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

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

By

Avery Ala Drake, Jr.

Introduction

The Hellertown quadrangle, in eastern Pennsylvania, contains 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, 1988), and lower Paleozoic rocks of the Lehigh Valley segment of the Great Appalachian Valley and Mesozoic rocks of the Newark basin. These rocks are obscured through much of the quadrangle by glacial deposits of pre-Wisconsinan age.

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

Stratigraphy

The oldest exposed rocks in the Hellertown quadrangle are gneisses and foliated granitoid rocks of Mesoproterozoic age, which are cut by a few Neoproterozoic dikes. These rocks are unconformably overlain by sedimentary rocks of Cambrian and Ordovician age, and sedimentary and intrusive rocks of Mesozoic age. Most of the Cambrian and Middle Ordovician rocks were deposited on the east-facing shelf (present direction) of the Laurentian craton after the opening of the Iapetus Ocean (Rankin and others, 1989). Water deepened at the beginning of the Taconic orogeny, and dark-colored limestone and shaly limestone of the Jacksonburg Limestone was deposited (Drake and others, 1989). In Triassic time, the Newark basin was formed by extension related to the opening of the Atlantic Ocean and was infilled with clastic rocks, which were subsequently intruded by Jurassic diabase (Manspeizer and others, 1989).

Mesoproterozoic Rocks

Mesoproterozoic rocks are abundant in the Hellertown quadrangle. The oldest of these rocks are hornblende-clinopyroxene-quartz-plagioclase gneiss (Y^2hc) and epidote-clinopyroxene-hornblende-plagioclase gneiss (Y^2he) of the Hexenkopf Complex (Drake, 1984). These rocks can be best seen on Pektor and Christines Hills in the northeastern part of the quadrangle. Chemical analyses are given in table 1 and additional analyses were presented by Drake (1984, table 12). Composition ranges from basalt to dacite (fig. 1). The Hexenkopf Complex was 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 more silicic rocks represent are probably the result of later alteration. The Th-Hf-Ta diagram of Wood (1980), which is usually the most reliable discrimination diagram for highly altered rocks such as those of the Hexenkopf Complex, suggests that these rocks were generated in a destructive plate-margin setting (fig. 2).

Quartz-oligoclase gneiss (Y^2lo) of the Losee Metamorphic Suite cores a synform in the Hexenkopf Complex on the west slope of Christines Hill and adjacent area where it unconformably overlies hornblende-clinopyroxene-quartz-plagioclase gniess (Y^2he). 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 direct observation in the field (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 in age.

The Losee Metamorphic Suite is unconformably overlain by a supracrustal sequence of quartzofeldspathic gneiss and amphibolite. Quartzofeldspathic gneiss in the 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 prominant compositional layering. The unit was interpreted to be metamorphosed graywacke (Drake, 1984). It is not abundant in the Hellertown quadrangle, but good outcrops can be seen on the east slope of Focht Hill near Campbell Pond. Bodies were also mapped on the Kohlberg and the Swoveberg.

Potassic feldspar gneiss (Y^2k) is abundant in the Hellertown 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 Green Hill.

Sillimanite-bearing gneiss (Y^2s) is not abundant in the Hellertown quadrangle, but excellent outcrops can be seen on the ridge west of the WGPA radio tower. It also crops out along the north border of the quadrangle west of the pipeline and on the Kohlberg south of Hellertown Reservoir. The unit has been interpreted to be a more aluminous phase of potassic feldspar gneiss (Y^2k) (Drake, 1969, 1984).

Amphibolite (Y^2a) is abundant in the Hellertown quadrangle, as it is throughout the Reading Prong. It has been found to have had more than one origin. Some is closely interlayered with rocks that are clearly metasedimentary and likely has a metasedimentary or perhaps volcaniclastic origin. In New Jersey, 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 or protoliths of amphibolite in this quadrangle cannot be determined.

Locally, such as in the Mocking Bird klippe, amphibolite has been migmatized. In these stromatic migmatites (Y^3ma), microperthite alaskite forms the leucosome and amphibolite the paleosome. At some places, migmatization has progressed to the point that the rocks could better be described as hornblende granite. Similar reactions have been described by Buckwalter (1958), Drake and others (1961), and Drake (1993).

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

In this quadrangle, the Byram Intrusive Suite consists of microperthite alaskite (Y^3ba), hornblende granite (Y^3bh) and biotite granite (Y^3bb). Microperthite alaskite is abundant in the Hellertown quadrangle, forming relatively small bodies throughout the crystalline terrane. The best outcrops are on the north slope of the Kirchberg, north of Switchback Road. Hornblende granite is very abundant throughout the crystalline terrane, with excellent exposures on South Mountain, the Kirchberg, and Granite Hill. Biotite granite is not abundant, but there are good exposures on the crest of the Swoveberg. Another body was mapped on the south slope of the Kohlberg along the Northampton-Bucks County line. 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).

Neoproterozoic Rocks

A sequence of arkose, ferrugenous quartzite, quartzite conglomerate, metavolcanic(?) rocks, and metasaprolite was mapped along the Delaware River by Drake (1967). The rocks, named the Chestnut Hill Formation, differ from the other metasedimentary and metavolcanic rocks of the Reading Prong in that bedding can be recognized, they have not been so homogenized as to lose their clastic parenthood, and they are at a much lower metamorphic rank. For these reasons, these rocks were interpreted to be of Neoproterozoic age (Drake, 1984). The rocks here mapped as Chestnut Hill Formation (Zc) on the northeast nose of South Mountain south of Bethlehem are identical to the arkose rocks along the Delaware River as illustrated by Drake (1984, fig. 21). They, therefore, are interpreted to be of Neoproterozoic age.

An altered metadiabase dike (Zd) crops out on the north slope of South Mountain about 1700 feet east of the west boundary of the quadrangle. Similar dikes were mapped on the basis of float on the western nose of the Kohlberg, the north slope of the Kirchberg, and on Christines Hill. These rocks are interpreted to be Neoproterozoic in age because they are altered and have intruded only Mesoproterozoic rocks. In addition, they have been enriched in TiO_2 and P_2O_5 (table 2), as have Neoproterozoic rocks elsewhere in the Appalachians (Puffer and others, 1991; Volkert and Puffer, 1995). In addition, they appear to belong to the intermediate P_2O_5 diabase suite of the New Jersey Highlands (Volkert and Puffer, 1995). If the above interpretations are correct, the dikes were emplaced during the rifting event related to the opening of the Iapetus Ocean.

Lower Paleozoic Rocks

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

Lehigh Valley Sequence

Rocks of the Lehigh Valley sequence occur in the footwall of the Black River thrust fault and constitute the cover rocks of the Musconetcong nappe (MacLachlan, 1979, 1983; Drake, 1993, in press b). Lehigh Valley rocks in this quadrangle include the Hardyston Quartzite (Ꞓh), Leithsville Formation (Ꞓl), and Allentown Dolomite (OꞒa).

The Hardyston Quartzite was mapped largely on the basis of float, but there are excellent outcrops on Bitts Hill, the unnamed mountain east of Cooks Creek, and particularly in the Springtown klippe. An especially important exposure east of Springtown along Route 212, at BM 298, shows several alternations of arkose and arkosic conglomerate with clean quartzite that presumably record the Iapetian rift-drift transition.

At the type locality of the Leithsville Formation there are few outcrops and the rocks are severely deformed. There are, however, excellent exposures in the Cooks Creek Valley east of Springtown and along the Lehigh River in the Freemansburg area. Good exposures of Allentown Dolomite can be seen along the Lehigh River and along the east bank of Saucon Creek.

Schuylkill Sequence

Rocks of the Schuylkill sequence occur in the hanging wall of the Black Run thrust fault and constitute the cover sequence of the Irish Mountain nappe (MacLachlan, 1979, 1983; Drake, 1993, in press b). Schuylkill rocks in this quadrangle include the Hardyston Quartzite (Ꞓh), Leithsville Formation (Ꞓl), Allentown Dolomite, Stonehenge Formation (Os), Rickenbach Dolomite (Or), Epler Formation (Oe), and Jacksonburg Limestone (Oj).

Good outcrops of Hardyston Quartzite can be seen on the western extension of Church Hill. The Leithsville Formation of the Schuylkill sequence does not crop out in the Hellertown quadrangle but was mapped on the basis of float in a horse along the Colesville fault. The Allentown Dolomite of the Schuylkill sequence cannot be divided in the Hellertown quadrangle. The unit can be best seen on the west bank of Saucon Creek north of Hellertown. The Stonehenge Formation, Rickenbach Dolomite, and Epler Formation can be seen on the west bank of Saucon Creek west of Bingen. The Jacksonburg Limestone crops out on the golf course north of Saucon Hill.

Mesozoic Rocks

Bedded rocks of the Passaic Formation are best exposed in the southeastern part of the quadrangle. Outcrops of claystone and mudstone (TRp) are especially abundant along Cooks Creek and its tributaries. Red sandstone (TRps) and gray sandstone (TRpsg) is abundant at and north of Pleasant Valley. Limestone fanglomerate (TRpl) crops out at two places near the western termination of the Triassic border fault. Quartzite fanglomerate (TRpq) is poorly exposed, but outcrops in the Flint Hill fan can be seen along a country road about 0.7 mi south-southeast of Leithsville. Here the fanglomerate contains small clasts of Mesoproterozoic rocks and dolomite as well as cobbles and pebbles of quartzite. Much of the rock is malachite stained. Diabase (Jd) of the Haycock sheet and its hornfels (TRph) collar crop out in the southeastern corner of the quadrangle. A chemical analysis of diabase from this sheet is given in table 2. It is of the Yorkhaven type of Smith and others (1975). Its difference from Neoproterozoic metadiabase is apparent. Diabase of the Shelly intrusion crops out in the southwestern corner of the quadrangle. The rock is well exposed in three quarries on the east margin of the pluton. Hornfels does not crop out, but was mapped on float.

Quaternary Deposits

The pre-Wisconsinan glacial deposits in this quadrangle were interpreted to be of Illinoian age by Leverett (1934) and were called Mercer drift by Berg and others (1983). The deposits of drift in the Saucon Valley, which are as much as 40 feet thick, were thought to constitute the Illinoian terminal moraine (Leverett, 1934).

Structural Geology

The Mesoproterozoic rocks were first deformed during the Mesoproterozoic Grenville orogeny (~ 1 Ga). They were later deformed along with their early Paleozoic cover during the Ordovician Taconic and late Paleozoic Alleghanian orogenies. The Mesoproterozoic rocks acted as a rigid basement plunger during the Paleozoic deformations and, therefore, constitute the newly defined raetide tectonic facies of Hsü (1995), that is structures dominated by rigid-basement thrusting. The lower 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. At most places, these planar elements are nearly parallel but in some outcrops foliation roughly paralleling layering on the limbs of small early folds, passes through the fold hinges rather than wrapping around them. This evidence, as well as the lens-shaped map units, suggests regional transposition. All mapped folds deform both layering and foliation, so none are first phase folds.

There are several F_2 folds on South Mountain that are upright and trend northwest. F_2 folds on the Green Hill-Christines Hill massif are either upright or are overturned to the west. These folds were refolded by nearly east-trending upright or overturned to the south F_3 folds. F_2 folds on the Kirchberg are overturned to either the north or south, or are upright. Because of refolding, they trend either north-northeast or nearly north. They are refolded by northeast-trending upright folds. F_2 folds on the

Kohlberg and its eastern extension are either upright or are overturned to the northwest. They trend northeast to nearly north. F_2 folds on Bitts Hill and the mountain east of Cooks Creek are overturned to the north and trend east-northeast.

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). At least five major nappes are known, from west to east and highest to lowest, they are the Lebanon Valley, the Applebutter, the Irish Mountain, the Musconetcong, and the Lyons Station. These nappes constitute a crystalline duplex, which is probably the northeastern extremity of a crustal duplex beneath the Newark basin and the Piedmont (Drake, 1991, in press b).

Rocks of the Applebutter, Irish Mountain, and Musconetcong nappes crop out in the Hellertown quadrangle. The Applebutter is separated from the Irish Mountain by the Applebutter thrust fault and the Irish Mountain from the Musconetcong by the Black River thrust fault.

Thrust Faults

Ten north-northwest-directed thrust faults emerge in the Hellertown quadrangle. Two other thrust faults are blind. The Applebutter, the highest emergent thrust fault in the hanging wall of the Black River thrust fault, has placed Mesoproterozoic rocks and Hardyston Quartzite onto Allentown Dolomite. Its trace is marked by mylonitic foliation. That the thrust sheet is underlain by carbonate rocks is proved by water well W-1, which bottomed in carbonate rock at a depth of 340 feet (Wood and others. 1972). A similar relation was documented in areas to the west (Drake, 1993, in press c; D.B. MacLachlan, Pennsylvania Geological Survey, written commun., 1980). In addition, neither Church Hill or Saucon Hill have an associated aeromagnetic anomaly (Bromery and others, 1959), therefore, the outcropping Mesoproterozoic rocks constitute thin sheets. The rocks in the hanging wall of the Applebutter thrust fault constitute the Applebutter nappe (Drake, 1973, 1993, in press b and c; Smith and Barnes. in press). The definition of the Applebutter nappe is helped by the much higher content of radioactive minerals in its rocks than in the other crystalline rocks of the Durham and Reading Hills (Smith and Barnes, in press).

The Saucon thrust fault has placed Allentown Dolomite onto Epler Formation and Jacksonburg Limestone. In the Allentown West quadrangle to the west (Drake, in press c), it disrupts major folds in the lower Paleozoic rocks in the Saucon Valley. It does not crop out, but the fault has been proved by core drilling (Callahan, 1968). The Saucon thrust fault appears to be cut off by the Black River thrust fault or the Haupts Mill thrust fault at Bingen. This relation, however, cannot be observed because of the thick cover of glacial deposits.

The Black River thrust fault has placed rocks of the Schuylkill sequence onto those of the Lehigh Valley sequence, and is the bounding fault between the Irish Mountain and Musconetcong nappes. Most of its trace in this quadrangle is obscured by glacial deposits. On the north slope of South Mountain it has placed Mesoproterozoic rocks onto Leithsville Formation. Near Bingen in the Saucon Valley, it cuts off an overturned syncline in Schuylkill sequence rocks and rocks in both the hanging wall and footwall are strongly deformed. North of Hellertown, Allentown Dolomite in both the hanging and footwall are strongly deformed. South of Leithsville, the Black River thrust fault is overlain by the Triassic Flint Hill fan. Rocks of the Leithsville Formation in its footwall are strongly deformed, and are characterized by bedding transposed into the schistosity. Folds plunge about parallel to the apparent dip direction of the fault. A highly generalized interpretation of the configuration of the Black River thrust fault in the subsurface beneath the Saucon Valley is given in section B-B'.

The Emmaus thrust fault is blind beneath South Mountain. It was projected into this quadrangle from the Allentown East quadrangle to the west (Drake, in press c). A horse of Leithsville Formation occurs between the Emmaus and Black River thrust faults.

The Black River thrust fault is cut by the Colesville fault. The Colesville fault was interpreted to be a normal fault by Miller and others (1941) and Callahan (1968) because core drilling proved that it is steep, and that it has brought younger rocks onto older rocks. It was interpreted to be a steep thrust fault by Drake (1969). It is here was interpreted to be an out-of-sequence thrust fault that has broken previously deformed rocks (Drake, 1993). Many similar out-of-sequence thrust faults have recently been mapped in New Jersey (Drake and others, 1996). The Colesville appears to be the same fault that was mapped by Drake (1967a) and Aaron (1975) as the Whippoorwill thrust fault in areas to the northeast.

The Colesville fault does not crop out, but its trace is marked by mylonitic foliation. Its continuation between South Mountain and Green Hill is supported by an uninterrupted aeromagnetic gradient (Bromery and others, 1959). The western extremity of the Colesville fault is decorated by a horse of Leithsville Formation (see section B-B').

The Musconetcong is the highest thrust fault in the footwall of the Black River thrust fault. It is a major thrust fault and has been mapped over a distance of 67 miles from this quadrangle to the Stanhope area in New Jersey (Drake and others, 1996). It can be observed in outcrop in the Riegelsville quadrangle to the east (Drake and others, 1967) and in a railroad tunnel in New Jersey (Drake, 1967b). It has been confirmed by core drilling at several places in New Jersey (Drake and others, 1994) and in the Riegelsville quadrangle (Drake and others, 1967). Everywhere it has brought Mesoproterozoic rocks, and in places, Hardyston Quartzite, onto carbonate rocks.

The Musconetcong thrust sheet is quite thin in this quadrangle. Mylonitic Mesoproterozoic rocks were exposed in a basement excavation on the ridge to the east of Cooks Creek. A well drilled at this site bottomed in carbonate rock at a depth of 280 feet. Bitts Hill and the small area of Mesoproterozoic rock and Hardyston Quartzite farther to the west may actually be klippen, as only severely deformed Leithsville Formation crops out in the Cooks Creek valley between the outcropping Mesoproterozoic rocks. If so, their trailing edges are buried beneath Triassic rocks of the Newark basin.

The Haupts Mill thrust fault has placed Leithsville Formation onto Mesoproterozoic rocks and Hardyston Quartzite, near the east boundary of the quadrangle. The trace of the fault is marked by mylonitic Mesoproterozoic rocks both in outcrop and float, and the hill slope north of Leithsville is littered with both mylonitic Mesoproterozoic and carbonate rocks. The Haupts Mill thrust fault appears to join, or be cut off by the Black River thrust fault, but the relations are totally obscured by glacial deposits.

The mountain mass of the Kohlberg, Swoveberg, Kirchberg, Focht Hill, Granite Hill, and an unnamed mountain farther north constitutes a large, but faulted, crystalline massif. The crystalline rocks of this massif were calculated to have a thickness of about 4000 feet on the basis of aeromagnetic data (Bromery, 1960). The Hellertown thrust fault bounds this crystalline massif, which in places, also contains some Hardyston Quartzite. The southern nose of the Kohlberg contains fairly abundant mylonitic Mesoproterozoic rocks, and the northern nose has an outcrop of mylonitic microperthite alaskite. There is scattered float of Mesoproterozoic mylonitic rock along the north slope of the Swoveberg toward Wassergass. Two klippen in the valley of Silver Creek confirm the thrusting. An excavation for a new basement briefly exposed mylonite on the nose of the Kirchberg just east of New Jersey Avenue. To the east, the Mocking Bird klippe could be mapped because float of transposed

Leithsville Formation was found along the road through the saddle in the ridge. Outcrops of north-dipping Leithsville Formation and a tiny klippe were mapped in the valley of East Branch. Conclusive evidence for a north-dipping thrust fault was found near the gas line pumping station north of East Branch. Here, mylonitic Mesoproterozoic rock clearly overlies mylonitic carbonate rock. The principal attitude of mylonitic foliation is N. 55° W. 35° NE. These exposures were destroyed by the construction of Interstate Route 78 (not shown on the base). Mylonitic Mesoproterozoic rock was observed overlying mylonitic carbonate rock in a gas pipeline trench near the previously described outcrop. The mylonitic foliation here had the attitude N. 65° W. 35° NE.

Another exposure of mylonitic Mesoproterozoic rocks overlying carbonate rocks was observed beneath a collapsed flume on the east bank of a tributary to East Branch about 500 feet north of their confluence. Here the mylonitic foliation had the attitude N. 50° W. 30° NW. A minor amount of carbonate rock was found in the draw to the south.

Hornblende granite and Hardyston Quartzite in the Steel Plant klippen are totally surrounded by Leithsville Formation. The Round House schuppen zone, first recognized by D.M. Fraser (in Miller and others, 1939), is a complex klippe consisting of several slices of mylonitic Mesoproterozoic and carbonate rocks. The Hellertown thrust fault along the Lehigh River has emplaced Mesoproterozoic rocks onto highly deformed Leithsville Formation.

The Raubsville thrust fault cuts the Hellertown thrust fault, and has placed carbonate rock onto carbonate rock and Hardyston Quartzite onto carbonate rock, Hardyston Quartzite, and Mesoproterozoic rocks. Its trace is marked by a float of mylonitic Hardyston Quartzite and Mesoproterozoic rocks. It has splayed and captured a large horse of Mesoproterozoic rock (see section A-A'). Its western extension from Polk Valley is not well constrained, but it was drawn through a large quarry on Saucon Creek about 1200 feet south of Friedensville Road. Here, the rocks are severely deformed and at least four thrust surfaces are obvious. Fold rotations in the upper plate of these faults confirm thrust movement. The Raubsville thrust fault is interpreted to be cut off by the Black River thrust fault, but the actual relations are totally obscured by glacial deposits.

The Rittersville thrust fault has placed Leithsville Formation onto Allentown Dolomite. Rocks in both its hanging wall and footwall are strongly deformed.

Another thrust fault was recognized in outcrop along the northern boundary of the quadrangle. It, however, was not mapped by Aaron (1975) in the Nazareth quadrangle to the north.

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

Folds

Only a few folds were mapped in the lower Paleozoic rocks because of the heavy glacial cover. Most of these folds have an axial surface cleavage, are generally overturned, and are thought to have formed during nappe emplacement. Those in rocks of the Musconetcong nappe are termed Musconetcong folds following Drake and Lyttle (1985). The syncline cored by Jacksonburg Limestone in the Saucon Valley is in the Irish Mountain nappe and is considered to be an Irish Mountain fold following Drake (1987). It is likely that the nappes and the folds therein formed during the same event, so the folds are likely of the same age. The dual terminology is retained, however, to be consistent with previous publications.

Three northeast trending folds were mapped along the Lehigh River. These folds have the altitude of Manunka Chunk folds as defined by Drake and Lyttle (1985) and are here considered to belong to that fold phase.

Mesozoic Deformation

The Triassic border fault could be mapped from the eastern border of the quadrangle to about Route 212-412. Farther west, there is no evidence of faulting. It is possible, however, that the border fault is a growth fault and is hidden beneath the Flint Hill fan.

Four north-northwest to nearly north trending folds were mapped in rocks of the Passaic Formation. Perhaps these formed during the emplacement of the Haycock diabase sheet.

Time of Deformation

Time of deformation is a major concern in Appalachian geology. Most geologists think that the regional nappes formed during the Taconic orogeny (Drake and others, 1989). If this is correct, the Musconetcong and Irish Mountain fold phases are Taconic. Lash (1982, 1987) presented evidence that the first fold phase in the area to the west, which I correlate with the Musconetcong and Irish Mountain folds, predates the deposition of Upper Ordovician molasse. This supports the idea that Musconetcong and Irish Mountain folds date from the Taconic orogeny. Lash (1982) also found that his D_3 folds (Manunka Chunk folds as used herein) have deformed both pre-Silurian and Silurian rocks, and therefore, must be Alleghanian in age. Manunka Chunk folds clearly deform slaty cleavage in the Martinsburg Formation (Drake and Lyttle, 1985; Drake, 1987, 1993). This suggests that the slaty cleavage is Taconic in age. In New Jersey, slaty-cleaved Martinsburg Formation occurs as xenoliths in Late Ordovician intrusive rocks (Rowlands, 1980; Ratcliffe, 1981; Drake and Monteverde, 1992) showing that the cleavage in the Martinsburg must be Taconic. Other geologists, such as Epstein and Epstein (1969) present evidence suggesting that cleavage in their areas formed during the Alleghanian orogeny. Recently, mica from the Pen Argyl Member of the Martinsburg Formation at Lehigh Gap, Pa., about 16 miles to the north, was interpreted to be Permian in age (Wintsch and 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? Until this question is answered, one can only speculate on the time of deformation.

The Musconetcong thrust fault has always been interpreted to be a Taconic structure (Drake, 1969; Drake and Lyttle, 1985). The Black River thrust fault is also probably a Taconic structure as are the Applebutter and Hellertown thrust faults. Most of the other, if not all, emergent thrust faults are probably Alleghanian in age. Thrust faults that have placed younger rocks on older rocks, such as the Colesville, must be.

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Table 1.--Chemical analyses of some rocks of the Hexenkopf Complex (weight percent)

	1	2	3	4
Major oxide composition (weight percent)				
SiO_2	54.2	52.0	72.4	48.3
Al_2O_3	10.9	9.2	5.9	11.4
Fe_2O_3	7.4	10.7	5.8	10.6
CaO	14.1	17.6	9.0	20.4
MgO	6.5	6.4	3.9	5.0
Na_2O	3.3	0.4	1.5	0.2
K_2O	1.3	0.6	0.5	---
TiO_2	1.0	0.6	0.5	0.6
MnO	0.2	0.2	0.1	0.2
P_2O_5	0.2	0.2	0.2	0.2
LOI	1.4	1.1	0.5	0.8
Total	100.5	99.0	100.3	97.7
Trace-element abundances (parts per million)				
Hf	2.5	2.4	2.2	2.5
Ta	0.3	0.3	0.6	0.1
Th	1.7	3.3	2.5	2.3

Analyses courtesy of R.C. Smith, II, Pennsylvania Geological Survey

Description of samples

1. Hornblende-plagioclase gneiss from outcrop of east slope of Hexenkopf about 800 feet southeast of Hexenkopf Rock at Lat. 40°36'56"N., Long. 75°14'26"W., Riegelsville 7.5-minute quadrangle (Drake and others, 1967)
2. Epidote-rich, hornblende-plagioclase gneiss from outcrop about 1200 feet south-southwest of Hexenkopf Rock at Lat. 40°36'54"N., Long. 75°14'32"W., Riegelsville 7.5-minute quadrangle (Drake and others, 1967)
3. Hornblende-plagioclase gneiss from outcrop on southeast slope of Christines Hill about 2250 feet N.15°E. of the intersection of Hexenkopf and Kich Line Roads at Lat. 40°36'40"N., Long. 75°15'24"W., Hellertown 7.5-minute quadrangle.
4. Epidote-hornblende-plagioclase gneiss from outcrop on ridge crest about 800 feet south of Hexenkopf Rock, Riegelsville 7.5-minute quadrangle

Table 2.--Chemical analyses of some diabase (weight percent)

	1	2
SiO_2	50.2	52.2
Al_2O_3	12.6	14.5
Fe_2O_3	4.5	0.8
FeO	9.2	8.7
MgO	5.0	6.8
CaO	4.7	11.5
Na_2O	3.3	2.0
K_2O	1.8	0.5
H_2O+	3.1	0.5
H_2O-	0.6	0.2
TiO_2	3.3	1.2
P_2O_5	0.8	0.2
MnO	0.2	0.2
CO_2	0.3	---
Total	99.6	99.3

Rapid rock analysis performed in the laboratories of the U.S. Geological Survey

Description of Samples

1. Altered Neoproterozoic metadiabase from outcrop on South Mountain Drive about 1000 feet west of its intersection with Hayes Street, South Mountain at Lat. 40°36'16", Long. 75°22'11"W.
2. Jurassic diabase of the Haycock sheet from an outcrop along County Road about 2200 feet southwest of Haycock Creek, southwest corner of the Riegelsville quadrangle (Drake and others, 1967) at Lat. 40°30'46"N., Long. 77°14'15"W.

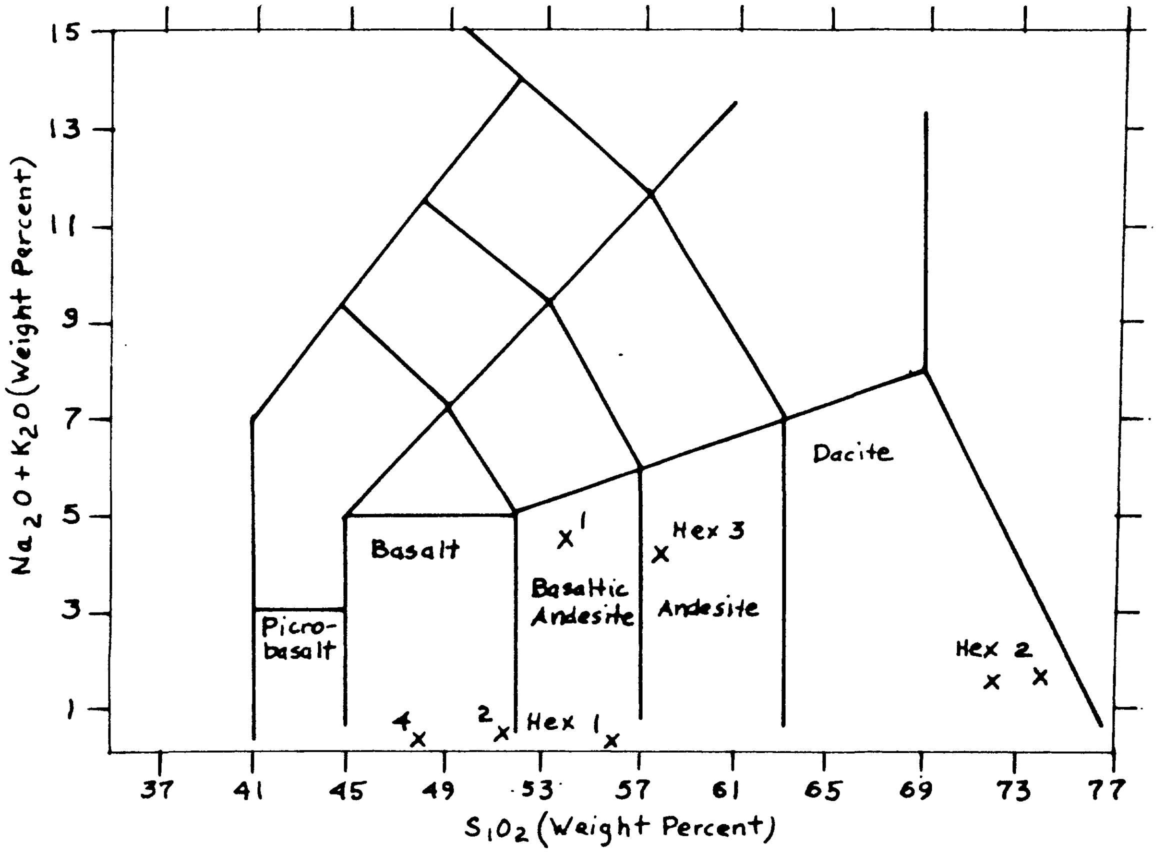


Figure 1.--Total alkali-silica (TAS) plot (Le Bas and others, 1986) of some rocks from the Hexenkopf Complex. Samples 1, 2, 3, and 4 from table 1. Samples Hex 1, 2, and 3 from Drake (1984, table 12).

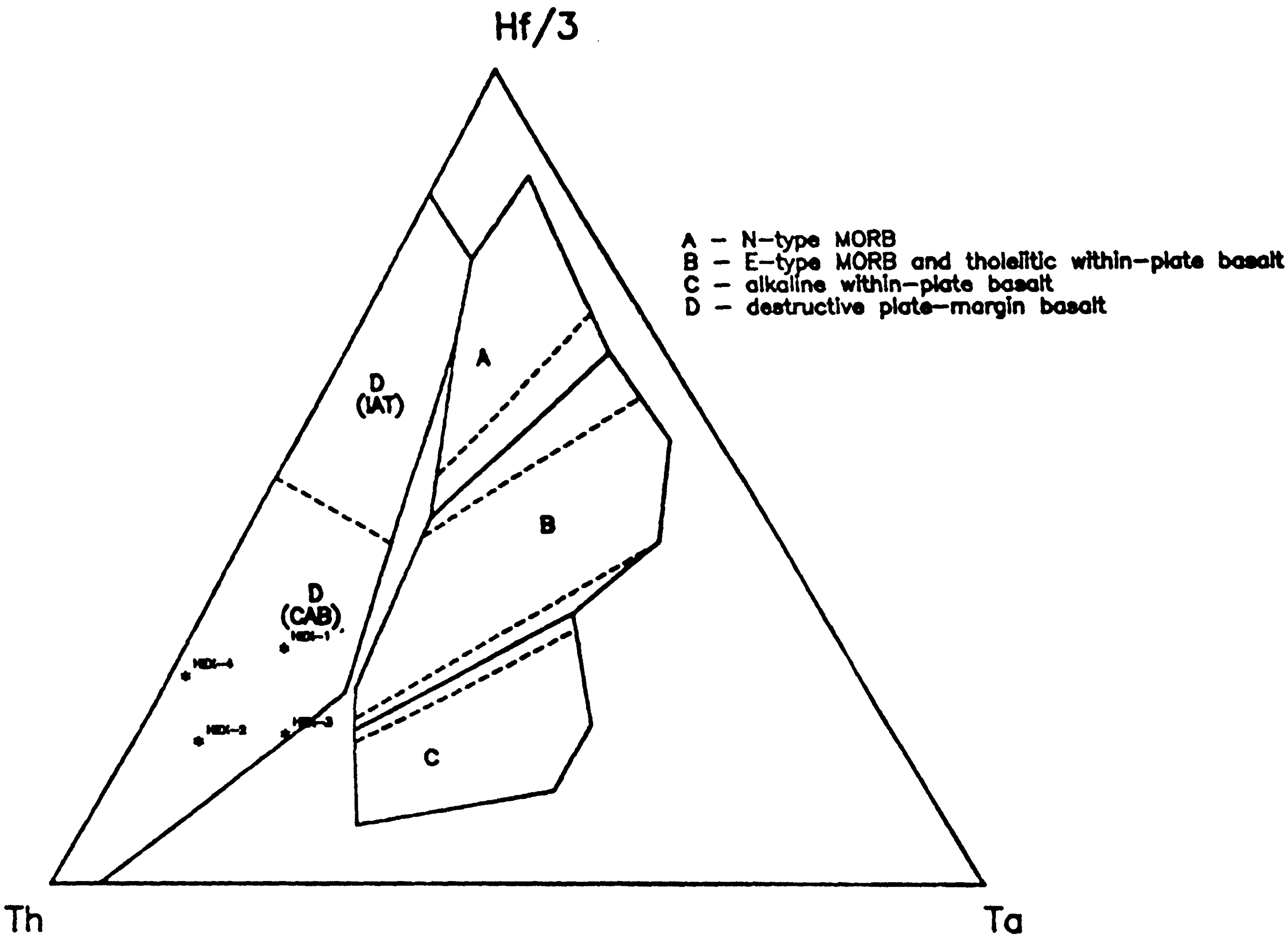
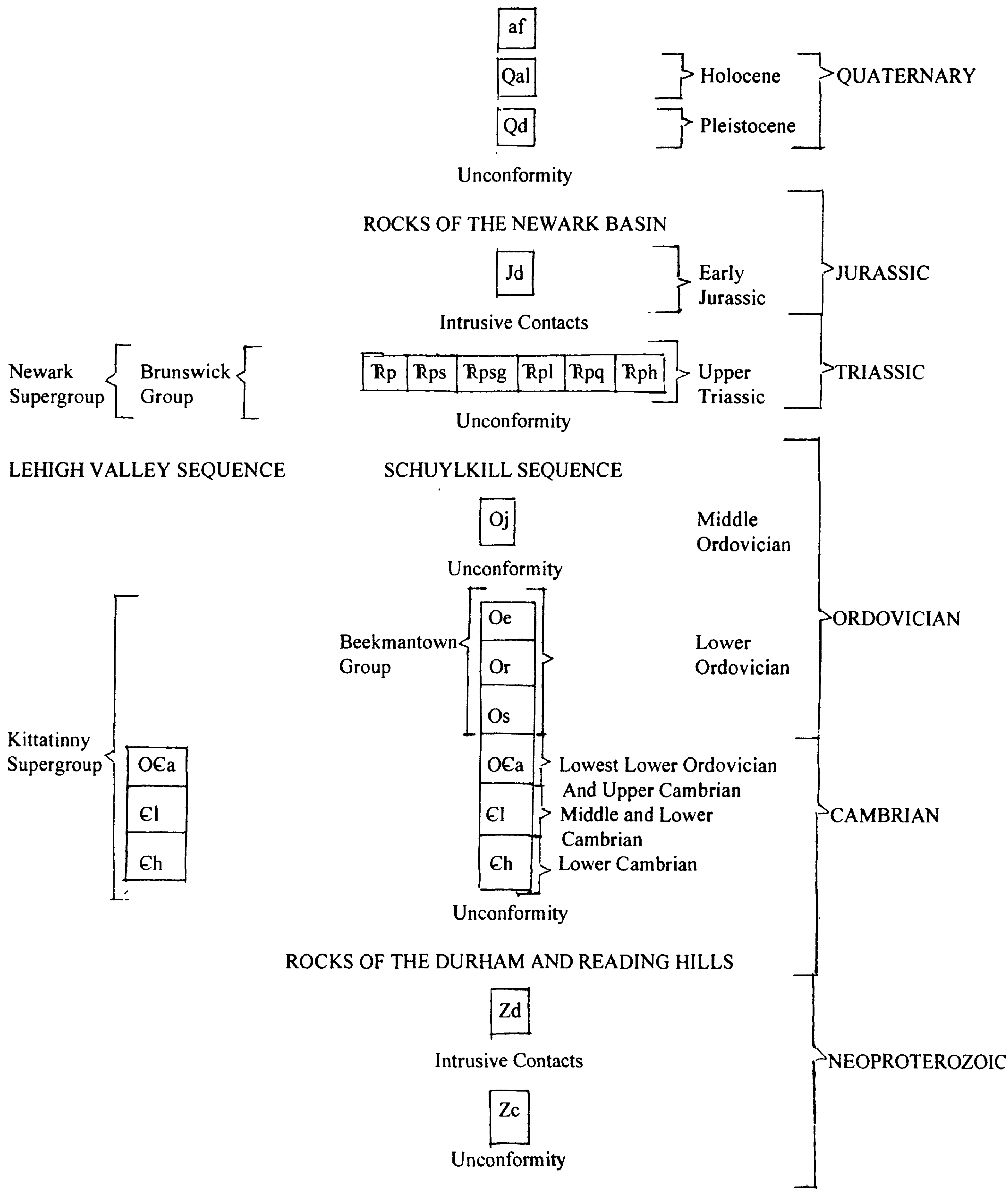
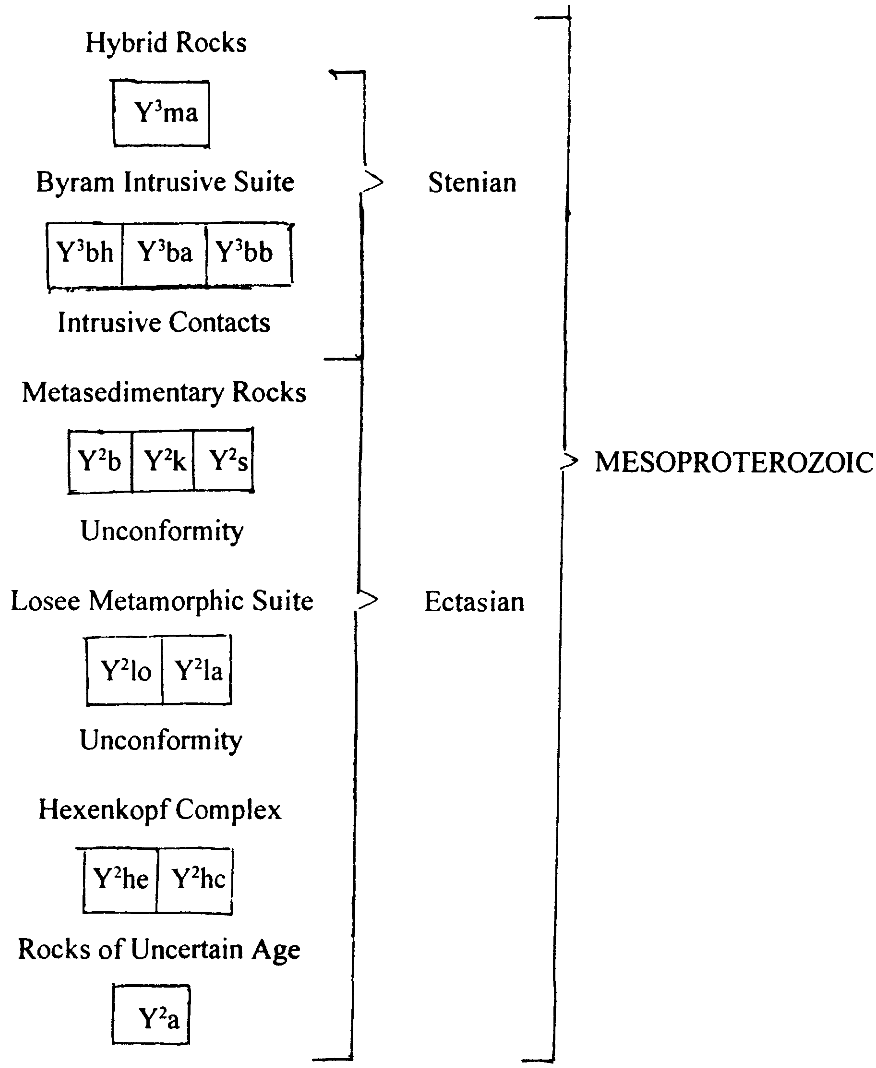


Figure 2.--Th-Hf-Ta plot (Wood, 1980) plot of some rocks of the Hexenkopf Complex.

CORRELATION OF MAP UNITS[1]




Hybrid Rocks
Y3ma
Byram Intrusive Suite
Y3bh
Y3ba
Y3bb
Intrusive Contacts
Metasedimentary Rocks
Y2b
Y2k
Y2s
Unconformity
Losee Metamorphic Suite
Y2lo
Y2la
Unconformity
Hexenkopf Complex
Y2he
Y2hc
Rocks of Uncertain Age
Y2a
Stenian
Ectasian
MESOPROTEROZOIC

DESCRIPTION OF MAP UNITS

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

af Artificial fill

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) clay, silt, and medium to coarse sand in terraces above the Lehigh River and poorly sorted, unstratified and unconsolidated grayish-orange (10 YR 7/4) to light-reddish-brown (3 YR 5/6) till

ROCKS OF THE NEWARK BASIN

Jd Diabase (Early Jurassic)--Medium- to coarse-grained, dark-gray (N3) to grayish-black (N2) quartz-normative, high-titanium diabase that has a typical diabasic texture, and is composed largely of grayish-green calcic plagioclase and green augite

Passaic Formation (Upper Triassic) (Olsen, 1980)

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

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

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

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

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

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

ROCKS OF THE LEHIGH VALLEY SEQUENCE

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

€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

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

ROCKS OF THE SCHUYLKILL SEQUENCE

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

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

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

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

O€a Allentown Dolomite (lowest Lower Ordovician and Upper Cambrian) (Wherry, 1909)--Cannot be divided in this quadrangle because of poor exposure

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

Ꞓh Hardyston Quartzite (Lower Cambrian) (Wolff and Brooks, 1898)--Is similar to the Hardyston Quartzite in the Lehigh Valley sequence (see above). Unconformably overlies Mesoproterozoic rocks

ROCKS OF THE DURHAM AND READING HILLS

Zd Metadiabase (Neoproterozoic)--Medium-dark (N4) to dark-gray (N3), fine-grained to aphanitic, highly altered dikes

Zc Chestnut Hill Formation (Neoproterozoic) (Drake, 1984)--Pale-red-purple (5 RP 6/2), pebbly meta-arkose containing clasts of microcline, microcline-microperthite, sericitized plagioclase and quartz set in a sand-sized matrix of similar composition and micaceous quartzite, the sedimentary fabric of which has been completely destroyed

Hybrid Rocks

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

Byram Intrusive Suite (Stenian) (Drake, 1984)

Y^3bh Hornblende granite--Medium- to coarse-grained, grayish-pink (5 R 8/2) to light-gray (N7) to light brownish-gray (5 YR 6/1) gneissoid to indistinctly foliated granite and sparse granite gneiss composed principally of microcline microperthite, quartz, oligoclase, and hornblende. Contains unmapped bodies of pegmatite and amphibolite. Unit has a U-Pb age of about 1090 Ma (Drake and others, 1991a)

Y^3ba Microperthite alaskite--Medium- to coarse-grained, grayish-pink (5 R 8/2) to light-brownish-gray (5 YR 6/1), gneissoid to indistinctly foliated alaskite composed principally of microcline microperthite, quartz, and oligoclase. Contains unmapped bodies of amphibolite

Y^3bb Biotite granite--Medium- to medium-coarse-grained, grayish-pink (5 R 8/2) to pale-yellowish-brown (10 YR 6/2), moderately foliated gneissoid granite composed of microcline microperthite, quartz, oligoclase, and biotite. Unit contains many layers and discontinuous bodies of biotite-quartz-feldspar gneiss (Y^2b). It is interpreted to result from the reaction of microperthite alaskite (Y^3ba) with biotite-quartz-feldspar gneiss (Y^2b)

Metasedimentary Rocks (Ectasian)

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^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. Parts of the unit are magnetite-rich and resemble metamorphosed iron-formation and may have an exhalative component (Drake, 1990). In places, unit has been mobilized to form sheets and irregular bodies of alkali-feldspar granite or quartz-rich granitoid

Y^2s Sillimanite-bearing gneiss--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

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 albite-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--Dark 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)

Rocks of Uncertain Origin

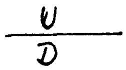
Y^2a Amphibolite (Ectasian)--Dusky-green (5 G 3/2) to grayish-black (N2), medium-grained rock composed of largely of hornblende and andesine. Some phases contain biotite, clinopyroxene, orthopyroxene, or magnetite

[1] The term "Neoproterozoic" follows the usage of Plumb (1991) and applies to rocks ranging in age from 1000 Ma to ~544 Ma (base of Cambrian following Bowring and others, 1993; and Landing, 1994). The terms "Mesoproterozoic," "Stenian," and "Ectasian" also follow the usage of Plumb (1991). Mesoproterozoic applies to rocks ranging in age from 1600 Ma to 1000 Ma, "Ectasian" to rocks ranging in age from 1400 Ma to 1200 Ma, and "Stenian" to rocks ranging in age from 1700 Ma to 1000 Ma.

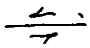
EXPLANATION OF MAP SYMBOLS

Contact--Dashed where approximately located; short dashed where inferred; dotted where concealed

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

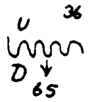


High-angle fault--U, upthrown side; D, downthrown side



Tear fault--Showing relative horizontal movement

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

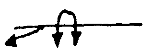


Fault seen in outcrop--Showing dip and relative motion

FOLDS

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

Antiform--Showing trace of crestline and direction of plunge



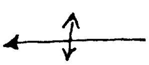
Overturned antiform--Showing trace of axial surface, direction of dip of limbs, and direction of plunge where known

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

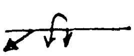
Overturned synform--Showing trace of axial surface, direction of dip of limbs, and direction of plunge where known

Folds of Paleozoic and Mesozoic age--Phases are named for geographic localities or for prominant major folds of that phase. Initials indicate phase, from older to younger (see text): IM and M, MC

Folds of Paleozoic and Mesozoic age



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



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

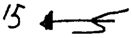
Syncline--Showing trace of trough line, direction of dip of limbs, and direction of plunge

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

MINOR FOLDS

 Minor anticline or antiform, showing plunge

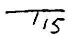
 Minor syncline or synform, showing plunge

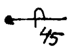
 Minor asymmetric fold--Showing bearing and plunge of axis and rotation sense viewed down plunge

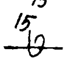
 Minor fold of cleavage--Showing plunge

PLANAR FEATURES
(May be combined with linear features)

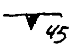
Strike and dip of beds--Ball indicates top known from sedimentary structures

 Inclined

 Overturned

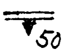
 Rotated more than 180°

Strike and dip of crystallization foliation

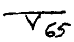
 Inclined

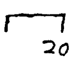
 Vertical

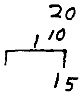
Strike and dip of mylonitic foliation

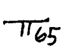
 Inclined

 Vertical

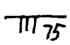
 Strike and dip of transposition foliation--Bedding rotated into parallelism with slaty cleavage

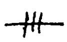
 Strike and dip of slaty cleavage

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

 Strike and dip of crenulation cleavage

Strike and dip of spaced cleavage

 Inclined

 Vertical

 Strike and dip of joints

LINEAR FEATURES

(May be combined with planar features)

10 Mineral lineation

Bearing and plunge of intersection of bedding and slaty cleavages

15 Inclined

Horizontal

10 Bearing and plunge of crenulations

15 Bearing and plunge of intersection of slaty cleavage and spaced cleavage

e 65 Bearing and plunge of elongation lineation

75 Bearing and plunge of striations

OTHER FEATURES

Magnetite deposit

Mine or quarry--l, limonite; m, magnetite; db, diabase; d, dolomite; s, saprolite; sh, shale

Gravel pit

Open cut

W-1 Water well

Location of chemically analyzed samples

Mesoproterozoic rocks (Drake, 1984): H-B-1-8B, analysis 6, table 10; H-C-3-7, analysis 7, table 10; H-B-3-2, analysis 8, table 10; H-A-5-10, analysis 1,table 12; H-A-6-12, analysis 2, table 12)

Hexenkopf Complex (reported herein). See table 1

Diabase (reported herein). See table 2