Karst Geology of NJ and Vicinity: Revisited

2021 CONFERENCE PROCEEDINGS

FOR

THE 37TH ANNUAL MEETING

OF THE

GEOLOGICAL ASSOCIATION OF NEW JERSEY

October 15 & 16, 2021

Edited by

Michael J. Hozik

Stockton University (Emeritus)

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Field Guides and Proceedings of Prior Annual Meetings

2019 XXXVI *Geology and Paleontology of Monmouth County*, James Brown and Tim Macaluso

2018 XXXV *Hydrology, Hydrodynamics, and Water Supply in New Jersey and the Delaware River Basin*, Tim Macaluso

2017 XXXIV *The Piedmont: Old Rocks, New Understandings*, Howell Bosbyshell

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2015 XXXII *Neotectonics of the New York Recess*, Gregory Herman and Suzanne Macaoay Ferguson

2014 XXXI *Global Environmental Issues and Local Consequences: Earth Processes and Urban Environmental Quality*, Nurdan Duzgoren-Aydin

2013 XXX *Igneous Processes During the Assembly and Break-up of Pangaea: Northern New Jersey and New York City*, Alan Benimoff

2012 XXIX *Geology and Public Lands*, Jane Alexander

2011 XXIII *Environmental Geology of Central New Jersey*, Emma Rainforth and Alan Uminski

2010 XXVII *Geology of the Greater Trenton Area and Its Impact on the Capital City*, Pierre Lacombe

2009 XXVI *New Jersey Coastal Plain Stratigraphy and Coastal Processes*, Deborah Freile

2008 XXV *Environmental and Engineering Geology of Northeastern New Jersey*, Matthew Gorring

2007 XXIV *Contributions to the Paleontology of New Jersey 2*, Emma Rainforth

2006 XXIII *Environmental Geology of the Highlands*, Suzanne Macaoay and William Montgomery

2005 XXII *Newark Basin - View from the 21st Century*, Alexander Gates

2004 XXI *Proterozoic, Paleozoic, and Mesozoic Mafic Intrusions of Northern New Jersey and Southeastern New York*, John Puffer and Richard Volkert

2003 XX *Periglacial Features of Southern New Jersey and Adjacent Areas*, Michael Hozik and Mark Mihalsky

2002 XIX *Geology of the Delaware Water Gap Area*, Dana D'Amato

2001 XVIII *Geology in the Service of Public Health*, Pierre Lacombe and Gregory Herman

2000 XVII *Glacial Geology of New Jersey*, David Harper and Fred Goldstein

1999 XVI *New Jersey Beaches and Coastal Processes from Geologic and Environmental Perspectives*, John Puffer

1998 XV *The Economic Geology of Central New Jersey*, John Puffer

1997 XIV	*The Economic Geology of Northern New Jersey*, Alan Benimoff and John Puffer
1996 XIII	*Karst Geology of New Jersey and Vicinity*, Richard Dalton and James Brown
1995 XII	*Contributions to the Paleontology of New Jersey 1*, John Baker
1994 XI	*Geology of Staten Island*, Alan Benimoff
1993 X	*Geologic Traverse Across the Precambrian Rocks of the New Jersey Highlands*, John Puffer
1992 IX	*Environmental Geology of the Raritan River Basin*, Gail Ashley and Susan Halsey
1991 VIII	*Evolution and Assembly of the Pennsylvania-Delaware Piedmont*, Maria and William Crawford
1990 VII	*Aspects of Groundwater in New Jersey*, James Brown and Richard Kroll
1989 VI	*Paleozoic Geology of the Kittatinny Valley and Southwest Highlands Area, New Jersey*, Irvin Grossman
1988 V	*Geology of the Central Newark Basin*, Jonathan Husch and Michael Hozik
1987 IV	*Paleontology and Stratigraphy of Lower Paleozoic Deposits of the Delaware Water Gap*, William Gallagher
1986 III	*Geology of the New Jersey Highlands and Radon in New Jersey*, Jonathan Husch and Fred Goldstein
1985 II	*Geological Investigation of the Coastal Plain of Southern New Jersey*, Ray Talkington and Claude Epstein
1984 I	*Igneous Rocks of the Newark Basin: Petrology, Mineralogy, and Ore Deposits*, John Puffer

SCHEDULE

Friday, October 15, 2021 (by Zoom)

2:00 pm	Opening Remarks—Michael Hozik
2:15 pm	Epikarst and the Transport of Groundwater Contaminants: An Overview by Alex R. Fiore and Trevor P. Needham2
2:45 pm	Using Electrical Resistivity to Delineate Active Sinkholes at Spruce Run Recreation Area by Michael P. Gagliano and Michelle Spencer
3:15 pm	Introduction to Karst Geology of NJ and Vicinity by Don Monteverde (with contributions by Bill Witte)
3:45 pm	Business Meeting State of GANJ Treasurer's Report Election of new officers Other business
4:15 pm	Keynote Address-- Follow the Water: How I Stopped Worrying about Caves and Learned to Love the Karst by John Tudek

Saturday, October 16, 2021 Field Trip

The field trip will assemble in the large parking lot at Swartswood State Park (GPS 41.0735° N, 74.8227° W). To get to the large parking lot, enter the park at the main entrance near the Headquarters and drive around toward the lake.

The bus will depart from Swartswood State Park at 8:00 am.

Stop 1: Ike Williams Road, Hampton Township, NJ, GPS Coordinates 41.0959° N, 74.8051°W.

Stop 2: Camp Lou Henry Hoover Road/ Five Points Road GPS Coordinates 41° 4' 30.74" N, 74° 51' 32.29" W.

Lunch Stop: Peter's Valley GPS Coordinates 41.1972°N, 74.8517898°W

Stop 3: Jager Road Sandyston Township, New Jersey GPS Coordinates 41.263°N, 74.824°W.

Stop 4: Intersection of Old Mine Road and Jager Road, Sandyston Twp, GPS Coordinates 41.263° N, 74.829° W

Stop 5: Old Mine Road and Tuttles Corner Dingmans Road GPS coordinates 41.2215° N, 74.8558°W

Return to parking lot at Swartswood State Park.

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Dedication

Richard Dalton

Richard Dalton became interested in caves when he was in elementary school, first by reading books and then on a trip to Lost River Caverns near Hellertown Pennsylvania. This interest led him to major in Geology at Rutgers University and to joining the National Speleological Society in 1963. Richard has explored and visited many caves, both wild and commercial, in New Jersey and nearby states. Over the years, Richard has enjoyed leading groups of children and adults on trips into wild caves and sharing the wonder of the natural world. Richard has also authored and co-authored numerous papers on caves and karst over the years, including one titled *Karst Features in New Jersey* in 2014. In 1996, he helped organize and co-lead the first Geological Association of New Jersey conference focused on karst geology.

Richard has the uncanny ability to mentally file all sorts of information. Almost everyone who knows him has a story of him directing them to some very pertinent, but often obscure, reference for some project they were working on.

When asked to talk about the project he was most proud of, he hesitated and then said it was working with Frank Markewicz on the location, design, and construction of the modern Pequest Fish Hatchery. After Frank noticed that a farmer plowed his corn rows in an unusual way, he was driving through the area in a very heavy rainstorm noticed that there was no runoff. All the water went straight down into the ground. They worked with a maintenance worker from the Hackettstown fish hatchery using three welded 55-gallon drums as a well to do the first pump test to show there was a significant amount of ground water available. From that simple pump test and a lot of detailed mapping as well as stream and spring flow measuring, a groundwater supply of up to 7,000 gallons per minutes was developed.

We have benefitted from Richard Dalton's knowledge and wisdom for more than 50 years, and we look forward to even more contributions from him in the future.

Michael Hozik

Epikarst and the Transport of Groundwater Contaminants: An Overview

Alex R. Fiore[1] and Trevor P. Needham[2]

[1] U.S. Geological Survey, Lawrenceville, NJ

[2] U.S. Geological Survey, Baltimore, MD

Dissolution voids in karst aquifers can be highly transmissive and can transport groundwater contaminants long distances from their source areas, creating a challenge for site remediation and potentially contaminating drinking water supplies far from the source. An important aspect of site-scale contaminant transport processes in karst aquifers is the storage and release of contaminants within the epikarst portion of the aquifer near the source area, where heterogeneities and large variations of hydrologic properties occurring over short distances can affect contaminant transport.

The epikarst ("epi-" meaning "over"), also known as the subcutaneous zone, is the portion of weathered carbonate bedrock located above more permanently saturated portions of the karst aquifer (Williams, 2008; Jones, 2013). The epikarst is formed by dissolution from infiltrating water through the vadose (unsaturated) zone, rather than by dissolution from groundwater flow through the deeper phreatic (saturated) zone, and is the primary recharge zone for karst aquifers (White, 2018). This distinction in formation mechanisms has an effect on the orientations of dissolution voids that are likely to occur in the epikarst compared to the those in the saturated portion of the bedrock. For New Jersey karst aquifers, voids in the bedrock generally tend to follow the overall geologic structure as lithostatic fractures and joints become enlarged by the flow of acid-bearing groundwater (Dalton, 2014). Voids in epikarst are instead formed by the more gravitationally-driven, downward infiltration through the unsaturated zone, which causes voids to be more vertically-oriented in the direction of the downward flow (Williams, 2008; Yager and others, 2013; Hartmann and others, 2014). Water flows through epikarst voids and enters the saturated portion of the aquifer at discrete locations where epikarst voids are connected with deeper, more structurally-oriented dissolution voids. However, not all voids in the epikarst are connected to these deeper voids if the dissolution process of the infiltrating water becomes limited before those depths are encountered, thus creating "dead-end" dissolution voids in the epikarst that are not hydraulically connected to the bedrock (Williams, 2008; Jones, 2013). Areas of perched groundwater may be present in the epikarst where groundwater is stored in "dead-end" dissolution voids above the primary bedrock water table.

Presence of perched epikarst groundwater tables can have implications for how contaminants are transported through the subsurface. Contaminants entering the subsurface through diffuse infiltration that encounter a "dead-end" epikarst dissolution void can remain in storage in that void (figure 1). Epikarst sediments also tend to be high in organic matter (Jones, 2013), which provide ample sorption sites for many contaminants. Contaminants can be stored in the epikarst over various lengths of time and at various depths below land surface depending on several factors, such as the extent of carbonate weathering, the particular chemical contaminant, the depth to the perched and main water table, and the energy at which water is infiltrated through the unsaturated zone. For example, areas with large fluctuations of groundwater levels with rapid responses to a precipitation event within a conduit can "flush" out contaminants from storage more quickly when water levels are increased enough to intersect other voids with better hydraulic connection to the bedrock (figure 1). Additionally, dense non-aqueous phase liquids (DNAPL) and/or contaminants that sorb to sediment particles are more likely to accumulate in the deeper portion of perched epikarst groundwater and less likely to be released by pulsed precipitation events than less dense and less stratified dissolved-phase compounds (Vesper and others, 2001; White, 2018). The flushing event can mobilize contaminated sediment particles or DNAPL transporting a large deposit of contaminated material rapidly.

As contamination sites in karst environments are characterized, the possibility of contaminant storage in the epikarst must be assessed. Pulsated release of contaminants from epikarst following precipitation events can temporarily raise contaminant concentrations in the underlying bedrock, particularly in high-transmissivity dissolution voids hydraulically well-connected to the epikarst (Jones, 2013). Contaminant concentrations in monitoring wells installed in the bedrock may therefore show large variations depending on how soon after a pulsated release from the epikarst the sampling occurred. If hydrologic responses in the bedrock voids are very rapid, the movement of the contaminant as determined by intermittent sampling of monitoring wells can potentially be missed completely and the source area may not be identified. Epikarst characterization also has remedial implications as characteristics such as thickness, suspended sediment content, structure, and carbon content may present challenges for remediation techniques. Perched groundwater in relatively thicker epikarst with associated deeper (and greater) storage can prevent utilization of remedial methods such as excavation. Treatments such as biostimulation with emulsified vegetable oil or zero valent iron that require groundwater flow coming into contact with contaminants would also be a challenge if the quantity of perched groundwater storage is high.

References:

Dalton, R., 2014, Karst features in New Jersey: New Jersey Geological and Water Survey Information Circular, 4 p.

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Hartmann, A., Goldscheider, N., Wagener, T., Lange, J., and Weiler, M., 2014, Karst water resources in a changing world: Review of hydrological modeling approaches: Reviews of Geophysics, v. 52, p. 1-25

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White, W.B., 2018, Contaminant Transport in Karst Aquifers: Systematics and Mechanisms, *in* Karst Groundwater Contamination and Public Health, Springer International Publishing, p. 55-81.

Williams, P.W., 2008, The role of the epikarst in karst and cave hydrogeology: a review: International Journal of Speleology, v. 37, n. 1, p. 1-10.

Vesper, D.J., Loop, C.M., and White, W.B., 2001, Contaminant transport in karst aquifers: Theoretical and Applied Karstology, v. 13, no. 14, p. 101-111.

Yager, R.M., Plummer, L.N., Kauffman, L.J., Doctor, D.H., Nelms, D.L., Schlosser, P., 2013, Comparison of age distributions estimated from environmental tracers by using binary-dilution and numerical models of fractured and folded karst: Shenandoah Valley of Virginia and West Virginia, USA: Hydrogeology Journal, v. 21, p. 1193-1217

Using Electrical Resistivity to Delineate Active Sinkholes at Spruce Run Recreation Area

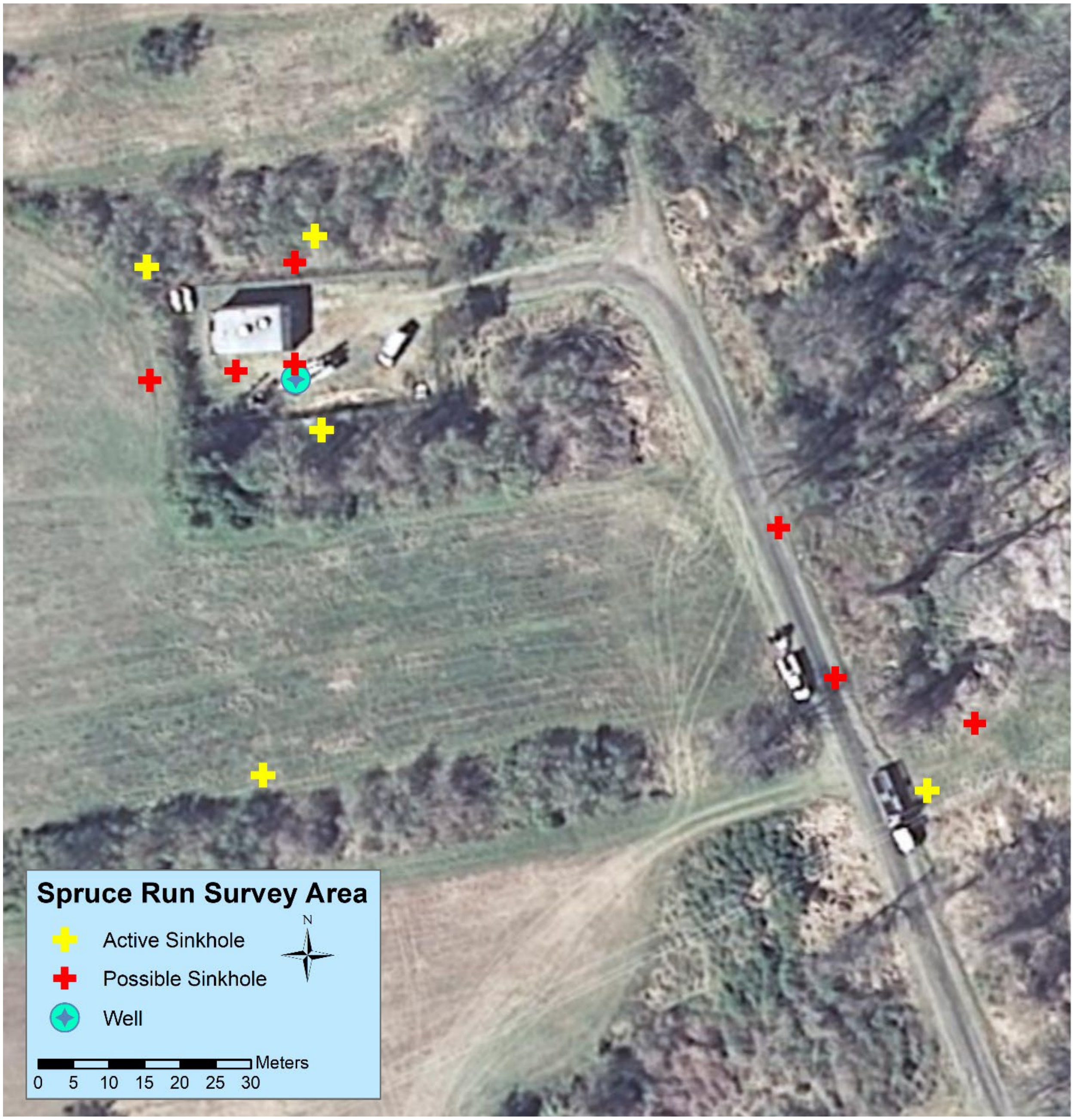
Michael P. Gagliano and Michelle Spencer
New Jersey Geological & Water Survey

The New Jersey Geological & Water Survey (NJGWS) conducted a subsurface investigation using electrical resistivity at the Spruce Run Recreation Area in Union Township, Hunterdon County. Spruce Run Recreation Area is underlain by karst geology and as such may contain sinkholes. There were at least five (5) active sinkholes on or near the study area. The location of the sinkholes raised the possibility that the well-house, well, or the pipe supplying water to the recreational area, may be compromised. The focus of the study was to determine the location and extant of any undiscovered sinkholes on the site. The NJGWS collected 2D and 3D electrical resistivity data to delineate clay-filled sub-surface voids which may compromise infrastructure and a park visitor's safety. The profiles were located over the main access road, in the adjacent fields, and near the main well and well house as these were the important places identified by the park. Sinkholes provide a strong contrast in resistivity data and at least seven (7) were located from the geophysical study (Figure 1). This project shows that both 2D and 3D electrical resistivity methods are an excellent tool for locating sub-surface voids quickly and accurately.

NJGWS recommended additional investigatory work, such as borings, that would target the anomalies to confirm the interpretation and determine if these are indeed possible sinkholes and whether there may be any open cavities at depth in the rock. This was subsequently completed by a private contractor who confirmed our findings and later excavated and filled the sinkholes with cement.

The full report can be found on the New Jersey Geological & Water Survey Website or at the link below:

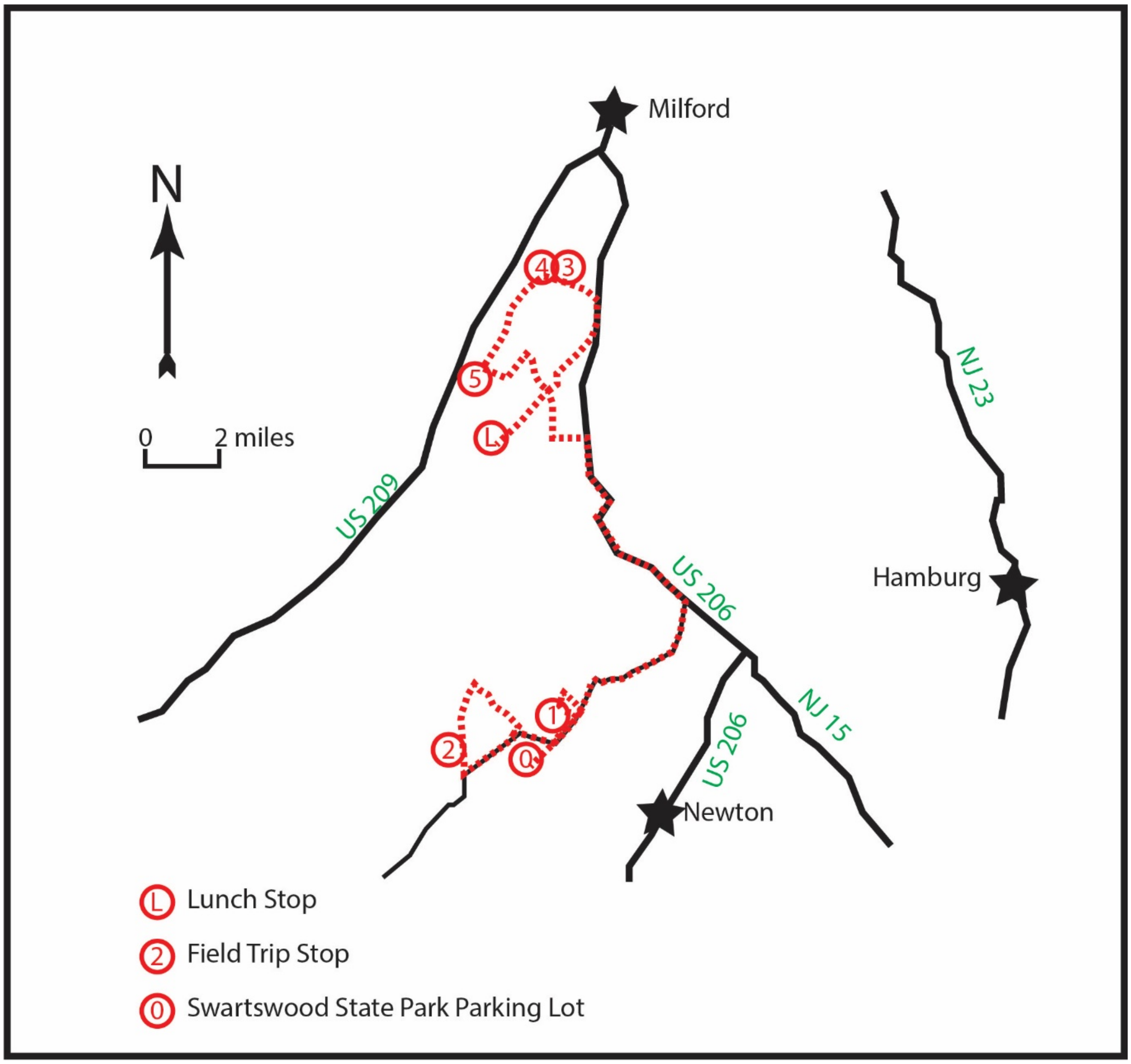
https://www.nj.gov/dep/njgs/pricelst/gsreport/gsr44.pdf


Spruce Run Survey Area
Active Sinkhole
Possible Sinkhole
Well
N
Meters
0 5 10 15 20 25 30

FIELD GUIDE

INTRODUCTION

This trip can be divided into two parts. At the first two stops we look at karst features underlain by Cambrian and Ordovician carbonates. At the last three stops we investigate karst features in Lower to Middle Devonian rocks of the Delaware Water Gap National Recreation Area, New Jersey. The second part of the trip is based on a previous trip in 2016 of the New York State Geological Association (Monteverde and Witte, 2016). Stops 3, 4 and 5 are modified from Witte, Monteverde and Domber, (2016).



Warning – This trip brings you to several sinkholes, some are active while others not so much. It is best not to walk in the sinkholes as they are inherently unstable. Everything can be clearly seen from safer vantage points.

STOP ONE: IKE WILLIAMS ROAD, HAMPTON TOWNSHIP, NEW JERSEY.

Location Coordinates: 41.098°N, 74.802°W

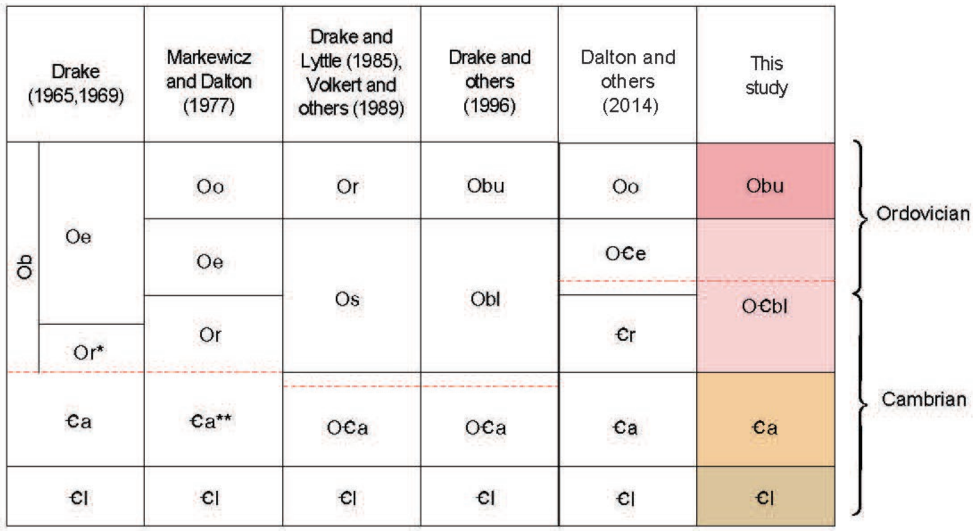
On Swartzwood State Park land along north side of Ike Williams Road, Hampton Township, NJ
Karst Geology and the Beekmantown Group, upper part: bedding-strike controlled(?) marking small discontinuous stream, regional structures

Sample collecting and the use of rock hammers is not permitted in State and National Parks. Most outcrops, and other features provide more than adequate inspection.
Check for ticks after this stop and after the trip. They are everywhere.

Stop 1 lies in the Newton West quadrangle on a detached section of Swartswood State Park in New Jersey's Valley and Ridge Physiographic Province. Karst features form on Cambrian and Ordovician carbonate rocks mostly dominated by dolostone with a much smaller percentage of limestone. Glacial surficial deposits blanket most of the karst area (Witte, 2012a). The karst features occur close to the contact of the Martinsburg Formation, an Ordovician deep-water turbidite that overlies the older carbonate rocks.

Stop 1 will consist of a short hike to the northeast through Swartswood State Park land. There is no defined trail so please be careful making the short walk up to the first stop. We will pass a small ridge to the west that exposes dolomitic rocks of the Beekmantown Group, upper part that dip gently to the west. Past the ridge is a small stream channel. There are karst features of two ages of karstification related to the stream that we will visit. Initially we will stay on the east side of the stream to investigate the modern/active karst features. Then we will proceed to the western side of the stream channel to see an older stage of karst development. The large boulders in the older sinkholes and along the stream are all quartzites from the Silurian-aged Shawangunk Formation that forms the major ridge of Kittatinny Mountain to the west. They tend to comprise the most common till erratic boulders within the Wisconsinan-aged surficial deposits here in the Kittatinny valley.

Discussion – Before focusing on the karst features, I want to explain the explain the nomenclature and correlation of the Cambrian – Ordovician rocks that I will be using. Other authors and organizations use different names. Figure 1 shows how these units correlate. It is my hope that with this background you will be able to make sense of maps of these units no matter who the author is or what school of thought they are following. A quick historical description of the evolution of the Cambrian and Ordovician carbonate margin helps in understanding how the changing interpretation of these formations arrived at the current state in New Jersey.



Oo - Ontelaunee Formation
Oe - Epler Formation
Or - Richenbach Formation
Or* - Rickenbach Dolomite
Os - Stonehenge Formation
Ob - Beekmantown Group
Obu - Beekmantown Group, upper part
Obl - Beekmantown Group, lower part
OꞒe - Epler Formation
Ꞓr - Rickenbach Formation
OꞒa - Allentown Dolomite
Ꞓa** - Allentown Formation
Ꞓa - Allentown Dolomite
Ꞓl - Leithsville Formation

Figure 1.2: Evolution of Paleozoic carbonate rock nomenclature. This guide follows the units of Drake and others (1996) with the inclusion of the revised age correlations due to changes in the International Stratigraphic Time Scale (U.S. Geological Survey, 2010) which raised the Cambrian-Ordovician boundary. Red dashed line indicates the volving placement of the Cambrian-Ordovician boundary.

The initial breakup of the Rodinia Supercontinent led to a broad carbonate passive margin. This margin developed during the Cambrian and Ordovician and is marked in New Jersey by a thick sequence of shallow water carbonate rocks. A clastic quartz-rich, fine to conglomeratic rock (Hardyston Quartzite) forms the basal part of the passive margin. Above the Hardyston lie several thousand feet of Cambrian and lower Ordovician carbonates which have been almost completely dolomitized in New Jersey. These units include, from oldest to youngest, the Leithsville Formation, Allentown Dolomite and the Beekmantown Group, Lower and Upper parts. You may wonder about the breakdown into "Lower and Upper parts" of the Beekmantown.

Workers in the 1960's and 70' (Drake, 1965, 1967; Markewicz and Dalton, 1977) originally agreed on the Ordovician carbonate mapping units by carrying the carbonate breakdown of oldest to youngest Stonehenge Limestone, Rickenback Formation, Epler Formation and the Ontelaunee Formation first described by Hobson (1963) in the Reading PA area. Markewicz and Dalton (1977) established a very useful breakdown of members that could be used across the state although the battle of formation names continued on a small scale. This agreement broke down after USGS paleontologists performed a regional study on fossil conodonts across the Pennsylvanian and New Jersey Cambro-Ordovician carbonate rocks (Repetski and others, 1995). Using the conodont breakdown Drake and Lyttle (1985) subdivided the Beekmantown Group carbonates differently leading over time to the use of Lower and Upper parts. This difference in interpretation is due to using the conodont dating or the increased degree in dolomitization between Reading, PA, where the Beekmantown was originally described and New Jersey. Before the study of conodont age dates, Hobson (1963) suggested the Stonehenge Limestone in the Reading area pinched out toward

New Jersey into the overlying Richenbach Dolomite He continued the Epler Formation and Ontelaunee Formation across into New Jersey. Drake (1967) and Drake and others (1967) followed Hobson's interpretation on early geologic maps of western Valley and Ridge in New Jersey. Conodont dating has shown that New Jersey units mapped as Richenbach and the overlying Epler Formation are age equivalent with the Stonehenge Limestone in the type area in Reading, PA. Drake started to include the Stonehenge in his quadrangle geologic maps (Drake and Lyttle, 1985) but changed the Stonehenge Limestone to Stonehenge Formation due to its dolomitization while Markewicz and Dalton (1977) kept a more lithostratigraphic approach. To avoid conflict, I use the breakdown established in the 1996 1:100,000 state geologic map (Drake and others, 1996). The boundary between the Lower and Upper parts of the Beekmantown in Drake and others (1996) is a formation boundary that both the Drake, USGS and the Markewicz and Dalton school of thought recognize (figure 1). For Drake (Drake and others, 1996) it marks the boundary between the Stonehenge and Richenbach formations and for Markewicz and Dalton (1977) between the Epler and younger Ontelaunee Formation. Cambrian-aged Leithsville Formation and the overlying Allentown Dolomite have been accepted stratigraphic units since the subdivision of the original Kittatinny Formation of the middle 1900's.

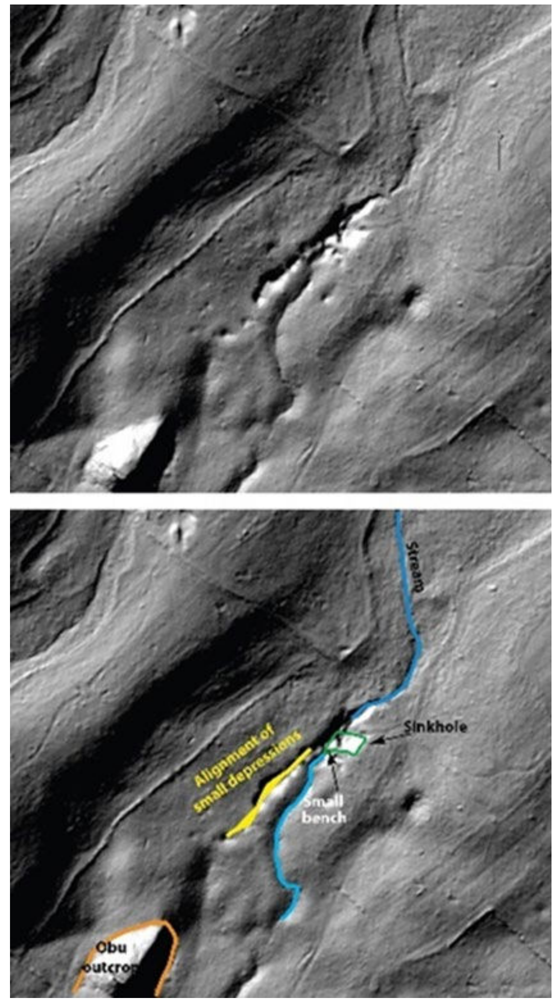


Figure 1.3: Lidar image of Stop 1. A ridge of Martinsburg underlies the ridge running north northeast on the left side of the image. All the material to the east of this ridge is underlain by carbonate rock. Orange line at bottom of image outlines the carbonate ridge. Small bench described in text and more clearly shown in Figure 1-4 is located at top (north) end yellow line. The bench marks the point where high stream flow would escape out of the enclosed ground marked by the green box-shaped polygon. This low depression displays zones where the stream flow and ground "sink". The yellow line marks the approximate trend of the small closed depressions.

Due to their total combined thickness of approximately 4000 feet (1200 m) and large lateral extent the Cambrian and Ordovician have the greatest amount of karst features in the state. Dalton (1976) lists seventy-eight caves, ten shelters, and eight major springs and sinking streams in these rocks. Twenty-six caves are known from the Proterozoic Franklin Marble (Dalton, 1976). Only six caves have been recorded in the carbonate rocks of the Silurian and Devonian of New Jersey (Dalton and Markewicz, 1972; Dalton, 1976).

Karst along the stream – By now we should be standing on the edge of a large sinkhole with a small stream entering from the northeast (figure 1.3). The stream approximately parallels the local geologic strike (the two closest strike and dip readings, including one from the ridge we walked past, are 053, 32 N and 032, 20 N). The stream cuts through glacial till deposits (Witte, 2012a) leaving large rounded pebbles and boulders of the Shawangunk lining the stream. Flow is intermittent as I have never experienced it in full flow but usually find a very low flow that descends into the large sinkhole and sinks into the ground. Small slump scarps in the bottom of the sink show evidence of activity (figure 1.3). Stream flow appears to originate from the Martinsburg ridge to the northwest. Witte (2012a) shows a boundary between two till types across this area. Till clasts to the west dominantly originate from Kittatinny Mountain and is probably around 10 feet thick. Till clasts to the east come from Kittatinny Valley with Martinsburg clasts dominant. Till along the east is generally less than 10 feet thick. Surface water is probably on the acidic side which would readily react with the basic pH of the carbonate rocks. Both Stop 1 and Stop 2 are in similar orientations with surface water flowing through thin till that overlies the Martinsburg Formation. In both cases karst features developed in the Beekmantown Group, Upper part near contact with the Martinsburg.

Along the southwest corner of the large sink is a low surface or bench approximately 3 ft above the sinkhole floor. It connects the large sink to the downstream part of the stream (figure 1.4). Considerable flow on the stream would be needed to fill the sinkhole and continue downstream to the south past the large sink. Downstream the floor of the stream often appears damp but flow is probably from the stream's high walls in this region. A small short subsidiary stream on the east displays a possible sink before reaching the "major" stream bed. There is little evidence of karst

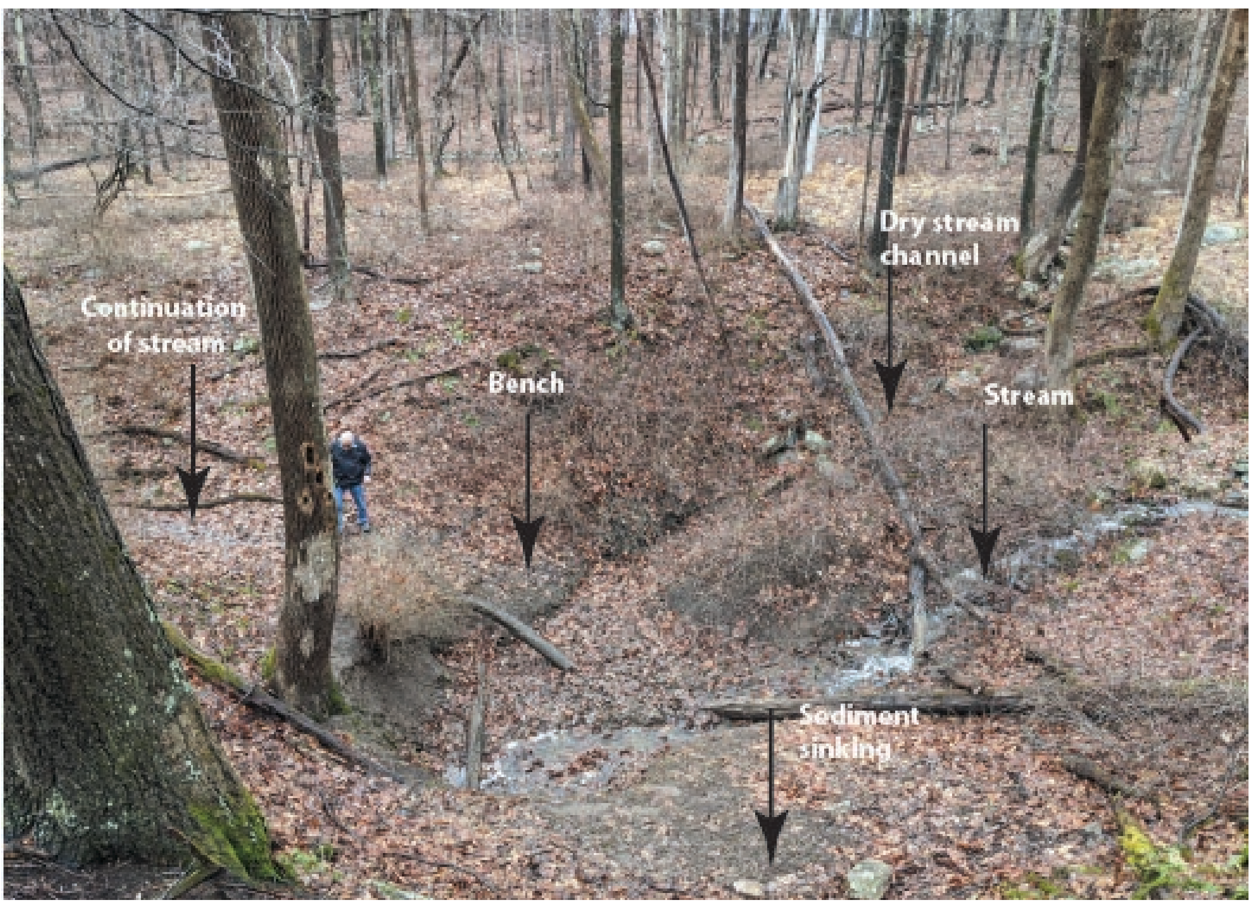


Figure 1.4: Photo looking northwest (Michael Hozik for scale) down into the depressed region where stream flow is trapped by the bench, a slightly higher elevation than the depression flow. Water can be seen pooling in the depression. At the bottom of the photo a black arrow marks the location where the ground had subsided between several small rain events. If stream flow is high, it may crest the bench and continue in the stream. I have only witnessed this part of the steam as being damp and muddy without any flow.

development farther downstream though again, I have not observed flow in the stream past this point.

Figure 1.5: Photo of Jeff Webber. standing within one of the depressions showing the dimensions of these depressions.

Karst(?) west side of the stream – the west side of the stream displays some rather unique features that could be karst related. Starting approximately parallel with the southern extent of the large sinkhole and walking to the southwest is an alignment of at least 9 depressions. Each depression contains Shawangunk boulders along the bottoms of the depression and some along the edges (figure 1.5). They are not active. Their alignment appears to define a shallow, linear depression slightly off parallel with the stream we just left. But they do project to the location of the current stream where it enters the large sinkhole. We just moved from data to the land of interpretation.

Projecting the strike of the outcrops on the ridge suggests that the bedrock here would be Beekmantown Group, Upper part which is almost totally dolomite. The ridge to the west is underlain by the Martinsburg Formation. Between the two would be the Jacksonburg Limestone which thins to the northeast. The Jacksonburg Limestone has been divided into two facies, the older Cement Lime and the overlying Cement Rock. Cement Lime is a shallow water facies commonly very fossiliferous while the Cement Rock contains an influx of clay due to a deepening of the basin. Chemistry of the Cement Rock is perfect for Portland Cement. Many cement quarries exist in eastern Pennsylvania and western New Jersey. Thomas Edison had a cement quarry in the Jacksonburg Cement Rock in Stewartsville, New Jersey (Pallis and Monteverde, 2015). The contacts between these formations have been just projected across this glacial till-covered landscape. Regional investigations suggest that the land underlain by the Jacksonburg develops sinkholes much less commonly than in areas underlain by dolomite.

Figure 1.6: Photo looking northward in an attempt to show the alignment of several of the small depressions outlined in Figure 1-3. It is difficult to photograph holes in the ground as well as showing their alignment in the woods.

There are several options here, 1) these depressions define an older location of the stream. Sometime in the past, after the depressions developed, the stream created a new channel possibly due to a heavy rain event and deflected to its present location. 2) these depressions have nothing to do with karst development. They could be related to downed trees. At the NJGWS we commonly receive calls from concerned citizens about land subsidence. We check geological maps to identify the bedrock of the location in question. If it does not have a carbonate bedrock then it is not related to karst development. It could be related to decaying organic material. In the past when land was turned into a new development the trees were commonly cut down to allow open land for building construction. Most of the wood can be sold except for the trunk. In the past developers may have buried the trunks on the land to be developed. After approximately 20 years the organic material has decayed and left a void. This can develop a soil arch in clay rich soil. Rain storms can saturate the soil thereby weakening the dried-out clay soil and causing the soil to collapse. There is an example of a boy in the Edison area who died due to a soil collapse into a void created by decaying organic material (https://www.mcall.com/news/mc-xpm-1993-04-25-2921612-story.html#:~:text=A%207%2Dyear%2Dold%20boy,neighbors%20to%20pull%20him%20out.). This event occurred in land underlain by Mesozoic age clastic rock. No dissolvable rock was in the area. It was believed to be an area of buried tree or construction debris. I currently have two small "sinks" that lie exactly where we cut down two large trees. We only had the stump cut to the ground surface. Over time they developed a subsurface void that has chosen this year to collapse.

DISCUSSION QUESTION: Could the weathering of buried organic material explain these "aligned" depressions or does the possibility of a channel avulsion moving the stream away from its previous location where the nine depressions occur to the stream's current location? Which would you pick?

STOP TWO: FIVE POINTS LANE, STILLWATER TOWNSHIP, NEW JERSEY

Location Coordinates: 41° 4' 30.74" N, 74° 51' 32.292" W

This Stop is on private land and permission must be received from the landowner.

Warning – This stop brings you to several sinkholes, some are active. It is best not to walk in the sinkholes as they are inherently unstable. Everything can be clearly seen from safer vantage points.

Drive to the nondescript place where Five Points Lane becomes Camp Lou Henry Hoover Road where we will exit the buses. Walk up the road a short distance to the junction with a dirt path trending west southwest. Part of this path is owned by the Girl Scouts Heart of New Jersey organization. Walk down the path to an outcrop on the east side of the dirt path (Fig 2.1).

The geology of this stop is similar to that of Stop 1 with the karst features developed in rocks of the Beekmantown Group, Upper part (Fig 2.2). Martinsburg rocks occur to the north and west. Again, a blanket of glacial till covers most of the land to the northwest and southwest (Witte, 2012a). The extensive till coverage and therefore limited outcrop exposures increases the difficulty to geologically map the area. Further difficulties in mapping the boundaries between the carbonate units and the Martinsburg arise due a few outcrops in the carbonate rocks to the immediate north and east that define several folds with their axes trending to the northeast.

Several small intermittent streams to the west generally have an eastward flow

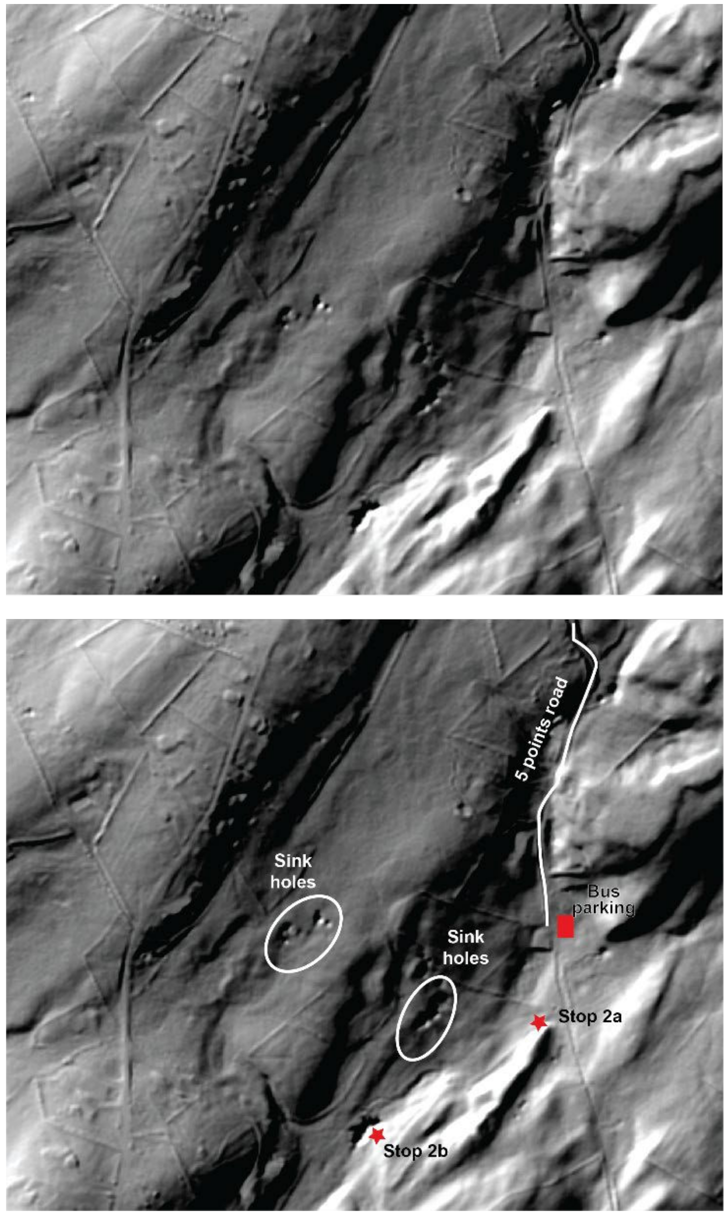


Figure 2.1: Lidar images of the area around Stop 2. Red symbols identify the location we will depart the bus, the exposure of the dolomite described in Stop 2a, and the location of the active sink in Stop 2b. The series of sinkholes near the center of the photo marks the approximate location of the Martinsburg – carbonate contact. Another set of sinkholes occurs to the east southeast.

Figure 2.2: Small exposure of the Beekmantown Group, upper part that appears to be the host unit to the sinkhole development at both Stop 1 and here at Stop 2. Here the dolomite exposure is slightly fetid when struck with a hammer. This is a

direction as they cross the glacial till. At a certain point the streams' flow drops into a series of small swallow and sinkholes (Figure 2.3). The streams do not flow past the swallow holes. These features define a general linear trend that outlines the probable break between Martinsburg rocks to the west and carbonates to the east. Without any indication of local faulting in the area the carbonates are suspected to be the Jacksonburg Limestone. Locally only a limited number of Jacksonburg Limestone exposures have been found and none are near these swallow holes (Drake, 1992, Monteverde and Herman, in review).

Stop Two A – Karst Geology and the Ordovician Beekmantown Group, upper part: bedding strike controlled(?)

Small outcrop on the south side of the west-southwest trending dirt path.

This is a small dolomite outcrop from the upper Beekmantown Group that corresponds to the Rickenback of Drake and the Ontelaunee of Markewicz and Dalton. One of the characteristics of this unit is its smell. When hit with a rock hammer a fresh piece gives off a fetid smell, similar to rotten eggs. The thickness of this unit is quite variable due to the migration of the peripheral bulge during the initial stages of the Taconic Orogeny (Jacobi, 1981). The approaching stacked thrust sheets and the island arc which collided with Laurentian continent during the Taconic Orogeny was sufficiently dense to depress the crust and form an adjacent bulge on the Laurentian margin. This bulge elevated the carbonate margin above sea level causing erosion of the carbonate rocks. There is evidence of paleokarst features developed during this process. As the bulge migrated into the Laurentian hinterland the margin subsided beneath sea level allowing the deposition of the Jacksonburg Limestone and leading to the development of a foreland basin and the deposition of the Martinsburg Formation.

The Beekmantown Upper part outcrop here is similar to rock forming the small hill close to stop 1 (Figure 1.3). Another example of this unit can be seen in the sinkhole farther to the southwest along this path which is part of the later portion of this stop.

Stop Two B – Active Karst development in the Ordovician Beekmantown Group, upper part.

Warning –Several active sinkholes are at this stop. Do not walk in the sinkhole area as they are inherently unstable. Everything can be clearly seen from safer vantage points.

This is private land. The landowner was gracious in allowing us access to this site. Land to the immediate east is owned by the Girl Scouts. Please gain access before bringing others here.

This geology of this stop is very similar to Stops 1 and 2a. We are in the Beekmantown Group, upper part with the overlying Jacksonburg Limestone and Martinsburg Formation rocks to the west (figure 2.1). Northwestward, at the Jacksonburg–Martinsburg contact small or intermittent streams lose water into small shallow depressions (Fig. 2.3). This occurs over an approximately 50 yard front that runs parallel to the mapped formation contact (Drake, 1992: Monteverde and others, in review).

Figure 2.3: Eastward flowing streams cross the approximate location of the Martinsburg – carbonate contact. Here the flow locally flows into a swallow hole where the water flow complete disappears into the ground water flow. To the right of the flow is a sinkhole that developed adjacent to the stream flow. Similar small streams occur across this Martinsburg-carbonate contact as seen in Figure 2.1.

We are standing at the base of a fairly large depression attached to several sinkholes and sinking streams. The land owner suggested that the area here is an old foundry that is filling with soil. I have been unable to find information supporting his ideas. The only foundry is to the west along Old Foundry Road along which we traveled before turning down Five Points Road and parking the bus for this stop. Several small intermittent streams coming from the west and south feed into the depression below where we are standing. The few times I visited this site a very small intermittent stream in the northwestern corner of the depression supplies water into the depression (Fig. 2.4). This flow crosses the depression flowing towards the northeastern corner of the depression where it sinks into the subsurface (Fig. 2.5). On one visit showing a GANJ team the site as a possible stop, one member suggested that the ground felt "soft" and unstable. We immediately moved away to a safer vantage point.

Figure 2.4: Small stream within the carbonate formations flowing to the east into a moderate flat-bottomed basin (Figure 2.5). This flow is intermittent. A similar stream enters this basin from a southward direction.

Figure 2.5: Region where flow from stream shown in Figure 2.4 sinks into the subsurface. There is not much evidence of recent ground subsidence.

Moving to the north along the base of the slope are several active sinkholes (Fig. 2.6), one of which exposes a dolomite block which resembles the outcrop of the Beekmantown Group, upper part seen earlier at this Stop. I am unsure if the block is floating or attached. The weathered nature of the exposure makes it difficult to record a viable bedding strike. Regional mapping outlines an anticline syncline pair with fold axes trending approximately 035º. This location lies on the west dipping arm of the anticline. The fold axis trends approximately parallel to the base of the slope and the alignment of the sinkholes. This suggests the possibility that the karst development follows the local Beekmantown strike belt due to this belt being more suspectable to dissolution possibly due to the water originating from the Martinsburg before reaching the carbonates.

Figure 2.6: Evidence of sinkhole development aligned in a northeast direction. These sinkholes are active as there was evidence of recent enlargement of the sinkholes. In this picture small and dead trees have slipped into the hole due to active ground subsidence.

A big question at both Stops 1 and 2 is what happens to the stream water once it enters the subsurface? A topographic low occurs at this stop and continues to the north before turning to the east towards Swartswood Lake. The topographic low surround the higher elevation of the Girl Scouts owned land. No karst features have been found in the Girl Scout land. Active karst development continues along the low topographic belt. Some suggest that the surface water sinks and enters a subsurface flow network controlled by the dissolution along joints of the carbonate rock and feeding into Swartzwood Lake. A dye test could add more understanding to the flow system related to these local karst features.

STOP THREE: JAGER ROAD (NEAR BRAU KETTLE), SANDYSTON TOWNSHIP, NEW JERSEY

Location Coordinates: 41.263°N, 74.824°W

STOPS 3a and 3b) – Jager Road – Karst Geology and the Onondaga Limestone: Joint-controlled karst, regional structures, sedimentology of the Onondaga Limestone, and shallow groundwater flow.

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.

Location and logistics

Stop 3 lies in the Milford quadrangle in the Delaware Water Gap National Recreation Area (fig. 3.1) 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 the Minisink Valley. Wallpack Ridge forms the eastern side of the Minisink Valley in New Jersey and it rises as much as 300 feet (91 m) above the valley's floor. At Stop 3, the Onondaga Limestone underlies the ridge's northwest flank forming a gentle dip slope that extends to Minisink Valley. The western side of the Minisink Valley in Pennsylvania is bordered by a 300-foot-high (91 m) escarpment held up by the Mahantango Formation.

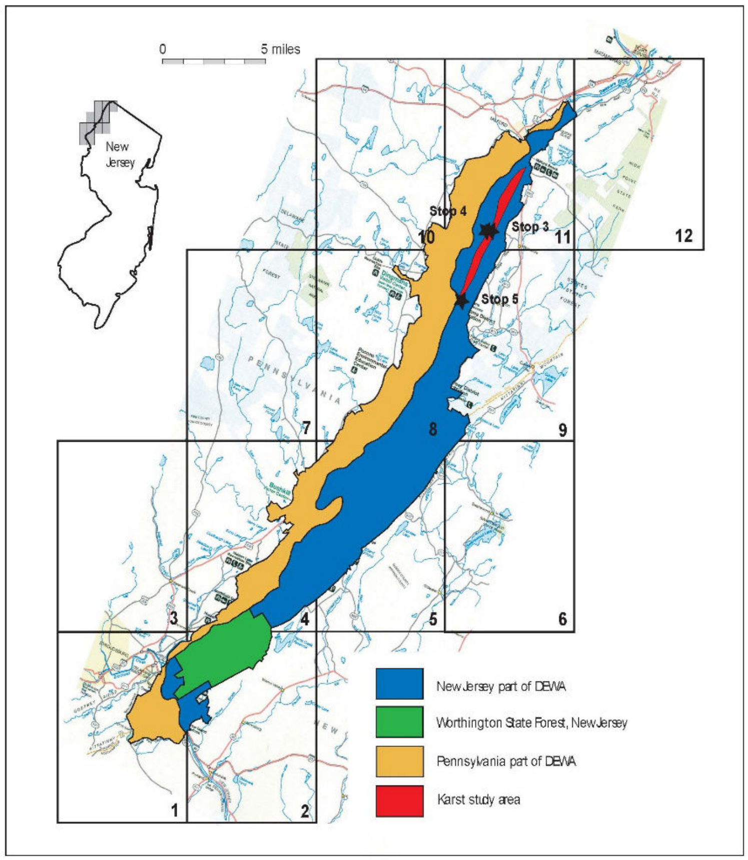


Figure 3.1. Location of Delaware Water Gap National Recreation Area (DEWA) in New Jersey and Pennsylvania, karst study area, field stops, and location of U.S. Geological Survey 1:24,000 quadrangles. 1. Stroudsburg, 2. Portland, 3. East Stroudsburg, 4. Bushkill, 5. Flatbrookville, 6. Newton West, 7. Twelvemile Pond, 8. Lake Maskenozha, 9. Culvers Gap, 10. Edgemere, 11. Milford, 12. Port Jervis South.

Stop 3 will consist of two parts: 3a 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. 3.2). Additional parking 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 the buses at the end of the hike (culvert 3) which will have driven down the hill to the parking area at intersection of Jager and Old Mine Road (fig. 3.2).

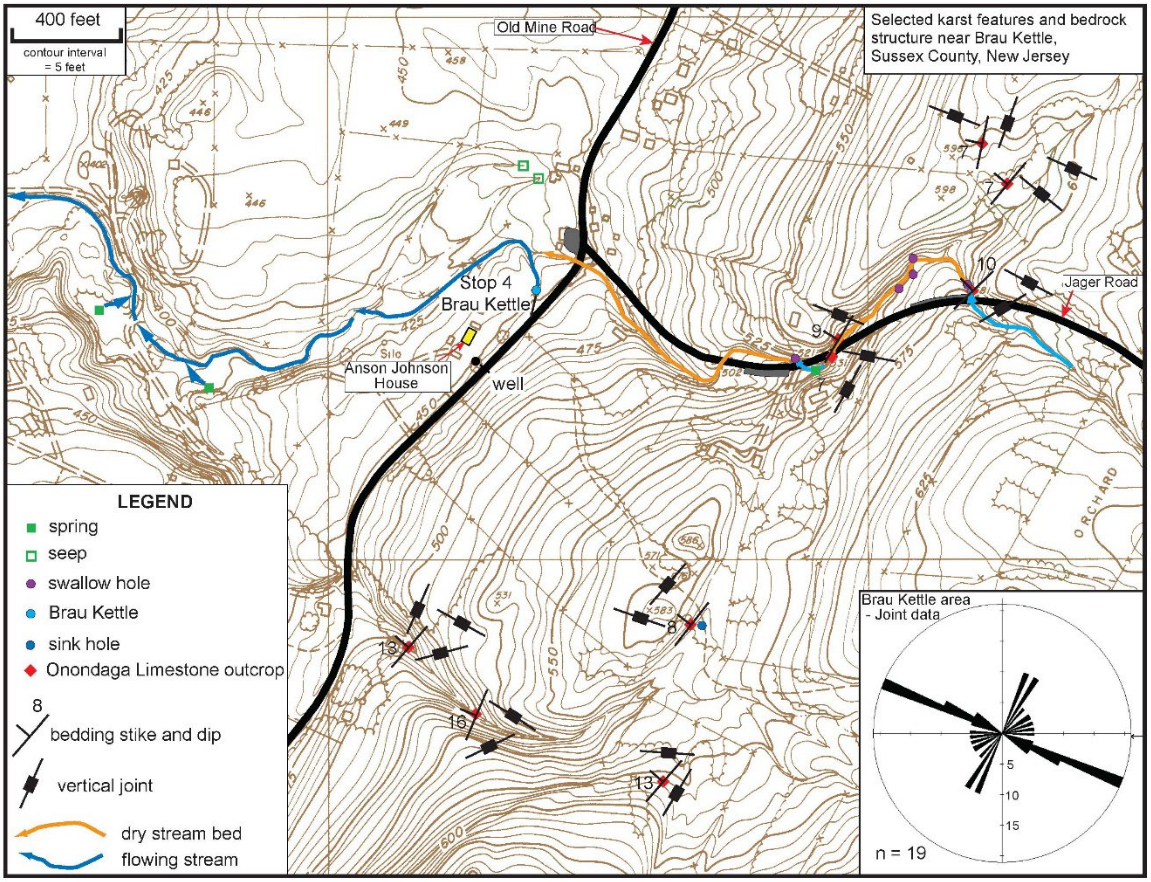


Figure 3.2: Stop 1 location map, karst features, and joint data for the Brau Kettle area.

Geologic Setting

Wallpack Ridge is a long, narrow, and slightly sinuous ridge extending 25 miles (30 km) from Wallpack Bend on the Delaware River to Tristates, New York (fig. 3.5). Its width varies between 0.7 and 1.7 miles and its highest elevation is 928 feet (283 m). 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. 3.3). These units comprise fifteen geologic formations (fig. 3.4) but may be grouped into six lithotypes (fig. 3.3) when studying karst at regional scales.

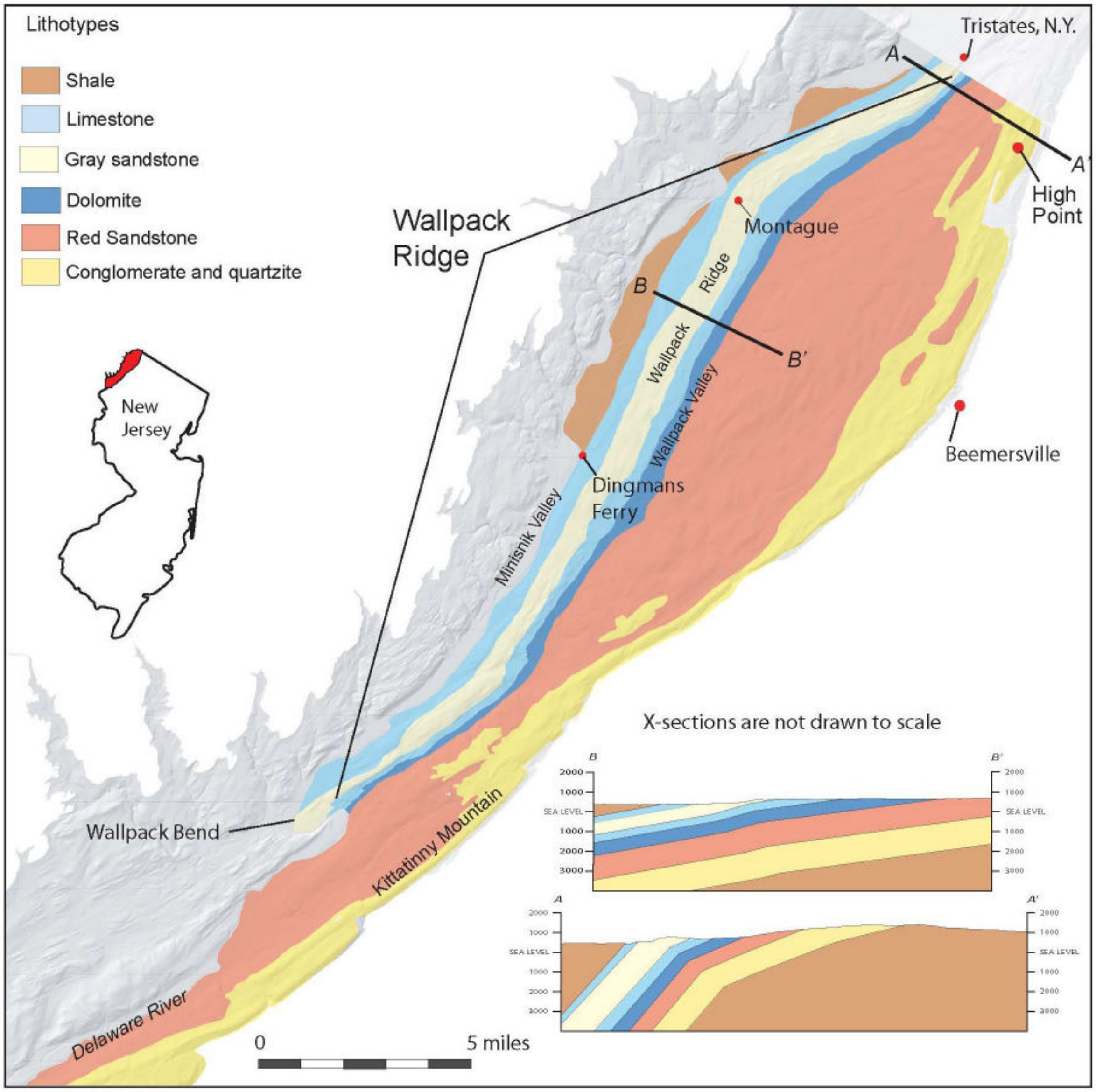


Figure 3.3: Simplified bedrock map of New Jersey in the vicinity of Wallpack Ridge. Modifed from Drake and others (1996). The Onondaga Limestone forms the most westerly limestone.

System	Series	Formation		Member	Description	Aprroximate thickness (feet)
		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
	Middle	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 "colum-nals" in lower half.	80
		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
Devonian			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
	Lower		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
		Helderberg Group	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
			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
Silurian	Upper		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 mudcracks. Conglomerate consists of matrix supported quartz, green adn 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 3.4: 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 susceptable to dissolution), thickness (thicker formations are more susceptable 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 susceptability 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).

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. 3.5). 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.

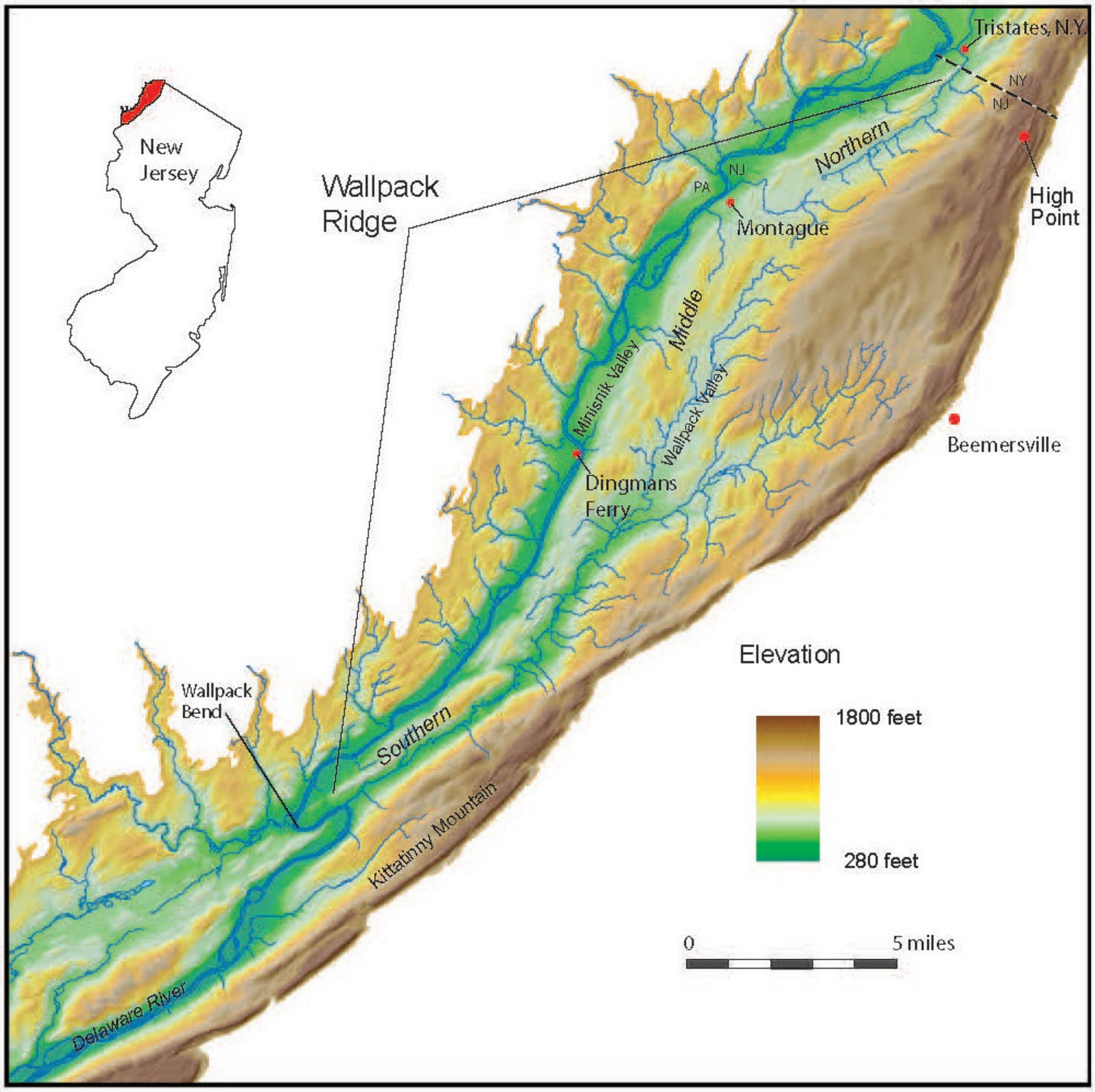


Figure 3.5. Color shaded-relief map of Wallpack Ridge and surrounding area.

The 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 selected sites of a planned hydroelectric and water storage project proposed by the Army Corps of Engineers. A dam planned for construction at Tocks Island would have flooded the Minisink Valley upstream to Port Jervis, New York, and the 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, lying east of our current location (fig. 3.5), is a prominent ridge that separates far northwest New Jersey from the Kittatinny Valley where our first stop lies. Kittatinny Mountain extends from the Shawangunk Mountains in New York southwestward through New Jersey into Pennsylvania. It rises as much as 1500 feet above the floor of the Minisink Valley and is underlain by the Shawangunk Formation, a tough and highly resistant quartzite and quartz-pebble conglomerate. Lying above the Shawangunk Formation and forming the lower area along the northwestern flank of the Kittatinny Mountain and extending to the Wallpack Valley are the Bloomsburg Red Beds.

Stop 3 lies about 28 miles (45 km) north of the late Wisconsinan terminal moraine. Nearby glacial deposits (Witte, 2012b) include valley train, meltwater terrace, and outwash-fan deposits laid down during systematic deglaciation of the Minisink Valley. The Dingmans Ferry and 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 the Wallpack ridge with a small field of sand dunes covering the outwash plain just up valley 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 investigation of surficial deposits in northwestern New Jersey (Stone and others, 2002; Witte, 2012b). Sinking streams, springs, a few small caves, and numerous small sinkholes were located with almost all of the features found within the Onondaga Limestone outcrop belt, especially in the area between Dingmans Ferry and Montague, New Jersey (fig. 3.6).

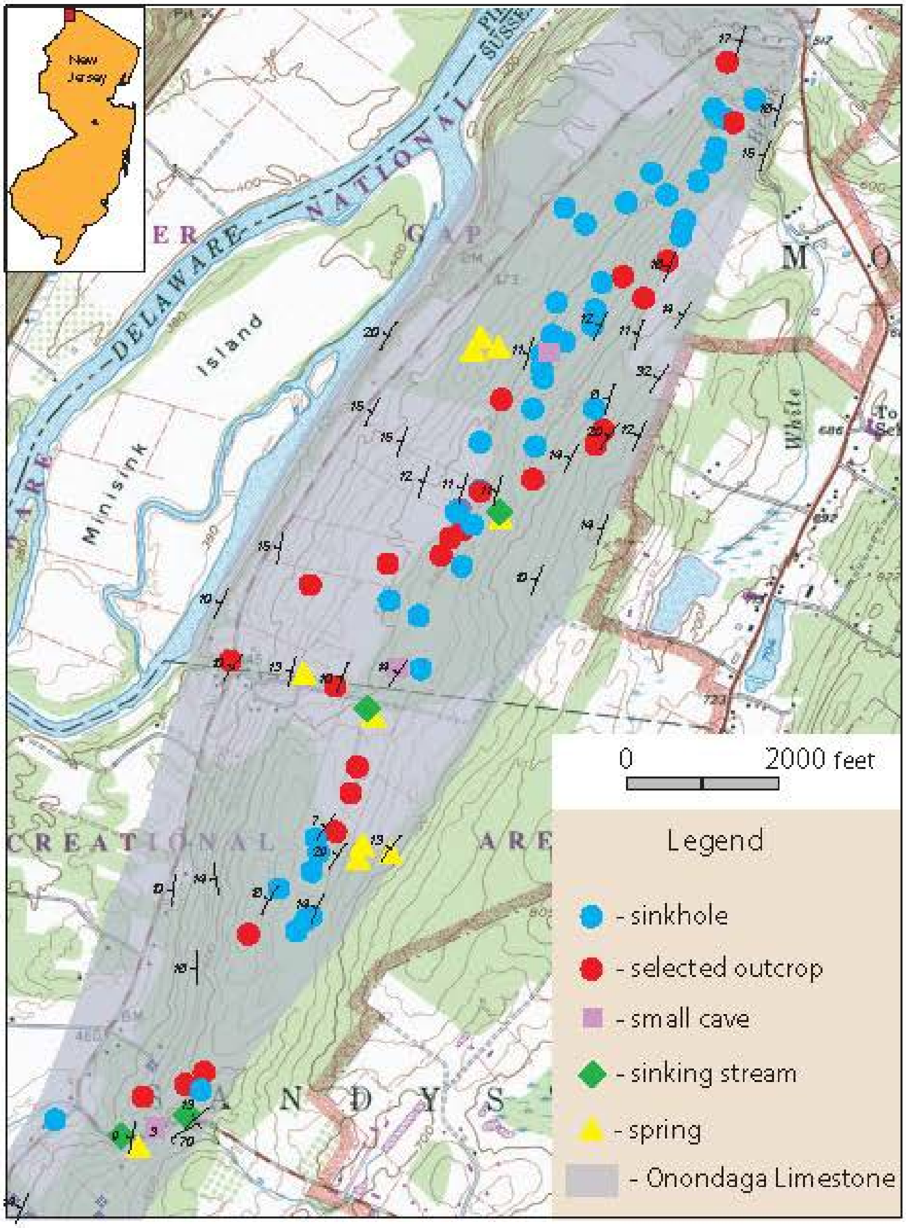


Figure 3.6: Karst features mapped on Wallpack Ridge between Jager Road. and U.S. Route 206, Delaware Water Gap National Recreation Area. Sinkholes may be solitary or form small clusters that are aligned with joints in the Onondaga Limestone.

The Onondaga Limestone in New Jersey was never formally divided into members (fig. 3.7) as it had been in New York (Oliver, 1954) and Pennsylvania (Epstein, 1984) (fig. 3.4). However, it was informally divided by Herpers (1952) into a lower section that is devoid of or contains only sparse chert (fig. 3.8a) and an upper section that contains abundant chert (fig. 3.8b). 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.

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. Thicknessis 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 3.7: 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 3.8: 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 (appendix A, field stop 2d). Ealier workers in New Jersey (see fig. 5) 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.

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 concluded 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 and others (2001) 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. 3.9) 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. 3.9). 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 occurs near Montague, New Jersey (fig. 3.9) in the northern part of the outcrop belt.

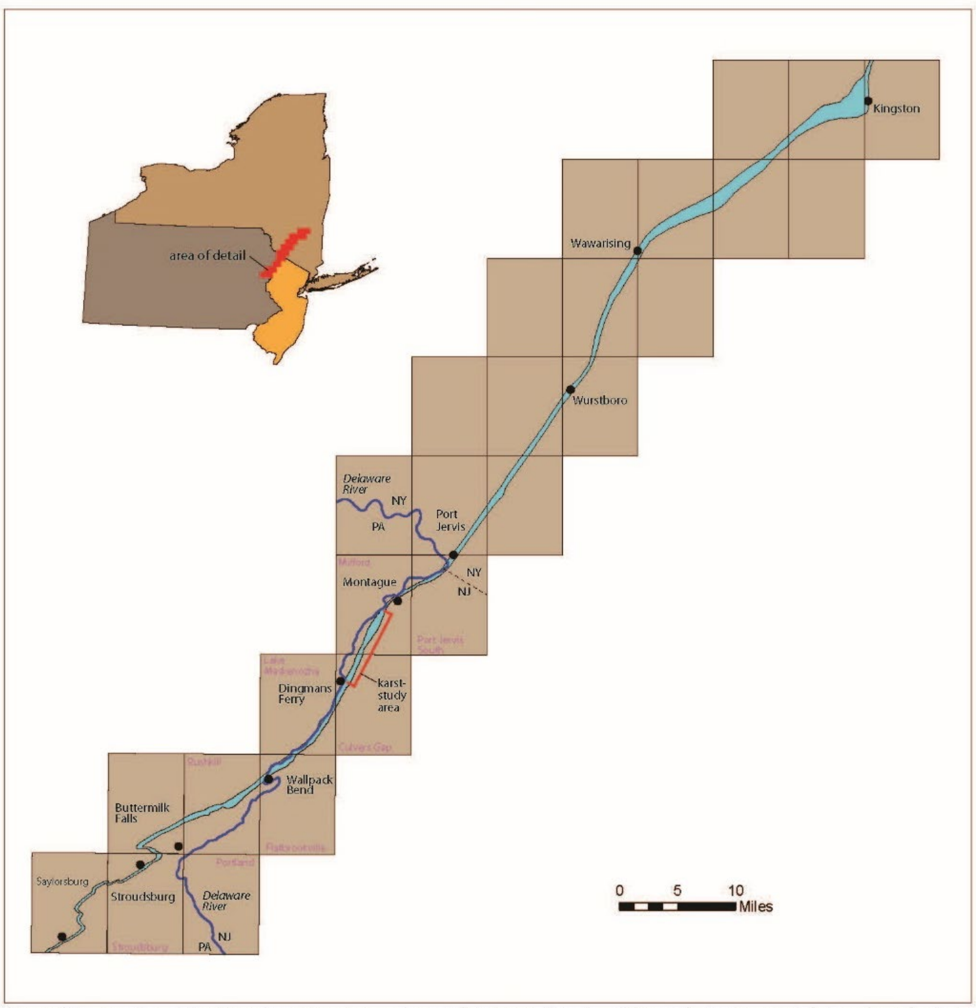


Figure 3.9: Location of the Onondaga Limestone outcrop belt between Kingston, NY and Saylorsburg, PA, index of 7 1/2 minute topograph-ic quadrangles, and places named in report. Modified from Oliver (1956, figure 2 and Epstein, 1984, figure 1). Only quadrangles in New Jersey are named.

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 3). The columnals have been also found by the authors 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 3a 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. The 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. 3.6) 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 exposures. Sinks may occur alone or in small groups that are aligned with local joints which are dominantly strike parallel. Most sinks or sink clusters lie along a 040° to 020° trend with a few sinks following 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. 3.10). 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.

Figure 3.10: Solution collapse sinkhole over the Onondaga Limestone. Delaware Water Gap National Recreation Area. Photo by R. Witte.

The second kind are solution sinks (fig. 3.11). 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 the solution sinks exhibit bedrock in the sink's walls and most are found along the intersection of major joints.

Figure 3.11: Soil collapse sinkhole over the Onondaga Limestone. Delaware Water Gap National Recreation Area. Photo by R. Witte.

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. 3.11). 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 rarely associated with rock outcroppings. Less common sinks occur as several closely spaced sinks formed along cross joints on gentle slopes. 3) sinks rarely occur at the base of a dip slope where slope meets the valley floor. No sinkholes have been found farther to the southwest than where Wallpack Ridge crosses the Delaware River and the Onondaga is steeply dipping to overturned.

Sinking streams and springs – Many small streams that flow over the Onondaga Limestone disappear and rarely reemerge 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, with the stream flowing into a small sink or large void (swallow hole). About 1800 feet upstream from Brau Kettle (fig. 3.2), approximately 70 percent of stream flow disappears into an opening about 2 feet in diameter (Stop 3a-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 by three possible methods 1) abrupt changes in slope along bedding or joints or 2) the surficial – bedrock contact (till-rock interface) and 3) bubbling up through surficial sediment along the edge of the Delaware River. In places, deposits of calcareous tufa (Stop 5a) are found just downstream from where the spring emerges. Brau Kettle is a peculiar spring (Stop 4). 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 4.

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 (though you would never catch me in one), 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. 3.12) and a more recently found unnamed cave have been located in the Onondaga Limestone. These represent the largest known Onondaga caves in New Jersey.

Figure 3.12: 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.

Cutters and limestone pavements – The Onondaga's long, gentle 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.3.13). 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). 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 important 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. 3.2 and 3.13). 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 for more than several meters. The second (called here J2) is a 110º to 120º set that is nearly perpendicular to bedrock strike. These cross joints commonly terminate against joints J1 and 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. Larger voids may develop at joint intersections due to increased dissolution along two different surfaces. Over time, 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 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 and locally can be vertical to

Figure 3.13: Cutters J1 (054°) and J2 (146°) in the Onondaga Limestone, Delaware Water Gap National Recreation Area. Photo by R. Witte.

overturned, most notably in the southern and northern sections (fig. 3.3). 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.

Figure 3.14: Bedding plane dissolution in the Onondaga Limestone. Photo by R. Witte.

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. 3.14). 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 Monteverde and Witte (2016) and Witte and others, (2016) 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, the gently dipping rocks along the middle section of Wallpack Ridge lack cleavage or it is only weakly developed, whereas rocks along the southern and northern sections have a pronounced northwest - southeast trending, steeply dipping cleavage (fig. 3.5). 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. Ratcliffe and others (2012) sampled a titanite mineral which yielded a TIMS age of 447±2 Ma.

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. 3.5) 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 Monteverde and Witte (2016).

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 of the sinks older than the last glaciation may 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 sands, which were 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 THREE A

Location 3a-1 – Creek bed just downstream from culvert 1 (fig. 3-15) near Schoharie – Onondaga contact.

Location Coordinates: 41.263°N, 74.824°W

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. 3.16). The rock is a thin to medium-bedded, fine-grained, faintly nodular, non-cherty, sparsely fossiliferous limestone. Given its proximity to the overlying Schoharie Formation contact, the limestone probably belongs to the Edgecliff Member. Large crinoid columnals that are used to define the Onondaga's base have not been found near Stop 3. 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 discussion is that the lower Onondaga in Karst Park is non- to sparsely-cherty and that is where many of the sinkholes occur.

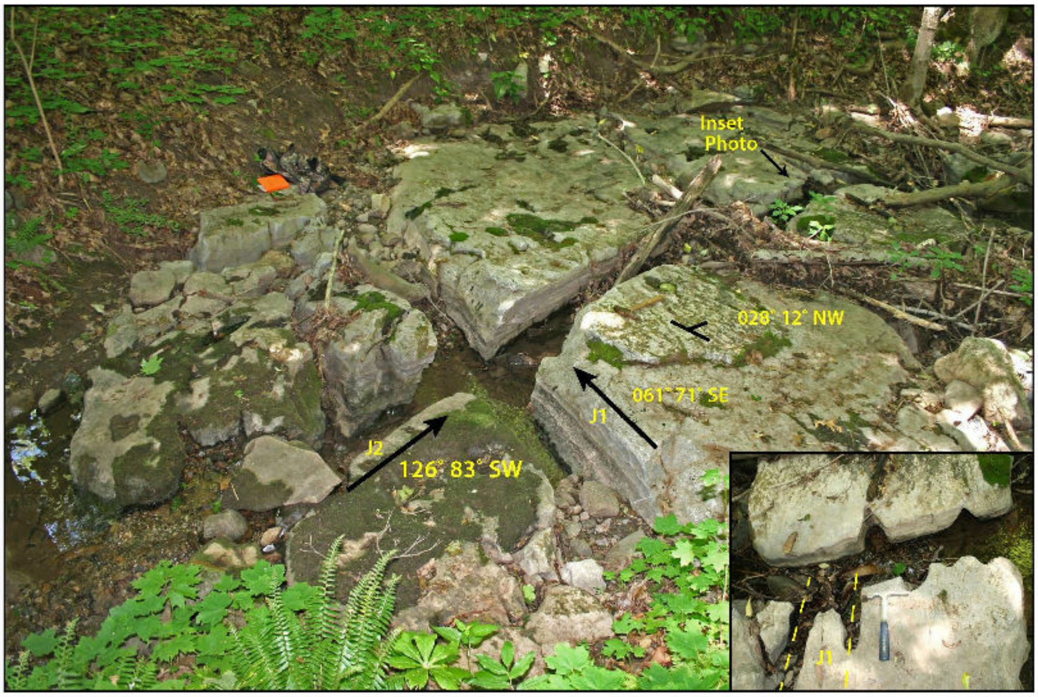


Figure 3.16: Solution joints in the Onondaga Limestone's Edgecliff Member just upstream from a small swallow hole and downstream from culvert 1. Water flows from left to right, rock hammer and fieldbook for scale. Insert photo shows dentate solution weathering along J1 joints. Water flow is right to left with hammer for scale. Photos by R. Witte

As stated previously the systematic joints in the Onondaga generally align along two major trends (fig. 3.2). 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 3b, 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. Solution along joints has resulted in various forms. In most places, joint surfaces are straight-walled to slightly curvilinear. Elsewhere, digitate forms (fig. 3.16) are observed, the result of dissolution along closely-spaced nearly perpendicular joint sets. Also, in a few places, short, narrow openings occur that suggest a distinctive vertical component to dissolution. These trends tend to parallel joint trends. They resemble the extended dissolution of the Onondaga where the stream crosses from the south side to the north side of the stream.

A small swallow hole is found near the base of the cascades, along the stream's south bank below the roots of a small tree (fig 3.17). 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 channel's coarse alluvium. Over the last few years, flow many times has been observed to continue downstream past the bend to Stops 3a-2, 3a-3, and 3a-4 (fig. 3-15). 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.

Figure 3.17: 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.

Head downstream to Stop 3a-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 the 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 of Stop 3-b, small sand dunes as much as 5 feet (2 m) high, cover the east side of the valley.

Location 3a-2 – Creek bed downstream from southwest bend.

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

Discussion – Stream flow to location 3a-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 3a-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. 3-18) 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 stream's left bank at Stop 3a-3.

Figure 3.18: 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 doe 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 swalllow hole. Since swalloe 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.

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 an 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 3a-1. Given the gentle dip of bedding (< 15°), this limestone and outcrops downstream probably belong to the Edgecliff member.

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

Feature - Swallow hole along west bank in collapsed till.

Discussion – The swallow hole (fig. 3.19) 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 February storm of 2016 was severe with runoff heightened by frozen ground and melting snow.

Figure 3.19: 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.

Location 3a-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°, possibly J2) and creek channel (possibly J1) forms the opening to a small cave (fig. 3.20). 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 3a-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.

Figure 3.20: 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.

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. 3-20).

Location 3a-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. 3.21) 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/bedrock 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.

Figure 3.21: 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.

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 3a - 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. 3.22). 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. Like the cave at Stop 3a-4, soil and tree roots form a ceiling. The opening has increased in size four-fold over the period of 2014-2016 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.

Figure 3.22: Sinkhole along right stream bank below culvert 3. Opening is 22 inches (56 cm) wide by 16 inches (41 cm) high. The subsur-face 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 largely caused by the blockage of swallow holes upstream. Photo by R. Witte.

Below culvert 3 (fig. 3.15) 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 (Stop 4).

STOP FOUR: BRAU KETTLE

Location Coordinates: 41.263º N, 74.829º W

Modified from Witte, Monteverde, and Domber, 2016.

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

Features – Brau Kettle (spring and sinkhole)

Brau Kettle is a unique sinkhole-spring located along the eastern edge of the Minisink Valley near the intersection of Jager Road and Old Mine Road in Sandyston Township, New Jersey (fig. 3-2). 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. 4.1) 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 and the small unnamed dry stream we walked past, 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 4.1: 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 flucuate greatly in response to rapid changes in groundwater levels in the shallow karst aquifer. Photos by R. Witte.

Figure 4.2 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 numbers on Figure 4.2) The dashed grey line is the elevation of the base of the 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) The 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) The rate of decline increases once the kettle stops flowing out through the outlet. 5) The kettle is dry while water level in the well continues to decline. 6) The increase in well water levels due to a small precipitation/recharge event, but not high enough to come above base of the kettle. 7) Water level in the well increases and the kettle temporarily fills in response to a precipitation/recharge event. 8) The kettle fills and begins to discharge out through the outlet and water levels in the well increase. 9) Note that water levels follow similar trends, but are at different elevations since the well water level represents a composite water level from multiple zones in the aquifer; whereas the kettle represents only the upper-most zone in the aquifer.

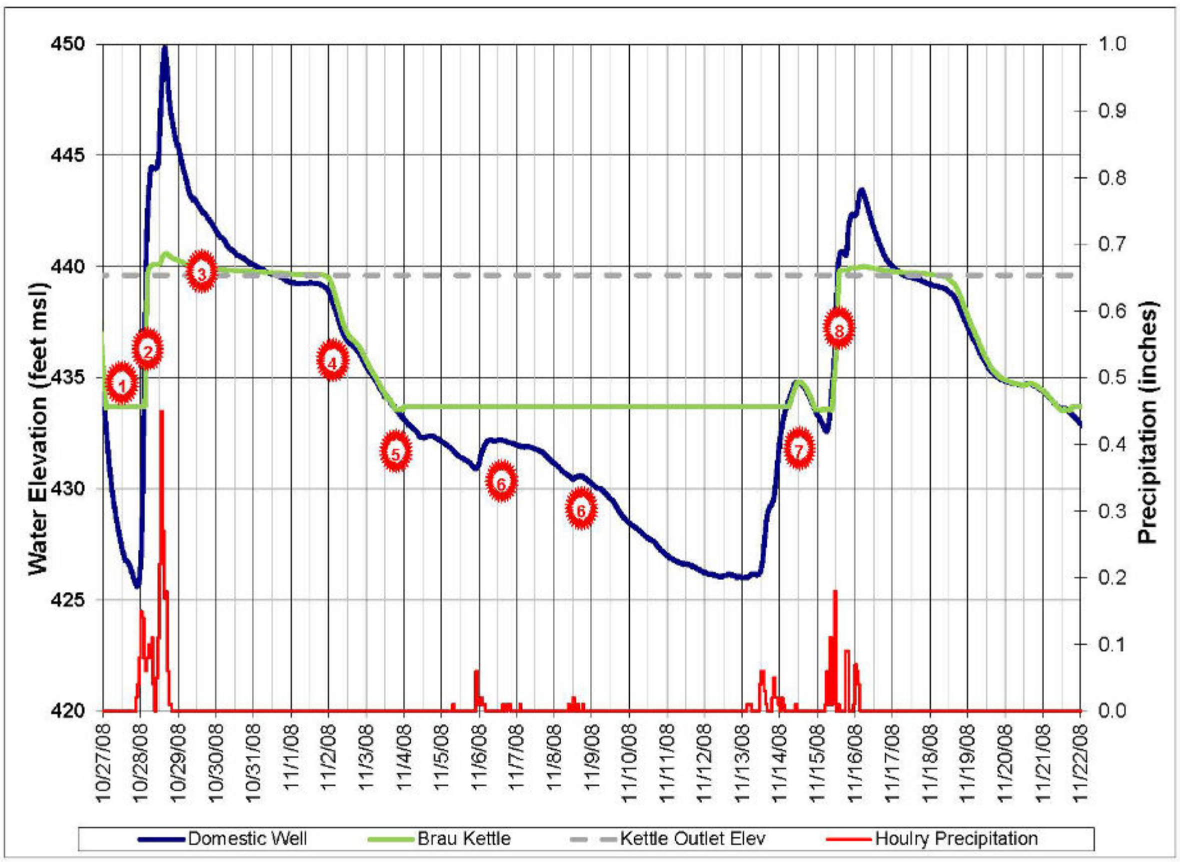


Figure 4.2: Daily water level and precipitation data for Brau Kettle and nearby domestic well at the Anson Johnson House from10/27/2008 to 11/22/2008.

Figure 4.3 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 4.2. Discharge is observed to have occurred in the wetter winter months when evapotranspiration is low and recharge 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 gallons per minute (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.

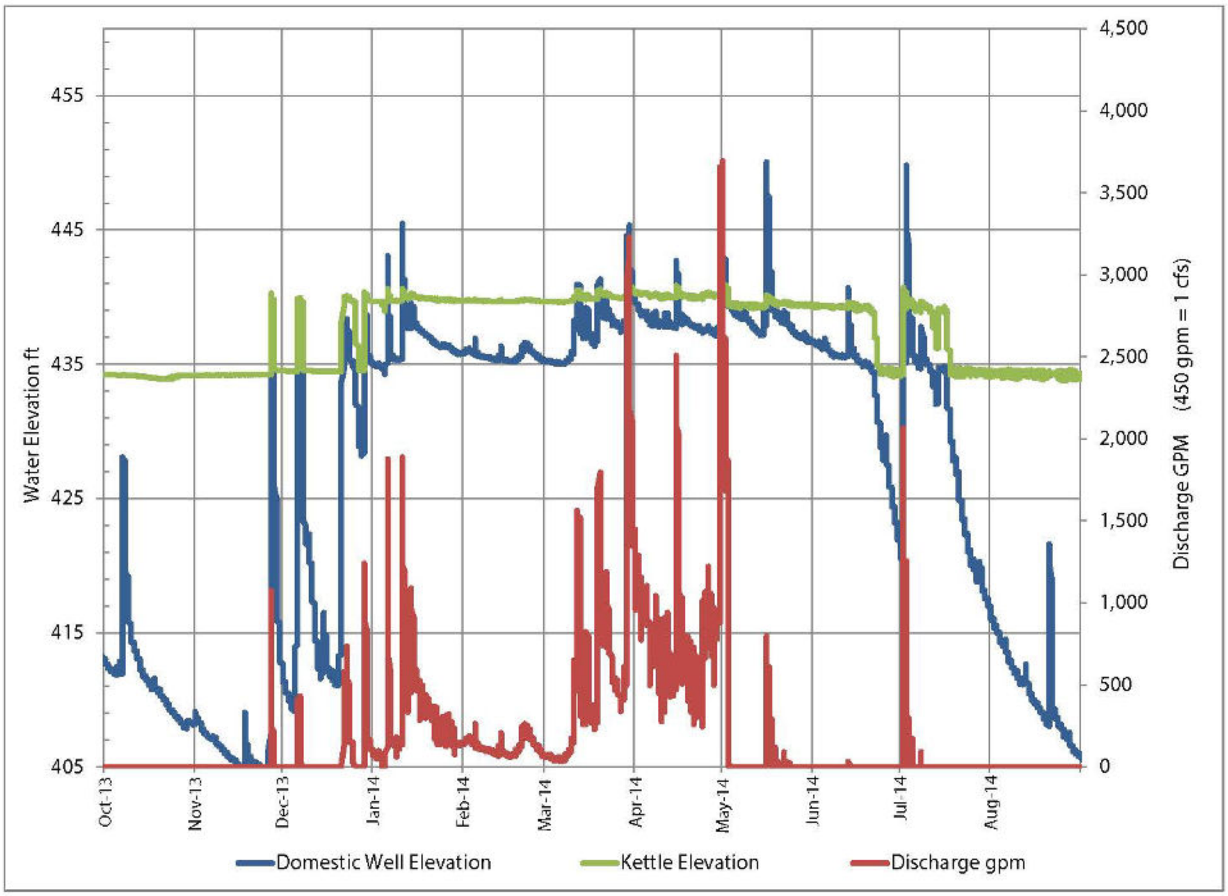


Figure 4.3: Water levels for the Anson Johnson House domestic well and Brau Kettle, and Brau Kettle discharge from October, 2013 to August, 2014.

Finally, because springs may be used to determine the health of the aquifer, floral and faunal studies have been conducted throughout New Jersey. Figure 2-26 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 4.4: 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 B. Henning.

STOP FIVE: OLD MINE ROAD AND OLD DINGMANS ROAD NEAR DINGMANS FERRY

Location Coordinates: 41.22148881332426° N, 74.85580457452018°W

Features: 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.

Modified from Witte, Monteverde, and Domber, 2016.

Location and logistics

Stop 5 is 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. 5.1) is divided into two parts: 5a 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.

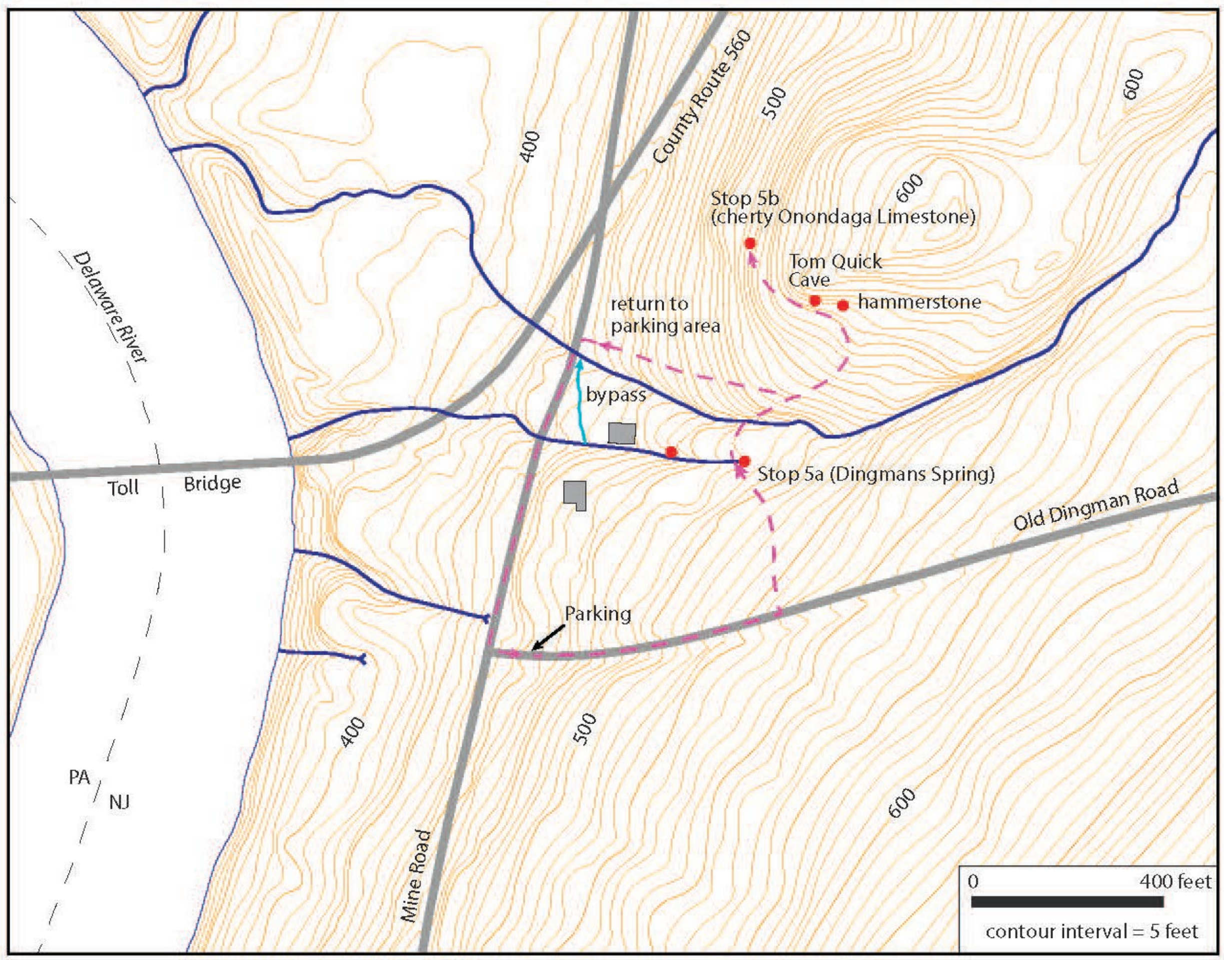


Figure 5.1: Site map of Stop 5 with areas labeled along route (purple-dashed line) and keyed to photographs in Guidebook.

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.

Geologic Setting

The geology is pretty much the same as Stop 3. 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 (as observed at Stop 3-1a) 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 Ron Witte and several more were found nearby along strike.

Stop 5a – Dingmans Ferry Spring (41.220°N, 74.855°W)

Location: Lower slope of Wallpack Ridge.

Discussion – The spring (fig. 5.2) flows out of a large solution joint (070º), and emerges from a large opening at the base of a slope break. From here it spills downstream, cascading over a lag of

Figure 5.2: 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 060°. Photo by Jon Inners.

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. The building ruins below near Old Mine Road (fig. 5.1) and a nearby spring box suggest settlers used the spring for potable water. Evidence of Amerind history in the area (Schrabisch, 1915) suggests the refreshing spring water was enjoyed well before this wild area was settled by colonists. Given the proximity of the spring, cave, and chert resources to each other, this area was probably sacred to the Minsi Lenape that lived along the banks of the Delaware river. The spring outflow has been sampled for chemistry (Table 5.1) by staff at the NJGW staff (Pallis and others, in press)

Table 5.1: Dingman's Ferry Spring			
	Sampling 1	**Sampling 2**	**Sampling 3**
Date	10/18/12 10:45	1/9/13 11:30	4/10/13 11:45
Weather	partly cloudy	cloudy	partly cloudy
Wind	light breeze	light breeze	light breeze
Water Color	brown	grey	brown
Water Clarity	clear	clear	clear
Water odor	no	no	no
Water odor desc.			
Air Temp °C	11.8	-2	24.8
Water Temp °C	11.6	10.3	9.9
pH Stand. Units	7.42	7.25	7.3
Specific Conductance µS/cm	358	351	326
Total Dissolved Solids ppm	179	175	161
Dissolved Oxygen mg/L	8.3	12.5	9.4
Method(s)	Hanna/Probes	Hanna/Probes	Hanna/Probes

Tufa, porous calcium carbonate (fig. 5.3), 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.

Figure 5.3: Moss-covered tufa (porous calcium carbonate) encrusting cobblestone at Dingmans Ferry spring, Delaware Water Gap National Recreation Area. Photo by R. Witte.

The nearby creek bed (fig. 5.1) is at a lower elevation than 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. 5.4). 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.

Figure 5.4: 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 orientaion 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.

Recently, the spring's small stream was diverted to a larger channel (fig. 5.1). 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 the 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 5b (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: 5b-1) possible evidence of Amerind chert utilization; 5b-2) Tom Quick Cave; and 5b-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. 5.1).

Discussion –

5b-1 – Slope below outcrop.

There are many small chert fragments and a quartzite hammerstone (fig. 5.5) 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 LaPorte, personal commun., 1996)). Given the location of this hill overlooking the Delaware River, the proximity to Amerind encampments situated on alluvial terraces near Dingmans Ferry (Schrabisch, 1915), and the 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.

Figure 5.5. 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 accomodate thumbhold and fingerholds. The pointed end of the stone exhibits small impact marks suggesting it may have been used to knap larger pieces of chert into blanks that were later worked into tools and projectile points. Photo by Don Monteverde.

5b-2 – Tom Quick cave.

The cave is a long, narrow slot (fig. 5.6) that runs about 25 feet (8 m) along a large joint (027º). Given the attitude of bedding (043º 12º 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 3b-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 027º fracture.

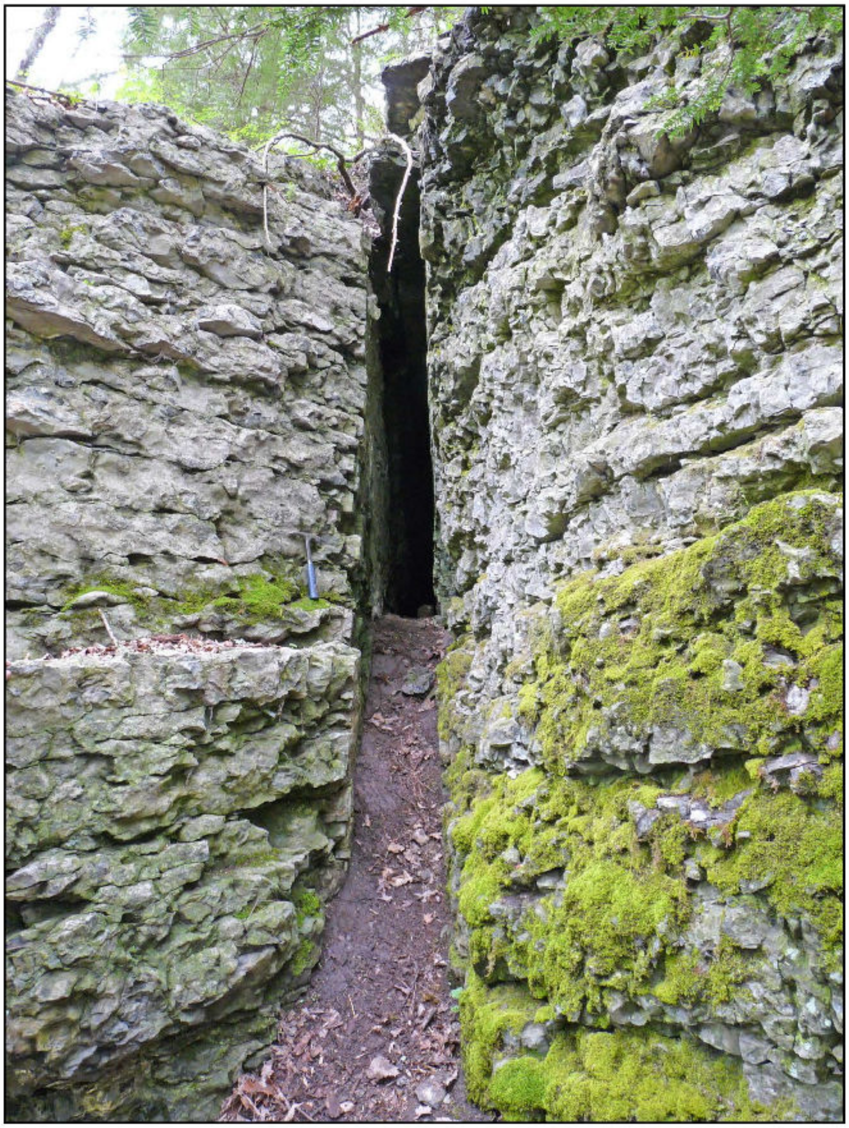


Figure 5.6: Entrance (w = 1.15 ft. (.35 m), ht = 8.2 ft. (2.5 m)) to Tom Quick cave, rock hammer for scale. The cave follows a enlarged vertical joint (027°) about 30 feet (9 m) long. Bedding = (043°, 12° NW). Based on bedding attitude and proximity along a steep slope the cave fracture may have become enlarged by mass movement (downslope creep) rather than solution weathering. Photo by R. Witte.

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.

5b-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 similar 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 5.7). 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 chertification are intriguing, very thin parallel black curving lines that are commonly associated with the mottled spots (fig. 5.7, 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.

Figure 5.7: 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.

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. 5.8) 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.

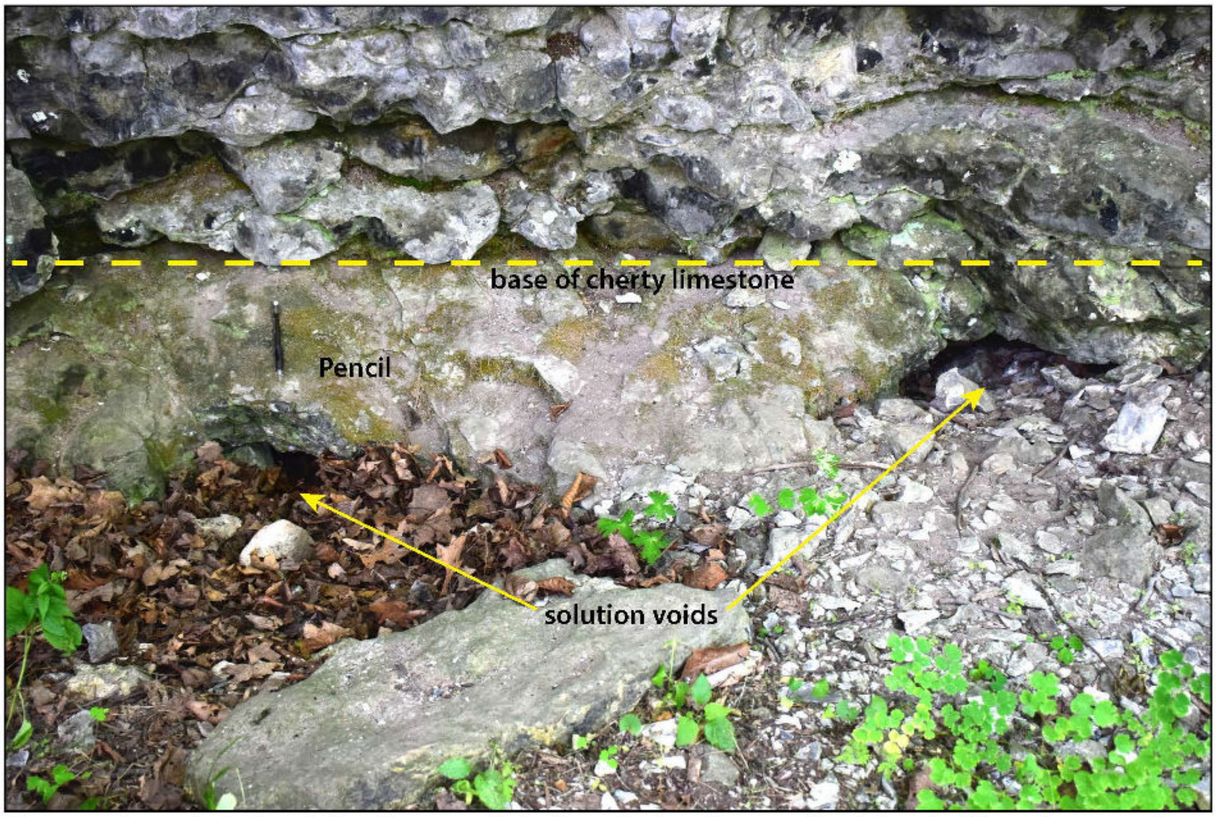


Figure 5.8: Two small solution voids in a limestone-rich bed beneath cherty limestone. Pencil for scale. The voids appear to have formed along a joint (068° 83° SW) - bedding (009° 13° NW) intersection. Photo by Don Monteverde.

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 present or because it may be indistinguishable from the Edgecliff or Moorehouse Members (Oliver, 1956) or because of its shaly nature it does not crop out 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 2a we believe the Seneca lies mostly buried beneath alluvium and glacial outwash making its identification problematic.

Return to the bus which will take the group back to Swartswood State Park.

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