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Geologic Map of the Catasauqua Quadrangle, Northampton and Lehigh Counties, Pennsylvania

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INTRODUCTION

The Catasauqua quadrangle, in the Lehigh Valley of eastern Pennsylvania, is underlain mostly by Cambrian and Lower Ordovician carbonate rocks of the Laurentian passive margin and Middle and Upper Ordovician flysch deposits of the Martinsburg foreland basin. An inlier of Mesoproterozoic rocks forms a low ridge in the southeastern corner of the quadrangle. Glacial deposits of pre-Wisconsinian, Illinoisian(?), age obscure the bedrock in many areas.

The outcropping rocks 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, 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), which was described in detail by Drake and others (1989). Here, the Mesoproterozoic rocks were first deformed during the Grenville orogeny (ca 1.1 Ga) (Rankin and others, 1989), and were again deformed with the lower Paleozoic rocks, during the Ordovician Taconic orogeny (ca 450 Ma) (Drake, 1980). These structures were later overprinted by those formed during the late Paleozoic Alleghanian orogeny (ca 300 Ma) (Drake, 1980).

STRATIGRAPHY

Most of the rocks in the Catasauqua quadrangle are sedimentary and are of Cambrian and Ordovician age. Pine Top, in the southeastern corner of the quadrangle, the northernmost ridge of the Durham and Reading Hills, is underlain by gneiss, amphibolite, marble, quartzite, and foliated granitoids 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 are poorly exposed in this quadrangle. Potassic feldspar gneiss (Y^2k) is the most abundant rock. It can be seen in outcrops east of Monocacy Creek. It is characterized by its high content 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 and quartz pebble conglomerate (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.

Calcite marble (Y^2mr) can be seen in a small abandoned quarry just west of Monocacy Creek. Two other small bodies were mapped on float.

A sparse amount of amphibolite (Y^2a) was mapped, largely on float. In New Jersey, amphibolite was found to have more than one origin (Drake, 1990). Some is probably metasedimentary, other amphibolite has relict pillows, and still other parts contain enclaves of undeformed metagabbro. The protolith or protoliths of amphibolite in this quadrangle cannot be determined.

The rocks described above occur throughout the Reading Prong, and similar rocks crop out in the Honey Brook Upland to the south and 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 probably Ectasian (1400-1200 Ma) (Plumb, 1991) in age because they are intruded by rocks of Stenian (1200-1000 Ma) (Plumb, 1991) age.

Microperthite alaskite (Y^3ba) of the Byram Intrusive Suite crops out in Westover Hills near the western end of Pine Top. Modes and chemical analyses of microperthite alaskite are given in Drake (1969, 1984) and Drake and others (1991a). The rocks of the Byram Intrusive Suite are similar to those of supposed intraplate, anorogenic granites (Volkert and Drake, in press), however they have a Stenian U-Pb age of about 1090 Ma (Drake and others, 1991a) and 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).

Lower Paleozoic Rocks

The Lower Ordovician and older sedimentary rocks in this quadrangle constitute the Kittatiny Supergroup of Drake and Lyttle (1980). These rocks, and the overlying Jacksonburg Limestone and Martinsburg Formation, constitute the Lehigh Valley sequence of MacLachlan (1967) and Drake (1969).

The oldest of these rocks, the Hardyston Quartzite (Ꞓh), does not crop out, but two small bodies were mapped on the basis float on Pine Top. The Allentown Dolomite (OꞒa) is abundant in the quadrangle. Excellent outcrops and quarry exposures can be seen along Monocacy Creek in the southeastern corner of the quadrangle and along Jordan Creek in the southwestern corner of quadrangle.

Prior to the work of Drake and Lyttle (1985) and Karklins and Repetski (1989) in New Jersey, the Stonehenge Formation (Os) was not recognized at the base of the Beekmantown Group in the Lehigh Valley sequence. It was mapped earlier as either Richenbach Dolomite or Epler Formation, which led to many erroneous structural interpretations. The Stonehenge can be best seen in an overturned section along the Lehigh River south of Fullerton and on the east border of the quadrangle south of Steuben Road. The Richenbach Dolomite (Or) can be best seen in the overturned section along the Lehigh River south of Fullerton.

The Epler Formation (Oe) is lithically similar to the Stonehenge Formation (Os), so at places, a characteristic conodont assemblage is necessary for correct identification. One surrogate technique is also useful. Strata-bound limonite deposits are common in the Epler Formation, a fact first recognized by geologists of the New Jersey Zinc Company who used the relation to prospect for zinc deposits because sphalerite is stratabound in the lower Beekmantown section (W.H. Callahan, New Jersey Zinc Company, written commun., 1968). Outcrops of Epler Formation are abundant on both banks of the Lehigh River both north and south of the Whitehall window, as well as in the Jacksonville and Bath areas.

The cement limestone facies of the Jacksonburg Limestone (Ojl) can be seen in natural outcrop in the Northampton area and in quarries of the Lehigh and Keystone Portland Cement Companies and the Penn Dixie Cement Corporation. There are abundant outcrops of the cement rock facies (Ojr) throughout its outcrop belt. This unit has lower and upper intervals of crystalline limestone identical to that the cement limestone facies. The lower crystalline limestone interval (Ojrl) can be seen in the quarries of the Keystone Cement Company and the Penn Dixie Cement Corporation. The upper crystalline limestone interval (Ojru) can be seen in an abandoned quarry of the Universal Atlas Cement Company.

There are abundant outcrops of Bushkill Member of the Martinsburg Formation (Omb) along all drainages in its outcrop belt. A unique feature of this unit in the Catasauqua quadrangle is its contained blocks of Allentown Dolomite and Stonehenge Formation. These blocks were interpreted by Miller (1937b) to be Martinsburg Limestone. Others, including me, suggested that they may be tectonic fragments within the Bushkill. Aldrich (1967) correctly recognized that the blocks are olistoliths within the Bushkill. Aldrich's interpretation was confirmed by a 12 in by 4 in by ? block of what is clearly Allentown Dolomite within the slate. The block was exaggerated on the map in order to show its presence. In addition, in 1970, a borrow-pit in the Bushkill exposed the top, sides, and ends of the boomerang-shaped block of Stonehenge Formation about 2900 ft west-northwest of Miller Manor. I have mapped the Bushkill outcrop belt from the Topton quadrangle, Pennsylvania (Drake, 1987) on the west into Orange County, New York (Drake and Monteverde, 1992a) and have never seen a fragment of carbonate rocks of any size within the Bushkill. Why here and nowhere else? I have no idea. There are abundant outcrops of the Ramseyburg Member of the Martinsburg Formation along the Lehigh River and its tributaries in the northwestern corner of the quadrangle.

STRUCTURAL GEOLOGY

The Mesoproterozoic rocks in the Durham and Reading Hills, of which Pine Top in the northernmost exposure, 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 of layering into the foliation. No macroscopic folds were mapped in the Mesoproterozoic rocks on Pine Top.

Rocks of the Byram Intrusive Suite were emplaced during the Grenville orogeny at about 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 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. 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). Rocks of the Musconetcong and Lyon Station nappes crop out in the Catasauqua quadrangle.

Musconetcong Nappe

The Musconetcong nappe, more properly nappe system, comprises the basement massifs and their cover in eastern Pennsylvania that lie 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. These studies suggested that a magnetic body, presumably Mesoproterozoic rocks, occurs at a depth of about 1 mile in the Catasauqua area. Their analyses showed that the gradient associated with the Catasauqua anomaly does not steepen where it intersects outcropping Mesoproterozoic rocks to the southwest of the Catasauqua quadrangle; 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 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!

Prior to 1970, the Allentown Dolomite in the Schoenersville, Industrial Park, and Stafore windows had not been recognized. The Allentown Dolomite, in the eastern half of the Schoenersville window, and that in the Industrial Park and Stafore windows, was not recognized in 1989 when major construction work exposed bedrock in what had previously been a series of cornfields.

Thrust Faults

Seven northeast-directed thrust faults emerge in the Catasauqua quadrangle. In addition, at least three thrust faults are known in the subsurface.

The highest thrust, which is unnamed, splays from the Jordan Creek thrust near Midway Manor. Its trace, entirely within the Allentown Dolomite, is marked by sheared rock and abundant striated surfaces. It is well exposed along the railroad spur both west and east of Allen Junction. The fault was not recognized in the Nazareth quadrangle to the east (Aaron, 1975).

Jordan Creek Thrust Fault

In the western part of the quadrangle, the Jordan Creek thrust fault has placed upright Allentown Dolomite onto an overturned section of Allentown Dolomite and rocks of the Beekmantown Group. This relation is well shown in outcrops on the west bank of the Lehigh River. In the southeastern part of the quadrangle, the fault has placed overturned Allentown Dolomite on the Stonehenge Formation. It continues east across the Nazareth (Aaron, 1975) and Easton (Drake, 1967) quadrangles into New Jersey (Drake and others, 1996). To the west, the Jordan Creek thrust fault was overridden by the Irish Mountain nappe on the Black River thrust fault (Drake, 1993).

Harmony Thrust Fault

The Harmony thrust fault has placed Stonehenge Formation on Mesoproterozoic rocks, and is the upper bounding surface of the large Pine Top "orphan," that is a duplex having an incompatible stratigraphy with the surrounding rocks (Lewis and Bartholomew, 1989). The Harmony thrust fault is cut off by the Jordan Creek thrust fault. It continues to the east across the Nazareth (Aaron, 1975) and Easton (Drake, 1967) quadrangles 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. It rejoins the Harmony thrust fault in the Nazareth quadrangle to the east (Aaron, 1975).

Fullerton Thrust Fault

The Fullerton thrust fault bounds the Whitehall, Schoenersville, Industrial Park, and Stafore windows, as well as the Mechanicsville window in the Cementon quadrangle to the west (A.A. Drake, Jr., unpublished data, 1971, 1976). The body of Allentown Dolomite that crops out in the Whitehall window was conventionally interpreted as an anticline (Miller and others, 1941), but detailed geologic mapping showed that the carbonate rock in contact with the Allentown Dolomite is Epler Formation, which is the highest formation in the Beekmantown Group. Conodonts from limestone both north and south of the Whitehall window confirm that the unit is Epler Formation (J.E. Repetski, U.S. Geological Survey, written commun., 1990, 1991, 1994). Rocks around the Whitehall and others windows are severely deformed (Drake, 1978, fig. 10) as are their contained conodonts. In most exposures, bedding has been transposed into cleavage and the resulting tectonic fabric is marked by a strong elongation (stretching) lineation. Many exposures contain mesoscopic sheath folds, the axes of which plunge essentially parallel with the stretching lineations.

The Allentown Dolomite, within the windows, is not especially deformed except near the fault frames where it is sheared. 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 Fullerton thrust fault has not been recognized east of the Catasauqua quadrangle. It, however, must be present in the subsurface as the aeromagnetic signature of the Lyon Station nappe can be recognized over a distance of about 42 miles (Drake, 1978).

Foul Rift Thrust Fault

The Foul Rift thrust fault has placed Epler Formation on cement limestone facies of the Jacksonburg Limestone near the east border of the quadrangle. It is a major thrust fault that has been mapped to the east in the Nazareth (Aaron, 1975), Easton (Drake, 1967), and Bangor (Davis and others, 1967) quadrangles, and well into New Jersey (Drake and others, 1996). The cement limestone in the footwall of the thrust fault has been severely sheared and conodonts from this rock have been "deformed nearly beyond belief" (J.E. Repetski, U.S. Geological Survey, written commun., 1990).

Haafsville Thrust Fault

The Haafsville is a major thrust fault in this part of eastern Pennsylvania. To the west, it has placed Epler Formation on the Bushkill Member of the Martinsburg Formation. Displacement decreases as the fault is traced east. In the eastern part of the adjacent Cementon quadrangle to the west (A.A. Drake, Jr., unpublished data, 1971, 1976), Jacksonburg Limestone has been placed on Bushkill and near the Cementon-Catasauqua boundary the Haafsville becomes intraformational within the Bushkill. The Haafsville thrust fault cannot be traced very far in the Catasauqua quadrangle, much of the slip apparently having been transferred to the subsurface Stockertown thrust fault (see section C-C'). The remaining strain was apparently dissipated as intraformationally distributed shear.

Stockertown Thrust Fault

The Stockertown thrust fault crops out as the frame for tectonic windows that expose Bushkill member of the Martinsburg Formation beneath Jacksonburg Limestone in the Bangor (Davis and others, 1967), Nazareth (Aaron, 1975), and Wind Gap (Epstein, 1990) quadrangles. It has thrown off many hanging wall splays that were mapped by Davis and others (1967) and Epstein (1990). The minor thrust faults in the Bushkill Member of the Martinsburg Formation are probably splays from the Stockertown thrust fault. There are almost certainly blind thrust faults beneath the Stockertown thrust fault as tectonic windows typically are on antiformal stacks (Hatcher, 1991).

Northwest-Dipping Thrust Faults

Two northwest-dipping thrust faults were mapped. One can be seen in an abandoned quarry of the Keystone Portland Cement company near Bath. The other crops out in a creek just east of Saurkraut Hill. Many other northwest dipping thrust faults were observed in outcrop, but could not be traced far enough to map.

Tear Faults

Two tear faults were mapped. One at Penn Dixie Pond, a flooded quarry, has experienced sinistral slip. The other in the abandoned Keystone Portland Cement company has experienced dextral slip.

Folds

The complex folds depicted on the cross sections were modeled on natural folds seen in outcrop, particularly along the Lehigh River, and in quarries. Such folds can be seen in photographs in Prime (1878), Miller and others (1939), Miller and others (1941), Sherwood (1964) and Drake (1969). The complexity of the deformation, however, cannot be shown in two dimensions. The subsurface relation of the cement limestone facies of the Jacksonburg Limestone and Bushkill Member of the Martinsburg Formation as depicted on section A-A' are based on core drilling by the cement industry. Hole DDH-1 passed from cement rock into slate at a depth of 1032 feet, the contact being picked at a marked change in insoluble residue content, cement rock 59.7 percent to slate 72.6 percent (Sherwood, 1964). In the upper 200 feet of core from DDH-2 the $CaCO_3$ content ranged from 58 to 72 percent. At 200 feet, the $CaCO_3$ content dropped to 38 percent and decreased irregularly to a depth of 245 feet where slate was encountered and was maintained for an additional 125 feet (Miller and others, 1939). The contact was picked at 245 feet. The overturned contact in both holes was gradational.

Two special types of folds can be seen in the Catasauque quadrangle. One type, called quasiflexural by Donath and Parker (1964), is common to interbedded limestone and dolomite sequences in the Stonehenge and Epler Formation 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 Jacksonburg Limestone and Martinsburg Formation. 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 is 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. The folds along the Lehigh River, as well as those between Bath and Hanoversville, 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 this quadrangle where folds of this phase were first recognized by Drake (1971). Hohendauqua folds were mapped in rocks of the Beekmantown Group, Jacksonburg Limestone, and 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, Portland, and Blairstown quadrangles. 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 Whitehall, Shoenersville, Industrial Park, and Stafore windows. 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 in Late Ordovician intrusive rocks (Rowlands, 1980; Ratcliffe, 1981; Drake and Monteverde, 1992b) showing that the cleavage in the Martinsburg surely must be Taconic. 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 are 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 Taconian 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 Haafsville and Stockertown thrust faults are of Taconic age because in the Allentown West and Topton quadrangles to the west they were folded by Iron Run phase folds (Drake, 1987, 1993). 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). The Harmony and Pine Top thrust faults are Taconic features as they are involved in a duplex with the Jordan Creek thrust fault and are deformed by Stone Church phase folds. The Fullertown thrust fault is Alleghanian in age because it has placed the Musconetcong nappe above the Lyon Station nappe. It is folded by the Alleghanian Stone Church folds.

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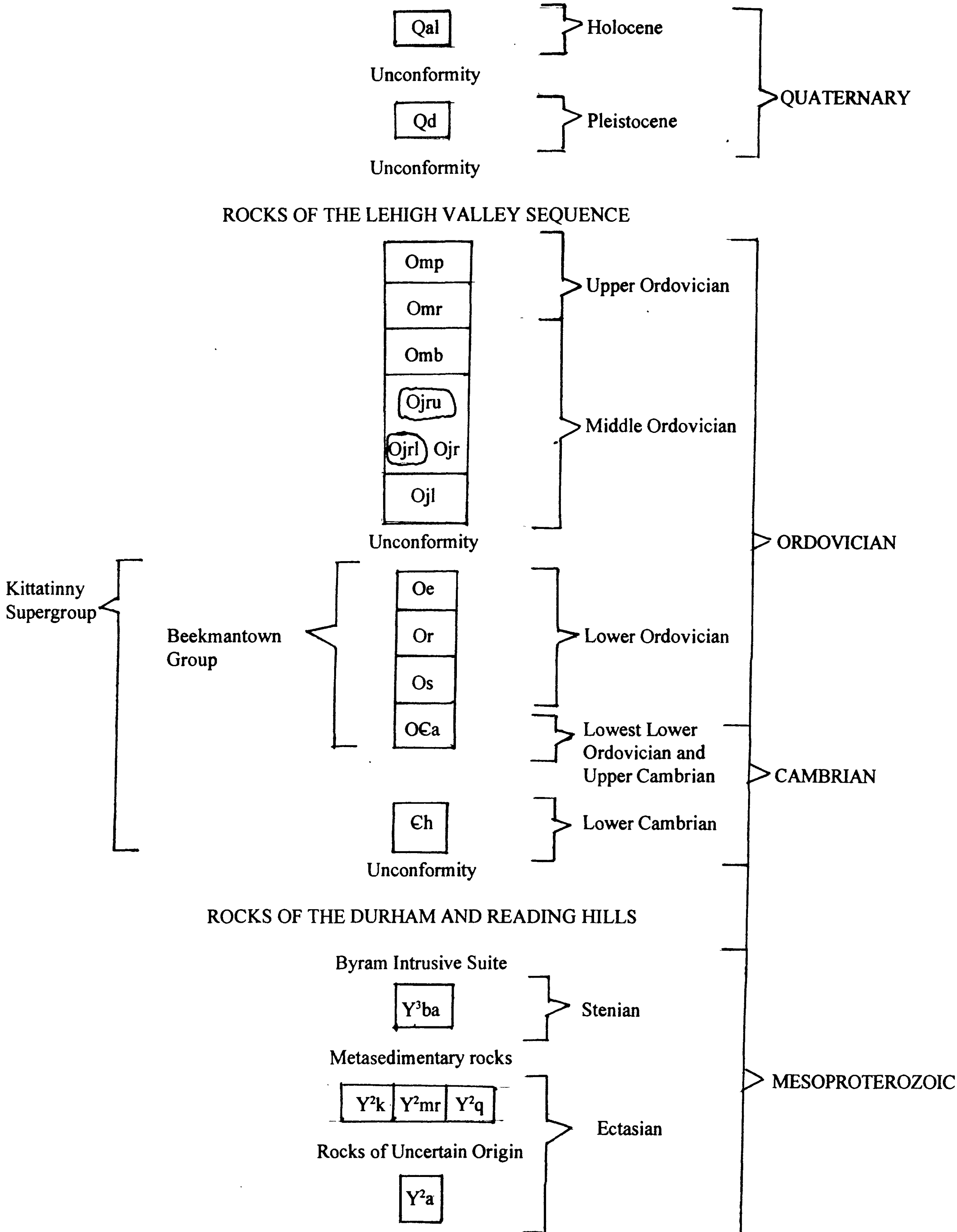
CORRELATION OF MAP UNITS[1]



DESCRIPTION OF MAP UNITS[1]

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)

Omp Pen Argyl Member (Upper Ordovician)--Dark-gray (N3) to grayish black (N2), thin- to thick-bedded (commonly more than 12 ft and in places 20 ft), evenly bedded slate rhythmically interbedded with carbonaceous slate, sandy slate, and very fine- to medium-grained graywacke with parallel laminations, lenticular bedding, convoluted bedding, and sole marks. Units occur in upward-fining cycles (muddy turbites). Quarried extensively for slate ("soft slate" belt of Pennsylvania quarrymen). Upper contact not exposed but unit is about 6900 ft thick in eastern Pennsylvania. Pelitic beds contain the mineral assemblage muscovite-chlorite-albite-quartz. Contains a graptolite fauna suggestive of an Edenian (Caradocian) age (Drake and others, 1989). Shown in section only

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 grained locally. Many beds contain the commplete 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. The unit is about 2800 ft thick in this area

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
Ojrl
Ojru

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) intervals of crystalline limestone 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). Is about 1900 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). Probably is less than 100 ft thick in this quadrangle

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

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. In places, unit has been mobilized to form sheets and irregular bodies of alkali-feldspar granite or quartz-rich granitoid

Y^2mr Marble (Ectasian)--Medium-grained, light-medium-gray (N6), graphitic, calcite marble

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

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

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[1] The terms "Mesoproterozoic," "Stenian," and "Ectasian" follows the usage of Plumb (1991) and applies to rock 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--dashed where approximately located; short dashed where inferred; dotted where concealed

Thrust fault--Sawteeth on upper plate. Dashed where approximately located; short dashed where inferred; dotted where concealed

Tear fault--half arrows show relative displacement

Folds--Fold phases are named for geographic localities where well displayed or for prominent 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 crest line and direction of plunge where known

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

Anticlinal cascade fold--Showing trace of axial surface and direction of plunge. Arrow indicates direction of dip of upper limb

C Cleavage arch

Syncline--Showing trough line and direction of plunge

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

Synclinal cascade fold--Showing trace of axial surface and direction of plunge. Arrow indicates directionof dip of upper limb

C Cleavage trough

Minor folds

10 Minor anticline

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

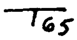
15 Minor recumbent fold

10 C Fold of cleavage

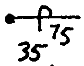
PLANAR FEATURES

(may be combined with linear features)

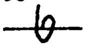
Strike and dip of beds--Ball indicates top known from sedimentary structures

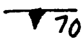


Inclined

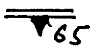


Overturned


Rotated more than 180°

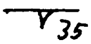


Strike and dip of crystallization foliation



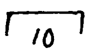
Strike and dip of mylonitic foliation

Strike and dip of transposition foliation

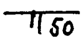


Inclined

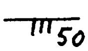

Vertical



Strike and dip of cleavage



Strike and dip of crenulation cleavage

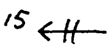


Strike and dip of spaced cleavage

LINEAR FEATURES

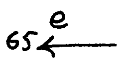
(May be combined with planar features)

Bearing and plunge of intersection of bedding and slaty cleavage



Bearing and plunge of crenulations

Bearing and plunge of intersection of spaced cleavage and slaty cleavage



Elongation lineation

Bearing and plunge of grove or striation

OTHER FEATURES


Abandoned mine or quarry--l, limonite; d, dolomite; ls, limestone; sl, slate; c, cement or rock

Active cement quarry: I, Dragon Cement Company; II, Universal Atlas Cement Company; III, Lehigh Portland Cement Company; IV, Keystone Portland Cement Company; V, Penn Dixie Cement Corporation

DDH

Diamond drill hole

x Float

Cement Quarries

I, Dragon Cement Company
II, Universal Atlas Cement Company
III, Lehigh Portland Cement Company
IV, Keystone Portland Cement Company
V, Penn Dixie Cement Corporation

Table 1--Fold phases in the Catasauqua 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 Church	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 slaty 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.