TRIP B4: LOWER TO MIDDLE DEVONIAN ROCKS OF THE DELAWARE WATER GAP NATIONAL RECREATION AREA, NEW JERSEY: FRACTURE AND LITHOLOGIC CONTROL ON ROCK-SHELTERS, KARST AND GROUNDWATER FLOW

DON MONTEVERDE
New Jersey Geological and Water Survey, Trenton, 08624

RON WITTE
New Jersey Geological and Water Survey, Trenton, 08624

ABSTRACT

Kittatinny Mountain is a major ridge that crosses eastern Pennsylvania, through northwestern New Jersey and into southern New York. It is underlain by Middle Silurian Shawangunk Formation, a resistant quartz sandstone to quartz-pebble conglomerate that separates younger Silurian and Devonian carbonate and clastic sediments on the west from Cambrian and Ordovician flysch and platform carbonates to the east. Kittatinny Mountain displays a change in structural trend from northeastward to northward near an exposure of Upper Ordovician nepheline syenite, part of the Beemerville Intrusive Complex. Westward this same structural trend is marked by upright and northwest directed overturned folds and well developed cleavage in Pennsylvania, which becomes a broad zone of gently dipping formations generally devoid of a penetrative cleavage in New Jersey. Here outcrop widths of the units are doubled. Tight and overturned folding with cleavage development and an associated decrease in outcrop width reappears farther to the north across the New York border. This undeformed zone widens to the west creating bowed margins on maps and DEMs with the syenite body at the center of the bow.

Did the Beemerville Intrusive Complex form a rigid block that created a strain shadow against Alleghenian westward directed compressional deformation? Preliminary field data in conjunction with regional gravity and seismic reflection studies while not definitively pointing to this hypothesis as the only possible conclusion it also does not negate it as a possible answer. Other possible explanations exist including indentor-controlled variability and margin-controlled geometry for example which require further research. At this point we favor an interaction with a foreland obstacle, the Beemerville Intrusive Complex.

The strain shadow creates an impact on weathering and groundwater flow as compared to the more highly deformed regions to the north and south. Karst development has to date only been found within the strain shadow, mainly in the Onondaga Limestone where beds dip uniformly gently to the northwest. Here joints, enlarged by dissolution, dominantly control groundwater flow. Other reactions of weathering to this change in structural style along strike are investigated such as joint cave development in non-carbonate rocks.

Key words: Devonian, shadow zone, cleavage, fracture

INTRODUCTION

The advent of DEM's (digital elevation models) and Lidar (acronym for Light Detection and Ranging) as well as Google Earth has allowed the investigation of the detailed landscape without leaving the office.

These tools are especially helpful with the geology of northwestern New Jersey. Using these tools, one sees a long curving ridge stand out in the topography that trends westerly out of eastern Pennsylvania, turning more northeasterly through New Jersey and more northerly into New York. Its name depends on its location, Blue Mountain in Pennsylvania, Kittatinny Mountain in New Jersey, and Shawangunk Mountains in New York (figure 1). It also forms a geological time break in that older rocks from Ordovician to Mesoproterozoic lie to the east and the younger rocks ranging from Silurian and younger to the west. One particular feature is an apparent nearly doubling of the outcrop width in New Jersey between Kittatinny Mountain and the Delaware River. Several different belts of rocks increase in width across the Culvers Gap, Branchville, Milford and Port Jervis South quadrangles (figure 1).

The best place to observe this morphologic change in the field is from High Point State Park in northwestern New Jersey. At the High Point monument (figure 1), beautiful vistas are open in all directions that offer a good vantage point to observe the changing topographic expression of the regional landscape. The visible topography is mostly controlled by the underlying bedrock with locally a blanket of thick glacial deposits. The ridge is the Middle Silurian Shawangunk Formation with the younger Bloomsburg Red Beds forming the western slope of Kittatinny Mountain. In a visual traverse beginning in the northwest, the distant ridges comprise the gently tilted Devonian and younger rocks of the Appalachian Plateau termed the Poconos in Pennsylvania and Catskills in New York. Northward is the termination of the Shawangunk Mountains/Formation. Eastward, there is a multilayered assemblage of rocks in both type and time. Just below the overlook the sandstone, greywackes and slates of the Ordovician Martinsburg Formation are visible. Farther afield are well-defined ridges in the Hudson and New Jersey Highlands consisting of Mesoproterozoic metamorphic rocks related to the Grenville Orogeny. A linear valley between the low lying Martinsburg ridges and the metamorphic ridges, named Kittatinny Valley in New Jersey, contains a belt of Cambrian and Ordovician carbonate rocks that lay in a recess position due to their higher degree of erosion. Southward, Kittatinny Mountain swings westward into Pennsylvania.

This field trip is not to investigate the reasons for this increased width of the exposed Middle Devonian through Middle Silurian rocks, though we will present two possible explanations. The field trip will offer examples of how the structural imprint, related to this increase of the outcrop belt, plays a role in many different features such as karst, groundwater flow, and habitation by early man.

Regional Geology

Martinsburg Formation represents the oldest units in this study (figure 2). It comprises several different members that vary along strike, all of which formed from turbidite deposition into a deep linear foreland basin. In northwestern New Jersey, the Martinsburg comprises three members. The Bushkill is a ribbon slate that forms the base of the turbidite deposition into a deepening basin that developed on a subsiding Cambrian and Ordovician carbonate bank. The Ramseyburg Member, which overlays the Bushkill and displays an increase of grain size with the addition of interbedded greywacke sands. These

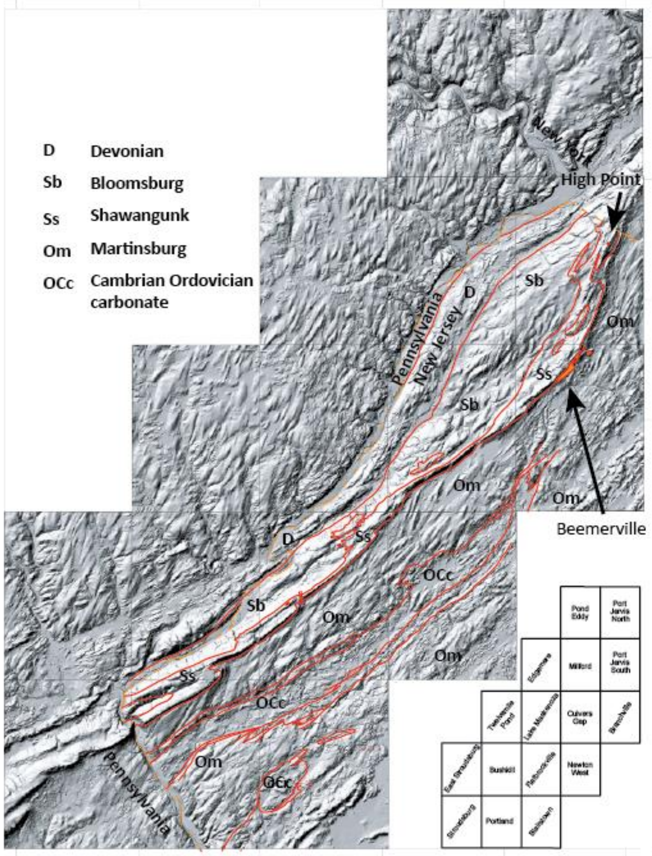


Figure 1. Regional digital elevation model (DEM) map of the Kittatinny Mountain region of New Jersey. Base map is a compilation of 16 DEM quadrangles with a 5x vertical distortion and a southeast looking illumination.

two units are found across northwestern New Jersey and into Pennsylvania (Drake and Epstein, 1967). McBride (1962) studied Martinsburg sedimentology and noted deposition occurred both downslope (northwestward) and parallel (southwest-northeast trending) to the basin axis. The third and youngest regional member of the Martinsburg varies by location and displays a pronounced along-strike morphology in the foreland basin. The Penn Argyl Member in eastern Pennsylvania, with its thick slate beds and associated commercial slate quarries, maps out a deeper depositional environment within the basin. Thick sandstone beds with rare shale ripups of the locally occurring High Point Member suggest a more proximal deposit to the sediment flow (Drake, 1991). McBride (1962) showed that Martinsburg paleoflow in New Jersey parallels the bathymetric basin axis towards the southwest; whereas sediments located farther westward were carried northeast both possibly accounting for the deep sedimentation of the Penn Argyl. The Martinsburg was considered late Middle Ordovician age (Parris and Cruikshank, 1992), but due to refining time boundaries (Cooper and Sadler, 2012), the same fossil assemblage is now considered Upper Ordovician (Dalton and others, 2014) with deposition synorgenic in the Taconic Orogeny.

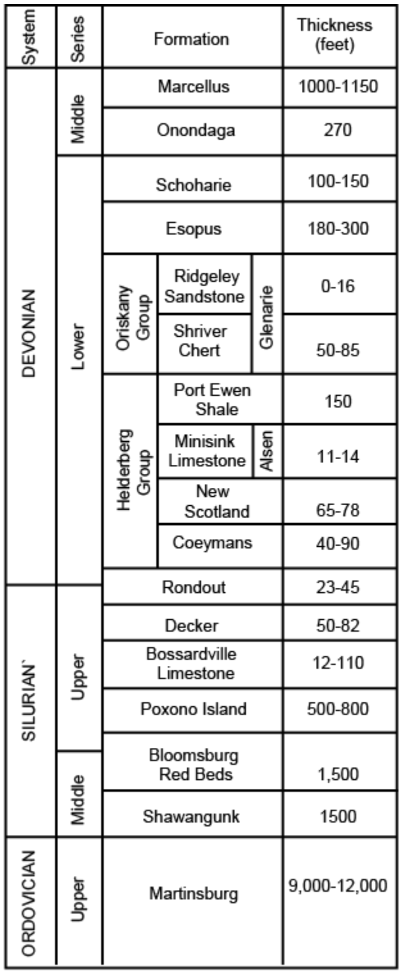
The ridge forming Shawangunk sits with an angular unconformity on the Martinsburg. It consists of thin- to thick-bedded quartz and feldspathic sandstone, quartzite, and quartz-pebble conglomerate. Clasts are primarily quartz, with some dark-gray argillite and black chert (as long as 5 cm (2 in)) in poorly- to well-sorted, planar tabular to trough cross-bedded sandstone. It developed as a clastic wedge, deposited under an alluvial fan to braided stream environment, after the uplift of the Martinsburg foreland basin at the close of the Taconic Orogeny (Epstein, 1993; 2001; Epstein and Epstein, 1972). Gray and Zeitler, (1997) showed the sediment provenance of the pebbles in the Shawangunk as an uplifted and unroofed Grenville terrain from the southeast. An angular unconformity, commonly termed the Taconic unconformity, forms the basal contact separating the Shawangunk from the Martinsburg, and varies in angular divergence along strike (figure 3; Epstein and Lyttle, 1989; 2001). Only a 5° to 10° difference in bedding exists on its few exposures across New Jersey. Exposures in eastern Pennsylvania continue the gentle angular difference (Wintsch and others, 1996) into central

Pennsylvania, near Hamburg, where a near 90° angular divergence exists, though the contact could represent a fault zone (Lash and others, 1984). In New York, the angular difference also increases. Here the Shawangunk is eroded away and a younger unit, the Upper Silurian-Lower Devonian Rondout rests atop the Martinsburg.

Lying within the Martinsburg is the Beemerville Intrusive Complex. This complex includes two nepheline syenite bodies, several diatremes and associated dikes that intrude the Martinsburg Formation. Maxey (1976) described another nepheline syenite body that intruded into the Shawangunk. This occurrence, however, may actually represent glacial erratics of late Wisconsinan age as there is no evidence of any contact metamorphism. Also, westerly glacial striations and syenite erratics found west of Kittatinny Mountain (Monteverde and Witte, 2012) show how the late Wisconsinan glaciation could have deposited these large blocks of syenite on the Shawangunk as described by Maxey (1976).

Previous workers have outlined several other igneous bodies related to the Beemerville complex, which is also called Beemerville Intrusive Suite (Drake and Monteverde, 1992). These include several diatremes near the syenite bodies and others in a small cluster farther to the southeast (Spinks, 1967; Maxey, 1976; Drake and Monteverde, 1992). Xenoliths within the diatreme include Mesoproterozoic Grenville metamorphics, lower Paleozoic dolomites and the Martinsburg, showing the magma traversed the entire geologic column of that time of New Jersey.

Ratcliffe and others (2012) used U-Pb TIMS method on titanite that yielded a 447±2 Ma age for the Beemerville complex. Several fission-track ages explain the cooling history of the intrusion. Eby (2004, 2012) calculated a fission-track age on titanite of 420 ± 6 Ma mean to mark the cooling to a ~275° C and a younger age of. 156 ± 4 Ma. The high resolution age date of Ratcliffe and others (2012) places the Beemerville intrusive older than Shawangunk deposition.



System	Series	Formation			Thickness (feet)
DEVONIAN	Middle	Marcellus			1000-1150
		Onondaga			270
	Lower	Schoharie			100-150
		Esopus			180-300
		Oriskany Group	Ridgeley Sandstone	Glenarie	0-16
			Shriver Chert		50-85
		Helderberg Group	Port Ewen Shale		150
			Minisink Limestone	Alsen	11-14
			New Scotland		65-78
			Coeymans		40-90
SILURIAN`	Upper	Rondout			23-45
		Decker			50-82
		Bossardville Limestone			12-110
		Poxono Island			500-800
	Middle	Bloomsburg Red Beds			1,500
		Shawangunk			1500
ORDOVICIAN	Upper	Martinsburg			9,000-12,000

Figure 2. Regional stratigraphic column (modified from Epstein, 2001)

The Bloomsburg Red Beds, an Upper Silurian red, fining-upwards clastic unit grades into and overlies the Shawangunk Formation. A complete fining-upwards sequence contains a basal medium-grained, cross- to planar-bedded sandstone with an erosional base that grades upwards through fine-grained, laminated sandstone/ siltstone and into a shale (Epstein and Lyttle, 1987; Prave and others, 1989; Alcala, 1990; Epstein, 2001b). Locally fining-upward sequences may be poorly defined and missing the shale cap. Bloomsburg sediments mark the transition from braided to meandering stream environments with rare paleosols (Epstein, 2001b; Driese and others, 1991) into marginal marine to brackish water marking a minor marine transgression (Epstein, 1971; Metz, 2000). Similar to the Shawangunk, sediment was transported westward and northwestward. Due to its increased iron content metamorphic rocks such as Grenville rocks uplifted and exposed by the Taconic Orogeny have been suggested as their sediment source (Epstein, 2001).

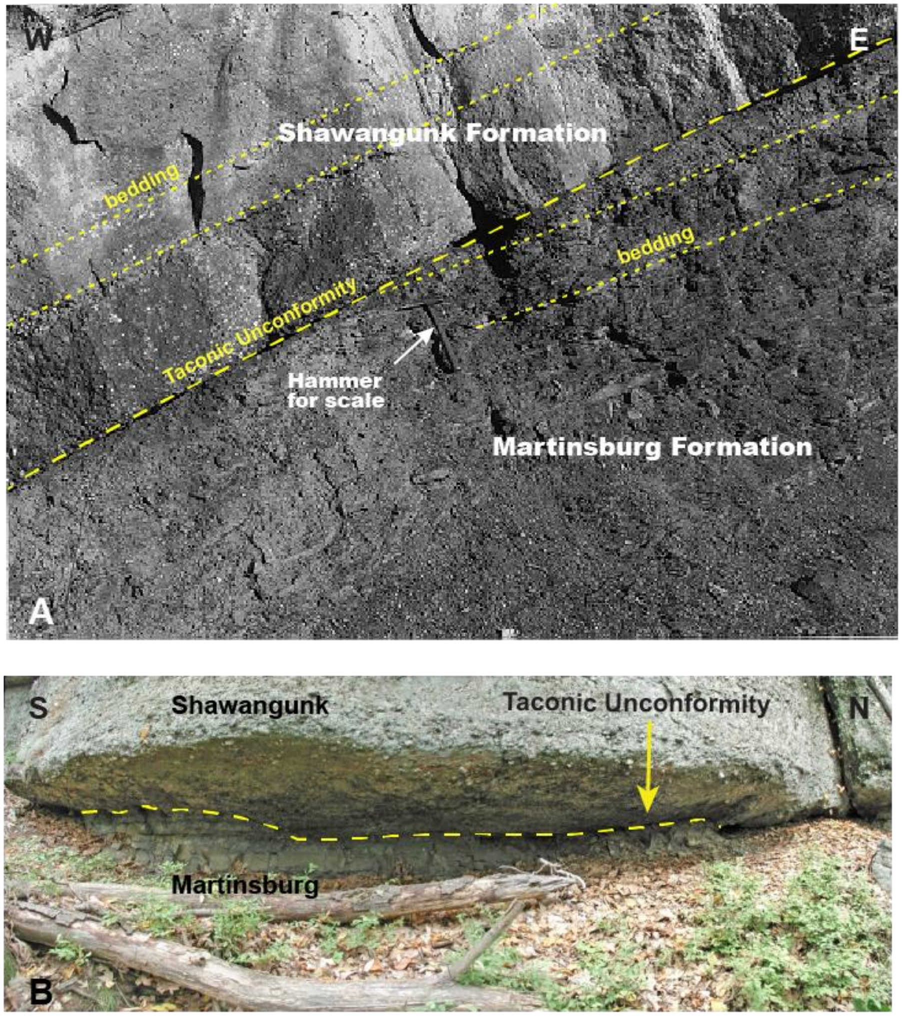


Figure 3 - Exposure of the Taconic unconformity. A) exposure looking north taken during construction of Interstate Route 84 in New York by Epstein. Note slight angular divergence between the Shawangunk and Martinsburg sediments. B) exposure looking west taken south of Sunrise Mountain in Stokes State Forest, New Jersey by Monteverde. Surface shows evidence of minor slip.

Generally, shallow marine waters blanketed this region for the remainder of the Silurian as shown by the sediments of four different units, Poxono Island Formation, Bossardville Limestone, Decker and Rondout Formations. Poxono Island and overlying Bossardville are dominantly carbonate deposited near sea level in highly saline and/or brackish water in intertidal to supratidal flats and partly lagoonal paleoenvironments (Epstein and others, 1967; Barnett, 1970; Epstein, 1986; 2001). Marine waters deepened in the Decker Formation as noted by its fine to coarse calcareous quartz sandstone and associated limestone beds. Epstein and others (1967) and Denkler and Harris (1989) interpreted the quartz sand-bearing lithofacies as deposited in a barrier bar environment. Abundant trace (Metz, 2003a) macrofossils and localized biohermal facies are present in the limestone beds. Their depositional environments include a biostromal bank to shallow subtidal crinoidal meadow (Epstein and others, 1967; Barnett, 1970; Denkler and Harris, 1989). Sediments of the younger Rondout Formation indicate a return to very shallow brackish water conditions that periodically dried up such as in restricted lagoonal and tidal flat paleoenvironments (Herpers, 1951a; Epstein and others, 1967; Epstein and Epstein 1969; Barnett, 1970). Denkler and Harris (1988) used conodonts to place the Silurian-Devonian boundary within the middle of the Rondout.

The Helderberg Group, which is dominantly composed of limestones, marks relative tranquil marine conditions before the onset of the Acadian orogenic event. Basal sediments of the Helderberg contain several different formations, which will be combined here as the Coeymans interval. Biogenic limestone units vary along strike with some stromatoporoid biostromes with massive tabulate corals. Multiple authors have suggested that the biohermal facies formed isolated patch reefs close to sea level (Precht, 1982; 1984; 1989; Finks and Raffoni, 1989; Raffoni and Finks, 1989). We will visit an example of this reef material at stop 4. Fossils, including ichnofossils are abundant in this lithologic interval (Epstein and others, 1967; Spinks, 1967; Barnett, 1970; Precht, 1982; 1984; 1989; Finks and Raffoni, 1989; Raffoni and Finks, 1989; Metz, 2003b). Limestones from this interval formed under high-energy, shallow subtidal conditions (Epstein and others, 1967; Spinks, 1967; Barnett, 1970) and are capped by calcareous quartz-pebble conglomerate and sandstone interpreted as a barrier beach deposit (Epstein and others, 1967; Spinks, 1967).

A thick sequence of siliceous, calcareous, fossiliferous shale with argillaceous, fossil-rich limestone interbeds of the New Scotland Formation blankets the older rocks formed in deeper water (Epstein and others, 1967; Epstein and Epstein, 1969). Overlying the New Scotland and depending on location is either a fine grained limestone to the southeast (Minisink Limestone) (Epstein and others, 1967; Monteverde, 1992) or a medium-to fine-grained highly fossiliferous limestone associated with either the Becraft Limestone (Weller, 1902) or Alsen Formation of New York (Rickard, 1962; Barnett, 1970). Deposition in deeper waters formed irregularly bedded calcareous silty shale to shaly siltstone of the Port Ewen that caps the Helderberg Group.

New Jersey again proved to be the location for changes in deposition patterns. Going into New Jersey from Pennsylvania the Lower Devonian Oriskany Formation/Sandstone was subdivided into shale, sandstone, limestone and chert of the Shriver Chert, which grades upwards to coarse-grained calcareous sandstone of the Ridgeley Sandstone (Epstein, 2001). Along strike, the Shriver and Ridgeley change over to entirely limestone of the Glenerie Limestone. Sea level lowering that was initiated during Port Ewen deposition continued into the Oriskany.

The Wallbridge Unconformity, a major regional unconformity, failed to develop in this region due to the deep water paleodepositional environment of the Oriskany (C. Ver Straeten, written communication, 2004). The upper part of the Oriskany marks a regional transgression (Johnson and others, 1985; Ver Straeten, 2001a).

Esopus and Schoharie formations that grade from argillaceous siltstone and sandstone into siliceous or calcareous siltstone, sandstone and localized limestone depict several sea level cycles (Epstein, 2001a; Ver Straeten, 2001a; 2001b). Several K-bentonites located in the basal Esopus have yielded ^{207}Pb/^{208}Pb ages of 408.3±1.9 Ma (Tucker and others, 1998; Ver Straeten, 2002; 2003).

The Schoharie grades upwards into the Lower to Middle Devonian Onondaga Limestone (termed Buttermilk Falls Limestone on Drake and others, 1996 and Monteverde, 1992). Onondaga lithologies grade from a basal limestone containing variable black chert through an argillaceous limestone and into a chert rich limestone that caps the unit. A bentonite bed correlated to the Tioga Ash bed is located in the upper Onondaga (Epstein and others, 1974). Ver Straeten notes several Tioga A-G K-Bentonite beds within the upper Onondaga or at the contact with the

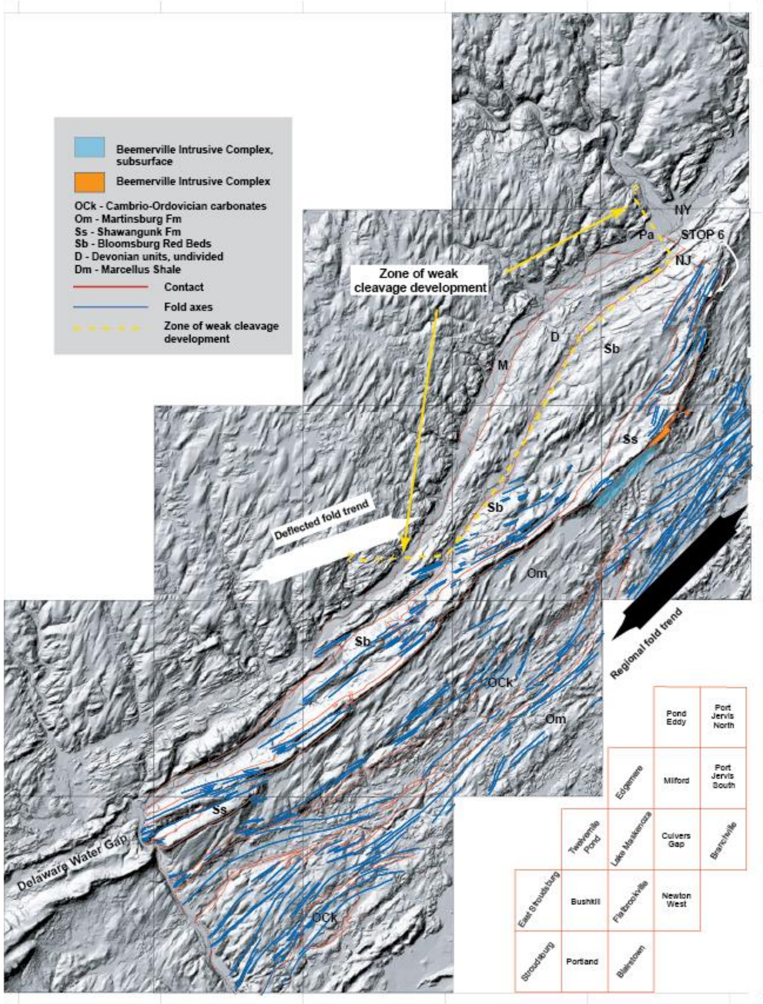


Figure 4. Regional structural interpretation of the Kittatinny Mountain region of New Jersey. Map depicts the outcrop location of the Beemerville Intrusive Suite shown in orange as well as the subsurface extension in blue, identified by Ghatge et al., 1992. The outcrop width of the Shawangunk and Bloomsburg increases markedly behind the intrusion. Fold trend deflects in the Silurian Devonian and also the Ordovician sedimentary units along the southern area of the intrusion. Base map is a compilation of 16 DEM quadrangle and has a 5x vertical distortion and a southeast looking illumination.

Marcellus. Tucker and others (1998) calculated 391.4±1.8 Ma ^{207}Pb/^{208}Pb age for the Tioga K-Ash bed.

Workers in eastern Pennsylvania and around the New York outcrop belt have subdivided the Onondaga into three to four members based on lithologic and paleontologic criteria that corresponds to variable sea level conditions (Epstein, 1984; Inners, 1975; Ver Straeten, 1996a; 1996b; 2001). Shallow water conditions prevailed during deposition of the basal Edgecliff Member's cherty limestone, but the argillaceous limestone of the overlying Nedrow Member suggests a deepening water environment. Shallow water conditions prevailed for the cherty limestone of the Moorehouse Member. This complete sea level cycle is repeated in the upper part of the Moorehouse Member into the youngest Onondaga Member, the Seneca Member (Ver Straeten, 2001).

The youngest rocks in northwestern New Jersey are thin-bedded dark-gray shales of the Middle Devonian Marcellus Formation, the shale-gas unit. Ver Straeten and others (1994), Ver Straeten and Brett (1995) and Ver Straeten (2001a) suggested the Marcellus should be elevated to "subgroup" status.

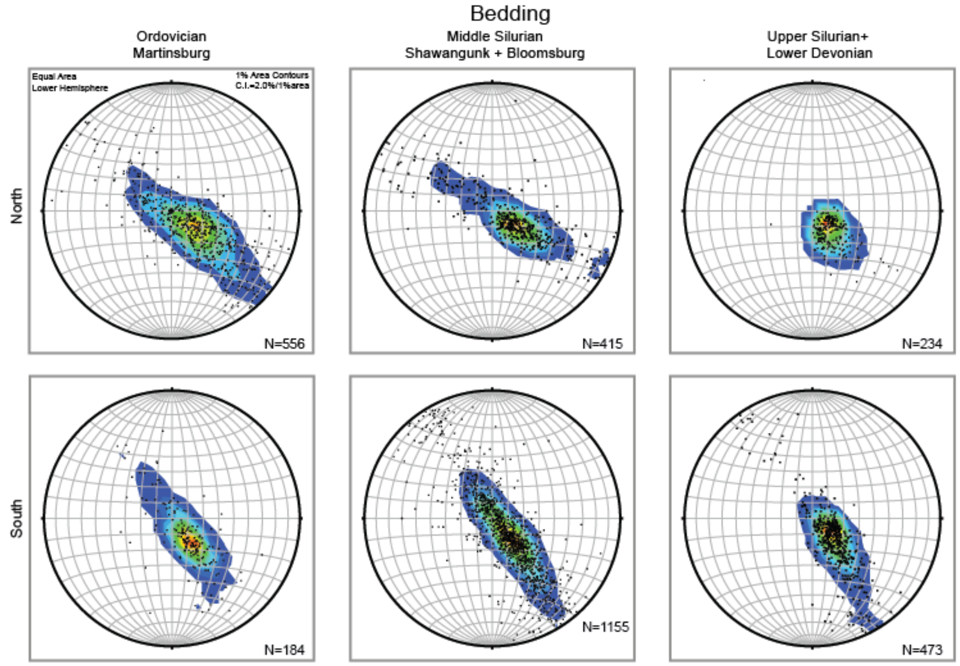
They place the Union Springs and Oatka Creek formations under the Marcellus. These formations are further subdivided into the shaly Bakoven and overlying Stony Hollow calcareous siltstones and sandstones, both within the Union Springs. The Oatka Creek was subdivided into 4 members that do not occur in New Jersey. The black shales mapped as Marcellus in New Jersey (Kummel, 1940) correlate to the Bakoven Member of the Union Springs. They are pyritic and contain a dwarf fauna indicative of an oxygen poor basin developed below wave base. These rocks are part of a prograding delta plain that culminates in the Catskill delta (Herpers, 1951b; Epstein, 1986; Faill, 1997).

DATA

Field Data

Regional field mapping allows an understanding of the influence of the different formations and a possible timing of events. The stratigraphy of this region has been known since before the map of Lewis and Kummel (1914). More recent detailed 1:100,000 and 1:24000 scale mapping has updated this early map product with recent advances in stratigraphy and structural interpretations (Epstein and others 1967; Spink, 1967; Monteverde, 1992; Drake and Monteverde, 1992; Drake and others, 1996; unpublished field data of Epstein and Monteverde). Mapping has shown that the trend of Kittatinny Mountain deflects at the Beemerville intrusive outcrop (figure 4; Drake and others 1996). Field data from both published and unpublished field mapping was analyzed to qualify the apparent change in structural orientation on both sides of the Beemerville outcrop. Structural data was subdivided geographically and stratigraphically. Data from the Lake Maskenozha (Monteverde, 1992) and Flatbrookville (unpublished data of Epstein and Monteverde) field mapping were combined as representative of structures south and west of the change in ridge trend and outcrop width increase. To the north, data was combined from Culvers Gap (Monteverde, 1992), Branchville, (Drake and Monteverde, 1992), Milford and Port Jervis South quadrangles mapping (unpublished field mapping of Epstein, Monteverde and Witte) for both the region of increased outcrop width and the change into a northern trend. It should be noted that the change from gentle dipping formations into the more northern steeply dipping beds were not sampled in sufficient quantity as mapping stopped at the NY-NJ state line. More mapping into New York is needed to create a more complete data set. Changes in dominant sediment type and age were reviewed independently. Martinsburg data (OM) collected east of the ridge was analyzed separately due its different sedimentology and being Ordovician age and was the only unit to have experienced any deformation from the Taconic Orogeny as well as younger deformational events. The younger units were subdivided more along rheological criteria such that the clastic Shawangunk and Bloomsburg Red Beds (S/B) were combined and separated from the dominantly carbonate Poxono Island through Marcellus (PIM) forming two separate data sets.

Field data is not conclusive. No statistics were run on this data and all interpretations are based on a visual inspection. Bedding data across all three sedimentary formation subdivisions show a strong agreement with the visual DEM data in that bedding south of the ridge trend changes strike more easterly than the more northerly strikes to the north (figure 5). Both show moderate dips and signs of folding. Cleavage differs in trend between the north and south OM data (figure 5). This trend difference is repeated in the S/B data but not as



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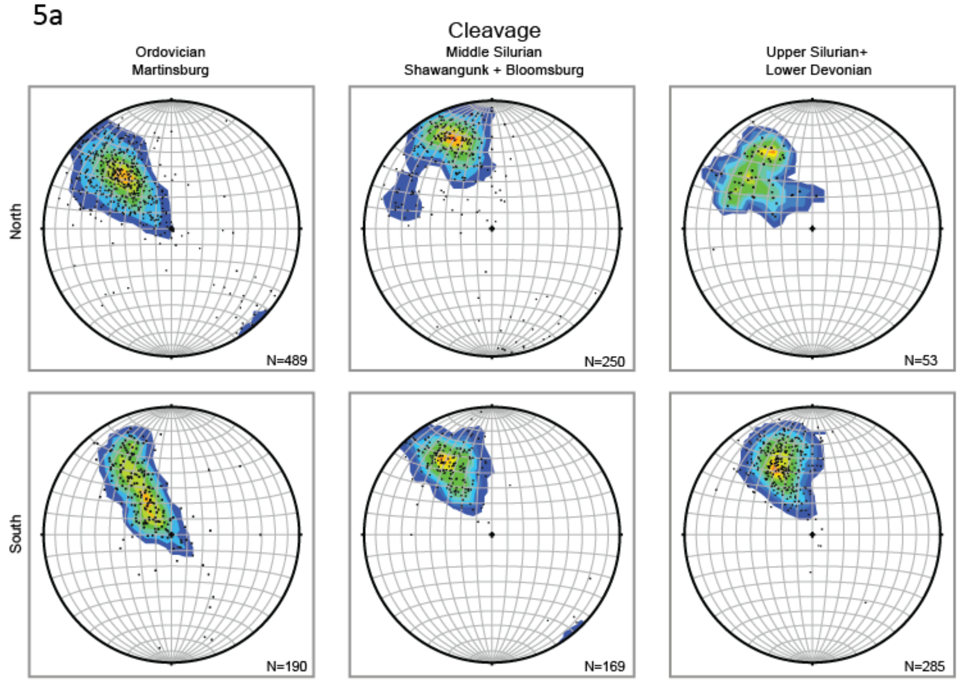

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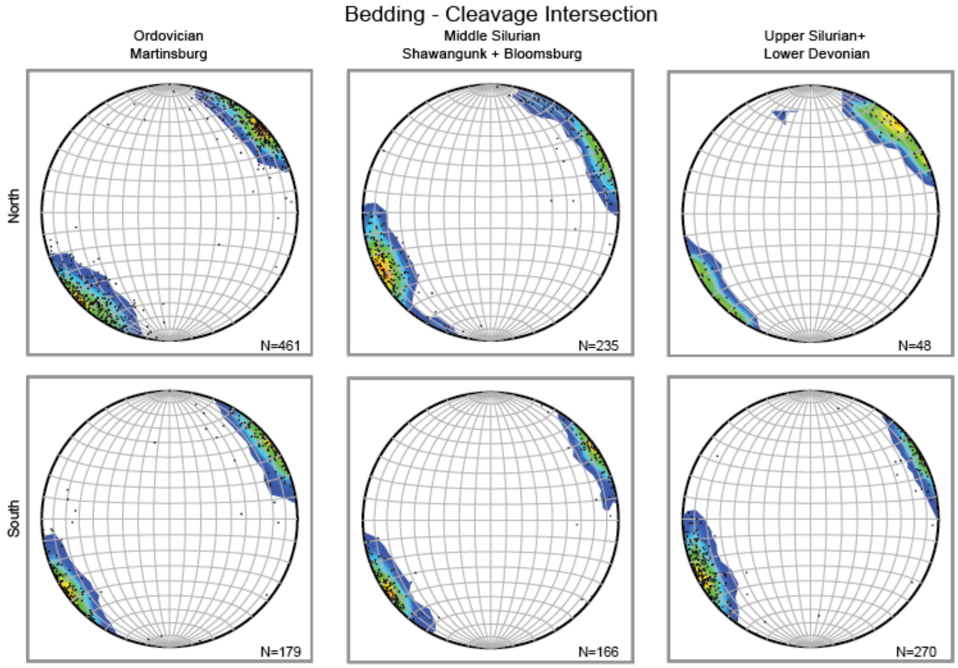
Figure 5. Equal area, lower hemisphere stereonet plots of regional data plotted using program of Allmendinger and others (2013) and Cardozo and Allmendinger (2013). Plots are divided into north and south segments as described in the text. Number of data points shown in lower right corner of each plot. Contour interval is 1% area. a) displays poles to bedding, b) poles to cleavage, c) displays bedding cleavage interseection, d) poles to joints.



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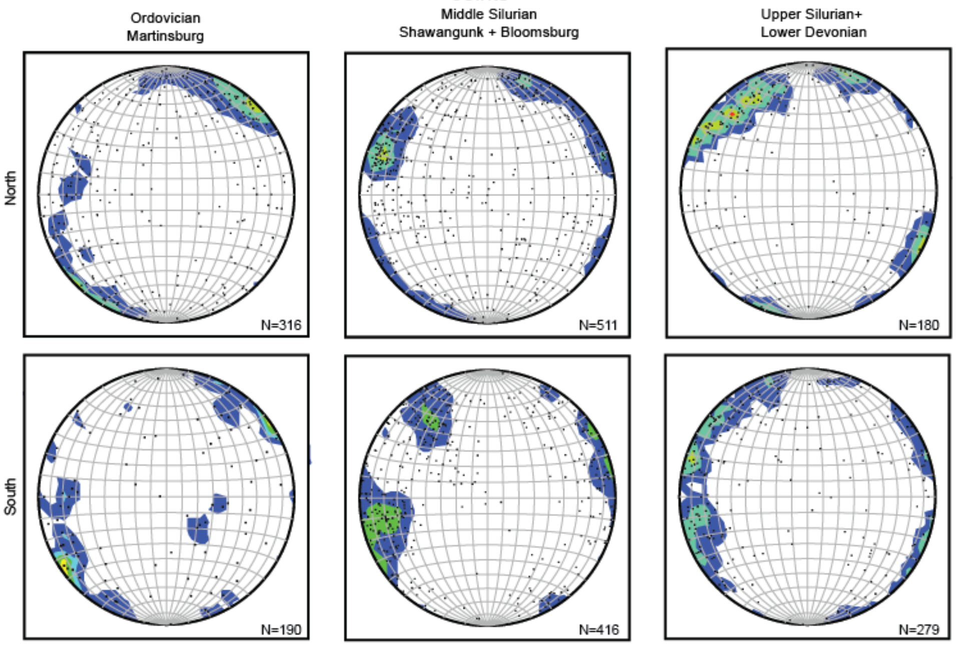

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clearly. Cleavage trends across the three southern sediment groups show a gradual rotation to more easterly strikes. Northern data display a strong rotation to a more easterly strike from OM to S/B with PIM presenting a broad maximum that “generally” parallels S/B trends. However, one must remember the general lack of cleavage in the northern PIM formations.

Bedding cleavage intersections somewhat mimic the cleavage trends (figure 5). South OM and S/B data display similar trends with PIM rotating slightly towards the east-west trend. Northern

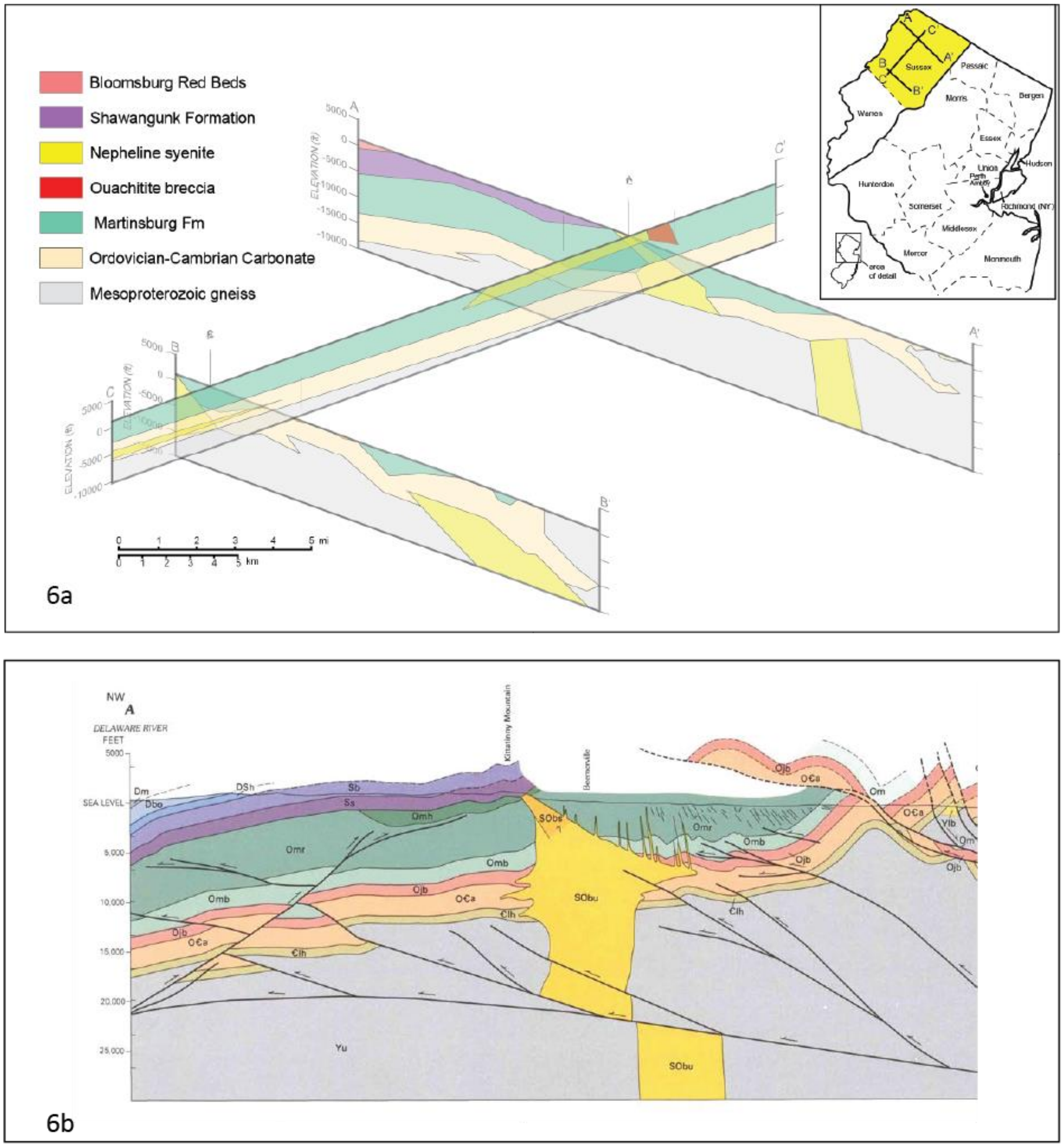
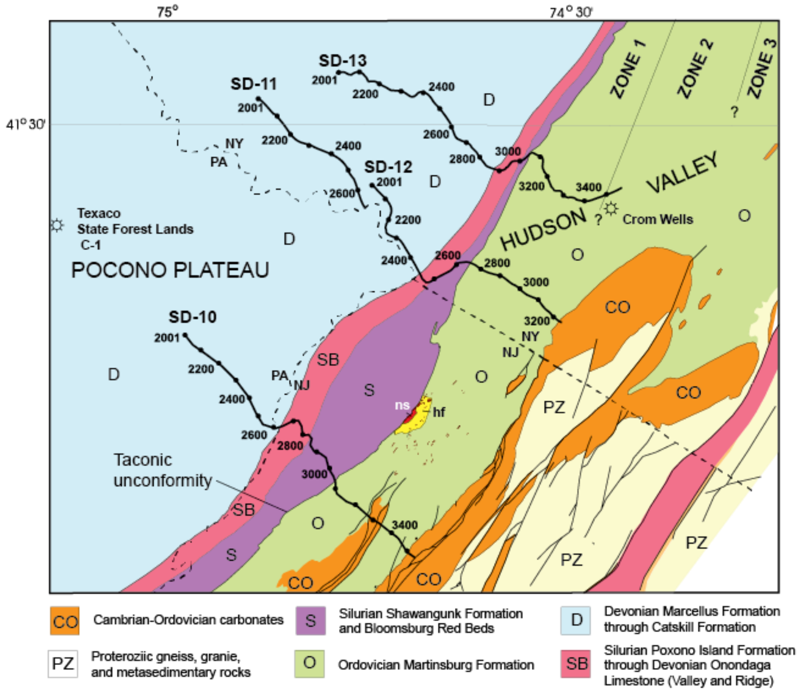


Figure 6. Results of gravity investigation to define the laterial extent of the Beemerville intrusive bodies (Ghatge and others, 1992). a) Modeled results of gravity data. Note that cross section have uniform scale but of variable depths. Two bodies were modeled on section A-A' that are interpreted as cut by a reverse fault, b) dip cross section from Herman and others (1996) showing intrusive bodies cut by thrust faults. Section does not conincide with located away from gravity sections. Unit SObu on section b represents the intrusive body, Sb=Bloomsburg, Ss=Shawangunk, Omh/Omr/Omb=Martinsburg, Ojb/OCa/Clh = Cambrian and Ordovician platform carbonates, Yu=Mesoproterozoic metamorphic units individed.

OM trends again shows a strong reorientation to the east-west trend, but more so that the South data. This compares to the north OM data trending more northerly than the south OM data. The north PIM is more diverse but has two slight maximums that correlate to either the OM or S/B both of the north. Again, the north PIM data are limited due to reduced cleavage development in the wider outcrop band.

Joint data is not that diagnostic (figure 5). They have a wider distribution and less defined maximums. Part of this reflects the data acquisition method in that all joints were given equal



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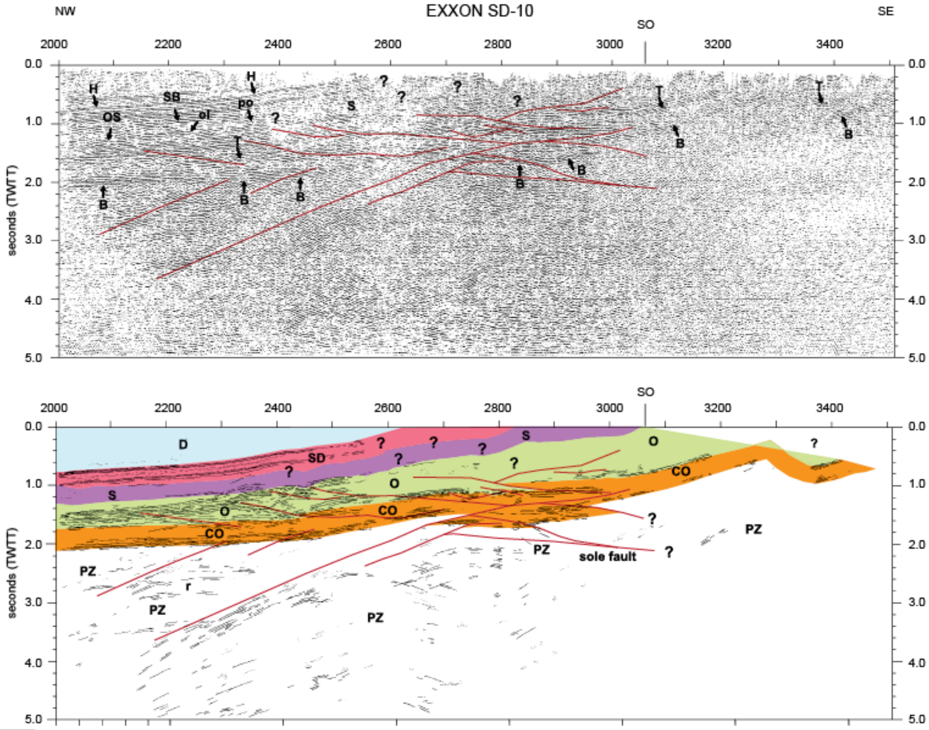

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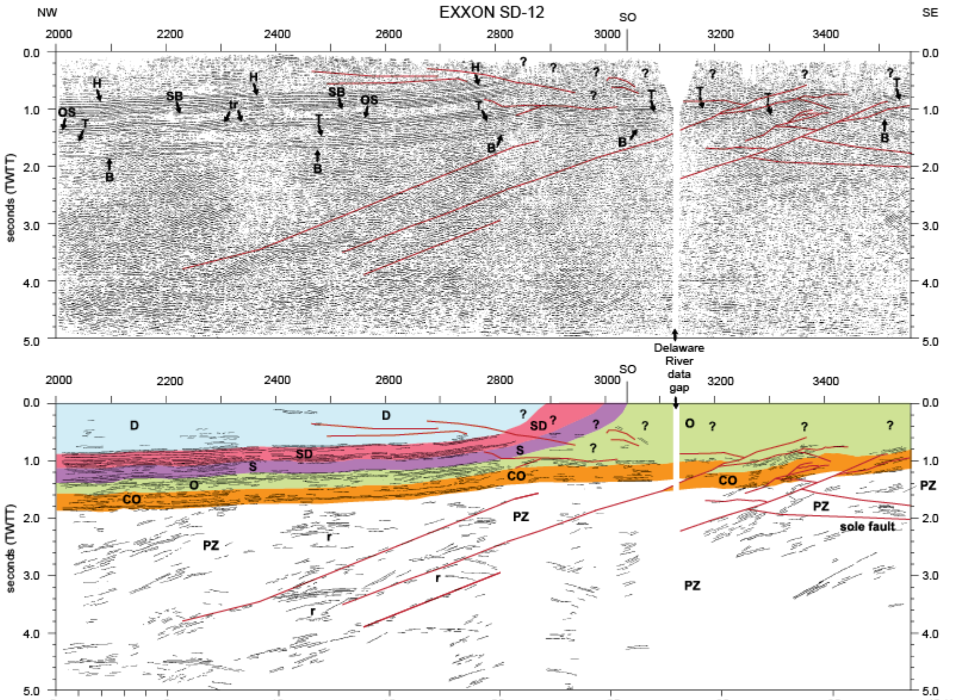
Figure 7. Location map of Exxon seismic lines and geological cross section based on 1:24,000 scale field mapping. b) Exxon seismic-reflection profile SD-10. Geologic interpretations are shown for both the migrated, full display (top) and the conventional line drawing (bottom). PZ – Proterozoic, B – upper boundary of PZ unit, CO – Cambrian and Ordovician carbonates, T – upper boundary of CO unit, O – Ordovician Martinsburg flysch, OS – upper



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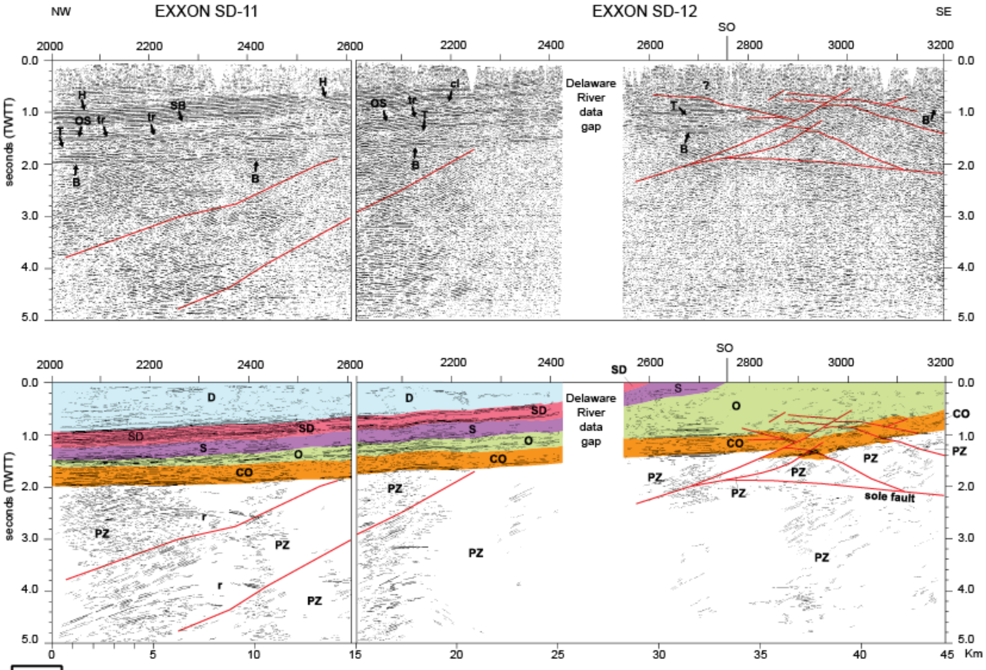

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Figure 7. (continued) boundary of O unit, S – Silurian molasse, SB – upper boundary of S unit, SD– Silurian and Devonian, undivided, H – upper boundary of SD unit, D – Devonian undivided, r – rollover, ol– onlap, po – pinch out. SO on map is location of the Taconic unconformity. Heavy red lines are faults. (modified from Herman et al., 1997). c) Exxon seismic-reflection profiles SD-11 and SD-12, abbreviations same as 7b. d) Exxon seismic-reflection profiles SD-13, abbreviations same as 7b

weight at each outcrop even though one particular trend may have been repeated multiple times at a single bedrock exposure.

Geophysical Data

The surface expression of the Beemerville Intrusive complex has long been known (Aurousseau and Washington, 1922; Spink 1967; Zartman and others, 1967; Drake and Monteverde, 1992; Drake and others, 1996), but not its subsurface extent. Jagel (1990) and Ghatge and others, (1992) used gravity and magnetic geophysical methods to investigate the subsurface continuation of the intrusive complex (figure 6). Their model greatly increased the subsurface extent of the Beemerville and showed that the sill thickened up to 2,000 ft (610 m) with a lateral extent of 5 mi (8 km) to the southwest following regional strike of Kittatinny Mountain. Farther to the south, a second southwest-trending syenite sill was modeled within Ordovician and Cambrian platform carbonates that thicken towards the northwest (figure 6). Ghatge et al. (1992) further suggested that the main intrusive body thickened dramatically with depth and also separated into two distinct bodies possibly offset by southeast-dipping Alleghanian thrust movement (Herman and others 1996). They modeled an extension of the pluton 5.5 miles (8.8 km) southeastward that thickened to 2 miles (3.2 km) at 7000 ft (2133 m) depth.

Exxon Co. USA collected three dip-trending seismic lines across Kittatinny Mountain and onto the Pocono Plateau (figure 7; Herman and others, 1997). Strata are combined into six seismic packages on the basis of seismic characteristics including Proterozoic basement (PZ), Cambrian and Ordovician carbonates (CO), Martinsburg (O), Shawangunk and Bloomsburg (S), Poxono Island through Onondaga Limestone (SB), and finally Marcellus into the Catskill Formation (D, figure 6). Fault displacement is primarily in pre-Shawangunk units (units PZ, CO and O) and shows a series of blind, gently easterly-dipping thrust faults in the east and younger moderately west-dipping antithetic faults in the western sections. Some blind faults end in broad and open cover folds in younger units and faulting just cuts the base of the Silurian on profile SD-10 suggesting post Taconic movement. Line SD-13, the farthest north line images steepened S and SB sections and an increased foreland-directed faulting into Devonian seismic units. It showed the return to the more highly deformed sections that continue northward. Profiles SD-10 and SD-12 image a broad region of Bloomsburg deposition as they sampled along the edges of the strain shadow (figure 7) Herman and others (1997) suggested this change marks a gradation into the increased foreland deformation of the Silurian and Devonian units (Marshak and Tabor, 1989; Burmeister and Marshak, 2006).

DISCUSSION

The structures in this region including some within the Martinsburg relate to Alleghenian deformation. Offield (1967) suggested that a broad fold in the Martinsburg is the deformational signature of the Taconic in this region. Epstein and Lyttle (1987; 2001) were able to separate Taconic from Alleghanian structures in their work with the Shawangunk and Martinsburg in the Ellenville area of New York. They interpreted that the Taconic only left gentle upright folds in the Martinsburg adjacent to the Shawangunk contact. Herman and others (1997) concluded similar ideas that the post-Taconic collisional event only left broad open folds in this region. In their research they uncovered an unpublished report by Merchant and Teet (1954) of the New Jersey Zinc Company that also advanced this idea. Cleavage age in the Martinsburg also has come into question as to whether it relates to the Taconic or Alleghenian Orogeny (see Monteverde and Witte, 2012) for a further discussion of this topic). Cleavage orientation between the Martinsburg and Shawangunk/Bloomsburg are very similar with the overlying rocks in close orientation (figure 5). Epstein and Lyttle (1987) have also proposed a different strain shadow to cleavage development in the Martinsburg proximal to the Shawangunk outcrop. These many sources conclude that the margin here in northwestern New Jersey was one of broad open folds at the end of the Taconic.

So the question becomes what occurred during the Alleghenian deformation event to account for the strain shadow in the Silurian and Devonian units in northwestern New Jersey? One hypothesis to explain this supposed strain shadow in northwestern New Jersey involves the Beemerville Intrusive Complex, at and near the Shawangunk-Martinsburg contact. Spink (1967, 1969, 1972) first suggested this model. It was thought to be similar to a water wave deflecting after hitting a stone. This would create a larger area behind the stone which does not feel the wave's influence. Some data could support the hypothesis that the Beemerville Intrusive Complex acted as a wall or buffer creating a 'strain shadow' to the Alleghanian tectonic strain propagation into the foreland. There is a marked difference in the amount of both penetrative and mechanical strains recorded in the Silurian and Devonian from eastern Pennsylvania through New Jersey and into New York (figure 4). Cleavage development in Upper Ordovician through Lower Devonian sediments displays similar regional trends southwest of Wallpack Center, New Jersey through Stroudsburg, Pennsylvania with the exception of a slight eastward overall trend in Lower Devonian units in relation to the older rocks (figure 5). This cleavage is penetrative in that it appears in most units as an intense southeast-dipping, closely spaced, locally slaty regional cleavage. Some units such as the Esopus with its high clay content developed a well-developed cleavage that is a defining characteristic used in bedrock mapping (Alvord and Drake, 1971). Within this 'strain shadow' the Esopus is almost devoid of cleavage as are the rest of the Devonian units. Locally some units express a hint of a spaced cleavage, but it is not penetrative. Cleavage plotted for these rocks on figure 4 is a poorly developed spaced cleavage.

Fold formation also differs across the region behind or west of the Beemerville intrusive. No folds exist within Poxono Island Formation and younger units within the strain shadow west of the Beemerville intrusive. Glacial sediments blanket most of the Bloomsburg so fold patterns are obscure, though its outcrop width is greatly increased suggesting little to no folding. Along strike south of Wallpack Center the Bloomsburg through Onondaga sediments delineate tight, upright to northwest directed overturned folds. Along the edge of the southern strain-shadow, several fold trends diverge by up to 20° from the northeast-southwest regional orientation into a more west-southwest direction (Monteverde, 1992). This fold deflection hints of involvement of the Beemerville Intrusive Complex in affecting stress propagation. A similar though muted trend appears with the Martinsburg fold pattern east of the pluton. Similar steep to overturned bedding occurs to the north just across the New Jersey border into New York, along Trilobite Mountain and farther northward. Within the strain shadow, these units display very gentle (8-30°NW) uniform dips which affects and enhances the groundwater flow and sinkhole development (see stops 1 and 2 on this trip).

Not all data supports the 'strain shadow' hypothesis. The Shawangunk and overlying Bloomsburg rests atop the Martinsburg and Beemerville. Shawangunk folds do not show any apparent change related to their location along Kittatinny Mountain. Overturned beds are found directly southwest of the exposed' and subsurface extension of Beemerville as indicated by the gravity surveys (Jagel, 1990; Ghatge and others, 1992). There is a decrease in overturned panels near to the pluton compared to those along strike to the southwest. Also, the mapped Shawangunk outcrop belt does not double its width behind the intrusion, similar to the Upper Silurian and Devonian units. This puts in question the validity of the buffering of tectonic strain in the Shawangunk by the pluton. The most dramatic increase in the outcrop is seen in the Bloomsburg.

There are many other possible scenarios to explain the geometry of deformational fronts (Macedo and Marshak, 1999). One of these options as a mechanism for the strain shadow effect is the morphology of the indenter plate during the Alleghenian Orogeny. In this model, promontories on the indenter accounting for the stronger deformational signature of Pennsylvania and New York and a recess covering the Beemerville area, created a lower deformational event. Could the outcrop width increase in the Bloomsburg be due to broad fold formation overlying thrusting as interpreted on the seismic by Herman and others (1997)? But if so, how would that account for the absence of cleavage in the younger units? All these questions and hypotheses need further work to evaluate their validity.

IMPACTS

The strain shadow impacts how the rocks react to normal weathering, which is the theme of this trip. Witte (personal commun, ongoing field work) performed detailed mapping of karst development in the Onondaga Limestone across northwestern New Jersey. His results have highlighted a dramatic preference for sinkhole development in regions of low dip, specifically within the strain shadow. Here the local joint trends are the major drivers of sinkhole formation and associated swallow holes, springs and groundwater flow networks. This will be explored in Stops 1 and 2. The diminished cleavage development in the Esopus along the southern boundary of the strain shadow also shows the larger impact of joint development. These localized joint openings were enlarged under the influence of postglacial weathering and possibly glacial ice wedging during the waning stages of deglaciation as will see at Stop 3.

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FIELD GUIDE AND ROAD LOG - Lower to Middle Devonian rocks of the Delaware Water Gap National Recreation Area, New Jersey: fracture and lithologic control on rock-shelters, karst and groundwater flow

by

Ron W. Witte, Don H. Monteverde, and Steve Domber – New Jersey Geological and Water Survey

Meeting Point: Doubletree by Hilton Hotel, Nanuet, New York.

Meeting Point Coordinates: 41.090°N, 73.995°W

Meeting Time: 8:00 AM. **Note** road log starts at last I-84 West exit (exit 1, bottom of ramp) before entering Pennsylvania. Don Monteverde will meet the group on Sunday morning and shepherd the caravan to Stop 1a (Brau Kettle, Delaware Water Gap National Recreation Area, Sandyston Township, New Jersey. Directions to the start of the official road log are as follows:

Get on Palisades Interstate Pkwy N in West Nyack – 0.5 miles (0.8 km).

Follow Palisades Interstate Pkwy N to Highlands. Take exit 18 from Palisades Interstate Pkwy N -

16.5 mi (26.6 km).

Continue to Woodbury and continue on US-6 W – 7.3 miles (11.7 km).

Take I-84 W to Exit 1 - 35.1 miles (56.5 km). Field guide road log starts at end of off-ramp.

Cumulative in miles (km)	Point to Point in miles (km)	Route Description
0.0 (0.0)	0.0 (0.0)	Bottom of I-84 ramp, turn left on U.S. Route 6 West.
0.1 (0.2)	0.1 (0.2)	Left on State Route 23 South.
0.8 (1.3)	0.7 (1.1)	Right on County Route 653 (Clove Road) South.
5.6 (9.0)	4.8 (7.7)	Pass Montague Mini Mall on left, site of Stop 4.
8.1 (13.0)	2.5 (4.0)	Left on U.S. Route 206 East.
9.8 (15.8)	1.7 (2.7)	Right on County Route 645 South to Hainesville.
10.6 (17.1)	0.8 (1.3)	Right on County Route 646 West (Jager Road).
12.0 (19.3)	1.4 (2.3)	Arrive at Stop 1a. Park on right shoulder below culvert.

STOP 1a: Jager Road (near Brau Kettle), Sandyston Township, New Jersey

Location Coordinates: 41.263°N, 74.824°

Sample collecting and the use of rock hammers is not permitted in Delaware Water Gap National Recreation Area without a research permit. Most outcrops and other features provide more than adequate inspection. If needed, trip leaders will provide samples for examination.

Guidebook figures for each field stop are listed at the end of their respective sections. A full-color field guide will be handed out to trip participants the morning of the field trip by Don prior to the group leaving the hotel. Additional copies will be available at Stop 1a.

STOPS 1a and 1b) – Jager Road and Old Mine Road – Karst Geology and the Onondaga Limestone: Joint-controlled karst, regional structures, sedimentology of the Onondaga Limestone, shallow groundwater flow, and Brau Kettle.

Location and logistics

Stop 1 lies in the Milford quadrangle in the Delaware Water Gap National Recreation Area (fig. 1-1) along the western edge of New Jersey's Valley and Ridge Physiographic Province. The Delaware River, which forms the border between Pennsylvania and New Jersey, flows southwestward through Minisink Valley. Wallpack Ridge borders on Minisink Valley in New Jersey and it rises as much as 300 feet (91 m) above the valley's floor. At Stop1, the Onondaga Limestone underlies the ridge's northwest flank forming a gentle dip slope that extends to Minisink Valley. The western side of Minisink Valley in Pennsylvania is bordered on by a 300-foot-high (91 m) escarpment held up by the Mahantango Shale.

Stop 1will consist of two parts: 1a will be a short hike along the upper reach of an unnamed creek that flows near Jager Road. Park along the north side of Jager Road below culvert 1 (fig. 1-2). Additional parking for a few more cars is found below culvert 2 along the south side of Jager Road. We will meet near culvert 1 for a short discussion on karst and the Onondaga Limestone. Return to your cars at the end of the hike (culvert 3) and drive down the hill to the parking area at intersection of Jager and Old Mine

Road (fig. 1-2). Depending on the number of participants, a short discussion on Brau Kettle well will be held in the parking area or near Brau Kettle.

Geologic Setting

Bedrock in the Wallpack Ridge area consists of Silurian and Devonian carbonate and siliciclastic (sandstone, siltstone, and shale) sedimentary rocks that overlie the Bloomsburg Red Beds and uniformly dip northwest forming a monocline (fig. 1-3). These units comprise fifteen geologic formations (fig. 1-4), but may be grouped into six lithotypes (fig. 1-3) when studying karst at regional scales.

Wallpack Ridge is long, narrow, and slightly sinuous, extending 25 miles (30 km) from Wallpack Bend on the Delaware River to Tristates, New York (fig. 1-5). Its width varies between 0.7 and 1.7 miles and its highest elevation is 928 feet (283 m). Topography consists of short, rocky northeast-trending strike-ridges and benches with long slopes forming the ridge's northwestern flank. Wallpack Ridge consists of three sections (southern, middle and northern) based on the ridge's topographic trend (fig. 1-5). The southern and northern sections trend about N 55° E while the middle trends about N 26° E. The middle is also the widest section because its rock formations dip to the northwest much less steeply than those in the southern and northern parts (see the manuscript accompanying this trip for a discussion of these differences).

Minisink and Wallpack Valleys lie on either side of Wallpack Ridge. Both are narrow, deep, and trend southwest following belts of weaker rock. The valleys were also the former sites of a planned hydroelectric and water storage project by the Army Corps of Engineers. A dam planned for construction at Tocks Island would have flooded Minisink Valley upstream to Port Jervis, New York, and Wallpack Valley upstream to Layton. The reservoir would have provided storage capacity of nearly 250 billion gallons. After years of controversy, Congress de-authorized the project in 1992.

Kittatinny Mountain (fig. 1-5) is a prominent ridge that separates far northwest New Jersey from Kittatinny Valley, and runs from the Shawangunk Mountains in New York southwestward through New Jersey into Pennsylvania. It rises as much as 1500 feet above the floor of Minisink Valley and is underlain by the Shawangunk Formation, a tough and highly weathering-resistant quartzite and quartz-pebble conglomerate. The lower area northwest of the mountain that extends to Wallpack Valley is largely underlain by the Bloomsburg Red Beds and is included with Kittatinny Mountain.

Stop1 lies about 28 miles (45 km) north of the late Wisconsinan terminal moraine. Nearby glacial deposits (Witte, 2012) include valley train, meltwater terrace, and outwash-fan deposits laid down during systematic deglaciation of Minisink Valley. The Dingmans Ferry, Montague moraines mark a minor pause or slight readvance of the Minisink Valley lobe. Elsewhere, thin till covers most of the bedrock slopes with thicker till forming small drumlins and aprons on north-facing slopes. Thick deposits (up to 10 feet (3 m) of eolian sand blanket the lower slope of Wallpack ridge with a small field of sand dunes covering the outwash plain just upvalley from Brau Kettle.

Onondaga Limestone and Karst

A large number of karst features were detected along Wallpack Ridge in the Delaware Water Gap National Recreational Area (DEWA) during the recent mapping of surficial deposits in northwestern New Jersey (Stone and others, 2002; Witte (2012). Sinking streams, springs, a few small caves, and numerous small sinkholes were located with most all of the features found overlying the Onondaga Limestone, especially in the area between Dingmans Ferry and Montague, New Jersey (fig. 1-6).

The Onondaga Limestone in New Jersey was never formally divided into members (fig. 1-7) as it had been in New York (Oliver, 1954) and Pennsylvania (Epstein, 1984) (fig. 1-4). However, it was informally divided

(Herpers, 1952) into a lower section that is devoid of or contains only sparse chert (fig. 1-8a) and an upper section that contains abundant chert (fig. 1-8b). Cook (1868) had also observed this bipartite division near Dingmans Ferry where the Onondaga Limestone represented the noncherty limestone and the Corniferous Formation represented the cherty limestone.

Oliver (1954) codified the previous lithologic divisions of the Onondaga into formal members. From oldest to youngest they included the Edgecliff, Nedrow, and Moorehouse members. The Seneca, previously named by Vanuxem (1839), was retained as the Onondaga's youngest member. In Pennsylvania, Epstein (1984) divided Willard's (1939) Buttermilk Falls Limestone into, from oldest to youngest, the Foxtown, McMichael, and Stroudsburg Members. Inners (1975) added the Echo Lake member to the formation in part based on recognizing the Tioga Ash Bed in an Onondaga outcrop near Stroudsburg, Pennsylvania. Ver Straeten and others (2001) have added that the four members of the Buttermilk Falls are "exact correlatives" of the Onondaga Limestone and its four members in central New York. The terms Buttermilk Falls Limestone of Willard (1939) and the members of Epstein (1984) and Inners (1975) will be abandoned." For this study, the authors accept the New York stratigraphic division of the Onondaga into the Edgecliff, Nedrow, Moorehouse, and Seneca members rather than the Buttermilk Falls divisions of Pennsylvania. Whether or not all four members occur in New Jersey remains to be seen.

The Stroudsburg stratigraphy (Buttermilk Falls or Onondaga divisions) have only been traced as far as Wallpack Bend by Epstein (1984), and Ver Straeten (2001 and others) have correlated the four members to central New York via central Pennsylvania (Selinsgrove area). A direct correlation along strike from Stroudsburg, Pennsylvania through New Jersey to New York (fig. 1-9) has not been done. Recent mapping in New Jersey (Drake and others, 1996, and Monteverde, 1992) show both the Buttermilk Falls and Onondaga Limestones with the former continuing across the Delaware River into New Jersey at Wallpack Bend, and the latter continuing from New York into New Jersey at Tristates (fig. 1-9). Mapping was based on the Buttermilk Falls being more argillaceous (darker gray and finer-grained) and cherty than the Onondaga. The gradational boundary between the two limestones (Monteverde, personal commun., 2016) occurs near Montague, New Jersey (fig. 1-9) in the northern part of the outcrop belt.

Oliver (1956) noted that the Edgecliff and Morehouse members are recognizable but greatly changed at Port Jervis and that Willards (1936) Buttermilk Falls Limestone is the approximate equivalent of the Onondaga at Port Jervis. If this correlation is correct, then its lower cherty unit has been replaced by a noncherty or sparsely cherty unit of the "lower Onondaga" in the study area. Oliver and others (1962) indicated that the Edgecliff southwest of Wawarsing is a thinner, darker, and finer-grained limestone with little chert and recognized mainly by its large crinoid columnals. The large columnals were also noted by Epstein (1984) in his Foxtown Member, the basal part of the Buttermilk Falls and Spink (1967) described the occurrence of large crinoid columnals as abundant in the basal section of an Onondaga outcrop near Dingmans Ferry along Dingmans Ferry – Layton Road (the southwest edge of the karst-study area near Stop 2). The columnals have been also found by the author's near Spink's Dingmans Ferry outcrop. Elsewhere, they have not been observed in New Jersey. Spink (1967) also noted that the base of the Onondaga where it lies in contact with the Schoharie consists of a five-foot thick limestone bed characterized by an anastomosing network of silt. A similar bed was observed about 2.5 miles northeast of Stop 1a where it overlies a two-foot thick bed of nodular limestone that may represent the Onondaga - Schoharie contact. Based on the above observations it appears that the Edgecliff Member does extend into the study area where it is represented by sparsely-cherty, thin to medium-bedded, dark gray, fine-grained, flaggy to nodular limestone.

Oliver (1956) indicated that the Nedrow Member becomes indistinguishable from the Moorehouse in the southeastern New York outcrop belt and at Wawarsing, New York; the Moorehouse rests directly on the Edgecliff. The Moorehouse at Port Jervis, New York is about 190 feet (58 m) thick (Oliver, 1962). Given that the overall thickness of the Onondaga in the study area is estimated at 200 feet (91 m) (Drake and others, 1996) to 250 feet (76 m) (Spink, 1967), then the Onondaga consists of a thin Edgecliff overlain by a much thicker Moorehouse. No exposures of the Seneca Member have been found in southeastern New York because it has been replaced by the lower part of the Marcellus Formation (Oliver, 1956).

Based on Oliver's (1956, 1962) descriptions of the Onondaga in southeastern NY, the presence of large crinoid columnals in New Jersey, and the informal division of the Onondaga into a lower noncherty member and an upper cherty member (Herpers, 1952; this study) it appears that Edgecliff and Moorehouse Members make up the Onondaga Limestone in the study area and that the majority of the sinkholes are found in the Edgecliff and lower part of the Moorehouse. The four-member stratigraphy of Pennsylvania's Buttermilk Falls (Epstein, 1984 and Inners, 1975) and the more recent Onondaga revision by Ver Straeten and others (2001) has not been traced through New Jersey into New York, specifically the Nedrow member. Main reasons for this include: 1) Lateral facies changes along strike from pure to argillaceous limestone and noncherty to cherty limestone are common in the Onondaga as shown by Oliver (1956 and 1962). This is also shown by faunal changes (Oliver, 1956) where "south from Leeds the Edgecliff thins, the coral fauna disappears, the rock becomes finer-grained and darker, and the light-gray chert is replaced by dark chert." 2) The Onondaga in New Jersey is largely found along the northwestern flank of Wallpack Ridge where it forms a dip slope of 8 to 30 degrees. Because of this geometry, there are few outcrops where thick sections are exposed, prohibiting a detailed examination of the limestone and mapping of its members. 3) The upper section of the Onondaga in many places is covered by thick glacial outwash and postglacial alluvium in the Delaware River valley, possibly concealing the thin Seneca member.

Karst Features

Sinkholes - Sinkholes are the most common karst features mapped on the Onondaga Limestone. More than one hundred sinkholes or clusters of closely-spaced sinks have been located (fig. 1-6) on a two-mile long section of Wallpack Ridge, south of Montague, New Jersey. As much as 15 feet (6 m) deep and 100 feet (34 m) in length, they formed in areas where the Onondaga Limestone is overlain by Late Wisconsinan till and in places, thin eolian sand. Most are oval- or trough-shaped with their long-axis oriented parallel to primary joints found in the local rock. Sinks may occur alone or in small groups that are aligned with local joints. Most sinks or sink clusters are aligned along a 040° to 020° trend with a few sinks aligned around a cross-joint trend of 120°. Also, most sinkholes are not found along streams or in places where they may receive concentrated surface runoff.

Sinkholes chiefly occur as two types. The first are solution sinks that form shallow surface depressions in the overlying surficial substrate (fig. 1-10). They do not exhibit an open throat or show evidence of recent collapse. They typically form over large open joints that have been covered by thin till and in some places postglacial eolian sand. Most of these sinks probably formed shortly after deglaciation, representing places where thin (< 20 feet (6 m) thick) surficial materials slowly filled subsurface voids chiefly by collapse, which resulted in the formation of a shallow depression or sag of overlying materials.

The second kind are solution sinks (fig. 1-11). They are generally smaller, have steep walls, and an open throat. They represent places where surficial material has been undermined, collapsing into a soil void and creating a steep-walled sink. They probably form more rapidly than soil-collapse sinks and may represent periods of episodic movement whereas solution sinks form more slowly representing a period of more steady and gradual collapse. Many of these do exhibit bedrock in the sink's walls and most are found along the intersection of major joints.

Sinkholes are typically found in three different topographic settings: 1) Many sinks lie adjacent to the up slope side of a rocky strike ridge (fig. 1-11). These sinks are rock-walled or at least partially lined by bedrock, 2) Additional sinks are found along topographic benches or on gentle dip slopes. Many of these occur in closely-spaced groups and outcroppings within them are uncommon. In rare instances, several closely-spaced sinks that formed along cross joints are found on gentle slopes. 3) more rarely they occur at the base of a dip slope where slope meets the valley floor.

Sinking streams and springs – Many small streams that flow over the Onondaga Limestone disappear or more rarely emerge at various places along the stream's course. Often these streams lose flow or completely disappear over the course of a few hundred feet. Mostly, water sinks through thin alluvium into bedrock through small open joints and voids. In a few places, seepage is much more dramatic, the stream flowing into a small sink or large void (swallow hole). About 1800 feet upstream from Brau Kettle (fig. 1-2), approximately 70 percent of stream flow disappears into an opening about 2 feet in diameter (Stop1a-1). The remaining water seeps into the streambed within the next 200 feet. Downstream, two additional swallow holes have been identified, but the creek bed is typically dry except during periods of heavy precipitation. Whether these swallow holes are the source for Brau Kettle remains to be investigated.

Springs are common and range from small ephemeral seeps to larger year-round flows (> 300 gallons per minute (gpm)). Springs typically discharge along either 1) abrupt changes in slope along bedding or joints or 2) the surficial – bedrock contact (till-rock interface). In places, deposits of calcareous tufa (Stop 2a) are found just downstream from where the spring emerges. Brau Kettle is a peculiar spring. During dry times of the year the kettle is a small soil collapse sinkhole, while during the wetter periods it fills with water and discharges to a nearby creek. The spring and its relationship to a nearby well are discussed at Stop 1b.

Caves – Several small caves have been discovered in the study area. Most have openings that are just large enough for a person to fit through, and then quickly diminish in size. No large caverns have been discovered in the karst study area, although the size of a few sinkholes suggest that bigger caves may exist. About two miles northeast of Montague, two larger caves, Vulture (fig. 1-12) and a more recently found unnamed cave have been located in the Onondaga Limestone. These represent the largest known Onondaga caves in New Jersey.

Cutters and limestone pavements – The Onondaga's long dip slope and thin surficial cover provides many places where limestone pavement crops out at the surface (also occurs along some of the streams). Bare areas of rock exhibit deep fissures (max depth – 10 feet (3 m), and max width 2 feet (0.5 m) that break the rock surface up into large rectangular blocks (fig. 1-13). They are chiefly the result of dissolution along joints that mostly occurred beneath a layer of thin soil. Given their size, many of these fissures are older than the Late Wisconsinan glaciation (24 ka); formation of extensive joint dissolution prior to the Late Wisconsinan glaciation. Glacial erosion during the last glaciation removed soil and loose rock from the land. In most places, the glacially eroded limestone pavement was covered by thin till. In places where till was not deposited or where the thin surficial material was eroded by postglacial slope erosion, the pavement is exposed.

Karst Formation

Several factors contributed to the formation of karst on the Onondaga Limestone. Most importantly, is that the limestone is susceptible to dissolution by surface water and groundwater, especially those parts of the formation that are a purer limestone. Because the rock formations that topographically lie above the Onondaga consist largely of siliclastic rocks, water that drains through them becomes slightly acidic. Also, rainwater that seeps through organic-rich soil in the area becomes slightly acidic. Over time, these waters dissolve the calcium carbonate that makes up the Onondaga Limestone.

Because the Onondaga has a very low primary permeability, water moves through the rock chiefly along fractures. Over time, these fractures widen by dissolution, and where flow is concentrated along fractures, dissolution is accelerated. Eventually, larger, connected conduits are formed, highly magnifying the rock's secondary permeability. Water flow through the Onondaga occurs mainly along solution–enlarged joints and to a lesser degree along bedding.

Two dominant joint trends have been measured in the Onondaga (figs. 1-2 and 1-13). The first (called here J1) is a 020º to 030º set that nearly parallels bedrock strike. They have long, straight traces that typically penetrate the rock more than several meters. The second (called here J2) is a 110º to 120º set that nearly bisects bedrock strike. These cross-joints typically have irregular traces and in most places are shorter than J1. Penetrative depth is typically less, being no more than a couple of meters and the joints tend to be much more bedding terminated than J1. Because joint intersections are especially prone to dissolution, larger voids may develop. Overtime, a connected system of conduits forms along systematic joints in the limestone. These joints are likely Alleghenian age (325 to 260 mya) and mostly formed as extensional fractures.

The shallow dip of the limestone beds also promotes dissolution by creating a larger surface area of limestone. In this section of the Wallpack Ridge the thin- to medium-thick beds of the Onondaga dip about 10 degrees or less. Elsewhere, the limestone dips as much as 35 degrees, most notably in the southern and northern sections (fig. 1-3). Because of this difference, the width of the Onondaga outcrop belt in the area most prone to karst formation is two to three times greater.

Although the primary conduits of subsurface flow are joints, some beds of the Onondaga are more prone to dissolution due to their higher calcium carbonate content (fig. 1-14). The trend and shape of sinkholes and open fractures indicates that water flow occurs mainly along systematic joints. However, based on outcrop observations, flow along bedding cannot be discounted and locally may be an important contribution to overall flow through the limestone.

Chert content will also affect dissolution. Most of the sinkholes occur in the lower part of the formation (interpreted in this report to be the Edgecliff and lower part of the Moorehouse members) where chert content is very low. Elsewhere, in the upper part of the formation where chert is more abundant, sinkholes are rare. Chert may lessen the effects of dissolution by retarding the growth of conduits along joints.

Finally, rocks along the middle section of Wallpack Ridge lack cleavage or it is only weakly formed whereas rocks along the southern and northern sections have a pronounced steeply-dipping southeast cleavage (fig. 1-5). Because cleavage planes may also act as conduits of subsurface flow, their absence here may have led to the concentration of water flow along joints, which accelerated rates of dissolution. The diminution of cleavage in the study area may be related to a large body of igneous rock that lies beneath Kittatinny Mountain near the village of Beemerville, New Jersey. The intrusive rock principally consists of syenite. It was emplaced sometime during the Ordovician period about 340 million years ago. The location of the Beemerville intrusive may have reduced the tilting of sedimentary strata to the west, and insulated these rocks from forces that produced cleavage. The large bulge found along Kittatinny Mountain (fig. 1-5) is a topographic manifestation of the strain shadow that could have occurred northwest of the intrusive when these rocks were deformed during the Alleghenian Orogeny. A more robust discussion on cleavage and jointing may be found in the paper by Monteverde and Witte.

Glaciation and Karst

There are no known dates for the age of karst features in DEWA or the nearby caves. Because the DEWA sinks formed on late Wisconsinan glacial (till) and postglacial deposits (eolian sand), we can estimate a maximum age at about 18,000 years based on the age of the late Wisconsinan deglaciation in northern New Jersey. Because glaciers erode rock and soil, most all of the sinks older than the last glaciation have been destroyed. The age of the subsurface conduits and voids that lie beneath the sinks is unknown, but based on their size they existed prior to the last ice age. Given the short time since deglaciation, it is doubtful whether any of these depressions were formed by postglacial subsidence related to solution weathering.

Several sinks occur in eolian sand, which was deposited in postglacial time prior to the growth of extensive vegetation (period of time between deglaciation and the growth of an extensive boreal forest; 15 – 12 ka). Sinks that formed after this eolian phase suggest a possible link between glaciostatic rebound and lowering of regional groundwater levels. Most sinks do not appear active because they lack an open throat and show no evidence of recent subsidence. There probably has not been extensive dissolution of the Onondaga since the late Wisconsinan glaciation. Glacial till was deposited over pre-existing voids and open fractures. Over time, this material settled, creating the many small sinks in the park.

STOP 1a (41.263°N, 74.824°W)

Presenters – Ron Witte and Don Monteverde

Location 1a-1 – Creek bed just downstream from culvert 1 (fig. 1-15) near Schoharie – Onondaga contact.

Features - Large solution joints, Onondaga Limestone (Edgecliff Member) and swallow hole along left bank.

Discussion – Here the Onondaga limestone forms the creek bed, which is primarily a bedding-plane dip slope cut by several large solution joints (fig. 1-16). The rock is a thin to medium-bedded, fine-grained, faintly nodular, non-cherty, sparsely fossiliferous limestone. Given its proximity to the Schoharie contact, the limestone probably belongs to the Edgecliff Member. Large crinoid columnals that are used to define Onondaga's base have not been found near stop 1. However, the scarcity of outcrops due to dip slope geometry and burial by glacial cover in this area makes their discovery fortuitous at best. The main point to take away from this "blah, blah, blah" discussion is that the lower Onondaga in Karst Park is non- to sparsely-cherty and that is where many of the sinkholes occur.

Systematic joints in the Onondaga generally are aligned along two major trends (fig. 1-2). Enlargement of these joints and their intersections over time by dissolution, as well as minor bedding-plane dissolution has resulted in an extensive, integrated network of subsurface conduits (will discuss further at Stop 1b, Brau Kettle). The long axis of oval to trough-shaped sinks and lines of multiple sinks in Karst Park are aligned along these trends showing that karst features are strongly controlled by jointing (probably not an epiphany to most, but the lead geologist at this stop has a surficial geology background and is amused by simple observations). Solution along joints has resulted in various forms. In most places, joint surfaces are straight-walled to slightly curvilinear. Elsewhere, digitate forms (fig. 1-16) are observed, the result of dissolution along closely-spaced orthogonal to perpendicular joint sets. Also, in a few places, short, narrow openings occur that suggest a distinctive vertical component to dissolution.

A small swallow hole is found along near base of cascades, along the stream's left bank below the roots of a small tree (fig 1-17). The swallow hole is following a large joint (020° trend), draining southwest. It is now partially covered in debris (mostly gravel). Scraps of screening and rebar (also found at other swallow holes) show manmade interference with natural flow conditions. These efforts generally fail, but once in a great while they're thwarted by inquisitive geologists (ask Don). Most of the time this area was observed, about 70% of stream flow entered the swallow hole. Remaining flow continued downstream toward the left-hand bend eventually disappearing into the channels coarse alluvium. Over the last few years, flow many times has been observed to continue downstream past the bend to Stops 1a-2, 1a-3, and 1a-4 (fig. 1-15). The main reason for this is that the swallow hole at Stop1a-1 has become partially blocked with gravel and debris, material washed in during periods of storm-related discharge or maybe Don (the geologist not the rock) had something to do with it.

Head downstream to Stop 1a-2 either by following the stream bed (only if it's dry) or by following the stream's left bank. The small pit you pass on your right supplied sand to local denizens. The sand is eolian, blown off late Wisconsinan glacial outwash braid plains in nearby Minisink Valley. The sand is part of an extensive eolian sheet that has been found as much as 200 feet (61 m) above the valley floor. Just north up Stop 1-b, small sand dunes as much as 5 feet (2 m) high, cover the east side of the valley (a story for another time).

Location 1a-2 – Creek bed downstream from left hand bend.

Features - Buried swallow hole below slump, Onondaga joint-blocks, coarse gravel bar.

Discussion – Stream flow to location 1a-2 is rare. During a field trip to this area in February, 2016, the typical view of stream flow downstream from culvert 1 (the one where the stream disappears before the bend) was not so typical. Upon arriving at location 1a-2, two observations stood out: 1) most stream flow (~ 75 %) was disappearing into an area of boulder alluvium beneath a small slump along the channel's right side (fig. 1-18) and the remaining flow was diverted around a coarse gravel bar (located just upstream from the slump) to a small swallow hole located along the streams left bank at Stop 1a-3.

The sinking stream was probably draining into a large open joint that may have been open for observation at one time. However, recently slumped sediment (eolian sand overlying till) and Onondaga joint-blocks have covered the swallow hole. It appears that under natural conditions, variable discharge along reaches between swallow holes may be due to blockage of swallow holes upstream. Over time, the cyclical filling and emptying of swallow holes (collapse into sink holes or erosion by running water) has resulted in a complex stream flow history. Also, heavy precipitation may overwhelm the capacity of the swallow holes to drain the creek, and channel bars may also divert flow around or to swallow holes.

Onondaga joint blocks here are non-cherty and sparsely fossiliferous limestone similar to that at Stop 1a-1. Given the gentle dip of bedding (< 15°), this limestone and outcrops downstream probably belong to the Edgecliff member.

Location 1a-3 – Creek bed just downstream from Stop1a-2.

Feature - Swallow hole along left bank in collapsed till.

Discussion – The swallow hole (fig. 1-19) is a small sinkhole formed mostly in till that underlies the left steam bank and hillslope. Shallow bedrock in the stream channel just downstream from this location suggests that bedrock is very near the surface below the sink. It is very probable that this sink overlies a large solution joint or solution joint intersection. Again, it's very rare for surface drainage to reach this location, but this year's February storm was severe with runoff heightened by frozen ground and melting snow.

Location 1a-4 –stream channel just upstream from culvert 2.

Features – Small cave along right stream bank, joints, Onondaga Limestone

Discussion – The intersection of a large solution joint (114° ~v) and creek channel (possibly JI) forms the opening to a small cave (fig. 1-20). The entrance is 28 inches (71 cm) wide and 32 inches (81 cm) high with the top of the entrance formed by soil and tree roots. Bedding is 021° 10° NW, similar to bedding at Stop 1a-1. The large solution joint that forms the cave entrance trends 114 degrees and has nearly vertical to slightly scalloped sides (possibly eroded by sediment laden water). The 114° trend is part of a regional set of cross joints that cluster around 120 degrees. The cave floor from its entrance extends about 5 feet (2 m) before it drops another 3 feet (1 m) into a gravel choked opening. During periods of very high stream flow, the creek partly flows into the cave and over the years its floor near the entrance has filled with sand and fine gravel. As elsewhere, a small grate near the entrance does prevent most of the coarse sediment from entering the cave.

The Onondaga here is very fine grained, non-cherty, thin to medium bedded and slightly flaggy limestone. In places, silty (?) laminae with bedding parallel, curvilinear traces mark the rock's weathered surface (fig. 1-20).

Location 1a-5 – stream channel downstream from culvert 2.

Features – Spring, small reservoir and box.

Discussion - Several small springs are located along south side of Jager Road. Here the small reservoir and box (fig. 1-21) are typical structures used to collect water where it is often directly piped down slope to another holding area. The springs and seeps found along the south side of Jager Road discharge at or very near the till/rock contact. The small stream-cut valley topographically cuts this contact and together with the northwest dip of bedding creates favorable conditions for the emergence of springs. Given the occurrence of open solution joints along the rock's surface springs probably represent areas where water flow has been concentrated.

The new retaining wall was built after flood waters from then Tropical Storm Sandy (10/29/2012) washed out the road, nearly removing most of the eastbound lane.

Location 1a - 6 – just downstream from culvert 3.

Features – small swallow hole along right bank near right concrete abutment. Located at base of steep slope.

Discussion – Lastly, if we look downstream from culvert 3, you'll notice a small opening (22" wide (56 cm) by 16" (41 cm) high) along the stream's right bank just below the concrete abutment (fig. 1-22). Just past the opening the swallow hole's floor drops 3 to 4 feet into a small trough that trends about 55 degrees. The trough walls are partially bounded by outcrop, suggesting that this opening is following a large solution joint. Similar to the cave at Stop 1a-4, soil and tree roots form a ceiling. The opening has increased in size four fold over the last two years. Presumably, decreased subsurface discharge upstream due to sediment infilling of swallow holes, has increased discharge in the creek's lower reaches. These hydraulic modifications are episodic and may only take one or two good storms to greatly alter stream flow.

Below culvert 3 (fig. 1-15) most of the stream drains into the swallow hole directly or seeps through the gravelly alluvium adjacent to it. Downstream the creek is usually dry until input from a small spring below culvert 4. From here discharge seeps into boulder alluvium within 100 feet (30 m) of where the spring enters the channel. Normally the creek is dry downstream until it picks up outflow from Brau Kettle.

Please return to your cars and drive to the small parking area at the end of Jager Road and Stop 1b, Brau Kettle. The group will assemble in the parking area (fig. 1-2). Given the limited space around Brau Kettle, we may discuss Brau Kettle and the Anson Johnson well before taking the short hike to the kettle.

Cumulative in miles (km)	Point to Point in miles (km)	Route Description
12.3 (19.8)	0.3 (0.5)	Arrive at Stop 1b. Intersection with Old Mine Road. Park in area across intersection.

STOP 1b (41.263°N, 74.829°W)

Presenters – Steve Domber and Ron Witte

Location – 125 feet south of Old Mine Road and Jager Road intersection.

Features – Brau Kettle (spring and sinkhole)

Brau Kettle is a unique sinkhole-spring located along the eastern edge of Minisink Valley near the intersection of Jager Road and Old Mine Road in Sandyston Township, New Jersey (fig. 1-2). References to the kettle go back to the early French and Dutch settlers. The name was likely derived from the Dutch word for "brewing" or "boiling" (Dalton, 1976), a fitting description of the spring during discharge.

The kettle (fig. 1-23) is a conically shaped depression approximately 10 feet (3 m) deep by 20 feet (6 m) wide with its floor located in till. The sloping walls of the kettle are in thin wind-blown sand and till. Depth to rock is unknown, but given the kettle's geometry and discharge history, it is assumed that the Onondaga Limestone is very near the kettle's floor. Brau Kettle can be classified as an intermittent spring that varies from dry, to partially filled, to spilling; with highly variable fill and spill periods. A hydrogeologic investigation of Brau Kettle and its relationship to the Onondaga Limestone commenced in 2008 by the New Jersey Geological and Water Survey under a research permit granted by the National Park Service. This investigation consisted of measured hourly water level data using an ADR logger from the kettle and a nearby domestic well, precipitation data, and kettle discharge measurements.

It is hypothesized that the kettle was formed when a near-surface solution feature (joint or joint intersection) in the Onondaga Limestone enlarged to the point where the overlying surficial materials collapsed creating a sinkhole. Over time the flowing groundwater removed most of the finer materials leaving a boulder lag on the kettle's floor. Because the kettle is well above the Delaware River near the base of Wallpack ridge, groundwater only rises in the kettle during wet recharge periods. Farther downstream (closer to the Delaware River) is a series of perennial springs which discharge (in a boil-like fashion) through glacial outwash and postglacial alluvium. The lower elevation springs can be thought of as the perennial "base-line" discharge points and the kettle can be thought of as the overflow or relief valve when groundwater levels are elevated and discharge is high through the local joint-controlled hydrogeologic system.

Figure 1-24 shows selected water-level elevation data for the kettle and a nearby domestic well and precipitation data. The numbered descriptions below refer to the corresponding number on Figure 1-24. 1) Dashed grey line is elevation of base of kettle outlet channel; kettle elevations above this indicate that the kettle is discharging to the adjacent stream. When the green line is flat at approximately 434 feet (132 m), the kettle is dry. 2) Water levels in the well and kettle increase in response to precipitation/recharge on Oct 28th. 3) Water levels in the kettle and well recess. 4) Rate of decline increases once kettle stops flowing out outlet. 5) Kettle is dry while water level in well continues to decline. 6) Increase in well water levels due to small precipitation/recharge event, but not high enough to come above base of kettle. 7) Water levels in well increases and kettle temporarily fills in response to precipitation/recharge event. 8) Kettle fills and begins to discharge out outlet, water levels in well increase. 9) Note that water levels follow similar trend, but are at different elevations since well water level represents a composite water level from multiple zones in the aquifer; whereas kettle represents only the upper-most zone in the aquifer.

Figure 1-25 shows the period when a square notched weir was installed in the Brau Kettle outlet channel and used to measure discharge. Calibration of the manual and data recorder measurements was poor with an R-squared error of 0.79 and seepage around the edges of the weir was observed after several months of operation. The discharge estimates should be assumed approximate at best. The kettle and domestic well water level elevation can be seen rising and falling in response to recharge events as described in Figure 1-24. Discharge is observed to have occurred in the wetter winter months when Evapotranspiration is low and recharges rates and water levels are typically highest. Discharge also periodically occurs during the summer and fall for short durations when heavy rains cause significant but temporary increases in water levels. Discharge rates hover in the 500 to 1000 gpm range and peak as high as 3,500 gpm. This would make the kettle a 3rd order spring and fairly large for what is typically observed in New Jersey. Also of interest is that a nearby stream channel (located approximately 100 feet (30 m) to the north and lower in elevation that the base of the kettle) is typically dry when the kettle is actively discharging. This suggests that groundwater flow is highly constrained along joint-controlled flow paths.

Lastly, because springs may be used to determine the health of the aquifer, floral and faunal studies have been conducted throughout New Jersey (biologists and geologists working together, hmmmm. another sign of the apocalypse). Figure 1-26 shows a recent monitoring of Brau Kettle where a brook trout was captured. An additional study by NJGWS, monitors spring chemistry and temperature. Water samples collected between 10/18/2012 and 7/26/2013 show a range of pH between 7.0 and 7.5 with temperature ranging between 8.6 to 12.0 centigrade.

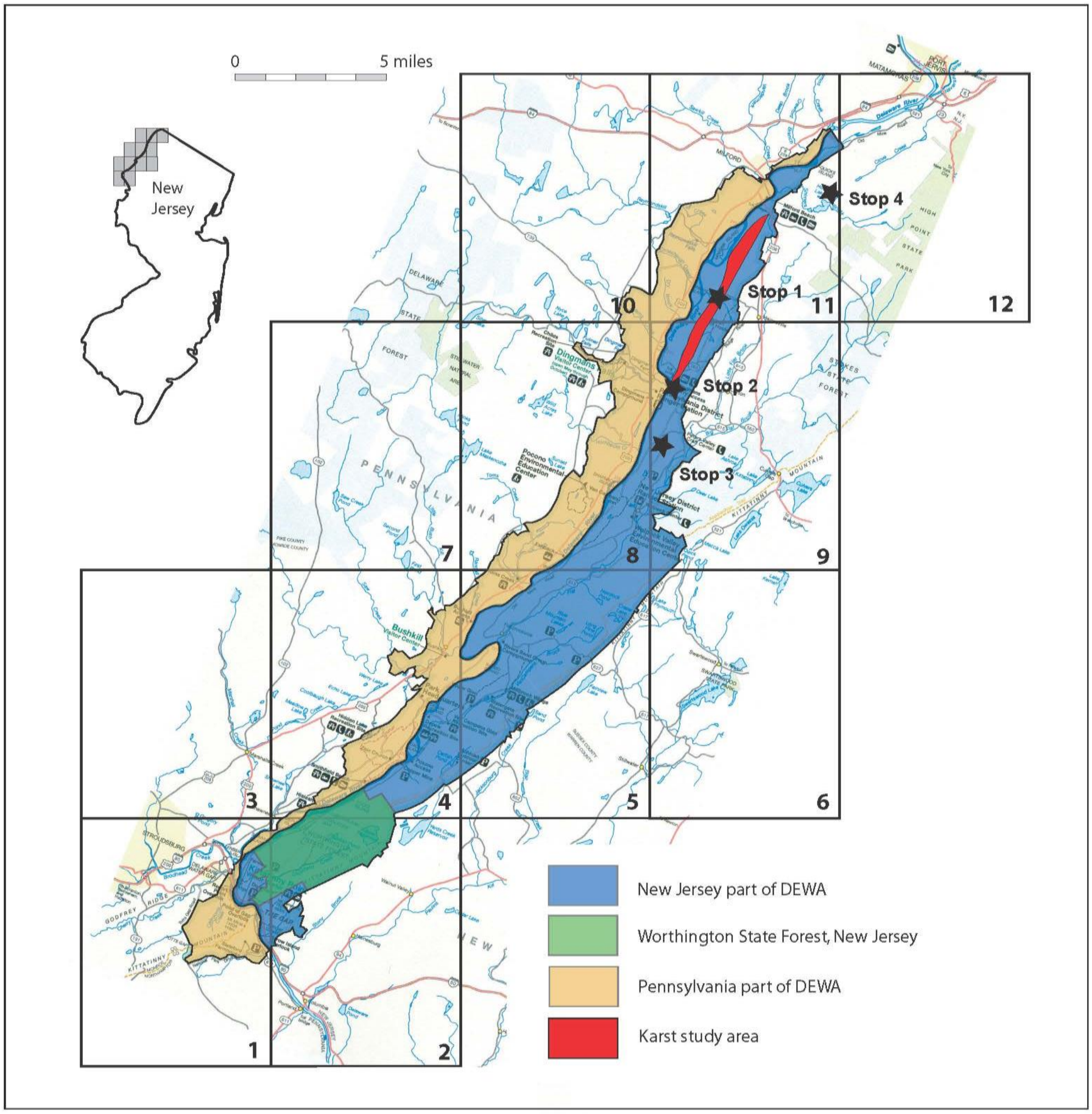


Figure 1-1. Location of Delaware Water Gap National Recreation Area (DEWA) in New Jersey and Pennsylvania, karst study area, field stops, and location of U.S. Geological Survey 1:24,000 quadrangles. 1. Stroudsdburg, 2. Portland, 3. East Stroudsburg, 4. Bushkill, 5. Flatbrookville, 6. Newton West, 7. Twelvemile Pond, 8. Lake Maskenozha, 9. Culvers Gap, 10. Edgemere, 11. Milford, 12. Port Jervis South.

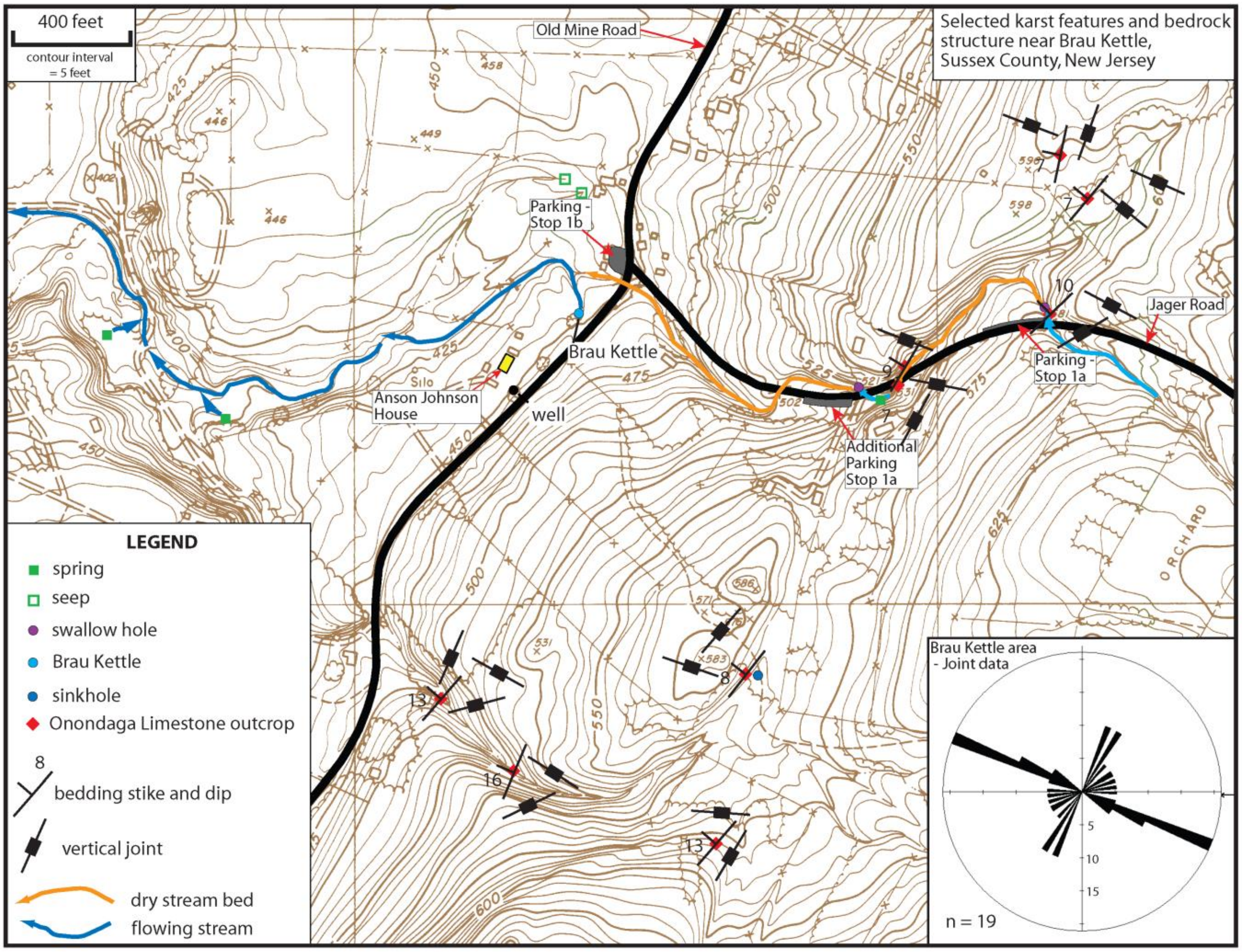


Figure 1-2. Stop 1 location map, karst features, and joint data for the Brau Kettle area.

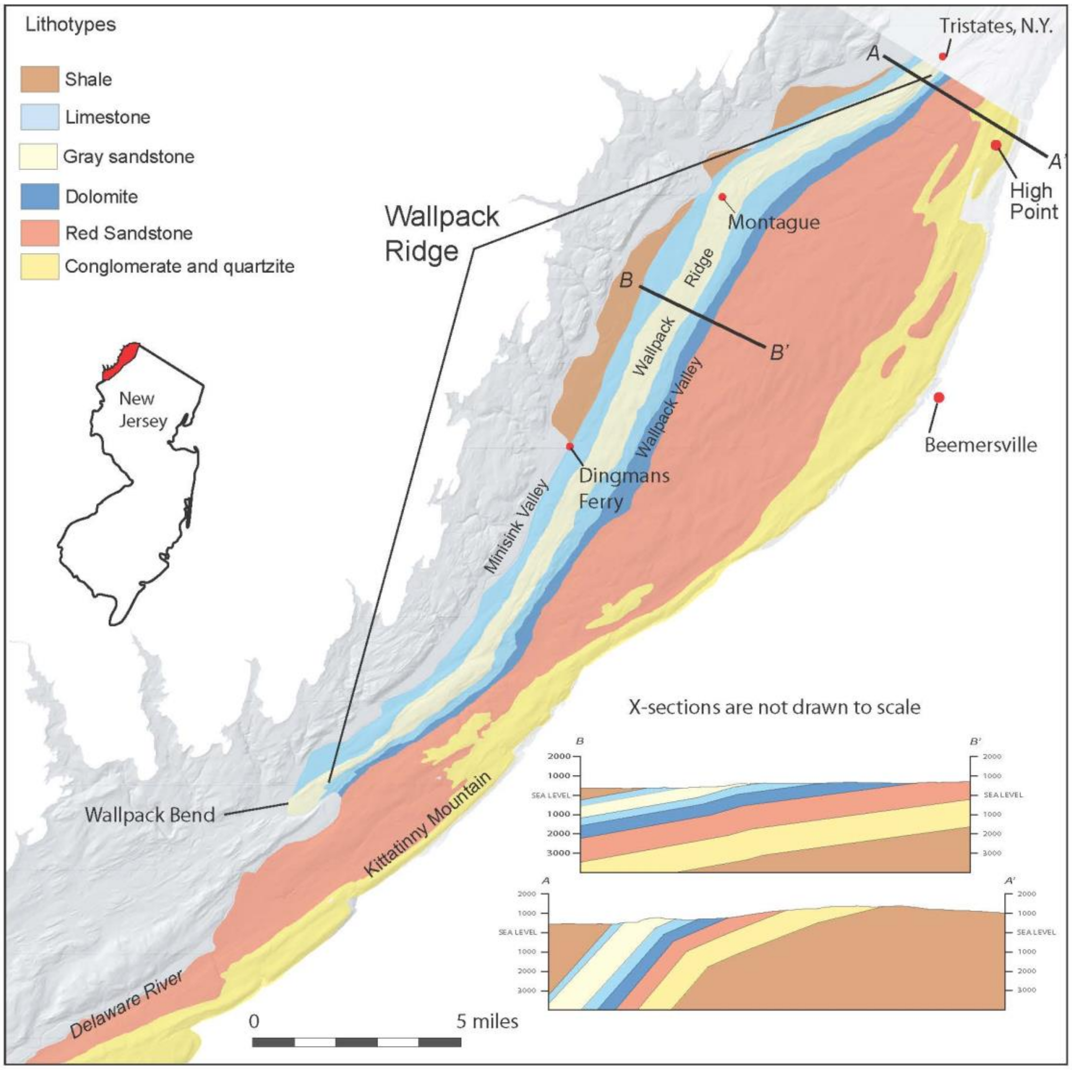


Figure 1-3. Simplified bedrock map of New Jersey in the vicinity of Wallpack Ridge. Modified from Drake and others (1996). The Onondaga Limestone forms the most westerly limestone.

System	Series	Formation		Member	Description	Aprroximate thickness (feet)
Devonian	Middle	Marcellus			Dark gray to black shale, locally silty, weathers medium gray; fissile, thin bedded though locally thick bedded and massive; limonite stained, and sparingly fossiliferous.	900
		Onondaga (Buttermilk Falls)		Seneca (Echo Lake)	Fossiliferous cherty limestone. Contains TIOGA ash bed.	15
				Moorehouse (Stoudsburg)	Medium-gray limestone and argillaceous limestone with beds, pods and lenses of dark-gray chert. Fossiliferous (brachiopods, ostracodes), burrowed.	135
				Nedrow (McMichael)	Medium-dark-gray calcareous argillite with lenses of light-medium gray fossiliferous limestone.	40
				Edgecliff (Foxtown)	Medium-dark-gray calcareous siltstone and argillaceous limestone containing lenses of dark-gray chert. Fossiliferous, one-inch diameter crinoid "columnals" in lower half.	80
	Lower	Schoharie			Medium to thick bedded; silty to shaly, locally dolomitic limestone containing local thin ribs or pods of black chert, weathers yellowish gray to locally pale olive and grades downward into medium to dark gray calcareous siltstone at base. Contains rare trace fossil Taonurus.	175
		Esopus			Medium to dark gray, shaly to finely arenaceous siltstone, containing minor calcareous siltstone near top. Laminated to medium bedded, as well as local massive thick bedded layers. Weathers medium gray and is limonite stained in places. Bioturbated by Taonurus. Thickness approximately 300 feet.	300
		Glenerie Formation			Upper section is medium to dark gray, fine grained silty limestone, containing a one inch thick tan gray weathering rind. Rock is wavy bedded, medium bedded, fossiliferous and contains local zones of siliceous limestone. Lower section is medium to dark gray, fine grained silty limestone; laminated to thin bedded and commonly trough cross bedded and fossiliferous.	170
			Port Ewen Shale		Medium-dark-gray poorly fossiliferous, irregularly laminated calcareous shale and siltstone grading up to fossiliferous, burrowed, irregularly bedded calcareous siltstone and shale.	150
			Alsen/Minisink Formation		Medium to dark gray, fine to medium grained limestone; medium bedded, black chert as beds and lenses, fossiliferous. Thickness approximately 20 feet.	20
			New Scotland		Upper part is dark gray, siliceous, laminated shale containing medium dark gray, very fine grained limestone pods; also scattered beds and lenses of medium gray, fine grained argillaceous, fossiliferous limestone. Limestone contains small dark gray chert nodules. Lower part is medium dark gray, siliceous, calcareous, fossiliferous shale containing beds and lenses of medium gray, fine grained, argillaceous, very fossiliferous limestone. Contains nodules, lenses and locally irregularly bedded dark gray chert.	75
		Helderberg Group	Kalkberg Limestone		Medium dark gray, fine grained argillaceous limestone; massively bedded and fossiliferous, containing very thin to thin beds and lenses of fine grained sandstone, and dark gray chert. Rock becomes a facies of the Coeymans to the southwest just beyond the quadrangle boundary.	40
			Coeymans Limestone		Medium light to medium gray, fine to medium grained, locally coarse grained, irregularly bedded argillaceous and arenaceous limestone. Irregularly bedded and fossiliferous, including the guide fossil Gypidula coeymanensis. Contains local bioherms consisting of light gray to light pinkish gray, very coarse to coarse grained, unbedded biogenic limestone which grades along strike back into nonbiohermal facies.	30
			Manlius Limestone		Medium dark to dark gray, very fine to fine grained limestone; few medium grained limestones. Undulatory bedding, flaggy to massive, fossiliferous. Unit grades into and becomes a facies of the Coeymans along strike to the southwest just past the quadrangle boundary.	35
			Rondout Formation		Upper part is medium dark gray, very fine to fine grained, medium bedded, calcareous shale and massive argillaceous limestone. The middle part is medium gray argillaceous dolomite, weathering grayish orange, medium bedded, massive to laminated. Basal beds consist of medium to dark gray, very fine to fine grained limestone and calcareous shale; medium bedded, generally massive. Unit is fossiliferous.	40
Silurian	Upper		Decker Formation		Unit is medium gray, medium to coarse grained, thin to medium bedded limestone containing very thin shale beds. Locally interbedded with light gray to medium gray shale, calcareous quartz siltstone and sandstone; locally cross bedded.	72
			Bossardville Limestone		Medium gray to medium dark gray, weathers medium bluish gray, very fine grained, argillaceous limestone and limestone. Thin bedded, laminated to ribbon textured.	10-100
			Poxono Island Formation		Greenish gray, finely crystalline to aphanitic dolomite containing discontinuous lenses of disseminated rounded quartz grains; local quartz sandstone beds and argillaceous dolomite. Unit is thin to medium bedded, and flaggy. Thickness based on well data to the southwest outside the mapped area (data source).	600
			Bloomsburg Red Beds		Grayish red, medium olive gray to light olive gray, thin to thick bedded mudstone, siltstone, fine to coarse sandstone, and local quartz pebble conglomeratic sandstone, poorly to moderately sorted, massive, with local planar to trough cross bedded laminations and mud cracks. Conglomerate consists of matrix supported quartz, green and red shale pebbles in grayish red, fine to coarse sandstone matrix; commonly containing an erosive base. Sandstone consists of subrounded grains of quartz and lithic fragments, poorly to well sorted, planar tabular to trough cross bedded. The finer grained beds consist of red to medium gray and lesser greenish gray to grayish orange, medium bedded, fine sandstone and siltstone.	1400

Figure 1-4. Stratigraphic column and description of rock formations found in the New Jersey part of the karst study area. Mapping of karst features indicates that lithology (purer limestones are more susceptible to dissolution), thickness (thicker formations are more susceptible to karst formation), and structure (low dip of bedding combined with long dips slopes, and high joint density) are important indicators of a formation's susceptibility to form karst. Onondaga members from Oliver (1954) and Vanuxem (1839). Buttermilk Falls (Willard, 1939) members from Epstein (1984) and Inners (1975). Figure modified from Epstein (2001).

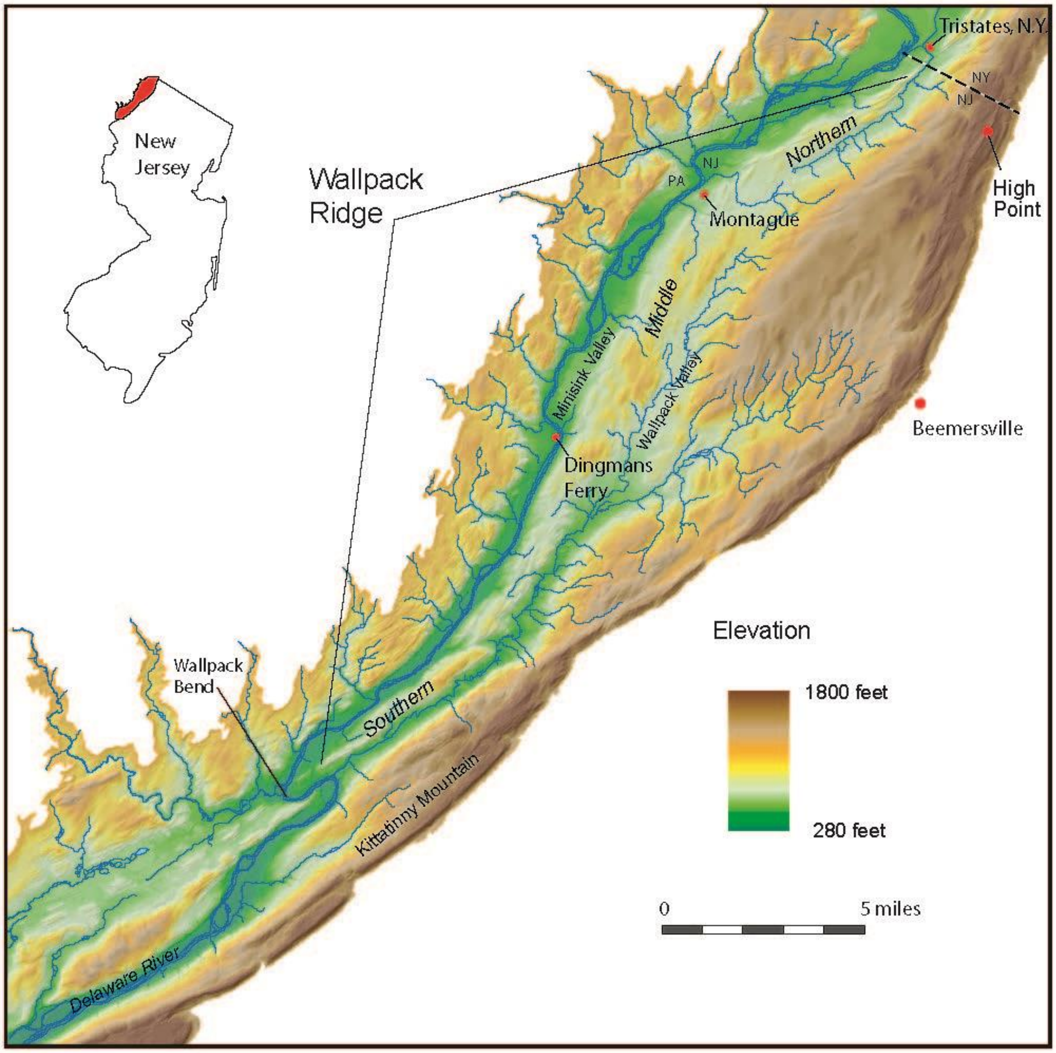


Figure 1-5. Color shaded-relief map of Wallpack Ridge and surrounding area.

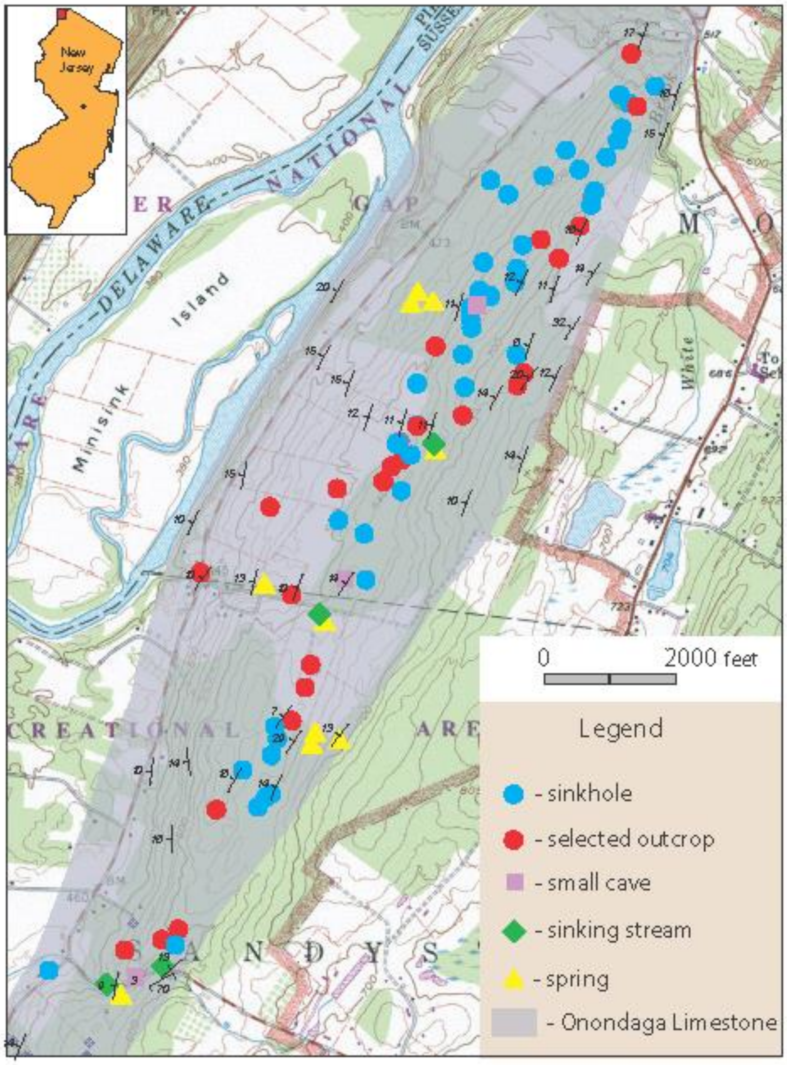


Figure 1-6. Karst features mapped on Wallpack Ridge between Jager Road and U.S. Route 206, Delaware Water Gap National Recreation Area. Sinkholes may be solitary or form small clusters that are aligned with joints in the Onondaga Limestone.

Rogers, 1840	Cook, 1868	Lewis and Kummel, 1915	Herpers, 1952	Spinks, 1967	Drake and Others, 1996
Fossiliferous limestone of the Delaware, base of Formation VIII	Corniferous (Cherty) Limestone and Onondaga Limestone (both are sometimes known as the Upper Helderberg Limestones) and they are not divided.	Onondaga Limestone	Onondaga Limestone: lower (Onondaga Limestone of previous workers) and upper member (Corniferous Limestone of previous workers).	Onondaga Limestone	Buttermilk Falls Limestone and Onondaga Limestone
Light blue and gray limestone, some argillaceous beds, many layers contain fossils. 200 feet thick.	Cornifierous - light blue, very fine-grained, uniformly-bedded limestone, argillaceous limestone with chert composing half the rock. Fossils are not common. Onondaga recognized as an encrinite and it does not form any considerable stratum. 600 feet thick (includes what is now mapped as the Schoharie Formation.)	Hard, cherty, regularly-bedded (3 to12 inches thick) limestone. Thickness is unknown (includes what is now mapped as the Schoharie Formation.)	Lower member – gray, fine-grained fossiliferous limestone with little or no chert; upper member – dark gray cherty limestone (equivalent to the Buttermilk Falls Limestone of Willard (1936) in northeastern Pennsylvania.	Fine- to medium-grained, medium-dark to dark gray, flaggy to massively-bedded limestone. Dark gray chert is commonly present in nodules and irregular layers. Fossils are common in the lower part of the formation. 250 feet thick.	Buttermilk Falls Limestone – light to medium-light gray, thin- to medium-bedded, fossiliferous limestone, flaggy, clayey to silty limestone and nodular black chert. Onondadga Limestone – Light-medium-gray, fine-grained, thin- to thick-bedded fossiliferous limestone. Black chert is more abundant in the upper half of the unit. 200 feet thick.

Figure 1-7. Nomenclatorial history of the Onondaga Limestone in New Jersey. Early studies were highly influenced by work in central New York where the Onondaga Formation was first described by Hall (1839) for cherty limestones in Onondaga County and the term "Corniferous" was first used by Eaton (1828) to discuss the same rocks. Later Drake and others (1996) combined Pennsylvania's Buttermilk Falls limestone (Willard, 1836) with the Onondaga as a undivided map unit noting that a facies change occurs in New Jersey along the northern part of the outcrop belt.

Figure 1-8. Onondaga Limestone in New Jersey showing typical exposures. Photo A - noncherty, thin- to medium-bedded, nodular fine-grained limestone. The outcrop is near the base of the formation and is located near Stop 1a. Photo B - cherty, thin- to medium-bedded fine-grained limestone. The outcrop is near Dingmans Ferry spring (Stop 2d). Earlier workers in New Jersey (see fig. 1-7) had informally divided the limestone into a lower noncherty unit (named the Onondaga Limestone) and an upper cherty unit (named the Corniferous Limestone). Photos by R. Witte.

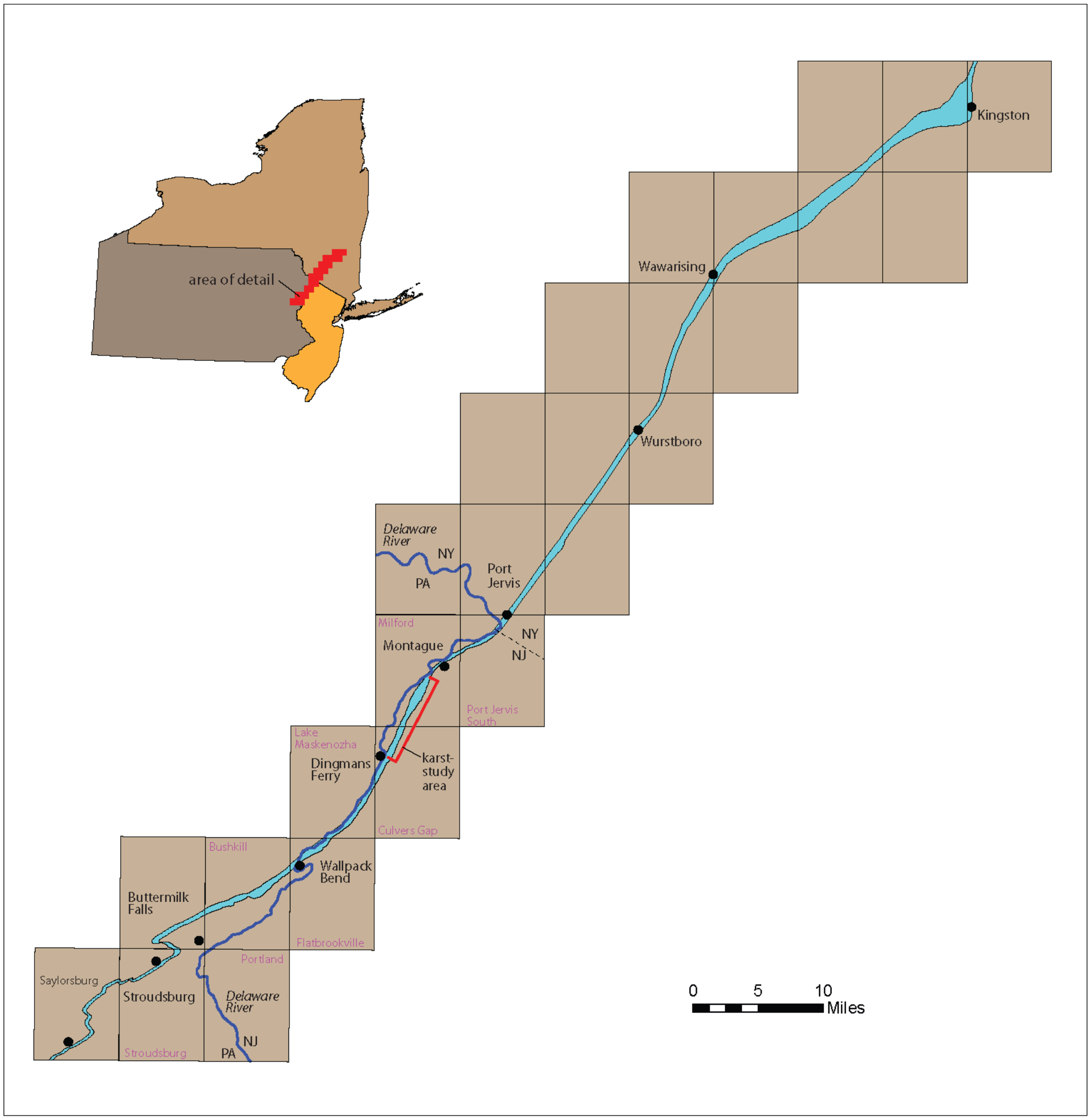


Figure 1-9. Location of the Onondaga Limestone outcrop belt between Kingston, New York and Saylorsburg, Pennsylvania, index of 7 1/2 minute topographic quadrangles, and places named in report. Only quadrangles in New Jersey named. Modified from Oliver (1956, figure 2) and Epstein (1984, figure 1).

Figure 1-10. Solution collapse sinkhole over the Onondaga Limestone. Delaware Water Gap National Recreation Area. Photo by R. Witte.

Figure 1-11. Soil collapse sinkhole over the Onondaga Limestone. Delaware Water Gap National Recreation Area. Photo by R. Witte.

Figure 1-12. Vulture Cave in the Onondaga Limestone, Delaware Water Gap National Recreation Area, Montague, New Jersey. The cave opening is about 4 feet (1.2 m) in diameter. The cave is partially filled with sand and debris deposited by the Delaware River during floods. Photo by R. Witte.

FIgure 1-13. Cutters J1 (054°) and J2 (146°) in the Onondaga Limestone, Delaware Water Gap National Recreation Area. Photo by R. Witte.

Figure 1-14. Bedding plane dissolution in the Onondaga Limestone. Photo by R. Witte.

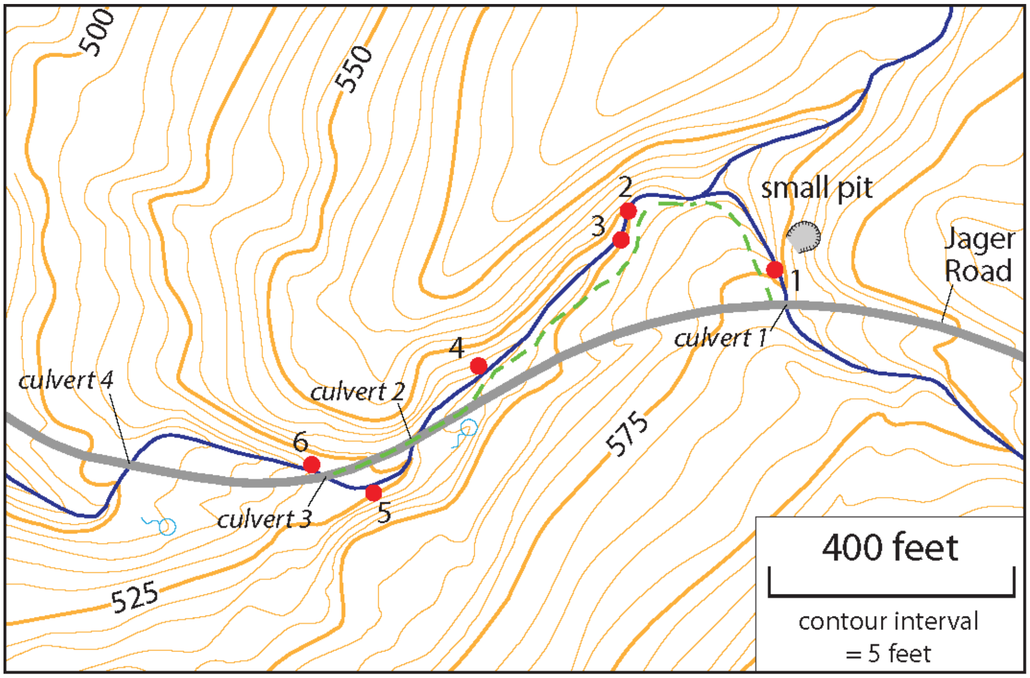


Figure 1-15. Site map of Stop 1a with numbered areas along route (green-dashed line) keyed to discussion and photographs in guidebook.

Figure 1-16. Solution joints in the Onondaga Limestone's Edgecliff Member just upstream from a small swallow hole and downstream from culvert 1. Water flows from left to right, rock hammer and fieldbook for scale. Inset photo shows dentate solution weathering along J1 joints. Water flow is right to left with hammer for scale. Photos by R. Witte.

Figure 1-17. Swallow hole formed in J1 joints, located along the left stream bank and downstream from culvert 1. Water flow is from left to right, hammer for scale. Photo by R. Witte.

Figure 1-18. Upstream view of debris-covered swallow hole below slump. Tree on right side of photograph is about 18 inches in diameter. Photograph was taken after a significant rain event in February 2016. Most of the time the flow does not reach this far downstream. The inset photo shows the slight depression formed in bouldery alluvium above what is assumed to be another large solution joint. This photo was taken a few weeks later and shows only a trickle of water (flow is from right to left). Note that secondary flow around a coarse gravel bar (main photo)diverts stream flow away from the buried swallow hole. Since swallow holes occupy positions along channel banks, stream flow to these features may be constrained by gravel bars and other debris (mostly fallen trees). Photos by R. Witte.

Figure 1-19. Downstream view (from end of gravel bar) and inset photo (shovel for scale) of the swallow hole located at 1a-3. Photos by R. Witte.

Figure 1-20. Small cave opening (28 inches (71 cm) wide by 32 inches (81 cm) high) located along the channel's right bank just upstream from culvert 2. Entrenching shovel is 32 inches long. Bedding (021° 10° NW) dips away from the viewer. The cave opening follows a large solution cross-joint (J2 - 114°) about 5 feet (1.5 m) across a sediment-filled floor before it drops another 3 feet (1 m) into a very small passage. The Onondaga here is noncherty, thin to medium bedded, very fine-grained limestone. In places (inset photo taken to the right of shovel, mechanical pencil for scale), wavy, silty laminae parallel bedding. On weathering surfaces these stand out in greater relief compared to the more limy beds that weather out in negative relief. Photo by R. Witte.

Figure 1-21. Small spring located just downstream from culvert 2. Over the years the low reservoir wall has been undercut resulting in the formation of a small sinkhole. Local denizens (inset photo) are the green-headed frog and orange long-tailed salamander, both common inhabitants of springs and seeps in karst areas. Spring photo by R. Witte and inset photo by Jon Inners.

Figure 1-22. Sinkhole along right stream bank below culvert 3. Opening is 22 inches (56 cm) wide by 16 inches (41 cm) high. The subsurface cavern beneath the sink is about 4 feet (1.2 m) deep and over 7 feet (2.1 m) in length. The inset photo shows that the sink lies over a large solution channel (~ 055˚). Typically, discharge from the spring upstream from culvert 3, drains into a gravelly area of alluvium near the sink. The sink has expanded over the last decade because of increased stream flow to this part of the channel, which was largely caused by the blockage of swallow holes upstream.

Figure 1-23. Seasonal views of Brau Kettle. The blue-capped standpipe housed the ADR logger that recorded water level and temperature. Photo A shows the kettle flowing during the late winter, typically a period of high groundwater levels in the Onondaga Limestone. Photo B shows the kettle partially filled, either filling or draining in response to summer thunder storms. During this period, water levels may fluctuate greatly in response to rapid changes in groundwater levels in the shallow karst aquifer. Photos by R. Witte.

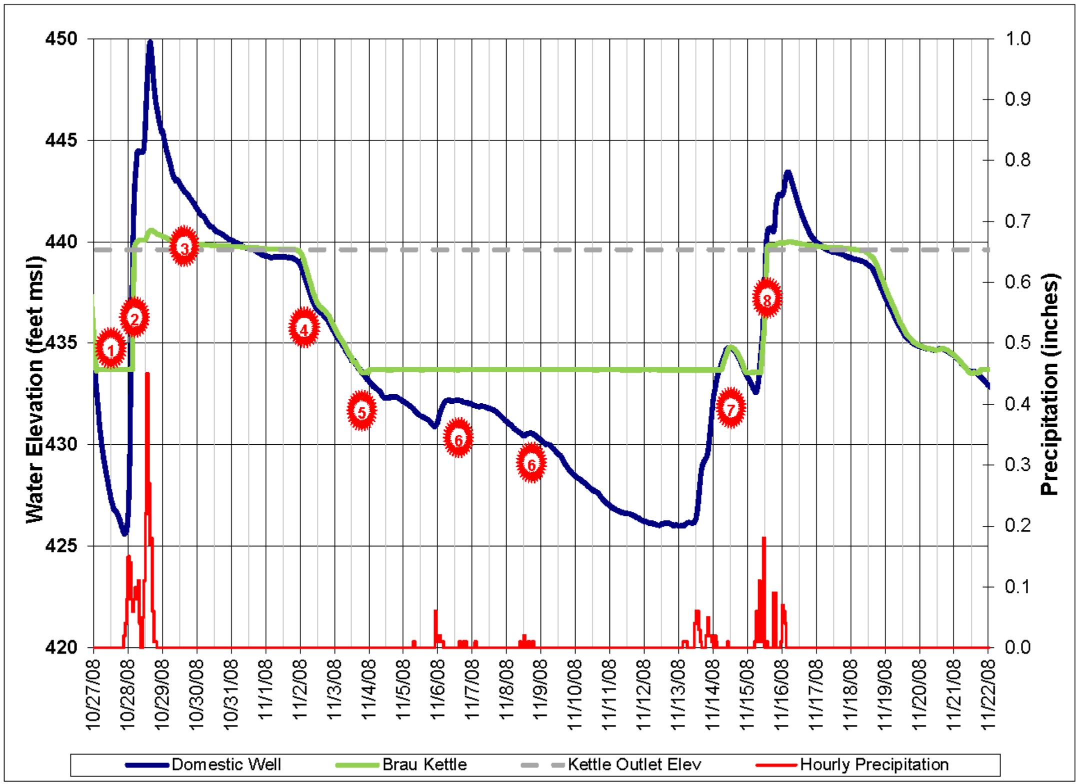


Figure 1-24. Daily water level and precipitation data for Brau Kettle and nearby domestic well at the Anson Johnson House from/27/2008 to 11/22/2008.

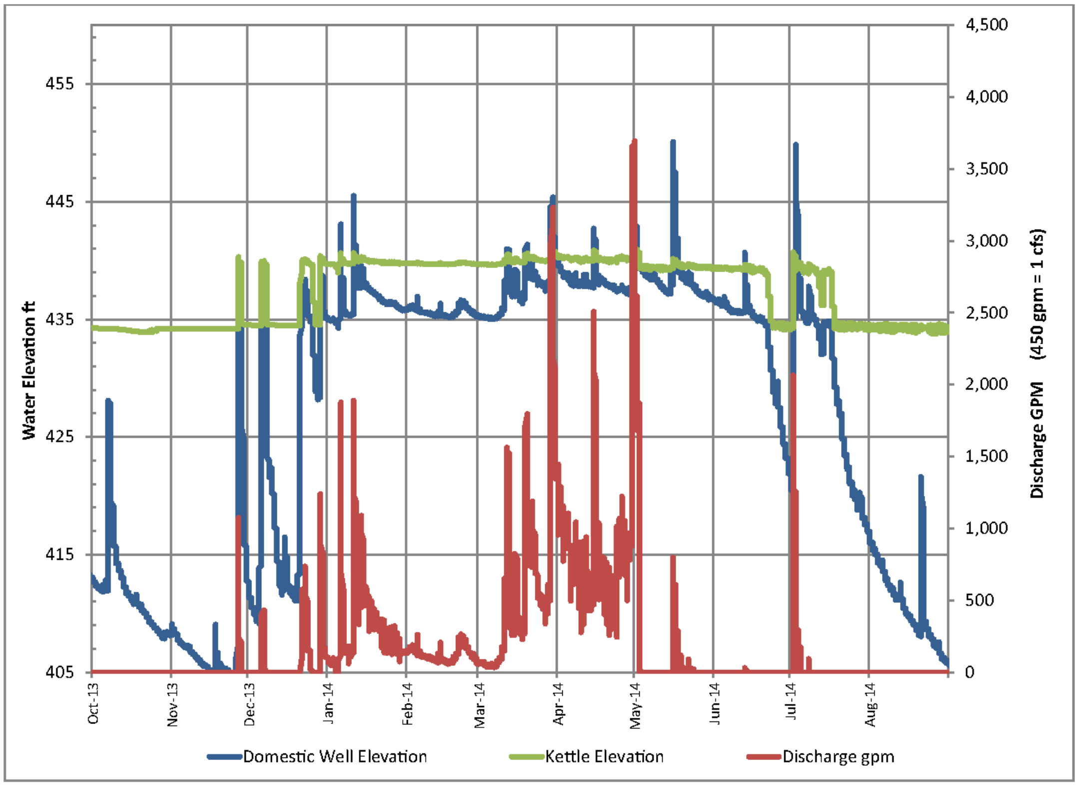


Figure 1-25. Water levels for the Anson Johnson House domestic well and Brau Kettle, and Brau Kettle discharge from October, 2013 to August, 2014.

Figure 1-26. NJDEP, Bureau of Freshwater and Biological Monitoring conducting a fish survey at Brau Kettle. Inset photo shows a mature 9 inch (23 cm) Brook Trout (netted in main photo) hiding amongst till stones on the Kettle's floor. Photos courtesy of Brian Henning (New Jersey Department of Environmental Protection, Bureau of Freshwater and Biological Monitoring).

Directions to STOP 2- Turn right out of parking area and head south on Old Mine Road.

Cumulative in miles (km)	Point to Point in miles (km)	Route Description
		Turn left onto Old Mine Road (south).
12.4 (20.0)	0.1 (0.2)	Pass Anson Johnson house well on right.
15.5 (24.9)	3.1 (5.0)	Cross County Route 560 (Tuttles Corner - Dingman Road) and continue on Old Mine Road.
15.8 (25.4)	0.3 (0.5)	Turn left into parking area, Old Dingman Road, Stop 2.

STOP 2 – Old Mine Road and Old Dingmans Road near Dingmans Ferry – Dingmans Ferry Spring, Tom Quick Cave, and Onondaga Limestone: solution and non-solution fractures, chert in the Onondaga Limestone, Amerind chert quarrying, and spring chemistry.

Field Stop leaders – Ron Witte, Don Monteverde, and Steve Domber.

Location and logistics

Stop 2 is located in the Culvers Gap quadrangle within the Delaware Water Gap National Recreation Area (DEWA) on the northwest slope of Wallpack Ridge. This field stop (fig. 2-1) is divided into two parts: 2a will consist of a short hike up Old Dingman Road and through the woods to Dingmans Ferry spring. After a short discussion, the group will cross a small stream (typically dry) and continue north through the woods to a large hill and outcrops of cherty Onondaga. **Safety Alert**. Be very careful traversing the steep slope and narrow game trail past Tom Quick Cave to the discussion area. The group will congregate along the west side of the hill for discussion and much arm waving by trip leaders especially by the one whose first name matches the rock's geo-abbreviation.

Geologic Setting

The same as Stop 1. We are still on the northwest flank of Wallpack Ridge formed here by a gentle dip slope of the Onondaga Limestone. In most places, the slope is covered by thin till. Along the Delaware River, glacial and postglacial terraces flank the river. The field stop route will traverse the lower and older part of the Onondaga first followed by a short ascent to the younger part of the formation. The lower part of the Onondaga is noncherty (similar to that observed at Stop 1-1a) whereas the upper part is very cherty. Large crinoid columnals that define the base of the limestone were observed by Spink (1967) along County Route 560, located about one mile (1.7 km) from the parking area. The columnals were confirmed by the trip leaders and several more were found nearby along strike.

Stop 2a – Dingmans Ferry Spring (41.220°N, 74.855°W)

Location – Lower slope of Wallpack Ridge.

Features – Dingmans Ferry spring, large solution joints, Onondaga Limestone (Edgecliff Member) and tufa.

Discussion – The spring (fig. 2-2) flows out of a large solution joint (070°), and emerges from a large opening at the base of a slope break. From here it spills downstream, cascading over a lag of till stones before coalescing into single channel. A very large oak tree (5-foot (1.5 m) diameter) stands sentient next to the spring, drinking its cool water for centuries. Building ruins below near Old Mine Road (fig. 2-1) and a nearby spring box suggest settlers used the spring for potable water. Evidence of Amerind history in the area (Schrabisch, 1915) suggest the refreshing spring water was enjoyed well before this wild area was settled by colonists. Given the proximity of the spring, cave, and chert resource to each other, this area was probably sacred to the Minsi Lenapi that lived along the banks of the Delaware river.

Tufa, porous calcium carbonate (fig. 2-3), covers many of the rocks near the spring. It was deposited by emerging spring water, following a decrease in pressure (subsurface to atmospheric) resulted in the precipitation of $CaCO_3$. Water samples collected by NJGWS show pH values ranging from 7.25 to 7.42 and total dissolved solids ranged from 161 to 179 ppm; all measurements typical for springs in this area.

The nearby creek bed (fig. 2-1) is lower along contour from the spring and is typically dry. Here the Onondaga Limestone forms the creek bed, primarily a bedding-plane dip slope cut by several large solution joints (fig. 2-4). The limestone exposed along the creek bed is a thin to medium-bedded, faintly nodular, non-cherty limestone with some fossils. Its lithology is similar to the Onondaga observed at Stop 1a, so it may belong to the Edgecliff member. Similar to the situation at Brau Kettle, the lower and dry creek next to the spring shows that groundwater flows along strata-bound solution joints. Upstream a few small seeps discharge into the channel and a small wetland also drains into the channel as well as a small stream that flows off the hillslope above the spring and well above the Schoharie – Onondaga contact. Present hydrologic conditions do not explain erosion observed along the creek. Perhaps the channel may have been cut by glacial meltwater or postglacial stream flow prior to a change in subsurface drainage and the formation of Dingmans Ferry spring.

Recently, the spring's small stream was diverted to a larger channel (fig. 2-1). Spring discharge can now be observed flowing into the dry channel just upstream from the culvert on Old Mine Road. This manmade diversion was in response to erosion abatement and icing along Old Mine Road.

Proceed across dry (hopefully) creek bed and head upslope. **Safety Alert**. Be very careful crossing channel. If wet, the sloping rock surface is very slippery and may also be covered by leaves and moss. Also, watch out for a paper wasp nest near the south side of the dry creek. Hopefully, these insects will vacate the premises before our trip.

Stop 2b (41.221°N, 74.855°W)

Location – Hill overlooking the Delaware River near Dingmans Ferry and the only privately owned toll bridge across the Delaware River. Add history of Dingmans Ferry.

Features - there are three things to see, 2b-1) possible evidence of Amerind chert utilization, 2b-2) Tom Quick Cave, and 2b-3) cherty Onondaga Limestone (flinty Don). Depending on the group size, slope conditions, and whether we're on schedule, we may stop at all three locations (fig. 2-1).

Discussion -

2b-1 – Slope below outcrop.

There are many small chert fragments and a quartzite hammerstone (fig. 2-5) near the base of a tree. Because tree root growth may concentrate rock fragments on the surface (old mapping trick in areas of sparse outcrop), their occurrence here may not indicate Amerind working of this chert resource. However, some chert fragments exhibit conchoidal fractures and the hammerstone's tip has been broken in a way to suggest it was used as a tool. Also, the hammerstone fits remarkably well into the palm of your hand. Amerinds quarried and collected chert throughout Wallpack Ridge to provide blanks for tools and projectile points (Phillip LaPorta, personal commun., 1996)). Given the location of this hill overlooking the Delaware River, proximity to Amerind encampments situated on alluvial terraces near Dingmans Ferry

(Schrabisch, 1915), and abundance of chert in the Onondaga here, this site would have been a prime location to collect chert. It may have been quarried from the outcrop or collected from loose rock on the slope below. Typically, larger pieces of chert were knapped into smaller blanks at the outcrop and then carried back to encampments where they were further worked into tools such as scrappers and projectile points. Hopefully, the evidence presented shows that this site was actively used to process chert. At least that's our story (spring, cave, chert) and we're sticking by it.

2b-2 – Tom Quick cave.

The cave is a long, narrow slot (fig. 2-6) that runs about 25 feet (8 m) along a large joint (027°). Given the attitude of bedding (043° 12° NW) and proximity to a steep slope down dip, the cave is probably a fracture cave that formed when a very large joint block moved downslope by creep., and not the result of solution weathering. However, the initial enlargement of the joint by solution weathering cannot be discounted. In addition to creep, movement may have been aided by root growth and ice wedging. Also, evidence for solution weathering beneath cherty limestone (Stop 2b-3) may have contributed to detachment along bedding along the base of the joint block. Above the cave small sinkholes are found that are aligned along the 027° fracture.

Eye witness accounts (Bathgate, 1916) of a small room at the cave's terminus about 55 feet from its entrance suggest the cave may have been larger than its current size. During a return visit, Bathgate could only proceed about 20 feet into the cave. One of the cave walls had moved closing off the passage. This account suggests that the cave may consist of several joint blocks that at times may move independently from one another.

As with most caves, local lore provides interesting stories where fact is not easily separated from fiction. The cave is named after Tom Quick Jr., who may have used the cave as a hideout during the mid-1700's following one or several Indian skirmishes (Dalton, 1967). Supposedly, Tom's father, Tom Quick Sr. was mortally wounded in a raid when the family was cutting ice on the Delaware River (njherald.com/article/20151206/ARTICLE/312069975#).

Currently the cave is closed by the National Park Service in order to protect bats from a deadly fungus that causes white nose syndrome.

2b-3 – Cherty Onondaga Limestone outcrop along west side of hill.

This face offers a good opportunity to investigate the cherty beds of the upper Onondaga. Originally named the Corniferous Limestone (Cook, 1868) based on similarities cherty limestones found in Pennsylvania and New York. This 14 foot-high (4.3 m) outcrop shows an abundance of chert nodules dispersed throughout the outcrop (figure 2-7). The chert nodules vary from 2 to 3 inches (5-7.5 cm) across. Close inspection shows areas where the chertification was incomplete yielding a dark gray mottled appearance. Associated with this incomplete certification are intriguing very thin parallel black curving lines that are commonly associated with the mottled spots (fig. 2-7, inset photos). There is no preferred orientation of these thin bands, which we suggest may relate to the secondary chert-forming process. Further study is needed to completely understand this appearance.

Due to the absence of a preferred fracturing in these beds the chert would be more easily worked and highly prized by the original inhabitants of this region. Farther to the north this same cherty upper part of the Onondaga is highly cleaved which would greatly inhibit the ability to work those cherts into usable points. Beds are generally wavy with variable thickness of 3 to 8 inches (7.6-20.3 cm). At the base of this outcrop are two small solution openings (fig. 2-8) in generally chert-free beds. The solution appears to occur at the intersection of the bedding plane and some weakly developed joints trending 068°. This minor bedding plane solution may have enhanced joint-block movement down slope which led to the development of Tom Quick cave.

Given its high chert content and younger stratigraphic position relative to the basal Onondaga, we believe we are looking at the Moorehouse Member (possibly its upper part). We have not encountered the Nedrow Member in our mapping because it may not be here because it may be indistinguishable from the Edgecliff or Moorehouse Members (Oliver, 1956) or because of its shaly nature it does not outcrop along the Onondaga dip slope. The Tioga bentonite, which defines the Seneca-Moorehouse contact has not yet been encountered in western New Jersey, but as stated in the long discussion preceding Stop 1a we believe the Seneca lies mostly buried beneath alluvium and glacial outwash making its identification problematic.

Return to parking area by retracing steps to flatter area above the creek and follow slope to Old Mine Road (fig. 2-1). For more adventurous types, straight down the hill is the shortest route. Mind you, if you fall and incapacitate yourself will give you a bottle of whiskey, GPS your position, and notify the Park Rangers at the end of the trip.

Directions to Lunch Stop (Peters Valley). Turn left onto Old Mine Road (south) from parking area along Old Dingman Road.

Cumulative in miles (km)	Point to Point in miles (km)	Route Description
16.5 (26.6)	0.7 (1.1)	Continue straight on Wallpack Road (south). Do not turn right onto Old Mine Road.
17.5 (28.2)	1.0 (1.6)	Turn right into driveway toward picnic pavilion at Peters Valley.

Lunch Stop – Peters Valley (41.197°N, 74.851°W), which is on route to Stop 3 (Bevans Rock Shelter). Park in upper lot near picnic pavilion (fig. 2-9). Rest rooms are located at the bottom of the hill across the street from the gallery. Please take a moment to stop by the gallery and checkout the many fine works of the local artisans.

Peters Valley School of Craft is a non-profit corporation, founded in 1970 in partnership with the National Park Service to promote and encourage education and excellence in craft. Peters Valley School of Craft's programs include adult summer workshops, youth programs, opportunities for artists, special studio programs, public exhibitions, demonstrations, and outreach. Peters Valley School of Craft maintains studios in eight disciplines: blacksmithing, ceramics, fiber surface design, fiber structure, fine metals, photography, special topics and woodworking. Description from https://www.nps.gov/dewa/planyourvisit/peters-valley.htm.

For more information about Peters Valley School of Craft and the programs offered, visit the campus at 19 Kuhn Road, Layton, NJ 07851, call (973) 948-5202 or visit their website at petersvalley.org.

We’ll probably spend about 45 minutes here and then take the short drive over to Stop 3 (Bevans Rock Shelter). Turn right onto Wallpack Road to continue trip.

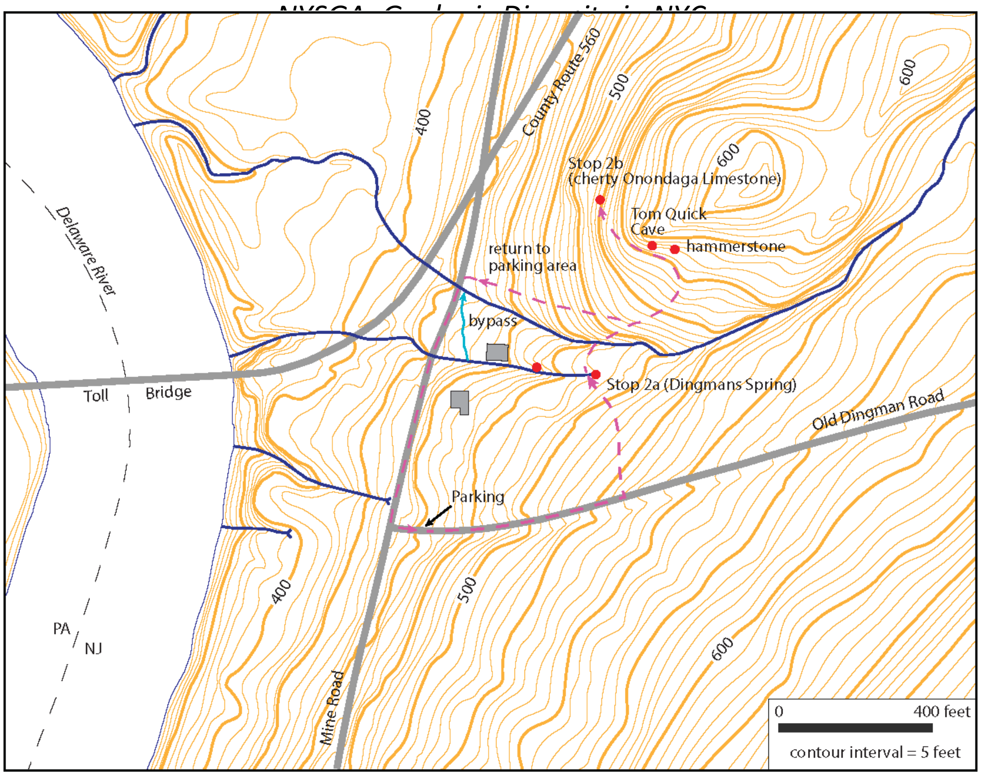


Figure 2-1. Site map of Stop 2 with areas labelled along route (purple-dashed line) keyed to discussion and photographs in guidebook.

Figure 2-2. Dingmans Ferry spring, Delaware Water Gap National Recreation Area, Sandyston Township, New Jersey. The spring flows from a large opening along the lower slope of Wallpack Ridge. Large oak tree to the right is 5 feet in diameter. Closer inspection (inset photo) shows that the spring's discharge is directed along a solution joint that trends about 060°. Photo by Jon Inners.

Figure 2-3. Moss-covered tufa (porus calcium carbonate) encrusting cobblestone at Dingmans Ferry spring. Photo by R. Witte.

Figure 2-4. Onondaga Limestone (bedding dip slope) in stream channel just north of Dingmans Ferry spring. Except for a few small seeps, the channel is typically dry, while the spring flows year round. The solution joints (one noted along arrow, 071˚) have a similar orientation as the joint where the spring emerges. The channel floor (measured along slope contour) is lower than the spring, showing that groundwater flow is highly controlled by joints and vertical zonation between beds. Photo by Jon Inners.

Figure 2-5. Chert fragments and quartzite hammerstone (right side of pencil) found on slope below outcrop of cherty Onondaga Limestone. Note indents along left side of hammerstone that could easily accommodate thumbhold and fingerholds. The stone's pointed end exhibits small impact marks, suggesting it may have been used to knap larger pieces of chert into smaller blanks. These were later carried back to encampments where they were worked into tools and projectile points. Photo by Don Monteverde.

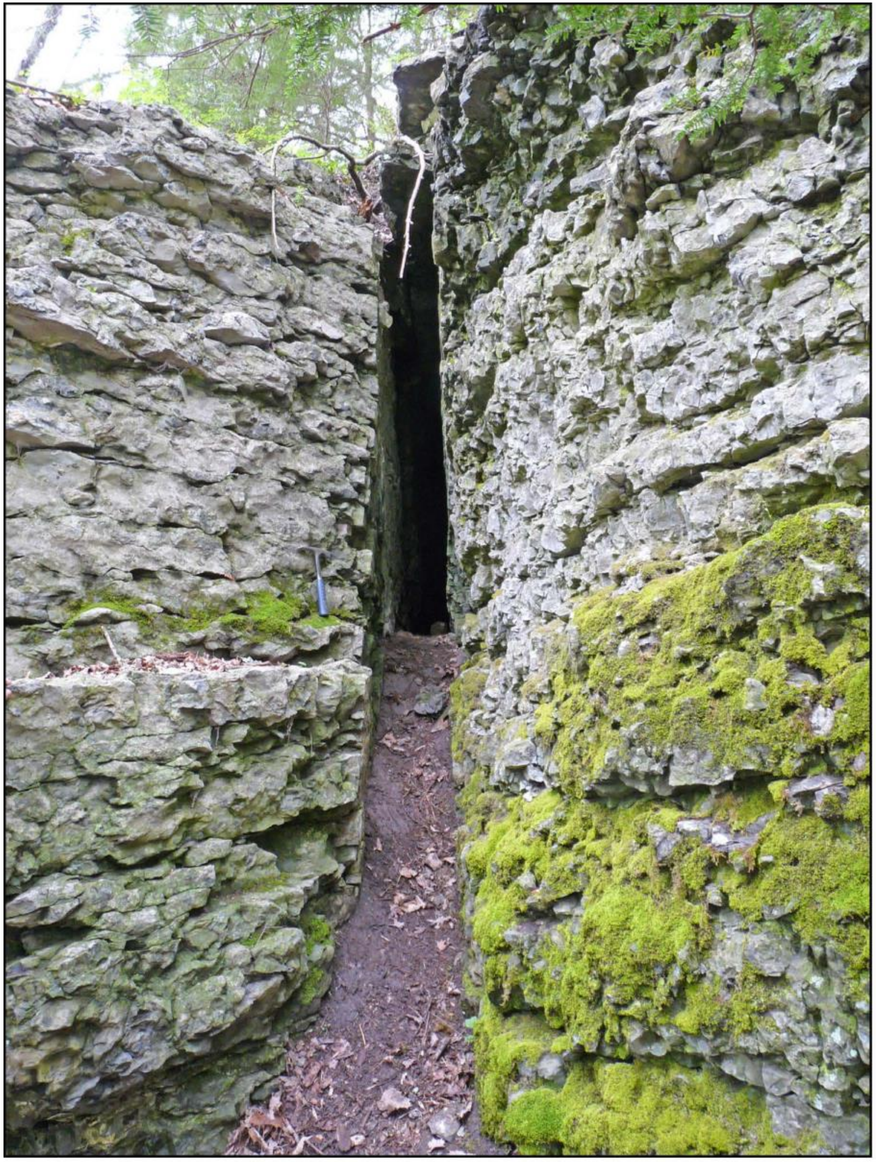


Figure 2-6. Entrance (w = 1.15 ft. (.35 m), ht = 8.2 ft. (2.5 m)) to Tom Quick cave, rock hammer for scale. The cave follows a enlarged vertical joint (027˚) about 30 feet (9 m) long. Bedding = (043˚, 12˚ NW). Based on bedding attitude and proximity along a steep slope the cave's fracture may have become enlarged by mass movement (downslope creep) rather than solution weathering. Photo by R. Witte.

Figure 2-7. Outcrop of chert-bearing Onondaga Limestone showing many dark gray to black chert nodules. Note mechanical pencil for scale. The abundance of chert places this exposure in the Moorehouse Member of the Onondaga. The overlying Seneca is also chert bearing, but is separated from the Moorehouse by the Tioga Ash bed which has not yet been found in New Jersey. Bedding (009˚ 13˚ NW, towards the viewer) is quite wavy, probably due to the original nodular sedimentology and the secondary chertification. Beds have a very rough parallel fracture pattern that does not commonly propagate upwards into adjoining beds. Inset photos A and B. Examples of thin, parallel dark silica (?) bands associated with locations of incomplete chertification. Band alignment is only parallel locally and there is no preferred orientation across the outcrop. They are associated with dark gray patches of incomplete chertification. Photos by Don Monteverde.

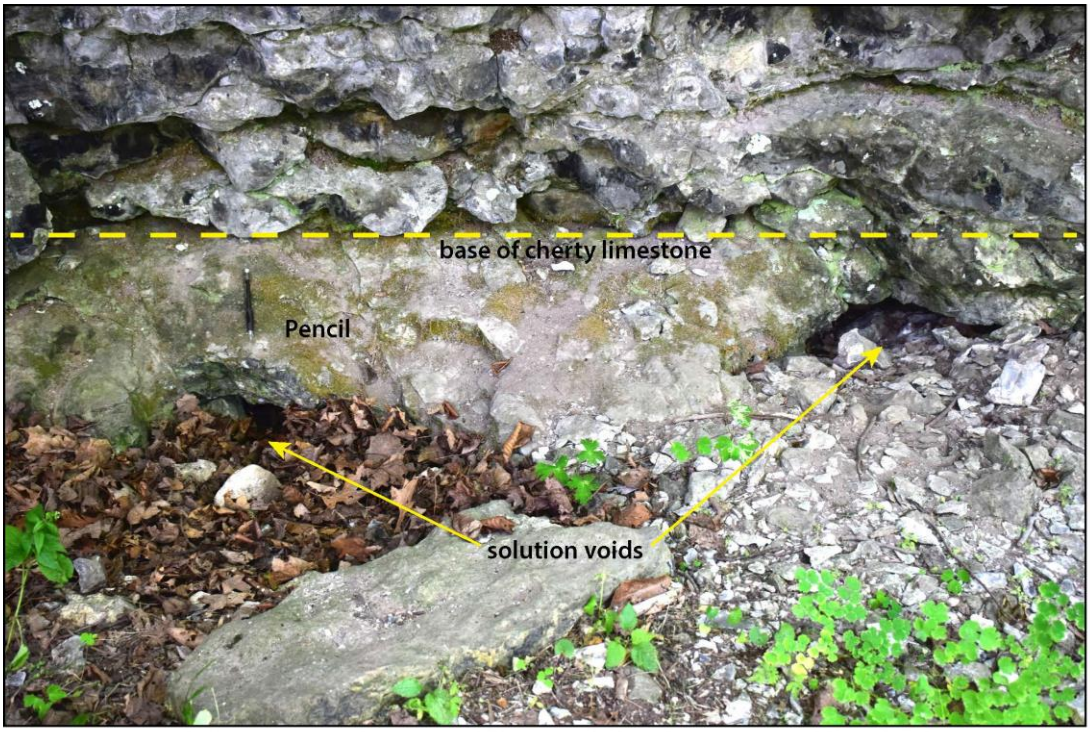


Figure 2-8. Two small solution voids in a limestone-rich bed beneath cherty limestone. Pencil for scale. The voids appear to have formed along a joint (068˚ 83˚ SW) - bedding (009˚ 13˚ NW) intersection. Photo by Don Monteverde.

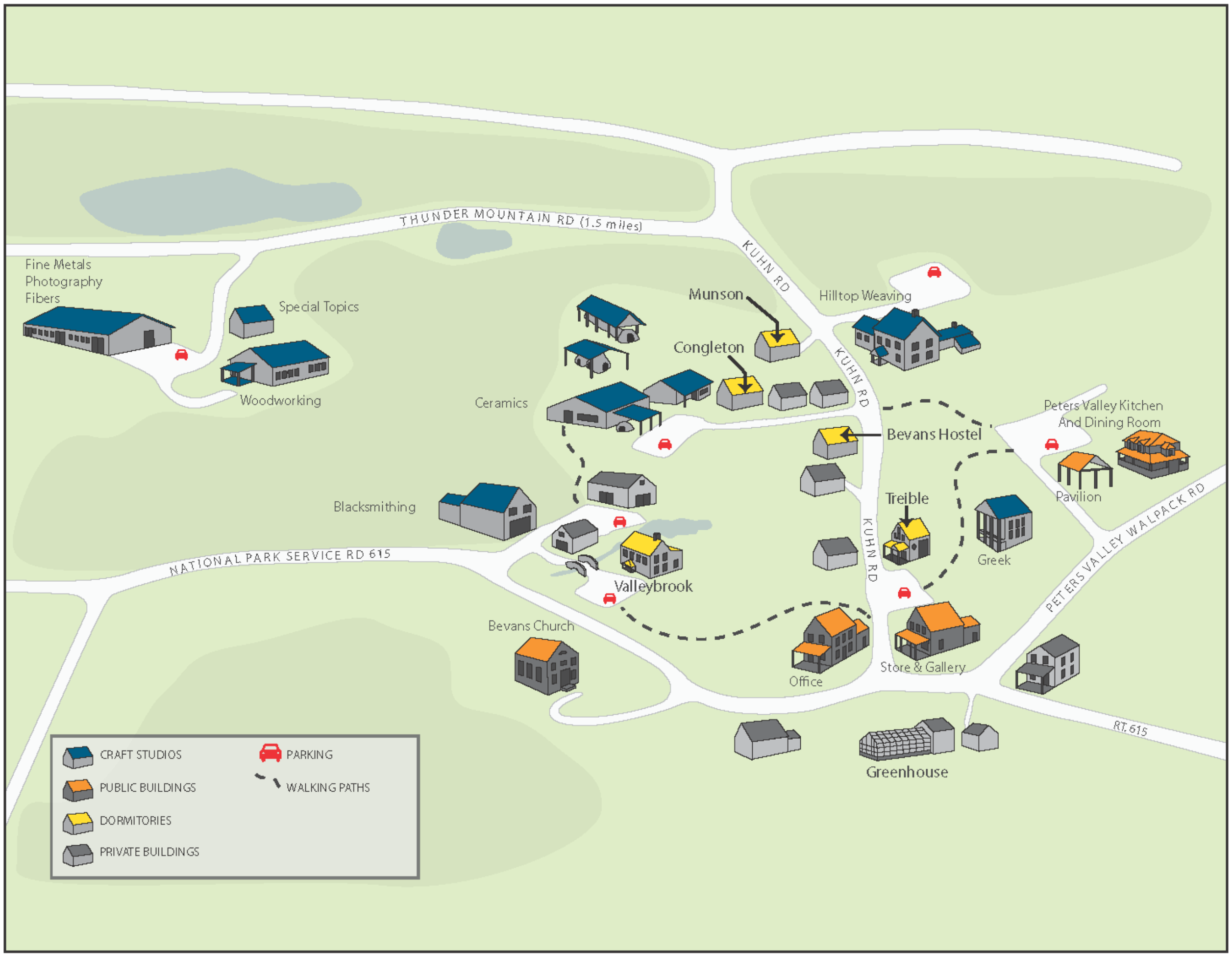


Figure 2-9. Campus map of Peters Valley. We'll stop for lunch at the pavilion. Please feel free to check out the store and gallery. Rest rooms are located across the street from the gallery along the right side of the office.
Map from - www.petersvalley.org/images/file/pv_student_map-8_5inx11in-trifold-inside.pdf

Directions to STOP 3 - Turn right out of driveway onto Wallpack Road (south).

Cumulative in miles (km)	Point to Point in miles (km)	Route Description
17.6 (28.3)	0.1 (0.2)	Turn right onto Kuhn Road (west), next to Peters Valley Gallery.
18.3 (29.5)	0.7 (1.1)	Turn left onto Thunder Mountain Road, park in small area about 100 feet past turn off. Arrive at Stop 3.

STOP 3 – Bevans Rock Shelter, Esopus Formation, fracture caves, Amerind history.

Location Coordinates (parking area): 41.194°N, 74.863°W

Field Stop leaders – Ron Witte, Don Monteverde, and Ted Pallis.

Location and logistics

Stop 3 is located in the Culvers Gap quadrangle in the Delaware Water Gap National Recreation Area (DEWA) on Wallpack Ridge above Peters Valley (fig. 1-1). The exact location of the rock shelter is not shown in order to protect the cultural integrity of the site. Follow trip leaders to secret parking area and then we'll proceed by foot to the rock shelter. The large outcrop near the parking area is the Esopus Formation, a very thin to thin-bedded, very fine-grained sandstone. Bedding is 046° 16° NW and the outcrop is cut by a well-developed cleavage (081° 72° SE).

Geologic Setting

The Bevans Rock Shelter (fig. 3-1) sits high on Wallpack Ridge about one mile (1.6) km from both the Delaware River and Flat Brook in Wallpack Valley. The rocks in the shelter area are oldest to youngest are the Glenerie Formation and Ridgely Sandstone of the Oriskany Group, Esopus Formation, Schohaire Formation, and the Onondaga Limestone (fig. 3-2). All formations dip northwestward with the Onondaga forming a long dip slope to the Delaware River. The Ridgely Sandstone, which consists of thick-bedded quartz-pebble conglomerate and coarse quartz sandstone (Monteverde, 1992) may not be present over the Glenerie at the shelter, but it has been observed nearby to the south, where it thickens along strike to Wallpack Bend and reaches a maximum thickness of 32 feet (9.8 m).

Oriskany through Onondaga time represents a sea-level cycle where 1: the Oriskany Group represents a carbonate shelf to clastic sequence (beach and nearshore fluvial deposits), 2: the Esopus Formation represents deeper water deposition marked by very low fossil content and occurrence of the trace fossil Zoophycus, 3: the Schohaire Formation is a transitional unit that marks a return to shallower seas, and 4: the Onondaga represents a carbonate shelf sequence, which in places contains patchwork reefs.

The shelter rocks over the years have had several interpretations. Henry Kummel's field sheets (1895, on file at NJGWS, Trenton, New Jersey) show that the Cauda Galli Grit (now recognized as Esopus) was mapped at the shelter with the Oriskany contact located just east of the shelter. Meredith Johnson, during a visit to the shelter in 1938 (NJGWS permanent notes on file at NJGWS, Trenton, New Jersey), indicated that the shelter rocks belonged to the Oriskany Limestone. Johnson also noted that base of the shelter contained "numerous small brachiopods of the type similar to *Anoplotheca flabellites*. Herpers (1952) noted that a contact between the Oriskany and Esopus occurs at the shelter and that the lower fossiliferous zone belongs to the *Acrospirifer murchisoni* zone of the Oriskany. Monteverde (1992) showed that the shelter lies within the Esopus Formation. Hmmm. multiple interpretations of the same outcrop, let's see if we can add to the confusion.

Discussion

Geology of Bevans rock shelter.

Take ten geologists to an outcrop and you'll wind up with 10 different interpretations. An old witticism to be sure, but one with a kernel of truth to it. Who's right and who's wrong? We'll present the facts and you can make up your own minds. Esopus, Oriskany, or both?

The outcrop at Bevans rock shelter looks much different than the Esopus outcrop near the parking area and above the shelter, which is a dark gray, noncalcareous, very fine-grained sandstone with a well-formed cleavage. The trace fossil *Zoophycos* is also found throughout the shelter's rocks. The shelter's roof rock (fig. 3-1) is similarly described so we're confident that this part of the shelter is Esopus. The 10.5 feet (3.2 m) section (fig. 3-1) below the roof is much different. The rock here is mostly (we did not check every bed) a thin- to medium-bedded, calcareous, very fine-grained sandstone where cleavage is not nearly as well-formed as it is in the overlying rocks. Throughout the shelter's back wall solution voids up to 6 inches (15 cm) in diameter (most are less than 2 inches (5 cm)) are found along bedding (fig. 3-3). Also, a few dark gray, calcareous concretions (fig. 3-3) occur along bedding about midpoint between the shelter's roof and floor. *Zoophycos* occurs throughout this section to at least 2 feet above the shelter's floor (fig 3-4). Lastly, a thin bed of small brachiopods (fig. 3-3) occurs about 5.4 feet (1.6 m) from the shelter's floor. Presumably, these are the same brachiopods observed by Johnson and Herpers, which were interpreted to be Oriskany fauna (fig. 3-3). Biostratigraphically, this is a mixed zone where Oriskany and Esopus faunas are transitional. Lithostratigraphically, a contact occurs between noncalcareous and calcareous sandstone at or just below the shelter's roof. As far as we are aware, no one has described *Zoophycos* in the Oriskany. However, Brett and others (2009) indicated that a few Oriskany brachiopods were transitional into the Esopus. Spink (1967) also noted, that the lower Esopus contact in places is "gradational through an interval of several feet in which arenaceous and calcareous siltstones become interbedded with, and then are replaced by, silty limestones." Spink's silty limestones are probably the Glenerie Formation.

Given the best available data (one of Don's favorite terms of escapism) and similarity to Spink' s description of the Esopus-Glenerie contact, the shelter section below the roof represents the basal, transitional facies of the Esopus Formation. The Oriskany contact lies just to the east, buried beneath a bog that flanks the shelter. However, if you want to place the contact elsewhere, that's fine, just publish your work after we retire.

Geomorphology

The rock shelter and the smaller caves on its flanks (fig. 3-5) were shaped by glacial erosion and postglacial mass weathering. The main shelter, with its resistant Esopus roof, was chiefly formed where the easily eroded transitional Esopus rock was removed by glacial plucking and abrasion. The scalloped surfaces on the shelter's back wall (fig. 3-3f) appear to be glacially scoured. Also, the absence of loose rock beneath most of the shelter's roof suggests this material was removed by glacial erosion. Admittedly, some of this material may lie buried in the bog that lies adjacent to the shelter. However, given the large size of current joint blocks in and around the shelter, one would expect that some of this material should be here on the floor of the open part of the shelter. Other than smaller stones, this material was probably not moved by the shelter's past inhabitants.

Over time, part of the shelter's roof and walls have collapsed (specifically the north end). The result of postglacial frost wedging and slump where joint blocks became dislodged and fell away from the outcrop. Similarly, the fracture caves on the shelter's flanks may have been formed by frost wedging. However, because bedding dips into the hillside, the movement of these very large joint blocks was not helped by gravity as it was at Tom Quick Cave (Stop 2-c). Another possibility is that ice wedging may have occurred during glaciation. Specifically, during deglaciation when overlying ice was thin and freeze-thaw cycles much more robust.

The smaller cave in the shelter (fig. 3-5) appears to be largely a result of mechanical weathering along a nearly vertical 096° joint that intersects the shelters back wall. However, dissolution in the lower Esopus beds may have aided the cave's formation.

Archaeology of the Bevans Rock Shelter

The Beans rock shelter (fig. 3-6), located in Sandyston Township, Sussex County is a prominent rock shelter that was used by Native Americans during the Late Archaic (3000 B.C to 1000 B.C.) and Woodland (1000 B.C. to 1550 A.D.) periods. This rock shelter sits about 300 feet (91 m) above the Delaware River, located halfway between the Delaware and Wallpack Valleys. The shelter has an eastern exposure and lies adjacent to a narrow bog. It has an overhanging roof that projects up to 20 feet outward from the rock face, creating a sheltered space underneath. The habitable area of the shelter consists of three parts (fig. 3-7). To the south (near fireplaces "a" and "b") lies a typical overhanging rock, 24 feet long, which projects eight feet outward about 10-14 feet above the floor. In the center (near dislodged rocks), another overhanging rock, 22 feet long, has a roof 8 feet high projecting 6 feet, and is protected in front by two detached masses of rock, one small, the other large, lying 5 feet from the rear wall. The central section has a higher degree of enclosure due to the two detached blocks which hold up the roof and form the eastern wall. At the right is a cave-like compartment (near fireplaces c and d), 16 feet long, 4 1/2 feet wide and 6 feet high. This northern section offers the most protection. All three parts lie in an approximate straight line at the foot of a low cliff and their total length is about 62 feet. The dirt floor underneath the rock is level and composed of light sand mixed with rocks.

Two archaeological surveys were conducted here, one from 1912-1913 by Max Schrabisch, archaeologist and writer and another in 1931 led by Dorothy Cross (State Archaeologist and Curator for the New Jersey State Museum). Several local collectors also reported finding material in the main shelter from time to time, but none of this was officially recorded.

Max Schrabisch partially excavated the Bevans rock shelter while making an archaeological survey of Sussex County for the state from 1912 - 1913. In the summer of 1931, from June 8 to July 7, the New Jersey State Museum and the University Museum, Philadelphia, sponsored the complete excavation of the four shelters at the Bevans Rock shelter under the direction of Dorothy Cross. These two surveys uncovered many artifacts or traces of human habitation. During the first excavation by Schrabisch, the southern open shelter (location b, fig. 3-7) yielded the most aboriginal remains while the middle section contained the least. The rear was smoke-stained and discolored by ancient fires but no relics were found on the surface. Native American relics were found from three inches to two feet below the surface. Items included both plain and ornamented pot shards, deer bones, projectile points (identified as arrow and spear points), multiple tools (drill, pestles, hammers, blades), net sinkers, many flint and jasper flakes, and at least 1000 pieces of pottery (most cord-marked) belonging probably to approximately 20 different pots were found in the three parts of this rock shelter. Also, several fire pits were excavated (fig. 3-7), some of which contained mussel shells. Figures 3-8 and 3-9 are some of the artifacts collected during the Schrabisch survey.

A second excavation was conducted in 1931 Led by archaeologist Dorothy Cross (fig. 3-10). Altogether, the second excavation produced 102 various stone artifacts (some of which included arrow points, blades, scrappers, one possible hoe, hammerstones, net sinkers, one maul, one anvil, and one rubbing stone), 11 bone artifacts, 1,428 potsherds (both cord-marked and plain), 100 fresh-water *Unio* shells (whole and fragmentary), three crinoid stems (possibly used as jewelry) and several thousand whole and fragmentary animal bones, a fragment of a trade pipe, and a lead bullet. Three undisturbed pits were found during this excavation. All pits showed traces of fire action and contained refuse material.

Both archaeologists who excavated the site came to different conclusions about the habitation of the site. According to Schrabisch, "based on the materials found here, the rock shelter was tenanted more or less permanently and perhaps used for winter quarters. The fireplaces suggest cooking and the pottery indicates that the women and children accompanied the men and shared their quarters." Cross believed "the Bevans shelters were used as temporary abodes and this is attested to by the absence of permanent household equipment. Almost all of the artifacts can be associated with hunting and fishing, either directly or indirectly; though the number of potsherds is a little greater than would have been associated with a hunting or fishing camp." Cross further stated that "if the entire contents of the shelter were available, more definite conclusions might be drawn" regarding Amerind habitation.

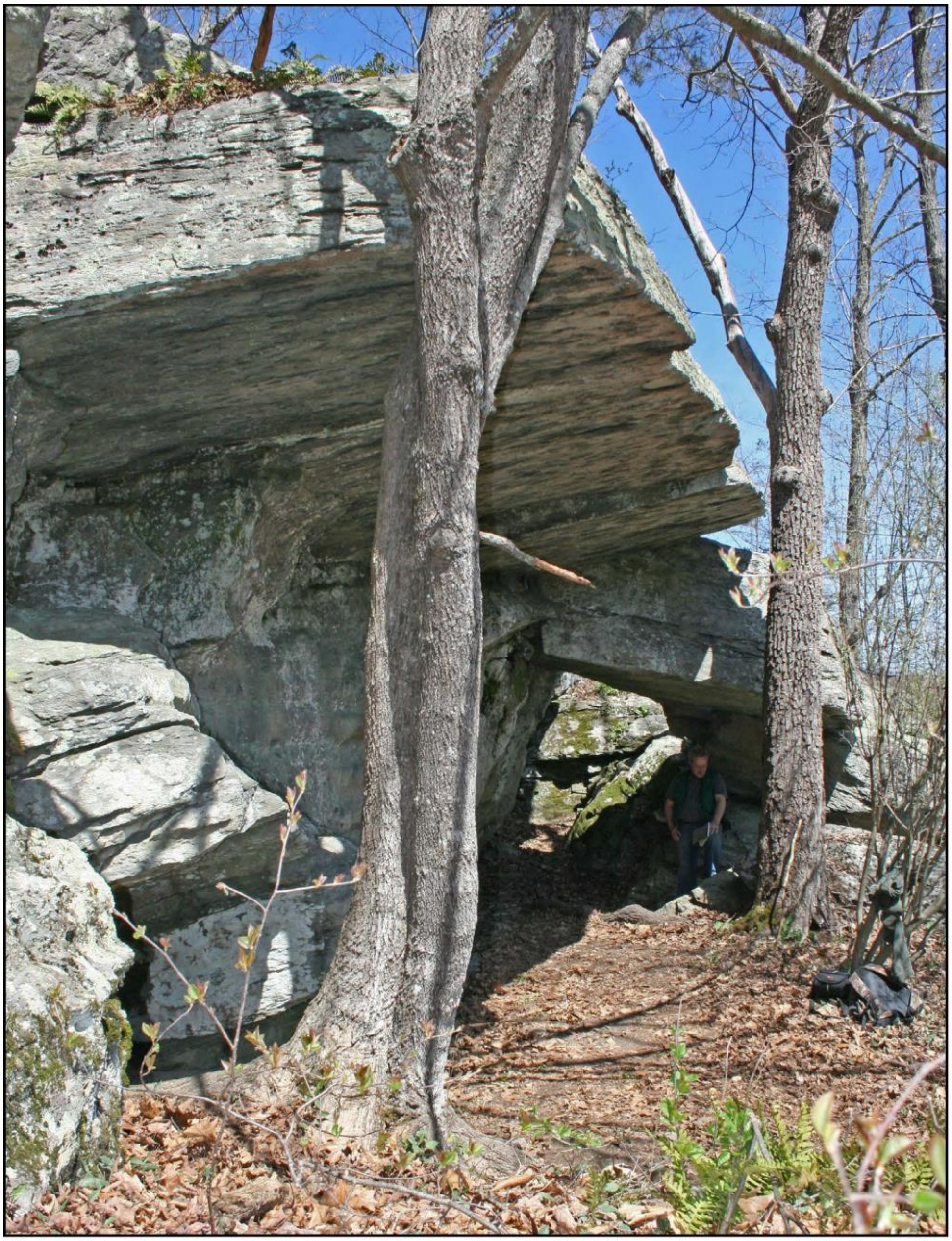


Figure 3-1. Bevans rock shelter looking northeast. Past the collapsed roof blocks to the left is a narrow vertical fracture that leads to a small cave (the enclosed part of the shelter). The roof and upper part of the shelter's back wall contain the trace fossil *Zoophycus*, a common fossil in the Esopus Formation. Near the base of the back wall, small brachiopods (*Anoplotheca flabellites*) have been found, a common fossil in the Oriskany. Note odd fellow in the shadows for scale.

System	Series	Formation		Member	Description	Aprroximate thickness (feet)
Devonian	Middle	Marcellus			Dark gray to black shale, locally silty, weathers medium gray; fissile, thin bedded though locally thick bedded and massive; limonite stained, and sparingly fossiliferous.	900
		Onondaga (Buttermilk Falls)		Seneca (Echo Lake)	Fossiliferous cherty limestone. Base contains Tioga ash bed.	15
				Moorehouse (Stoudsburg)	Medium-gray limestone and argillaceous limestone with beds, pods, and lenses of dark-gray chert. Fossiliferous and burrowed.	135
				Nedrow (McMichael)	Medium-gray calcareous argillite with lenses of light-gray fossiliferous limestone.	40
				Edgecliff (Foxtown)	Medium-dark-gray calcareous siltstone and argillaceous limestone containing lenses of dark gray chert. Fossiliferous, one-inch diameter crinoid columnals in lower half.	80
	Lower	Schoharie			Medium to thick bedded; silty to shaly, locally dolomitic limestone containing local thin ribs or pods of black chert, weathers yellowish gray to locally pale olive and grades downward into medium to dark gray calcareous siltstone at base. Contains rare trace fossil Taonurus.	175
		Esopus			Medium to dark gray, shaly to finely arenaceous siltstone, containing minor calcareous siltstone near top. Laminated to medium bedded, as well as local massive thick bedded layers. Weathers medium gray and is limonite stained in places. Bioturbated by Taonurus. Thickness approximately 300 feet.	300
		Oriskany Group	Ridgely Sanstone		Medium-gray, medium- to thick-bedded quartz-pebble conglomerate and coarse quartz sandstone. Sand grains are moderately well sortd and subrounded. Rock has a carbonate cement and contains abundant braciopods. Unit occurs west of Peters Valley and thickens to the southwest.	0-32
			Glenerie Formation		Upper section is medium to dark gray, fine grained silty limestone, containing a one inch thick tan gray weathering rind. Rock is wavy bedded, medium bedded, fossiliferous and contains local zones of siliceous limestone. Lower section is medium to dark gray, fine grained silty limestone; laminated to thin bedded and commonly trough cross bedded and fossiliferous.	55-170

Figure 3-2. Description of rock units near Bevans rock shelter. Modified from Epstein (2001). Onondaga members from Oliver (1954) and Vanuxem (1839). Buttermilk Falls (Willard, 1939) members from Epstein (1984) and Inners (1975). Ridgely Sandstone description from Monteverde (1992).

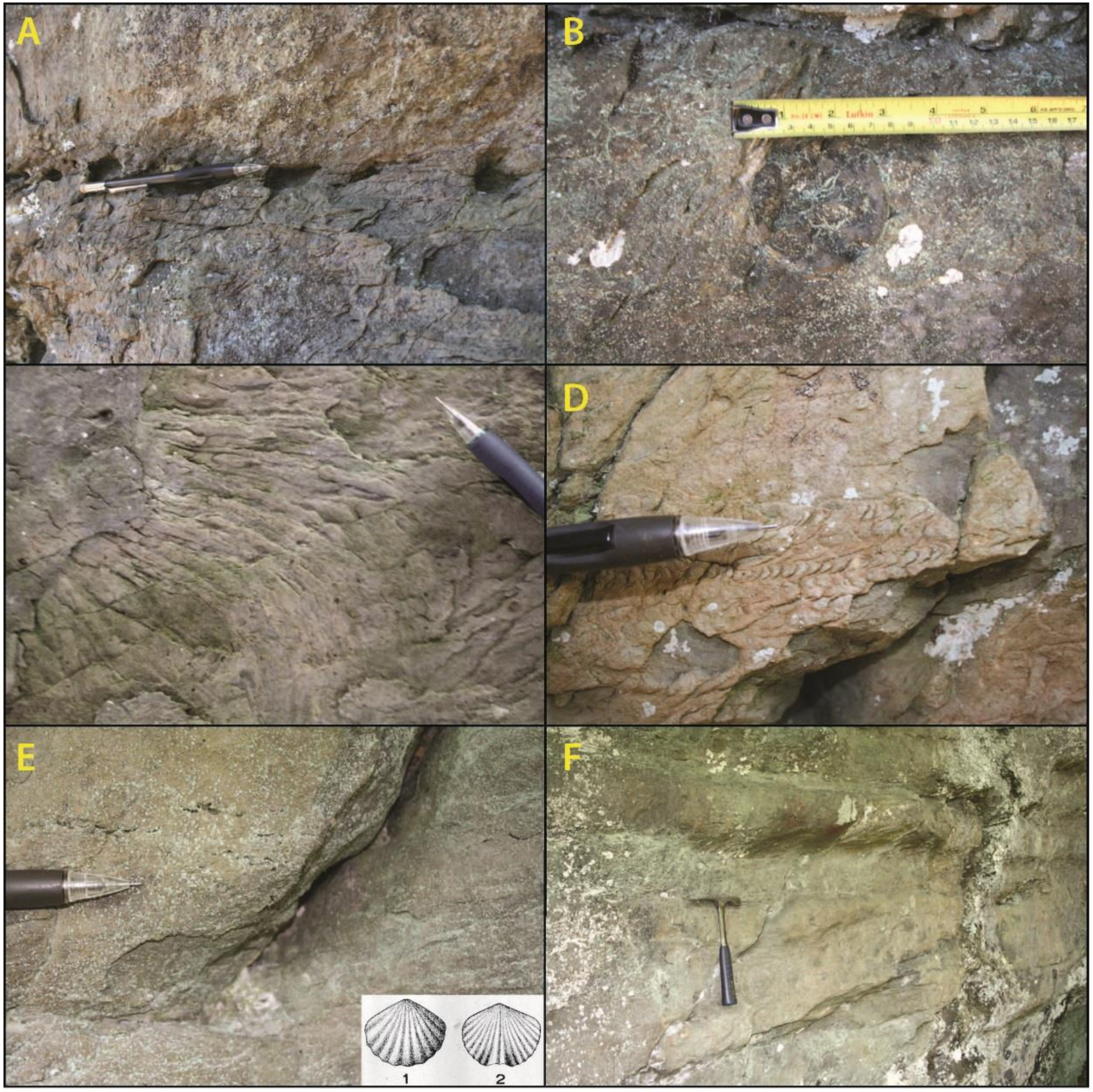


Figure 3-3. Features along the back wall of the Bevan rock shelter: A) solution voids along bedding , B) calcareous concretion, C) *Zoophycos* (planar view, bottom of roof rock), D) *Zoophycos* (cross-sectional view), E) small brachiopods (dark-curved lines - *Anoplotheca flabellites*?), inset illustration from Weller (1903, Plate XLIX), *Anoplotheca flabellites* (1) complete pedicle valve and (2) complete brachial valve collected near Layton, New Jersey, and F) glacial scour. Photos by R. Witte. Photo of planar view of *Zoophycos* by Yelena Stroiteleva (NJGWS).

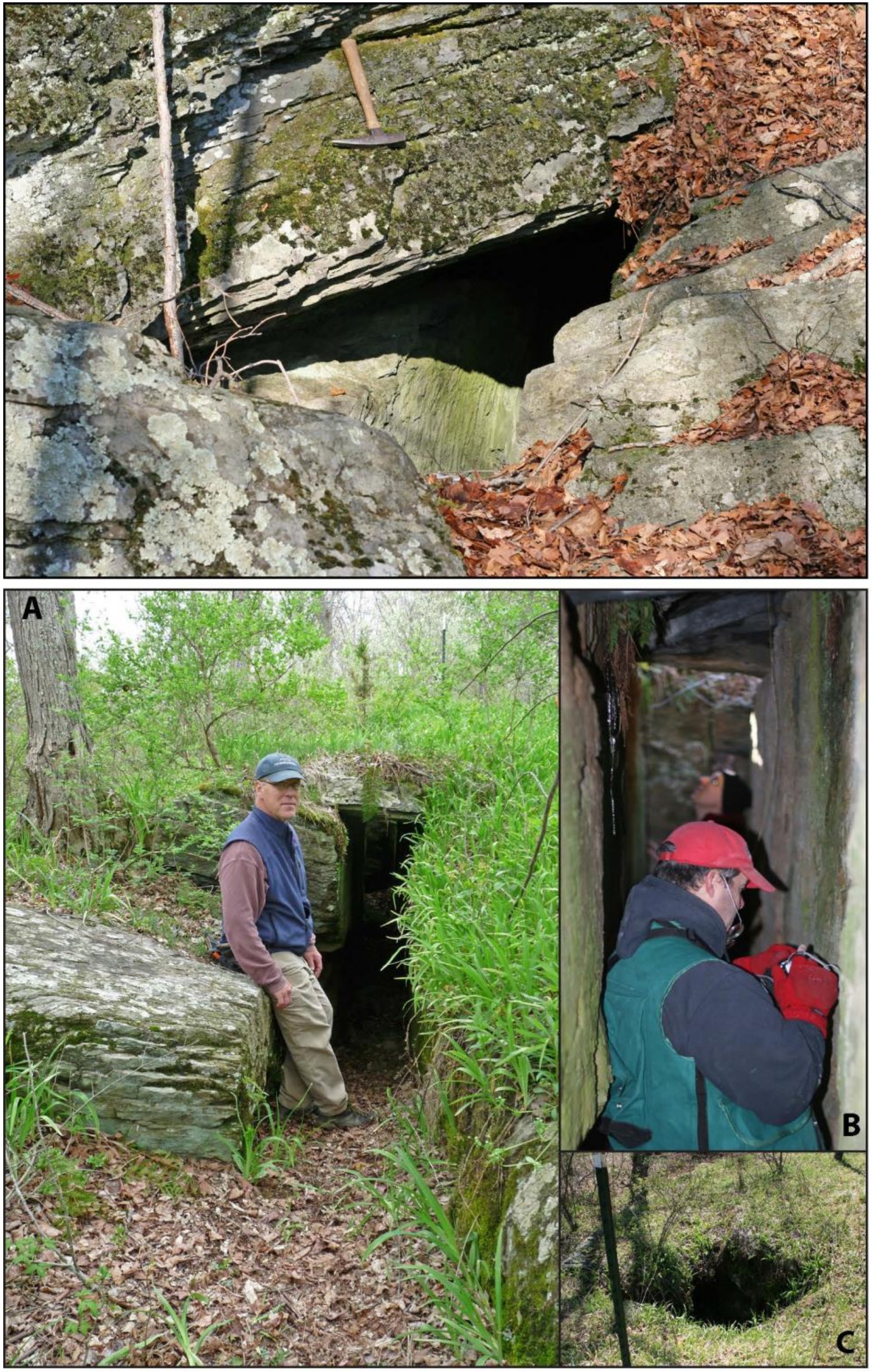


Figure 3-4. Upper photo. Small fracture cave located on the southwest side of the Bevans rock shelter. Bedding (010˚ 18˚ NW) dips right to left. The cave is about 12 feet (3.7 m) in length and follows a nearly vertical joint that trends 019˚. Lower photo. Fracture cave located on the northeast side of the Bevans rock shelter. Follows 017˚ joint. (A) Cave entrance, bedding dips left to right into hillside. B. Don Monteverde and Ron Pristas (NJGWS) collecting joint data during a much colder time of the year. Cave length is 27 feet (8.2 m). C. Small sinkhole (about 4 feet (1.2 m) in diameter) that formed over the far end of the cave where a cross joint (098˚) cuts the cave's walls. Photos by R. Witte and photo A by Jon Inners.

Figure 3-5. Small cave along the back wall of the rock shelter. Joint blocks, cut by 019° (parallel to shelter wall) and 096° (cross joint into the cave) joints, have collapsed forming the shelter within a shelter. Photo by R. Witte.

Figure 3-6. Bevans Rock Shelter (looking west), c. early 1930's. Photo from New Jersey State Museum.

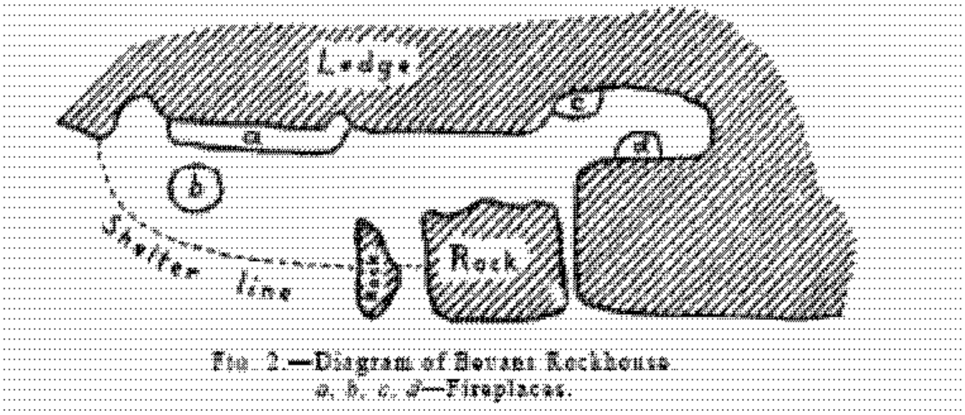


Figure 3-7. Diagram of Bevans rock shelter with location of fireplaces from Schrabisch, 1915.

Figure 3-8. Tools and pointed projectiles from the New Jersey State Museum Collection; Max Schrabisch Excavation, 1912 - 1913.

Figure 3-9. Rope-designed pottery fragments from the New Jersey State Museum Collection; Max Schrabisch Excavation, 1911 - 1912.

Figure 3-10. Dorothy Cross, October 21, 1931 at the Bevans rock shelter. Photo from New Jersey State Museum.

Directions to STOP 4 – Turn right on Kuhn Road (east) toward Peters Valley.

Cumulative in miles (km)	Point to Point in miles (km)	Route Description
19.0 (30.6)	0.7 (1.1)	Turn left onto County Route 615 North (Bevans Road) toward Layton. Intersection is just pass Gallery and Wallpack Road on left.
21.0 (33.8)	2.0 (3.2)	Village of Layton.
21.3 (34.3)	0.3 (0.5)	Turn left onto County Route 645 North toward Hainesville.
24.1 (38.8)	2.8 (4.5)	Village of Hainesville.
25.1 (40.4)	1.0 (1.6)	Turn left onto U.S. Route 206 West.
26.9 (43.3)	1.8 (2.9)	Turn right onto County Route 653 North (Clove Road).
29.4 (47.3)	2.5 (4.0)	Turn right into Montague Mini Mall and arrive at Stop 4. Stop 4 is behind self-storage facility behind the Sussex Bank, stay to right when entering mini mall."

STOP 4: Montague Mini Mall, Montague, NJ

Location Coordinates: (41.313°N, 74.756°W)

Field Stop leader – Don Monteverde.

Location and logistics

Stop 4 is located in the Milford quadrangle along Clove Road behind the Montague Mini Mall (fig. 4-1). An exposure of the Coeymans Limestone was uncovered during quadrangle-scale mapping around 1990. A short discussion will precede a good look at this unique exposure. Please do not use your hammers at this site. We wish to protect the outcrop from further degradation so others can also enjoy this interesting outcrop.

Fractures and Weathering

This outcrop was originally excavated in the 1980's during the construction of a self-storage facility. Since its initial exposure, the outcrop has been weathering fairly rapidly. Both regional strike and cross strike joints were originally evident across these fossil-rich carbonate beds. The strike joints, probably through dissolution and freeze thaw have forced large carbonate joint blocks to break away. Some, I am sure have been picked up for ornamental rocks in personal gardens. Only a single strike joint is visible on the back of the outcrop in the trees. However, a nice cross joint which exposes several thick calcite-filled veins lies near the southern part of this rock body (figure 4-2). The calcite veins appeared to have dissolved faster than the surrounding bedrock which enhanced the formation of large loose blocks.

Even though the fractures here tie in with the main theme of this trip, they were just used as bait to allow us to include this field stop. So read on through the following explanation and enjoy an unusual carbonate outcrop in northwestern New Jersey.

Regional Geology

Rocks of Middle Silurian through Lower Devonian age trend northeast-southwest across northwestern New Jersey (figure 4-2). To the east, gentle, upright folds occur in the Middle to Upper Silurian

Shawangunk Formation and Upper Silurian Bloomsburg Red Bed. Moving up section and still eastward of our present location, lies the Upper Silurian through Lower Devonian Poxono Island Formation, Bossardville Limestone, Decker and Rondout Formations and Manlius Limestone. All are locally covered by surficial deposits. The Lower Devonian Coeymans Formation, the lower part of the Helderberg Group, is exposed in front of us. Continuing westward and sparsely exposed lies the rest of the Helderberg Group including from oldest to youngest, the Kalkberg Limestone, New Scotland and Alsen Formations and Port Ewen Shale. As one migrates still farther westward towards the Delaware River the successively younger northwest-dipping units consist of the Glenerie Formation of the Oriskany Group, Esopus (seen at stop 3) and Schoharie Formations, the Onondaga Limestone (seen at stops 1 and 2) and lastly the Marcellus Shale. Regional investigations suggest that the Bloomsburg is the youngest folded unit while the remaining younger unfolded units dip gently northwestward (Monteverde, 1992, Monteverde and Epstein, unpublished data, Drake and others, 1996). Folds in these units reappear immediately south of Wallpack Center (Monteverde, 1992) and to the north across the New York state line into Port Jervis.

Silurian and Early Devonian sediments record the paleoenvironmental change from the end of the Taconic Orogeny into the oncoming Acadian Orogeny. Workers have mapped the changing continental sediments of the Shawangunk into the marginal marine sediments of the Bloomsburg Red Beds (Epstein and Epstein, 1969, 1972). The Bloomsburg displays different sedimentary assemblages indicative of fluvial, estuarine, lagoonal, tidal flat and offshore bar and beach paleoenvironments. These rocks continue to grade upwards into the Poxono Island and Bossardville that mark the continuing transgression through a brackish supratidal and intertidal flats depositional environment into a carbonate depositional environment (Epstein and others, 1967; Barnett, 1970, Epstein, 1986). The overlying Decker Formation witnessed a developed carbonate shelf with minor clastic sediment influx as well as locally developed biostromal reef complexes consisting of possible corals ± stromatoporoids(?). Time progressed and the sediments of the Rondout mark a relative sea level fall into restricted lagoonal and tidal flat paleoenvironments (Herpers, 1951; Epstein and others, 1967; Epstein and Epstein, 1969). Denkler and Harris (1988) used conodonts from the Rondout to identify the Silurian to Devonian boundary.

Sediments of the overlying lower part of the Helderberg Group record a deepening and corresponding marine transgression. The Manlius Limestone suggests changes from lagoonal and intertidal environments to the high-energy conditions of a carbonate shelf/ shoal and associated patch reefs of the Coeymans Formation (Epstein and others, 1967; Barnett, 1970; Smosna, 1989). Succeeding deeper shelf settings are observed in the Kalkberg sediments and into the argillaceous limestones of the New Scotland Formation (figure 4-3). In this region the overlying Alsen Formation records a minor regression and redeposition of fossiliferous cherty limestone. The same regression is marked in eastern New York by crinoidal grainstones of the Becraft Limestone. Sea level returned to subtidal conditions as shown by the Port Ewen Shale sediments (Barnett, 1970), which marked the end of the Helderberg Group deposition.

Epstein and others (1967) subdivided the different Helderberg formations into members from eastern Pennsylvania to southern New York (figure 4-4). The different members highlight the regionally shifting paleoenvironment along this carbonate margin. Because the descriptive terminology of carbonate units differs from clastic units, one not actively working in these units may become confused with respect to their meaning. Therefore, figure 4-5 outlines the terminology originally devised by Dunham, (1962), and subsequently modified by Embry and Klovan, (1971) so a non-carbonate geologist can understand the meaning of the discussion.

The Shawnee Island Member of the Coeymans Formation is the sole unit exposed at this stop. In the woods to the east the older Thacher Member of the Manlius Limestone is exposed. he overlying Kalkberg and New Scotland locally emerge from the Pleistocene cover to allow their mapping along strike to the northwest and southwest.

Patch Reefs and Flank Paleoenvironments

Along its outcrop belt from eastern Pennsylvania through western New Jersey, eastern New York and westward into central New York, the Coeymans Formation contains at least 14 isolated reef deposits (Oliver, 1960; Rickard, 1962; Epstein and others, 1967; Isaacson and Curran, 1981; Precht, 1982, 1984, 1989; Smosna, 1989). Nine-reefs have been documented in the Deansboro Member of the Coeymans Formation in the Syracuse, New York region and the remaining are in the Shawnee Island Member in northeastern Pennsylvania and northwestern New Jersey (figure 4-6). Each Shawnee Island build up is a patch reef with a central core ranging up to 160x70 m and 15 m thick, accompanied by associated flank beds (figure 4-7) (Epstein and others, 1967; Precht, 1982, 1984, 1989; Finks and Raffoni, 1989; Raffoni and Finks, 1989).

Flank Beds

Reef flank facies consist of bedded bioclastic reef debris that thin away from the reef proper (James and Bourque, 1992) (fig. 4-7). Wilson (1975) differentiates two separate facies, that of flank beds and talus. Bioclastic debris is the exclusive sediment of flank beds, while talus also contains lithoclastic material. Lithoclastic material consists of partially lithified micritic material ripped up from underlying beds. Talus facies deposits are rare compared to flank bed facies (Wilson, 1975). Tucker and Wright (1990) suggest that these flank deposits only form near wave base and are therefore grainstone dominated. High energy waves and currents washed over these skeletal debris deposits and removed all micritic material (Smosna, 1989).

Reef flanks, as seen here, contain a high content of reef debris. This material lies broken and fragmented without any accompanying micritic or lithoclastic material. Fragmental hemispherical *Favosites* and crinoids constitute the greatest percentage of debris (fig. 4-7). Scarce stromatoporoids are also exposed. Rare brachiopods are present, though I have yet to find any good examples. Crinoids, although not typically part of a reef complex, are exposed here as broken fragments that commonly weather in relief. The character of the limestone beds indicates a reef flank paleoenvironment. The absence of micritic material and lithoclasts suggests an environment above wave base, in strong currents, but not reef proximal enough to be considered talus. The corresponding reef could be south of this exposure as indicated by this outcrops apparent coarser grain size in that direction. Finks (oral communication, 2001) suggested that this site is proximal to a patch reef, currently not exposed.

Relative abundance of the different bioclastic material varies over the outcrop. Corals exist across the outcrop, but they dominate in the southern beds. Crinoids occur as dispersed debris and also concentrated as bed load. They are moderately sorted in the absence of coralline material. Stromatoporoids, distantly related to modern sponges are less common across the exposure.

Grain size is variable across the exposure with a general north-south trend across the central beds. A rudstone texture from fragmented hemispherical corals appears more common in the south. Across the outcrop towards the north a general grainstone texture developed from smaller coralline debris exits. The oldest beds remain as a wackestone to packstone across the outcrop that changes through younger beds as fragmental crinoid lenses that grade into a bioclastic rudstone. Having trouble following this discussion without a figure showing outcrop geometry

Local Reefs

One of the Shawnee Island reef examples occurs in Montague Township only 1.5 miles (2.4 km) south-southeast of this stop. First documented by Epstein and others (1967), it has subsequently been studied by Precht (1982, 1984, 1989), Finks and Raffoni (1989) and Raffoni and Finks (1989). Precht (1989) described four zones that follow the successive reef growth stages of stabilization, colonization, diversification and domination (figure 4-8) as described by James and Bourque (1992). The four growth stages of Precht (1989) are:

1. Deposition of massive bedded crinoidal packstones to grainstones that stabilized the substrate.
2. Large domal and branching forms of the tabulate coral Favosites colonize the substrate, initiating reef formation.
3. Development and diversification of reef core where bafflestones, floatstones, and framestones predominate. Reef growth includes branching tabulate corals, (Cladopora and Favosites), domal and planar tabulate corals (Favosites), rugose corals, and domal and laminar stromatoporoids.
4. Massive stromatoporoids overgrown by laminar and encrusting stromatoporoids and encrusting algae predominate and develop into bindstones and framestones under shallow water conditions. Diversity of tabulate corals and stromatoporoids diminishes drastically as compared to lower stages.

James and Wood (2010) suggested that tabular stromatoporoids locally bound with other material have been found in rough-waters, but as they commonly do not have an encrusting habit, they would not fare well in the surf zone (figure 4-9). Hydrodynamics of the different stromatoporoid forms control where they would have the best chance to flourish. Those with low profiles would have the best chance to grow under high turbulent waters while encrusting forms are more common in reef margin environments (Cole and others, 2015). Forms that developed below wave base included bulbous, domal and dendroid forms (James and Wood, 2010).

Finks and Raffoni (1989) and Precht (1989) suggested that deeper, more open water existed north of the Montaque reef. The reefs formed and prograded across gently northward-sloping sea floors in 33-66 feet (10-20 m) water depth (Smosna, 1989; Precht, 1989) (figure 4-11). Reefs built up to sea level and higher energy flow conditions (Epstein and others 1969; Finks and Raffoni, 1989; Precht, 1989).

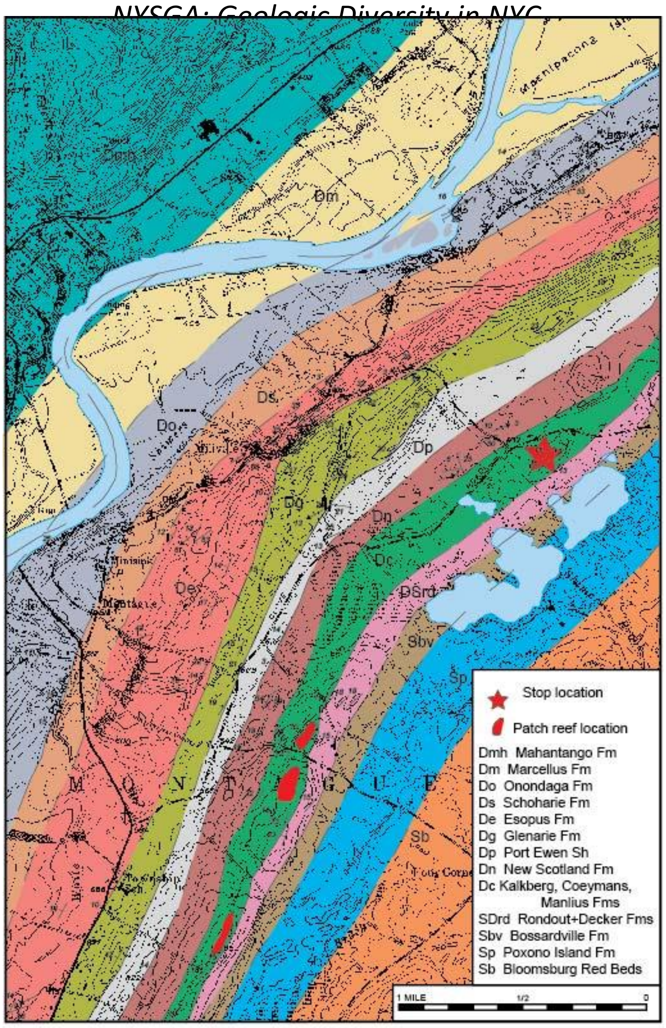


Figure 4-1. Location map of Stop 4 within the Milford PA-NJ quadrangle along Clove Road in Montague, New Jersey. Star marks the actual stop location. Geological map displays Lower Devonian to Upper Silurian sedimentary units by Monteverde and Epstein, unpublished. Southeast of the stop location are several patch reefs within the Shawnee Island Member of the Coeymans Formation identified by Epstein and others (1967), Spinks (1967) and Finks and Raffoni (1989).

Figure 4-2. Photograph looking north at a cross joint surface within the Coeymans Fm limestone that exposes two different solution gaps identified by arrows created by dissolution of calcite-filled discontinuous veins. Third arrow locates a calcite vein that slowly dissolving. Dashed line identify bedding trend. Pencil and geologic compass for scale.

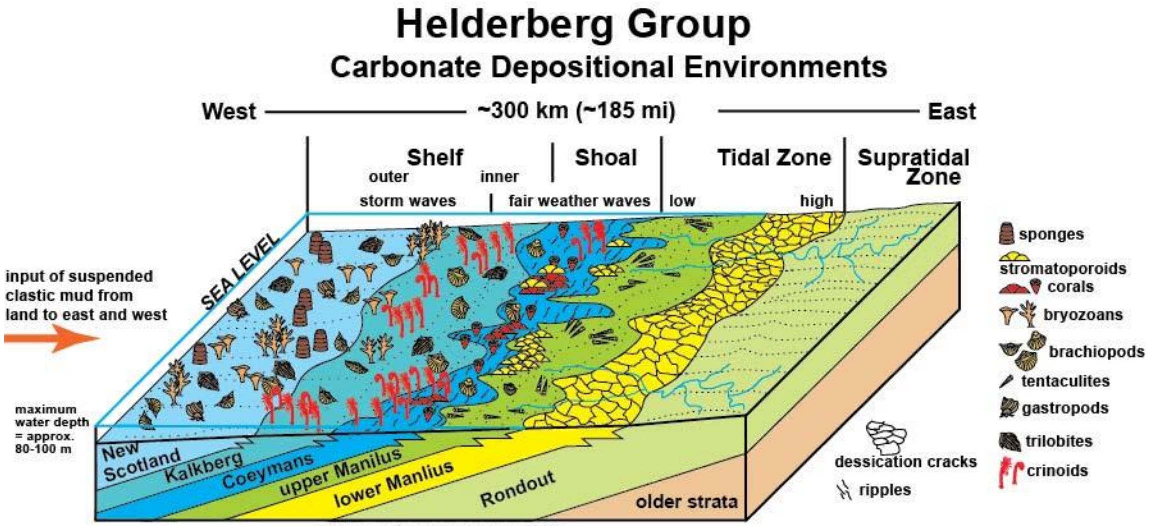


Figure stolen from C. Ver Straeten, NYSM
Don't tell him.

Figure 4-3. Diagram depicting the deepening marine paleoenvironments through the Helderberg Group formations. Associated fossil types for each water depth are also shown. Graphic from Ver Strataen.

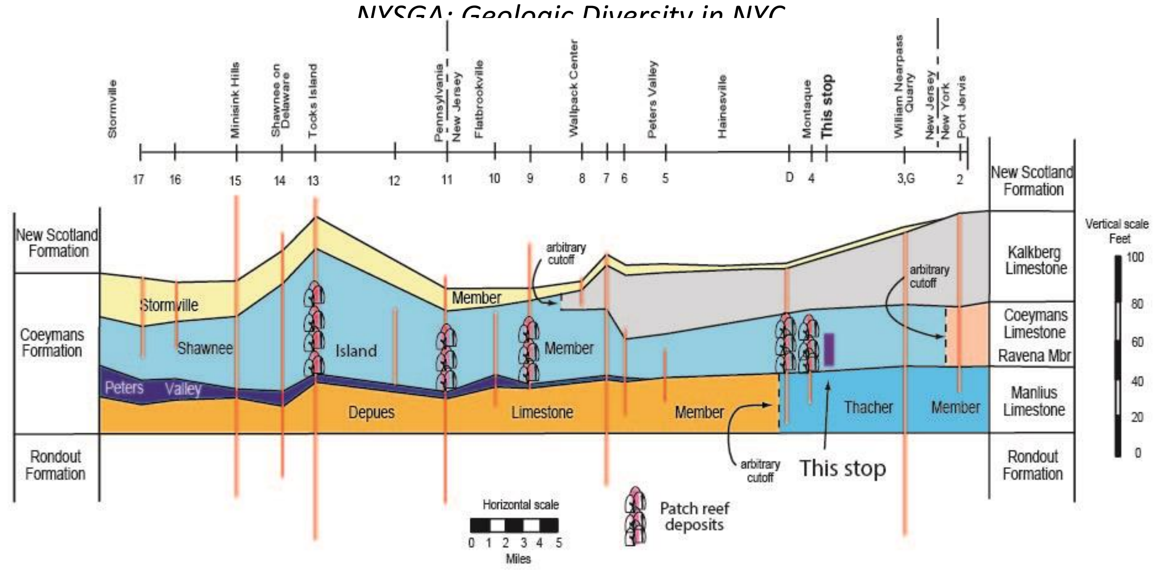


Figure 4-4. Fence diagram portraying the relationship of different members of the Coeymans Formation from eastern Pennsylvania through western New Jersey and into New York. Four patch reefs are identified in the Shawnee Island Member. Numbered measured sections are from Epstein and others (1967) and lettered sections from Spinks (1967).

<table>
<tr><td colspan="6">Allochthonous limestones
original components not organically bound during deposition</td><td colspan="3">Autochthonous limestones
original components organically bound during deposition</td></tr>
<tr><td colspan="4">Less than 10%> 2mm components</td><td colspan="2">Greater than 10%>2mm components</td><td rowspan="4">By organisms that act as baffles</td><td rowspan="4">By organisms that encrust and bind</td><td rowspan="4">By organisms that build a rigid framework</td></tr>
<tr><td colspan="3">Contains lime mud (<.03 mm)</td><td>No lime mud</td><td rowspan="3">Matrix supported</td><td rowspan="3">>2mm component supported</td></tr>
<tr><td colspan="2">Mud supported</td><td colspan="2" rowspan="2">Grain supported</td></tr>
<tr><td>Less than 10% grains (>.03mm <2mm)</td><td>Greater than 10% grains</td></tr>
<tr><td>Mudstone</td><td>Wackestone</td><td>Packstone</td><td>Grainstone</td><td>Floatstone</td><td>Rudstone</td><td>Bafflestone</td><td>Bindstone</td><td>Framestone</td></tr>
</table>

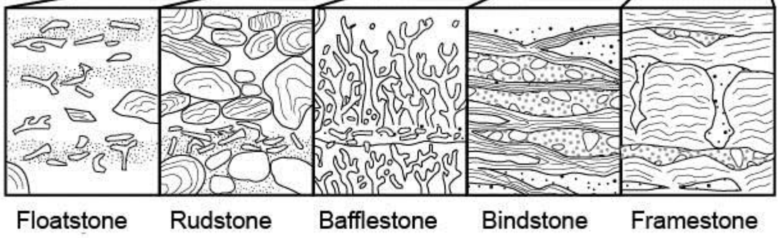


Figure 4-5. Carbonate classification as devised by Dunham (1962) and later modified by Embry and Klovan (1971). It should be noted that bafflestone, bindstone and framestone are commonly applied to reef facies while floatstone and rudstone are more indicative of flank deposits.

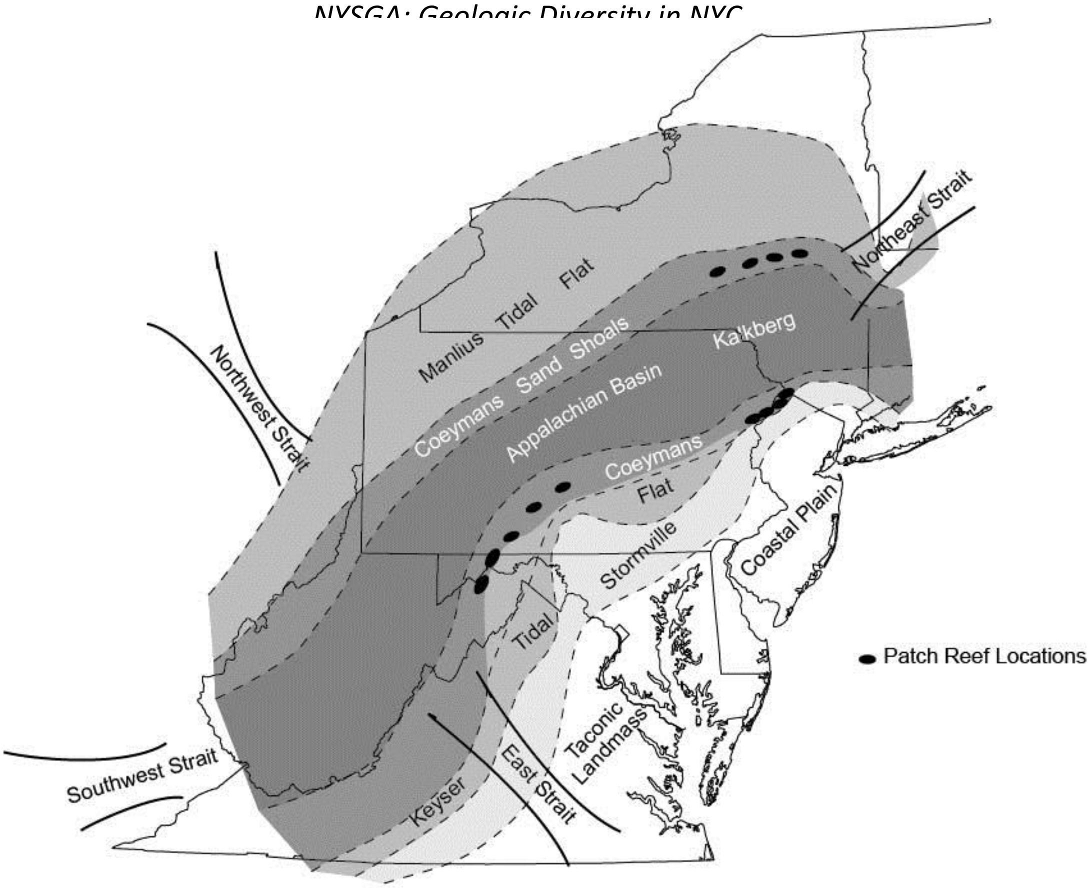


Figure 4-6. Regional map of known reef facies within the Coeymans Formation across central Appalachians Modified from Precht (1989) and Smosna (1989).

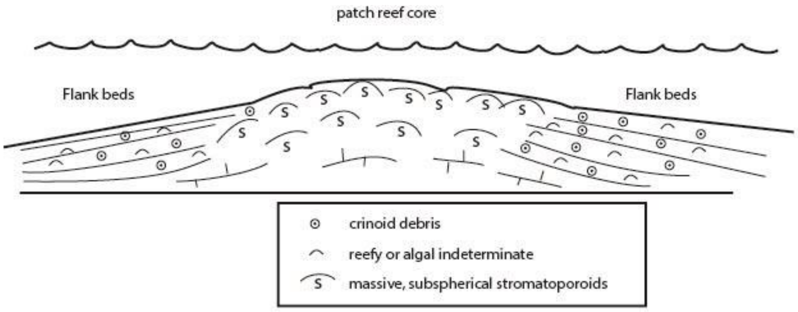
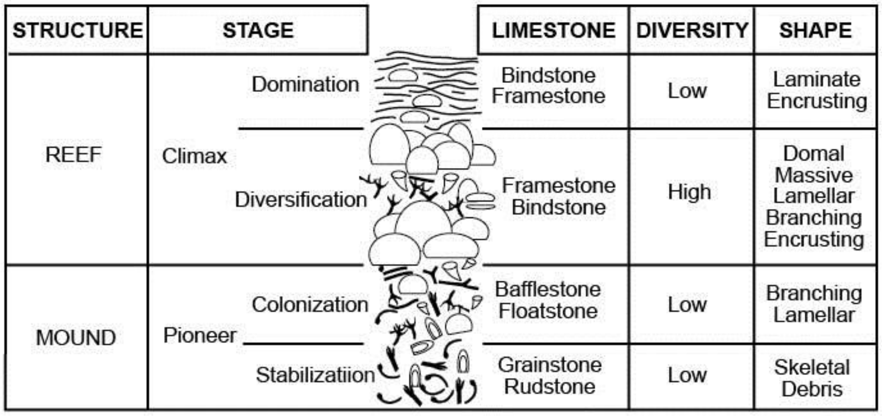


Figure 4-7. Devonian stromatoporoid patch reef portraying flank beds containing crinoidal debris. As reefs prograde both horizontally and vertically towards sea level they may grow additional cores and flank beds. Windward and leeward sides have been identified at the Montague reef (Finks and Raffoni, 1989). Shapes tend to be elongate and trend parallel to depth contours. Modified from Wilson (1975).



STRUCTURE	STAGE		LIMESTONE	DIVERSITY	SHAPE
REEF	Climax	Domination	Bindstone Framestone	Low	Laminate Encrusting
		Diversification	Framestone Bindstone	High	Domal Massive Lamellar Branching Encrusting
MOUND	Pioneer	Colonization	Bafflestone Floatstone	Low	Branching Lamellar
		Stabilizatiion	Grainstone Rudstone	Low	Skeletal Debris

Figure 4-8. Description of the different growth stages of reefs. Precht (1989) established a similar growth pattern for the nearby Montague patch reef. Modified from James and Bourgue (1992)

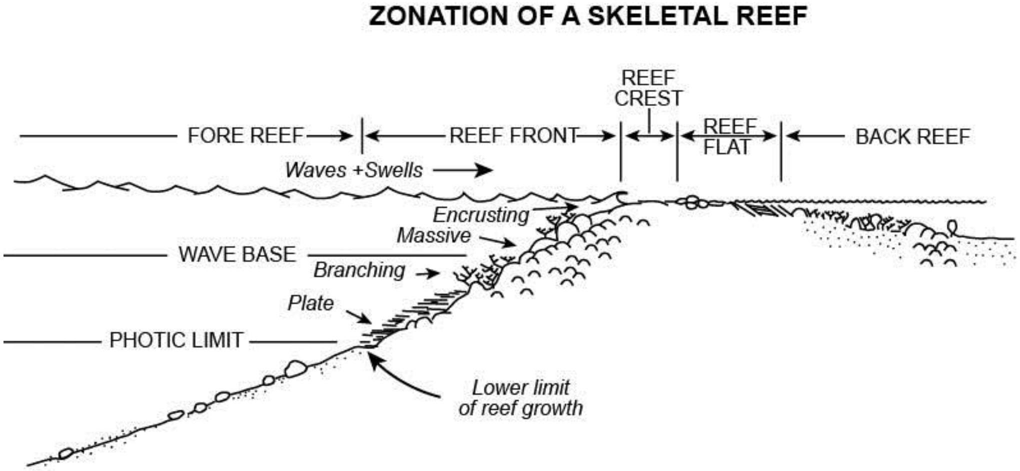


Figure 4-9. Generalized architecture of a Lower Devonian reef containing stromatoporoids. Modified from James and Wood (2010).

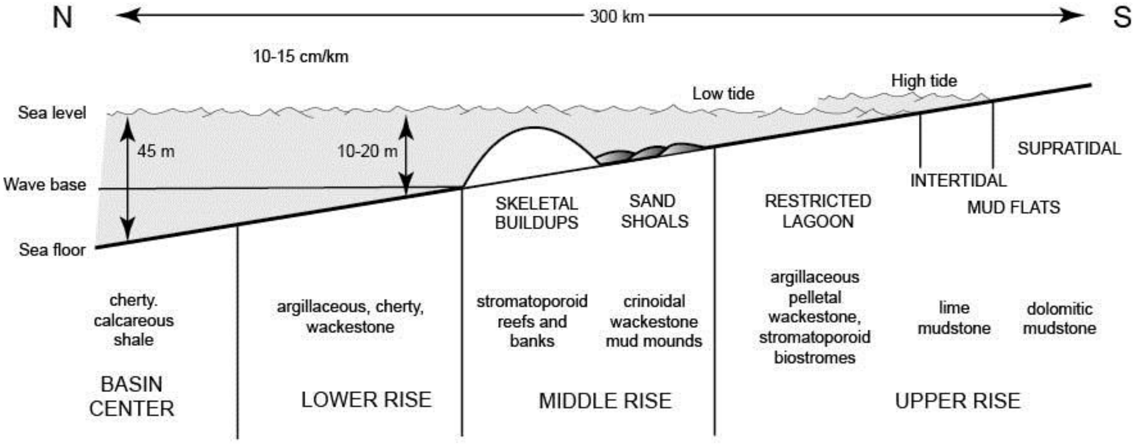


Figure 4-10. Paleoenvironmental ramp reconstruction of Lower Devonian Coeymans deposition on the southeastern side of the margin. Similar geometries existed in the Syracuse region except the geographic directions were reversed. Modified from Smosna (1989)

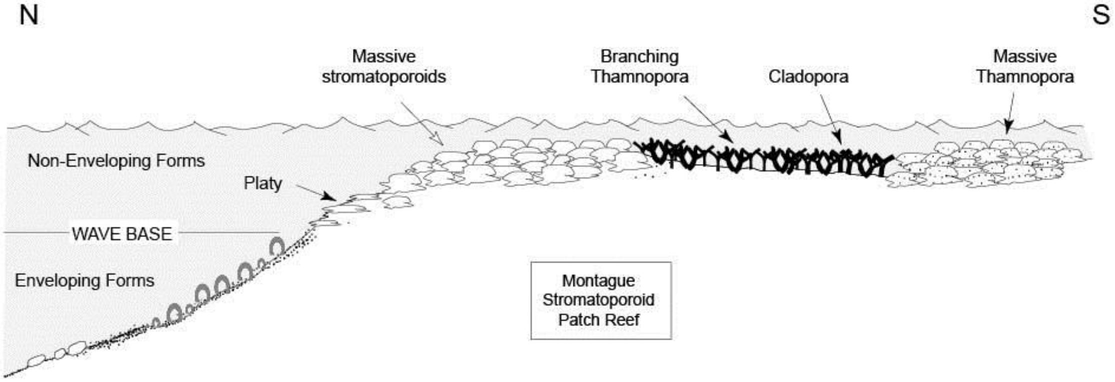


Figure 4-11. Construction of a Lower Devonian stromatoporoid reef (James and Bourque, 1992) altered to account for the different coral densities across the Montague reef as defined by Finks and Raffoni (1989).

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