Williams Township
Northampton County, PA

GEOLOGIC SETTING AT THE CHRIN BROTHERS SANITARY LANDFILL, WILLIAMS TOWNSHIP, NORTHAMPTON COUNTY, PA

Prepared for:
Williams Township
Attn: Jennifer Smethers, Township Manager
655 Cider Press Road
Easton, PA 18042

November 13, 2013

Prepared by:
EMS Environmental, Inc.
4550 Bath Pike
Bethlehem, Pennsylvania 18017

EMS
ENVIRONMENTAL

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DRAKE (1999) GEOLOGICAL PAPER

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MICHAEL SERFES (PHD) RESUME

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Executive Summary

This independent geological evaluation was prepared at the request of Williams Township, Northampton County, PA by EMS Environmental, Inc (EMS). The major goal was to evaluate the geologic setting underlying the Chrin Brothers Sanitary Landfill, with a focus on the proposed eastern expansion area. This evaluation was based upon reviewing pertinent existing geologic information and inspecting geological materials collected at the landfill. Special attention was given to the 1988 Pennsylvania Municipal Waste Regulations specific to the carbonate geology exclusion criteria.

The Carbonate exclusion criteria: § 273.202 address areas where municipal waste landfills are prohibited and reads:

> (a) Except as provided in subsections (b) and (c), a municipal waste landfill may not be operated as follows (Note, there are18 instances). Number (7 of 18), Limestone or carbonate formation: In areas underlain by limestone or carbonate formations where the formations are greater than 5 feet thick and present at the topmost geologic unit. These areas include areas mapped by the Pennsylvania Geological Survey as underlain by these formations, unless competent geologic studies demonstrate the absence of limestone and carbonate formations under the site.

Based on the Drake (1967) geologic map of the Easton Quadrangle, the northern portion of the Chrin Landfill appears to be on the Leithsville Formation which is a carbonate unit comprised of dolomite. As part of Chrin's solid waste permit application for the repermitting of Fill Area 4 in 1989, an intensive geologic study was conducted by Applied Geotechnical and Environmental Service Corp, or AGES (1989), inpart to address the 1988 Carbonate exclusion criteria as described above. Their key findings were that the topmost geologic unit is not a carbonate formation, it is comprised of an unconsolidated highly weathered remnant of original bedrock called saprolite, and, because of complex fold geometry, the topmost unit was originally the non carbonate Hardyston Formation bordered by a thrust fault along Industrial Drive (Figure 5).

Based on inspections of grab samples collected during the drilling of MW-14 and continuous split spoon samples from MW-16, and other associated geologic logs describing the materials at and around the proposed eastern expansion area, EMS concludes that it is underlain by non-carbonate highly weathered unconsolidated saprolite. This saprolite was found to occur to a depth of at least 100 feet, final depth of DM-6 near the southwestern boarder of the expansion area, to over 260 feet in MW-16 near the northeastern boarder. It is interpreted to be the weathered remnants of the non-carbonate Hardyston and carbonate Leithsville Formations.

Based on the available data within the landfill footprint bounded by Industrial Drive, it was found that the depth to bedrock varies greatly and the shallowest dolomite encountered was at 103 feet below the land surface in monitor well DM-2.

The pH of groundwater from monitor wells can potentially be used as an indicator to differentiate water in contact with non-carbonate aquifer materials, which would generally have a lower pH, than that in contact with carbonate materials. Comparisons of pH of groundwater from monitor wells at the landfill with regional dolomite carbonate units, that include the Leithsville Formation, and, non-carbonate Precambrian Gneiss, show that the pH median of 6.5 from the monitor wells are more similar to that of the non-carbonate gneiss, median of 6.8, than the dolomite carbonate units in Northern Lehigh County, Sloto and Shaffer (1994), median 7.8, and in New Jersey, Serfes (2004), median 7.7 (Figure 9). Also, the pH from samples collected on March 15 and 16, 2012 in wells drilled by Chrin Landfill, MWs 14, 15, 16, 17 and 18, around the proposed eastern expansion area were 6.8, 5.8. 5.6, 6.0 and 5.6 respectively. On average, these pH values are more representative of non-carbonate aquifer material than carbonate.

Across Industrial Drive from the landfill, and just south of the electric sub station, dolomite was encountered within 22 feet of the land surface in MW 9a and local depressions consistent with karst topography exist. It must be noted however that this area was once quarried and differentiating between those depressions related to man's activities and those due strictly to natural processes may not be obvious. However, this area is not part of the landfill footprint and is over 3000 feet southwest of the proposed eastern expansion area.

EMS also found that the Civil and Environmental Consultants Inc. (CEC), bedrock geologic map in Figure 5, that reflects data and conclusions from the AGES (1989) report and the Drake (1967) geologic map with the inferred thrust fault, is out dated. Drake's (1999) reinterpretation dismisses the existence of his Drake (1967) inferred thrust fault within the existing landfill footprint, and we do not see significant evidence to support the projected CEC bedrock outcrop pattern for the Hardyston Formation that is much wider than what Miller and Others (1939), Drake (1967) or Drake (1999) proposed. Based on Drake's (1999) reinterpretation, we do not see the need to pursue the hunt for a major thrust fault in or around the landfill footprint.

Part 1: Background

1.1 Problem Statement and Approach

The interpretation of the geological setting under and around the Chrin Brothers Sanitary Landfill in Williams Township, Northampton County, PA has been controversial because of it's complexity. Geological studies conducted by Chrin Brothers to secure operating permits in fulfillment of PADEP requirements have been viewed by some community members as potentially biased. To resolve this debate, Williams Township contracted EMS Environmental, Inc. to review the existing geological data and independently draw a conclusion as to the geological setting under and around Chrin Landfill. The two professional geologists from EMS who worked on this geologic assessment are geologists, Dr. Donald Monteverde and Dr. Michael Serfes. This report is a summary of their findings based upon:

1. Reviewing available and applicable geologic and hydrogeologic information associated with the landfill.
2. Constructing a Google Earth kmz file using well and boring locations, depth drilled, geologic materials encountered and overlays of published geologic maps as an interpretive tool.
3. The inspection of geological materials kept at the Chrin Landfill that were collected during the installation of monitor wells 14 and 16 in the proposed eastern expansion area.
4. Consideration of Avery Drake's (1999) written re-evaluation of thrust fault locations in the Chrin Landfill area.
5. Comparison of pH values from the Chrin Landfill monitor wells with those from carbonate aquifers and non-carbonate Precambrian gneiss from similar geological settings in Pennsylvania and New Jersey.
6. Consideration of all available data from Chrin Landfill and the Committee to Save Williams Township was used to make a best professional judgment concerning the geologic setting under the Chrin Landfill.

1.2 Key Definitions

Bedrock[3] : The solid rock that underlies loose material, such as soil, sand, clay or gravel.

A bedrock geologic map depicts the types of solid rock that either are exposed at the surface, called an outcrop, or
underlie unconsolidated materials of varying thickness at the surface.

Geologic Formation and Unit[1]

Formation: The fundamental unit in the local classification of rocks into geologic units. Based on similar characteristics in lithology (rock type), which is the description of rocks on the basis of such characteristics as color, mineralogic composition, and grain size. (Therefore, a geologic formation is a geologic unit).

Gneiss[2]: rock formed by high grade (hot but not enough to melt the rock) regional metamorphic processes from pre-existing formations that were originally igneous or sedimentary rocks. It has alternating darker and lighter mineral bands that are a type of foliation (rock fabric) called gneissic banding. The non-carbonate Precambrian (older than 540 million years) crystalline rock forming most of the Morgan Hill upland is gneiss.

Limestone or Carbonate Formation[1]

Carbonate rocks: Rocks consisting mainly of carbonate minerals, which contain the carbonate radical (CO_3^{-2}) combined with other elements. Examples are limestone and dolomite.

Limestone: A sedimentary rock consisting mostly of calcium carbonate, $CaCO_3$, primarily in the form of the mineral calcite.

Dolomite: A sedimentary rock composed primarily of calcium-magnesium carbonate, $CaMg(CO_3)_2$.

Saprolite[3]: Soft, thoroughly decomposed and porous rock, often rich in clay, formed by the in-place chemical weathering of igneous, metamorphic, or sedimentary rocks. Common in humid and tropical climates. It is usually reddish brown (iron oxides) or grayish white (aluminum oxides) and contains structures present in the original rock from which it formed. Also note: that the carbonate minerals calcite and dolomite that characterize carbonate rocks are very soluble and are therefore rarely found in highly weathered saprolites.

1. http://pubs.usgs.gov/ha/ha747/pdf/definition.pdf
2. http://en.wikipedia.org/wiki/Gneiss
3. The American Heritage® Science Dictionary Copyright © 2005 by Houghton Mifflin Company. Published by Houghton Mifflin Company all rights reserved.

1.3 Geological Setting

In the area of the Chrin Brothers Sanitary Landfill, three geologic bedrock units, shown at the bottom of the stratigraphic column (Figure 1), are present at or near the land surface. These are, from older to younger, the Precambrian highly metamorphosed basement rocks (gneiss) that make up the Morgan Hill upland area, the overlying and younger sedimentary Hardyston Quartzite with an approximate 60 ft thickness near the Delaware River (Drake, 1999), and grading upwards, the slightly younger and much thicker sedimentary dolomite-rich Leithsville Formation (unit). Originally, the Hardyston Quartzite and the overlying Leithsville were deposited horizontally on the older gneiss. Subsequent compressional deformation starting with the Taconic Orogeny produced extreme folding and thrust faulting that sometimes resulted in sections of rocks ramping upwards creating duplex structures by the stacking of one sequence of geologic units on top of the same units. This process of deformation was repeated during the Alleghanian Orogeny. These multiple deformational events can make these geologic settings complex.

Figure 1 also describes each geologic unit's characteristics, environments of formation (if applicable), and, major tectonic compression mountain building events (orogeny's) they experienced. All these variables along with natural rock weathering and erosion resulted in each rock unit's present surficial aerial extent. Variable climate over millions of years led to their topographic expression and, in turn, their depth below residual weathered geological material at the land surface. Deformation features such as faults and folds derived from the tectonic events occur at microscopic to regional scales in these rocks.

1.4 Weathered Residual Overburden

The decomposition and disintegration of bedrock at or near the land surface is an ongoing process. In areas where erosion carries these weathered materials away at a rate equal to their formation, residual materials do not collect. However, in areas where erosion processes are less effective, residual weathered materials can remain behind. Saprolite is an example of residual materials that have remained in place and are found at varying depths throughout our region. Two local examples of saprolite residuum are given below. One is from an EPA superfund investigation conducted in Emmaus, PA in a geologic setting similar to the Chrin Landfill, and the other is the NUS superfund investigation that was conducted in the 1980's at and around the Chrin Brothers Sanitary Landfill.

A description of the geology underlying the Rodale Manufacturing Superfund Site in Emmaus, Lehigh County, Pennsylvania from a USEPA Superfund Record of Decision (EPA/ROD/R03-99/086 1999) states:

"The first bedrock unit encountered at the Site consists of carbonate rocks of the Leithsville Formation. Deep sections of weathered bedrock (saprolite) occur above the competent bedrock of the carbonate units of the Little Lehigh Creek Basin, overlain in some areas in the vicinity of the Site by glacial drift deposits, and generally capped with a soil loam horizon. The saprolite varies in thickness from 50 feet to more than 250 feet in the Site vicinity."

A similar description from an EPA Superfund Record of Decision associated with Chrin Landfill and called the Industrial Drive EPA ID: PAD980508493 OU01 Williams Township, PA (EPA/ROD/R03-86/028) states:

"Compression forces have generated deformation which has left the area with more or less parallel longitudinal folds consisting of crystalline rock overlain by sedimentary strata. These folds are broken by faults but tend to follow the general northeast-southwest trend of the strata. Extensive weathering of the Precambrian crystalline rock and Cambrian strata have left large clay deposits such as the one on which the Chrin site was constructed. "

Three borings drilled for well installations during that superfund investigation along the Chrin property boundary, going westward along Industrial Drive, include N-7 that encountered only saprolite to the final depth of 300 feet, N-8 that drilled through 92 feet of saprolite before encountering dolomite (carbonate rock) that continued to the final depth of 222 feet and N-2 that encountered only saprolite to a final depth of 203 feet.

Various thicknesses of recent non-carbonate glacial deposits are also found in Northampton County.

Part 2: Investigation Findings

2.1 Review of Previous Geologic Interpretations

One of the first comprehensive bedrock geologic maps of Northampton County was compiled by Miller and others (1939, revised 1966). It must be noted that bedrock geologic maps depict the types of solid rock that either are exposed at the surface, called an outcrop, or underlie unconsolidated materials of varying thickness at the surface. The part of that map in the vicinity of Morgan Hill and Chrin Landfill is shown in Figure 2. Shown is the extent of gneiss on Morgan Hill (pink) the Hardyston Quartzite (yellow), the Leithville Formation (light blue) and iron mine locations as crossed picks. These mines, described as mountain ores are confined to areas of weathered residual material of the Cambrian quartzite better known as the Hardyston Formation (see page 315 in Miller and others, 1939). Therefore, the aerial extent of the weathered residual material that originally comprised the Hardyston Formation can be defined, at the scale of this map, by the location of those iron mines. Note there are no presumed faults on the north side of Morgan Hill in Miller and others (1939, revised 1966) interpretation, Figure 2.

The bedrock geologic map and interpretation by Drake (1967) in the Morgan Hill and Chrin Landfill area is shown in Figure 3. The major difference between this interpretation and Miller and others (1939) is that there is a thrust fault mapped on the north side of Morgan Hill. However, since the fault line shown as stippled, not continuous, it was inferred and therefore not directly observed. The location of this thrust fault, if one exists, has been reinterpreted by Drake (1999) to occur farther to the north in the Allentown Formation, not between the Hardyston and Leithsville Formations as originally proposed (Figure 4). In the 1999 report, Drake states on pages 249 to 250, "Abundant geologic mapping in eastern Pennsylvania and New Jersey since 1970 necessitates a new interpretation of the structural geology", and further in the same paragraph, "Those (referring to faults) on the north margins of the outcropping bodies of crystalline rock were incorrectly interpreted to be the Musconetcong thrust fault repeated by folding".

Other regional work includes Herman and Monteverde (1989) and Herman (1989) who investigated the deformational history of southwest NJ Highlands area and projections into Easton, PA region. In maps and cross sections those authors suggest no fault occurs across the Chrin Landfill and instead map a thrust fault farther to the north within the Allentown Dolomite (formation), which Drake's (1999) reinterpretation depicted a similar interpretation.

The Civil and Environmental Consultants, Inc. (CEC) geologic map shown in Figure 5 was based on the extensive data collected for the AGES report (1989) and the 1967 Drake interpretation. Therefore, from a structural geology interpretive perspective, it has inherent flaws due to the subsequent reinterpretation by Drake (1999).

The data in the AGES Report shows that a thick saprolite unit lies on top of competent bedrock under the Chrin Landfill. After reviewing that and other relevant data, Mr William Kochanov, a Senior Geologic Scientist and carbonate rock expert at the PA

Geoloical Survey agreed with that general conclusion in an email dated November 4, 2010, (Chrin Brothers Inc. 2012). The well or borehole identification and the associated geologic material encountered either at the final depth if no bedrock was encountered, or the bedrock type if encountered, is shown in Figure 6. In Figure 7 the depth to bedrock if encountered is shown. Depth to bedrock on the southern side of Industrial Drive varies from about 2 to over 292 feet below the surface. Samples collected during the drilling of MW-14 and MW-16 in 2012 in the proposed eastern expansion zone were inspected by EMS for this project and were determined to be non-carbonate saprolite to their final collection depths of 255 and 260 feet respectively (Figure 8).

The shallowest depth to carbonate bedrock below the Chrin Landfill is 103 feet at DM-2 along Industrial Drive. However, on the northern side of Industrial Drive, outside of the landfill disposal footprint, carbonate rock occurs at 30 feet in depth at MW-9, 22 feet at 9A and no bedrock was encountered to the final depth of 195 feet in N-6. These three wells are within several hundred feet of each other, mapped as Leithsville Formation and show a topographic depression in that area (shown best in figure 2). These observations are consistent with a karst feature but may actually reflect quarrying activity that took place there.

2.2 Hydrochemistry

The pH of groundwater from monitor wells can potentially be used as an indicator to differentiate water in contact with non-carbonate aquifer materials, which would generally have a lower pH than that in contact with carbonate materials.The concentration of hydrogen ions (H+) in water is routinely reported using a pH scale, which is derived by calculating the negative logarithm of the hydrogen ion concentration. The scale ranges from 0 (the most free hydrogen ions or extremely acidic) to 14 (least free hydrogen ion concentration or extremely alkaline). A pH of 7.0 is considered neutral.

The groundwater system is recharged by precipitation such as rain, snow and sleet. Precipitation is normally a dilute, acidic, oxidizing solution. Ambient atmospheric carbon dioxide concentrations produce carbonic acid in water yielding an acidic pH of about 5.7 in precipitation. Further acidification of precipitation in the atmosphere, yielding acid rain, can result from contact with sulfur and nitrogen compounds associated with the burning of fossil fuels.

Hydrogen ions in aqueous solution (water) readily react with carbonate minerals such as calcite and dolomite and much less so with silicate minerals like feldspars and others that comprise the gneiss. These are examples of chemical weathering reactions and their rate and effect depends on the solubility of the individual mineral, the length of time water is in contact with them and the surface area exposed to the solvent. Therefore, granulated loose dolomite will react much more rapidly in water than a single block of equal mass. As shown below in reaction (1) and (2), hydrogen ions associated with carbonic acid are consumed in reactions with calcite and dolomite and form a product called bicarbonate. These reactions increase the water's pH and alkalinity:

Calcite plus carbonic acid yields a calcium ion and two bicarbonate ions

$$(1)\ CaCO_3 + H_2CO_3 \rightarrow Ca^{+2} + 2HCO^-_3$$

Dolomite plus carbonic acid yields a calcium and magnesium ion and four bicarbonate ions

$$(2)\ CaMg(CO_3)_2 + 2H_2CO_3 \rightarrow Ca^{+2} + Mg^{+2} + 4HCO^-_3$$

Other minerals in aquifers are generally much more stable than carbonate minerals and therefore take longer to decompose, however, given enough time they will. Therefore, young newly recharged groundwater in geologic units that contain little or no calcite and/or dolomite, generally have a lower pH because hydrogen ions are not readily consumed in weathering reactions.

Comparison of pH measurements taken on January 18, 2012 of groundwater from 14 monitor wells (representing carbonate and non-carbonate wells) at the landfill with regional dolomite carbonate units (data included the Leithsville Formation) and, non-carbonate Precambrian Gneiss, show that the pH median of 6.5 from the monitor wells are more similar on average to that of the non-carbonate gneiss, median of 6.8, than the dolomite carbonate units in Northern Lehigh County, Sloto and Shaffer (1994), median 7.8, and in New Jersey, Serfes (2004), median 7.7 (figure 9). Also, pH values from samples collected on March 15 and 16, 2012 in wells drilled by Chrin Landfill, MWs 14 to18, around the proposed eastern expansion area have an even lower median of 5.7.

Part 3: Discussion

3.1 The Fault

Drake's (1999) reinterpretation places the inferred thrust fault farther north of Morgan Hill, in the Allentown Formation which as depicted would therefore locally exist on the northern side of Interstate 78 (Figure 4). It must be noted that no evidence for a fault under the Chrin Landfill was ever found and it's presumed existence was based on Drake's (1967) conceptualization of the structural geological setting (Figure 3), which he has since reinterpreted. Therefore, based on the above, it is unlikely a thrust fault as depicted by Drake (1967) exists under the landfill.

3.2 The CEC Map

The CEC geologic map shown in Figure 5 was based on the extensive data collected for the AGES report (1989) and the Drake (1967) interpretation that included an inferred thrust fault (Musconetcong Fault) between the Hardyston and Leithville Formations. This map was constructed on the assumption that a near surface 90 +/- degree fold with a northeast axis exists under the landfill and resulted in the Hardyston Formation forming the upper part of a northwest dipping fold limb thereby encompassing the entire near surface Chrin Landfill site. However, after reviewing the AGES report and inspecting the split spoon core samples from MW-16, we do not find convincing evidence that such a large scale fold exists. Also, the location of the iron mines associated with mountain ores in the Hardyston Formation (Miller and others, 1939) do not support this presumption as the mine locations were confined to a narrow band along the southern side of the Chrin Landfill, not all the way up to Industrial Drive. The inferred thrust fault shown on the CEC geologic map as occurring along Industrial Drive (Figure 5) has been addressed above.

Based on the above, and the information reviewed for this report, we believe the Drake (1999) interpretation in Figure 4 is the most relevant and depictive of the actual geological setting.

3.3 Weathered Residual Overburden

Intense bedrock chemical weathering in the landfill area has occurred due to the infiltration of water from precipitation moving downward from the land surface, recharging groundwater. Soluble minerals such as calcite and dolomite were dissolved and many other minerals dissolved and altered. Dissolved ions such as Ca^{2+}, Mg^{2+}, and HCO_3^- were flushed downward and became part of, and flowed with the groundwater. This continual process, in combination with the lack of removal of these unconsolidated materials via erosion processes, resulted in a thick residuum of saprolite which was observed in previous work, and was observed by EMS in the MW-14 grab samples and the split spoon core samples from MW-16. It must be noted that that portion of the carbonate units such as the Leithsville dolomite that were subject to this intense weathering are no longer carbonate geologic units since they now contain little if any carbonate minerals. No carbonate lithologies, outside of an apparently random pebble found at 14.5 feet, out of 260 feet, in the MW-16 core were encountered in the materials observed by EMS.

3.4 Hydrochemistry

At the Chrin Landfill site, before the landfill, some of the acidic precipitation that fell directly on the land surface infiltrated it and percolated down to and recharged the groundwater system. It is conceivable that much of the precipitation that fell on the resistant gneissic bedrock comprising the upland area of Morgan Hill, flowed down slope onto and into the weathered remnants of the Hardyston and Leithsville Formations. This flow will mostly occur either directly on the land surface as overland flow or along the shallow bedrock surface. Therefore, a combined and volumetrically greater localized recharge will occur along the base of Morgan Hill than away from it, resulting in a greater flushing action leading to the relatively deeper weathering profile found there. Weathered saprolite was found at depths of up to almost 300 feet in NUS well N-7 along Industrial Drive and greater than 260 feet in MW-16 associated with the proposed Eastern Expansion area. Groundwater contour maps derived from measured water levels in monitor wells at that site indicate, as would be expected, that groundwater flows downward and in a north-northwest direction from Morgan Hill toward the Lehigh River. The pH of the groundwater in monitor wells 14 to 18 installed in 2012 and surrounding the proposed Eastern Expansion area are acidic (median pH 5.7) and more similar to that found in non-carbonate rock than in dolomite bedrock (Figure 9). This observation strongly suggests that the geologic materials the water contacted in the unsaturated zone as it percolated downward to the groundwater system there, and in the groundwater system itself, are not now carbonate units, although some likely were in the geological past.

Part 4: Conclusions

1. The thick saprolite geologic unit comprising the topmost geologic unit under much of the Chrin Landfill property does not violate the PA Carbonate Rule as written, because it is not a carbonate unit. Around the proposed eastern expansion area, saprolite is at least greater than 100 feet thick, maximum depth of DM-6, and definitely greater than 260 feet at MW-16.
    - Rule: Landfills cannot be established in areas underlain by limestone or carbonate formations where the formations are greater than 5 feet thick and present at the topmost geologic unit.

    From the available data, the only solid bedrock unit comprising the topmost geologic unit under parts of the landfill is the Precambrian gneiss, the remainder is saprolite.

2. EMS believes the best conceptual model for the geologic structure underlying the Chrin Landfill is Drakes 1999 interpretation as presented in Figure 4 that indicates that the inferred thrust fault would occur on the northern side of Interstate 78. From plan view this would look like Drakes 1967 geologic bedrock map without the inferred thrust fault along Morgan Hill.

3. Comparisons of pH measurements of groundwater from monitor wells at the landfill with regional dolomite carbonate units show that the pH median of 6.5 from the monitor wells are more similar to the non-carbonate gneiss, median of 6.8, than the dolomite carbonate units in Northern Lehigh County, Sloto and Shaffer (1994), median 7.8, and in New Jersey, Serfes (2004), median 7.7 (Figure 9). Also, the median pH of 5.7 from samples collected on March 15 and 16, 2012 in wells drilled by Chrin Landfill, MWs 14 to 18, around the proposed eastern expansion area are indicative of non-carbonate aquifer material. The geological materials collected during the installation of MWs 14 and 16 were presented to EMS for inspection and determined to be non-carbonate saprolite, further supporting this interpretation.

4. A topographic depression suggestive of a karst feature exists in the Leithsville Formation just north of Industrial Drive and south of the electrical sub station near MWs 9 and 9A and N-6. While this may inpart be the case, the surface depression may also reflect the quarrying and/or mining activities that took place there in the past. This area is outside of the landfill footprint and is over 3000 feet southwest of the proposed eastern expansion area

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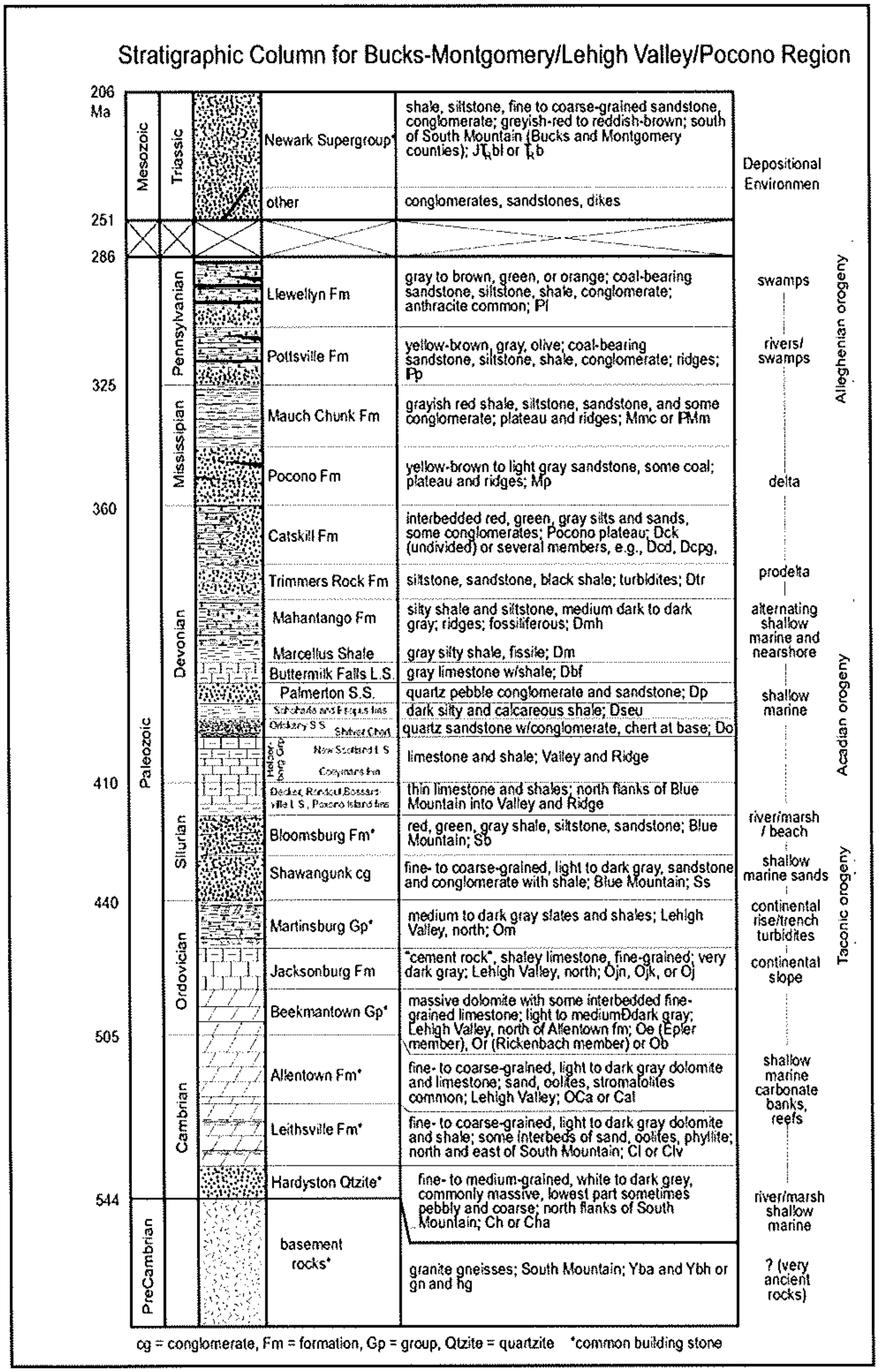


Stratigraphic Column for Bucks-Montgomery/Lehigh Valley/Pocono Region

Ma			Formation	Description	Depositional Environmen	
206	Mesozoic	Triassic	Newark Supergroup*	shale, siltstone, fine to coarse-grained sandstone, conglomerate; greyish-red to reddish-brown; south of South Mountain (Bucks and Montgomery counties); JTRbl or TRb		
			other	conglomerates, sandstones, dikes		
251						
286	Paleozoic	Pennsylvanian	Llewellyn Fm	gray to brown, green, or orange; coal-bearing sandstone, siltstone, shale, conglomerate; anthracite common; Pl	swamps	Alleghenian orogeny
			Pottsville Fm	yellow-brown, gray, olive; coal-bearing sandstone, siltstone, shale, conglomerate; ridges; Pp	rivers/ swamps	
325		Mississipian	Mauch Chunk Fm	grayish red shale, siltstone, sandstone, and some conglomerate; plateau and ridges; Mmc or PMm		
			Pocono Fm	yellow-brown to light gray sandstone, some coal; plateau and ridges; Mp	delta	
360		Devonian	Catskill Fm	interbedded red, green, gray silts and sands, some conglomerates; Pocono plateau; Dck (undivided) or several members, e.g., Dcd, Dcpg,		
			Trimmers Rock Fm	siltstone, sandstone, black shale; turbidites; Dtr	prodelta	
			Mahantango Fm	silty shale and siltstone, medium dark to dark gray; ridges; fossiliferous; Dmh	alternating shallow marine and nearshore	Acadian orogeny
			Marcellus Shale	gray silty shale, fissile; Dm		
			Buttermilk Falls L.S.	gray limestone w/shale; Dbf		
			Palmerton S.S.	quartz pebble conglomerate and sandstone; Dp	shallow marine	
			Schoharie and Esopus fms	dark silty and calcareous shale; Dseu		
			Oriskany S.S. Shriver Chert	quartz sandstone w/conglomerate, chert at base; Do		
			Helder-berg Grp: New Scotland L.S. Coeymans Fm	limestone and shale; Valley and Ridge		
410		Silurian	Decker, Rondout, Bossard-ville L.S., Poxono Island fms	thin limestone and shales; north flanks of Blue Mountain into Valley and Ridge		
			Bloomsburg Fm*	red, green, gray shale, siltstone, sandstone; Blue Mountain; Sb	river/marsh / beach	Taconic orogeny
			Shawangunk cg	fine- to coarse-grained, light to dark gray, sandstone and conglomerate with shale; Blue Mountain; Ss	shallow marine sands	
440		Ordovician	Martinsburg Gp*	medium to dark gray slates and shales; Lehigh Valley, north; Om	continental rise/trench turbidites	
			Jacksonburg Fm	"cement rock", shaley limestone, fine-grained; very dark gray; Lehigh Valley, north; Ojn, Ojk, or Oj	continental slope	
			Beekmantown Gp*	massive dolomite with some interbedded fine-grained limestone; light to mediumÐdark gray; Lehigh Valley, north of Allentown fm; Oe (Epler member), Or (Rickenbach member) or Ob		
505		Cambrian	Allentown Fm*	fine- to coarse-grained, light to dark gray dolomite and limestone; sand, oolites, stromatolites common; Lehigh Valley; OCa or Cal	shallow marine carbonate banks, reefs	
			Leithsville Fm*	fine- to coarse-grained, light to dark gray dolomite and shale; some interbeds of sand, oolites, phyllite; north and east of South Mountain; Cl or Clv		
			Hardyston Qtzite*	fine- to medium-grained, white to dark grey, commonly massive, lowest part sometimes pebbly and coarse; north flanks of South Mountain; Ch or Cha	river/marsh shallow marine	
544	PreCambrian		basement rocks*	granite gneisses; South Mountain; Yba and Ybh or gn and hg	? (very ancient rocks)	

cg = conglomerate, Fm = formation, Gp = group, Qtzite = quartzite   *common building stone

Figure 1: Stratigraphic Column for Bucks-Montgomery/Lehigh Valley/Pocono Region. Anastasio and others (no date).

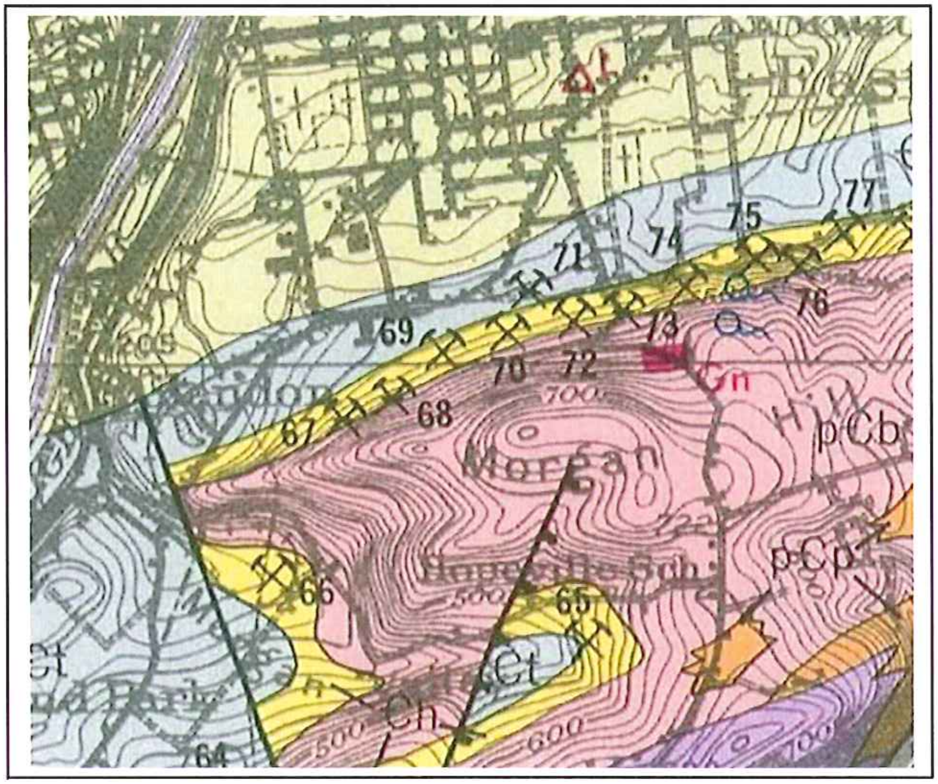


Figure 2. Bedrock geologic Map of Northampton County 1939 (revised 1966) Miller and others. Note, no fault inferred on north side of Morgan Hill. Note that the iron mines (cross picks) are found in the weathered and now unconsolidated saprolitic Hardyston Formation, and therefore, define the near surface extent of that formation.

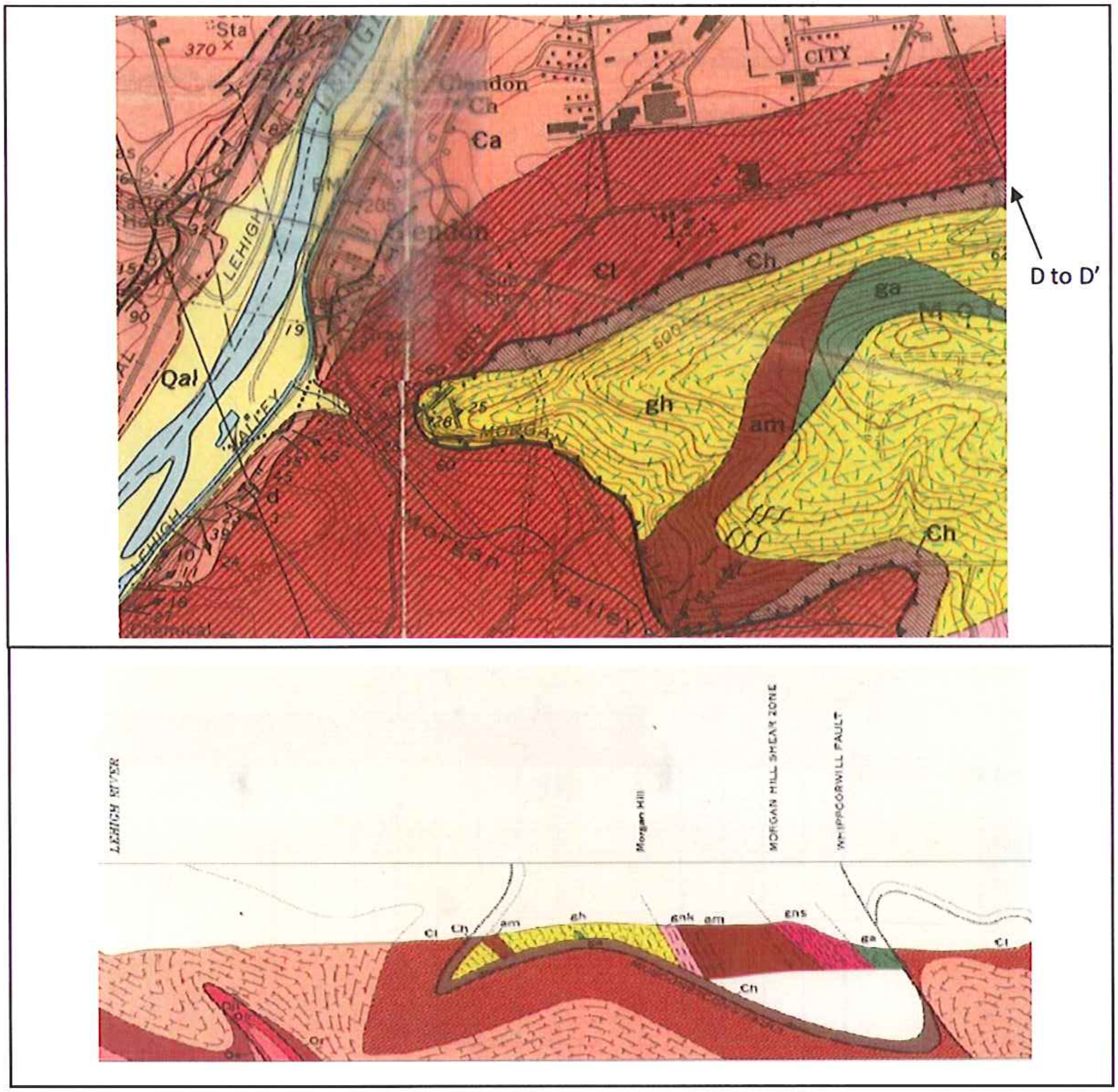
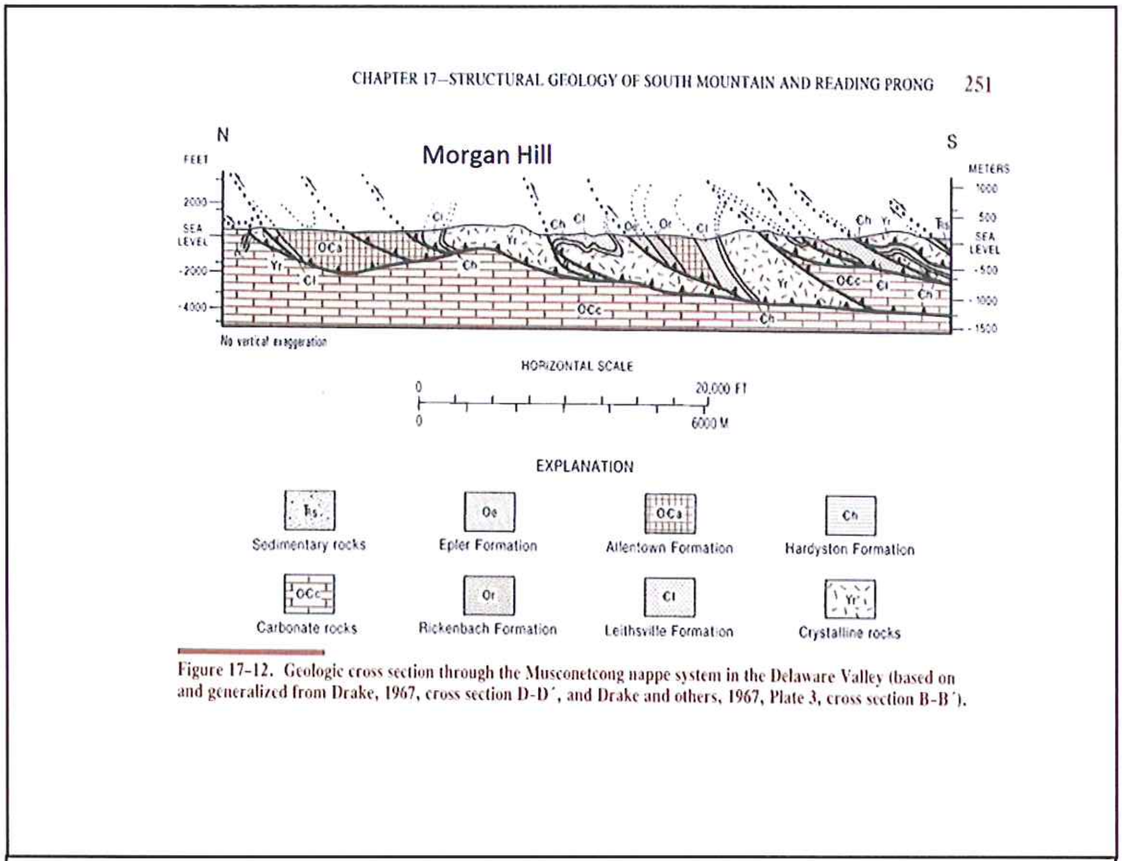


Figure 3. Top: Part of bedrock geologic map (Drake, 1967) in the Chrin Landfill area. Note that the thrust fault separating the Hardyston (Єh) from the Leithsville (Єl) on the north side of Morgan Hill is not a solid line and is therefore "inferred ". This indicates that no direct evidence for the fault at this location was found and it's existence is speculative. It is based on a conceptual model. Bottom: Drake geologic cross-section, part of D – D', interpretation across Morgan Hill from this same map.



CHAPTER 17—STRUCTURAL GEOLOGY OF SOUTH MOUNTAIN AND READING PRONG 251

Figure 17-12. Geologic cross section through the Musconetcong nappe system in the Delaware Valley (based on and generalized from Drake, 1967, cross section D-D´, and Drake and others, 1967, Plate 3, cross section B-B´).

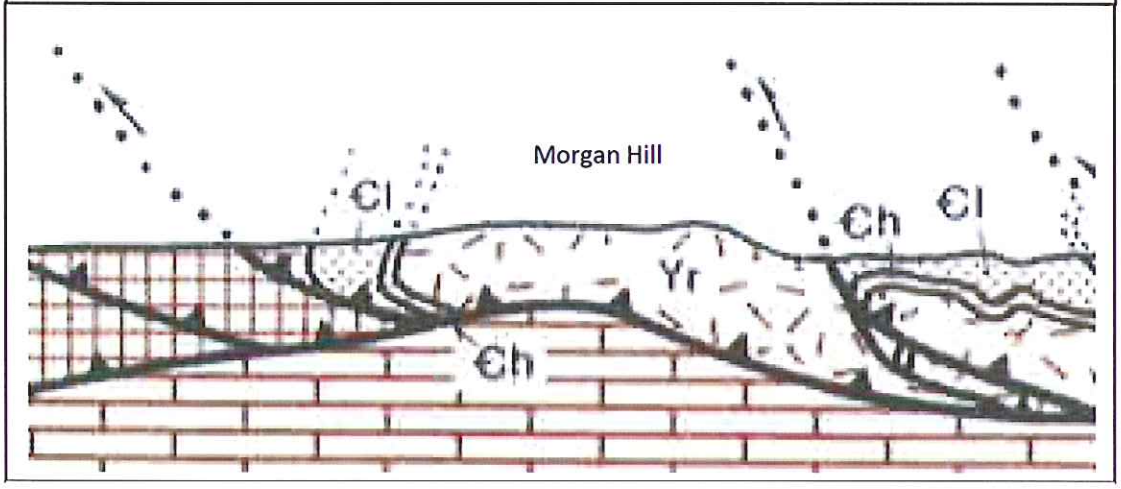


Figure 4. Cross section (Drake, 1999) shows Morgan Hill area and the newer interpretation of the inferred fault boundary on the north side which is no longer at the Hardyston-Leithsville contact as the Drake (1967) map shows. Note: lower image is the blown up portion from the top in the area of Morgan Hill.

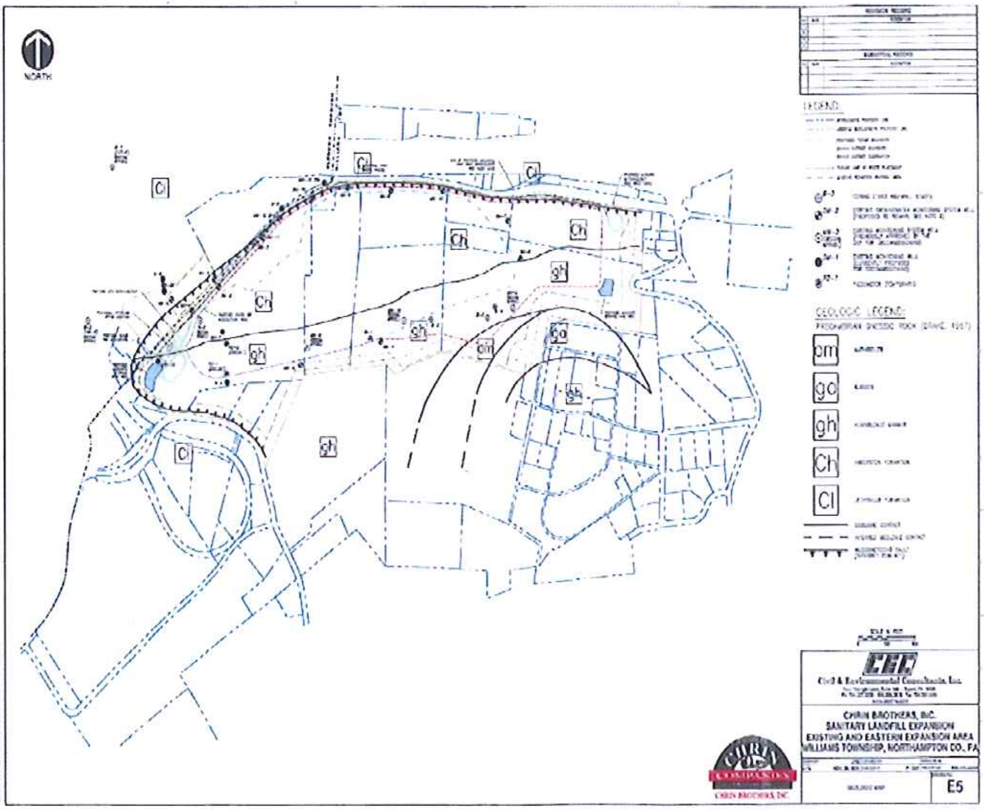


Figure 5. CEC map based on AGES Report (Furgeroli and others, 1989). Note: based on that site investigation it was concluded that the topmost geologic unit under the landfill is saprolite. Also the now saprolitic Hardyston Formation comprises the surface and near surface materials up to industrial lane, and, the thrust fault inferred by Drake (1967) between the Hardyston and Leithsville has been moved to just north of Industrial Lane.

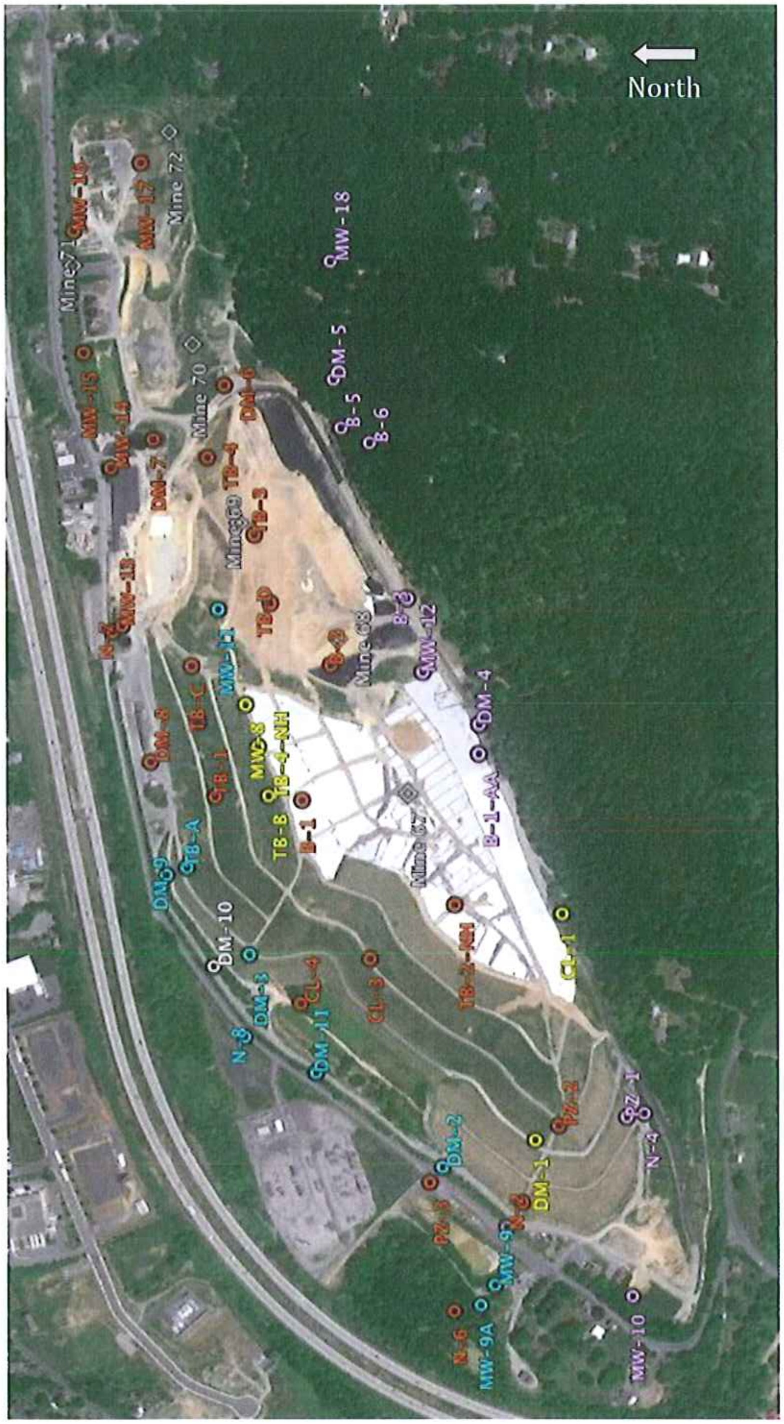


Figure 6. Borehole identifications and locations are from previous geologic investigations at Chrin Brothers Landfill. Colors correspond to bedrock units identified in boring logs: Pink = Granite Gneiss bedrock; Yellow = Sandstone (Hardyston Quartzite); Blue = Leithsville Fm; Brown = Weathered bedrock (Saprolite); White = no geologic information on log. Mine locations (gray) were taken from Miller and others (1939).

Figure 7. Depth to bedrock. Borehole locations are from previous geologic investigations at Chrin Brothers Landfill. Colors correspond to bedrock units identified in boring logs: Pink = Granite Gneiss bedrock; Yellow = Sandstone (Hardyston Quartzite); Blue = Leithsville Fm; Brown = Weathered bedrock (Saprolite); White = no geologic information on log. Mine locations (gray) were taken from Miller and others (1939).

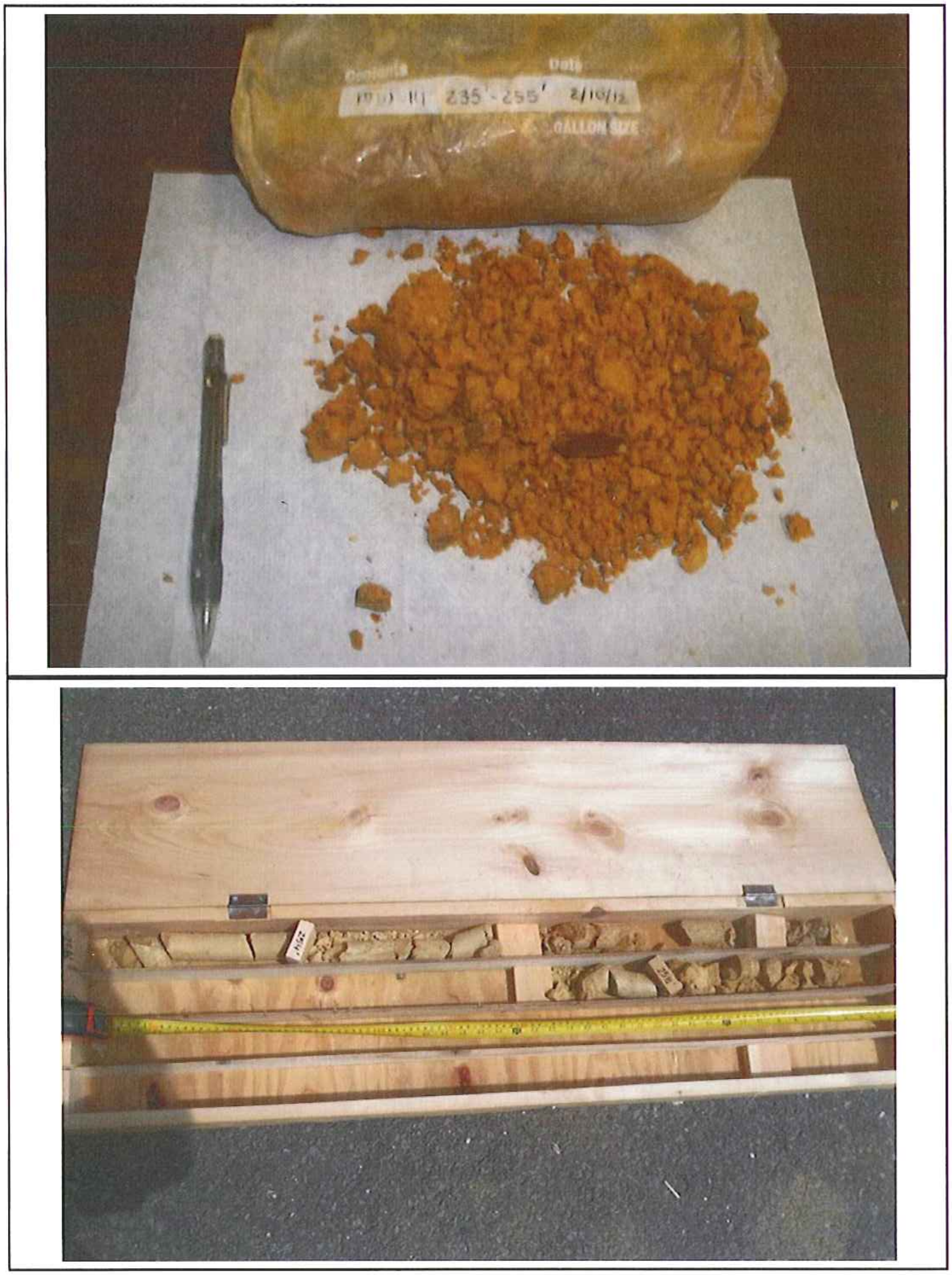


Figure 8. Photograph (top) of the geological material collected at 235 to 255 feet at the bottom of MW-14 in the proposed eastern expansion area at the Chrin Landfill (top). Photograph (bottom) is the last core box containing the deepest material collected (~250 to 260 feet) from MW-16, also in the proposed expansion area. Both examples are saprolite.

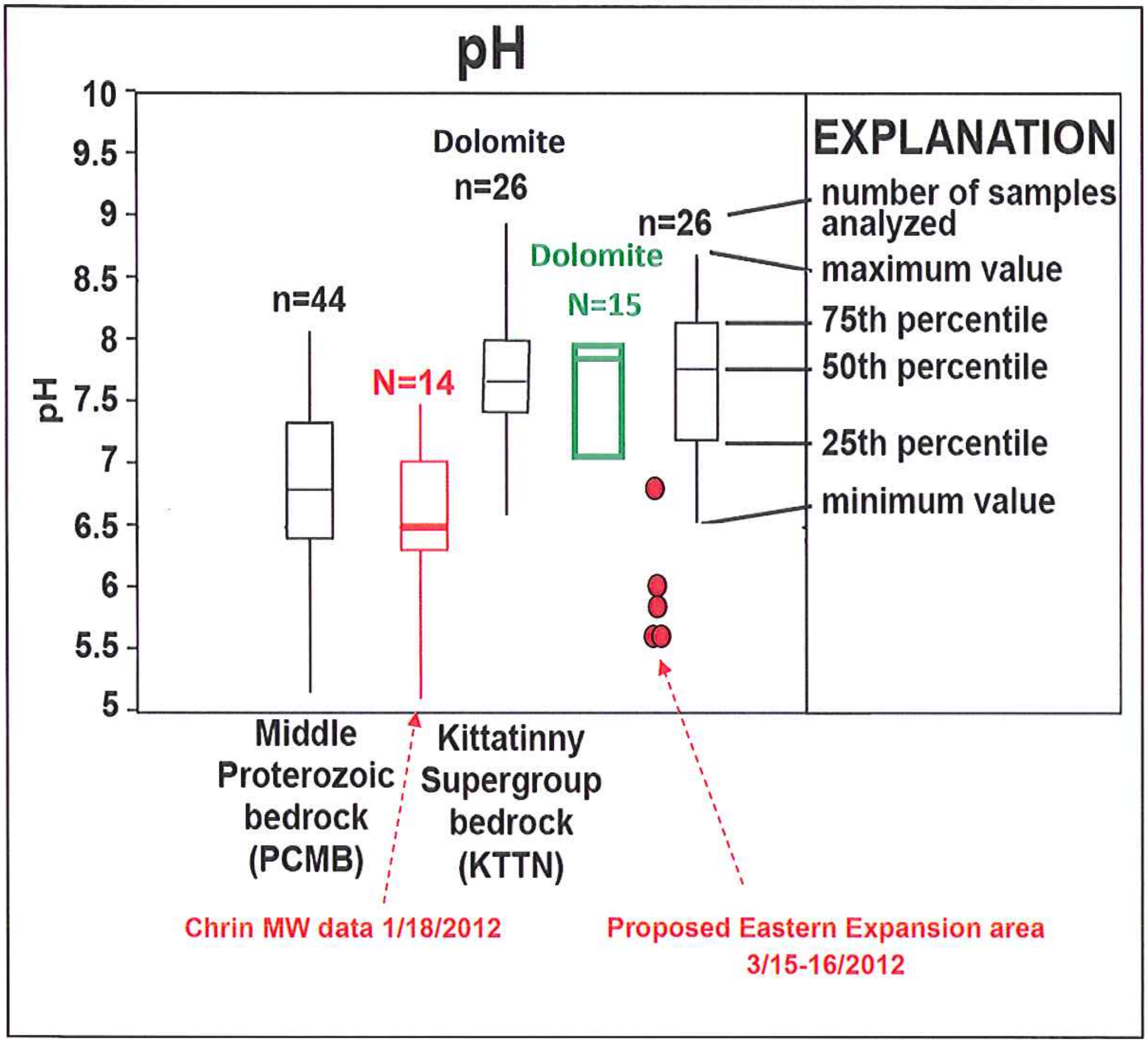
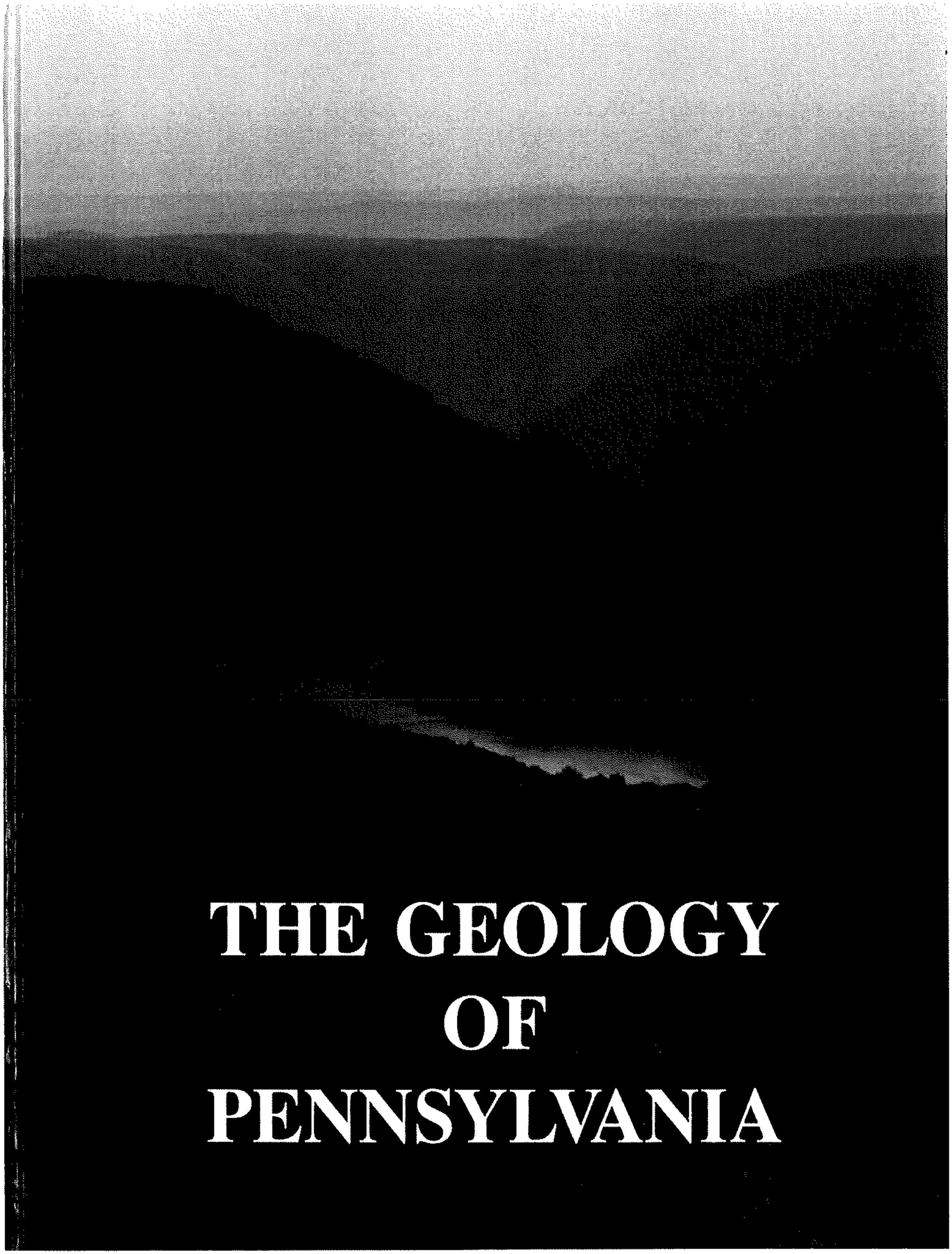


Figure 9. Groundwater Chemistry (pH) from wells at landfill (**red**) compared with regional similar dolomite units in New Jersey (**black**) from Serfes (2004) and from upper Bucks County (**green**), Sloto and others (1994) where the lower box is the 10th percentile and the upper the 90th. Precambrian Gneiss units from New Jersey also shown which should be similar to the gneiss on Morgan Hill.



THE GEOLOGY OF PENNSYLVANIA

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CONTENTS

PART II. STRATIGRAPHY AND SEDIMENTARY TECTONICS *(Continued)*

Part III. Structural Geology and Tectonics

CHAPTER 17 SOUTH MOUNTAIN AND READING PRONG

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INTRODUCTION

South Mountain, which is the northern extremity of the Blue Ridge-South Mountain anticlinorium, and the Reading Prong are the largest external basement massifs in the central Appalachians (Drake and others, 1988) (Figure 17-1). Basement rocks, however, do not crop out in the Pennsylvania segment of South Mountain (Chapter 3B). These massifs differ both structurally and in their tectonic histories. The Reading Prong constitutes a complex nappe megasystem in which crystalline basement rocks and their sedimentary cover are involved in large, thrust-faulted, recumbent folds formed during the Taconic orogeny (Chapter 18). The nappe megasystem was later deformed by thrust faulting and attendant folding during the Alleghanian orogeny (Drake, 1978, 1980), leading to extremely complicated geologic relations.

South Mountain, on the other hand, has long been considered to be an extremely large, basement-cored anticlinorium formed by passive slip along cleavage (Cloos, 1971). With the advent of modern seismic-reflection techniques, however, it became apparent that, although it is an anticlinorium, South Mountain is a hanging-wall anticlinorium above a ramp in a deep thrust fault (Harris and others, 1982) (so-called "Eastern Overthrust Belt"). Deformation features in the igneous and metamorphic rocks of the anticlinorium can be related to features in even the youngest cover rocks (Chapter 18), and thereby would appear to be of Alleghanian age. To date, no pre-Alleghanian structural feature has been recognized within the rocks of South Mountain. The Reading Prong and South Mountain massifs, then, differ both in style and timing of deformation.

READING PRONG

The Middle Proterozoic rocks of the Reading Prong have had a long and complicated tectonic history. They were presumably first deformed during the Grenville orogeny at about 1 Ga. Subsequently, they experienced the entire Appalachian orogenic cycle from the Late Proterozoic through the Pennsylvanian-Permian. Finally, they were deformed during the extensional event related to the opening of the Atlantic Ocean during the Mesozoic. Their structure and current position are, therefore, the cumulative result of this long and complicated tectonic history.

Structures of Proterozoic Age

The structures formed during the Grenvillian orogenic event are not well understood. The metamorphosed sedimentary and volcanic-volcaniclastic rocks are both compositionally layered and foliated (Figures 3B-8 and 17-2). Most geologists think that the compositional layering is relict bedding, although some probably results from metamorphic differentiation. Many also think that the foliation in the rocks is mimetic after bedding because layering and foliation are roughly parallel in most exposures. Even if the layering is relict bedding, it may have little stratigraphic meaning, because units map out as lenses (Drake, 1967; Drake and others, 1967), suggesting regional transposition. Foliation, however, is not mimetic after bedding; observation of small, early, first-phase folds clearly shows that the foliation, which roughly parallels the layering on limbs, passes through the hinges rather than going around them.

Figure 17-2. Light- and dark-layered biotite-quartz-feldspar gneiss on Chestnut Hill, Easton 7.5-minute quadrangle, Northampton County. The long dimensions of the biotite and feldspar crystals define a foliation. The coin at the base of the rock is 0.75 inch in diameter.

Lineation is well to poorly developed in the Middle Proterozoic rocks and is mostly expressed by aligned minerals or streaks of minerals and, less commonly, by crenulations, rods, or fluted surfaces. The lineation everywhere appears to parallel second-phase fold axes.

Folds are common throughout the Middle Proterozoic terrane, although they are difficult to map because of poor exposure. The folds range from upright and open (Figure 17-3) to isoclinal overturned or isoclinal recumbent (Figures 3B-7, 3B-9, and 17-4). They range from a few inches in wavelength and magnitude to as much as 7 miles long parallel to the axis and 1 mile in width. All mapped folds are of foliation as well as layering (Figures 3B-7, 3B-9, 17-3, and 17-4), so none are first folds. Few geologists have mapped more than one fold phase. Two (possibly three) fold phases were mapped on South Mountain (of the Reading Prong) in Lehigh County (Figure 17-5). It is uncertain whether the east-northeast-trending folds in the western part of the map are a different phase than the north-northeast-trending folds in the eastern part of the area, because there is no overprinting relationship. It would appear, then, that the Middle Proterozoic rocks of the Reading Prong have experienced at least three (possibly four) phases of folding, the earliest of which produced the regional foliation. The concordant sheets of intrusive rocks appear to have been emplaced synkinematically during this fold phase, as their foliation and lineation parallel that in the layered rocks. The entire terrane then experienced the later deformations. Mineral lineation apparently formed during the first phase of folding and was transposed, so that it is now roughly parallel to the axes of second-phase folds and is refolded by the later phases.

Structures of Paleozoic Age

Early workers in eastern Pennsylvania recognized the complexity of the structural geology of the area, and Lesley and others (1883) likened it to that of the Alps. Nevertheless, most geologists considered the Reading Prong to be a large anticlinorium. Stose and Jonas (1935), however, proposed that the Middle Proterozoic crystalline rocks and Cambrian Hardyston Formation of the Reading Prong were part of a large thrust sheet lying upon the carbonate rocks of the Great Valley and that the carbonate-floored valleys within the crystalline terrane were tectonic windows.

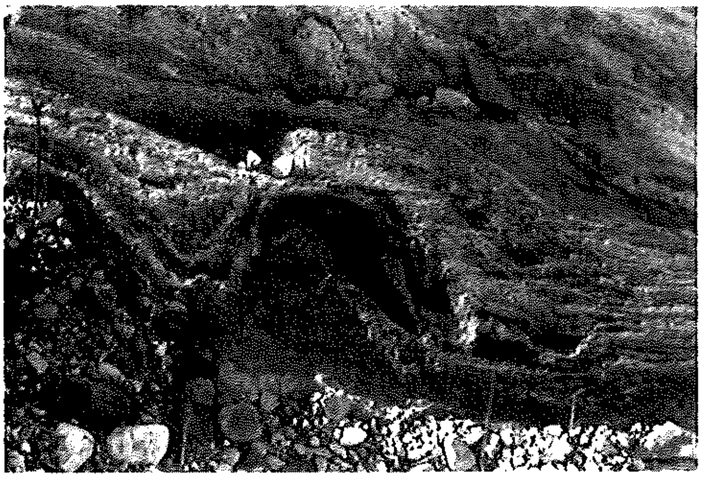


Figure 17-3. Upright antiform-synform pair in biotite-quartz-feldspar gneiss on Chestnut Hill, Easton 7.5-minute quadrangle, Northampton County. The coin at the top of the antiform is 0.75 inch in diameter.

Figure 17-4. Isoclinal recumbent folds in potassic feldspar gneiss on Chestnut Hill, Easton 7.5-minute quadrangle, Northampton County. The field of view is about 4 feet by 2.5 feet.

Work since World War II led to the recognition of large recumbent nappes in the Great Valley (Chapter 18) and that thrust faults and overturned folds were a major factor in the distribution of the Middle Proterozoic crystalline rocks. A collation of these data with those gained from aeromagnetic surveying led to the interpretation that the Middle Proterozoic crystalline rocks were involved in the same Alpine structures as the rocks in the Great Valley and led Drake (1969, 1970) to make the rather naive suggestion that the Reading Prong constituted one gigantic nappe.

More recent geologic and geophysical work allows for a more sophisticated interpretation of Reading Prong geology. The Middle Proterozoic rocks are transported, as is clearly shown by the fairly abundant proprietary seismic-reflection profiles that suggest that basement is at a depth of about 15,000 feet in easternmost Pennsylvania and is perhaps as deep as 45,000 feet in the Reading area. Detailed mapping shows that the Pennsylvania segment of the Reading Prong consists of at least four nappes or, more properly, nappe systems that are defined largely by their cover sequences (Chapter 18) and that constitute the Reading Prong nappe megasystem (Drake, 1978). From west to east, these are the Lebanon Valley, Irish Mountain, Lyon Station-Paulins Kill, and Musconetcong nappe systems (Figure 17-6).

It must be pointed out that the Middle Proterozoic crystalline rocks were not folded as such with their lower Paleozoic cover, but were thrust into it. The crystalline rocks accommodated themselves to the nappe-form surfaces by movement on zones of ductile and brittle deformation (Drake, 1969, 1970).

Lebanon Valley Nappe System

The Lebanon Valley nappe system (Gray, 1959) was the first recognized element of the megasystem. Its crystalline core underlies Little South Mountain

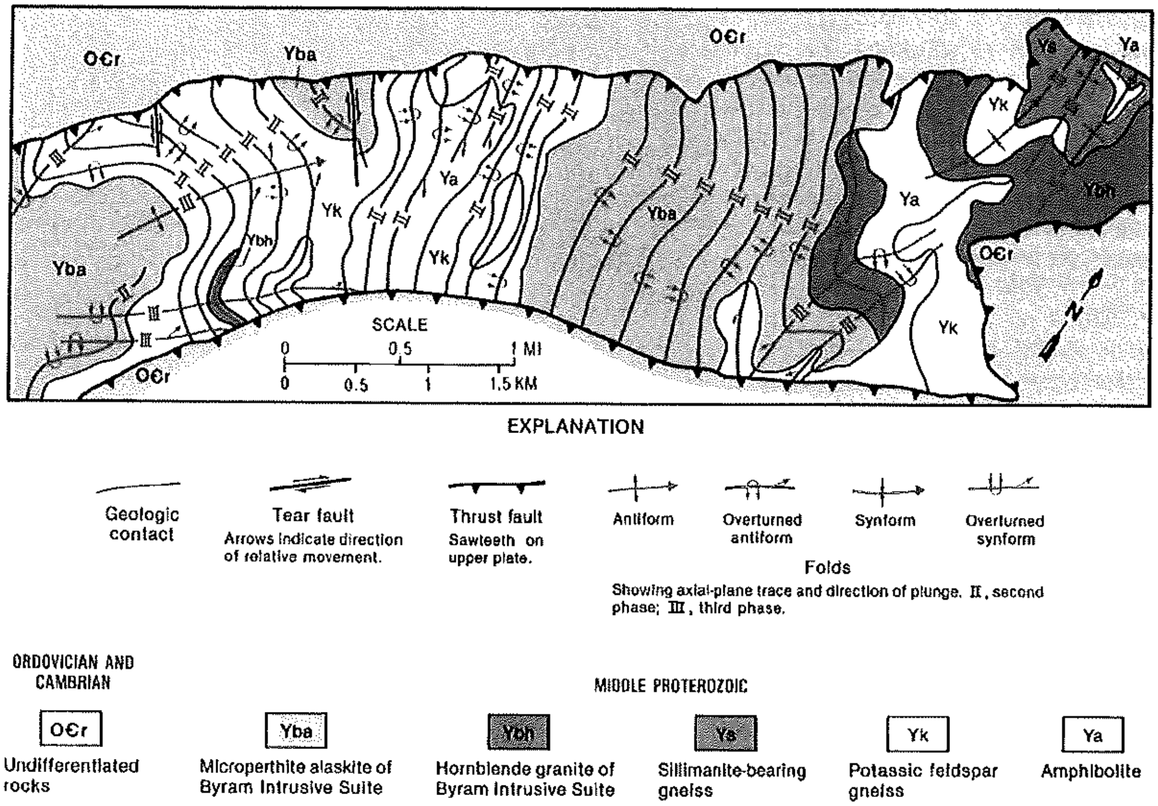


Figure 17-5. Structural geology of Middle Proterozoic rocks in part of South Mountain (Reading Prong) in the Allentown East 7.5-minute quadrangle, Lehigh County.

(Figure 17-6). These rocks resemble those of the Honey Brook Upland to the south (see Chapter 3A) more than the rocks of the Reading Prong nappes, which is in keeping with their cover of Lebanon Valley sequence rocks that have Piedmont affinities (MacLachlan, 1979). The crystalline rocks have been thrust over regionally inverted rocks of the Lebanon Valley sequence (Figure 17-7). East of Little South Mountain, the Lebanon Valley nappe system tectonically overlies the Irish Mountain nappe system on the Sinking Spring thrust fault (Figure 17-6).

Irish Mountain Nappe System

The Irish Mountain nappe system embraces all of the crystalline rocks, and their cover of Schuylkill sequence rocks (MacLachlan, 1983), from the Reading area in Berks County to the gap in outcropping basement rocks south of Hellertown (just southeast of Bethlehem in Northampton County) (Figure 17-6). A visualization of the Irish Mountain nappe system in the Reading area is given in Figure 17-8, and in the Allentown area in Figure 17-9. The presence of carbonate rocks beneath outcropping crystalline rocks and Hardyston Formation is confirmed by water wells all along the Irish Mountain nappe trace (Wood and others, 1972). The crystalline rocks of the southern part of the Irish Mountain nappe system, as used herein, have a much higher content of radioactive minerals than the other crystalline rocks of the megasystem and may constitute another nappe (R. C. Smith, II, written communication, 1988). These rocks constitute the Applebutter thrust sheet of Drake (U.S. Geological Survey, 1973).

Lyon Station-Paulins Kill Nappe System

The Lyon Station-Paulins Kill nappe system occurs largely in the subsurface and was defined by Drake (1978) on the basis of aeromagnetic data and the mapping of cover rocks in windows. It lies beneath both the Irish Mountain and Musconetcong nappe systems (Figure 17-9). Its core, as shown by a magnetic anomaly, passes beneath the outcropping Middle Pro-

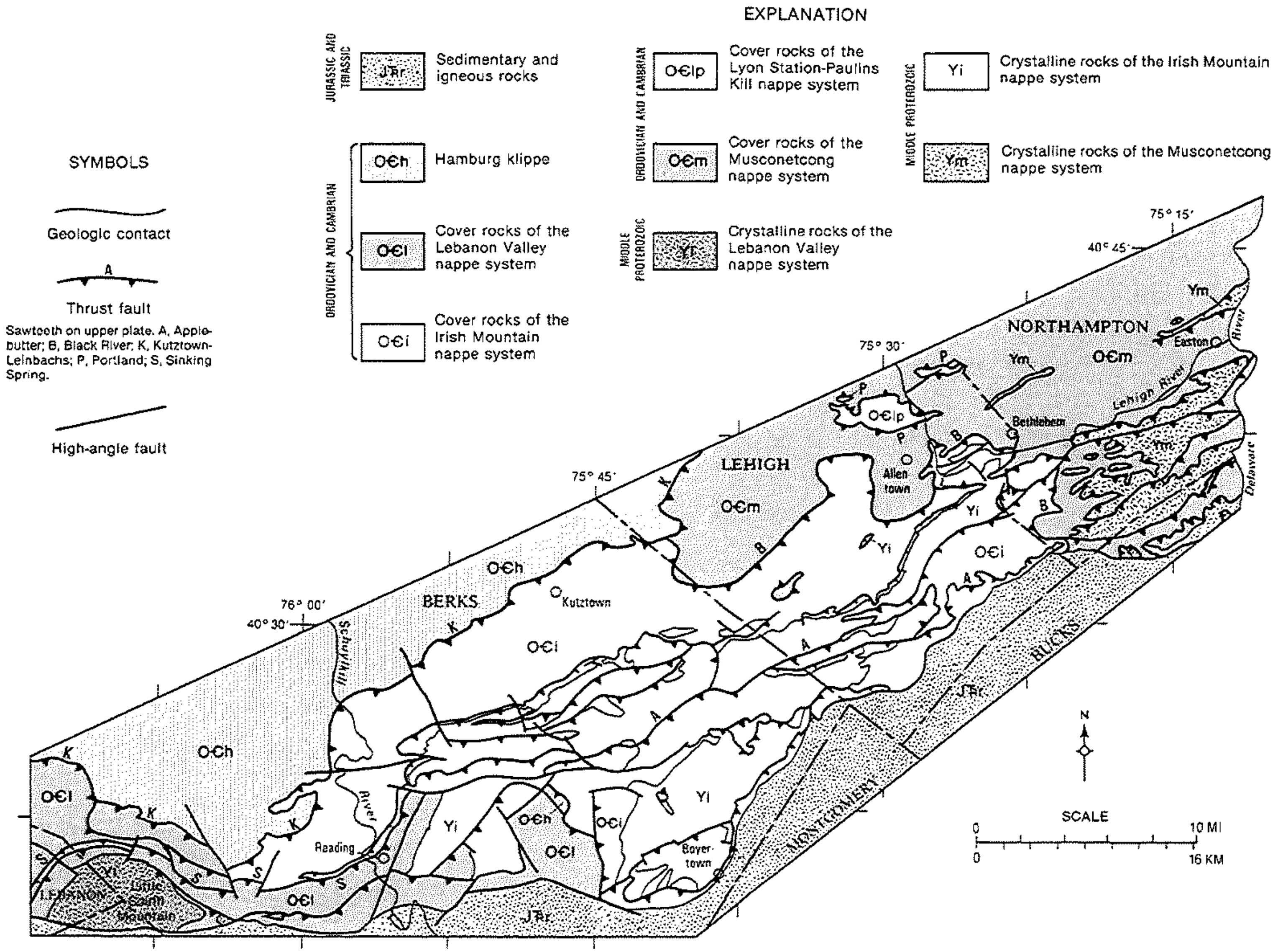


Figure 17–6. Tectonic sketch map of east-central Pennsylvania showing the distribution of nappe systems in the Reading Prong nappe megasystem (modified from Lyttle and Epstein, 1987, and Faill, in preparation).

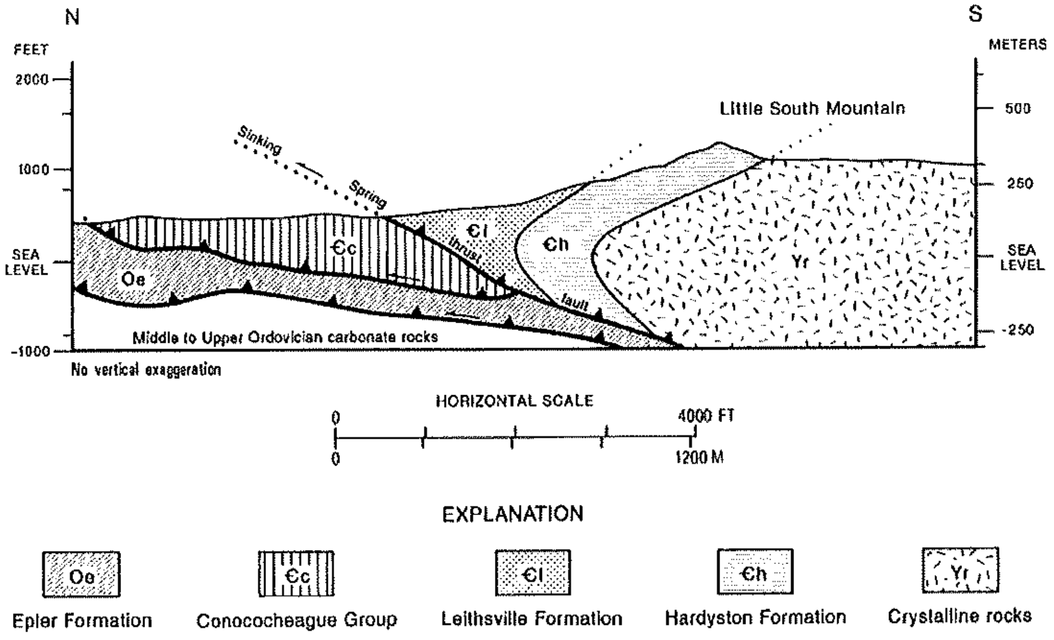


Figure 17-7. Geologic cross section through the brow and part of the lower limb of the Lebanon Valley nappe system in Little South Mountain (modified from Geyer and others, 1963, Plate 1, cross section C-C′).

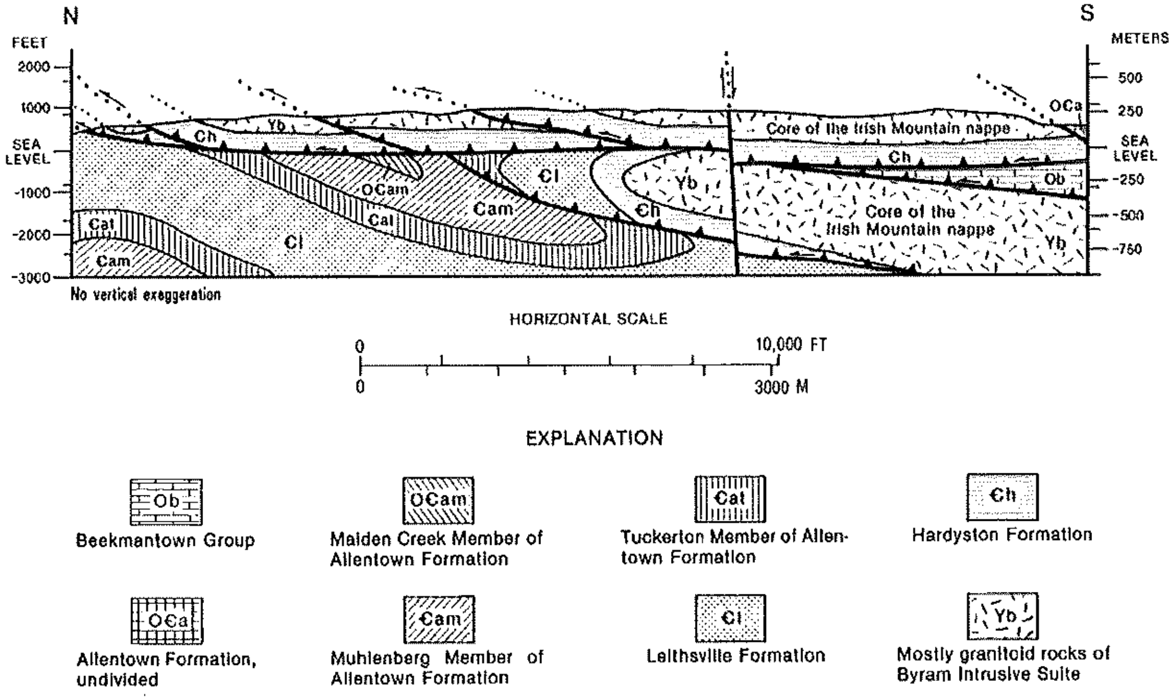


Figure 17-8. Geologic cross section through the Irish Mountain nappe system northeast of Reading (modified from MacLachlan, 1979). The high-angle normal fault is Mesozoic.

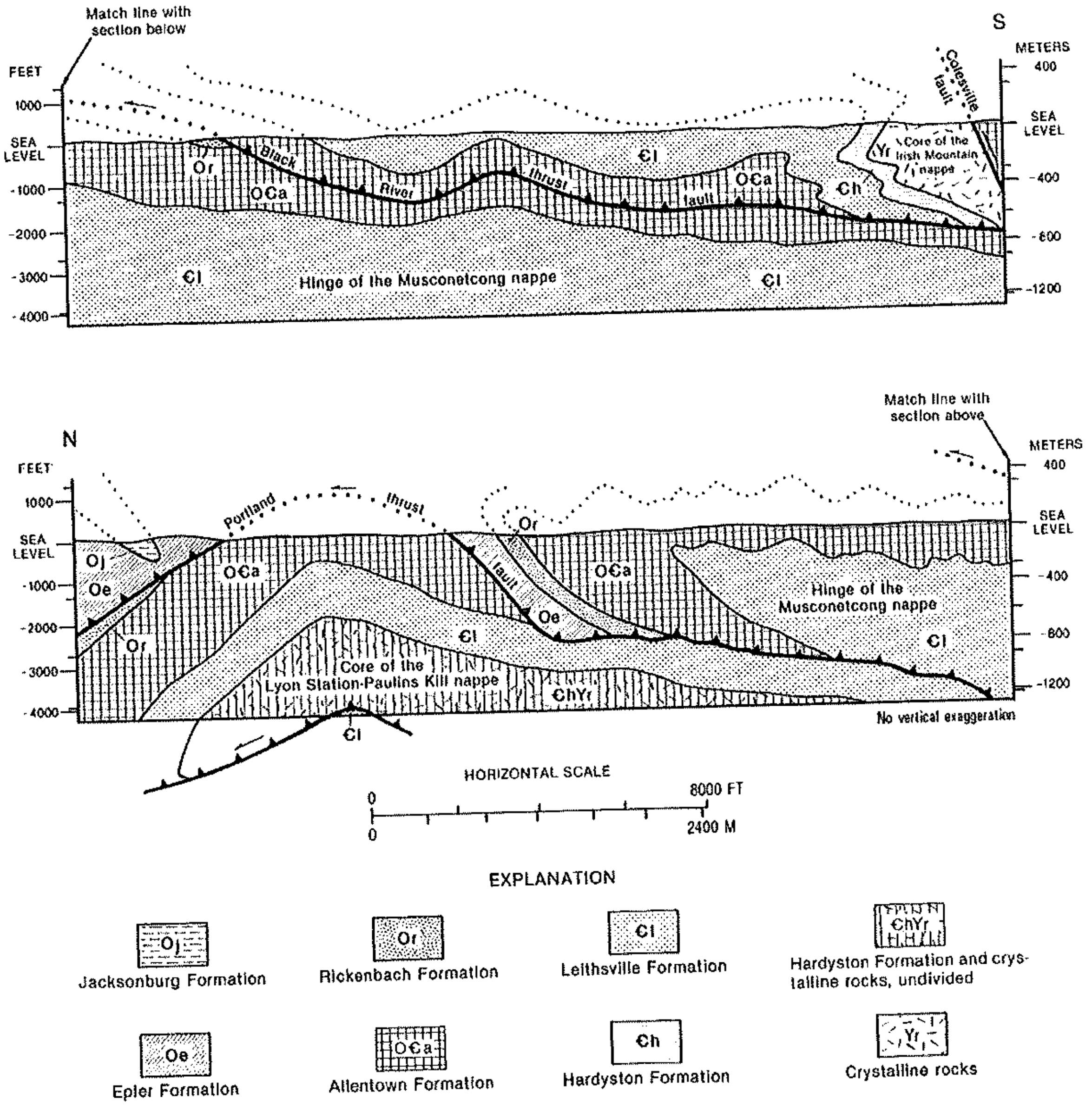


Figure 17-9. Geologic cross section showing the relationship of the Irish Mountain, Musconetcong, and Lyon Station-Paulins Kill nappe systems in the Allentown area (modified from Drake, 1978, Plate 3, Section B).

terozoic rocks of the Irish Mountain nappe system (Bromery and Griscom, 1967) and can be traced to the Delaware River but not into New Jersey.

Musconetcong Nappe System

The Musconetcong nappe system is made up of the basement massifs in eastern Pennsylvania that lie beneath the Black River thrust fault (Figure 17-6) and continue on into New Jersey. This nappe system was first interpreted by Drake (1969) to be one gigantic basement-cored structure produced by both folding and thrusting. The distribution of the crystalline rocks and their cover, as well as many recumbent folds and a regionally inverted sequence in eastern Pennsylvania (Figures 17-10 and 17-11), were thought to have resulted from the refolding of the nappe.

Abundant geologic mapping in eastern Pennsylvania and New Jersey since 1970 necessitates a new

Figure 17-10. Recumbent anticline in the Lower Cambrian Leithsville Formation on the west bank of the Lehigh River near Glendon, Easton 7.5-minute quadrangle, Northampton County. The fold rotation sense is reverse, showing that rocks are overturned. The outcrop is about 300 feet long by 150 feet high.

interpretation of the structural geology. This interpretation of the Musconetcong nappe system along the Delaware River is shown in Figure 17-12. The interpretation relies greatly on thrust tectonics. Most of the faults that are shown have been known for many years. Those on the north margins of outcropping bodies of crystalline rock were incorrectly interpreted to be the Musconetcong thrust fault repeated by folding, whereas faults on the south margins were interpreted to be later thrust faults. The faults are now interpreted to constitute a thrust system. The basement rocks shown in Figure 17-12 coalesce to the west and form a large, but faulted, massif, basement being brought onto basement. This massif was calculated to have a thickness of about 4,000 feet on the basis of aeromagnetic data (Bromery, 1960). This is taken to be the depth to the basal thrust fault of the Musconetcong nappe system in Pennsylvania. No geology is depicted beneath the basal thrust because seismic data are not available for this area.

Figure 17-11. Recumbent folds in the Lower Ordovician Epler Formation in a quarry in West Catasauqua, Catasauqua 7.5-minute quadrangle, Lehigh County. The fold rotation sense is reverse, showing that rocks are overturned. The outcrop is about 150 feet long by 95 feet high.

The array of thrust faults shown in Figure 17-12 has the geometry of an imbricate-fan suite between a basal floor thrust and an eroded roof thrust, constituting a duplex or schuppen structure. Modern work has shown that basement rocks in both the external massifs and Pennine nappes in the Alps, the basement wedges of Cadisch (1946) and Umbgrove (1950), are giant crystalline duplexes (Boyer and Elliott, 1982). To date, three small duplexes or schuppen zones have been recognized in the Musconetcong nappe system. The roundhouse schuppen zone of Drake (unpublished data) contains five repetitions of crystalline rock and Leithsville Formation at the westernmost extremity of the Musconetcong system. Two other such zones have been mapped in New Jersey (Drake and others, 1993, 1994).

Time of Deformation

The time of deformation producing the Reading Prong nappe megasystem is uncertain, but it probably began during the Ordovician Taconic orogeny.

Tectonics

Lash and Drake (1984) presented a tectonic model for this part of the central Appalachians in which a relatively small ocean basin was opened between the Laurentian craton and a microcontinent (Baltimore terrane?) during the Late Proterozoic or earliest Cambrian (Figure 17-13A). Extension during this opening formed a number of listric normal faults on the Laurentian margin. If one does not accept the model of Lash and Drake (1984), one can consider the listric extensional faults to have formed on the Laurentian

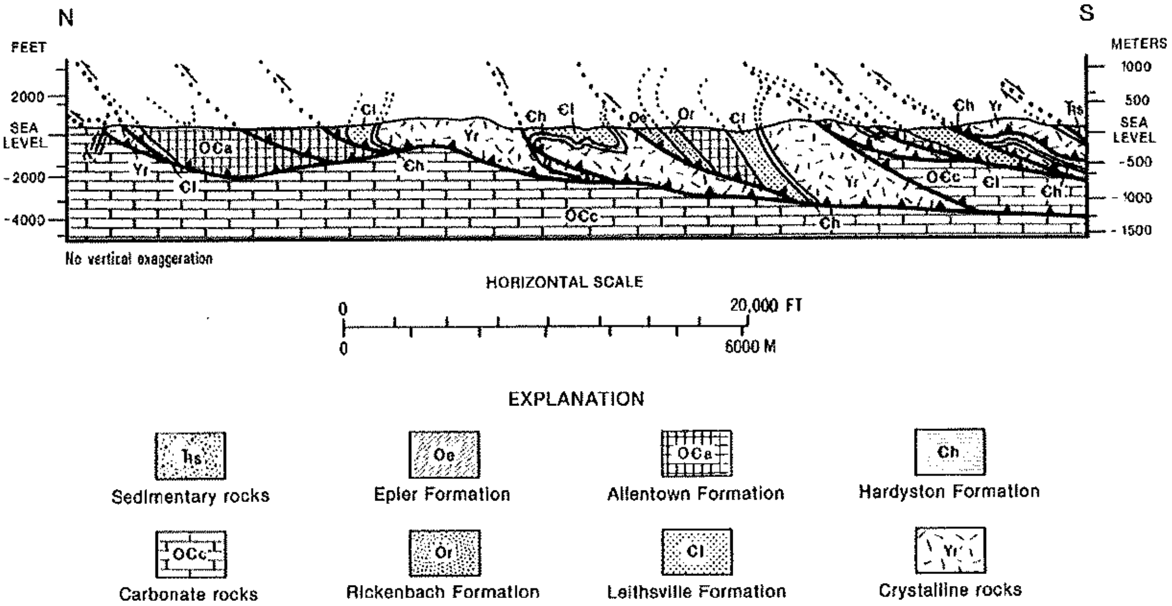


Figure 17–12. Geologic cross section through the Musconetcong nappe system in the Delaware Valley (based on and generalized from Drake, 1967, cross section D–D′, and Drake and others, 1967, Plate 3, cross section B–B′).

margin during the opening of the large Iapetus Ocean. In any case, the carbonate shelf on the cratonic margin collapsed during the attempted subduction of Laurentia beneath the microcontinent at the beginning of the Taconic orogeny, and the Martinsburg foreland basin was developed (Figure 17–13B). Subsequently, the basin closed and the listric extensional faults were reactivated as thrust faults along which wedges of basement rocks were driven into the carbonate and Martinsburg cover rocks, and the Reading Prong nappe megasystem was formed (Figure 17–13C).

SOUTH MOUNTAIN

In Pennsylvania and adjacent Maryland, the Blue Ridge-South Mountain anticlinorium is essentially a very large asymmetrical overturned fold that has a southeast-dipping axial surface. In Pennsylvania, particularly where it plunges out, the west limb of the fold is only slightly overturned.

Structural Geology

Smaller folds are developed within the anticlinorium and have the same style as folds in the Ridge and Valley province (Figure 17–14). They are characterized by straight, doubly plunging axes that can be traced for more than 25 miles. The rocks are well cleaved (Figures 17–15 and 17–16); the cleavage fans the folds (Figure 17–14). The cleavage surfaces are commonly marked with a downdip elongation lineation. The cleavage and downdip lineation are taken to define the South Mountain deformation plan of Cloos (1947), which has a very uniform relation over a wide area. Cloos interpreted the anticlinorium to have originated by laminar flow along the cleavage, which allowed great shortening without faulting, making it a large "shear fold." There are, however, several faults within the anticlinorium (Figure 17–17). The Carbaugh-Marsh Creek fault (Root, 1970), the most important of these faults, starts within the core of the anticlinorium as a right-slip fault. It passes westward into the carbonate rocks of the Cumberland Valley, where it turns to the southwest and becomes a steep thrust fault that can be traced at least as far south as the Potomac River (Root, 1970). The fault has an apparent lateral separation of 2.5 miles within the anticlinorium and a stratigraphic separation of about 4,700 feet at the Pennsylvania-Maryland border, bringing Lower Ordovician limestone onto Middle Ordovician shale. The array of thrust faults in the hanging wall (Figure 17–17) suggests that it might be the floor thrust of a sizable duplex. This type of fault, which begins as a strike-slip fault within the anticlinorium core and turns into a thrust fault within the carbonate valley, may be an important feature all along the length of the Blue Ridge-South Mountain structure, as at least two other

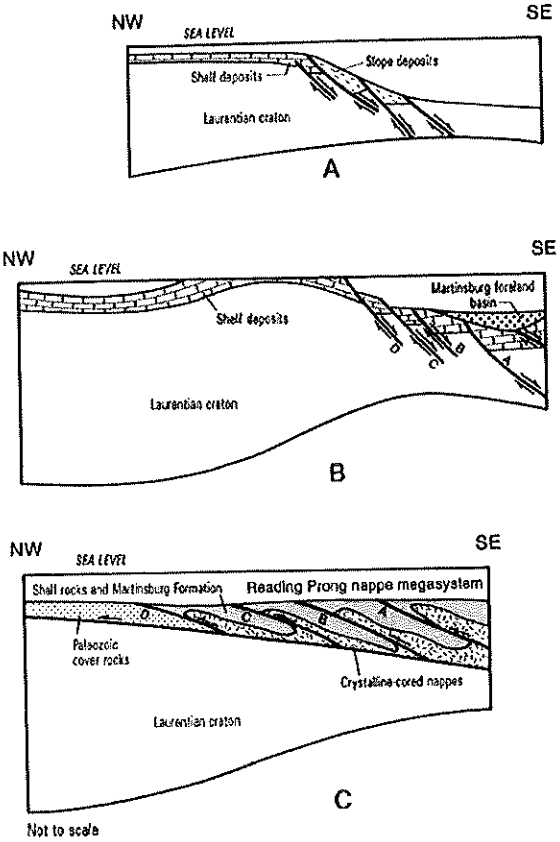


Figure 17-13. Schematic representation of the development of the Reading Prong nappe megasystem. A. Extensional faults related to the opening of a small ocean basin or the Iapetus Ocean formed on the margin of the Laurentian craton during the Late Proterozoic or earliest Cambrian. B. Shelf collapse related to the attempted subduction of Laurentia beneath the microcontinent at the beginning of the Taconic orogeny allowed the formation of the Martinsburg foreland basin during the Middle Ordovician. C. Closing of the small ocean basin or the Iapetus Ocean during the early Late Ordovician Taconic orogeny reactivated the extensional faults as thrust faults, forming the nappe megasystem. Thrust faulting during the Alleghanian orogeny greatly complicated the nappe megasystem. Rifting related to the opening of the Atlantic Ocean during the Late Triassic reactivated the thrust faults on the southeast as listric extensional faults. The amount, if any, of extensional movement of the other thrust faults is currently not known. The model presented here, therefore, suggests three periods of movement on the same faults: extensional, contractional, and extensional.

examples are known in Virginia. These faults may have been mechanisms to accommodate some of the regional shortening within the anticlinorium core.

The other faults shown in Figure 17-17 would appear to have less regional importance. The Antietam Cove fault was interpreted by Root (1971) to be a left-slip fault, that is, a second-order wrench fault, related to the Carbaugh-Marsh Creek fault. The Cold Springs, Reading Banks, and Piney Mountain faults are interpreted to be steep thrust faults, whereas the Laurel Forge and Clay Pit faults are thought to be high-angle normal faults (Root, 1970).

The above structural picture is a conservative reading of the field geology. More recently, however, geophysics and a better understanding of the mechanics of structural geology have allowed a much different solution. Geophysical data, particularly seismic reflection, summarized by Gwinn (1970) show that gently southeast-dipping basement rocks occur at a depth of greater than 25,000 feet beneath the Cumberland Valley. This, combined with the fact that the core rocks of the Blue Ridge-South Mountain anticlinorium had to be shortened as much as the rocks in the Great Valley and Appalachian Mountain sections of the Ridge and Valley province, led him to suggest that the anticlinorium was allochthonous above a deep thrust fault. Root (1970), also using geophysical data, came to the same conclusion, and the interpretative sections drawn by both geologists are essentially identical. David Elliott (personal communication, 1972) reported that the anticlinorium had to be allochthonous on the basis of data gained from unfolding the digitations on its west limb. Harris (1979) called attention to the geometry of the Blue Ridge-South Mountain anticlinorium and its similarity to that of the

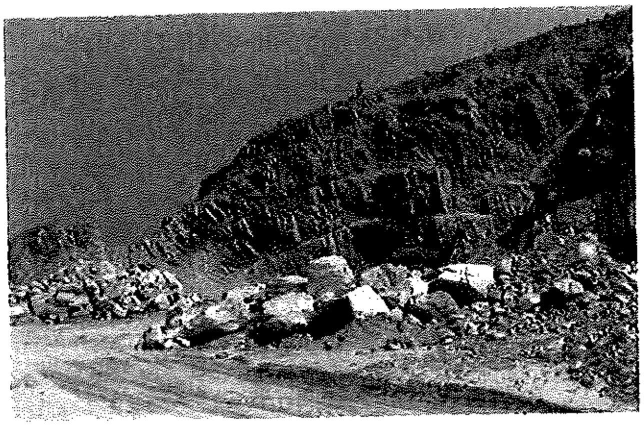


Figure 17-14. Open concentric fold in the Cambrian Antietam Formation in Franklin County. The cleavage occurs in a fan. Photograph by J. M. Fauth.

Figure 17-15. Bedding and cleavage in the Cambrian Conococheague Group northeast of Scotland in the Caledonia Park 7.5-minute quadrangle. Bedding dips steeply left, and cleavage dips gently right. The hammer is 16.75 inches long. Photograph by J. M. Fauth.

Figure 17-16. Layering and cleavage in the Late Proterozoic Catoctin Formation, Iron Springs 7.5-minute quadrangle. Layering dips steeply right, and cleavage dips gently left. The arrow is about 18 inches long. Photograph by J. M. Fauth.

Powell Valley anticline in Virginia, the type hanging-wall anticline of the Appalachian orogen. He concluded that the anticlinorium was allochthonous and drew an interpretative section not far different from those of Gwinn (1970) and Root (1970). Harris and others (1982) reported on a seismic-reflection survey from the Ridge and Valley to the Atlantic Coastal Plain in central Virginia that showed the basal reflector passing beneath the anticlinorium, as well as the Piedmont, thereby proving that the anticlinorium is allochthonous. The depth to the basal reflector, the presumed sole thrust, is between 26,000 and 28,000 feet, depending on a choice of travel time. This is essentially the same depth that was proposed by Gwinn (1970) and Root (1970) and that is shown on the interpretative section (Figure 17-18) presented herein. The seismic section shown in Harris and others (1982) is the only published seismic section across the anticlinorium, but all of the available data suggest that the central Virginia survey is directly applicable to Pennsylvania.

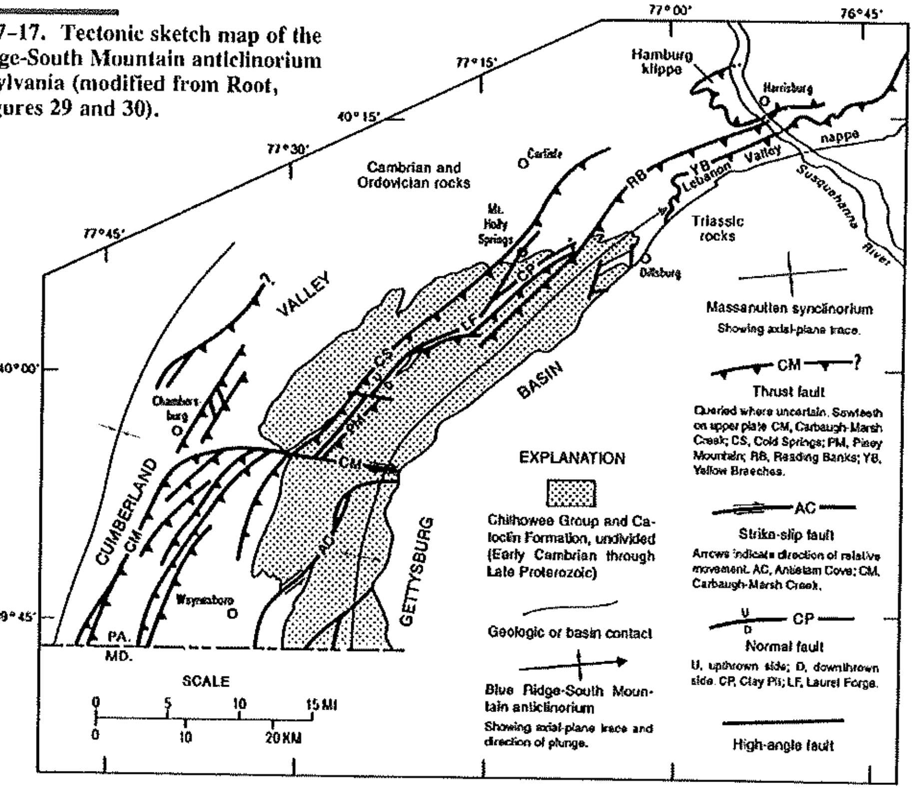
The interpretation presented in Figure 17-18 suggests that the anticlinorium proper moved on a thrust within the Martinsburg Formation and that there are two major thrust faults beneath this slip zone. Many thrust faults splay from this surface, forming an imbricate fan. The concept of duplex structure immediately comes to mind. A recent analysis of Ridge and Valley geology in central Pennsylvania (Chapter 19), however, suggests that the thrust system there lacks a roof thrust and thereby constitutes a "passive-roof duplex." The applicability of this solution to the imbricate fan associated with the Blue Ridge-South Mountain anticlinorium is beyond the scope of this paper.

In summary, the Blue Ridge-South Mountain anticlinorium is an allochthonous hanging-wall anticline above a major nonemergent thrust fault. The importance of such faults (Drake, 1978; Boyer and Elliott, 1982) cannot be overemphasized and should be considered in the analysis of any antiformal structure in a tectonic realm. The early proponents of an allochthonous Blue Ridge-South Mountain anticlinorium, George and Anna Jonas Stose, have been proved correct; the "Blue Ridge thrust" does not crop out at the base of the anticlinorium and does not emerge at the surface.

Time of Deformation

No structural feature has been observed within the pre-Silurian rocks of the anticlinorium that cannot be found in younger rocks to the west, a point first put forth by MacLachlan and Root (1966). Additional data were summarized by Drake (1980). South Mountain is overridden on the northeast by the polydeformed rocks of the Lebanon Valley nappe system on the Yellow Breeches thrust fault (Figure 17-17; Chapter 18). This terrane boundary is important (Drake, 1980), but it cannot be satisfactorily explained at this time. Mesozoic deformation must have been active along the east limb of the anticlinorium, which adjoins the Gettysburg basin. Presumably, the steep normal faults shown on Figure 17-18 are of Mesozoic age and may be reactivated Paleozoic faults like those in the Reading Prong.

Figure 17-17. Tectonic sketch map of the Blue Ridge-South Mountain anticlinorium in Pennsylvania (modified from Root, 1971, Figures 29 and 30).



Tectonics

Many geologists have taken the Blue Ridge-South Mountain anticlinorium to lie along the transition of miogeoclinal rocks on the west to eugeoclinal rocks to the east. It has been suggested (Wehr and Glover, 1985) that the anticlinorium lies along the hinge zone related to the opening of the Iapetus Ocean. Certainly the immense quantities of volcanic rock and rift-facies rocks in the lower part of the Chilhowee Group (Chapter 3B) show that the Pennsylvania part of the anticlinorium contains rift-related rocks. Basement rocks exposed to the south contain vast quantities of Catoctin feeder dikes that in places constitute at least 50 percent of the rock volume. This mixture of rift-related igneous rocks and Laurentian granitoid rocks would appear to constitute the elusive "transitional crust" known only heretofore as the "stuff that makes squiggly lines" on reflection profiles. These relationships suggest that the hinge line of Wehr and Glover (1985) in Virginia can be transported to Pennsylvania with some validity. It is likely that the collision of Gondwana and Laurentia that caused the Alleghanian orogeny reactivated the extensional faults along the hinge zone as thrust faults of the Blue Ridge-South Mountain thrust system. This reactivation model differs little in concept from that put forth above for the Reading Prong, but differs greatly in timing and tectono-environment setting. The lack of volcanic rocks and feeder dikes in the Reading Prong basement supports the model of Lash and Drake (1984) of a small ocean that never progressed past the intracontinental phase. Therefore, although a fault-reactivation model is proposed for both the Reading Prong and the Blue Ridge-South Mountain anticlinorium, they formed at different places and at different times. The boundary between these two external basement massifs remains obscure. The Yellow Breeches thrust fault (Figure 17-17) is locally important, but it is doubtful that it is the prime contact.

PROBLEMS AND FUTURE RESEARCH

South Mountain and the Reading Prong have been almost completely mapped at the scale of 1:24,000 and constitute two ideal field laboratories for further research. The Middle Proterozoic deformational framework in the Reading Prong is not well understood. This would make an excellent topical study. Although the area is poorly exposed, there are many excellent outcrops that could be studied in detail by a researcher not hindered by the necessity of covering the ground.

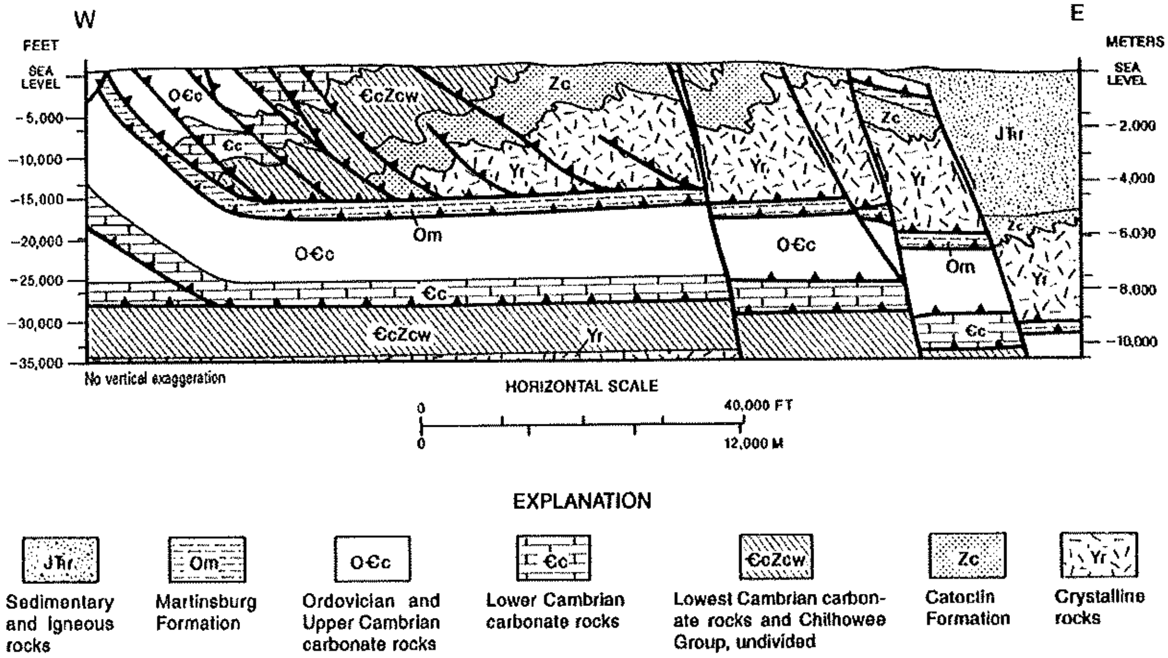


Figure 17-18. Geologic cross section through the Blue Ridge-South Mountain anticlinorium near the Maryland state line (modified from Berg and others, 1980, cross section D-D′).

Results from this work combined with those suggested in Chapter 3B would be of major importance in understanding the Grenvillian history of the Appalachians.

The effects of the Taconic and Alleghanian orogenies are difficult to separate in the Reading Prong. A concentrated effort to study the many faults in detail, as well as the relation of the basement to the cover rocks, should be undertaken. New laser techniques may be useful in dating different fabrics and, thereby, in separating the results of different orogenic periods.

Detailed topical structural studies should also be made in South Mountain to determine if evidence for pre-Alleghanian deformation might exist. The northern Blue Ridge is an anomaly in Appalachian external massifs because of its lack of Taconian deformation. Perhaps it is separated from the Reading Prong by a major strike-slip fault. A study of this possibility should be made.

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Profile

Professional hydrogeologist with 30+ years of applied experience. Managed major regional and site scale hydrogeologic/environmental projects, including in the Highlands and Valley and Ridge Physiographic Provinces in PA and NJ that contain karst geology. Published numerous geologic reports, and, presented findings to large and small groups.

Education/ Licenses

Rutgers University, New Brunswick, NJ Geological Sciences Ph.D.	2005
Lehigh University, Bethlehem, PA Geological Sciences M.S.	1984
University of Southern Maine, Portland, ME Earth Sciences B.A.	1981
PA Professional Geologist PG-001006-G	1994
8 Hour Hazardous Waste Site Worker Refresher	2013

Career History

Environmental Management Services, Inc., (EMS Environmental), *Bethlehem, PA*
Senior Hydrogeologist (April 2011 to present)

- Oil and Gas Exploration and Production Waste Facility Auditor in Ohio & North Dakota (90 facilities) for a Fortune 500 Company
    - Documented, evaluated, ranked & reported quality of facilities receiving and disposing of O &G exempted (RCRA) non-hazardous waste. Facilities included: saltwater disposal wells, landfills, drill cutting handling, metal recyclers, NORM receiving, transfer & disposal
- Environmental Health and Safety Coordinator
- Project Manager for Petroleum Contaminated Retail Gasoline Stations
    - Conduct investigations and interpret environmental fate and transport of contaminants in complex hydrogeological settings including Karst.

New Jersey Geological Survey
Research Scientist 1 (1986 to 2009)

- Project manager for As in groundwater research projects in NJ that focused evaluating sources, mobilization and transport mechanisms of As in various geological settings. Involved, funding proposal prep, work/QA plan prep, well installation oversight, collection and analyses of groundwater, surface water, mine pit water and soil and rock, use of public and private laboratories, electron microprobe analysis and data compilation, interpretation, presentation and publication.
- Project manager for design and implementation of New Jersey's Ambient Groundwater Quality Monitoring Network (NJDEP/USGS cooperative project) to evaluate status and trends of non point source pollution in shallow groundwater in watersheds as a function of land use. Involved grant proposal prep, work/QA plan prep, site selection, well drilling oversight, sample event coordination and data compilation, interpretation, presentation and publication.
- Project manager to determine the sources of lead (Pb) in well water in Lafayette Township, Sussex County, NJ. Involved funding proposal prep, work/QA plan preparation, collecting samples of well water, plumbing materials and scale, ore deposits, data compilation, interpretation, presentation and publication.

New Jersey Geological Survey
Research Scientist 1 (1986 to 2009)

- Researched, developed/applied and published an innovative methodology to filter lunar and solar tidal frequencies in groundwater for flow direction evaluation
- Provided hydrogeologic technical support for CERCLA (Superfund)
- Groundwater expert on multiple water quality focused committees
- Used Visual MODFLOW and MINQL 4.5 models

Adjunct Professor* Rutgers University Dept. of Earth and Planetary Sciences New Brunswick, NJ (2006 to 2009), Bucks County CC in Newtown, PA *(1993 to 2011)

- Physical Science, Earth Science and Physical Geology

Vibratech Engineers
Project Manager (1984 to 1986)

- Conducted mine blasting related ground vibration, and, geochemical ground-water assessments at coal mines and construction sites

Northeast Geochemical
Field sampler and Assistant lab supervisor (1979 to 1981)

- Collected soil samples and geophysical data (VLF, magnetometer) for regional geochemical surveys in Maine. Conducted soil/rock analysis using AA spectrophotometry.

Presenter

- Environmental Management Services, Inc., Bethlehem, PA-Shale Gas 2011
- Rutgers University Geological Colloquium-As in groundwater 2008
- National Water Monitoring Conference-Atlantic City-Regional GW quality 2008
- Public Meeting Presenter, Oxford, NJ-As in groundwater 2008
- Field trip leader-Arsenic in Ground Water, National GSA, Philadelphia, PA 2006
- Geological Society of America-National-Arsenic 2006
- Geological Society of America-Northeast section-Arsenic 2006
- Volunteer Water Monitoring Conference- Ambient Network 2004-2007
- Regional Workshop, Hydrogeology in the Newark Basin, NJ- Arsenic 2004
- Department of Environmental Science, Rutgers University- Arsenic 2003
- American Chemical Society, NY, NY-Arsenic 2003
- United States Geological Survey, NJ-Arsenic 2003
- Rutgers University Museum, Rutgers University-Arsenic 2003
- Department of Environmental Sciences, Drexel University-Arsenic 2002
- Department of Geological Sciences, Rutgers University-Arsenic 2001
- Columbia University, Arsenic in Drinking Water Conference-Arsenic 2001
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Military

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United States Air Force Reserves 1975 to 1979 – Honorable Discharge

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Education

2008, Ph.D., Rutgers the State University, New Brunswick, NJ, Geological Sciences
1984, M.S., Lehigh University, Department of Geological Sciences,
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Professional Experience

1984- Present, Research Scientist 2, New Jersey Geological Survey, Conducts Field Geology and Compiles and Publishes Geologic Maps focusing on the Highlands, Valley and Ridge and Piedmont Physiographic Provinces.
2008-Present, Adjunct Professor, Department of Geological Sciences, Rutgers University
  2009 Stratigraphic Correlator, IODP Expedition 313
  2002 Cruise, *R/V Endeavor*, multichannel seismic cruise, Mid Atlantic continental margin
1980-1981 Geologist, Utah Development Co, Bobo Dioulasso, Burkina Faso, mineral exploration
1978-1980 Peace Corp Volunteer on UNDP UPV78 Mineral Exploration, Upper Volta
1978 Hydrocarbon Mud Logger, Core Laboratories

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