of northern New Jersey: U.S. Geological Survey Miscellaneous Investigations Map I-2540A, scale 1:100,000.

Drake, A.A., Jr., Volkert, R.A., Monteverde, D.H., and Kastelic, R.L., Jr., 1994, Bedrock geologic map of the Washington quadrangle, Warren, Hunterdon, and Morris Counties, New Jersey: U.S. Geological Survey Geologic Quadrangle Map GQ-1741, scale 1:24,000.

Epstein, J.B., 1990, Geologic map of the Wind Gap quadrangle, Northampton and Monroe Counties, Pennsylvania: U.S. Geological Survey Geologic Quadrangle Map GQ-1645, scale 1:24,000.

Ewing, Maurice, 1936, Seismic study of Lehigh Valley Limestone: Pennsylvania Academy of Science Proceedings, v. 10, p. 72-75.

Ewing, Maurice and Pentz, H.H., 1936, Magnetic survey in the Lehigh Valley: American Geophysical Union Transactions, v. 17, p. 186-191.

Goddard, E.N., Trask, P.D., DeFord, R.K., Rove, O.N., Singewald, J.T., and Overbeck, R.M., 1948, Rock-color chart: Washington, D.C., National Research Council, 6 p., reprinted by Geological Society of America, 1951, 1963, 1970, 1991.

Gray, M.B., and Mitra, Gautam, 1990, Migration of deformation fronts during progressive deformation: evidence from detailed structural studies in the Pennsylvania Anthracite Region: Geological Society of America Abstracts with Programs, v. 22, p. 225.

Hague, J.M., Baum, J.L., Herrmann, L.A., and Pickering, R.J., 1956, Geology and structure of the Franklin-Sterling area, New Jersey: Geological Society of America Bulletin, v. 67, p. 435-474.

Hatcher, R.D., Jr., 1991, Interactive property of large thrust sheets with footwall rocks--the subthrust interactive duplex hypothesis: a mechanism of dome formation in thrust sheets: Tectonophysics, p. 237-242.

Hobson, J.P., 1957, Lower Ordovician (Beekmantown) successionin Berks County, Pennsylvania: American Association of Petroleum Geologists Bulletin, v. 41, p. 2710-2722.

Howell, B.F., 1945, Revision of the Upper Cambrian faunas of New Jersey: Geological Society of America Memoir 12, 46 p.

Howell, B.F., Roberts, Henry, and Willard, Bradford, 1950, Subdivision and dating of the Cambrian of eastern Pennsylvania: Geological Society of America Bulletin, v. 61, p. 1355-1368.

Hsü, K.J., 1995, The geology of Switzerland, an introduction to tectonic facies: Princeton, New Jersey, Princeton University Press, 250 p.

Hull, Joseph, Koto, Robert, and Bizub, Richard, 1986, Deformation zones in the Highlands of New Jersey, in Husch, J.M., and Goldstein, F.R., eds., Geology of the New Jersey Highlands and radon in New Jersey: third annual meeting of the Geological Association of New Jersey, Field Guide and Proceedings, p. 19-66.

Johnson, M.R.W., 1956, Conjugate fold systems in the Moine thrust zone in the Lochcarron and Coulin Forest area of Weter Ross: Geological Magazine, v. 93, p. 345-350.

Karklins, O.L., and Repetski, J.E., 1989, Distribution of selected Ordovician conodont faunas in northern New Jersey: U.S. Geological Survey Miscellaneous Field Studies Map MF-2066, scale 1:250,000.

Lash, G.G., 1982, The geology of the Kutztown and Hamburg 7 1/2-minute quadrangles, eastern Pennsylvania: U.S. Geological Survey Open File Report 82-493, 240 p.

_____1985, Geologic map of the Kutztown quadrangle, Pennsylvania: U.S. Geological Survey Geologic Quadrangle Map GQ-1577, scale 1:24,000.

_____1987, Geologic map of the Hamburg quadrangle, Pennsylvania: U.S. Geological Survey Geologic Quadrangle Map GQ-1637, scale 1:24,000.

Leverett, Frank, 1934, Glacial deposit outside the Wisconsin terminal moraine in Pennsylvania: Pennsylvania Geological Survey, 4th ser., Bulletin G7, 123 p.

Lewis, S.E., and Bartholomew, M.J., 1989, Orphans-Exotic detached duplexes within thrust sheets of complex history: Geological Society of America Abstracts with Programs, v. 21, p. 136.

MacLachlan, D.B., 1967, Structure and stratigraphy of the limestones and dolomites of Douphin County, Pennsylvania: Pennsylvania Geological Survey, 4th series, Bulletin G44, 168 p.

_____1979, Geology and mineral resources of the Temple and Fleetwood quadrangle, Berks County, Pennsylvania: Pennsylvania Geological Survey Atlas 187ab, 71 p.

_____1983, Geology and mineral resources of the Reading and Birdsboro quadrangles, Berks County, Pennsylvania: Pennsylvania Geological Survey, 4th series, Atlas 187cd, scale 1:24,000.

MacLachlan, D.B., Buckwalter, T.V., and McLaughlin, D.B., 1975, Geology and mineral resources of the Sinking Spring quadrangle, Berks and Lancaster Counties, Pennsylvania: Pennsylvania Geological Survey, 4th series, Atlas 177d, 228 p.

Miller, B.L., Fraser, D.M., and Miller, R.L., 1939, Northampton County Pennsylvania, Geology and Geography: Pennsylvania Geological Survey, 4th series, Bulletin C48, 496 p.

Miller, B.L., Fraser, D.M., Miller, R.L., Willard, Bradford, and Wherry, E.T., 1941, Lehigh County, Pennsylvania: Pennsylvania Geological Survey, 4th series, Bulletin C39, 492 p.

Miller, R.L., 1937, Stratigraphy of the Jacksonburg Limestone: Geological Society of America Bulletin, v. 48, no. 11, p. 1687-1718.

Offield, T.W., 1967, Bedrock geology of the Goshen-Greenwood Lake area, New York: New York State Museum and Science Service Map and Chart Series, no. 9, 78 p.

Palmer, A.R., and Rozanov, A.Y., 1976, Archaeocyatha from New Jersey, evidence for an intra-Cambrian unconformity in the north-central Appalachians: Geology, v. 4, p. 773-774.

Peck, F.B., 1911, Preliminary report on the talc and serpentine of Northampton County and the Portland cement materials of the Lehigh district: Pennsylvania Topographical and Geologic Survey Report no. 5, 65 p.

Plumb, K.A., 1991, New Precambrian time scale: Episodes, v. 14, no. 2, p. 139-140.

Prime, Frederick, Jr., 1878, The brown hematite deposits of the Siluro-Cambrian limestones of Lehigh County, lying between Shimersville, Middletown, Schnecksville, Ballietsville, and the Lehigh River: Pennsylvania Geological Survey, 2d series, Report of Progress 1875-76, 99 p.

Puffer, J.H., and Volkert, R.A., 1991, Generation of trondhjemite from partial melting of dacite under granulite facies conditions: an example from the New Jersey Highlands, U.S.A.: Precambrian Research, v. 51, p. 115-125.

Rankin, D.W., Drake, A.A., Jr., and Ratcliffe, N.M., Proterozoic North America (Laurentian) rocks of the Appalachian orogen, 1993, in Reed, J.C., Jr., Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., and Van Schmus, W.R., Precambrian: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. C-2, p. 378-422.

Rankin, D.W., and nine others, 1989, Preorogenic terranes, in Hatcher, R.D., Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geology of North America, v. F-2, p. 7-100.

Ratcliffe, N.M., 1981, Cortlandt-Beemerville magmatic belt; a probable late Taconian alkalic cross trend in the central Appalachians: Geology, v. 9, p. 329-335.

Repetski, J.E., Harris, A.G., and Stamm, N.R., 1995, An overview of conodonts from New Jersey, in Baker, J.E.B., ed., Contributions to the Paleontology of New Jersey: Geological Association of New Jersey Proceedings, v. 12, p. 191-208.

Rowlands, David, 1980, Age of slaty cleavage in the Martinsburg Formation; evidence from the Beemerville area, northwestern New Jersey: Geological Society of America Abstracts with Programs, v. 12, p. 521.

Salisbury, R.D., 1892, Certain extramoraine drift phenomena of New Jersey: Geological Society of America Bulletin, v. 3, p. 173-182.

_____1902, The glacial geology of New Jersey: New Jersey Geological Survey, Final Report, v. 5, 802 p.

Sherwood, W.C., 1964, Structure of the Jacksonburg Formation in Northampton and Lehigh Counties, Pennsylvania: Pennsylvania Geological Survey, 4th series, General Geology Report G45, 64 p.

Sloss, L.L., 1963, Sequences in the cratonic interior of North America: Geological Society of America Bulletin, v. 74, p. 93-114.

Spencer, A.C., Kümmel, H.B., Wolff, D.E., Salisbury, R.D., and Palache, Charles, 1908, Franklin Furnace, N.J.: U.S. Geological Survey Geology Atlas Folio 161, 27 p.

Stose, G.W., 1908, The Cambro-Ordovician limestones of the Appalachian Valley in southern Pennsylvania: Journal Geology, v. 16, p. 698-714.

Tobisch, O.T., and Fleuty, M.J., 1969, Use of geographic names for successive fold phases in areas of multiple folding [abs.]: Geological Society of America Abstracts with Programs, v. 1, pt. 7, p. 225-226.

Volkert, R.A., and Drake, A.A., Jr., in press, Geochemistry and stratigraphic relations of Middle Proterozoic rocks of the New Jersey Highlands, in Drake, A.A., Jr., ed., Geologic studies in New Jersey and eastern Pennsylvania: U.S. Geological Survey Professional Paper 1565-C.

Walcott, C.D., 1896, The Cambrian rocks of Pennsylvania: U.S. Geological Survey Bulletin 134, 43 p.

Wherry, E.T., 1909, The early Paleozoics of the Lehigh Valley district, Pennsylvania: Science, m.s., v. 30, p. 416.

Wintsch, R.P., Kunk, M.J., and Epstein, J.B., 1996, $^{40}Ar/^{39}Ar$ whole-rock constraints of Acadian diagenesis and Alleghanian cleavage in the Martinsburg Formation, Lehigh Gap area, eastern Pennsylvania: American Journal of Science, v. 296, p. 766-788.

Wolff, J.E., and Brooks, A.H., 1898, The age of the Franklin White Limestone of Sussex County, New Jersey: U.S. Geological Survey 18th Annual Report, pt. 2, p. 431-456.

Zadnik, V.E., 1960, Petrography of the Upper Cambrian dolomites of Warren County, New Jersey: Unpublished Ph.D. thesis, University of Illinois, Urbana, Illinois, 155 p.

Table 1--Fold phases in the Nazareth quadrangle

Phase	Trend	Foliation	Lineation	Style
Stone Church	Nearly due east	Sparse poor spaced cleavage	Intersection of spaced cleavage with slaty or rough cleavage. Overprints earlier formed lineations	Open, upright folds of bedding and slaty and rough cleavage. Folds axial surfaces of map scale Iron Run folds. Plunge nearly east or west
Manunka Chunk	Northeast	Crenulation Cleavage	Intersection of crenulation cleavage with slaty or rough cleavage. This intersection overprints that of both Irish Mountain and Hokendauqua phases	Folds of bedding and slaty or rough cleavage that range from open to isoclinal and from upright to gently inclined. Plunge either northeast or southwest.
Hokendauqua	Northwest to north-northwest	Poor to fair spaced cleavage	Intersection of spaced cleavage with slaty or rough cleavage. This lineation overprints that of Musconetcong phase	Folds of bedding and or rough cleavage that are open and upright to steeply isoclinal. Most plunge southeast (fig. 2)
Iron Run	West-northwest, due east or east-northeast	None recognized	None recognized	Large folds of bedding and slaty or rough cleavage. Many, but not all, are isoclinal and strongly overturned to the northwest and in places are rotated past the horizontal. Plunge either easterly or westerly
Musconetcong	East-northeast where not reoriented	Slaty cleavage, rough cleavage in graywacke, spaced cleavage in some carbonate rock, at many places bedding is transposed into slaty cleavage forming a transposition foliation	Intersection of slaty cleavage with bedding	Isoclinal flattened folds of bedding that are strongly overturned to the northwest or are recumbent. Where not reoriented plunge east-northeast or west-southwest

CORRELATION OF MAP UNITS[1]

Qal — Holocene

Unconformity

Qd — Pleistocene

QUATERNARY

Unconformity

ROCKS OF THE LEHIGH VALLEY SEQUENCE

Omr — Upper Ordovician

Omb

Ojru

Ojrl

Ojr

Ojl

Middle Ordovician

ORDOVICIAN

Unconformity

Kittatinny Supergroup

Beekmantown Group

Oe

Or

Os

Lower Ordovician

OЄa — Lowest Lower Ordovician and Upper Cambrian

Єl — Middle and Lower Cambrian

Єh — Lower Cambrian

CAMBRIAN

Unconformity

ROCKS OF THE DURHAM AND READING HILLS

Byram Intrusive Suite

Y^3ba — Stenian

Intrusive Contacts

Metasedimentary Rocks

Y^2k	Y^2s	Y^2b	Y^2sp

Unconformity

Losee Metamorphic Suite

Y^2lo	Y^2la

Unconformity

Hexenkopf Complex

Y^2he	Y^2hc	Y^2hg

Rocks of Uncertain Origin

Y^2a

Ectasian

MESOPROTEROZOIC ROCKS

DESCRIPTION OF MAP UNITS

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

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, 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 LEHIGH VALLEY SEQUENCE

Martinsburg Formation (Upper and Middle Ordovician (Drake and Epstein, 1967)

Omr — Ramseyburg Member (lower Upper and upper Middle Ordovician)--Interbedded light- (N7) to medium-gray (N5) graywacke and graywacke siltstone and medium- (N5) to dark-gray slate. The graywacke beds range from about 1 in to 5 ft in thickness and average about 1 ft. The beds are very continuous in outcrop. Most graywacke is fine grained, but is medium locally. Many beds contain the complete Bauma (1962) sequence, but basal cut-out sequences, particularly T_{c-e} sequences, are most common. The Ramseyburg has been difficult to date because of its sparse and poorly preserved graptolite fauna. Drake and others (1989) estimate that it is Edenian (Caradocian) in age. Grades down into Bushkill Member. The unit is about 2800 ft thick in this area. Shown in section only

Omb — Bushkill Member (uppermost Middle Ordovician)--Basal part of unit is black (N1) to dark-gray (N3) slate that passes upward into interbedded slate and graywacke siltstone. Few beds exceed 4 in in thickness; most are less than 0.5 in thick. Silt-clay ratios range from about 1:3 to 1:6, and the different rock types form "ribbons" on slaty cleavage surfaces. In terms of Bouma's (1962) turbidite model, most beds lack one or more of the basal units and can be classed as T_{b-e}, T_{c-e}, or T_{d-e} turbidites. T_{c-e} beds appear to be most common. Unit grades down into the cement rock facies of the Jacksonburg Limestone (Ojr) by a decrease in pelitic material and an increase of carbonate. The Bushkill has been difficult to date because of its sparse graptolite fauna that represents a very restricted and extreme biofacies. Only a few species have been found, and they are both long-ranging and hard to identify. The Bushkill is younger than the cement rock facies of the Jacksonburg Limestone (Ojr) so its lower part is probably Kirkfieldian (Repetski and others, 1995) (Caradocian) in age. On the basis of graptolites collected elsewhere in Pennsylvania and New Jersey, the Bushkill ranges from Kirkfieldian to Edenian (Caradocian) in age (Drake and others, 1989). The Bushkill is about 4,000 ft thick in this area.

Jacksonburg Limestone (Spencer and others, 1908; Miller, 1937a) (Middle Ordovician)

Ojr, Ojru, Ojrl — Cement rock facies--Dark-gray (N3) to grayish-black (N2), fine- to very-fine-grained, argillaceous limestone. In most exposures, bedding has been totally obliterated by slaty cleavage. Contains lower (Ojrl) and upper (Ojru) crystalline limestone intervals identical to the underlying cement limestone facies (Ojl). Structural complications and poor exposure make it difficult to estimate the unit's thickness, which, however, may be as much as 1000 ft

Ojl Cement limestone facies--Light- (N7) to medium-gray (N6), largely well-bedded, medium- to coarse-grained calcarenite and fine- to medium-crystalline, high-calcium limestone. In New Jersey, contains a North American Midcontinent Province Conodont Fauna 9, so is of Kirkfieldian (Caradocian) age (Repetski and others, 1995). Total thickness is uncertain, but may be as much as 400 ft.

Oe Epler Formation of Beekmantown Group (Lower Ordovician) (Hobson, 1957)--Medium- (N5) to medium-dark-gray (N4), thin- to thick-bedded, fine-grained and much less medium-grained silty limestone interbedded with thin- to thick-bedded, light- (N7) to medium-dark (N4) gray, cryptogranular to medium-grained dolomite. Contains a North American Midcontinent Province Conodont Fauna low D through E, so is of Ibexian (Tremadocian to Arenigian) age (Repetski and others, 1995). Grades down into the Richenbach Dolomite (Or). Is about 800 ft thick

Or Rickenbach dolomite of Beekmantown Group (Lower Ordovician) (Hobson, 1957)--Medium- (N5) to medium-dark-gray (N4), medium- to coarse-grained dolomite containing rosettes of light-gray (N7) chert as well as medium-light (N6) to medium-gray (N5), fine grained, 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 (Repetski and others, 1995). Grades down into Stonehenge Formation (Os). Is about 600 ft thick

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, and solution collapse breccia. Contains conodonts of the Rossodus manitonensis Biozone so is of early Ibexian (Tremadocian) age (Repetski and others, 1995). Grades down into 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). Is about 700 feet thick

O€a 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 stromalolites, intraformational conglomerate, ripple marks, and mud cracks. Shelly fauna collected from near the bottom and top of the formation in the Buckingham Valley to the south and in New Jersey are of, respectively, Dresbachian and Trempealeauan age (Howell, 1945; Howell and others, 1950). Grades down into the Leithsville Formation (€l). Is about 1900 ft thick

€l 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 (€h). It is 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, quartz-pebble conglomerate, and silty shale. 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 DURHAM AND READING HILLS
Byram Intrusive Suite (Drake, 1984)

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

Metasedimentary Rocks (Ectasian)

Y^2k Potassic feldspar gneiss--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. 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--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 seriticized oligoclase

Y^2b Biotite-quartz-feldspar gneiss--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^2sp Serpentinized marble--Pale green (5 G 7/2) to moderate green (5 G 5/6), massive to schistose serpentinite. Schistose phases contain vermiculite-like phlogopite. Lenses and irregular masses of crypto-crystalline silica are common, as are veins of white calcite and pink dolomite. Parts of the rock have been further altered to talc and other parts contain relic diopsodic pyroxene and tremolite

Losee Metamorphic Suite (Ectasian) (Drake, 1984)

Y^2lo Quartz-oligoclase gneiss--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

Y^2la Albite-oligoclase granite--Light-greenish-gray (5 G 8/1) to bluish-white (5 B 9/1), medium- to coarse-grained, gneissoid granite composed principally of ablite-oligoclase and quartz. Interpreted to be a rheomorphic phase of Y^2lo

Hexenkopf Complex (Ectasian) (Drake, 1984)

Y^2he — Epidote-clinopyroxene-hornblende-plagioclase gneiss--Grayish-olive (10 Y 4/2), medium- to medium-coarse grained, very heavy, massive, dense, well-foliated gneiss

Y^2hc — Hornblende-clinopyroxene-quartz-plagioclase gneiss--Drak gray (N3) to greenish-black (5 GY 2/1), medium- to medium-coarse-grained, well-foliated to nonfoliated rock. Contains numerous veins of microperthite alaskite (Y^2ba)

Y^2hg — Quartz-garnet-augite granofels--Medium-gray (N5) to greenish gray (5 G 6/1), medium- fine grained to medium-grained, equigranular, heterogeneous, highly siliceous granofels. Contains minor amounts of saussuritized plagioclase and chlorite

Rocks of Uncertain Origin

Y^2a — Amphibolite (Ectasian)--Dusky-green (5 G 3/2) to grayish-black (N2), medium-grained rock composed largely of hornblende and andesine

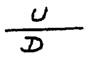
---

[1] The terms "Mesoproterozoic," "Stenian," and "Ectasian" follows 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--dotted where concealed

Faults--Showing dip where known. Dotted where concealed; queried where fault must be present, but precise location is uncertain

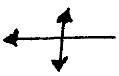


High angle fault--U, upthrown side; D, downthrown side

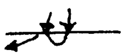
Thrust fault--Sawteeth on upper plate

FOLDS

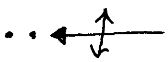
Folds of Proterozoic age in Proterozoic rocks--Folds of both layering and foliation can be no older than F_2. At least one phase of earlier folds can be recognized in outcrop

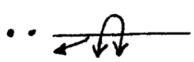
 Antiform--Showing trace of crestline and direction of plunge

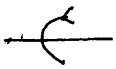
 Synform--Showing trace of troughline and direction of plunge

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

Folds of Paleozoic age--Fold phases are named for geographic localities where displayed or for prominant major folds of that phase. Initials indicate phase, from oldest to youngest: M, Musconetcong; IR, Iron Run; H, Hokendaqua; MC, Manunka Chunk; SC, Stone Church

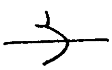
 Anticline--Showing trace of axial surface and direction of plunge. Dotted where concealed

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

 Anticlinal cascade fold--Arrow indicates dip of upper limb

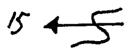
 Antiform--Showing trace of axial surface and direction of plunge

 Syncline--Showing trace of axial surface and direction of plunge

 Synclinal cascade fold--Arrow indicates dip of upper limb

MINOR FOLDS

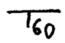
 Minor anticline, showing plunge



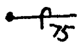
Minor asymmetric fold--Showing bearing and plunge of axes and rotation sense viewed down plunge

PLANAR FEATURES
(May be combined with linear features)

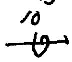
Strike and dip of beds--Ball indicates top known from Sedimentary structures



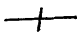
Inclined



Overturned



Rotated more than 180°

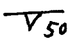


Vertical

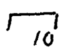
Horizontal

Strike and dip of crystallization foliation

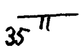
Strike and dip of mylonitic foliation



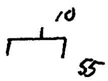
Strike and dip of transposition foliation



Strike and dip of slaty cleavage



Strike and dip of crenulation cleavage



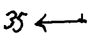
Strike and dip of slaty cleavage and bedding parallel in strike but divergent in dip

Strike and dip of joints

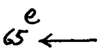
Inclined

Vertical

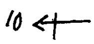
LINEAR FEATURES
(May be combined with planar features)



Mineral lineation



Elongation lineation



Intersection of bedding and slaty cleavage

OTHER FEATURES

⚒	Active quarry--c, cement; r, rock
⚒	Abandoned quarry--l, limonite; c, cement
F	Fossil (conodont) locality
x	Float

Quarries

I National Portland Cement Company
II Industrial Limestone Company
III Penn Dixie Cement Corporation, Penn Allen quarry
IV and V Penn Dixie Cement Corporation, Christian Springs quarries
VI Lone Star Cement Corporation
VII Nazareth Cement Company
VIII Trumbauer Crushed Stone
IX Hercules Cement Corporation