Geology of the Greater Trenton area and its impact on the Capital City

Twenty Seventh Annual Meeting
Geological Association of New Jersey
October 8-9, 2010
Field Guide and Proceedings
Edited by
Pierre Lacombe
U.S. Geological Survey

New Jersey State Museum, Trenton, N.J.

Geological Association of New Jersey Executive Board

Front Cover: Photograph of New Jersey State Capital and Falls of the Delaware at high tide. Photo taken from the flood levee in Morrisville, PA.

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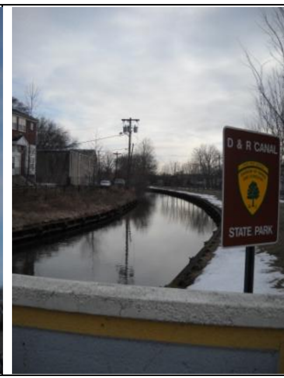

Twenty-Seventh Annual Meeting
of the
Geological Association of New Jersey
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Field Guide and Proceedings

Compiled and Edited by
Pierre Lacombe
U.S. Geological Survey
810 Bear Tavern Road
West Trenton, New Jersey

New Jersey State Museum
Trenton, New Jersey

Thank you to our 2010 Geological Association of New Jersey Conference Sponsors

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The Geological Association of New Jersey is deeply appreciative of the following government agencies, and businesses for providing the time and energy of their expert staff to produce articles and develop fieldtrips for this proceeding.

Pierre Lacombe,
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Julia Barringer

Richard Volkert,
Peter Sugarman,
Steve Spayd

Greg Herman,
Scott Stanford,
Karl Muessig

Richard Hunter,
Ian Burrow

David Parris,
Jay Schwartz

JR Capasso

J Mark Zedepski

Past GANJ and proceedings

First Annual Meeting - 1984
Puffer, John H., ed., 1984, *Igneous Rocks of the Newark Basin: Petrology, Mineralogy, and Ore Deposits, and Guide to Field Trip.*

Second Annual Meeting - 1985*
Talkington, Raymond W., and Epstein, Claude M., eds., 1985, *Geological Investigations of the Coastal Plain of Southern New Jersey: Part 1 - Field Guide; Part 2A - Hydrology and Coastal Plain; Part 2B - Paleontologic Investigations (The set, Parts 1, 2A, 2B, priced as one volume).*

Third Annual Meeting - 1986
Husch, Jonathan, M., and Goldstein, Fredric R., eds., 1986, *Geology of the New Jersey Highlands and Radon in New Jersey.*

Fourth Annual Meeting - 1987*
Gallagher, William B., ed., 1987, *Paleontology and Stratigraphy of the Lower Paleozoic Deposits of the Delaware Water Gap Area.*

Fifth Annual Meeting - 1988
Husch, Jonathan, M., and Hozik, Michael J., eds., 1988, *Geology of the Central Newark Basin.*

Sixth Annual Meeting - 1989*
Grossman, I. G., ed., 1989, *Paleozoic Geology of the Kittatinny Valley and Southwest Highlands N. J.*

Seventh Annual Meeting - 1990
Brown, James O., and Kroll, Richard L., eds., 1990, *Aspects of Groundwater in New Jersey.*

Eighth Annual Meeting - 1991
Crawford, Maria L., and Crawford, William A., eds., 1991, *Evolution and Assembly of the Pennsylvania - Delaware Piedmont.*

Ninth Annual Meeting - 1992
Ashley, Gail M., and Halsey, Susan D., eds., 1992, *Environmental Geology of the Raritan River Basin.*

Tenth Annual Meeting - 1993
Puffer, John H., ed., 1993, *Geologic Traverse Across the Precambrian Rocks of the New Jersey Highlands.*

Eleventh Annual Meeting – 1994
Benimoff, Alan I., ed., 1994, *Geology of Staten Island*, *New York*.

Twelfth Annual Meeting – 1995
Baker, John E. B., ed., 1995, *Contributions of the Paleontology of New Jersey.*

Thirteenth Annual Meeting - 1996
Dalton, Richard F., and Brown, James O., eds., 1996, *Karst Geology of New Jersey and Vicinity.*

Fourteenth Annual Meeting - 1997
Benimoff, Alan I., and Puffer, John H., 1997, *The Economic Geology of Northern New Jersey.*

Fifteenth Annual Meeting – 1998
Puffer, John H., ed., 1998, *The Economic Geology of Central New Jersey.*

Sixteenth Annual Meeting – 1999
Puffer, John H., ed., 1999, *New Jersey Beaches and Coastal Processes from a Geologic and Environmental Perspective.*

Seventeenth Annual Meeting – 2000
Harper, David P. and, Goldstein, Fredric L., eds., 2000, *Glacial Geology of New Jersey.*

Eighteenth Annual Meeting – 2001
Lacombe, Pierre, and Herman, Gregory, eds., 2001, *Geology in Service to Public Health.*

Nineteenth Annual Meeting – 2002
D'Amato, Dana, ed., 2002, *Geology of the Delaware Water Gap Area.*

Twentieth Annual Meeting – 2003
Hozik, Michael J., and Mihalasky, Mark J., eds., 2003, *Periglacial Features of Southern New Jersey.*

Twenty-first Annual Meeting – 2004
Puffer, John H., and Volkert, Richard A, eds., 2004, *Neoproterozoic, Paleozoic, and Mesozoic Intrusive Rocks of Northern New Jersey and Southeastern New York.*

Twenty-second Annual Meeting - 2005
Gates, Alexander E., ed., 2005, *Geology of the Central Newark Basin - The View From the 21st Century.*

Twenty-third Annual Meeting - 2006
Macaoay, Suzanne, and Montgomery, William, ed., *Environmental Geology of the Highlands.*

Twenty-fourth Annual Meeting - 2007
Rainforth, Emma C., ed., 2007, *Contributions to the Paleontology of New Jersey (II)*.

Twenty-fifth Annual Meeting - 2008
Gorring, Matthew L., ed., 2008, *Environmental and Engineering Geology of Northeastern New Jersey.*

Twenty-sixth Annual Meeting – 2009
Freile, Deborah, ed., 2009, *New Jersey Coastal Plain Stratigraphy and Coastal Processes*.

Twenty-seventh Annual Meeting – 2010
Lacombe, Pierre, ed., 2010 Geology of the greater Trenton Area and its Impact on the Capital City

*out of print; available for download only

Copies of all GANJ guidebooks may be purchased from

Greg Herman
New Jersey Geological Survey
P.O. Box 427
Trenton, NJ 08625
Price: $20.00 each (including shipping and handling)
Checks or money orders must be payable to GANJ

PDF files of complete guidebooks are available for download.

Go to www.ganj.org for more information on the availability of download documents.
Price $20.00

The Geological Association of New Jersey Web page is www.ganj.org

With links to many other geologically oriented web pages.

Friday Activities

Friday, October 8th – NJ State Museum Auditorium and Surroundings

<u>Morning Session</u>

9:00-5:00 Registration

9:00-12:00 Self-guided tours of NJ State Museum exhibits, including:
New HiDef Planetarium
Fossil Mysteries; Auditorium Galleries
Pretty Big Things: Story of New Jersey History
Self Guided Tour of Old Trenton Barracks, including
Exhibit on French and Indian War (fee required)
Tour of NJ State Capital Building (Free, ID required)
Self Guided tour of new World War II Memoral Plaza showing influnce of
NJ industry and laborers in support of the War effort, (free)

10:00-11:00 Teacher Workshop – **Jay Schwartz,** Planetarium Director,
Planetarium Presentation of <u>Extreme Planets</u>. With live talk on N.J.s October sky, and of the upcoming lunar eclipse for Dec. 21, 2010 from 1:32 AM to 5:02 AM.

11:00-12:00 Tours of the Inner Workings of NJ Museum, **David Parris,** State Museum Curator, Limited to 15 people per tour; 2 to 3 tours of about 20 minutes each, will bring you on a tour to see the New Jersey archives of natural history, including rock, mineral, fossil, and archeological collections.

12:00-1:00 Lunch on your own. There is the Café NJ in the nearby Capital building and many restaurants at the intersection of West State (the road the museum is on) and South Warren Streets (approximately 10 minute walk).

Friday, October 8th – NJ State Museum Auditorium

Afternoon session

1:00-1:20 **Welcoming Remarks**/Conference Overview –
Pierre Lacombe, U.S. Geological Survey, GANJ President

1:20-1:40 **Geologic overview of the Metamorphic rocks of the Trenton Prong, West Central, New Jersey**
Richard Volkert, N.J. Geological Survey

1:40-2:00 **Geology, Iron, Steel and the Archeological of Petty's Run** –
Ian C. Burrow, Ph.D., Hunter Research, Inc.

2:00-2:20 **Brownstone Quarrying Industry in the Wilburtha District and City of Trenton, Mercer County** –
J. Mark Zdepski, JMZ Geology

2:20-2:40 **Overview of Trenton Brownfields Program** –
J.R. Capasso, City of Trenton

2:40-3:00 **Break**

3:00-3:20 **Trenton as a Transportation Nexus and Seat of Hydropower** –
Richard W. Hunter, Ph.D., Hunter Research, Inc.

3:20-3:40 **Possible Investigations of the Hydrogeology of the Lockatong Formation**
Pierre Lacombe, U.S. Geological Survey

3:40-4:00 **Geological sources of radionuclides and arsenic in Triassic age rift-valley sediments (Newark Supergroup) and in Mercer County, New Jersey, and implications for distribution in ground water**
Zoltan Szabo[1], Julia L. Barringer[1], and Steve Spayd[2]
[1] U.S. Geological Survey, [2] N.J. Geological Survey

4:00-4:20 **Geology of the Pennington Trap Rock (Diabase) Quarry, Rt. 31 South, Mercer County**
Gregory C. Herman, John H Dooley, and Larry F Mueller, NJ Geological Survey

4:20-4:40 **Overview of the NJ State Museum Education Programs**
Kenneth Jones, David Parris, New Jersey State Museum

5:00-6:00 **<u>Keynote Speaker</u>** –
Karl Muessig, Ph.D., New Jersey State Geologist, N.J. Geological Survey
175 years of history and achievements of the New Jersey Geological Survey'

6:30 **Dinner and Business Meeting** – Joe's Mill Hill Saloon,
Corner of South Broad and Market Street, Trenton, New Jersey

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Saturday October 9 2010

8:00 AM Field trip will Start and Finish at Old Trenton Barracks on Barracks Street Located one block from Museum

Parking is available in: State Parking Garage (ID needed) (free) and Trenton War Memorial Theater parking lots (free).

Chapter 1

Introduction

The 27th annual meeting of the Geological Association of New Jersey (GANJ) describes the basic geology including location, rock types, and ages of the major geologic formations that underlie the greater Trenton City and Mercer County area of central New Jersey (fig. 1, 2 and 3). The geology includes the basic rock types: metamorphic, sedimentary, igneous, and unconsolidated sediments.

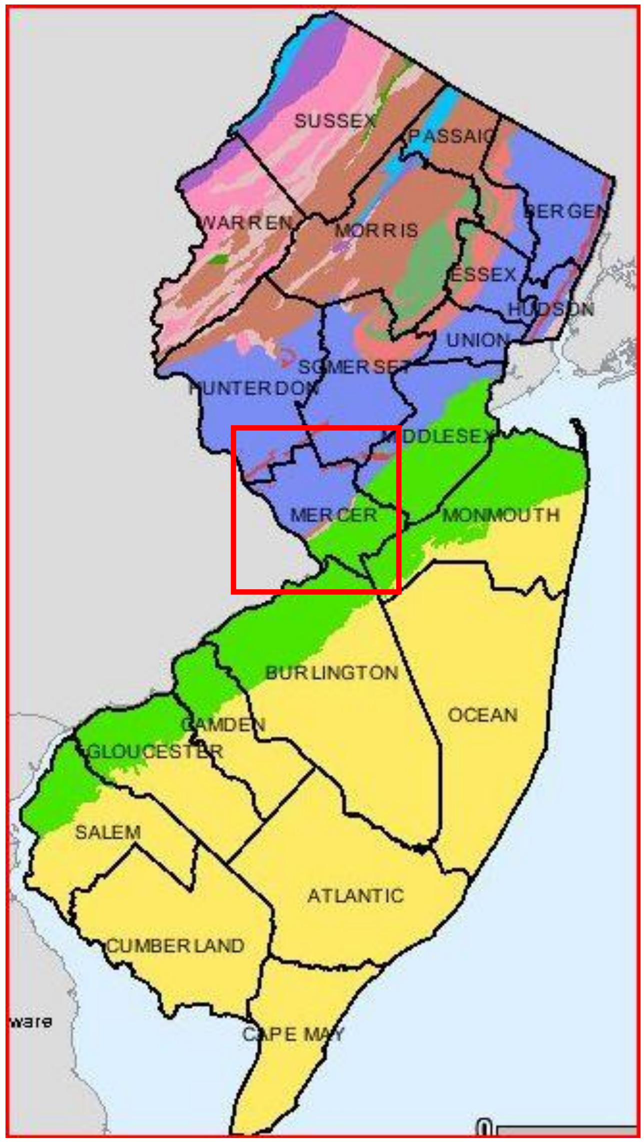


Figure 1. Geologic map of New Jersey showing the location area of this year's proceedings

In addition to the basic geology, the theme of this year's GANJ meeting is to recognize the impact and influence that geology has had on how human use the rocks for commercial, residential, military, transportation, agricultural, and recreational purposes for the past 5,000 years and how it will continue to influence land use in the future.

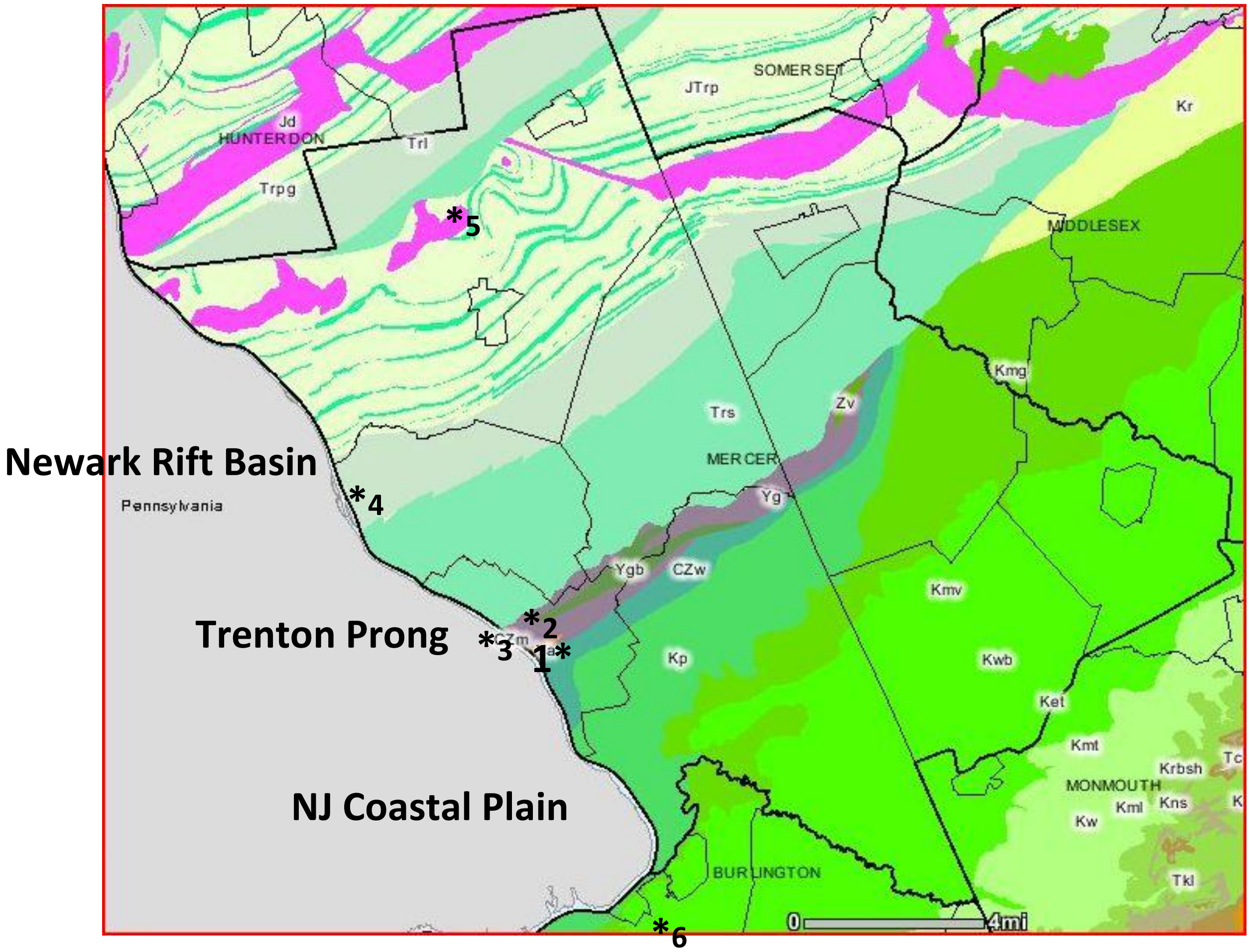


Figure 2. Geologic map of Mercer County showing stops for Saturday field trip (from I-MapNJ accessed August 1, 2010)

Cretaceous	Ket	Englishtown Formation	NJ Coastal Plain
	Kwb	Woodbury Formation	
	Kmv	Merchantville Formation	
	Kmg	Magothy Formation	
	Kp	Potomac Group	
Jurassic	Jd	Jurassic diabase	Newark Rift Basin
Triassic	Jtrp	Passaic Formation	
	Trpg	Passaic Formation, graybed	
	Trl	Lockatong Formation	
	Trs	Stockton Formation	
Cambrian	Czm	Manhattan Schist	Trenton Prong
	Czw	Wissohickon Schist	
Precambrian	Ya	Amphibolite	
	Yg	Gneiss granofels and Migmatite	

Ygb Gabbro

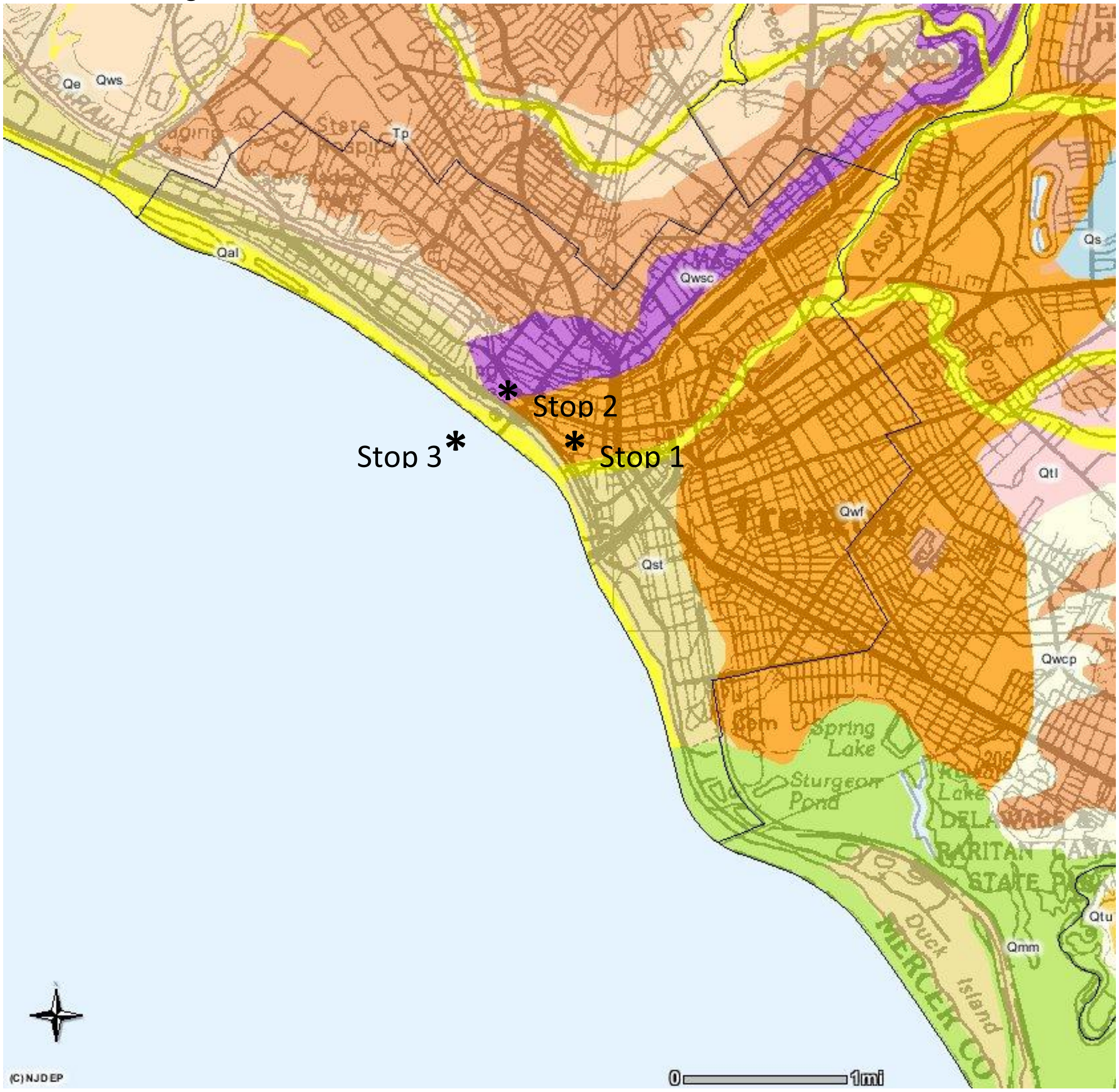


Figure 3. Overburden geologic map of Trenton showing stops for Saturday field trip (from I-MapNJ accessed, 2010)

		Qwf	Late Wisconsin glacial fluvial deposit
Qal	Alluvium	Qst	Post glacial stream terrace deposits
Qe	Eolian	Qwcp	Weathered Coastal Plain Fm
Qmm	Salt marsh and estuarine deposits	Qws	Weathered Shale and sandstone
Qtl	Lower stream terrace deposits	Qwsc	Weathered Schist and gneiss
Qtu	Upper stream terrace deposits	Tp	Pennsauken formation

I would also like to convey a minor but impart feature of the formations of the Trenton area. The feature is the multiple cycles or sequences of erosion, deposition, burial, lithification, intrusion, and uplift which reused the same material with each cycle. The first cycle's duration was the late Proterozoic/early Paleozoic; the second cycle's duration was the late Triassic/Jurassic, and the third cycle duration was the Cretaceous. The forth cycle includes the glacial outwash of the Pleistocene.

The Geologic time scale (Table 1) highlights rock units of the greater Trenton area, and describes the source and fate of each unit

Table 1 Four major rock groups of the Trenton Area (Trenton Prong rock ages, tentative)

ERA	Period	Epoch	began in million years before present	Rock units	Major events in the Trenton Area
Cenozoic	Quaternary	Recent	0.01	Fill and alluvium	Humans mine, till, and otherwise transport sediment as well as erode hill tops.
		Pleistocene	2	Trenton Gravel Qtl, Qtf, Qwf, Qst	Glaciers form multiple times and extend from central Canada to about 40 miles north of Trenton. Trenton has permafrost, and heavy winds. As glaciers melt, Delaware River floods with 10 to 100 times more water than of the Recent epoch. Massive boulders, gravel, and sand are deposed in Trenton area.
	Tertiary		65		
Mesozoic	Cretaceous		136	Merchantville Fm Kmv Woodbury Fm Kwb Magothy Fm Kmg Raritan Fm Kr Potomac Fm Kp	Atlantic Ocean continues to open. Newark Basin and other areas northwest of Trenton rise and erode. Sediment is deposited in proto Atlantic in Bordentown area.
	Jurassic		190	diabase Jd	Rift basin opens south east of Trenton. Igneous rocks intrude between around Pennington
	Triassic		225	Passaic Fm JTrp Lockatong Fm Trl Stockton Fm Trs	Newark Basin forms as Atlantic Ocean opens. Sediment eroded from Mountains and hills in the Trenton and more southeasterly area are deposited in the rift basin
Paleozoic	Permian		280		Mountains of Trenton area are eroded. Sediment is deposited in central PA area
	Pennsylvanian		325		
	Mississippian		345		Acadian Orogeny forming Pangaea
	Devonian		395		Mountains of Trenton area are eroded. Sediment is deposited in central PA area
	Silurian		430		
	Ordovician		500	Whissahickon Fm Czw*	Taconian Orogeny Mountains west of Trenton erode mud, sand, clay, silt and lime deposited in deeper water
	Cambrian		570	Chickies Fm Cc	
PreCambrian	Neo- & Meso-proterozoic		1000	gneiss, Yg* Manhatten Schist CZm*, gabbro Ygb*	Mountains west of Trenton erode. sand and gravel deposited in shore line of Iapetus Ocean

* ages of these units are modified in Volkert's report

The oldest strata in Trenton were sand and mud that were deposited, lithified, and intruded during the pre-Cambrian/ early Paleozoic. There source was likely from the North American craton. The lithified sediments were metamorphosed during orogenies of the Paleozoic when the Baltica and North America Cratons collided to form the mega continent of Pangaea. During the Triassic, the metamorphic rocks eroded and were transported northward filling the newly forming Newark Rift basin located in the middle of Pangaea. The gravel, sand, and mud of the Newark basin were buried lithified and then intruded during the Jurassic. The Paleozoic, Triassic, and Jurassic age rocks eroded and transported southeastward to from the New Jersey Coastal Plain. In the last 20,000 years, the glaciers of North America stopped moving southward about 35 miles north of Trenton. As the glaciers melted, massive volumes of water mud gravel and boulders cascaded southward to inundate Trenton leaving behind a veneer of water warn clasts.

The age of the rocks spans about 500 Million years (table 1). The rocks of downtown Trenton and the Fall of the Delaware are the oldest and the delta at the mouth of Crosswicks Creek is being deposited today.

Metamorphic rocks form the rapids and falls of Trenton and were deposited during late Precambrian and early Paleozoic. Sedimentary rocks underlying Ewing and Hopewell were deposited during the Triassic. Igneous rocks that form Baldpate Mountain, Belle Mountain and Bowman Hill (PA) were intruded as magma during the Jurassic. Unconsolidated sediments consisting of gravel, sand, silt and clay, underlie Hamilton, Bordentown and all areas south of Trenton were deposited during the Cretaceous and Cenozoic. Most of the landscape in the greater Trenton area is covered by a veneer of Pleistocene glacial outwash and consist of boulders, cobbles, and sand to clay size sediments.

Pangaea rifted less than 10 miles northwest of Trenton during the middle Triassic to form the Newark Basin. Initially the Newark Basin was filled with gravel and sand and can be seen in outcrops in southern Ewing Township but latter the deposits were mostly sand, silt, and clay as are seen in northern Ewing and Titusville.

Pangaea continued to rift during the Jurassic. The rifting caused magma to flow onto land surface near NYC and formed the Palisades east of New York City. In Hopewell area the magma never reached land surface and solidified underground. Belle Mountain and the quarries south of Lambertville and north of Pennington are the cooled magma.

The center of rifting moved southeast of the Trenton area a few hundred miles forming the proto-Atlantic Ocean. With the continual rifting and widening of the Atlantic Ocean during the Cenozoic, the metamorphic rocks of Trenton, the sedimentary rocks of the Newark Basin, and rocks from north and west of the Newark basin eroded and were deposited along the shore of the expanding Atlantic Ocean. The deep bedrock valleys that underlie the sediments in the Bordentown area are the former river basins of the metamorphic rock. Sediments that fill the bedrock valleys and make up the Coastal Plain consist of sand, silt, and clay that were derived from the rock of Trenton and more northerly areas.

During the Pleistocene the southern end of the continental glaciers were only 40 miles north of Trenton. Katabatic winds were blowing southward off of the 1000 miles broad ice sheet. The wind would have been constant, hard, cold, and dry. Global warming began. The glaciers started to recede and melt water flowed from the glaciers to carry boulders, cobbles, gravel, sand, silt, and clay from the north. These deposits form a veneer over all the older sediments of the greater Trenton area.

The second concept of this conference is how the geology of the greater Trenton area has controlled its cultural, industrial, commercial, agricultural, artistic, military and economic development.

Stone-age Indians of 5,000 years ago mined quartzite in Trenton NJ and Morrisville PA for points; clay from outcrops along Crosswicks Creek and the Delaware River for pottery; pebbles of different rock types from river gravel deposits for fishnet anchors, grain grinding, and food cooking stone. Indians built communities on sandy strata or upland areas because of drainage issues and develop farm fields on the fecundant sediments.

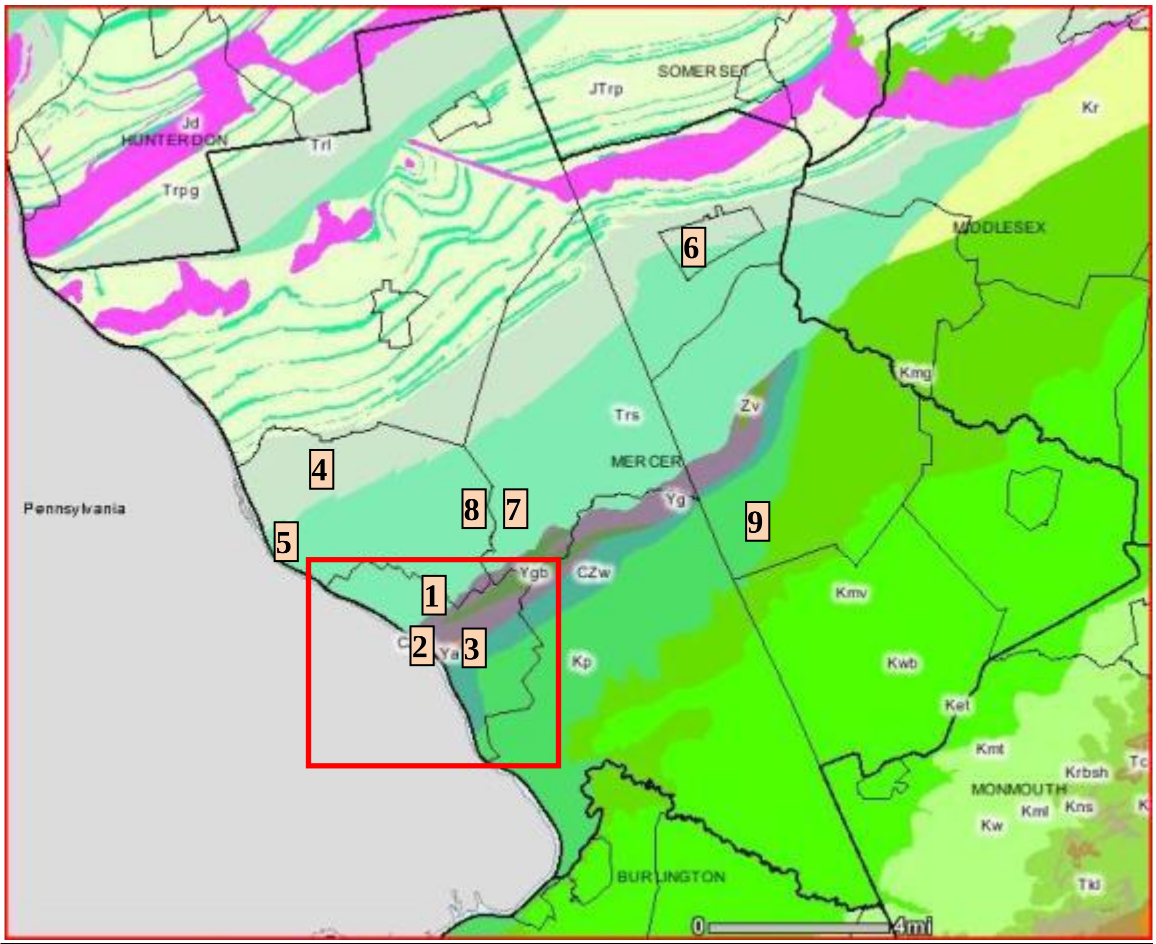
European settlers in the 1600 and 1700s followed in the Indians footsteps mining of clay for pottery but expanded the mining of clay and sand for bricks. Early Europeans expanded the Indian mortar and pestle for corn grinding with grist mills and Indian stone adz with hydromechanical saw mills. Iron ore mined from areas 40 miles upstream from Trenton was brought to Trenton and converted to steel to replace pottery cooking vessels and stone tools. Early settlers built roads along Indian trails but enhanced them with stone, wood, or steel bridges and ferry crossing. Farm fields of European immigrants replaced the farm fields of the Lenape. Hamlets, villages, and cities were established on upland area that remained dry after rains much like their predecessors.

After the American Revolution, Trenton was in the forefront of the Industrial Revolution. During the 1800 and 1900, the geology of the Trenton area continued to influence it development. Major brick yards were close to the Coastal Plain clays. Steel mills and pottery mills first used water power then Pennsylvania coal power the machines. Anvils, I-beams, gun-barrels, torpedo bombers, submarine compressors, Mercer Automobile, American Brand Toilettes, Lenox China, rubber tires, parachutes, air conditioners Homosote, wire rope for Otis elevator and the Golden Gate Bridge were made in Trenton. With the growth of America, Trenton made nearly everything. What Trenton made the world took.

Geology will continue to plays a pivotal role in the future of the greater Trenton area. Diabase mines will provide durable rock for buildings and transportation. Coastal Plain clay and sand mines with continue providing the raw material for brick, blocks and road bed material, Coastal Plain clay strata will continue be the underlayment for the landfills. Geologic engineers will use the local geology to design and build two new bridges over the Delaware River Geologist and hydrologist will continue to evaluate and remediate contamination problem of the Industrial Revolution and of the indigenous rocks. Colleges and universities will continue to educate students in the growing field of geology and hydrogeology State, Federal, and Industrial geologic researchers will develop new and modify past method of investigating the geology of Trenton and the world.

Chapter 2

Institutions of Geology and Geologic Education in the Greater Trenton Area



Geologic Map of greater Trenton and locations of Institutions
(from I-MapNJ accessed August 1, 2010)

Institutions that Study New Jersey Geology in Greater Trenton area

1 New Jersey Geological Survey
2 New Jersey State Museum
3 New Jersey Department of Environmental Protection
4 U.S. Geological Survey
5 Delaware River Basin Commission
6 Princeton University
7 Rider University
8 The College of New Jersey
9 Mercer County Community College

1) New Jersey Geological Survey (NJGS)

Arctic Parkway, Trenton, New Jersey

NJ Geological Survey maintains a staff of about 35 geologists, technicians, and administrators. The NJGS is a public service and research agency within the NJ Department of Environmental Protection.

Founded in 1835, the NJGS is one of the oldest state geological Surveys in the United States. New Jersey became the first state to publish a topographic map. Subsequent cooperation with the U.S Geological Survey resulted in complete topographic coverage of the entire state, another "first" in the nation.

The Survey has evolved from a mineral resources and topographic mapping agency to a modern environmental organization that collects and provides geoscience information to government, consultants, industry, environmental groups, and the public. The NJGS web page provides access to much of this information.

The mission of the Survey is to map, research, interpret and provide scientific information regarding the state's geology and ground water resources. This information supports the regulatory and planning functions of NJ DEP and other governmental agencies and provides the business community and public with the information necessary to address environmental concerns and make economic decisions.

2) New Jersey State Museum

East State Street, Trenton, New Jersey

The NJ State Museum was officially established in 1895 by the NJ legislature. However, collections of natural history objects predate the Museum by at least 50 years. The NJ Geological Survey's collection of rocks and minerals, important for economic development of New Jersey, in addition to their fossil collections, provide the initial core of the Natural History collection of the Museum. The assemblage of natural history objects from the following entities are incorporated into the museum: 1893 World's Columbian Exposition in Chicago, Louisiana Purchase Exposition, southern New Jersey greensand marl mines, Burlington Lyceum, Ellisdale Dinosaur Site, Natural History Museum of Princeton University and many other sources.

In 1964, when the Museum began operations in its current building, a planetarium was opened, and educational services expanded to include astronomy and space exploration.

The NJ State Museum maintains a staff of about 25 and is a division within the NJ Department of State.

Fossil exhibit at the NJ State Museum

3) New Jersey Department of Environmental Protection (NJ DEP)

401 East State Street, Trenton

On America's first official "Earth Day" — April 22, 1970, the New Jersey Department of Environmental Protection was born. New Jersey became the third state in the country to consolidate its past programs into a unified major agency to administer aggressive environmental protection and conservation efforts. Former Governor William T. Cahill appointed Richard J. Sullivan as the first commissioner.

Since that day, NJDEP began a role to manage natural resources and solve pollution problems. In what started with about 1,400 employees in five divisions, NJDEP now has a staff of approximately 2,900 and is a leader in the country for its pollution prevention efforts and innovative environmental management strategies.

4) US Geological Survey (USGS)

USGS Water Science Center, 810 Bear Tavern Road, West Trenton NJ,

Created by an act of Congress in 1879, the USGS has evolved over the ensuing 125 years, matching its talent and knowledge to the progress of science and technology. Today, the USGS stands as the sole science agency for the Department of the Interior. It is sought out by thousands of partners and customers for its natural science expertise and its vast earth and biological data holdings. The USGS is the science provider of choice in accessing the information and understanding to help resolve complex natural resource problems across the Nation and around the world.

The New Jersey Water Science Center staff is composed of about 85 professional scientists, technicians, and support personnel who are committed to providing accurate and timely natural-resource information to New Jersey and the Nation. By integrating our diverse scientific expertise, we work in cooperation with the NJDEP and NJGS to analyze and understand complex hydrogeologic systems and excel in:

Operating and maintaining state-wide groundwater level, stream discharge, and water quality data-collection networks

Investigating a suite of ground-water and surface water issues in cooperation with Federal, State, and local agencies

5) Delaware River Basin Commission (DRBC)

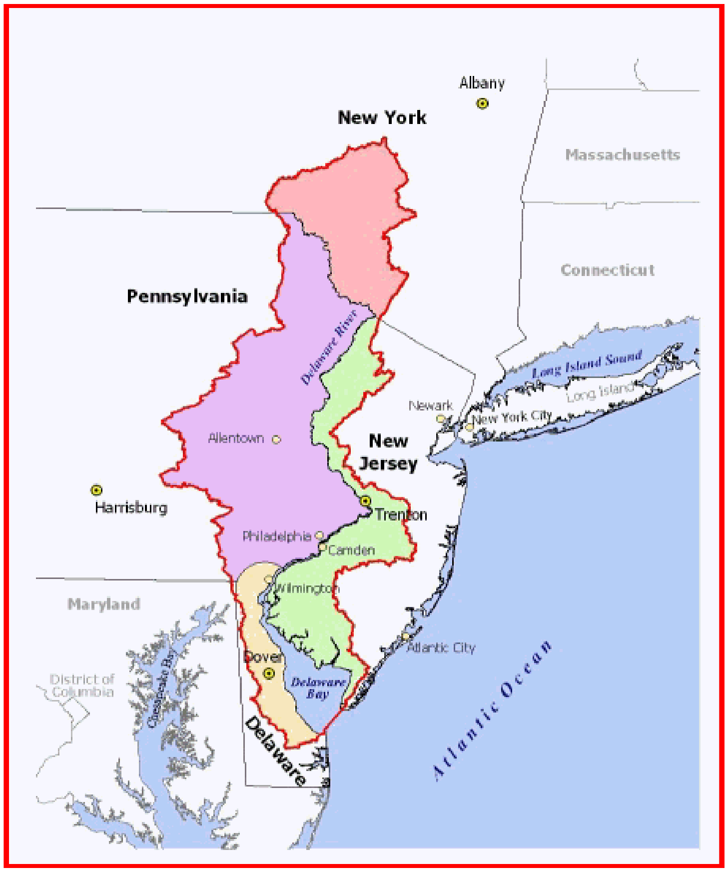
25 State Police Drive West Trenton NJ

Unified water resource management of the Delaware River Basin began in 1961 when President Kennedy and the governors of Delaware, New Jersey, Pennsylvania, and New York signed legislation creating the Delaware River Basin Commission, a regional body to oversee management of the water within the basin without regard to political boundaries. Formation of the DRBC marked the first time since the nation's birth that the federal government and a group of states joined together as equal partners in a river basin planning, development and regulatory agency.

Commission programs include water quality protection, water supply allocation, regulatory review (permitting), water conservation initiatives, watershed planning, drought management, flood loss reduction, and recreation.

The DRBC maintains a staff of about 45 scientist, technicians, and administrative personnel. Activities of the DRBC include monitoring the withdrawal and discharge of surface water for public supply and industry in the Delaware River Basin.

The Delaware River is the longest un-dammed river east of the Mississippi, extending 330 miles from the confluence of its East and West branches at Hancock, N.Y. to the mouth of the Delaware Bay where it meets the Atlantic Ocean. The river is fed by 216 tributaries, the largest being the Schuylkill and Lehigh Rivers in Pennsylvania. The Delaware River Basin contains 13,539 square miles, draining parts of Pennsylvania (6,422 square miles or 50.3 percent of the basin's total land area); New Jersey (2,969 square miles, or 23.3%); New York (2,362 square miles, 18.5%); and Delaware (1,004 square miles, 7.9%). Included in the total area number is the 782 square-mile Delaware Bay, which lies roughly half in New Jersey and half in Delaware.



Delaware River Basin area.

6) Princeton University

Princeton NJ

Princeton's Department of Geosciences covers a wide range of fields and actively promotes interdisciplinary study and research. Students with an interest in structural geology, tectonics and geophysics, geochemistry, petrology, mineral physics, geochemistry, biological oceanography, paleontology, paleoceanography, paleoclimate and environmental geology will find most of their research and educational needs. Princeton University reports 23 faculty, 36 staff, and 33 students in the field of geology in 2010

In addition the Geosciences Department has associated programs in water resources (shared with Civil Engineering), materials science (in collaboration with the Princeton Institute for the Science and Technology of Materials) and environmental science .

The department of geoscientific studies at Princeton University dates from 1854, when Arnold Guyot was appointed as Professor of Geography and Physical Geology. Despite the growth of geological and paleontological studies at Princeton in the mid- to late 1800s, there were no formally discrete departments or sections in geosciences until the early 1880's when concentrations in "Physical Geography" and "Geological Paleontology" were introduced.

Arnold Henri Guyot - 1807-1884

Stone carvings on Geology building at Princeton

The stone carvings (above) adorning the exterior of the Guyot Geology building (below) and are thought to have been the work of the studio of Gutzon Borglum, the sculptor who created the presidential effigies of Mt. Rushmore. Guyot Hall hosts the greatest number of the educational gargoyles on campus -more than sixty-five and include: trilobite, ammonite, horseshoe crab, giant scallop, ram, elephant, rhinoceros, eagle, wild boar, pelican, frog, turtle, sea horse and pterodactyl.

Guyot Hall Built: 1909

Princeton's geology department has art legacy paintings on pre-historic life by the British naturalist-artist Benjamin Waterhouse Hawkins (above) and Charles Knight (below). Both collections are housed in the Princeton University Art Museum.

Cretaceous Life of New Jersey (PP336)

7) Rider University

Route 206, Lawrenceville

Rider University's Department of Geological, Environmental, and Marine Sciences (GEMS) prepares students for future Earth-related careers and graduate studies, the GEMS faculty ensures students, are knowledgeable to meet the needs of private companies, public agencies that may employ them, and the graduate or professional schools they may attend.

Rider Geology Department has 6 professors and 4 adjunct professors

8) College of New Jersey

Route 31 Lawrenceville

The College of New Jersey does not have a geoscience program per se however The science program at the university recently received a $200,000 grant from the National Science Foundation (NSF) to support the creation of curricular materials that foster hands-on and active engagement with cutting-edge research and authentic data in seismology.

9) Mercer County Community College

Mercer County Community College offers a wide range of courses with introductory geology and earth science courses intended to stimulate the two year student.

NJ State Legislature and Geology

The NJ Capital building houses the State Legislature. This is the second longest used building for State government in the nation. The foundation of the 1792 part of the Capital building is local metamorphic rock (?) that has been white washed. The foundations of the additions to the Capital building are Stockton Sandstone. Princeton was the National capital in 1783. Trenton was the National capital in 1784.

Among the many governmental tasks the legislature deals with include overseeing the declaration that the world's first nearly complete dinosaur skeleton that was uncovered in a farmers pit in 1858, Hadrosaurus *foulkii*, became the official state dinosaur in 1991.

New Jersey has an official state animal, a state flower, even a state dance, but it does not have an official state mineral. In order to become "official", the State Legislature has to adopt the item and sign documentation to acknowledge such recognition. For many years now, geologists and non-professional "Rock Hounds" around the state have argued over which mineral should be considered the "state mineral". The choices have been narrowed to:

Franklinite with a chemical formula of $(Zn, Mn_2+,Fe_2+)(Fe_3+,Mn_3+)_2O_4$, a specific gravity of 5.0-5.2, and a hardness of 6 and

Prehnite with a chemical formula of $Ca_2Al(AlSi_3O_{10})(OH)_2$, a specific gravity of 2.9+, and a hardness of 6-6.5,

	
Franklinite	Prehnite

Franklinite discovered in, and named after, the town of Franklin, New Jersey, Franklinite, is found in great abundance in the northwest part of the state, but is very rare in other parts of the world. Franklinite, which contains zinc, iron, and manganese, was mined in great quantity from colonial times up till the early 20th century. Franklinite is dark black, has a reddish brown streak and a metallic luster. It is found in massive, granular and, occasionally, in crystallized forms. The crystal system is cubic (isometric) and the mineral is slightly magnetic. Specimens are still collected at Franklin and Sterling Hill.

Prehnite discovered at the Cape of Good Hope, South Africa, by Colonel Hendrik Von Prehn. Colonel Prehn became the first person to ever have a mineral named after him. Prehnite contains calcium and aluminum and forms as a result of low grade metamorphism usually from hydrothermal solutions. The crystals are often found as thick crusts within cavities of igneous rocks. Prehnite is usually a translucent light green, but can be grey, white or colorless. The streak is white, and the luster is vitreous to waxy or pearly. The orthorhombic crystals are brittle and fracture unevenly. Prehnite is found in many locations around the world, with notable occurrences in Connecticut, Pennsylvania, Virginia, and Patterson, New Jersey.

Brownstone, Although the legislature is working diligently on many important issues, brownstone has not yet officially recognized as the state rock. Brownstone was used as a building stone in thousands of houses, apartments, churches, libraries, bridges, and train stations built in the northeastern United States between the early 1700's and about 1900. New Jersey was the nation's most important producer of brownstone and supplied most of the material used in New Jersey, New York, and Philadelphia.

Earthquakes in Mercer County

The USGS reports only two earthquake in Mercer County

ID	Quad	Date	Time	Lat	Long	depth	Magnitude	location
13	Trenton E	1/25/1933	2:00	40.2	74.7	0	2.8	near Trenton
22	Hopewell	10/16/1949	23:33	40.400	74.800	0	3.2	Hopewell

Floods of the Delaware River in Trenton in Mercer County

The Delaware River experienced three major floods in 2003-04. Peak flow of 201,000 ft^3/s was measured on September 19 2004 at 2045 hours. The peak discharge recorded for the 2004 flood was 128,000 ft^3/s less than the peak flow for the period of record on August 20th, 1955. The peak gage height recorded for this flood was 23.39 ft, 5.21 ft less the previous record of 28.60 ft set on August 20, 1955.

USGS hydrologic technicians made discharge measurements on September 19th and 20th at Delaware River at Trenton, N.J. were the highest flows ever measured aat these site. The direct discharge measurements were made with a Price AA meter suspended from a bridge crane with a 150 pound weight. The discharge measurement made from the Calhoun Street Bridge just downstream from the Trenton gaging station on September 20th, after the river peaked, measured 147,000 ft^3/s.

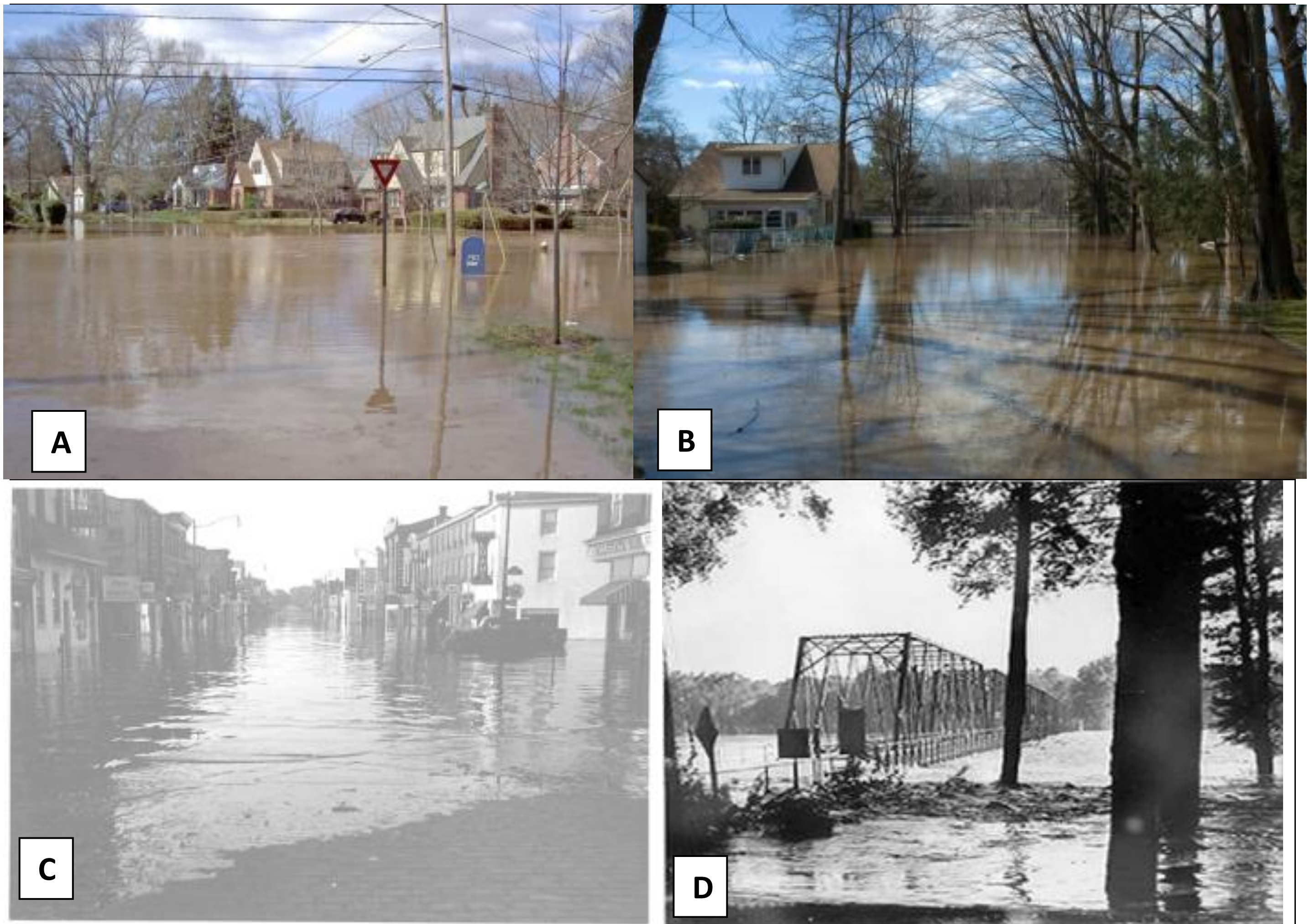
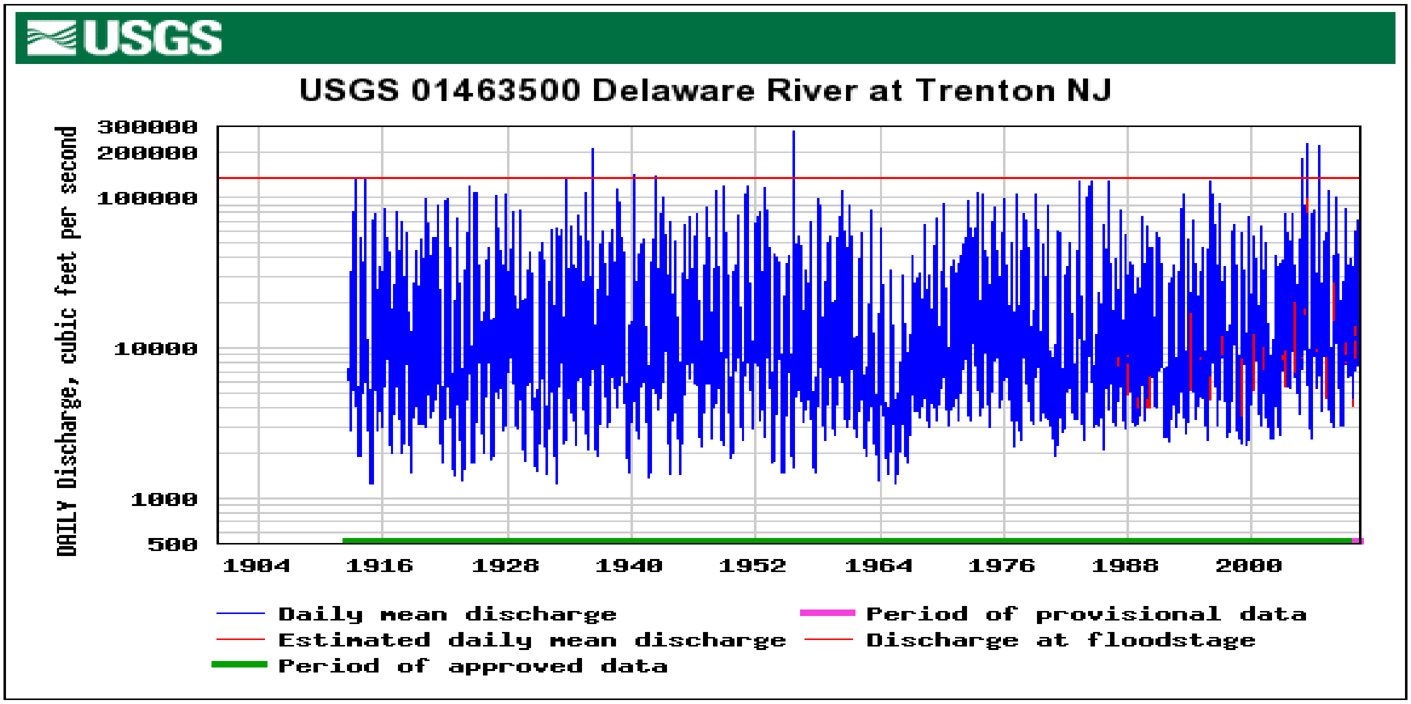


Fig A and B. Flooded Street on the island section of Trenton, 2004. The 1955 flood was 5.21 feet higher.
Fig C. Flooded South Warren Street, looking south from Lafayette Street, during the Flood of '55.
Fig D Washington Crossing bridge, overwhelmed by the Delaware in 1955. Further downstream, the Ewing bridge was destroyed.



Hydrograph showing discharge in the Delaware River at Trenton. Note: Three floods after 2000 and the drought during the early 1960s.

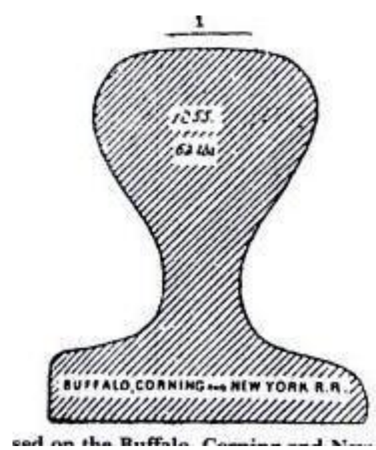
Industry, Geology, and Trenton

The first thing to understand about Trenton's most famous slogan is that it originated at a time when Trenton really did *make* things. Nearby geologic resources included the iron ore deposits of Morris, Warren, and Hunterdon Counties, zinc deposits of Sussex County, coal deposits of Pennsylvania, clay and sand deposits of the NJ Coastal Plain, hydromechanical power of the Delaware River and Ocean ports of the Delaware and Hudson Rivers connected by canal.

Trenton made the first I-beams, bulb railroad tracks, and steel rope used to hold up the world's longest suspension bridges and more than 150 other suspension bridges. Trenton made anvils used to forge the nation's iron. It made automobiles, the fastest. It made pottery and rubber and wall plaster and farm tools and mattresses and watches and bricks and linoleum and cigars. It even made the world's largest bathtub and shipped it to Washington so the president, William Howard Taft, could soak his

350-pound body. Pottery is, the oldest of human crafts. By the turn of the 20th century, iit was also a $40 million industry that supplied the nation's homes with plates, tiles, vases, china, sinks, tubs and toilets -- and Trenton was its capital. More than 4,000 potters, painters, glazers and kiln men toiled in the city's ceramics factories, painstakingly turning out pieces praised as equal to the finest of English stoneware.

However labor strife, trust-busting, mechanization, imports and environmental responsibility lead to a decline of the major industries.

	
George Washington Bridge wire cables and I beams	Fine China
	
Trenton Water Power Canal and Trenton War Memorial circa 1935	Bulb type railroad

Mercer Automobile tire industry and steel industry	Brick Industry, William Trenton House

Extra Terrestrials and the Trenton area

Orson Wells "War of the Worlds": Ladies and gentlemen, I have a grave announcement to make. Incredible as it may seem ... those strange beings who landed in the Jersey farmlands tonight are the vanguard of an invading army from the planet Mars!

The broadcast news that Sunday night, Oct. 30, 1938, sounded real enough to many and they thought Martians landed in Grover's Mill, about 3 miles southeast of Princeton and 12 miles northeast of Trenton.

Geology, talcum powder and poetry

Talcum Powder was developed in central NJ by Dr. Frederick Kilmer of Johnson and Johnson. His son Joyce Kilmer was a famous American poet and is the namesake for Joyce Kilmer Elementary School, Stuyvesant St, Trenton. Joyce Kilmer's most famous poem.

I think that I shall never see
A poem lovely as a tree.
A tree whose hungry mouth is prest
Against the earth's sweet flowing breast;
A tree that looks at God all day,
And lifts her leafy arms to pray;
A tree that may in summer wear
A nest of robins in her hair;
Upon whose bosom snow has lain;
Who intimately lives with rain.
Poems are made by fools like me,
But only God can make a tree.

Geology and the military

During the French and Indian Wars the British built the Trenton Barracks out of local Trenton stone to house soldiers. First American victory in the Revolutionary War was in Trenton, December 26, 1776. George Washington located cannons on the top of a small hill (resistant gabbro, Mesoproterozoic)) north of the main part of town, near the Trenton Monument. He discharged cannon balls down the gravel streets (King and Queen streets, now Warren and Broad Streets). The cannon balls kicked up Trenton Gravel (Pleistocene) from the street thus discouraging many Hessians from exiting the buildings along the street. During the second battle of Trenton, Washington is on the Mill Hill (resistant Whissohickon Schist) side of the Assunpink Creek and the British are on the north side of the Creek. The British intend to overwhelm the American in the morning but George and troops use campfires on the hill slope to trick the British into thinking they remained the night. George and his insurgents leave under darkness and trickery to fight in Princeton the next day

During the Civil War, Trenton Iron Works made rifle barrels (using iron from northern New Jersey, coal from Pennsylvania, and water power from the Delaware River). During WWII, observation towers were constructed above Trenton's municipal reservoir and on the Diabase hills around Harbourton to enable civil defense volunteers to scanned the skies for enemy airplanes.

Geology and Transportation

Indian trails made way to carriage trails, railroad lines, canals and interstate highways. The D&R canal opened in 1834. The first bridge over the Delaware River opened in January 1806. The first train track in NJ and the John Bull the first locomotive was put into service in September 1831 ties on the track were blocks of igneous and metamorphic rock. The New Jersey Turnpike opened on Nov. 30, 1951, for traffic between The Delaware Memorial Bridge and Woodbridge.To build the turnpike, enough dirt was hauled away to fill three trains extending from New York to San Francisco. Construction of the new Scudder's Falls bridge and the new Pennsylvania Turnpike Bridge north and south of Trenton respectively are being geoengineered at this time.

Geology and the origin of geologic names

Lenape words

Assunpink Creek--*Ahsën'pink*, meaning "stony, watery place"
Wissahickon Creek-- "catfish creek" or "stream of yellowish color".
Passaic-- "pahsayèk" meaning "valley"
Manhattan-- "island of many hills"
Chickies Formation--Chikiswalungo or Chiques creek from the Lenape "Chiquesalunga", meaning "place of crayfish".

People

Woodbury- The City of Woodbury, had its beginning in 1683 when Henry Wood, a Quaker from Bury, England, settled here.

Stockton, Richard (October 1, 1730 – February 28, 1781) was an American lawyer, jurist, legislator, and a signer of the Declaration of Independence.

Other

Sourland Mountains--- origin is unclear.

1)"*sorrel-land*" which describes the sorrel (reddish-brown) colored soils encountered by the pioneering German farmers,

2) German immigrants from the Sauerland region simply anglicized the name of their home region.

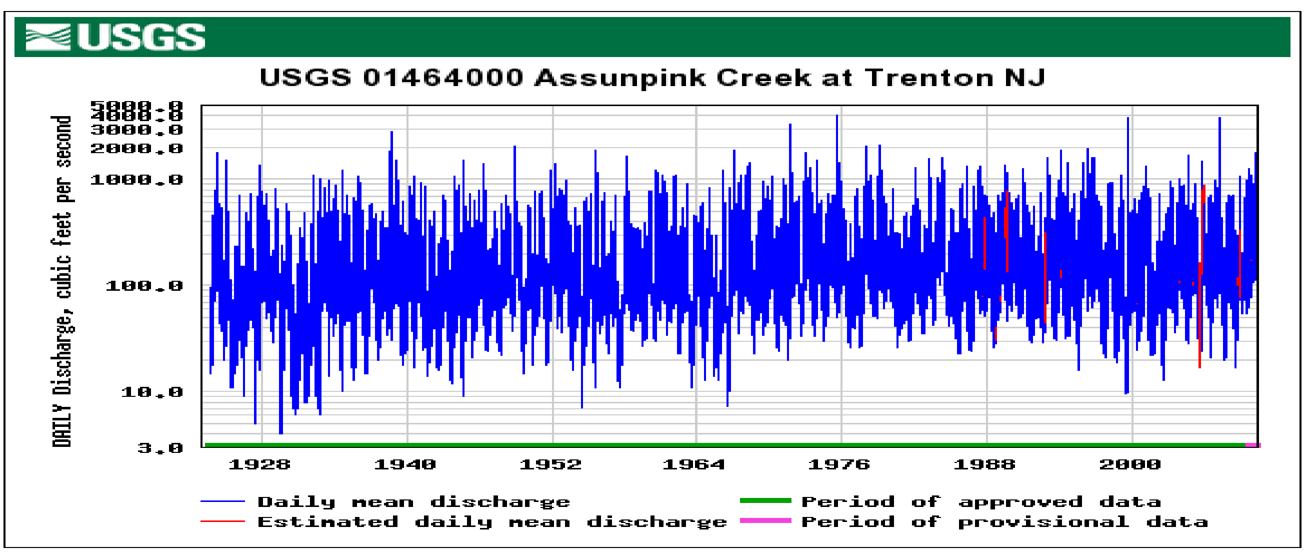
3)17th century Dutch settlers who referred to the region as "*sauer landt*" because the region was clearly not suitable for farming.

Geologic and hydrologic data collection and research in Trenton area

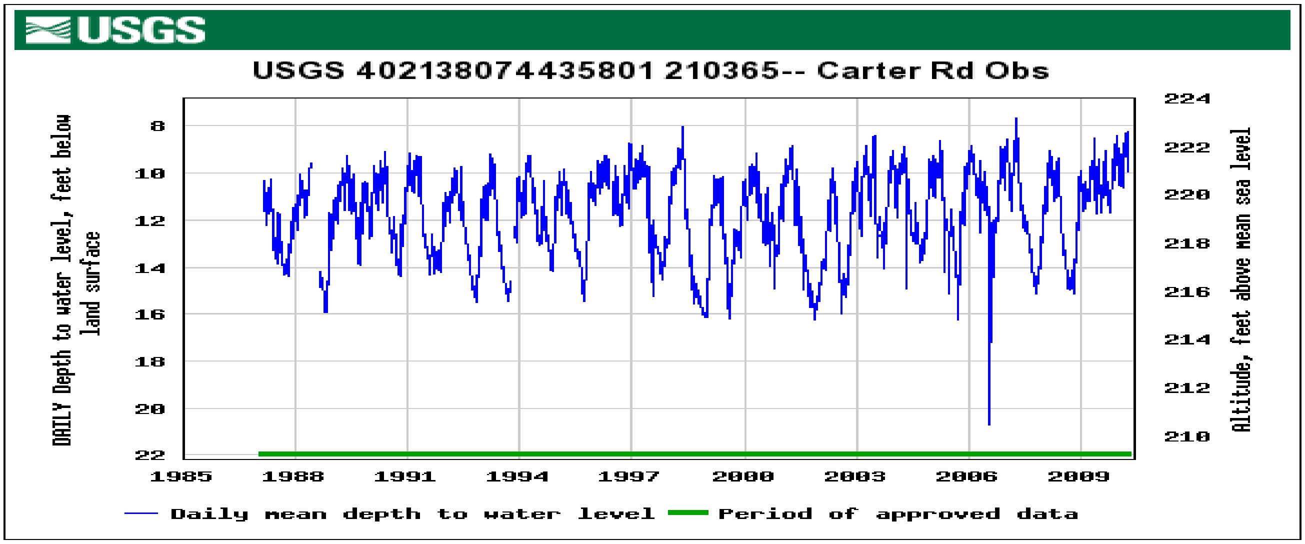
The USGS in cooperation with the NJGS and NJDEP maintain stream discharge records on the Delaware River and Assunpink Creek in Trenton and groundwater levels in Ewing and Hopewell.

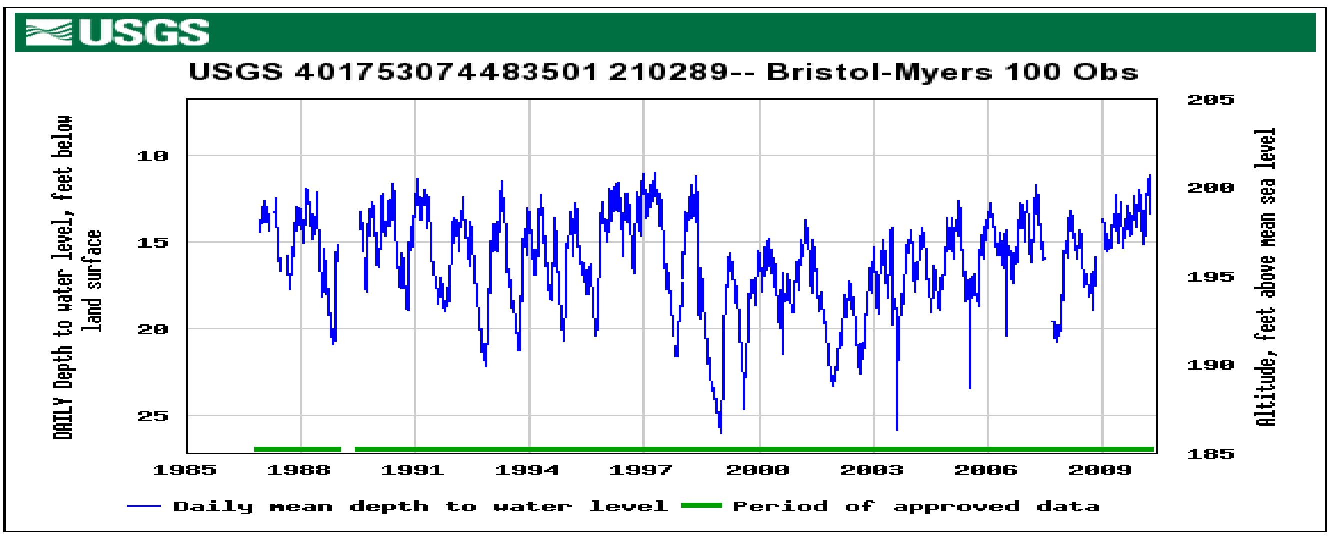
The data are used for drought warning and flood management USGS in cooperation with the NJGS has conducted investigations in the Trenton Area on flow and water quality in Jacobs Creek, the D&R canal, and Crosswick Creek. USGS maintains a national research site addressing remediation of TCE in fractured bedrock at the former Naval Air Warfare Center in West Trenton.

The NJDEP and private consulting firms monitor over 150 groundwater contamination sites in Mercer County. Rutgers and Columbia University as part of the Newark Basin Coring Project drilled three 1Km deep rock cores in Mercer County to investigate the geology of the Newark Basin.



Discharge measurements for the stream gaging station on the Assunpink Creek in Trenton





Ground water levels for two monitoring wells in Mercer County.

US Geological Survey's Toxics Substances Hydrology Research Program

Geochemical and Microbiological Processes that Affect Migration and Natural Attenuation of Chlorinated Solvents in Fractured-Sedimentary Rock — Naval Air Warfare Center (NAWC) Research Site, West Trenton, NJ

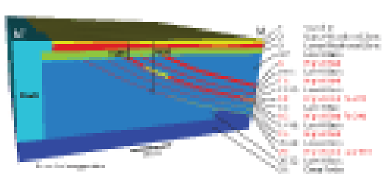
The USGS selected the NAWC site in West Trenton NJ as the national research site for the investigation of chlorinated solvent in fractured rock aquifers. The purpose and scope of the research is focused to:

- ✓ Develop an understanding of the physical, chemical, and microbiological processes that affect the movement and fate of toxic chemicals through fractured-rock aquifers
- ✓ Develop and test predictive models of the complex interactions among these processes
- ✓ Examine the processes by which toxic chemicals are removed naturally from aquifers
- ✓ Evaluate methods to enhance the natural cleanup process
- ✓ Insure the transferability of the knowledge, understanding, model designs, processes, and methods from this research site to other sites

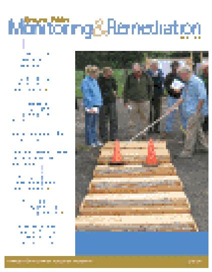
Ultimately, the research is intended to develop a fundamental understanding of:

- ✓ The hydrogeologic framework in fractured-bedrock aquifers
- ✓ Aqueous and non-aqueous phase contaminant movement in fractured-bedrock aquifers
- ✓ Biodegradation methods and rates in shallow and deep fractured-bedrock aquifers

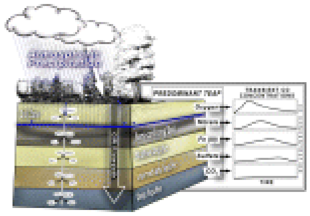
The research will advance the state of fractured-bedrock aquifer knowledge and will provide information that can be used to form the scientific basis for policies and regulations concerning the remediation of hazardous materials in fractured rock of the temperate northeast.



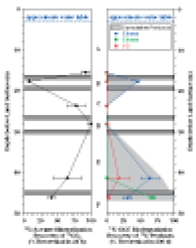
Multi-well shutdown tests are a cost-effective method for characterizing the hydraulic characteristics of heterogeneous fractured rock: *Ground Water* journal article by [Tiedeman and others, 2010]



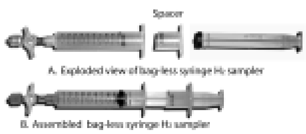
Hydrogeologic framework developed for understanding three-dimensional flow in dipping fractured rocks: *Ground Water Monitoring & Remediation* journal article by [Lacombe and Burton, 2010]



Indicators for the bioavailability of dissolved organic carbon developed: *Ground Water* journal article by Chapelle and others, 2009



Protocol validated for assessing biodegradation in fractured-rock aquifers: *Ground Water Monitoring & Remediation* journal article by Bradley and others, 2009.



New syringe diffusion sampler for hydrogen gas: *Ground Water* journal article by Vroblesky and others, 2007.

Chapter 3

Geologic Overview of the Trenton Prong, West-Central New Jersey

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INTRODUCTION

Sparsely exposed pre-Mesozoic rocks of the New Jersey Piedmont crop out in the Trenton prong, a thin, east-northeast-trending wedge that disappears beneath cover to the northeast near Princeton Junction (Fig. 1). The geology of the Trenton prong in New Jersey has remained poorly studied over the last century largely because of the paucity of bedrock exposures. Most of the outcrops in the Trenton area are along the western shore of the Delaware River at Morrisville, Pennsylvania, or are exposed in the river when water levels are low. The few outcrops in New Jersey are mainly along tributary streams such as Assunpink Creek. Bedrock is also encountered in artificial exposures for construction or development, in archeological sites such as Petty's Run, or is penetrated in boreholes drilled for construction or environmental issues.

Possibly the earliest work on the bedrock geology of the Trenton prong was that of Rogers (1865) who correlated gneisses there to bedrock in the New Jersey Highlands based on their mineralogical similarity. While Rodgers assigned no age to the rocks, he recognized they were the oldest in the state. Cook (1868) similarly interpreted gneisses in the Trenton area to be among the oldest rocks in the state, and also correlated them to the gneisses in the New Jersey Highlands based on their mineralogical similarity. Bascom et al. (1909) interpreted most of the gneisses in the Trenton prong to be Precambrian in age, but based their interpretation on the presence of the non-conformably overlying Chickies Quartzite of Cambrian age. They correlated the gneiss in the Trenton area to the Baltimore gneiss that is exposed in a series of structural domes in the eastern Maryland Piedmont (Fig. 2). Although Trenton prong gneisses are undated, gneisses in the New Jersey Highlands have yielded U-Pb zircon ages of 1366 to 1240 Ma (Volkert et al., 2010), and felsic gneisses of the Baltimore domes U-Pb zircon ages of 1256 to 1240 Ma (Aleinikoff et al., 2004) confirming a Mesoproterozoic age for the rocks of both areas.

Bascom et al. (1909) also interpreted Wissahickon micaceous schist and gneiss in the Trenton prong to be Precambrian in age and correlated these rocks to the Wissahickon Formation in southeastern Pennsylvania. Recent geochronological work on the Wissahickon Formation in the Piedmont of Pennsylvania and Delaware (Bosbyshell et al., 2001; Aleinikoff et al., 2006) has shown that while this lithologic correlation is correct, the Wissahickon Formation is intercalated with metavolcanic rocks dated at 481 Ma and is thus Ordovician in age and not Precambrian as originally interpreted.

The crystalline rocks of the Trenton prong were revisited in 1988 by Volkert and Drake (1993) as part of reconnaissance-scale mapping for the new bedrock geologic map of New Jersey (Owens et al., 1998). In a separate petrographic and geochemical study of the crystalline rocks buried beneath the New Jersey Coastal Plain, Volkert et al. (1996) correlated schist and gneiss and intercalated amphibolite east of the Delaware

River in Burlington, Camden, Gloucester, and Salem Counties to the Wissahickon Formation and extended these rocks along strike from Trenton south into northern Delaware.

This paper presents the provisional results of more recent bedrock mapping, combined with geochemical and isotopic studies undertaken by the New Jersey Geological Survey, partially in collaboration with Rutgers University, which bear directly on the geologic evolution of the Trenton prong. These results provide the basis for an improved understanding of the lithologic, stratigraphic, geochemical, and tectonic framework of the pre-Mesozoic rocks. Equally important, they provide information upon which a correlation of bedrock of the Trenton prong and the New Jersey Highlands, as well as other Grenville-age inliers in the Appalachians may one day prove possible.

GEOLOGIC SETTING

Metamorphosed pre-Mesozoic rocks of the Trenton prong occur along the Fall Line, which forms the contact between bedrock of the Piedmont province to the north and the more easily eroded, unconsolidated sediments of the New Jersey Coastal Plain province to the south (Fig. 1). Along the Fall Line, from Trenton east to Princeton Junction, gneisses of the northern belt are overlain unconformably on the north by the Upper Triassic Stockton Formation (Owens et al., 1998), a basal unit of the strata deposited in the Newark basin, but nowhere is the contact between them exposed.

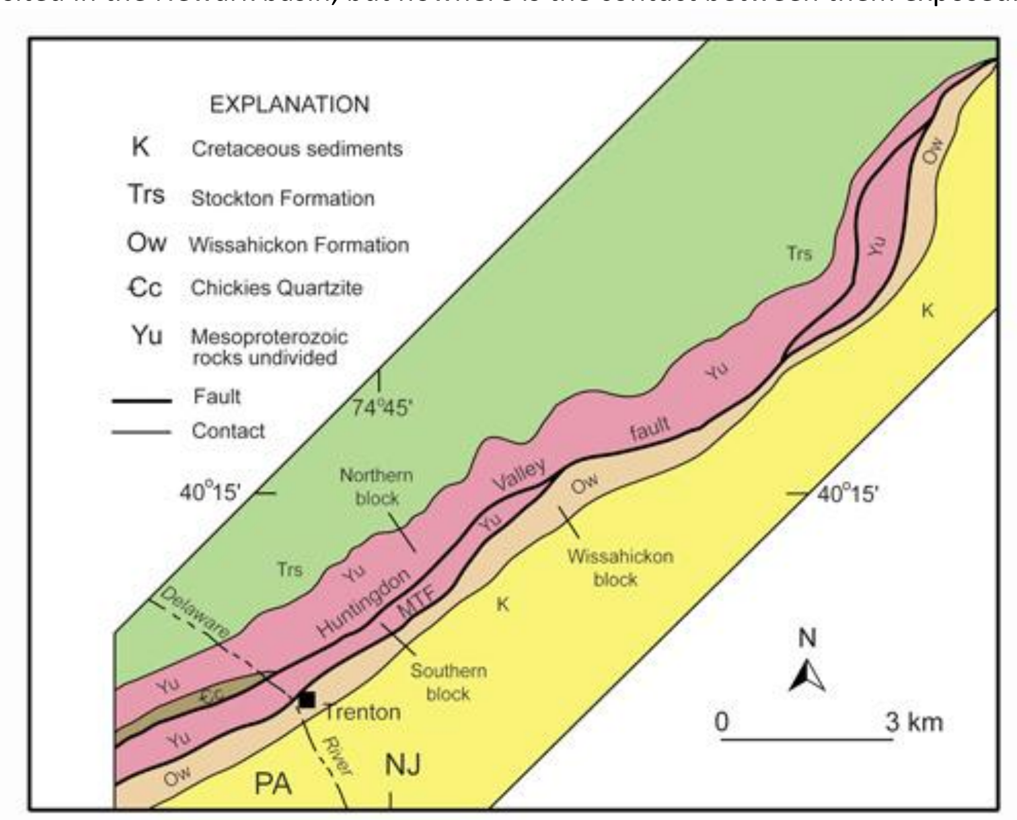

Figure 1. Simplified geologic map of the Trenton prong (Drake and Volkert, 1993) showing the lithologic subdivision into a northern block, southern block and Wissahickon block. See text for discussion.

Much of the lower part of the Stockton is arkosic sandstone that contains 50 to 70 percent quartz and 15 to 40 percent feldspar, plagioclase being more abundant than K-feldspar (Van Houten, 1980), which was derived from the underlying Mesoproterozoic rocks. Bascom et al. (1909) described an exposure of the Stockton at Cadwalader Park in Trenton of arkosic conglomerate containing large clasts of quartz and feldspar. More recently, the author logged drill core from a monitor well drilled in 1994 along Spruce Street in Ewing Township that penetrated Stockton Formation containing clasts of Chickies Quartzite up to 1 cm long from a depth of -20 to -27 ft.

From Trenton northeast to Princeton Junction, pre-Mesozoic rocks of the Trenton prong are unconformably overlain on the south by sediments of the Upper Cretaceous Potomac and Magothy Formations (Owens et al., 1998). Northeast of Princeton Junction the Stockton Formation is in direct contact with the Magothy Formation, and from there northeast the Mesoproterozoic rocks and Wissahickon Formation remain buried. Rocks of pre-Mesozoic age emerge from beneath this cover north of Raritan Bay, where serpentinite and Manhattan Schist were mapped (Drake et al., 1996) from sparse bedrock outcrops and from borings drilled along the west side of the Hudson River (Volkert et al., 1996).

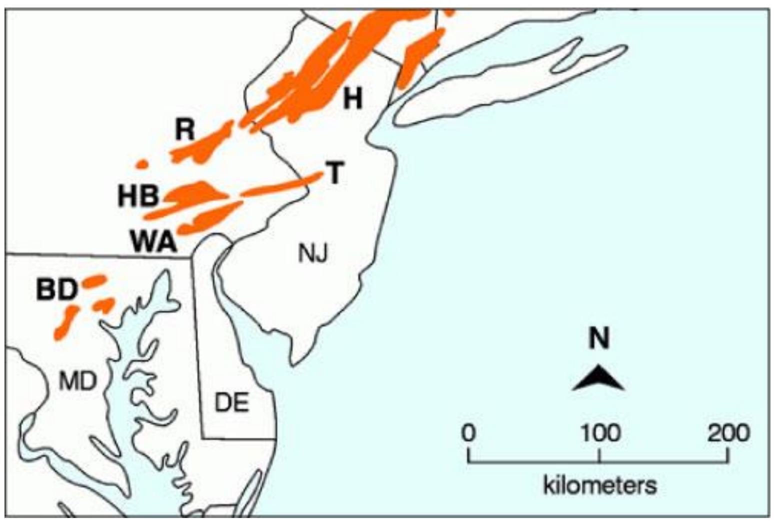

Figure 2. Simplified geologic map showing distribution of Mesoproterozoic rocks in the New Jersey Highlands (H), Reading prong (R), Trenton prong (T), Honey Brook Upland (HB), West Chester prong and Avondale anticline (WA), and Baltimore domes (BD).

Along the Hudson River, undated rocks of postulated Neoproterozoic to Early Cambrian, and possibly Ordovician age include serpentinite and Manhattan Schist (Drake et al., 1996). Serpentinite was also recovered from drill holes to the southwest in central New Jersey. Small bodies of serpentinite also occur within the Wissahickon Formation west of the Trenton prong in the Pennsylvania Piedmont. Serpentinite from along the Hudson waterfront in the Manhattan prong is a tectonic mélange containing blocks of serpentine as much as several meters across within a matrix of scaly-cleaved, fine- grained serpentine and talc schist, and likely represents a remnant of ocean crust

(Volkert et al., 1996). Serpentinite has been thrust over the Manhattan Schist (Lyttle and Epstein, 1987; Baskerville, 1990; Volkert et al., 1996) on Cameron's Line thrust fault. Cameron's Line continues southwestward beneath the eastern edge of the Newark basin, merging with, or becoming the Huntingdon Valley-Morrisville fault system northeast of Trenton (Volkert et al., 1996).

The Trenton prong includes a heterogeneous assemblage of metamorphosed rocks interpreted to be of Mesoproterozoic age that are divisible into northern and southern blocks separated by the steeply southeast-dipping Huntingdon Valley fault (Fig. 1). The northern block contains well foliated orthogneisses of felsic and mafic compositions that are spatially associated with quartzofeldspathic and calc-silicate paragneisses and minor marble (Volkert and Drake, 1993). These rocks are non-conformably overlain on the south by the Lower Cambrian Chickies Quartzite (Fig. 1). The southern block contains foliated orthogneisses that have felsic and mafic compositions, quartzofeldspathic and calc-silicate paragneisses, and minor amounts of K-feldspar augen granite gneiss (Volkert and Drake, 1993). The Wissahickon block includes schist and gneiss of the Wissahickon Formation, intercalated amphibolites, and minor amounts of coarse-grained, quartz and feldspar granite that may be an anatectic phase of Wissahickon gneiss. Rocks of the Wissahickon block have been thrust onto Mesoproterozoic rocks of the southern block along the Morrisville fault, a splay of the Huntingdon Valley fault (Volkert and Drake, 1993).

To the west of Trenton, Mesoproterozoic-age rocks crop out in numerous detached bodies in southeastern Pennsylvania that include the Honey Brook Upland and Mine Ridge anticline to the north of the Huntingdon Valley fault and West Chester prong and Avondale anticline to the south (Fig. 2). Although some lithologies in these areas resemble those of the Trenton prong, many do not such as kyanite gneiss, anorthosite, and ultramafic rocks (pyroxenite) (Rankin et al., 1993), suggesting that while the bedrock in these areas correlates temporally to the Trenton prong, it may have experienced a different geologic history.

EVIDENCE FOR A MESOPROTEROZOIC AGE

Although geochronologic data are lacking for bedrock of the Trenton prong, several lines of evidence suggest that the rocks in the northern and southern blocks are Mesoproterozoic in age as originally proposed by Bascom et al. (1909). Gneisses in the northern block are nonconformably overlain by the Chickies Quartzite at Morrisville, Pennsylvania and to the west. The Chickies contains the fossil *Skolithus linearis* confirming a Cambrian age for that unit. Therefore, based on biostratigraphic evidence and field relationships the gneisses are clearly older than Cambrian. Furthermore, there is a metamorphic discontinuity between the gneisses in the northern belt, which have undergone high-grade metamorphism (see discussion below), and the Chickies which records low-grade, greenschist-facies metamorphic temperatures of ~320^{o}C as determined by a study of coexisting monazite and xenotime (Pyle, 2006).

Gneisses in both the northern and southern blocks of the Trenton prong are intruded by thin, discordant diabase dikes. In the New Jersey Highlands widely distributed diabase dikes intrude Mesoproterozoic rocks but not Cambrian or younger cover rocks. There the dikes are interpreted to be Neoproterozoic in age and emplaced during rifting of the eastern Laurentian margin coeval with breakup of the super-continent Rodinia (Volkert and Puffer, 1995). The Trenton prong dikes formed from mainly alkalic basalt protoliths, and the dikes have compositions that are high in TiO_2 and incompatible-elements that closely overlap the compositions of Neoproterozoic diabase dikes in the Highlands (Volkert et al., 1996; Volkert, 2004a) (Fig. 3). Emplacement of the Trenton prong and Highlands dikes into a continental setting is supported by their ocean-island-basalt-like (OIB) and within-plate basalt geochemistry, which is consistent with early plume-related magmatism (Volkert, 2004a). If a Neoproterozoic age assignment is correct for the Trenton prong dikes, gneisses in the northern and southern blocks are older than Neoproterozoic.

A third piece of evidence for the age of gneisses involves $^{40}Ar/^{39}Ar$ data from hornblende in mafic gneisses from the southern block that yielded ages of ~880 Ma (C. Swisher III, 2009, personal communication). This indicates that the rocks were cooling from a high-grade metamorphic event through the ~550-500^{o}C argon closure temperature of hornblende during the Mesoproterozoic. A similar $^{40}Ar/^{39}Ar$ hornblende age of 880 Ma was obtained from the Honey Brook Upland in the Pennsylvania Piedmont (Crawford and Hoersch, 1984). Ages of ~900 Ma from the New Jersey Highlands reflect slow cooling from the Ottawan orogeny, the terminal phase of the Grenville Orogenic Cycle, the thermal peak of which took place at ca. 1050 Ma in the Highlands (Volkert, 2004b).

Despite many lithological, mineralogical and geochemical similarities between Mesoproterozoic rocks of the Trenton prong and the New Jersey Highlands, the relationship between the rocks of these two areas remains speculative. It is tempting to interpret gneisses of the Trenton prong as simply being the continuation of the Highlands beneath the Newark basin. That is, the Trenton prong represents the emergent part of the down-dropped block on the hanging wall of the Ramapo fault. Moreover, rocks of both the Trenton prong and the Highlands appear to share a common geologic history in that rocks of both areas have undergone similar granulite-facies metamorphism at ca. 1050 Ma. However, it is also possible that Mesoproterozoic rocks of the Trenton prong are not continuous with the Highlands and instead represent a separate Grenville-age terrain that was tectonically sutured to the Highlands during the Ottawan orogeny. More work is needed to unequivocally link the Mesoproterozoic rocks of the Highlands and Trenton prong.

METAMORPHISM

All of the rocks of the Trenton prong have undergone at least one, and likely more than one episode of high-grade metamorphism. Mesoproterozoic rocks in the northern and southern blocks contain the mineral assemblage clinopyroxene + plagioclase + quartz ± orthopyroxene ± garnet in rocks of felsic to intermediate composition, and hornblende + clinopyroxene + plagioclase in mafic rocks, that are representative of metamorphism to granulite-facies conditions. Petrographic evidence suggests that the rocks of both blocks have been retrogressively metamorphosed, and more work is needed to unravel the metamorphic history of the Mesoproterozoic rocks.

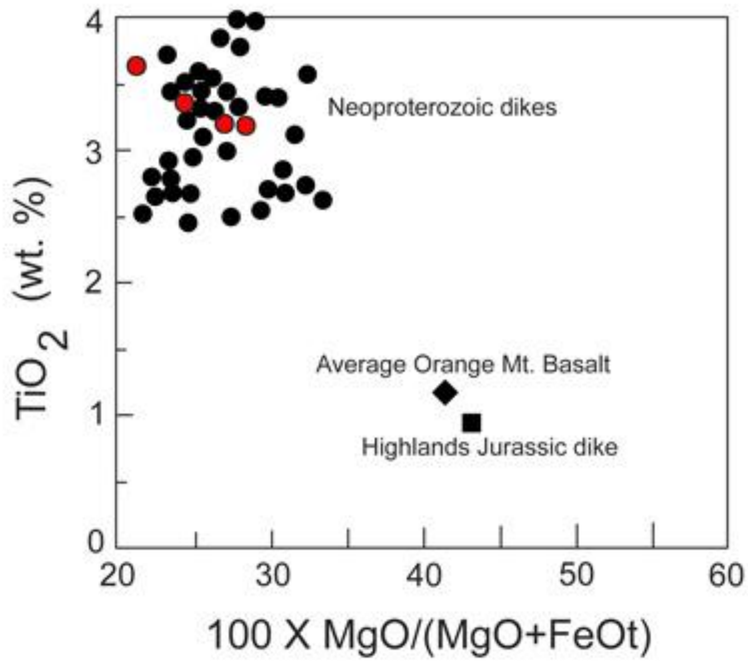

Figure 3. Plot of Neoproterozoic diabase dikes from the New Jersey Highlands (filled circles) and from the Trenton prong (red circles) (Volkert, 2004a) compared to average Jurassic Orange Mt. Basalt (diamond) from the Newark basin (Puffer, 1992) and a Jurassic diabase dike (square) from the eastern New Jersey Highlands (Volkert and Puffer, 1995).

Timing of the granulite-facies metamorphism of rocks of the northern and southern blocks is constrained by the $^{40}Ar/^{39}Ar$ hornblende ages as being Mesoproterozoic, as discussed earlier. Temperature estimates during this metamorphism have not been determined, but are presumed to have been >700°C. The absence of a Paleozoic metamorphic overprint in the $^{40}Ar/^{39}Ar$ hornblende data indicates the rocks were not heated above ~500°C during subsequent tectonothermal events. $^{40}Ar/^{39}Ar$ biotite ages of 420 and 400 Ma (C. Swisher III, 2009, personal communication) were obtained from gneisses in the northern and southern blocks, respectively. The Ar closure temperature of biotite is ~350°C, and so the Mesoproterozoic rocks in both blocks were clearly affected by a younger tectonothermal event that may reflect the Taconian orogeny, the thermal peak of which was about 450 Ma, and (or) a younger tectonothermal event.

Schist and gneiss of the Wissahickon block contain the mineral assemblage plagioclase + K-feldspar + quartz + biotite + muscovite ± garnet that is representative of metamorphism to amphibolite-facies conditions. Drill core samples of Wissahickon schist from beneath the New Jersey Coastal Plain examined by Volkert et al. (1996) contain the assemblage plagioclase + quartz + biotite ± garnet ± sillimanite, and spatially associated amphibolites contain the assemblage plagioclase + hornblende ± biotite ± garnet, also consistent with metamorphism to amphibolite-facies conditions.

Timing of the amphibolite-facies metamorphism of Wissahickon Formation schist and gneiss is complex and reveals a multi-stage cooling history as determined by studies in the Pennsylvania and Delaware Piedmont. U-Th-total Pb ages of metamorphic monazite from the Wissahickon record ages of ~455 Ma from cores and 415 Ma from rims (Bosbyshell et al., 2007). Zircon and monazite grains from the Delaware Piedmont have yielded SHRIMP U-Pb ages of 435-425 Ma for amphibolite-facies metamorphism (Aleinikoff et al., 2006). It is noteworthy that these younger ages are similar to the $^{40}Ar/^{39}Ar$ ages obtained from biotite in Mesoproterozoic gneisses of the Trenton prong. Metamorphic temperature estimates for this ~450-430 Ma event are ~640^{o}C (Bosbyshell et al., 2007). $^{40}Ar/^{39}Ar$ hornblende ages of 400-375 Ma from amphibolites in the Pennsylvania Piedmont interlayered with the Wissahickon (Blackmer et al., 2007) are nearly identical to $^{40}Ar/^{39}Ar$ hornblende ages of 413-360 Ma obtained by (Sutter et al. 1980. They, and metamorphic monazite ages of 365-360 Ma from the Wissahickon Formation (Bosbyshell et al., 2001; Crawford et al., 2001), suggest a more complex tectonic and cooling history involving reheating from intrusions of Silurian-age plutonic rocks (Aleinikoff et al., 2006) and a subsequent Devonian tectonothermal event at ~385-372 Ma (Srogi et al., 2007). Metamorphic temperature estimates for this younger event are ~600^{o}C (Bosbyshell et al., 2007; Srogi et al., 2007).

The extent to which Ordovician, Silurian and Devonian magmatic and metamorphic events have affected the rocks of the Trenton prong is currently unknown. However, it is clear that the Mesoproterozoic gneisses and the Wissahickon of the Trenton prong do not appear to share a common metamorphic history. While the biotites sampled from Mesoproterozoic rocks of the southern block show evidence for having grown or being reset at ~400 Ma, metamorphic temperatures must not have exceeded 500^{o}C or the $^{40}Ar/^{39}Ar$ hornblende age spectra would show disturbance and likely have been reset as well. Thus, the evidence suggests that the Wissahickon in the Trenton prong was metamorphosed to amphibolite-facies conditions independent of the Mesoproterozoic rocks and then subsequently tectonically emplaced onto rocks of the southern and northern blocks.

STRUCTURE

Metamorphic foliations in all rocks of the Trenton prong, whether in the northern block, southern block, or the Wissahickon block, display the same east-northeast strike that averages N66^{o}E (n=61) (Fig. 4) and dips toward the southeast at an average of 74^{o}. Thus, this concordance likely reflects tectonic transposition inherited from various tectonothermal events affecting the rocks. Preservation of primary sedimentary features or sedimentary and igneous contacts is lacking and all contacts have been tectonically modified. The timing of formation of the metamorphic fabric in rocks of the northern and southern blocks is likely Mesoproterozoic in age for reasons discussed earlier. However, the concordance of metamorphic fabric in rocks of the Wissahickon block with the northern and southern blocks implies that foliations in the Mesoproterozoic rocks were overprinted by a younger event(s) involving thrusting that may have been Taconian in age and younger.

A strike of about N70^{o}E (n=15) that is similar to the strike of Mesoproterozoic metamorphic fabric defines the axial surface of isoclinal folds developed in metamorphic foliations in the northern and southern blocks (Fig. 5). All folds plunge toward the northeast at an average of 29° and display similar geometries. A comparison with fold geometries of Wissahickon rocks is unable to be made owing to the scarcity of Wissahickon outcrops in the Trenton area.

Faults in the Trenton prong strike east-northeast at about N70°E and dip steeply toward the southeast at about 70 °-75°. The Huntingdon Valley fault thrusts rocks from the southern block onto the Chickies Quartzite, and farther to the northeast onto Mesoproterozoic rocks of the northern block (Fig. 1). Rocks of the Wissahickon Formation have been thrust northwestward onto rocks of the southern block along the Morrisville thrust fault, a southeast-dipping splay of the Huntingdon Valley fault, and further to the northeast onto rocks of the northern block (Fig. 1) (Volkert and Drake, 1993). Both the Huntingdon Valley fault and the Morrisville thrust fault are characterized by an early ductile deformational fabric. Deformed outcrops of Chickies Quartzite in the Delaware River display a slip lineation on bedding surfaces that plunges 62° to S44°E and records reverse movement sense involving transport to the northwest. Other kinematic indicators from along the fault in Pennsylvania (e.g., Hill, 1991;

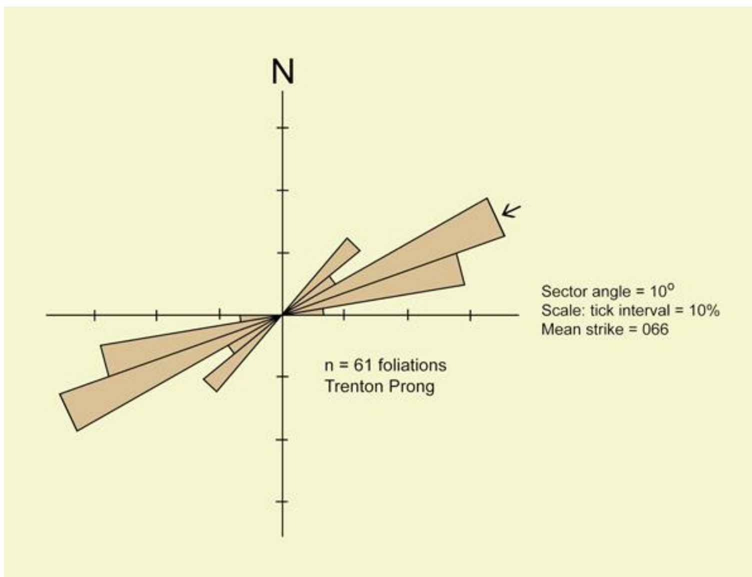

Figure 4. Rose diagram of metamorphic foliations in Mesoproterozoic rocks of the northern and southern blocks and schist and gneiss of the Wissahickon block of the Trenton prong.

Valentino, 1999) and from the Trenton prong (Volkert, unpublished data) also suggest a right-lateral sense of movement. Timing of this strike-slip movement is uncertain. The thrusting was likely a result of Taconian orogenesis (ca. 450 Ma), as indicated by $^{40}Ar/^{39}Ar$ ages of 420-400 Ma on mica from gneisses proximal to the fault. The right-lateral movement may be much younger, and possibly Alleghanian in age, as proposed by Kroll et al. (1999) based on $^{40}Ar/^{39}Ar$ ages of 311 Ma from white mica formed at greenschist-facies metamorphic conditions along the Huntingdon Valley-Pleasant Grove fault in Maryland.

Figure 5. Northeast-plunging, northwest verging isoclinal folds developed in metamorphic foliation in gneiss from the southern block of the Trenton prong. East is toward top of photograph. Pencil is 14 cm long.

PRE-MESOZOIC ROCKS OF THE TRENTON PRONG

Lithology and Geochemistry

Metasedimentary Gneisses (Paragneisses)

Mesoproterozoic paragneisses interpreted to have formed from sedimentary protoliths are common in both the northern and southern blocks of the Trenton prong. Quartzofeldspathic paragneisses are tan, pinkish-white, or light gray, medium grained, and well foliated. They are composed of blue and milky quartz + K-feldspar + oligoclase + biotite ± garnet. Muscovite is a common secondary mineral. Calc-silicate paragneisses are much less abundant. They are light gray, to light greenish-gray, medium grained, well foliated, and form thinner layers than quartzofeldspathic gneisses. Calc-silicate rocks contain oligoclase + clinopyroxene (mainly diopside) + hornblende + biotite. Quartz and titanite are present locally.

Major element geochemical compositions of the paragneisses are relatively uniform and suggest they formed from protoliths that were mainly sandstones. Paragneisses have SiO_2/Al_2O_3 of 3.37-6.11, K_2O/ Na_2O of 0.08-0.23, and high contents of Na_2O (3.12-5.33 wt. %) that correspond to the quartz-intermediate graywacke of Crook (1974). Ratios and contents of trace elements that are particularly sensitive discriminants of provenance and tectonic setting (Bhatia and Crook, 1986), such as Ti/Zr (7.1-29.9), Th/Sc (0.01-2.5), Zr (78-252 ppm), Hf (2.1-6.2 ppm), La (13.3-26.8 ppm), Th (0.21-7.44 ppm), and low contents of Co (3-16 ppm) and Ni (<20 ppm) closely overlap those of volcanogenic graywacke and reflect formation from sediment sources that were predominantly calc-alkaline and dacitic to andesitic (Fig. 6). Moreover, their compositions are characteristic of graywacke deposited in fore-arc or back-arc basins adjacent to magmatic arcs developed on thin continental margins (Bhatia, 1983; Roser and Korsch, 1988).

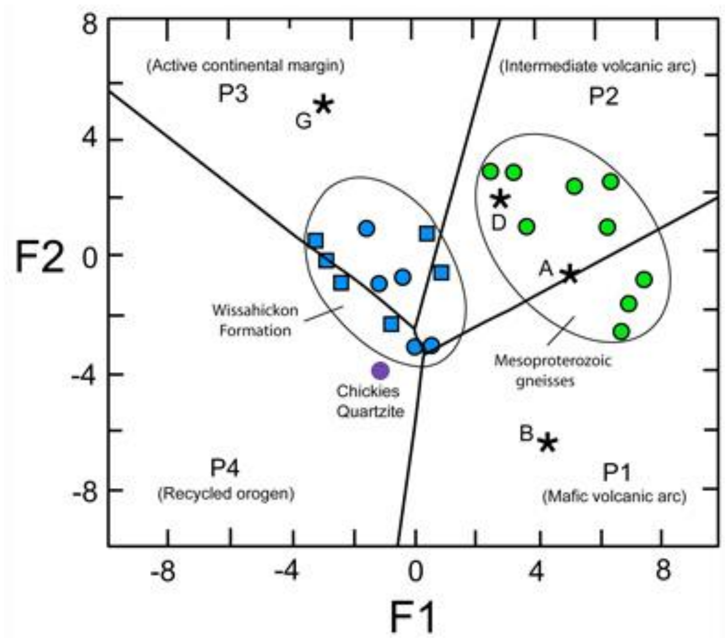

Figure 6. Plot of Mesoproterozoic gneisses and Wissahickon schist and gneiss from the Trenton prong on a tectonic discrimination diagram (Roser and Korsch, 1988) of F1 versus F2 calculated from discrimination function analysis using Al_2O_3, TiO_2, Fe_2O_3, MgO, CaO, Na_2O, and K_2O. G, D, A, and B are average compositions of granite, dacite, andesite, and basalt, respectively, from Le Maitre (1976). Squares are samples from drill core (Volkert et al. 1996). Sample of Chickies Quartzite is from Bascom et al. (1909). All other data are from Volkert (unpublished data).

Felsic Igneous Gneisses (Orthogneisses)

Felsic orthogneisses form conformable layers that are spatially associated with paragneisses in both the northern and southern blocks. Although they are not easily distinguished in the field from the paragneisses, the absence in orthogneisses of detrital zircons and their geochemical compositions provide a useful discriminant. Felsic orthogneisses weather pinkish-white, pinkish-gray or tan, are medium grained, foliated, massive, and are composed mainly of quartz + K-feldspar + oligoclase + biotite.

Felsic orthogneisses are interpreted as formed from rhyolitic protoliths (Fig. 7) rather than emplaced as granite sheets because they occur in layers that are too thin to be granite intrusions. They have high SiO_2 (71.40-77.30 wt. %) and are peraluminous with aluminum saturation index of 1.02-1.14. Felsic orthogneisses have high Ba (612-1782 ppm), Zr (271-433 ppm), Zr/Y (>7), FeO*/MgO (4.6-11.8), K_2O/Na_2O (1.13-3.05), Zr+Nb+Ce+Y (>400), and low MgO (0.18-0.76 wt. %), CaO (0.30-1.13 wt. %), and Sr (55-530 ppm) that are characteristic of A-type granites (e.g., Whalen et al., 1987). High Y/Nb (1.3-4.0), Yb/Ta (5.7-29.4) and Ce/Nb (7.5-10.6) also indicate an A-type granite affinity and correspond to the A_2-type of granite (Eby, 1992), interpreted to represent magmas derived from continental crustal sources having undergone previous continent-continent collision or subduction-zone processes. Low Ba/Th (77-211) of felsic orthogneisses further supports their derivation from a felsic crustal source.

Felsic orthogneisses are geochemically distinguishable from quartzofeldspathic paragneisses in having higher K_2O/Na_2O, Zr (see values above) and La (17.3-74.4 ppm). In addition, Ba (612-1782 ppm) and Rb (54-180 ppm) are considerably higher than in the

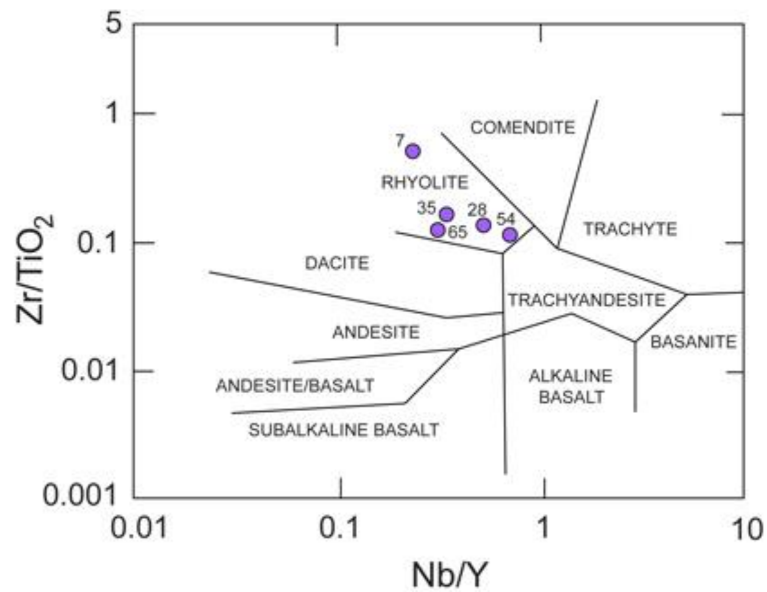

Figure 7. Plot of felsic orthogneisses from the northern and southern blocks of the Trenton prong on a diagram of Zr/TiO_2 versus Nb/Y (Winchester and Floyd, 1977). Data are from Volkert (unpublished data).

paragneisses, which have Ba of 89-586 ppm and Rb of 3-21 ppm.

Felsic orthogneisses have geochemical compositions and field relationships that are similar to rhyoltic gneisses in the New Jersey Highlands interpreted as having formed in a back-arc basin at 1299 to 1250 Ma as part of a bimodal volcanic succession with mafic volcanic rocks (Volkert et al., 2010). Trenton prong felsic orthogneisses may have formed in a similar, or perhaps even the same tectonic environment as rhyolitic gneisses in the Highlands. High-precision geochronology of Trenton prong rocks is a necessary first step in providing an answer.

Mafic Igneous Rocks (Orthogneisses)

Several types of mafic orthogneisses are recognized in the Trenton prong. The first type (type one) occurs as very thin bodies, possibly dikes, that are enclosed within Mesoproterozoic rocks. These mafic rocks are dark greenish-gray, medium grained, unfoliated and are composed of plagioclase + clinopyroxene + hornblende. The second type (type two) forms amphibolite layers in both the northern and southern blocks that are conformably intercalated with felsic orthogneisses and paragneisses. These amphibolites are characteristically grayish-black, medium grained, well foliated, and are composed of plagioclase (oligoclase to andesine) + hornblende + clinopyroxene ± biotite. Accessory minerals include magnetite, epidote and sulfide. Some exposures of amphibolite are injected by bodies of white pegmatite containing quartz and plagioclase, or veins containing plagioclase. A thin body of amphibolite in the northern block contains abundant small phenocrysts of amphibole in a matrix of plagioclase grains. The rock is foliated and so it is unclear if this represents the preservation of a primary igneous texture, or if the rock is intrusive into adjacent lithologies and thus younger. The third type of mafic rock (type three) occurs as amphibolite that is interlayered with Wissahickon schist and gneiss. Type three mafic rocks are similar texturally and mineralogically to type two Mesoproterozoic amphibolites except they lack clinopyroxene.

A single outcrop of gabbro has been mapped within paragneisses of the northern block (Volkert and Drake, 1993), but this gabbro body does not continue along strike and it appears to be an isolated occurrence. The gabbro is black, medium grained, weakly foliated, and composed of plagioclase + orthopyroxene + clinopyroxene + hornblende ± biotite. Similar small, irregular and discontinuous bodies of gabbro in the Pennsylvania Piedmont are described as intruding both Mesoproterozoic rocks and Wissahickon Formation (Bascom et al., 1909). Whether gabbroic rocks of the Trenton prong are of multiple ages, or they are younger than, and intrusive into Mesoproterozoic rocks is impossible to say at this time.

All mafic orthogneisses have less than 50 wt % SiO_2 and geochemical compositions that define the three distinct types described above based on ratios and concentrations of major and trace elements. Type one rocks (Neoproterozoic dikes) have an alkalic composition (Fig. 8) and are characterized by high TiO_2 (3.47 wt. %), Zr (320 ppm) and low Cr (32 ppm) (Fig. 9). They have Zr/Y of 9-18, Ti/V of 51-68 (Fig. 10) and consistently plot in the field of within-plate basalts on various tectonic discrimination diagrams (e.g., Figs. 9, 10). Type one mafic rocks have compositions that closely overlap those of diabase dikes that intrude Mesoproterozoic rocks in the New Jersey Highlands (Fig. 3).

Type two mafic rocks (Mesoproterozoic amphibolites) are characterized by tholeiitic compositions (Fig. 8), and compared to type one rocks they have lower concentrations of TiO_2 (0.70-1.50 wt. %) (Fig. 8) and Zr (17-110 ppm) and higher Cr (30-360 ppm). Type two rocks have Zr/Y of 1.2-3.3 and Ti/V of 11-24 (Fig. 10) that overlap the fields of IAT and MORB on various tectonic discrimination diagrams (e.g., Figs. 9, 10). However, the Ti/V and high La (5.6-22.5) and Ba/La (21-102) of type two rocks more closely resembles basalts from an arc-related environment, which have Ti/V of 10-20 (Shervais, 1982), than MORB which has Ti/V of 20-50, La of 2.5-6.3 and Ba/La <20 (Sun and McDonough, 1980). This fact is consistent with the intercalation of type two mafic rocks with paragneisses that have an affinity to sandstones formed in an arc-related environment.

Type three mafic rocks (Wissahickon amphibolites) have tholeiitic compositions (Fig. 8), and compared to type two rocks they have comparable Cr values (40-340 ppm), but higher TiO_2 (0.76-2.06 wt. %) (Fig. 8), Zr (20-200 ppm), Zr/Y (3.1-11), and Ti/V (29-41) (Fig. 10). Type three rocks also overlap the fields of IAT and MORB on various tectonic

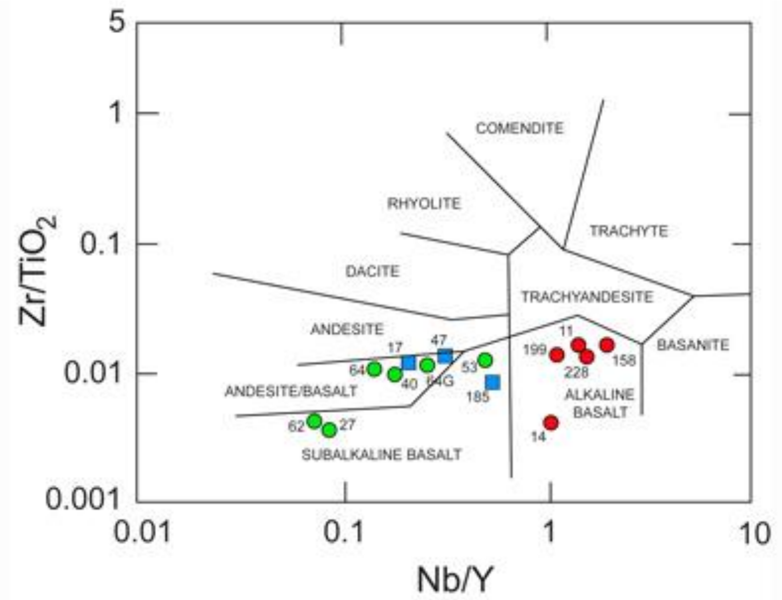

Figure 8. Plot of mafic rocks from the Trenton prong on a diagram of Zr/TiO_2 versus Nb/Y (Winchester and Floyd, 1977). Symbols are: green circles, amphibolites from the northern and southern blocks; blue squares, Wissahickon amphibolite; red circles, Neoproterozoic dikes from the northern and southern blocks. Data are from Volkert et al. (1996), Volkert (2004a) and Volkert (unpublished data).

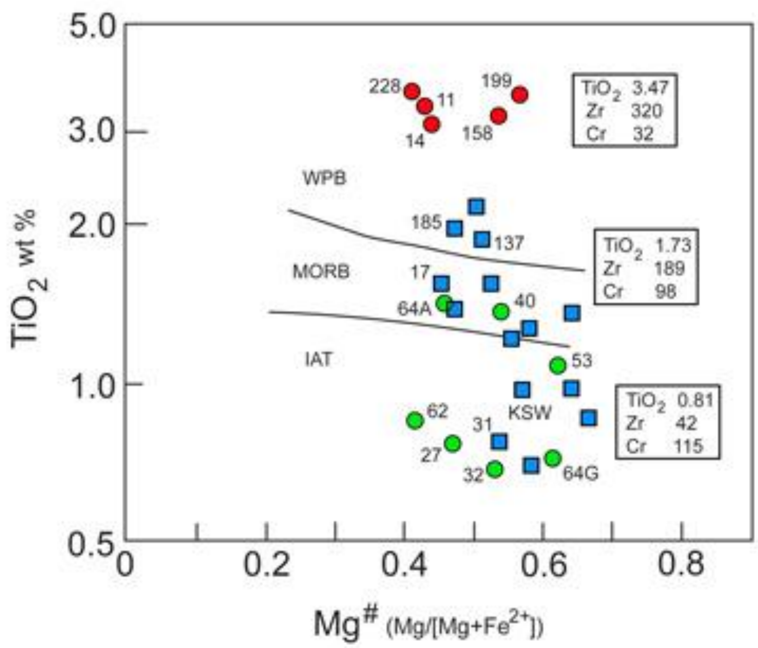

Figure 9. Mafic rocks on a plot of log TiO_2 versus Mg# (Basaltic Volcanism Study Project, 1981). Fields: IAT, island arc tholeiite; MORB, mid-ocean ridge basalt; WPB, within-plate basalt. Unnumbered squares are Wissahickon amphibolites from Pa. and Del. Piedmont (Wagner et al., 1980). KSW is average of 7 Wissahickon amphibolites from Del. Piedmont (Plank et al., 2001). Symbols and other data sources are as in figure 8.

discrimination diagrams (e.g., Figs. 9, 10). However, their higher Ti/V ratio more closely resembles MORB which has Ti/V of 20-50 (Shervais, 1982), and they have MORB-like Ba/La ratios of ~15. Amphibolites interlayered with the Wissahickon Formation in the Piedmont of Pennsylvania and Delaware were similarly interpreted as representing ocean-floor basalts that were formed in a marginal, possibly fore-arc basin (Plank et al., 2001).

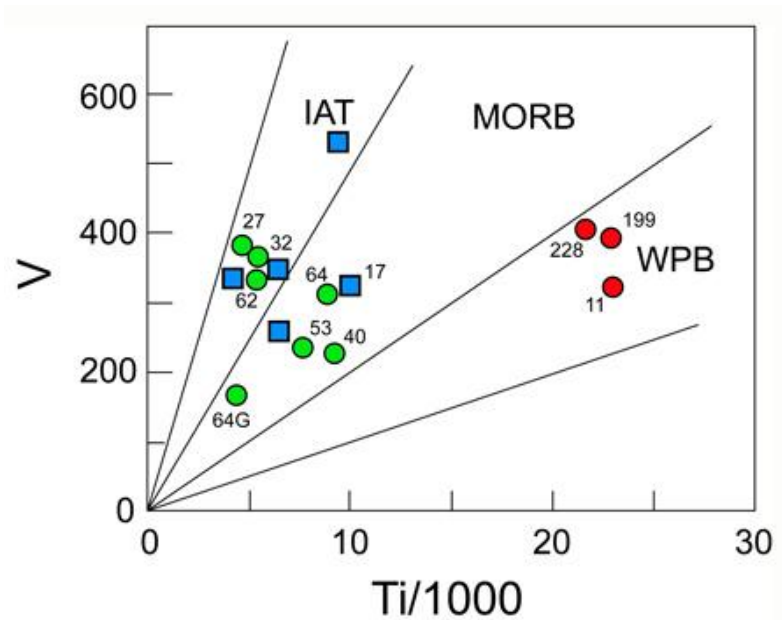

Figure 10. Plot of mafic rocks on a diagram of V versus Ti/1000 (Shervais, 1982). Symbols and data sources are as in figures 8 and 9.

Wissahickon Schist and Gneiss

Schist and gneiss of the Wissahickon Formation outcrop sparsely in the Trenton prong but are abundantly exposed to the west in the Piedmont of Pennsylvania. Schist is medium- to dark-gray, medium grained, well foliated, and composed of oligoclase + biotite + K-feldspar + quartz + muscovite ± garnet. Schistose rocks differ from gneiss in having higher contents of biotite and less quartz. Gneiss is tan or pinkish-white, medium grained, foliated, and composed of quartz + K-feldspar + oligoclase + biotite ± muscovite. Drill core samples of Wissahickon schist from beneath the New Jersey Coastal Plain locally contain sillimanite and tourmaline (Volkert et al., 1996). Some outcrops of Wissahickon gneiss contain thin veins of local melt composed of quartz and feldspar that are conformable to moderately discordant to gneissic foliation. Very locally, the Wissahickon is intruded by layers of coarse-grained granite that are discordant to the gneissic foliation (Fig. 11).

Major element geochemical compositions of the Wissahickon Formation indicate that it formed from protoliths that were sandstones (psammites) and shales (pelites). Metapsammites have SiO_2 of 69.19, SiO_2/Al_2O_3 of 5.17, TiO_2 of 0.70, K_2O/Na_2O of 0.79, and Ti/Zr of 16.2. Metapelites are easily distinguished by their lower SiO_2 of 55.56, SiO_2/Al_2O_3 of 3.6, and higher TiO_2 of 1.56, K_2O/Na_2O of 1.83, and Ti/Zr of 29.8. Contents of Cr (~70 ppm) and Ni (<20 ppm) are similar in both metapsammites and metapelites.

Figure 11. Outcrop from along the Delaware River of a thin layer of coarse-grained granite (beneath hammer) cutting across gneissic foliation in the Wisshickon Formation. The granite layer likely formed through local melting of the gneiss.

Overall, the composition of the Wissahickon Formation in the Trenton prong reflects a different sediment source than Mesoproterozoic paragneisses, with the Wissahickon formed from a mixture of felsic, arc-derived sediment and detrital input from a quartzo-feldspathic, continentally-derived source. This is consistent with Wissahickon rocks plotting mainly in the field of active continental margin sandstones (Fig. 6), indicating deposition in a basin that was likely situated between a magmatic arc and a continental margin and receiving sediment from both sources. The mixture of interbedded psammitic and pelitic protoliths resembles turbidite deposits, such as those of the Ordovician Martinsburg Formation, which were deposited in an outer shelf and slope setting. Thus the Wissahickon Formation may be coeval with the Martinsburg Formation and represent its metamorphosed equivalent.

The Wissahickon in the Pennsylvania Piedmont is interpreted as representing a deep-water marine lithology in which the sediments were deposited oceanward of a continental margin and inboard of a magmatic arc (Crawford, 1991). A continental sediment source for the Wissahickon is further confirmed from the recovery in it of Grenville-age detrital zircons, indicating proximity of the depositional basin to the Laurentian margin during the Ordovician (Aleinikoff et al., 2006). Serpentinite bodies within the Wissahickon represent altered remnants of the ocean floor that were thrust onto the Laurentian margin along with sedimentary protoliths of the Wissahickon (e.g., Crawford, 1991). The spatially associated magmatic arc is interpreted to be the Wilmington Complex that crops out in the northern Delaware Piedmont (Wagner and Srogi, 1987). A suite of gabbroic to granitic rocks comprising the Wilmington Complex yields Ordovician U-Pb ages of 485-475 Ma (Aleinikoff et al., 2006) that overlap the age of amphibolite-facies schist and gneiss of the Wissahickon Formation.

Chickies Quartzite

Lithologies that are representative of the Chickies Quartzite include: medium-grained, light gray to light greenish-gray quartz-sericite schist with disseminated, fine grains of black tourmaline; less abundant conglomerate composed of pebble-size clasts of blue quartz (Fig. 12); and white to light gray, vitreous, thin-bedded quartzite. In the Trenton area the Chickies has an estimated thickness of about 730 feet. The Chickies there locally displays graded beds and tabular cross-beds that indicate bedding is right-side-up and also support a sedimentary origin for the unit. The presence elsewhere of *Skolithus linearis* burrows in the Chickies fixes its age as Cambrian (Bascom et al., 1909) and suggests that it is coeval with the Hardyston Quartzite in the New Jersey Highlands and Reading prong in southeastern Pennsylvania.

The geochemical composition of the Chickies, particularly its high SiO_2 content (~88 wt. %) and SiO_2/Al_2O_3 of 13.3 (Bascom, et al., 1909), are indicative of mature sediment formed from recycling of older, quartz-rich basement rocks in a passive margin type of tectonic environment (Fig. 6). The presence of blue quartz as a detrital phase in the Chickies, which can be traced to a local source in the Mesoproterozoic rocks of the Trenton prong (Fig. 12) provides strong support for this interpretation. Based on the texture, bedforms, burrows, lithologic characteristics, and compositional maturity of the Chickies, Adams and Goodwin (1975) proposed a similar type of depositional environment during the Cambrian for the Chickies, namely an estuarine marine environment along a passive margin.

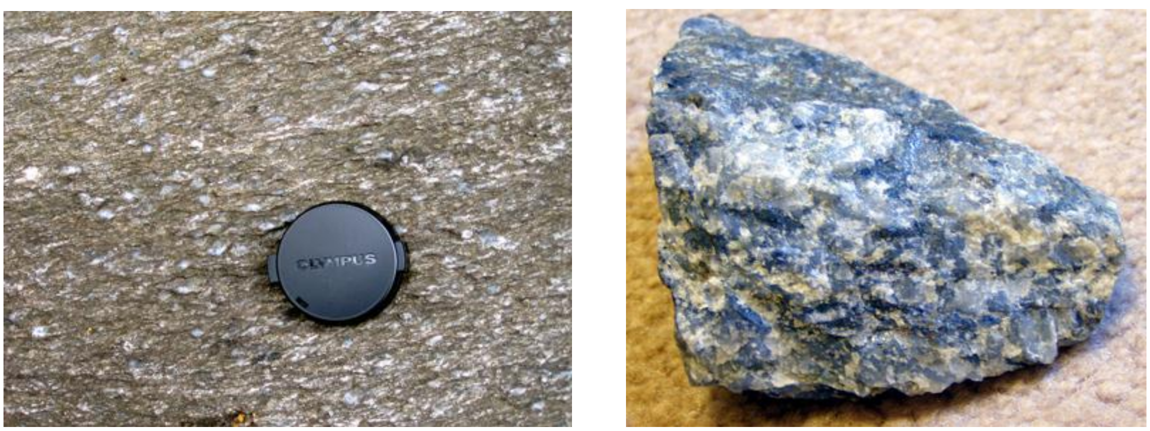

Figure 12. Blue quartz pebbles in the Chickies Quartzite (left) from Morrisville, PA have a local source in Mesoproterozoic gneisses of the Trenton prong (right).

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Chapter 4

Geology, Iron, Steel, and the Archaeology of Petty's Run

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Trenton was established in the late 1670s at what was then known as the falls of the Delaware, so-called from the zone of rocky rapids on the river at this point. This critical spot in the landscape is at the head of navigation, head of tide and furthest downstream fording point on the Delaware River at the mouth of Assunpink Creek.

Around 1720 a small planned town was laid out on the north bank of the Assunpink by William Trent, a wealthy Philadelphia merchant who, a few years earlier, had bought the core of a plantation established in 1679 by Quaker Mahlon Stacey. Trenton was a logical place for the secondary processing of metals. Iron ore, mined and then subjected to primary processing in the forges and blast furnaces of the New Jersey Highlands and northeastern Pennsylvania, could be shipped as cast-iron pigs and wrought-iron bars downstream along the Delaware by raft and shallow-draft vessels all the way to the falls at Trenton. Here the falls obstructed further progress downstream for most of the year. Iron was offloaded on the riverbank above the falls and further processed in the forges and shops of Trenton before being shipped on downstream to Philadelphia and other Lower Delaware towns from the wharves below the falls. Trenton therefore developed as a classic "break-in-bulk" point in the iron industry's regional transportation system.

Starting 2008, a chronologically and spatially extensive urban archaeological project has examined the area immediately east of the New Jersey State House. The extensive and significant remains of 18th and 19th century water-powered industries - iron, steel, textiles and paper- have been recovered form this location. Their existence and survival is due firstly to the presence of a small stream (Petty's Run), which provided the energy to power these operations, and secondly to the cliff-like configuration of the Paleozoic outcrop over which the stream flows. Tucked beneath the bluff, the remains of these industrial operations were covered with fill in the 19th and 20th centuries, thus preserving some their key components

Sponsored by the State of New Jersey, this investigation forms part of the planning and design phases for a new urban park, the intention being to interpret the history of the site as a feature of the park. The area excavated is in excess of 15,000 square feet (1400 square metres). Deep historic cultural deposits extended over 20 feet (six metres) below the 2008 ground level to the bedrock of Petty's Run in places. Excavation depth was typically about nine feet (three metres) over most of the site. The excavations have been both logistically and technically demanding. Large amounts of late 19th and early 20th century fill material had to be removed by machine, while at the same time the very complex 5-phase history of the site, extending over almost 300 years, had to be dissected and documented

Five periods of historic land use can be identified on the site. The earliest, of c. 1730-90, is an industrial iron & steel phase of international importance. In the second phase the site itself was largely abandoned. In the 1810-76 period the site returned to industrial uses based on waterpower, with cotton- and paper mills occupying the locations of the earlier iron and steel operations. Civic improvement in 1876-1913 resulted in the culverting of Petty's Run and the construction of row houses. Starting in 1913 the area was reworked as a park setting.

The colonial iron and steelworks phase has its origins in a plating mill (a water-powered trip-hammer forge specializing in producing items from iron plate) that was established in the early 1730s by one Isaac Harrow. Harrow built his plating forge at what was then the northwestern limits of the town, on the east side of Petty's Run right at the point where it tumbled over a bluff in a narrow ravine The plating mill was the only reported example in the colony in 1750. Archaeological excavations have located the lowest portions of the western and southern foundation walls of this building, and probably a short potion of the raceway system. These are constructed of massive quarried blocks of the gneiss bedrock, some weighing several hundred pounds. Unfortunately the greater part of this probably two-story building has gone. It was "slighted" by American forces in September of 1777, and any major remnants appear to have been removed by a later cotton mill using the same site. Our fantasies of finding an *in situ* trip hammer and anvil were dashed. The mill was acquired in 1745 by Benjamin Yard, another Trenton blacksmith.

It was Benjamin who commenced steel production alongside Petty's Run. We don't know exactly when he built the steel furnace – sometime between 1745 and 1750. Nor do we know his motives, but it's safe to assume he saw the production of steel as an activity that would happen in tandem with the plating mill, where he could fashion superior steel-edged tools, and that he anticipated a growing market for steel in Philadelphia.

It is hard to overstate the importance of this initiative of Yard's. Steelmaking was in its infancy in the American Colonies. The industry was only about 25 years old when Yard built his furnace: one almost definitely using the cementation process. It is safe to say that there were only a handful of steelmaking facilities, certainly less than ten, in existence in the American colonies in 1750. Steelmaking was capital-intensive and technically difficult, requiring sustained and consistent high temperatures, lowphosphate iron, and large amounts of charcoal for the cementation process and even large amounts of good cordwood as the heat source. Paradoxically, it did not require water power.

The surviving features of the furnace lie beneath, and were incorporated into, the industrial buildings of both the 1810-76 industrial phase and the 1876-1913 row-house episode. Almost miraculously, the foundation of both the furnace house and what we interpret as the furnace itself, survived these transformations The Furnace House is a stone-walled rectangular building lying the west of Petty's Run, and roughly oriented to the cardinal directions. In exterior dimensions it extends 31 ft (9.4 metres) north-south and at least 36 feet (10.9 m) east-west. The east-west dimension may be as much as 45 feet (13.7 m), of which the eastern 9 or 10 feet may be raceway and wheel pit structures removed by the construction of the paper mill waterpower system from 1827 onwards.

The walls, which generally survive to a height of two feet (0.60 m) or less, are composed chiefly of local quarried and roughly dressed gneiss set in a medium sand mortar with a distinctive orange-yellow hue (10 YR 6/8). Large water-rounded boulders and cobbles, probably recovered from the nearby Delaware River floodplain, are also used as foundations in places. The west and south walls are two feet (0.60 m) thick, the north wall 1.75 feet (0.5 m). No door, window or other openings were observed.

The Furnace Base lies five feet south of the north wall of the House, very close to the center of the 45-foot maximum east-west dimension of the building. Although much truncated by later building episodes, it retains some structural detail. In plan it is 10.5 feet east-west by 9.5 feet north-south (3.2 x 2.9 m). The interior foundation is of tightly packed mortared gneiss rubble surrounded by stone retaining walls standing up to two feet (0. 6m) high. In the center of each of the east and west walls is a distinctive long piece of quartzitic sandstone 32.5 inches (82.5 cm) long.

The northern wall of the Forge Base is buttressed at its eastern and western ends by short north-south walls of mortared stone braced against the inner side of the north wall of the Furnace House. The most likely explanation for these walls is that they are buttresses intended to address developing weaknesses in the furnace structure after repeated use.

The space between these two bracing walls was filled (probably at the time they were constructed) by a very distinctive coarse yellow sand that was reddened and blackened by heat in the area closer to the furnace.

The southwest corner of the Furnace House was a focus of some as-yet poorly understood activity during and after its demolition, probably in the late 1700's. Several recumbent sections of mortared stone walling lay inside and outside the building where they had either collapsed or been deliberately torn down. Evidently quite soon after this, two dry-stone revetment walls were built, extending from the southwest corner of the House in a southwesterly direction. These walls incorporated large squared pieces of steatite, well known for its use as an insulating material which can function safely at temperatures up to 2,000° F. These are very probably from the furnace. The deposit also contained substantial massive pieces of curved ferrous metal bar. These have yet to be analyzed to establish their chemical composition. The current consensus is that they are either anconies (partially hammered iron bars), or, more likely, pieces of the furnace or forge grates.

The rectangular brick and stone structure along the north side of the Furnace House might be interpreted simply as a finery forge, perhaps converting some of the blister into shear steel, and possibly heated with water-powered bellows placed immediately to the south We now argue however with some confidence that this feature is indeed the base of a small cementation furnace: the only archaeologically documented example from Colonial America

The other major structural feature on the site, indeed the one that speaks most to the importance of water-power here, is the spectacular wheel-pit from the paper mill that was established here in 1827 and in operation until 1876. In contrast to the earlier colonial buildings, the wheel-pit was built of finely cut and rusticated red sandstone, probably from quarries just northwest of Trenton. This material is extensively used later on in the century when the Delaware and Raritan Canal (1830's) and railroads (late 1830's and 1850's) made transportation of bulk materials easier. Documentary evidence references at least two rebuilds of the wheel-pit and wheel before 1876, and it would be interesting to know if the masonry we seen in the pit does indeed date to before the 1830's.

Chapter 5

Brownstone Quarrying Industry in the Wilburtha District and City of Trenton, Mercer County, NJ

by J. Mark Zdepski, CPG

Abstract

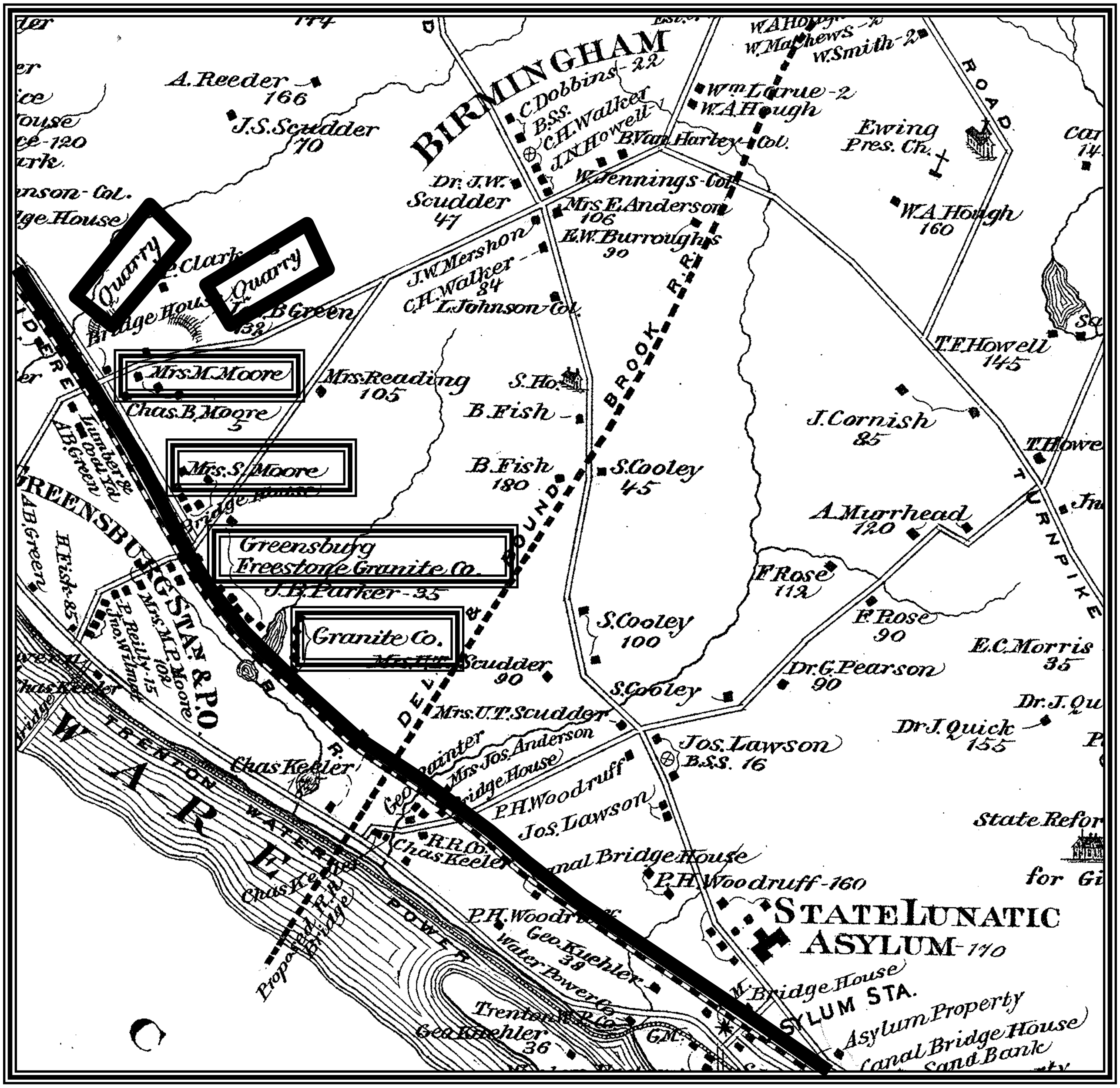
Brownstone quarrying in Triassic sandstones took place in the Wilburtha District from before 1791 until 1932. The construction of the Delaware & Raritan Feeder Canal between 1832 and 1834 provided both a market and transportation for the production of the five quarries along it. Quarry operations in Wilburtha were often paired with stone yards in the West Ward of Trenton. Quarrying in Trenton during Colonial times occurred in Precambrian aged gneiss and schist, but the later brownstone-cutting and staging took place in the same general area. In addition to local consumption, the output from the District was used in large government, institutional and railroad projects. The dip of 10° to 15° northwest caused the quarries to become elongate due to stripping of overburden along strike and economic depth limitations in the downdip direction.

Introduction

The Triassic Stockton Sandstone and Juro-Triassic sandstones of the Passaic Formation were important for supplying building stone used in private homes, civil projects, ecclesiastical, governmental and institutional buildings. Triassic sandstones of the Newark, Connecticut and Gettysburg sedimentary basins have been termed “brownstones” by the architectural, design and construction professions. Quarries in Mercer County were particularly productive due to favorable geology and the proximity to both the Delaware & Raritan Feeder Canal and the Belvidere & Delaware Railroad **(Figure 1).**

Early Quarry Industry

This area was originally known as Greensburg (Everts & Stewart, 1875), but in 1883 was renamed Wilburtha as an amalgam of the first names of Wilbur and Bertha Fisk, children of investor and resident Harvey Fisk (Britton, 1993a). Mr. Fisk’s estate is now Villa Victoria Academy. The first reference to quarrying in the Wilburtha area comes from a short memo in the Ewing Presbyterian Church archive which notes the foundation stones of the original edifice were carted from the quarry of John Clark on Upper Ferry Road in February 1791 (Felcone, 1991). Some local quarrying existed in earlier colonial times because the Ewing Presbyterian Church has brownstone grave markers dated from at least from 1735 through 1820's (personal inspection).



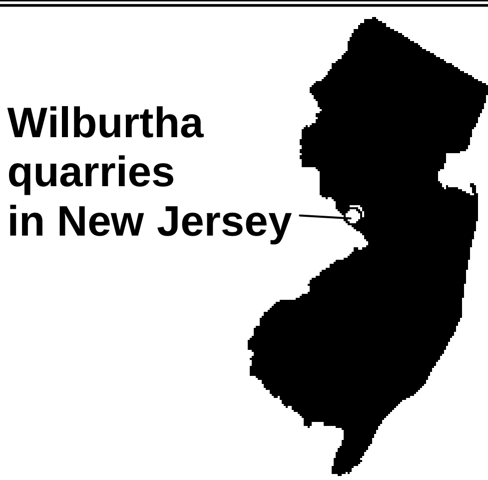


Figure 1. Wilburtha and Trenton quarry locations shown on Evert's & Stewart base map from 1875. D&R Canal is emphasized. Location in New Jersey is shown to the left.

The New Jersey Register (1837) notes that The State Prison, Green's and Hill's quarries are all present along the Canal northwest of Trenton. This is the only document that mentions a "State Prison" quarry and it may be referencing the Moore Quarry. In 1801, a will gave William Green the right to a quarry and an access road to Upper Ferry Road (Felcone, 1983). The quarry locations shown on Everts & Stewart (1875) can be found on aerial photographs and on the ground today **(Figure 1).** William Green's quarry appears to have been previously owned by John Clark. Colonial quarries (1744, 1767) within the City limits of Trenton are referenced in newspapers (Sunday Times Advertiser, 1945), and dissertations (Toothman, 1977), but usually with very poor location information. These early quarries did not mine brownstone. Courthouse Deed searches were beyond the scope of the research conducted for this article.

Features Favorable to Quarry Industry

The geological features which contribute to a profitable brownstone quarry operation are: orthogonal jointing, thick sandstone beds (from 7 to 30 feet in Wilburtha (Cook, 1881)) and few shale interbeds. A shallow dip and thin overburden are also desirable, as these minimize the stripping ratio. Overburden and unmarketable broken stone were often left in the quarry, being pushed or stacked on the footwall-side of the deepest mining horizon. Gravity drainage of the groundwater is also a desirable feature. The presence of cheap transportation is a major consideration in siting a quarry. Performance of the stone during compression tests and fire tests was important for the product to be accepted for heavy civil projects and railroad construction (McCourt, 1906). All of these qualities are present in the Wilburtha District.

Wilburtha District and Trenton Stone Yards

The Wilburtha quarries were subordinate in output to the Newark and Bellville (Nutley) quarries in 1880 (US Tenth Census), but was ahead of those in Stockton. The Delaware & Raritan Canal completion in 1834, the Belvidere & Delaware Railroad in 1851 and the Delaware River below the fall-line allowed the Wilburtha quarries to export stone from the region. The quarry of John Clark (1791) and William Green (1821) were in a perfect position to profit from the construction of the D & R Canal. The canal naturally tied the Wilburtha quarries to markets in Trenton and beyond. John C. Grant operated a quarry in Wilburtha and had a large stone cutting yard on West Hanover Street (Britton, 1993b; Sunday Times Advertiser, 1942), next to a stone yard operated by Keeler, another Wilburtha quarry operator (Scarlet & Scarlet 1891; see **Figures 2 and 5).** S. B. Packer and H.S. Booz also operated stone yards adjacent to the Feeder Canal and were dealers in "Trenton Brownstone" which originated in Wilburtha quarries (Everts & Stewart, 1875; Scarlet & Scarlet, 1891; Sunday Times Advertiser, 1942). The stone yards were located in the East Ward, in areas that had been quarried in Colonial times.

Cook (1868) counts five quarries "near Greensburg", which correspond with the 1875 Atlas (Everts & Stewart) locations and notes they are mining red shale and feldspathic sandstone with a few beds of conglomerate. The sandstone units varied from three to seven feet thick and were noted to have a dip of 10° to 15° degrees north,

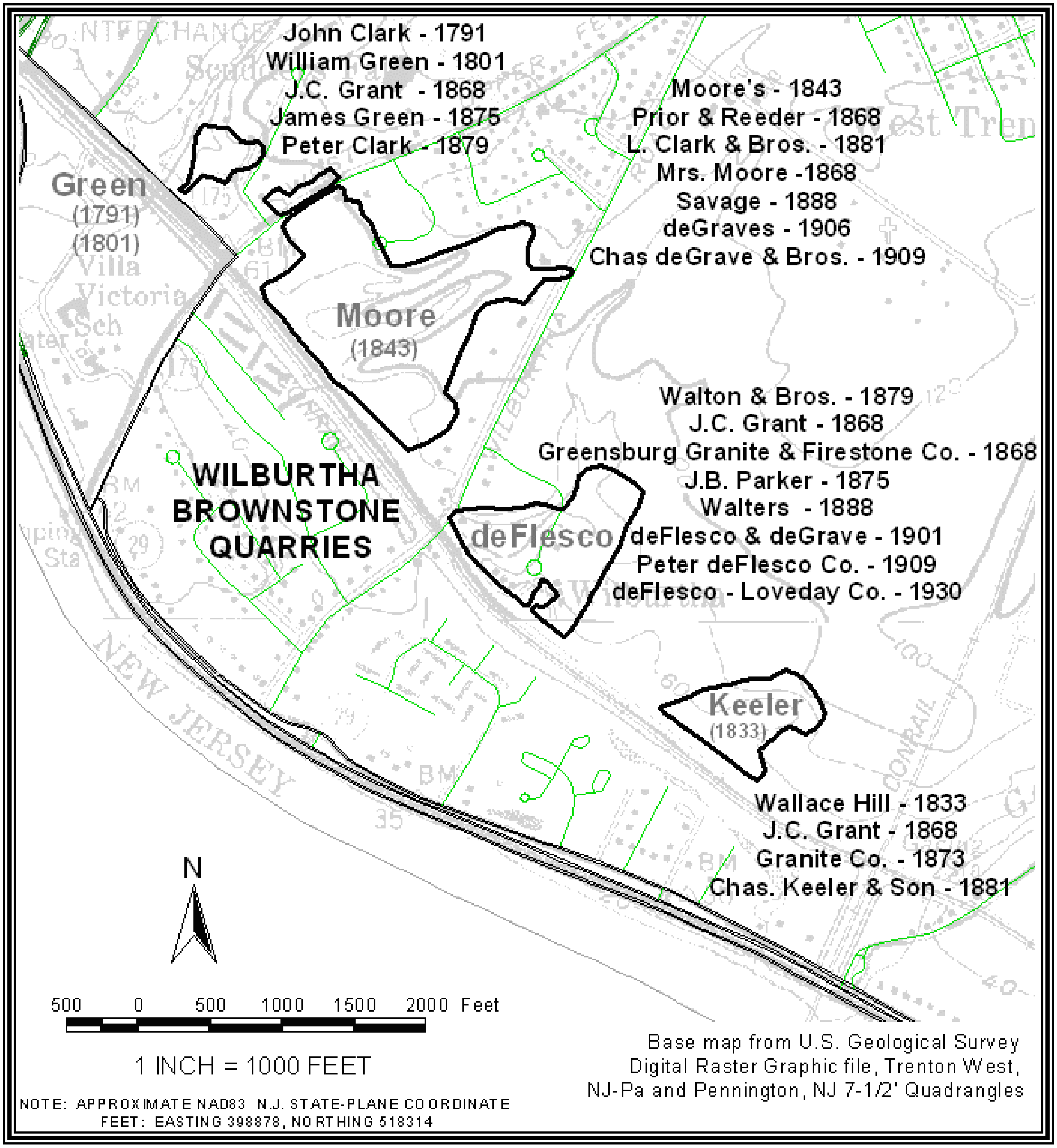


Figure 2. Individual quarry operations showing the names used in this article, the dates of opening, and the lists of operators through time.

striking N70E. These five quarries were all mining separate beds, with the stratigraphically oldest in the south. The quarries were noted as having 10 to 15 feet of drift cover. The earliest quarries must have been developed at outcrops (such as the John Grant and Green Quarry). Some of the sandstone surely was discovered during the excavation of the D&R Feeder Canal during 1832-1834, as the Canal Company purchased right-of-way from an early operator in the Moore Quarry area and the Keeler Quarry (Sec. of State Archives, 1833-1934). The Canal Co. contracted with the four members of the Hill family in 1833 for access to a preexisting stone quarry on the northeast side of the canal (Sec. State Archives, Agreement, 1833). This is most likely the Keeler Quarry shown on Figure 2, although it is listed as being in Trenton, not Ewing Township. Both the deFlesco and the Keeler Quarries had turning basins for loading and collecting canal boats (Sec. State Archives, 1934).

The Central Sheet of the NJ Geologic Map (Owens and others, 1998) shows minor N10°E faulting in the Wilburtha area, but none that cause stratigraphic repetition (Figure 3). Fault fracturing or brecciation is undesirable in a quarry, so operators and geologists should have been looking for features that affected the market value of the product. These faults were not recognized by the well-trained primary observers who were present when the maximum exposure of stratigraphy was present in the quarries (Cook, 1881, pg. 58). The sandstone mined in Wilburtha varied in color from light gray to brown to red (Cook, 1868; Lewis, 1909). A table of dips (State Geol., 1882) lists dips from 10° to 15° degrees to the north-northwest and a strike of N80° to N70°E (Figure 4). The orthogonal jointing made this stone easy to quarry by simple wedging, with dynamite only being used to "throw down" shale waste and the drift overburden in several of the quarries (Cook, 1881). This type of sandstone occurrence was termed "freestone", due to its accessibility, ease of removal, and minimal need for dressing.

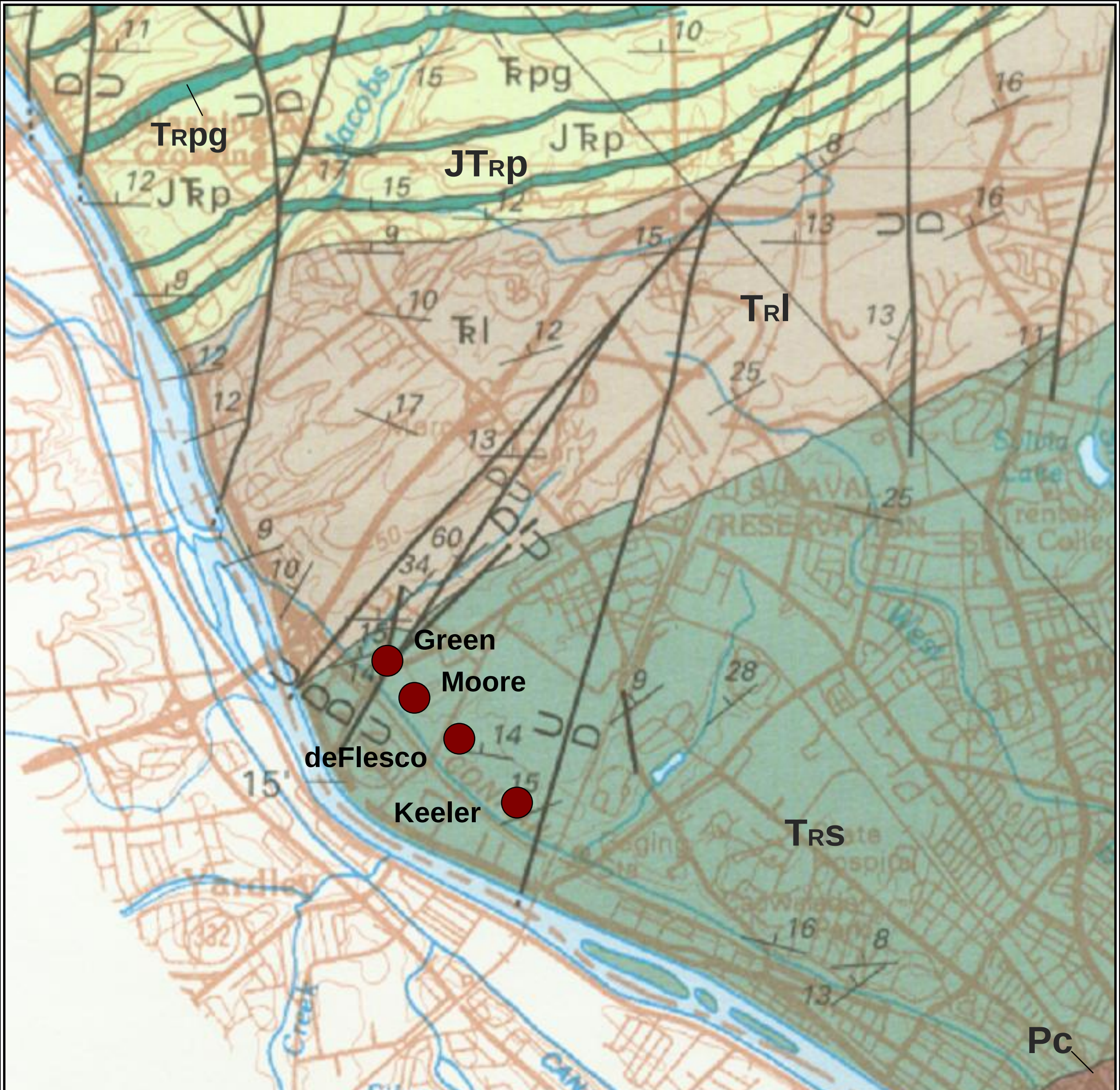
In the southern Keeler quarry (Figures 2 and 3) the operator did blast with black powder. Cleary (1921), reported that in April 1871 operator John C. Grant invited 40 "prominent" guests to view a blast that took 65 kegs of powder weighing 25 pounds each. The blast threw out 22,000 perches (a volume measure of 25 cu.ft.; Cook, 1881, p. 60) of stone and loosened 40,000 perches weighing together 150,000 tons in total. Although the article is not clearly written, it appears that the powder was placed into a "fissure in the rock...two inches wide, thirty feet deep and 55 feet long from end to end" (Cleary, 1921). Black powder was preferred over dynamite by the brownstone quarrymen as the propagation of the blast did not shatter the stone as was the case with dynamite (Lamotte, 1930; Shuck Family Papers, 1957). The 1850 Census "Products of Industry" for Mercer County shows that William Philips inventoried 6,000 perches of stone and 30 kegs of black powder, while John Grant had 10,000 perches of stone, 50 kegs of black powder and 4,000 fuses (Sec. State Archives, 1850). Two stone cutters are noted in the East Ward of Trenton (Sec. State Archives, 1850).

Two quarries were noted as having fossils of the crustacean estheria ovata found in brick red-weathering dark-gray shale horizons (Cook, 1888). Poorly preserved plant remains, as well as fish scales and spines were also noted in the same horizons (Cook, 1888). Our examination of the Moore quarry during 2010 located plant remains in shale waste-rock, but soil and vegetative cover hampers any attempt to locate the thin (2-inch) fossiliferous black shale horizon mentioned by Nason, (in Cook, 1888).

The location of the Trenton stone yards in relation to Wilburtha are shown on **Figure 5.** As mentioned, these stone yards are clustered in an area that was first quarried in the Colonial years. West Hanover and the nearby Cook's Basin east of Perry Street were the sites of J. C. Grant, Keeler (Everts & Stewart, 1875; Scarlet & Scarlet, 1890) and S.B. Packer stone yards (Scarlet & Scarlet, 1890). Also in this area were H.S. Booz, B. Ridgeway, Dwyer & McMahon and Prior & West, all stone dealers (Potts, 1874). S.B. Packer earlier operated a stone yard between Feeder Street and New Brunswick Avenue along the Canal near the present day Route 1, where now the canal is within a box culvert (Everts & Stewart, 1875). A cross-check between owners on Figure 2 and the stone yard operators above shows that Grant, Keeler, Prior and Packer are names on both lists.

Trenton was the site of several quarries, with West Hanover Street being known as Quarry Street or Quarry Alley as late as 1891 (Scarlet & Scarlet, 1890). A quarry was present at Academy and Prospect and other quarries were in "Camptown" the intersection of present day West State and Calhoun Streets. Quarries within the City of Trenton plot on the subcrop expression of the middle Proterozoic Trenton Prong metamorphic rocks (Unit Yg). This map unit contains everything from granite gneiss to graphite schist and marble (Owens and others, 1998). The quarried stone was noted as being the "of a flinty gray type, like... in the Old Barracks and some other buildings in the western section" (Sunday Times Advertiser, 1945).[1] These quarries, just north and west of the State House disappeared under urban development, including the Peabody School and brick homes (Sunday Times Advertiser, 1942, Scarlet & Scarlet, 1891, Figure 5).

[1] We examined the Old Barrack walls and found them to contain schistose siliceous metasedimentary rocks with an apparent subordinate calcareous component. The calcareous rocks are inferred from differential weathering taking place high on an east-facing wall.



Base map from: Owens, J.P., Sugarman, P.J., Sohl, N.F., Parker, R.A., Houghton, H.F., Volkert, R.A., Drake, A.A., Jr., and Orndorff, 1998, Bedrock geologic map of central and southern New Jersey, U.S. Geological Survey Miscellaneous Investigation Series Map I-2540-B, scale 1;100,000

Explanation:

JTRp - Passaic Formation
TRpg – Passaic Formation gray bed
TRl - Lockatong Formation
TRs - Stockton Formation
Pc – Precambrian

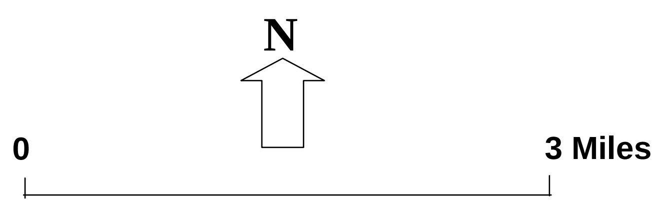


Figure 3. Wilburtha quarry locations superimposed on the current New Jersey State geological map.

Discussion

The popularity of brownstone covered a long interval between the 1700's and 1920's, but its use as a building material peaked in the 1870's. By the 1850's problems were already appearing with crumbling and disintegration in some applications (Lockwood, 1972). In the 1880's and 1890's, spalling occurred soon after sawn veneer blocks were placed with the bedding planes oriented vertically. This practice was adopted by architects and contractors trying to achieve an even color and texture across the entire building front. The natural variability of the calcareous cement in the sandstones contributes to spalling in some rocks. Also, in the rush to boost production during a boom, perhaps some quarry owners began selling weaker and less indurated variants. Brownstone is subject to chemical (from carbonic acid formation) and mechanical attack (force of crystallization) from use of salt for de-icing. Cook (1868) stated that "the red sandstone in the vicinity of Newark has been used as a building stone ever since the first settlement of the country. The first Presbyterian Church, which was built in the last century, and for a long time was the largest church in the State, was built of this stone, and still is a conspicuous sample of its good qualities." Older buildings built from blocks with the bedding planes oriented on the horizontal are much more resistant to weathering, but some spalling does occur.

The hand-method of quarrying is called “plug and feather”, or “wedge and feather”, and it involves drilling closely-spaced vertical holes in a line to cut blocks by wedging and then drilling horizontal holes and wedging up to loosen them along bedding (Figure 6a). Hoisting was done by wooden derricks called stiff-legged cranes that were hand-powered, and later steam-powered (Figure 6b). In-pit hauling and local delivery was done with small animal-traction wagons and carts (Figure 7a). Bulk delivery from Wilburtha was made by rail car and canal boat (Figure 7b). Fine cutting and dressing of stone was done at remote locations and at building sites. Carving and polishing for monuments was accomplished in specialized shops, only rarely associated with the quarry operation. No reference located in this study indicated any carving or polishing occurred in the Wilburtha District.

The individual quarries changed hands many times as seen in ownership lists on Figure 2. This suggests that the quarry business is difficult. Individual family groups did keep control of some sites, with tenant operators and changing business entities working the sites. The final operators in Wilburtha District were the deFlesco and the deGrave families, with the deFlesco-Loveday Co. business name persisting until the death of President Thomas Loveday in 2007. Both of these families had members that had worked in the Moore Quarry before creating a partnership, then splitting to become competitors. Both family names are Welsh, but the deFlesco’s emigrated from France (Felcone, 2010, pers. comm.). The deFlesco-Loveday operation finished business in 2007 as a kitchen counter top fabricator, using imported stone.

In 1903, the deGrave family was photographed at what appears to be a Sunday picnic excursion in the Keeler Quarry (Figure 8a). A 1930 vertical aerial photography (Permanent Notes of State Geologist, 1930) shows that all the quarries in Wilburtha were overgrown with vegetation, except a small portion of the deFlesco Quarry. When the NJ Geological Survey visited deFlesco's in the 1930's they were using steam power to operate a metal stiff-legged crane (Figure 8b), but there was water in the pit and vegetation is growing in areas that should be highly trafficked, indicating intermittent usage of the quarry.

The Wilburtha quarries all became linear as the operators followed the strike of the thick sandstones once they reached the stripping limits on the down-dip extension of the beds. The Moore Quarry, the largest has at least one septum of unquarried material separating two linear pits that are 40 feet deep at the high wall ends. This trend can be seen on the USGS 7.5 min. topographic quadrangle (Figures 3 & 4). One of the Green, the Moore and the Keeler Quarries are still in the state the operators left them prior to 1930. The other Green Quarry along West Upper Ferry Road is filled and developed, the deFlesco Quarry was re-graded and developed as the Mansion Hill subdivision in the mid-1980's.

The precipitous decline in the quarry business is chronicled by the NJGS Mineral Bulletins, but it is best summed up in Bulleting 31 , Mineral Industry 1926 -

> The seriousness of the decline in New Jersey's building-stone industry is reflected in the figures for the combined value of the sandstone and granite production. In 1908 that production was valued at $280,226; whereas, in1926 the reported production was valued at $77,308. When one considers that the purchasing value of the dollar at present is only half of what it was in 1908, the actual decline in the building stone industry is seen to be even more severe than the figures would indicate.

The brownstone quarry industry was finished off by the Great Depression, both deFlesco and Raven Rock (Chas. T. Eastburn Co.) were the last operators and both closed by 1932. At the time of closure, the former was making building stone, the latter large blocks for jetties in Asbury Park and Belmar. The nearest quarry occasionally working Triassic brownstone today is the Delaware Quarries in Lumberville, PA, directly across the Delaware River from Bull's Island State Park and the Raven Rock Quarry.

It seems that none of the written accounts of buildings constructed from the Wilburtha Quarries production are very specific as to the exact quarry. Most of them credit the quarry of origin to the deFlesco Quarry, perhaps because deFlesco's were interviewed the most often. With more historical research the following list could no doubt be expanded and refined:

New Jersey State Prison	-	1836
Trenton State Psychiatric Hospital	-	1848
Ewing Presbyterian Church	-	1867
Fisk Victorian Manor (Villa Victoria)	-	1869
St. Mary's Catholic Church	-	1871
St. Elizabeth's Convent, Philadelphia	-	1891
Ewing Cemetery Wall	-	1910
Penna. RR viaduct, New Brunswick	-	Not Given

The brownstone industry played an important part in the development of Trenton and Ewing Township. The product of quarrying is durable with reminders visible from many streets today. As a whole, the industry is documented in sketchy and difficult to find sources.

Acknowledgements

Pierre Lacombe suggested that the Wilburtha District could be a subject of a GANJ article in the face of my initial skepticism; he deserves thanks for the gentle push. Jim Brown and Mike McGowan compiled brownstone quarry information and created a data-base that is linked to an ArcView map as part of general research and a previous talk. Matt Metcalf and Wendy Nardi of the Trentonia Room of the Trenton Public Library opened their files during a move and provided Figure 7A. The Ewing Historic Preservation Society generously copied records and provided Figure 8A. Other historical photographs (except Figure 7B) came from the Permanent Notes of the State Geologist and at different times Dick Dalton, Bill Graff and Dan Dombroski provided access to these valuable resources. The staff at the Secretary of State Archives always cheerfully pulled maps and other records for examination. Research for this paper could not be completed without the efforts and generosity of these individuals.

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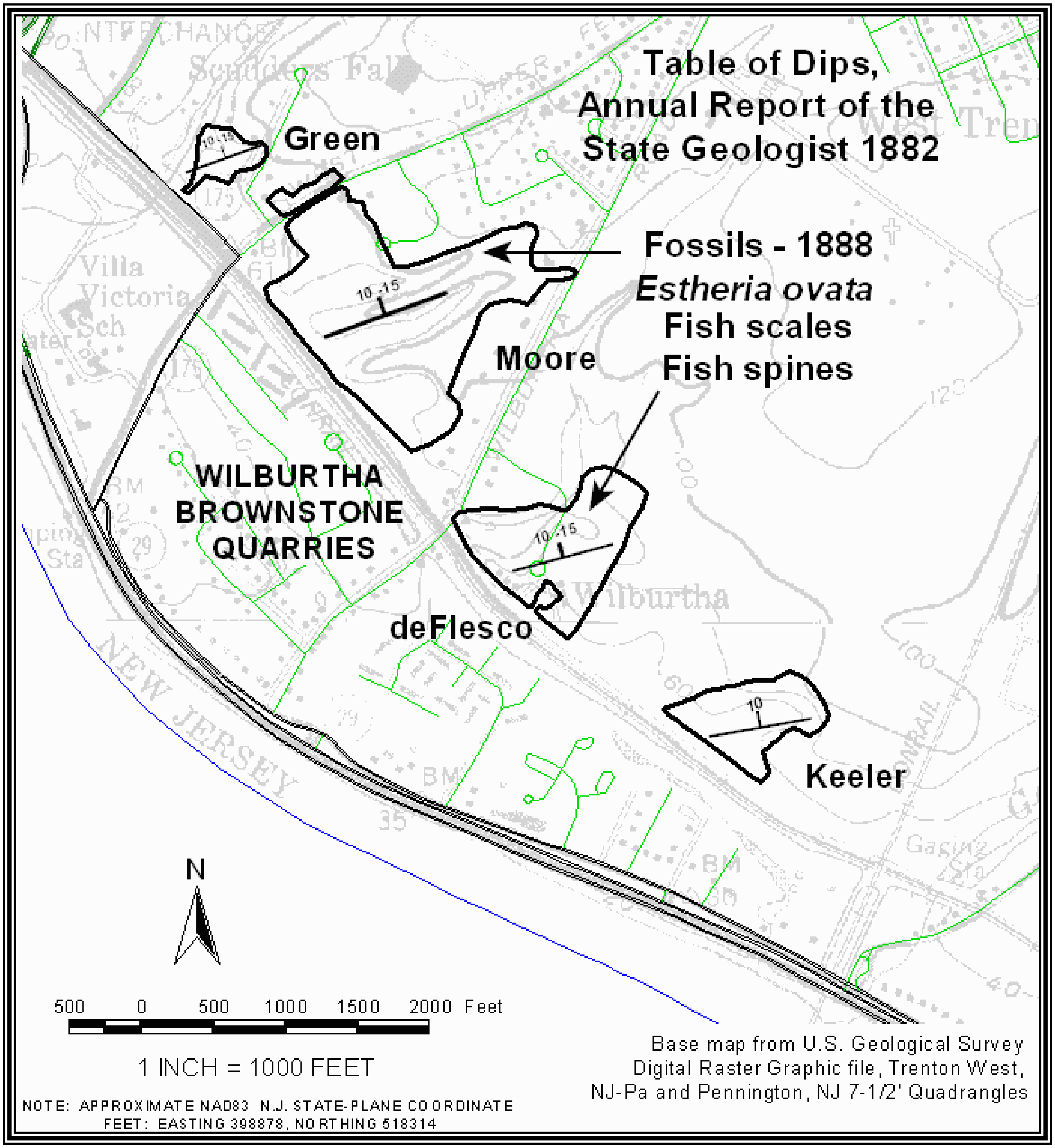

Figure 4. Wilburtha quarries with measured dips and indicating reported fossil locations.

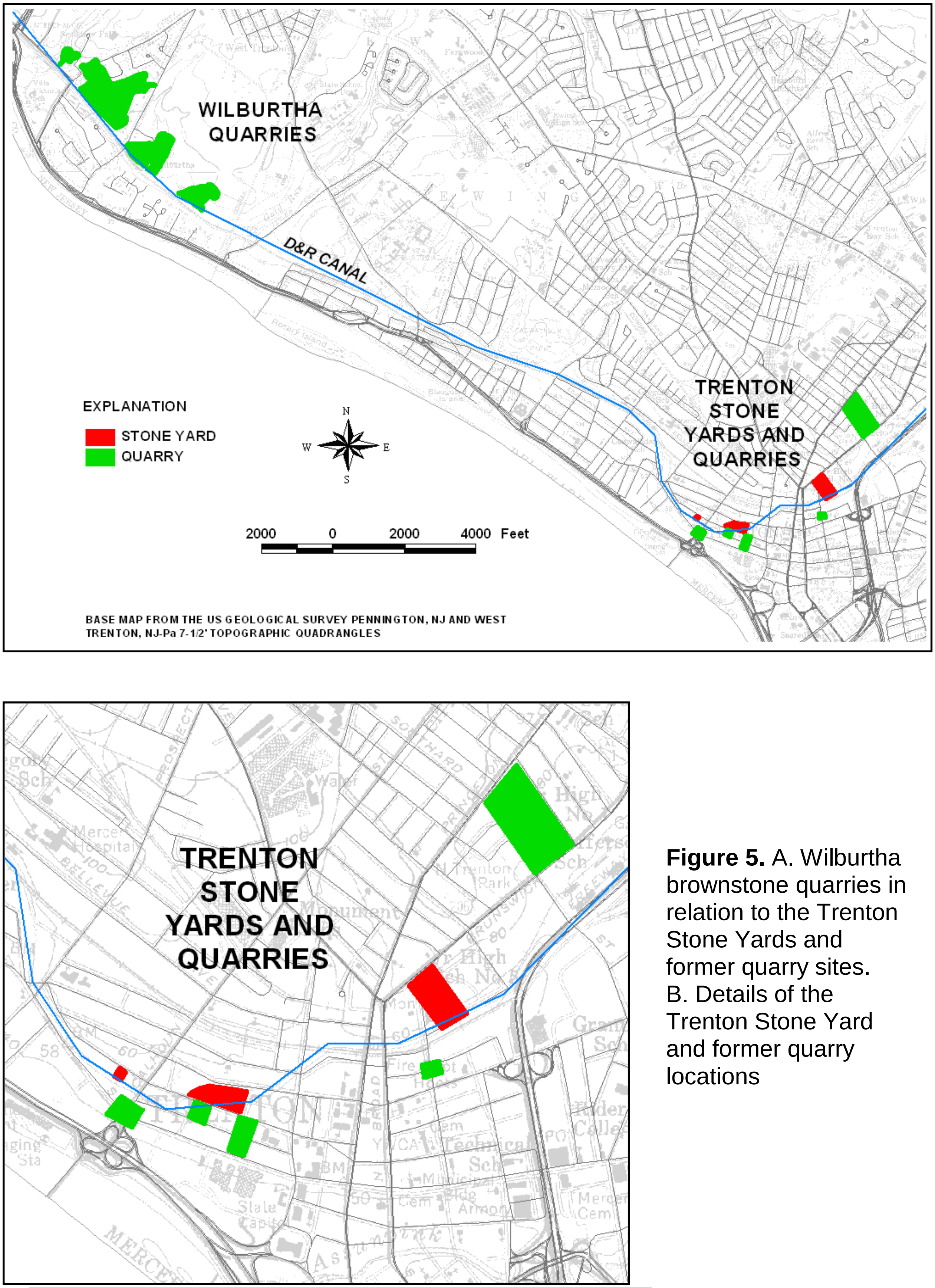

Figure 5. A. Wilburtha brownstone quarries in relation to the Trenton Stone Yards and former quarry sites. B. Details of the Trenton Stone Yard and former quarry locations

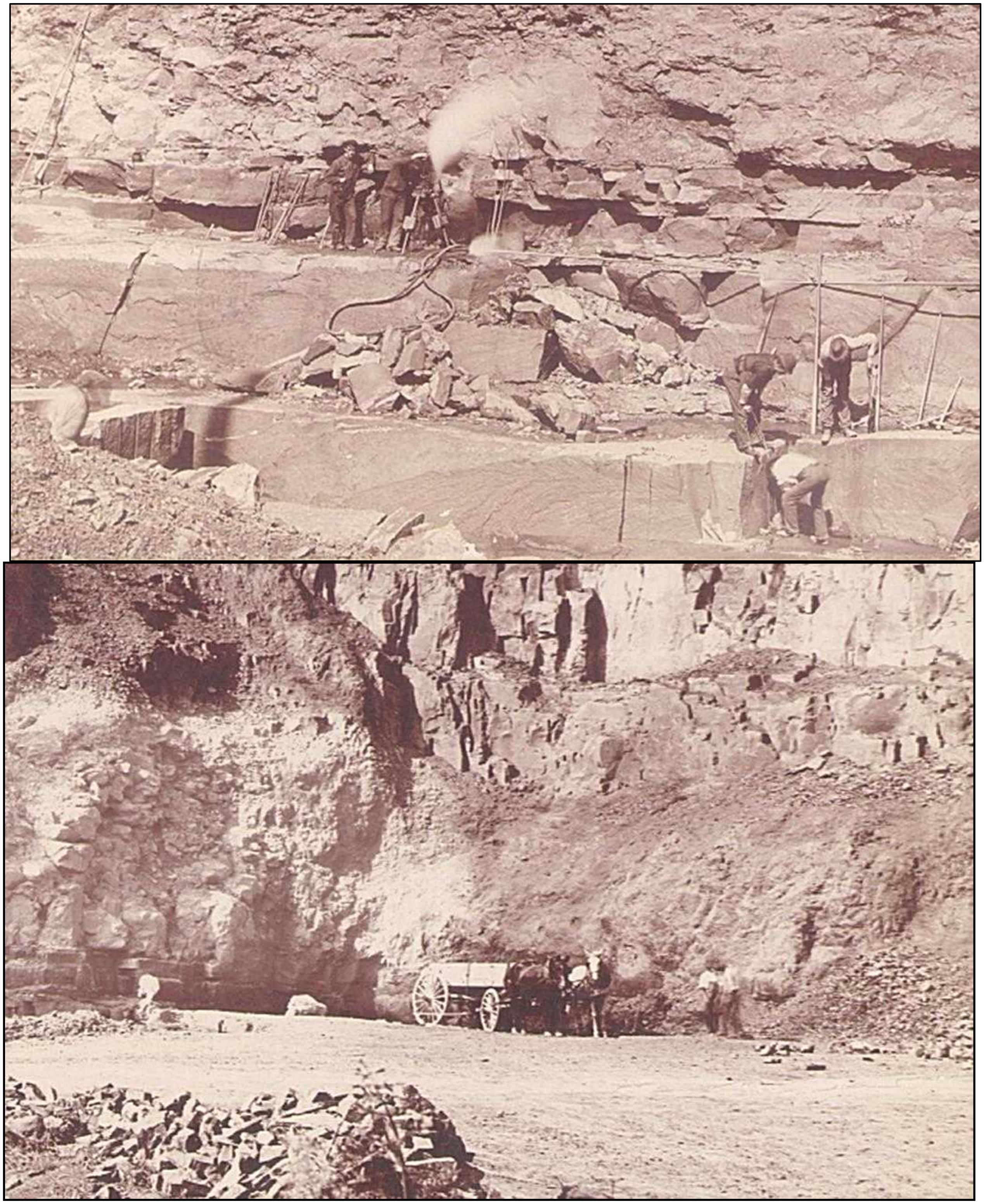

Figure 6. Montclair brownstone quarry operations circa 1905. A. Wedge and feather quarrying of blocks with a steam drill on one bench drilling vertical holes and a crew on another bench working on horizontal holes. B. Wagon team in the Montclair brownstone quarry.

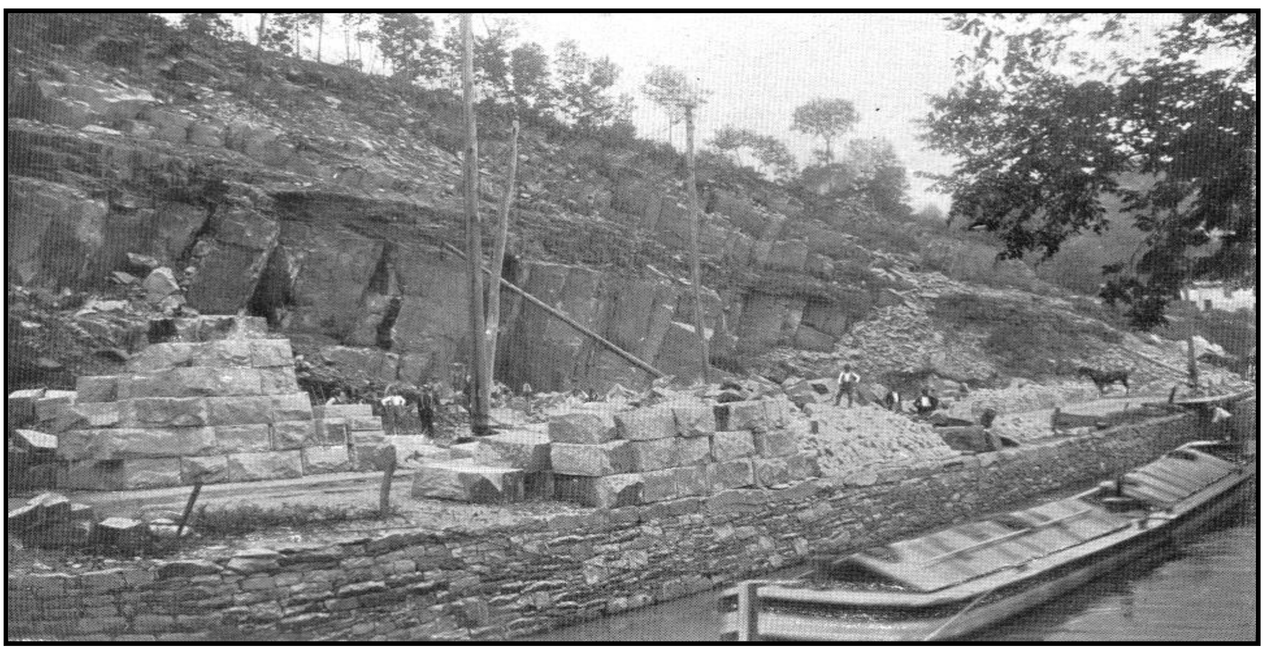

Figure 7. A. A Penna. RR Quarry in Stockton, w/ three stiff-leg cranes and gondola cars spotted for loading, note the dip and blocky fracturing, the crews in the pit and at the rim on the right. A man in the right foreground is probably rigging a boom (across the foreground) for a fourth crane. B. Loading facilities at Paxon's quarry along the canal at Lumberville, Pa., note the cranes and stacked, dressed blocks. The thick sandstone bed dips into the quarry pit and is capped with shale, all overburden is stripped.

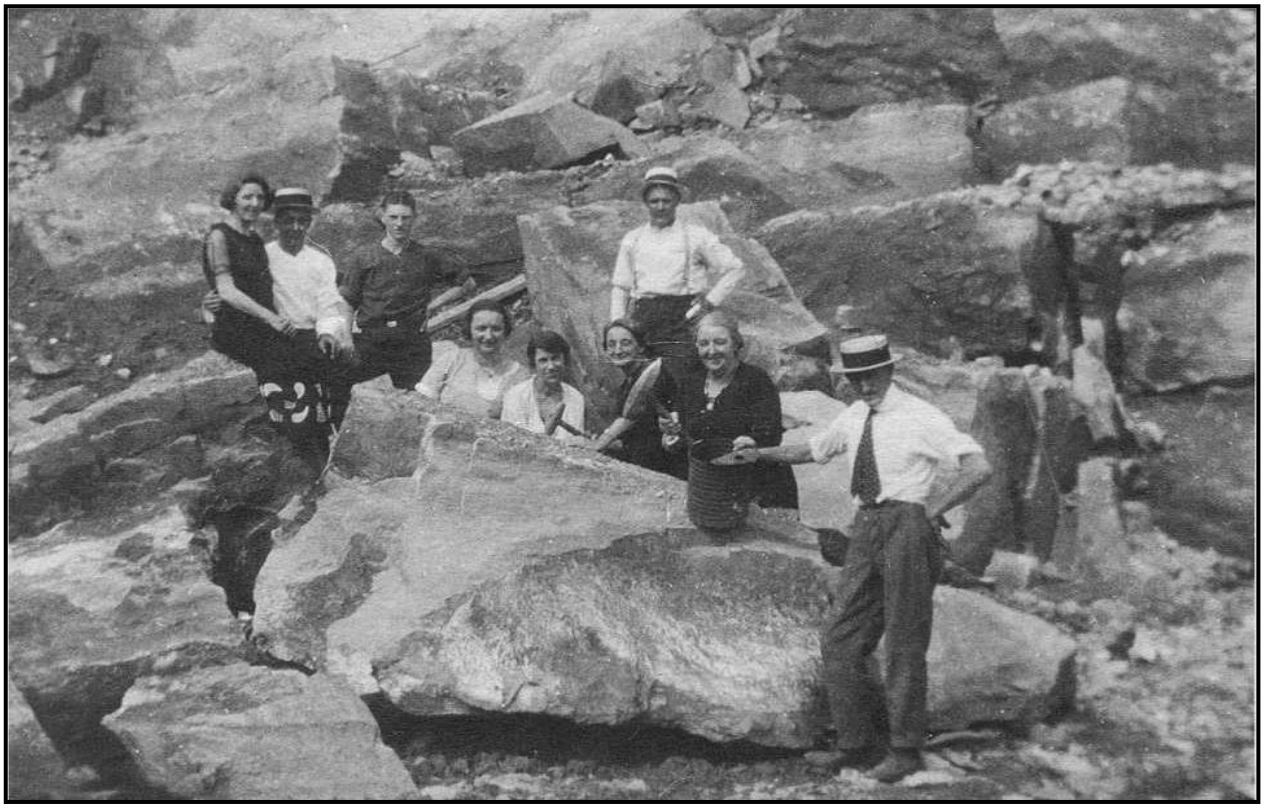

Figure 8. A. deGrave family picnic in the Keeler quarry. Man on right is resting his hand on a black powder can. The woman second from right wields a stone axe and the woman third from right holds a drill hammer. B. deFlesco quarry circa 1930, the steam engine and stiff-legged crane are loading a truck.

Chapter 6

Trenton as a Transportation Nexus and Seat of Hydropower

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The history of Trenton may be presented as a study in geological and geographical and topographical determinism. The pattern of rocks and drainage that underlies the modern city explains much of Trenton's historical development and also the attraction of this section of the Delaware Valley to Native Americans. Settlement and industry in the Trenton area have evolved in response to the "falls of the Delaware" acting as a point of transportational convergence in the natural and cultural landscape.

The falls of the Delaware, formed on the schist and gneiss outcroppings in the bed of the Delaware River between Trenton and Morrisville, represent the furthest downstream point on the river where a crossing may be achieved on foot or on horseback. A fine French map drawn by General Rochambeau's cartographer, Louis-Alexandre Berthier, in 1781 shows the route of the "gué" or ford at the time of the American Revolution. From the late 17th century through to the early 19th century ferries, upstream and downstream of the falls, carried freight and less nimble travelers across the river en route by land between Philadelphia and New York.

In 1804-06 the first bridge across the Delaware at Trenton was built, its supporting structure securely set into the hard rock of the falls. Used first for pedestrian and wagon traffic, the bridge was later adapted to carry rail traffic as well. Today's "Trenton Makes" bridge, erected in 1928, occupies the same alignment as the early 19th-century span and incorporates the original piers and abutments. Another pedestrian and vehicular bridge followed at the Calhoun Street location at the upstream end of the falls in 1860, replaced in 1884 by the iron span that still survives today. The Pennsylvania Railroad bridge, at the downstream end of the falls, was built in 1903; the Trenton-Morrisville toll bridge on the Route 1 Freeway opened in 1952.

Hand drawn map showing path of ford across the Delaware River at Trenton

The falls also mark the head of tide and the head of navigation on the Delaware. Anadromous fish moving upstream from the ocean to breed (notably sturgeon, alewife and shad) spawned in abundance in the river below Trenton and in the tidal wetlands at the mouth of Crosswicks Creek. This led to intensive occupation and fishing activity by Native Americans along the riverbanks, expressed now in the archaeology of the Abbott Farm National Historic Landmark in the Hamilton/Bordentown area. Fishing in this section of the Delaware was also a vital element in the colonial economy, both above and below the falls. Today, the springtime shad runs are but a vestige of a once thriving industry.

At the falls, portage was required of Native Americans traveling on the Delaware in canoes and dugouts. In the colonial period, the oceangoing, coastal and larger river vessels of European settlers and traders could navigate no further upstream than the wharves at Lamberton or the dock at the foot of Ferry Street. Iron ore, bar iron and pig iron from the mines, forges and furnaces of the New Jersey Highlands and northeastern Pennsylvania could be shipped in shallow-draft vessels as far as Trenton, but then had to be off-loaded above the falls, reloaded on to vessels below the falls, or transported onward overland. Rafts of lumber cut in the Upper Delaware were poled downstream and, with skill and daring, could just about survive the rapids at the falls during the spring freshets.

Prior to the Industrial Revolution and improvements in hydropower technology the Delaware River at Trenton was too large and unruly a waterway to permit any harnessing of its flow for industrial energy purposes. However, its tributaries lent themselves well to the founding of individual mill seats at key locations where steep stream gradients existed on the local geology. Trenton originated as a settlement clustered around a gristmill established by Mahlon Stacy on the Assunpink Creek in 1678. This mill was sited at the point where this stream tumbles over a ledge of schist bedrock down into the Delaware River floodplain. Other similarly situated early mills are evident on nearby Petty's Run, Black's Creek and Jacob's Creek, all first-order tributaries of the Delaware.

In the second decade of the 19th century, a wing dam was built in the Delaware at Trenton and water was siphoned off to power a new gristmill next to the Trent House, just downstream of the mouth of the Assunpink. The most ambitious water power development, however, took place in the early 1830s when the Trenton Delaware Falls Company constructed a seven-mile-long canal from Scudder's Falls along the left bank of the Delaware and into downtown Trenton. This power canal was designed to service industrial development at several potential mill seats at the mouth of the Assunpink, where a fall of roughly 14 feet was engineered, and it continued on for another mile or so downstream to the area between modern Federal and Cass Streets, where an 18-foot fall was available for another cluster of mills.

The Trenton Water Power, as the canal later became known, helped spur Trenton's emergence as a manufacturing center in the 19th century. No fewer than 20 different facilities made use of the water power, including several textile mills, gristmills and sawmills, a number of ironworking businesses, and the city's water pumping station. The dominant user, which effectively controlled the Trenton Water Power Company from the mid-1840s onwards, was the immense rolling mill of the Trenton Iron Company (later the New Jersey Steel and Iron Company) located at the furthest downstream point on the canal. This factory, just one of many in the Cooper, Hewitt & Company industrial empire, is best known for first mass-producing iron rails for the railroads and structural iron and steel for multi-storied buildings. The sole survivor of this enterprise today is a machine shop built in the early 1870s, adapted into the Katmandu restaurant. Very little also remains of the water power canal, now mostly lying beneath Route 29.

The Trenton Water Power is not to be confused with Trenton's other better known and far better preserved waterway, the Delaware and Raritan Canal. A 66-mile-long water transportation system built between 1830 and 1834 (the exact same time as the Trenton Water Power), the Delaware and Raritan Canal was designed to allow boats to pass between Bordentown on the Delaware and New Brunswick on the Raritan, thus avoiding an often hazardous and much longer coastal trip. The canal defined much of Trenton's physical growth in the 19th-century and also strongly influenced the development of the regional railroad network.

Trenton lay at the hub of the Delaware and Raritan system. A 22-mile-long feeder canal tapped the Delaware River at Bull's Island, ran along the left bank of the river to Trenton and there delivered water into the upper level of the canal's main line between Bordentown and New Brunswick. The Delaware and Raritan Canal, unlike the Trenton Water Power, was primarily intended for freight transportation usage. Indeed, the Trenton Water Power was likely built as a separate energy system specifically to avoid or limit the use of water in the Delaware and Raritan Canal for powering Trenton industry.

For some three decades the Delaware and Raritan Canal co-existed with the Camden and Amboy Railroad under the "joint companies" arrangement that enabled these two transportation ventures both to be built in the early 1830s. By 1839 the Camden and Amboy had constructed a branch line along the bank of the main canal through Trenton, and in 1851 the Belvidere-Delaware Railroad likewise opened a line adjacent to the Feeder Canal. Together, canals and railroads framed the growth of the city for the balance of the 19th century, acting as magnets for new factories which could easily ship in raw materials and fuel, and ship out finished products. In this manner Trenton's celebrated industries – pottery, iron and steel, and rubber – all rose to prominence and provided the impetus for accompanying residential and commercial growth.

Chapter 7

Possible Investigations of the Hydrogeology of the Lockatong Formation

Pierre Lacombe
U.S. Geological Survey

Introduction

Groundwater investigations at anthropogenic and natural contamination sites and at water supply locations generally describe strata at the site as part of the Stockton, Lockatong, or Passaic formations. The three Formations in central and western New Jersey are divided into 58 Members. Identification of a contamination or water-supply site by the Member or Members that underlie the site will permit a better understanding and investigation of the hydrogeology of the site and the Newark Basin.

Olsen, Kent, and others (1996) divided the three formations as follows: Stockton Formation, 4 members; Lockatong Formation, 12 members and Passaic Formation, 42 members. The Members of the Lockatong Formation and most members of the Passaic Formation in western and central NJ are laterally extensive for tens of kilometers.

Three rock core holes were completed in Mercer County NJ. (fig. 1). Each rock core hole was about one kilometer deep. The Princeton core collected about 2800 ft of the Stockton Formation and about 800 ft of the base of the Lockatong Formation. The core hole did not reach the metamorphic basement rocks. The Nursery core, located on Nursery Road in Hopewell Twp cored the full length (2,700 ft) of the Lockatong Formation and about 300 ft of the upper Stockton Formation (fig 2). The Titusville core collected about 2,600 feet of the base of the Passaic Formation and about 400 ft of the upper Lockatong Formation.

Each member of the Lockatong Formation (fig. 2) is a McLaughlin cycle, a 413,000-year orbital eccentricity cycle (deviation of a perfectly circular orbit (fig. 3). The McLaughlin cycles are composed of about 20 Van Houten cycles. Van Houten cycles are celestial induced deposition patterns based caused by changes in the climate as a result of the processional cycle of the earth (change in the orientation of the rotation axis). Each Van Houten cycle is made up of 3, 4, or 5 strata with specific cyclic characteristics.

Some strata or groups of strata are fissile and water bearing. Other strata are indurated and act as a semi-confining unit. Some fissile strata are the major conduits for contaminated ground water. Some strata are sources of natural contaminates such as arsenic and uranium.

Developing a method to first map the extent of the 58 members and then map the extent of strata in each member may have the long-term potential to evaluate the fate and transport of groundwater contamination, the contributing are to major supply wells, and the exclusion of strata with high natural contamination.

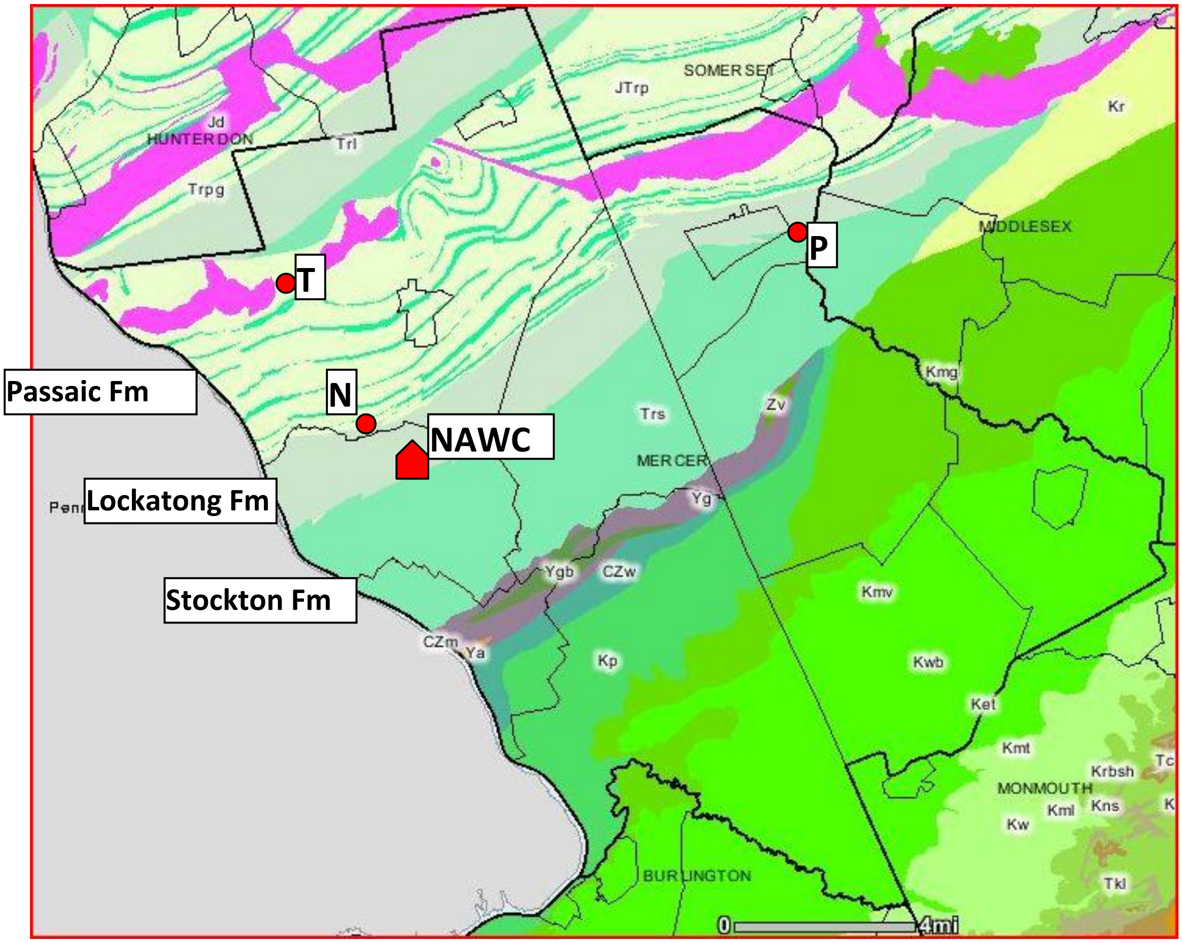

Figure 1. Map showing the Bedrock Geology of Mercer County and the location of the Newark Basin Core Project coreholes(N, Nursery Road; T, Titusville; P, Princeton) and the Naval Air Warfare Center (NAWC) Fractured Rock Research Site. Map accessed in September 2010 from http://njgin.state.nj.us/dep/DEP_iMapNJGeology/viewer.htm

Purpose for subdividing the outcrop area of the Lockatong Formation

Geologic maps of the Newark Basin historically show the Lockatong and Stockton Formations as monolithic bands of rock whereas the Passaic Formation is sometimes shown as a series of broad bands of red strata interbedded with numerous narrow bands of dark gray strata. Figure 1 is typical for the outcrop depiction of the Lockatong Formation.

Lacombe (1998) during fractured rock research at the Naval Air Warfare Center (NAWC) Ewing Township, Mercer County NJ developed hydrogeologic map and multiple sections of bedrock of the jet engine test facility. The maps and sections were based on geophysical logs and multiple rock cores.

Lacombe compared the rock core and logs with the Newark Basin Coring Project (NBCP) Nursery core and determined that strata at NAWC were the base of the Skunk Hallow Member, the Byram Member, and the upper Ewing Creek Member of the Lockatong Formation. Lacombe has used similar geologic correlations methods at contamination site for the US Environmental Protection Agency (USEPA) and was able to redefine the strata that the contamination was located in as specific members of the Passaic Formation in Central NJ.

It is proposed that the outcrop areas in western and central New Jersey could be subdivided into the Members of the Stockton, Lockatong, and Passaic Formations. This Member based subdivision of the Formations would assist researchers and regulators in their assessment of the thousands of groundwater contamination sites and hundreds of public-supply wells. Each contamination site and potable supply well could be assigned to a member or multiple members as opposed to the three major Formations. The method of division might be similar to the NJDEPs division of stream basins with Hydrologic Unit Codes (HUC). A contamination site such as at the NAWC would be in the Byram Member, not just the Lockatong Formation.

An extension of this concept is to subdivide the a Member into strata with individual identifiers. Lacombe identified the strata at NAWC based on rock color, rock type gamma ray signature and other characteristic followed by an identification number. Specific strata names within the Members at NAWC are black262, mas263, lam 272, red279, (black is a black, carbon-rich mudstone; red is a red massive mudstone; mas is a gray massive mudstone; and lam is a laminated dark-gray mudstone.

Hydrogeologic investigators often highlight specific strata that contain high concentrations of natural contaminants such as arsenic and uranium, strata with anthropogenic high concentration of contaminant. Public water companies try to avoid contaminated strata and use high production strata. However, Newark basin wide labeling of strata or groups of strata such as a Member is not done at this time.

Identification of the Members of the Stockton, Lockatong, and Passaic Members has been completed. Mapping the lateral extent of the Members would require a concerted effort. Identification of specific strata within each member will require a basin wide acceptable method of Identification. This identification method would enable comparison of the members and their multiple strata thus making for a more comprehensive understanding of the hydrogeologic framework of the Newark basin and our multiple uses of the bedrock in the basin.

Result of initial subdivision of Lockatong outcrop area into members

Outcrops of the Lockatong Formation are rare in Mercer County. Large outcrops are mostly red massive mudstone such as the road cut on Interstate-95 at Exit 2. Other large outcrops include the outcrop at Scudder's Falls and the outcrop at the D&R canal overflow weir north of Scudders Falls. Small pavement like outcrops are exposed on the top of many of the linear ridgelines at the Mercer County Mountain View Golf course and on the Mercer Trenton Airport property. In addition, a few small outcrops expose light gray massive mudstone. Exposures of laminated dark gray and black carbon-rich mudstone strata are ephemeral. Such exposures are generally found in recent or ongoing excavations. Within a year of exposure, the bedrock disintegrates and is covered with vegetation and all vestige of the exposure are gone in 3 years.

Lacombe hypothesized that the geologic log from the Nursery Core can be used to divide outcrop area of the Lockatong Formation into many of the 12 Members. A map of the Lockatong Formation outcrop area in western Mercer County (fig. 5) shows the Nursery Core site and the NAWC research site. Nursery core drill site is the top of the NBCP log and the NAWC site is the outcrop area of the Skunk Hallow, and Byram Members. Mapping the members along the transect between the Nursery Road and the NAWC assumes that there are no major faults or fold between the two sites and the dip is constant. It also assumes that the ridges and valleys along the transect are controlled by the resistive and fissile strata. Red massive mudstones are more indurated and form ridges. The black and dark mudstone strata are fissile and form valleys. Based on these assumptions, the massive red mudstone road cut at Exit 2 and the E-W ridgeline that passes thorough the road cut and to Scudders Falls is the broad red stratum in the upper part of the Prahls Island Member. The narrower red strata in the upper part of the Tumble Falls member is the red strata the is exposed as pavement outcrops along the ridgeline at the County golf course and the outcrop of the overflow weir for the D&R canal located 1000 ft north of Scudders Falls. The hypothesis in this area could be tested by comparing geophysical logs and driller's logs from USGS and other observation and supply wells in the Lockatong outcrop area.

Conclusion

The ability to concisely map the outcrop of the members of the Stockton, Lockatong and Passaic Formations in western and central New Jersey now exits since the coring effort of the Newark Basin Coring Project. By expanding the outcrop and subcrop mapping, research at groundwater contamination sites, of ambient groundwater contamination and of drinking water supply area would be enhanced with the regional interpretation of the framework as opposed to the present site-by-site investigation of the framework for such sites.

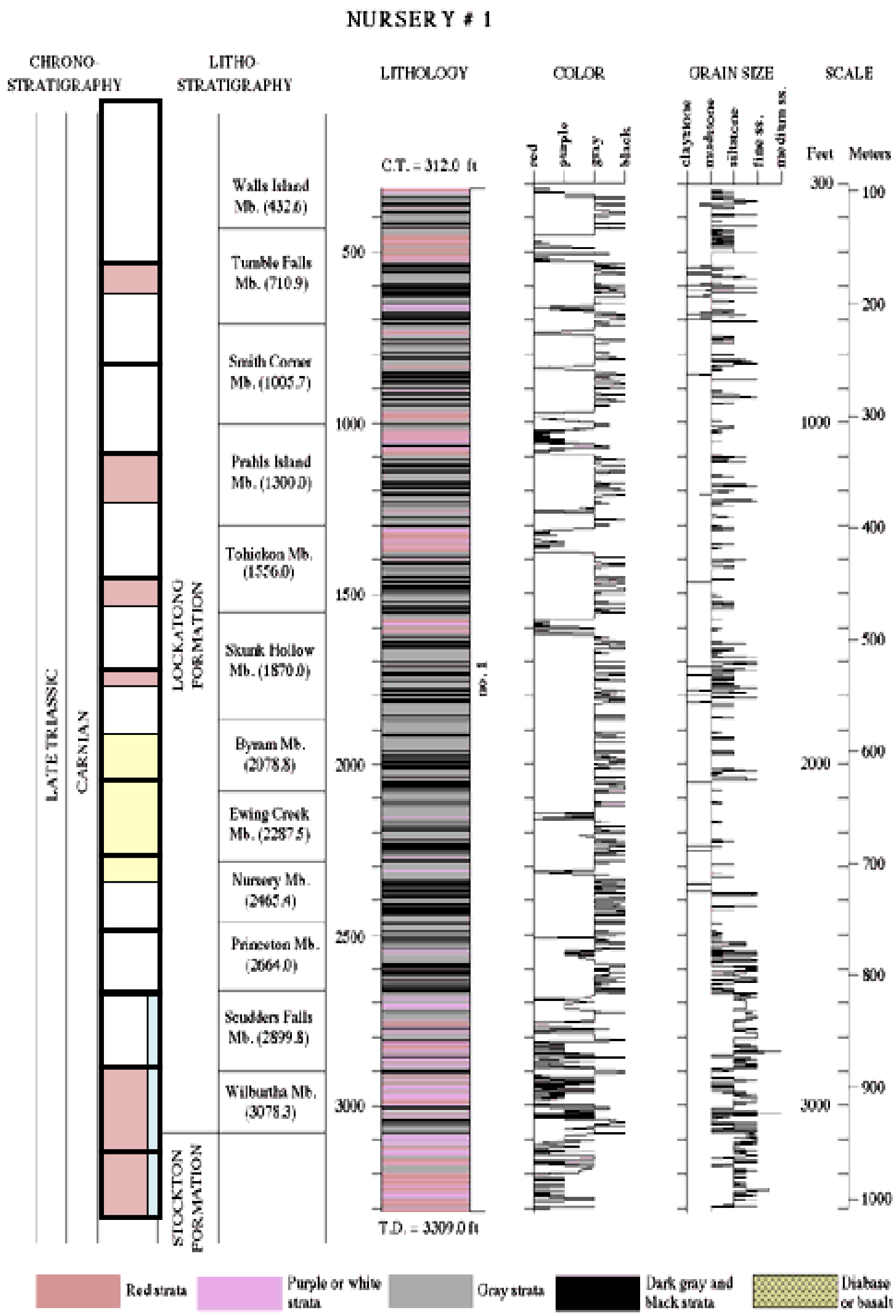

Figure 2 Core record for the Nursery Road Core hole.

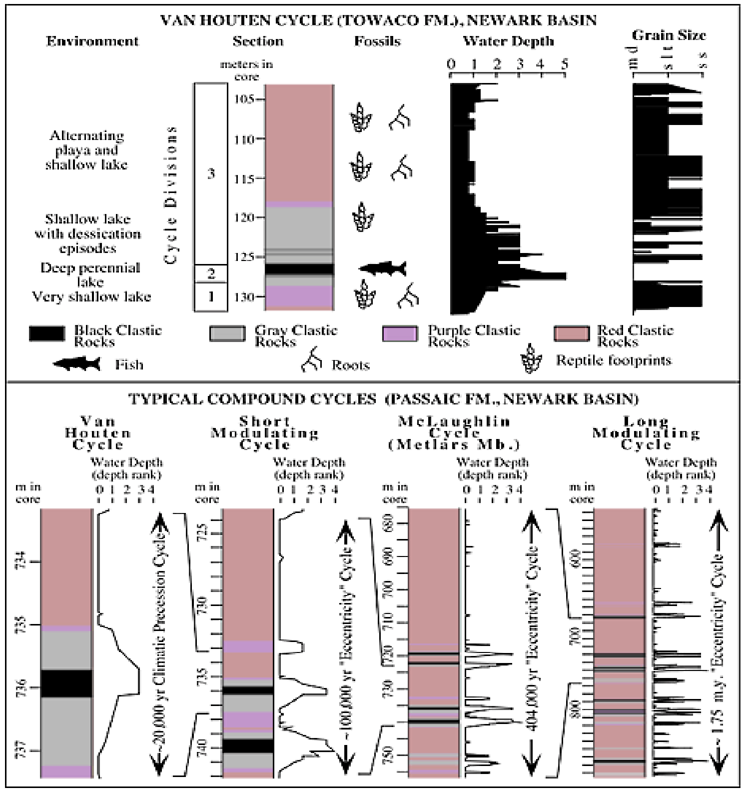

Figure 3 Graph showing the Van Houten and McLaughlin cycles of the Lockatong Formation

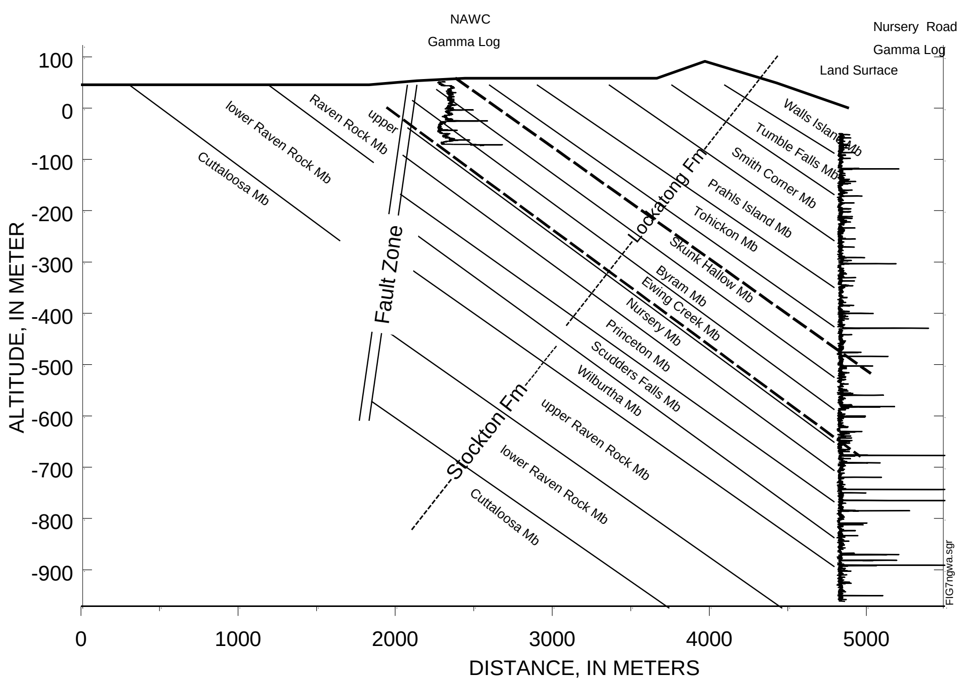

Figure 4. Section of the Lockatong Formation from the Nursery Road core hole site of the Newark Basin Coring project to the NAWC site.

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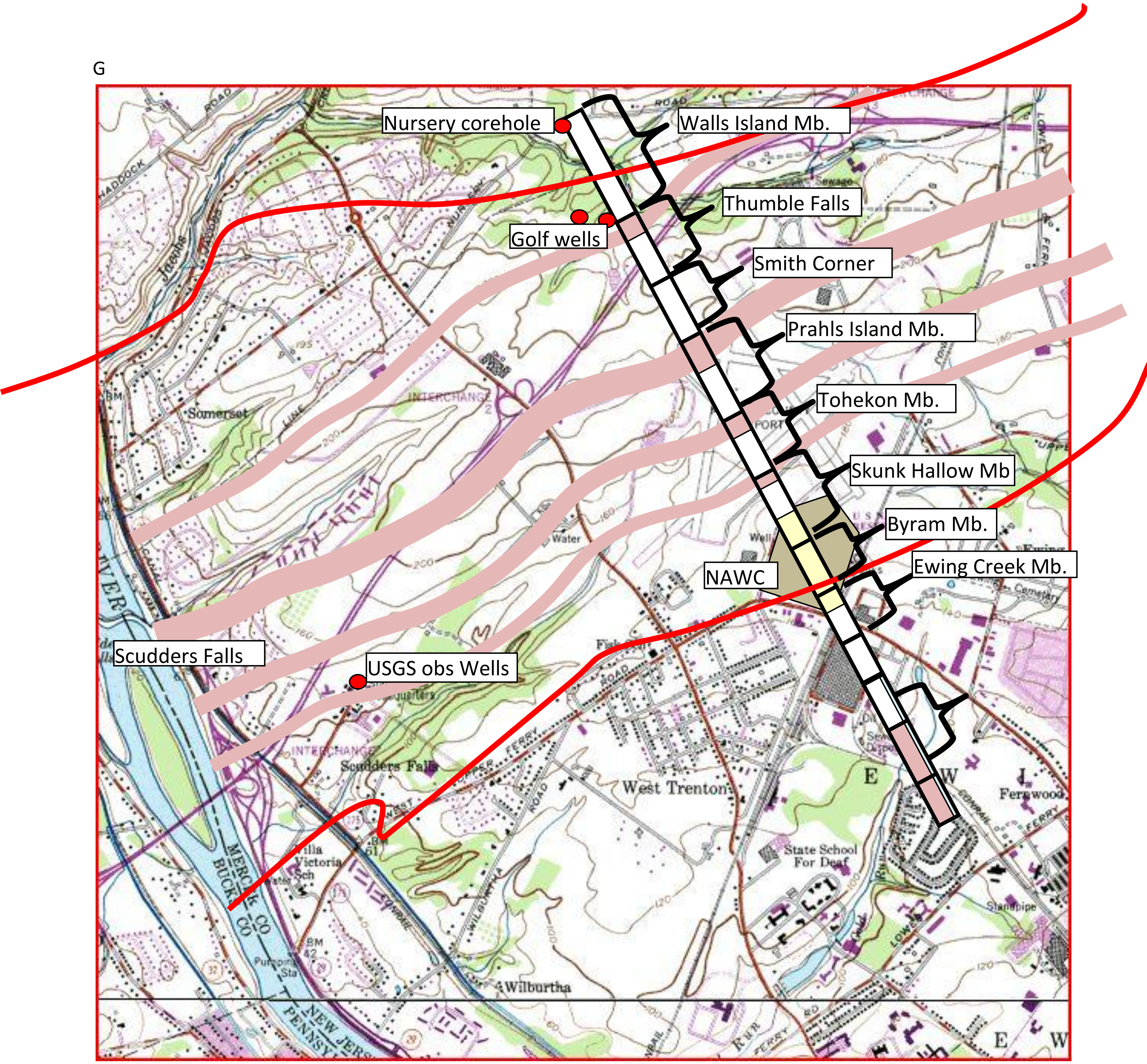

Figure 5. Topographic map showing the proposed outcrop of the members of the Lockatong Formation.

Chapter 8

Geological sources of radionuclides and arsenic in Triassic age rift-valley sediments (Newark Supergroup) and implications for distribution in groundwater in Mercer County, New Jersey

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Radionuclides and arsenic, known carcinogens that pose human health risk upon ingestion, are common, naturally occurring, inorganic contaminants that have been found in concentrations of concern in groundwater used for drinking water in Mercer County in central New Jersey. Studies to understand the geologic sources of these constituents and the geochemical pathways by which they are released to the groundwater are being conducted by the U.S. Geological Survey in cooperation with the New Jersey Department of Environmental Protection. The ongoing investigation includes sampling and analysis of ground and surface water, rock core, and geophysical logs of domestic wells and boreholes to obtain information about the relations between the lithology and the hydrology where radionuclide- or arsenic-bearing waters occur. Mercer County is located on the Fall Line, the physiographic boundary between lithified sedimentary bedrock on the northwest side and unconsolidated Cretaceous Coastal Plain sediments on the southeast side. Erosion of Proterozoic and lower Paleozoic granitic and metamorphic rocks during the Triassic and Jurassic resulted in cyclic deposition of uraniferous, trace-element rich sediments that filled the Newark Basin rift valley that was forming at the time. North and east of Trenton is the Stockton Formation, a coarse to fine gray, pink, and red arkose. Northwest of the Stockton Formation in the County are the Lockatong and Passaic Formations that consist of interbedded red and black mudstones deposited as cyclic lenticular lacustrine/playa sequences. The distribution of radionuclides and arsenic in the deposits were also affected by lithification, diagenesis, and low-grade thermal metasomatism associated with Jurassic basaltic intrusions. Many residential areas in northern Mercer County obtain potable water supply (drinking water) from groundwater that is withdrawn from these lithified sediments.

Preliminary results from the ongoing sampling in 2010 of domestic wells within Mercer County show elevated concentrations of uranium and arsenic, with maximum concentrations of 19 and 10 ug/L (micrograms per liter), respectively, from wells in the Passaic Formation. Analyses of gross alpha-particle activities and isotopes of Ra are ongoing. The maximum concentration of radon (Rn-222) in water from among the domestic wells was from the Stockton Formation. The concentration of Rn-222 in the water from that well was monitored in the field with a portable alpha spectrometer and surged to about 5,500 pCi/L (picocuries per liter) after the initiation of well purging, but then diminished with time and stabilized at 3,400 pCi/L. One possible explanation for such a change in concentration during well purging may be that the well intercepts at least one strongly radioactive stratum that bears water with great amounts of Rn-222, but possibly also intercepts other water-bearing zones with smaller amounts of radioactivity that may dilute the Rn-222 concentration after a period of pumping. To interpret the production of water from the various strata, the characteristics of the rock strata and the fractures in this domestic well are being determined using a suite of geophysical logging tools. Six boreholes studied in Mercer and adjoining counties that contained water with concentrations of Rn-222 greater than 3,000 pCi/L and/or gross alpha-particle activity greater than 15 pCi/L all penetrated highly radioactive strata.

The gamma logs obtained from the boreholes in the Lockatong and Passaic Formations show many radioactive strata that are associated with organic-rich fissile black lake-bed mudstone, interbedded with black-and-white mudstones and siltstones, deposited at depth near the center, or at slightly shallower depths nearshore, within the lake that occupied the Newark rift basin. In Mercer and adjoining counties, these radioactive black beds are frequently present and commonly separated vertically by less than 100 ft of low-radioactive strata. Anomalous gamma peaks from gamma logs correlate from boreholes in Mercer County that are 850 ft apart in the direction of dip. The strata show vertical differences of 1 foot using an assumed dip angle of 5.7 degrees. Results of chemical and gamma-spectral analysis of the core samples and gamma-spectral logging of the boreholes indicated that some or all of the black mudstone rock strata are strongly enriched in uranium relative to thorium. The maximum uranium/thorium ratio is greater than 1,000. Maximum uranium concentration in Mercer County in a core of black mudstone was 300 ug/g (microgram per gram), and even higher concentrations were observed in core samples from nearby counties. Typical concentrations of uranium were more on the order of 5 to 10 ug/g, however, but even these values are high relative to most common rock types. The presence of many uranium-enriched continuous black mudstone strata increases the probability that water-bearing fractures will intercept radioactive zones and will, in turn, be intercepted by wells within the basin. The stratigraphic continuity of the lake-bed-deposit type radioactive zones in the Lockatong and Passaic Formations indicates there is high potential for water produced from wells located near each other along strike (typically for strata in northern Mercer County, about 70 degrees northeast) of such a zone to contain high radioactivity. Geologic mapping and stratigraphic correlation might be useful in indicating those areas most vulnerable in terms of the occurrence of elevated radioactivity in well water.

The black mudstones also are enriched in arsenic. In a core sample from Mercer County, the maximum arsenic concentration was 240 ug/g. The arsenic is primarily present in pyrites within the black mudstones, with a maximum concentration of arsenic in the pyrite of 40,000 ug/g. Streambed sediments collected from reaches of the Neshanic River that flow over black mudstone in Hunterdon County also were rich in arsenic and uranium with maximum concentrations, 38 and 5.5 ug/g, respectively. Gray and red mudstone core samples obtained in Mercer County contained substantial arsenic (50 and 13 ug/g, respectively). While the highest concentrations of arsenic in groundwater appear to be associated with black mudstone, water from wells completed in red mudstone also have been found to contain arsenic concentrations greater than 5 ug/L, the Maximum Contaminant Level for the State of New Jersey. The concentrations of uranium and arsenic correlate weakly or not at all in either groundwaters or stream waters from the region of Mercer and Hunterdon County. This result indicates geochemical differences in mobility for these elements must be considered when evaluating their occurrence in water. Consequently, a simple approach of trying to identify a few strata most likely to be the source of local water contamination in the Lockatong and Passaic

Formations does not appear to be as feasible for understanding arsenic occurrence as it does for radionuclides.

Deposition of the fluvial sediments of the Stockton Formation also can be considered cyclic, with basal conglomerates adjoining fine-grained silts in vertical succession in repeating fining-upward sequences. Zones of anomalously high radioactivity in the gamma logs from boreholes completed in the Stockton Formation appear as clusters of anomalous peaks grouped in sections of strata several tens of feet thick. Basal conglomerate units were enriched in uranium during diagenesis by fluids moving through these most permeable zones. Radioactive deposits formed as a result of precipitation of uranium minerals from the migrating pore fluids. Stratigraphic correlation between radioactive strata in the Stockton Formation in nearby wells is more tenuous than in the Passaic Formation as the spatial and vertical distribution of stream-channel deposited conglomeratic units is less continuous than that of lake beds. Easily observable or mappable stratigraphic correlation likely does not exist for radioactive zones in this Formation, and nearby areas vulnerable to contamination of well waters with radionuclides cannot be readily delineated. The hypothesis that radionuclides can be released to the circulating groundwater because radioactive zones in the Stockton Formation are intercepted by fractures occurring along the contacts between conglomerate and siltstone is being tested by geophysical logging.

Chapter 9

Geology of the Pennington Trap Rock (Diabase) Quarry, Mercer County

Gregory C. Herman, John H Dooley, and Larry F Mueller, NJ Geological Survey

Introduction

The purpose of this field stop is to visit the Pennington Trap Rock quarry where crushed stone products of Jurassic diabase are quarried, processed, and sold. Stratigraphic and structural features exposed in the 3rd level of the quarry will be examined and agate (banded cryptocrystalline silica), jasper (colored and massive cryptocrystalline silica), and opal (hydrous amorphous silica) from some late-stage hydrothermal veins will be collected. The term 'trap rock' refers to Early Jurassic igneous rocks in the region, including the intrusive diabase sheets and dikes, and the extrusive basalt flows. The focus of this stop and discussion is diabase.

Geological Setting

The Pennington Trap Rock quarry is located in Pennington Mountain in the center of the Newark basin (fig. 1). The Newark basin is one of a series of tectonic rift basins of Early Mesozoic age formed on the eastern North American plate margin during the breakup of the supercontinent Pangaea preceding formation of the Atlantic Ocean. The basin covers about 7500 km^2 and extends from southern New York across New Jersey and into southeastern Pennsylvania (fig. 1). Its filled with Upper Triassic to Lower Jurassic sedimentary and igneous bedrock that is fractured, faulted, tilted, and locally folded (see summaries in Schlische, 1992, 2003; Olsen et al., 1996a). Rifting in the Newark basin region probably began during the Middle Triassic and intensified during the latest Triassic and into the earliest Jurassic as evidenced by widespread igneous activity and a marked increase in sediment-accumulation rates (de Boer and Clifford, 1988; Schlische, 1992). Tectonic deformation and synchronous sedimentation in the region continued into the Middle Jurassic, at which time extensional faulting and associated folding became less-widespread, or may have ceased. Some time afterwards, the basin began a period of post-rift contraction, uplift and erosion (basin inversion) similar to that of other Mesozoic rift basins on the eastern North American continental margin (de Boer and Clifford, 1988; Withjack and others, 1998; Olsen and others, 1996a).

Extension fractures in the basin, including unmineralized joints and mineralized veins formed in three, overlapping groups (S1-S3) that record a counterclockwise strike progression including an early, border-fault orientation (S1; N045^o-060^{o}E), an intermediate intrabasin-fault orientation (S2; N015^o-030^{o}E) and a late stage (S3; N10^{o}W-N10^{o}E) set (fig. 1 and Herman, 2009a). All sets are paired with orthogonal cross joints, and the latest cross-fracture set (S3C; N80^{o}E-N110^{o}E) shows localized mineralization in fracture interstices and maybe dilation in response to ~ E-W compression at some late stage during the basins history. The directions of current crustal compression (CCC) and current plate-motion (CPM) are shown in figure 1.

The Pennington quarry is located within a kilometer of the trace of the Hopewell fault in the northern part of Mercer County (figs. 2 and 3). The Hopewell fault is a major, intrabasin, normal fault cutting the central part of the basin. In the vicinity of Pennington Mountain, the strike of the Hopewell fault departs from the regional strike of about N50^{o}E and includes segments that strike about N30^{o}E to N80^{o}E (fig. 2). The fault is interpreted to dip at moderate

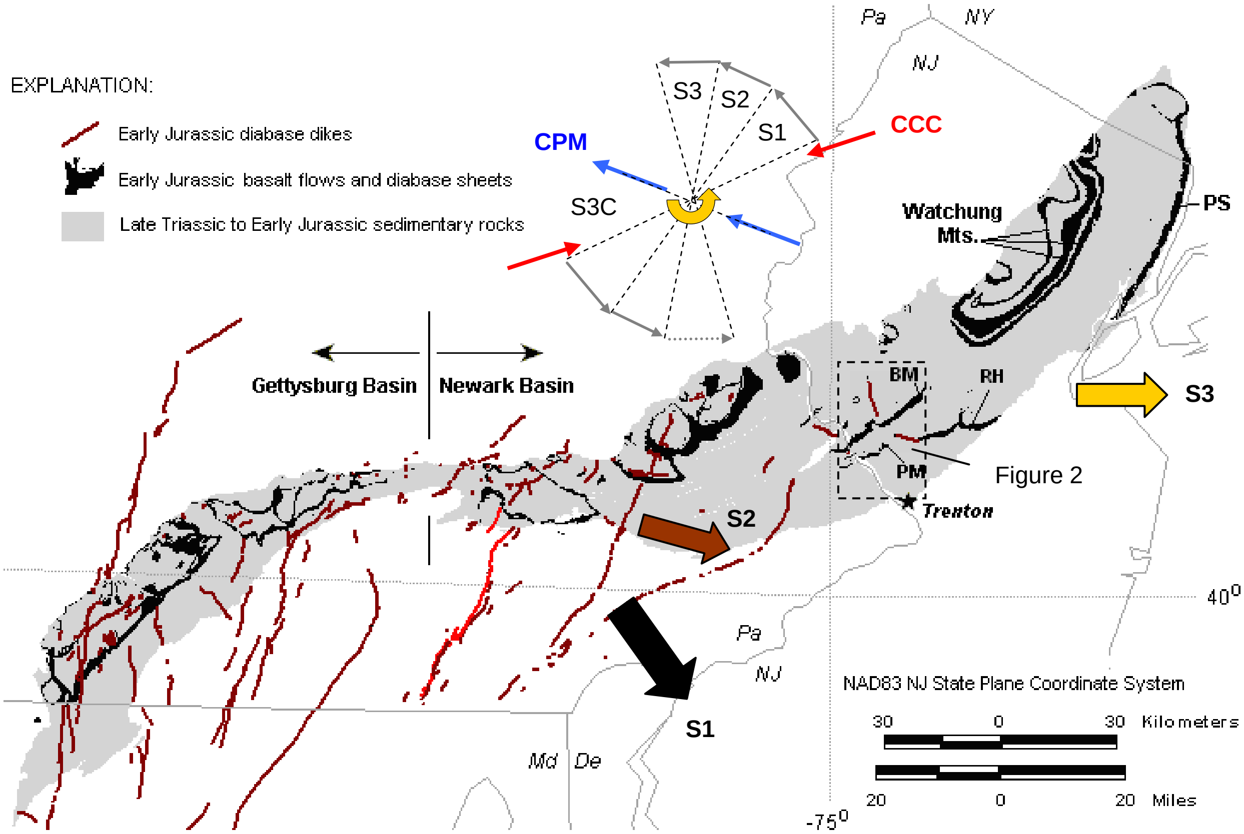

Figure 1. Generalized geologic map of the Newark and Gettysburg basins showing the distribution of Early Jurassic diabase and basalt (trap rock) in Maryland (Md), Pennsylvania (Pa), New Jersey (NJ) and New York (NY). Diabase sheets and dikes occur throughout the region, whereas basalt flows are mostly restricted to the area of the Watchung Mountains. The rotation of the progressive, extensional strain field from the Late Triassic through the Early Jurassic was counterclockwise from S1 to S3. PM – Pennington Mountain, PS – Palisades Sill. Belle Meade quarry, RH – Rocky Hill quarry. CPM – current plate-motion vector, CCV– current crustal compression

(45°-59°) angles to the south, with the hanging wall having dropped downward with over 5 kilometers of dip-slip movement (Drake and others, 1996). The amount of strike-slip movement on the fault is uncertain.

Schlische and Olsen (1988) described the Flemington and Hopewell faults as having developed late in the extensional history of the basin because strata cut by the fault lack thickness changes across the fault. Rocks close to the fault, especially in the hanging wall, are highly strained with many fractures, mineral veins, folds, and faults. The faults are composed of systematic networks of branching and splaying shear zones that include mineralized breccias and shear planes that cut late-stage leucocratic dike, hydrothermal veins, and joints. Compositional layering and fractures are commonly crumpled, folded and sheared.

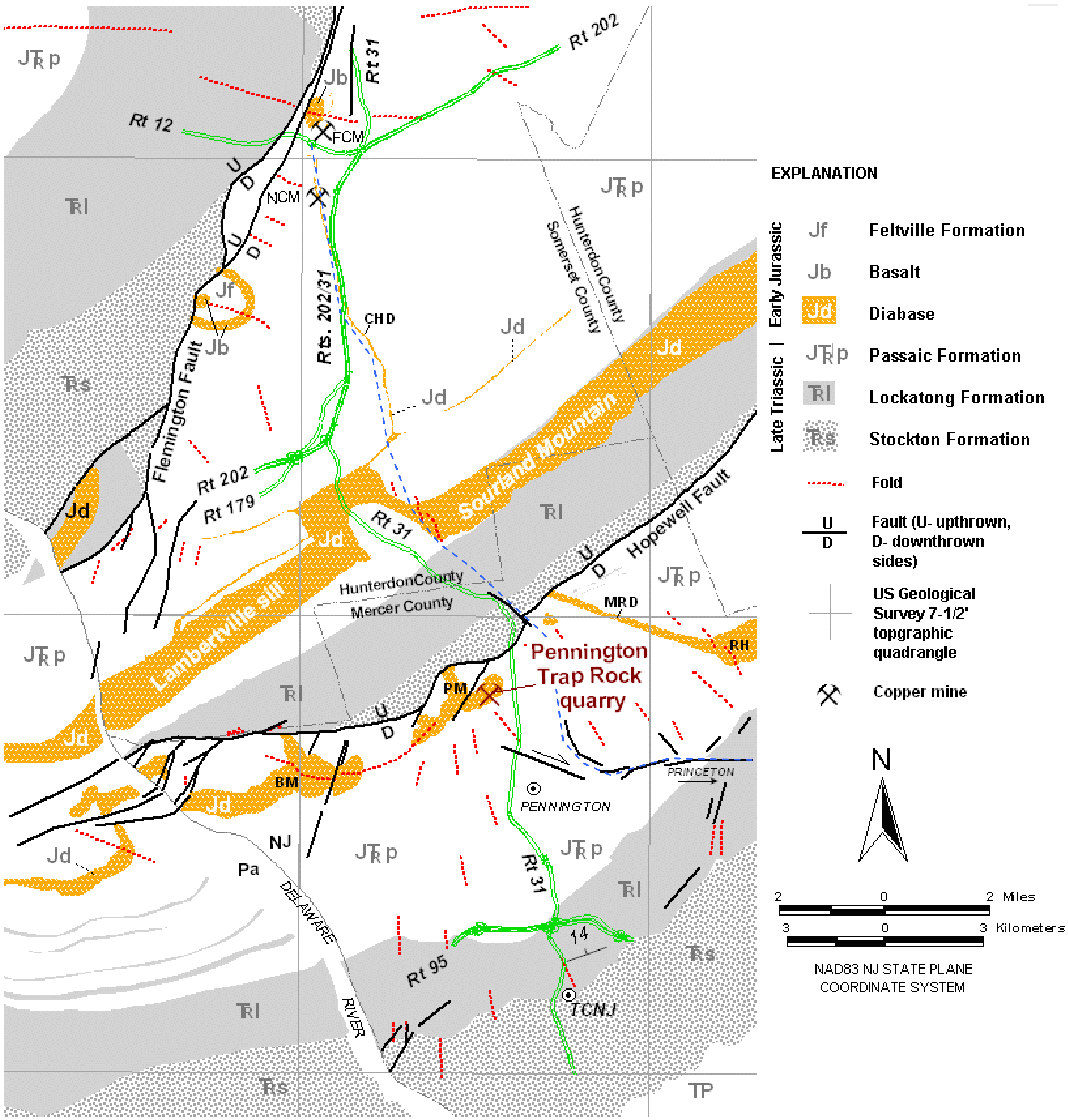

Figure 2. Geologic map in the central part of the Newark basin along Rt. 31 from Trenton to Flemington showing the location of the Pennington trap rock quarry. The blue dashed line that parallels the Copper Hill dike traces a suspected, late-stage pull-apart structure that cuts across strata and early faults. BM – Baldpate Mountain, CHD – Copper Hill dike, FCM – Flemington copper mine, MRD – Mount Rose dike, NCM – Neshanic copper mine, PM - Pennington Mountain, RH – Rocky Hill sill, TCNJ – The College of New Jersey.

Trap Rock Background

During the period of continental breakup and associated igneous activity, many diabase dikes intruded large extensional cracks in the Earth's crust and ultimately resulted in the extrusion of

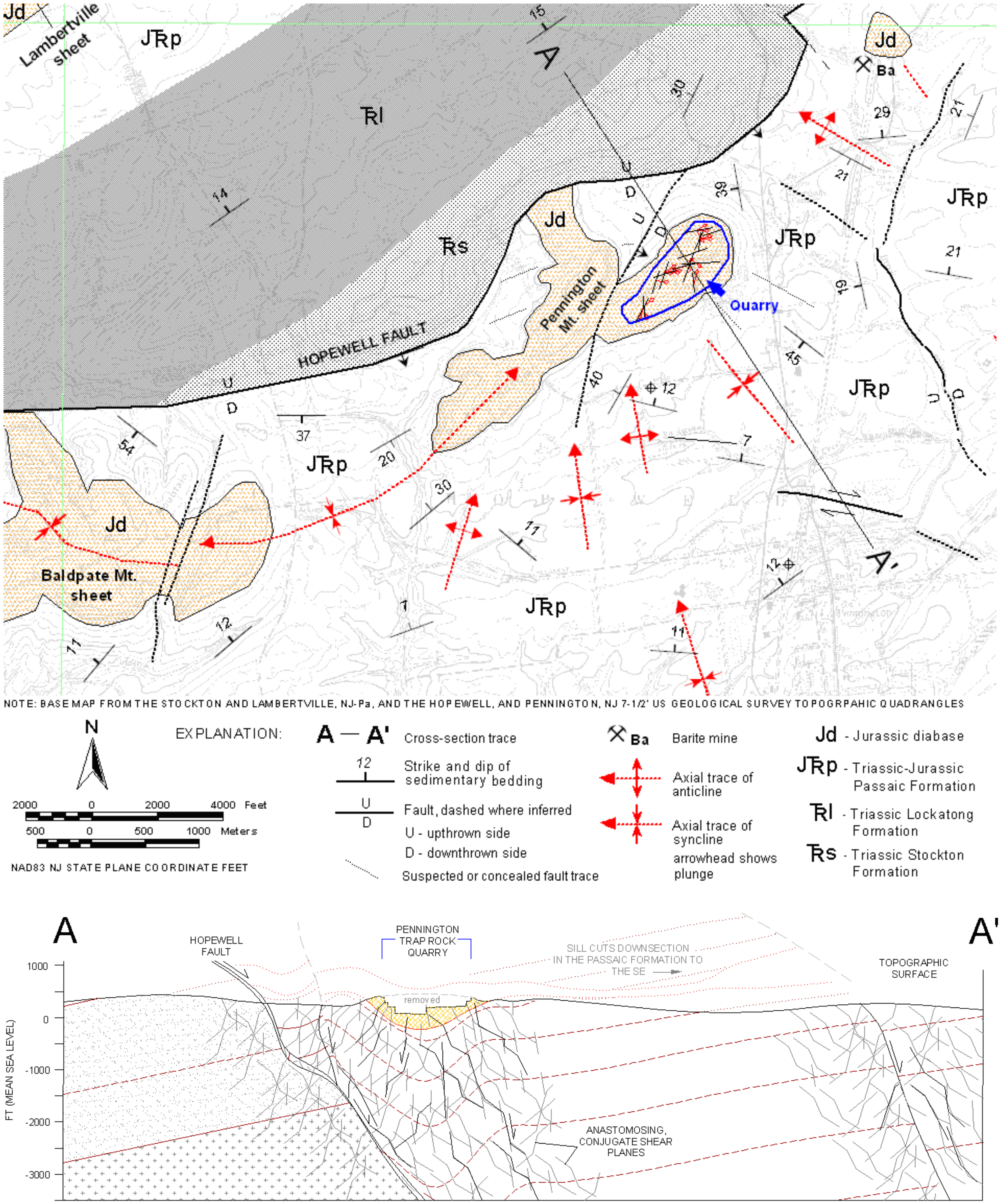

Figure 3. Geologic map (above) and cross section (below) in the area of the Pennington Trap Rock quarry, Pennington, NJ. Measured features in the quarry including fault-slip directions are detailed in figures 5, and 6, and table 1. The Pennington Mountain diabase sheet and the Pennington trap rock quarry sit in the hanging wall of the Hopewell fault, a large normal fault with late, strike-slip movements. Braided, splaying, and branching shear planes form close to the fault to accommodate crustal extension, subsidence, and warping in a collapsing basin.

flood basalts on land surface during an estimated 580 ky time span (Olsen and others, 1996b). The combined basalt and diabase and rocks preserved in the basin are commonly called “trap rock” because of the distinct, systematic columnar joints formed in these rocks from slow cooling following emplacement at or near the land surface. These fractures sometimes resemble blocky stair steps (fig. 4) and the “trap” adjective is thought to have originated from a Scandinavian noun "trappa” (stair) or trappasteg" (stairstep), according to Wikipedia.

In the Newark basin, the basalts are extrusive flows that are interbedded with Early Jurassic sedimentary rocks, mostly in the area of the Watchung Mountains, whereas diabase occurs as thin dikes and thin-to-thick sheets, or sills, that cut up through and intrude into Late Triassic sedimentary rocks. Diabase dikes commonly extend outside of the basin in Pennsylvania and Maryland where they also cut into the surrounding Precambrian and Paleozoic basement rocks (fig. 1).

Much previous work has been done on characterizing the trap rocks with respect to their locations, mineralogy, and commercial usages. Johnson (1957) covered the geological setting of the New Jersey trap rocks during a Geological Society of America field trip originating

Figure 4. West view of diabase layering and columnar jointing in the western rock face, 3rd quarry level at station 77916 (fig. 5). Layering is about 2 to 15 m thick and dips steeply from the upper right to the lower left (~N094E/80S) with polygonal cooling joints (below) formed in each set of layers and generally oriented at high-angles to layered contacts. The density of fracturing varies among and within layers. Most fracture surfaces are slickensided shear planes that locally form sigmoid structures (S - white dotted line), suggesting that cooling and slip may have been contemporaneous. No compositional differences were seen between the more massive and finely fractured intervals within the same layer, but different layers locally vary in both composition and texture.

out of Atlantic City, NJ. He noted then, that these rocks had been quarried for over 100 years for road metal, railroad ballast, aggregate, rip-rap and jetty stone based on properties such as their weight, reactivity, resistance to abrasion, and bonding characteristics. He also noted that because of their resistance to erosion, they typically form topographic highs that favor quarrying with faces and benches. He commented on the ever-increasing demand for trap-rock stone products to meet the needs of extensive industrialization, an expanding highway system, and to help in the continuing battle of beach erosion, despite unfavorable zoning restrictions on quarrying and the encroachment of residential districts.

With respect to the composition, texture, and structure of diabase, the first geologic studies on diabase in the New Jersey area were focused on the Palisades sill (fig. 1) because of its prominent exposure along the banks of the Hudson River. These outcrops led Lewis (1908) to characterize the diabase as dark gray to medium gray rock with locally developed greenish tints developed in the altered chloritic parts. He also reported the occurrence of an olivine-rich layer near the base of the sheet due to gravity-induced magmatic differentiation, horizontal sheeting in the sill near the upper and lower contacts, and sets of steeply-dipping joints and faults striking primarily N-S and orthogonal cross joints that are prominent from Jersey City northward. Hotz (1952) found that a typical diabase sheet has the gross shape of a saucer with upturned margins; geometry later illustrated by Husch (1990) for the Palisades sill and related diabase sheets in the Newark basin.

Johnson (1957) characterized the mineralogy of the "typical diabase" as consisting of augite, plagioclase feldspar, quartz, orthoclase and magnetite "in that order of abundance", except for an olivine lens, that consists of nearly pure, granular olivine. Froelich and Gottfried (1985) pointed out that up until about 40 years ago, lower Mesozoic diabase intrusive rocks in the Eastern United States were considered essentially uniform in chemical and mineralogical composition. However, detailed geochemical studies of diabase in North Carolina (Weigand and Ragland, 1970) and Pennsylvania (Smith and Rose, 1970; Smith and others, 1975) found unique chemical signatures among the different dikes and sheets, including olivine-normative and quartz-normative tholeite compositions, the latter type including high and low TiO_2 varieties.

Husch and others (1988) conducted detailed geochemical and petrologic studies of a number of diabase sheets in the central part of the Newark basin, including samples of the Pennington Mountain diabase from the Pennington trap rock quarry. They concluded that these diabase sheets evolved from quartz-normative, high-titanium tholeitic magmas that were selectively contaminated by surrounding country rock. They found evidence of multiple magma injections in individual sheets, and proposed that residual magmas enriched in quartz and alkali feldspar were displaced horizontally and vertically in the crust by ensuing magmatic pulses. They also found consistent and homogenous chill-margin compositions and a spatial relationship where pyroxene-laden cumulate layers occur in sheets occupying the lowest stratigraphic positions in the Triassic section, whereas highly-fractionated, coarse-grained granophyres occur at higher stratigraphic levels (such as with the Pennington Mountain sheet). They proposed that the classic petrogenetic model of olivine-dominated, vertical fractionation was not supported by the available geochemical, petrographic, and structural data. Rather, the occurrence of the olivine cumulate layer of the Palisades sill may have formed as a separate intrusion of a distinct magma type, perhaps stemming from deep crustal fractionation of a high-titanium, quartz normative magma, leaving behind a residual melt enriched in olivine and parent magma to that part of the Palisades sill.

Mason (1960) conducted a detailed mineralogical study of the trap rock minerals in New Jersey as a curator of physical geology and mineralogy with the American Museum of Natural History in New York City. This work included a list of active quarries then, detailed petrographic (microscopic) and X-ray analyses of mineral associations in the rock and in rock voids. He found the mineral association in the intrusive trap rocks to be the same as reported by Schaller (1932) which include:

1) Solidification of magma and initial cooling,
2) Residual melts become saturated with silica, which locally replaces and alters the primary rock,
3) Water is added from the outside and residual melts become saturated in lithophile elements, including calcium and aluminum, forming minerals such as prehnite, that marks the prehnite-pumpellyite metamorphic facies characterized by 250^{o} - 300^{o} C and pressures on the order of 2-7 kb (~7-20 km depth),
4) More water is added with more lime (Ca) and soda (Na) and zeolite minerals form, and
5) Late-stage calcium carbonate (calcite) period.

Puffer and Horter (1993) describe the occurrence of pegmatite segregation veins in the Watchung basalt and relate their formation to downward propagation of columnar joints through rigid barriers capping accumulating, water-enriched, segregated melts during the magmatic solidification process. These veins are aligned in the plane of compositional layering and are different from the hydrothermal veins crosscutting layering (S0) in the diabase. Different types of leucocratic, magmatic dikes and hydrothermal veins are found cutting diabase layers. Laney and others (1992) detail leucocratic dikes that were injected into and cut the diabase sheets that were probably derived from residual granophyric magmas produced by crustal fractionation. Mineral veins are reported in the diabase sheets within the many Newark-type basins along the eastern coast of North America (Walker, 1940; Robinson, 1988; Puffer and Peters, 1974; Laney, 1992; Laney and others 1995; among others). Many different mineral associations are reported including albite, calcite, chlorite, clinopyroxene, epidote, magnetite, oligoclase, prehnite, pyrite, quartz, sericite, and sphene, among others. Steckler and others (1993) reported that relatively high temperature hydrothermal systems operated in the Newark basin through the Early Jurassic, with most of the exposed strata cooled below ~220^{o}C at 180 Ma (Late Jurassic) and ~100^{o}C at 140Ma (Early Cretaceous).

Stratigraphic and Structural Notes on the Pennington Trap Rock Quarry

We visited the trap rock quarry on three days in 2004 and 2010 to collect geologic notes as part of a geological mapping effort in the Pennington 7-1/2' topographic quadrangle, and to prepare this field stop for GANJ. Structural measurements of compositional layering, fractures, dikes, veins, and faults were taken at a number of spots in the quarry (figs. 5, 6 and table 1).

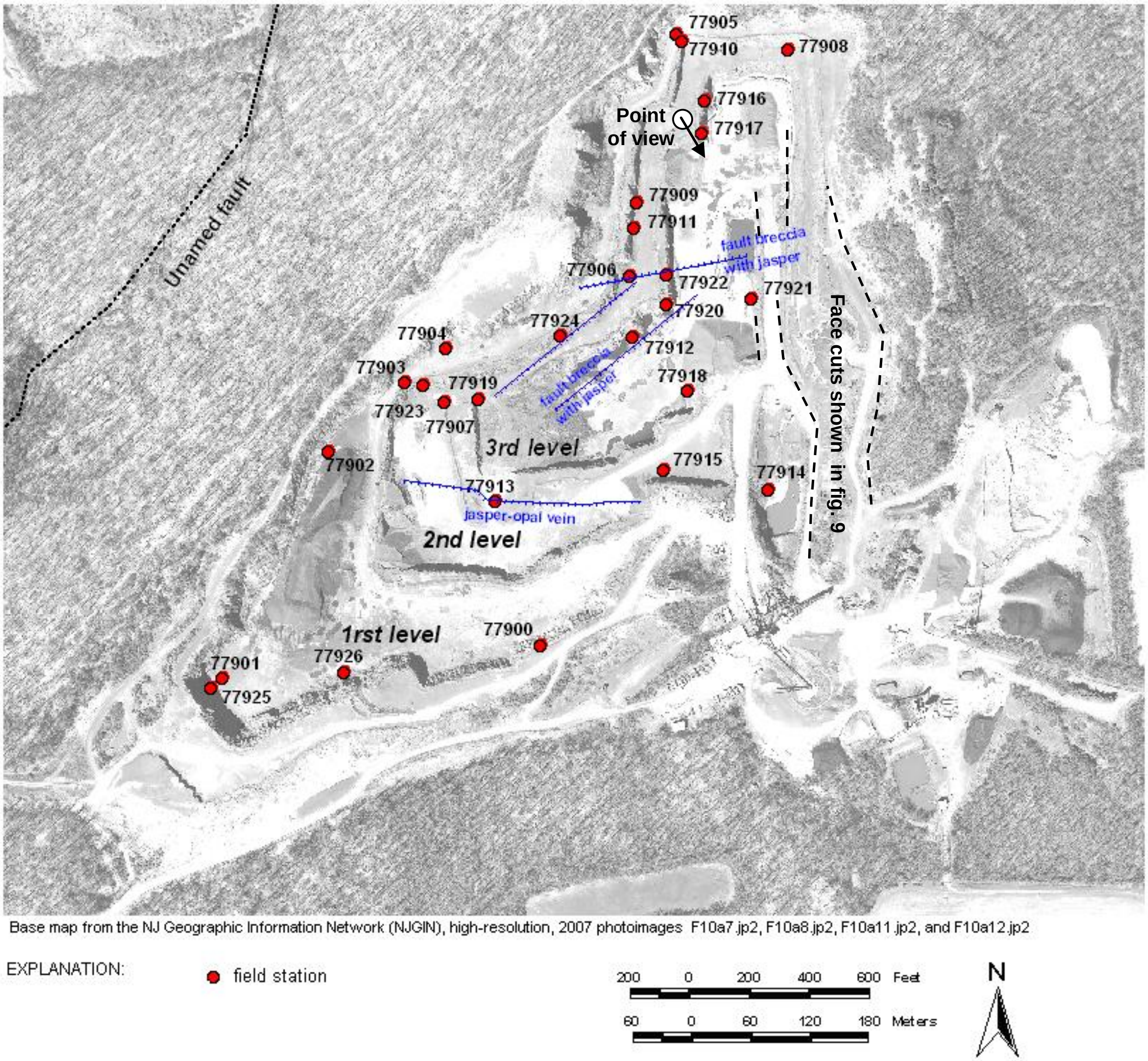

Figure 5. Aerial photograph of the Pennington trap rock quarry showing the location of geologic field stations and a panoramic perspective (fig. 6). This field stop focuses on features exposed in the western walls of the 3rd level.

X-Ray diffraction and microscopic analyses of the minerals associated with the diabase, dikes, and veins were conducted in 2010 in laboratories of the NJ Geological Survey.

The diabase here is medium-grained common diabase to coarse-grained granophyric diabase that is highly strained with complex structures resulting from repeated episodes of dip-slip and strike-slip movement along the Hopewell fault. More detailed mapping is needed to more fully characterize the exposed stratigraphic and structural features. Layering is complex and highly strained. We found sheeted magma layers about 1 to 15 m thick with varying compositional textures that were intruded along complex and locally conjugate flow paths, with some layers pinching out along other layers (fig. 7b). Layers dip gently to steeply in many directions (fig. 8), and are locally sheared and folded by faults striking NE-SW, N-S, and

Table 1. Structures mapped in the Pennington Trap rock quarry; March 3, 2004, June 11, and August 27, 2010

Structures by Station	Plane strike/dip	with Lineation plunge/trend and movement sense, if any if determined
STATION 77900		
Leucocratic vein	019/87S	
Leucocratic vein	012/87S	
Early normal fault	048/87S	
Leucocratic vein	130/87NE	
Leucocratic vein	124/85N	
STATION 77901		
Mineralized shear plane	026/70S	with slickenlines 52/164 normal, right lateral and 10/160
Mineralized shear plane	176/52W	with slickenline 25/165 normal
Leucocratic extension vein	101/60S	
Leucocratic extension vein	072/60N	
Fault with breccia and Mineralized shear plane	055/72S	with slickenline 50/197
STATION 77902		
Mineralized, polished shear plane	012/58S	
Mineralized, polished shear plane	020/58S	with slickenline 58/095 normal
STATION 77903		
Mineralized shear plane	049/77S	with slickenline 4/058 left lateral
cut by fault	015/30S	with slickenline 25/080 normal, right lateral
STATION 77904		
Mineralized (epidote) shear zone	063/82N	
Calcite vein	090/82N	
STATION 77905		
Layering	045/50S	
Joint	074/65S	
Joint	050/85N	
Joint	060/60S	
Mineralized (epidote) shear plane	035/28S	with slickenline 28/125 normal
Mineralized (epidote) shear plane	075/62S	with slickenline 42/088
Mineralized (epidote) shear plane	080/45S	with slickenline 2/090 (left lateral?)
Mineralized (epidote) shear plane	058/82S	with slickenlines 10/58 normal and 80/147 strike slip
STATION 77906		
Mineralized (epidote) fault zone	106/90	
Mineralized shear zone with malachite (copper carbonate)	104/80N	
Mineralized shear plane	018/76S	with slickenline 11/192
STATION 77907		
Mineralized shear zone	065/52N	
Mineralized shear zone	075/60S	with slickenline 5/069 right lateral
STATION 77908		
Joint	058/59S	
Vein (calcite?)	100/86S	
STATION 77911		
Mineralized shear plane	070/57N	with slickenline 3/055 right lateral
STATION 77913		
Mineralized (light-blue opal) vein	090/65-76N	

Table 1 (Continued). Structures mapped in the Pennington Trap rock quarry, March 3, 2004, June 11, and August 22, 2010

Structures by Station	Plane strike/dip	with lineation plunge/trend and movement sense, if any
STATION 77914		
Joint	010/80N	
Joint	010/65S	
STATION 77915		
Leucocratic-feldspathic dike	004/78E	
Mineralized shear plane	175/82/E	with slickenline 38/010 normal, oblique slip
STATION 77916		
Layering	094/80S	
Mineralized shear plane	005/35E	with slickenlines 25/075 and 26/090 normal, oblique slip
Mineralized shear plane	025/80E	
Mineralized shear plane	010/55E	
STATION 77917		
Leucocratic vein	100/88S	
Leucocratic vein with calcite	051/80S	
STATION 77918		
Layering	038/80N - 055/80S	
Fault with breccias and veining	055/85S	
STATION 77919		
Layering	020/46E	
STATION 77920		
Mineralized (epidote) shear plane	090/88N	
Vein with Jasper	090/80N	
STATION 77921		
Leucocratic-feldspathic dike	076/76N	
STATION 77922		
Fault breccias with Malachite and jasper	080/82N	
STATION 77923		
Fault breccias	050/90	
Mineralized (chlorite) shear plane	075/76S	with slickenline 11/090 right lateral
STATION 77924		
Fault with breccias (epidote)	035/69S	
Fault with breccias (epidote, calcite Brown jasper and light-blue opal)	050/40S	
Mineralized (epidote and calcite) Shear plane	050/40S	with slickenline 3/050 strike slip
Mineralized (epidote) shear plane	076/70S	
Mineralized (epidote) shear plane	030/64S	
STATION 77925		
Leucocratic (calcite) vein	128/86S	
Layering (compositional)	000/65W	
Layering (compositional)	032/60N	
Fault (anastomosing shear zone)	042/85S	
Fault (anastomosing shear zone)	055/85S	
STATION 77926		
Leucocratic (feldspathic) dike	105/62S	

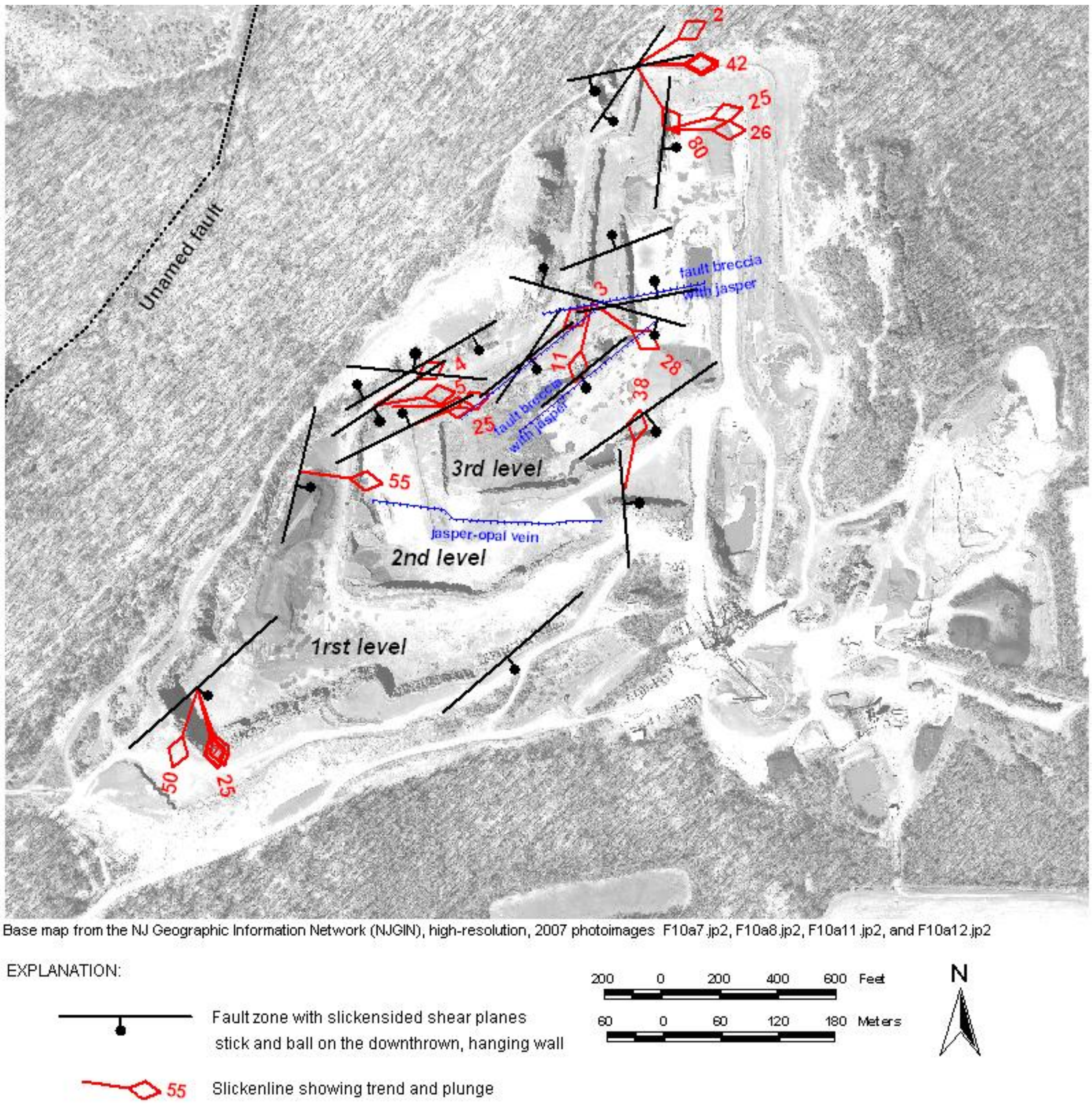

Figure 6. Some geologic faults and slip directions measured in the Pennington Trap Rock quarry at the stations noted in figure 5.

E-W that cut the quarry in many places (fig. 6 and table 1). Therefore, layers typically show much brittle deformation and locally form warped, steep, tall colonnades in open faces (fig. 7a).

Partially and unmineralized extension fractures (joints) show plumose structures on excavated surfaces (Herman, 2005) and are locally cut by shear planes showing normal dip-slip and strike-slip movements (fig. 9). In many places, polygonal joints are coated by iron-oxide minerals, and locally form in sigmoid alignment (fig. 4), suggesting that they formed when the diabase was both cooling and shearing. Joints that occur near shear zones commonly show

Figure 7. Examples of diabase layering. A. Warped and fractured diabase layers dip steeply west in a face cut on the East side of the first level of the quarry. Each layer has a thick base and polygonal jointed upper sequence that truncates against the base of the next layer. Note the curved extension fractures cutting the layers on the right. Dave Hall is looking north. B. Larry Mueller (left) and John Dooley (right) inspect unconformable layers along the north side of the quarry, 2nd level near station 77910. Layers are dipping steeply East (right). Dashed line traces the break in layering.

Figure 8. Panoramic view looking SE from the point of view noted in figure 5. Layers of magma caused by magma pulses are highlighted using white line in open faces on the 2^{nd} and 3^{rd} levels. The layering dips both NW and SE but is locally folded and cross cut by faults and shear zones.

Figure 9. Steeply-dipping, slickensided shear planes showing oblique-normal slip. A. Dark, chloritic shear planes striking/dipping ~N20°E/80°E (S2) are highly-polished with sub horizontal, tool & groove slickenlines indicating right-lateral strike slip. B. Epidote and calcite mineralized shear planes are highly grooved with striae, or 'slickenlines' showing normal-oblique slip . Many smaller shear planes branch and splay off of the larger planes within the shear zones. Light-blue, botryoidal opal coats depressions on the exposed shear-plane faces and is the latest mineral phase filling voids within the shear zones (box below and fig. 16A). An early, hydrothermal (quartz-feldspar-calcite) vein seen in the lower right hand corner (arrow) is cut by the shear plane.

evidence of minor slippage, having striated surfaces with thin mineral selvages of chlorite, epidote and then calcite. Joints are sometimes folded, or kinked with sharp fold hinges and straight, planar limbs.

Leucocratic, late-stage, magmatic dikes cut the diabase in a few places (fig. 10). These dikes range in thickness form a few centimeters to less than a meter thick, and occur in extension fractures cutting sharply across magmatic layering. In some places, they form in en echelon, brittle fracture arrays. They are medium- to light-pinkish gray containing plagioclase feldspar, pyroxene, and epidote. X-ray analysis of one sample showed that plagioclase is both albite and anorthite. These dikes have alteration rinds up to an inch or two thick (fig. 10B) and are locally sheared along their contacts with the diabase. These dikes are cut by the brittle faults. Laney and others (1995) and Walker (1940; 1969) reported sodic leucocratic dikes that intrude diabase elsewhere in the basin.

A few different types of hydrothermal veins also cut the diabase. These veins include: 1) quartz-feldspar-calcite veins, 2) calcite veins, and 3) chalcedony and opal veins. The first type show complex mineral banding of quartz, feldspar and calcite and pronounced wall-rock alteration rinds (fig. 11A). These veins have quartz cores that are flanked by plagioclase feldspar, then calcite concentrated along the vein walls. They also have sulfide minerals associated with the silica minerals (fig. 11B). The calcite veins occur in systematic, en echelon fracture swarms (fig. 12) that probably post-date the veins containing quartz and feldspar. The early, banded veins of quartz and feldspar with overgrowths of calcite may represent reactivated vein growth concurrent with the period of calcite veining. However, no interactions were seen between the different vein sets.

The chalcedony and opal veins also include different types. An extension vein at station 77913 (fig. 4 and table 1) is filled with about 2 to 10 cm of chalcedony in the form of a orange-brown jasper (fig. 13) and white to light gray agate (fig. 14). This vein strikes ~E-W and curves from dipping steeply north to south, and shows little fault slip. The core of the vein varies in thickness up to about 8 cm where it’s filled with massive orange-brown jasper containing translucent, streaks of clear chalcedony or opal (fig. 13B) and veinlets of similar looking material. We have yet to inspect them petrographically. Other parts of this vein core are banded or streaked, brown-black jasper, or agate, depending upon if the banding accreted gradually or was rapidly chilled upon injection with preserved flow structure. This also needs further inspection. Open voids and within this vein show overgrowths of medium gray agate and late pyrite (fig. 14C). Malachite ($Cu_2CO_3(OH)_2$) also occurs along fracture walls in altered diabase. Dark gray and brown chalcedony (jasper) also occurs as smeared accretions in the cores of epidote-and-calcite mineralized shear planes within larger shear zones (fig. 1). These zones show similar hydrothermal alteration and associated iron, sulfide, and copper mineralization.

Light blue opal occurs on large shear planes, cored by the chalcedony and oriented along S1 and S3C orientations (table 1 and fig. 5). The blue opal coats extended pockets within fault horses and diabase blocks that are splayed and separated by faulting (fig. 9B and 16A). The epidote-green, slickensided shear planes (figs. 9B and 16B) that locally form open faces shows spotty coatings of the light-blue, botryoidal opal laying in vugs and depressions on the shear planes (fig. 16B). The light-blue opal coating postdates normal dip-slip movements (fig. 16B).

Figure 10. Leucocratic, feldspathic dike cutting the diabase. This dike, at station 77915 (fig. 4), is about 1 ft thick and strikes/dips ~N4^{o}E/78^{o}E. It is sheared along its eastern contact with the diabase (table 1). The dike has a one- to two-inch alteration rind along the diabase contact. This is visible in the upper part of 10B.

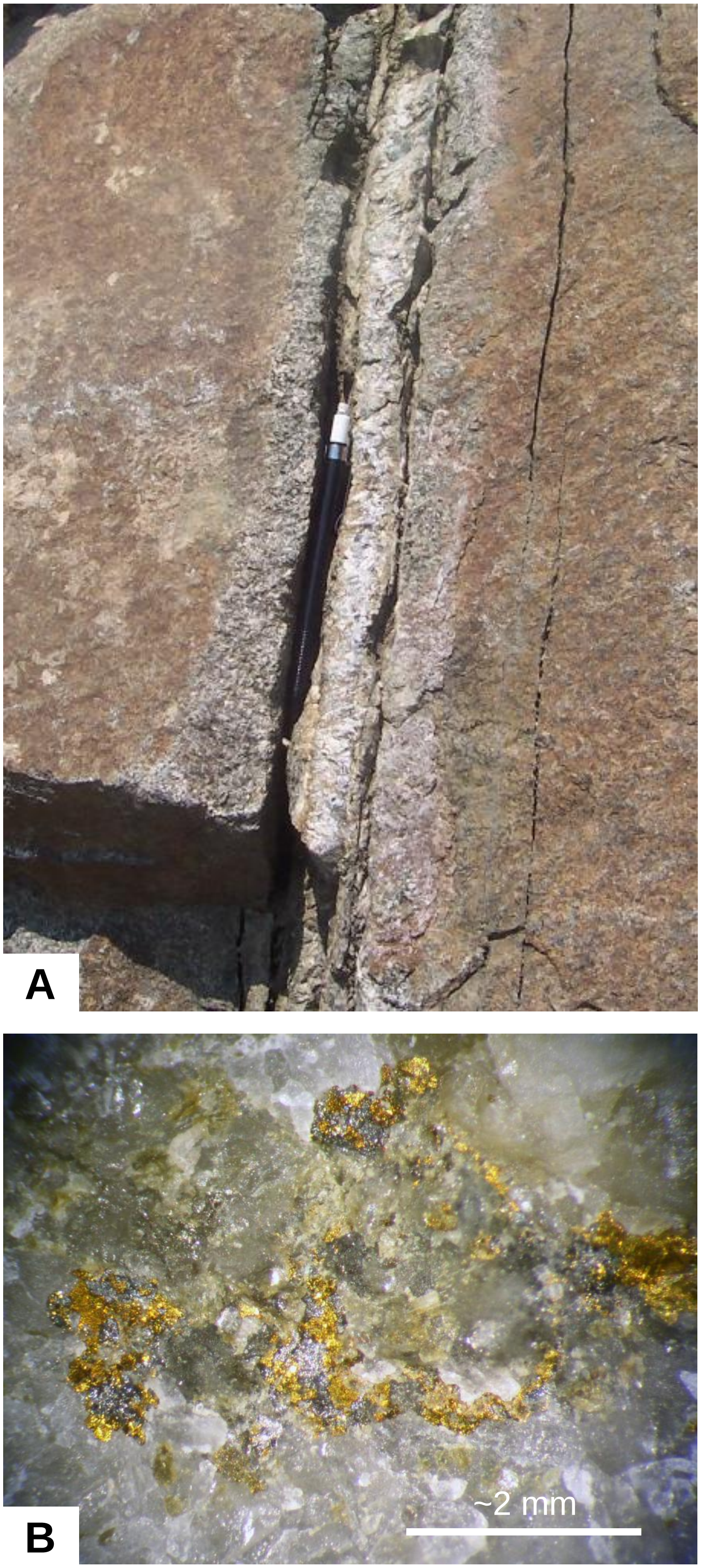

Figure 11. A. Hydrothermal, complexly banded quartz, plagioclase feldspar, and calcite vein showing wall rock alteration rinds. Note the pencil for scale, and the parallel, en echelon fractures immediately to the right of the vein that are partially mineralized. A vein core of quartz is flanked by feldspar and then calcite.
B. Sulfide minerals associated with the quartz-feldspar-calcite veins. Chalcopyrite ($CuFeS_2$ -bright yellow) surrounding chalcocite (CuS_2 - gray and silver).

Figure 12. Hydrothermal calcite veins at station 77925 striking/dipping ~N128^{o}E/78^{o}SW. They show alteration (bleaching) of the wall rock. These veins commonly occur as systematic swarms of cross fractures with fracture densities of about of 2-5 per meter measured normal to the vein plane. They locally form large, continuous and expansive surfaces in the quarry face cuts as seen at high elevations in the first level of the quarry. Field book for scale.

The mineralized shear planes in some places have both dip-slip and strike-slip striae on the same plane (table 1), with those having oblique and strike slip overprinting and postdating those with dip slip. These polished, chlorite and epidote-calcite mineralized shear zones (fig. 9) include strike-slip duplexes with many splaying, interconnecting and anastomosing shear planes similar to those reported cutting the Lambertville sill about 10 km north, and in another diabase quarry near the Hopewell fault at Belle Meade, NJ (Laney and Gates, 1996). Some of the striated fault blocks show the green (epidote) mineralized shear planes cutting hydrothermal veins that are also striated (fig. 16B). In general, the complex shear planes show early dip-slip movement along S1 (N045^{o}E-N066^{o}E) strikes that are cut by and reactivated by later S2 and the last S3-SC3 faults (fig. 17).

Discussion

The stratigraphic, structural and mineralogical aspects of the Pennington Mountain diabase are very complex and warrant further inspection. The absolute timing of diabase emplacement and faulting in the basin is unclear, but Schlische and Olsen (1988) suggest that the intrabasin faulting post-dates the Early Jurassic Feltville Formation. The Feltville Formation is the Early Jurassic shale, siltstone and sandstone sequence sandwiched in between the first (lower) and second (middle) Watchung flows. If intrusion of diabase spanned the entire time interval (~570 ky) during which the Watchung Mountain basalts were extruded (Olsen and

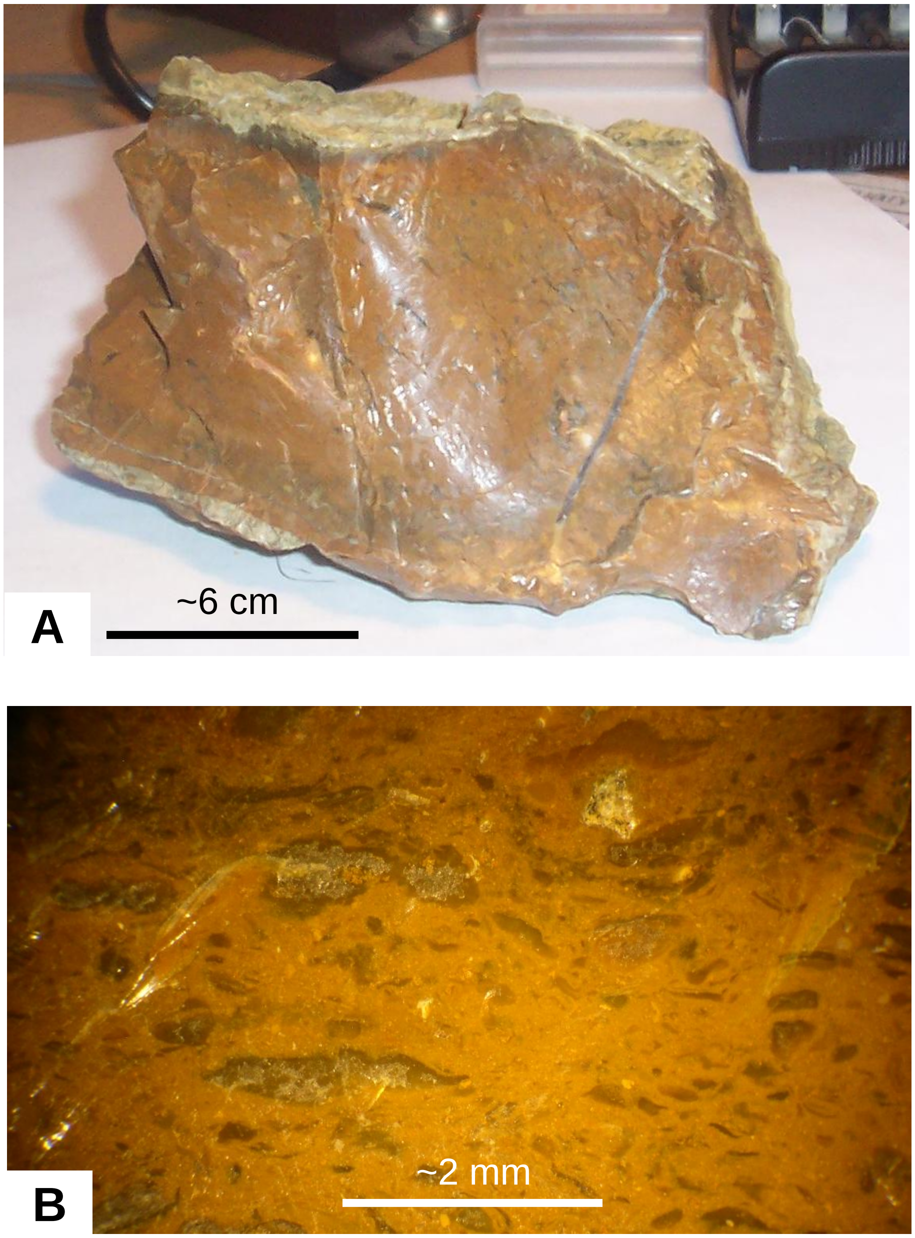

Figure 13. Photographs of the orange-brown jasper from station 77913. A. Hand sample of the vein-fill material showing the entire width of the vein and clear silica streaks and cross cutting veinlets (right side). The jasper is glassy and conchoidally fractured.
B. Photomicrograph of the jasper's internal texture . Transparent, light- to medium gray silica granules are entrained within the more iron-rich matrix of the jasper. Elsewhere, the veins fill includes dark gray to dark brown jasper with streaky flow banding.

others, 1996b) then intrabasin faulting postdating the Feltville Formation would allow ample time for diabase emplacement and faulting to overlap. Stratigraphic and structural evidence from the Pennington Trap rock quarry appears to support at least synchronous cooling and shearing of the diabase (fig. 4).

All three sets of extensional fractures (Herman 2009) and faults mapped in the basin are found in the quarry (fig. 6 and table 1). The strike of the different fracture sets, together with the recorded slip lineation (fig. 6) show that the hanging wall of the Hopewell fault was first subjected to southwest stretching and normal dip slip (S1), then was wrenched and down dropped eastward (S2, S3 and S3C), deforming and reactivating early structures (fig. 17). The S3C structures in the quarry striking E-W have steep dip angles and are part of a larger, regional oblique-slip transform-fault system involving strike-slip faults near Princeton to the east (figs. 2)

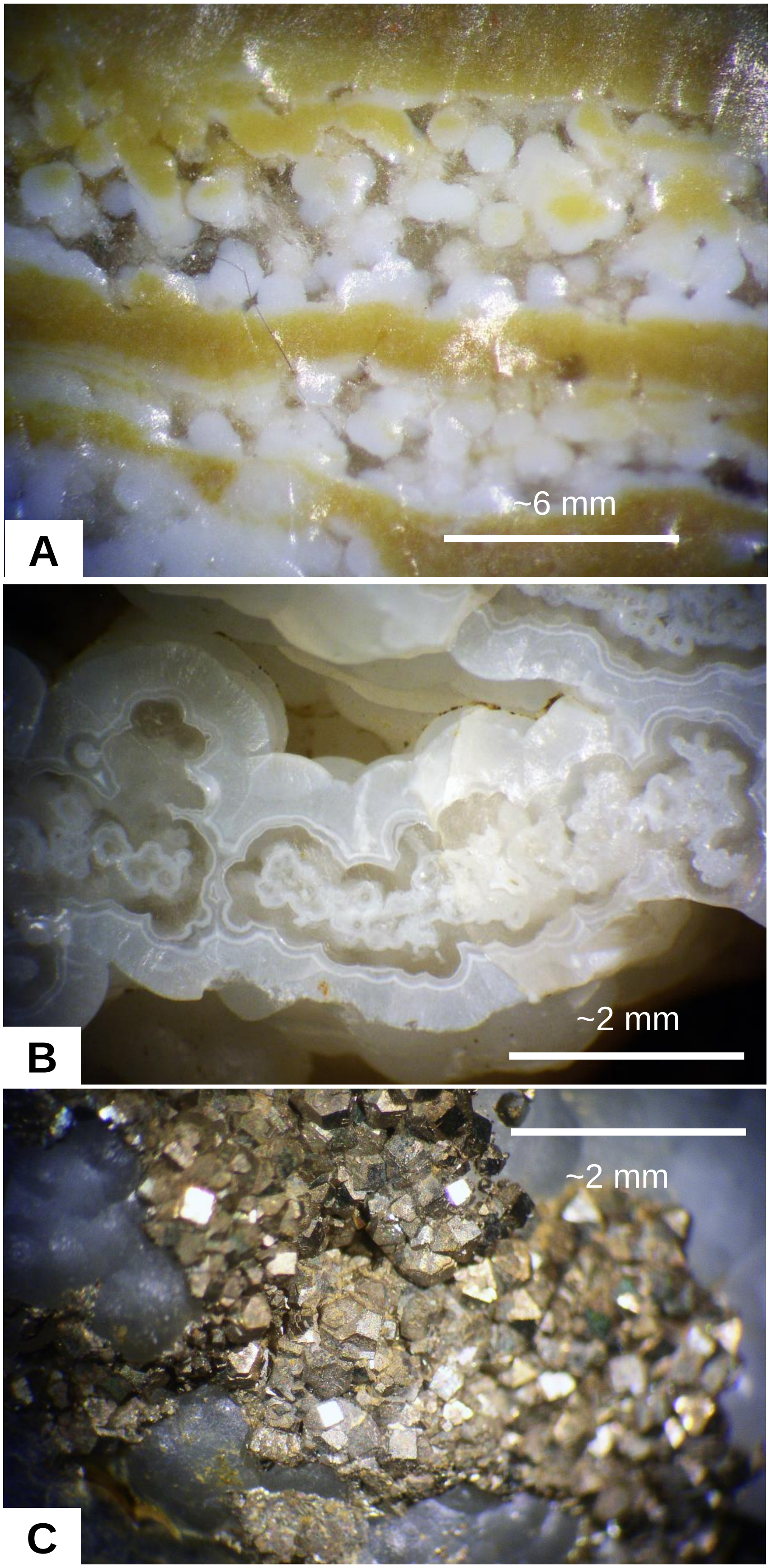

Figure 14. Photomicrographs of translucent, clear to milky-white agate lining pockets in the orange-brown jasper. A. The agate is spherically banded nodules that infill voids in the jasper matrix. B Detail banding and coalescence of agate nodules showing the banded, accretion textures. C. Details of the pyrite coating the opal.

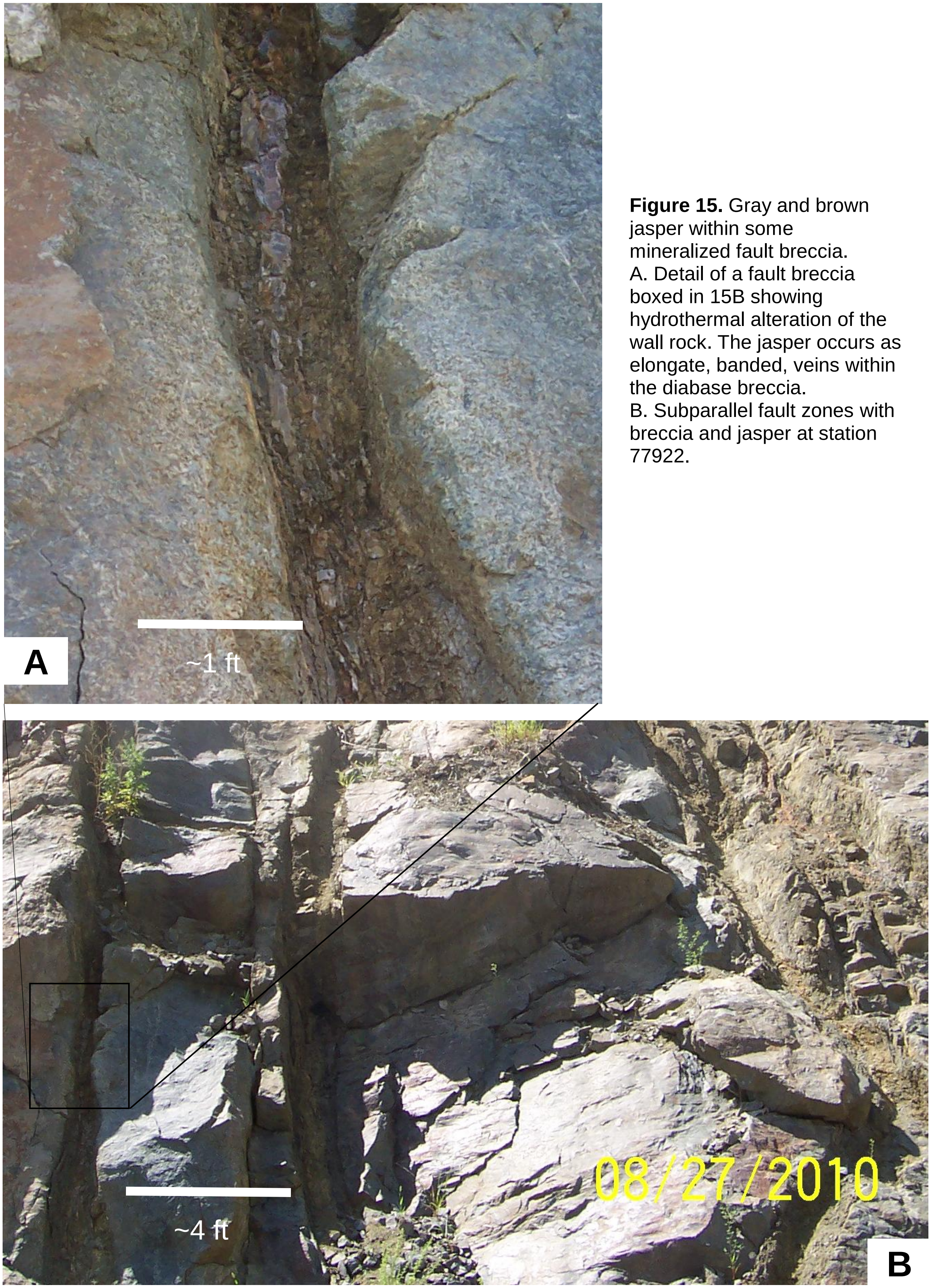

Figure 15. Gray and brown jasper within some mineralized fault breccia.
A. Detail of a fault breccia boxed in 15B showing hydrothermal alteration of the wall rock. The jasper occurs as elongate, banded, veins within the diabase breccia.
B. Subparallel fault zones with breccia and jasper at station 77922.

Figure 16. Late stage light-blue opal is also found within vugs developed in brecciated shear zones having other secondary minerals including chlorite, epidote, calcite, and iron oxyhydroxides. The slickensided shear planes are striated with slickenlines, A. Opal coating the walls of voids developed within a brecciated shear zone at station 77912 (fig. 9B shows a larger view of this fault). A Brunton compass is included for scale at lower center. B. Light-blue opal coating a steeply dipping S1 shear plane with normal dip-slip slickenlines at station 77924.

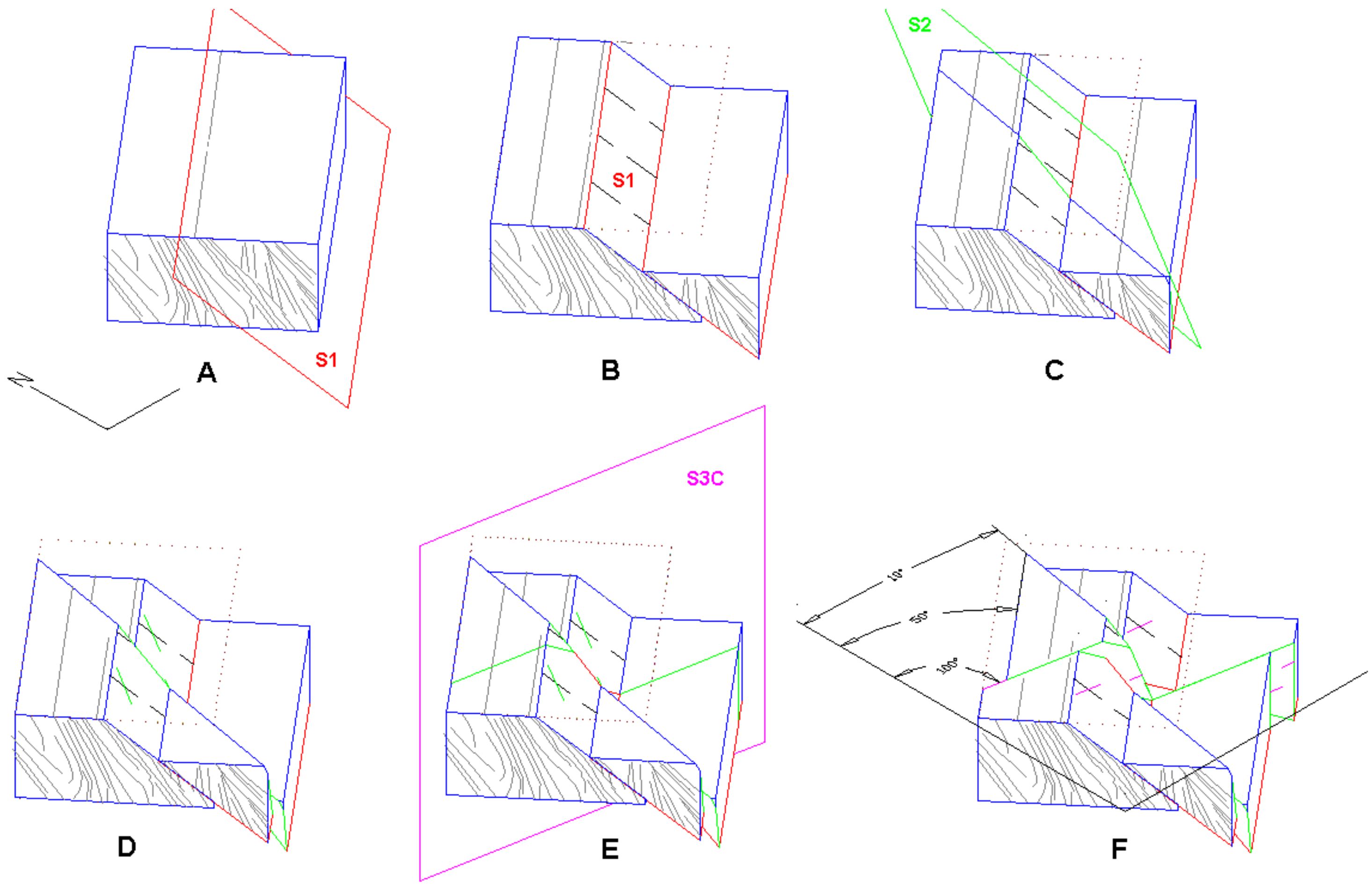

Figure 17. Block diagrams showing the structural sequence of faulting in the Pennington trap rock quarry. A. Layering and early faults strike about N50^{o}E, with S1 fault dipping at moderate-to-steeply SE. B. Predominant normal dip slip on S1 fault and shear planes. C. Layering and S1 faults cut by S2 stage steeply-dipping faults striking N10^{o}-20^{o}E (S2) and N-S (S3). One fault plane is used to represent the later S2 and S3 shear planes for simplicity. D. Dip slip on S2-S3 shear planes with possible right-lateral slip. E. All earlier features are cut by the latest cross-cutting shear planes oriented about E-W (S3C). F. Normal-oblique dip-slip and right-lateral strike slip shear zone and shear planes.

and western segments of the Hopewell fault that link with the Chalfont fault in Pennsylvania (Ratcliffe and Burton, 1988). The latest stretching event produced renewed, oblique slip on older (S1 and S2) fault surfaces that were being pulled obliquely apart in an easterly direction. The light blue opal now fills open voids in shear zones that are otherwise grooved and striated at points of contact and grinding. The jasper and opal filled hydrothermal vein striking E-W (station 77913) appear to have only small amounts of fault slip associated with it, and may have been dilated during a late-phase E-W compression of the region.

The fault geometries and their interactions in the quarry support a hypothesis that the different orientations of intrabasin fault segments were active in different stratigraphic levels at different times (Herman, 2009b). For example, those segments orientated parallel to the border fault (~N40^{o}E to N60^{o}E or S1 faults) were probably active early in the depositional history of the basin, locally cutting early sedimentary deposits, and then were succeeded and overprinted by the later, S2 and S3 structures that cut through all strata, but primarily occur at the highest stratigraphic levels. The leucocratic dikes and veins within the quarry follow S1 through S3 orientations and suggest that repeated episodes of extension, cooling, and cracking allowed fractionated melts originating at depth to repeatedly migrate upward through the diabase during punctuated phases of extension.

The map geometry of the diabase bodies forming Pennington and Baldpate Mountains include discordant stems locate on their northwest side that are apparently truncated by the fault, whereas the bulk of both bodies are sill-like sheets that are concordant to surrounding beds (figs. 2 and 3). The main parts of both of these igneous bodies now sit within the keel of a syncline that is located close and parallel to the trace of the Hopewell fault (fig. 3). The truncated stems could indicate that the S1 fault segments provided localized flow conduits for diabase emplacement and migration upward through the sedimentary pile.

X-ray analysis of a vein-fill material of the opal-jasper vein at station 77913 showed the presence of witherite ($BaCO_3$), a low-temperature mineral often found associated with fluorite (CaF_2) and barite (BaSO4), both of which are found with diabase and faulting elsewhere in the hanging wall of the Hopewell-Chalfont fault system (Dombroski, 1980; Cummings, 1991; Laney, 1992). It is likely that the Barite deposit near Hopewell (figs. 2 and 3) and other barite deposits in the Hopewell-Chalfont fault block are positioned in the Triassic shale hornfels immediately beneath the eroded parts of the diabase sheets.

The main diabase sheet was being emplaced and sheared during the S1 phase of extension. Polygonal cooling joints commonly occur in the basal parts of layers, suggesting that the sheet was being partly formed by injection of magma pulses on the underhand side of the body, or incrementally thickening from the top down in some places. Perhaps, late, punctuated phases of strain extended blanketing layers to allow segregated melts accumulating at the bottom of the sill to break through to the top, feeding granophyres and dike complexes upsection within the Upper Triassic and Lower Jurassic sedimentary section. Leucocratic dikes and cooling joints following S2 trends are pronounced. However, these are also cut and sheared by later S3 and S3C faults. It’s also possible that the granophyres and leucocratic dikes stem from magma differentiates at lower crustal levels.

Other nearby geological evidence shows that diabase within the basin was being emplaced along large, discordant crustal fractures during the S3 phase of regional extension. For example, the Copper Hill and Mount Rose diabase dikes (fig. 2) align with folds along a down warped hinge in the Lambertville diabase sheet (Herman, in press) located immediately east of the saddle and midway along its strike length (fig. 2). The eastern half of the sill is mapped as intruding a lower stratigraphic position than the western half (fig. 2), but this apparent offset may be a result of structural down warping above a blind, late stage, normal shear zone cutting across the sill. This great fracture continues northward where the Copper Hill dike shoots off the uppermost part of the sill, striking towards Flemington, cutting across all of the Late Triassic section, and driving hydrothermal fluids that emplaced copper minerals at the Neshanic and Flemington copper mines. It is likely that the Copper Hill and Mount Rose dikes are late-stage, discordant parts of the intrusive complex that follow partly buried, crustal planes of weakness associated with the S3 fracture system and crosscutting earlier S1 and S2 structures, allowing the central part of the basin to collapse eastward in one of the latest phases of basin extension.

The sequence of mineralization found in the quarry is probably the same as reported by Shaller (1932) and Mason (1960) for trap rock elsewhere in the basin. But some uncertainty remains with respect to the timing of the late-stage, epithermal veins of hydrous silica minerals and associated sulfide and copper carbonates. Copper sulfides are found in the early veins cored with silica and feldspar. Copper carbonates are found in the altered diabase in contact with both the epidote-calcite shear zones, and the lower temperature and pressure chalcedony and opal veins. Additional sampling and petrographic work is needed in order to assign relative ages to the late opal and calcite mineralization phases. Also, more work is needed to better establish the association of the metal sulfides with respect to he different types of veins. We also don't know if the opal and jasper veins extend outside of the diabase into the Upper Triassic red and gray shale.

The Trenton region may hold many keys that will help to resolve some long-standing questions regarding the emplacement of the diabase and stages of cooling, mineralization as tectonism. For example, which Early Jurassic diabase dikes, if any of those currently mapped, were feeder dikes to the basalt flows? Which parts of the trap-rock plumbing system were active during the span of time over which the different basalt formations were extruded? How does the geometry of this plumbing system relate to the different phases of tectonism? To what extent does the regional plumbing system reflect synrift faulting, and to what extent did this system utilize large, crustal faults in spreading diabase throughout the basin? How does the cooling history of the basin and the associated sets of hydrothermal veins relate to the extensional versus compress ional tectonic phases that the New Jersey region was subjected to? And finally, how does the architecture of this grand pull-apart structure relate to the modern tectonic setting?

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Chapter 10

Pliocene and Quaternary Geology of the Trenton Area

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Introduction

Surficial deposits and landforms in the coastal areas of the unglaciated U. S. mid-Atlantic region record the interplay of rising and falling sea level, warming and cooling climate, and waning and waxing estuarine-fluvial and glaciofluvial sedimentation since the Pliocene, when continental glaciers first appeared in the northern hemisphere. The Trenton area is in a pivotal location in this region, because preglacial, glaciofluvial, and interglacial deposits and landforms meet and intersect here. Following a period of high sea level in the middle Pliocene, during which the Pensauken Formation aggraded to form a broad fluvial plain in the Trenton area, sea level declined as northern hemisphere glaciers grew. For the vast majority of the past 2 million years sea level has been lower than at present, permitting gradual incision of the Delaware and its tributaries. Significant sedimentation episodes occurred during glacial and interglacial maxima. Glaciofluvial sediment was carried down the Delaware River from upvalley glacier margins during the Illinoian (150,000 years ago) and the late Wisconsinan (20,000 radiocarbon years ago) glaciations, forming gravel plains in the Trenton area. Estuarine sediment was laid down in the Delaware valley during at least two interglacials (at about 400,000 and 125,000 years ago), when sea level was as much as 70 and 30 feet, respectively, higher than at present. In the longer intervals between the glaciations and the interglacial highstands, the Delaware and its tributaries channeled into the estuarine and glaciofluvial deposits, forming incised valleys, straths, and fluvial terraces. This paper will describe the history of surficial mapping in the Trenton area and our current understanding of the Pliocene and Quaternary geomorphology and sediments here.

History of Investigations

These deposits have been studied for over 100 years. Early work on the surficial deposits in the Trenton area includes Lewis (1880), who recognized a younger gravel (the "Trenton gravel"), which he considered a postglacial fluvial deposit, inset into an older gravel (the "Philadelphia red gravel", equivalent to the Pensauken Formation today), which he considered a glacial deposit. Cook (1880) considered the Trenton gravel to be of glacial origin and recognized that it was distinct from, and younger than, the quartz gravels of the Coastal Plain. R. D. Salisbury and G. N. Knapp (in Bascom and others, 1909) completed the first systematic surficial geologic map of the Trenton area, and defined the Pensauken and Cape May formations (Salisbury and Knapp, 1917). They included the Trenton gravel in the Cape May and recognized that the Cape May included estuarine, glaciofluvial, and non-glacial fluvial sediments, but did not attempt to separately map these facies, in part because they thought that periods of high sea level coincided with glacial maxima rather than with interglacials. MacClintock and Richards (1936) recognized the correlation of high sea levels with interglacials, and low sea level with glacials. They redefined the Cape May as an interglacial marine and estuarine deposit, and used

“Trenton gravel” to refer to the younger glaciofluvial gravel inset into the Cape May deposits. Owens and Minard (1975, 1979) subdivided the Trenton gravel in the Trenton area into an upper terrace (their “Spring Lake beds”) and a lower terrace (their “Van Sciver Lake beds”), both of which they considered to be of last interglacial (the Sangamonian interglacial, 125,000 years ago) age. They correlated the Van Sciver Lake beds to the Cape May Formation on the Cape May peninsula, and the older Spring Lake beds to an estuarine clay (the “Fish House clay”) in the Cape May Formation in Pennsauken, Camden County, and restrict any glaciofluvial deposits in the Trenton area to elevations at or below the modern river. Berg and others (1980) followed Owens and Minard (1979) and map both the Cape May and glaciofluvial sediments in Pennsylvania as “Trenton gravel”. Newell and others (2000) partially follow this scheme, with the Spring Lake beds identified as an interglacial fluvial facies of the Cape May Formation, and the Van Sciver Lake beds possibly including glaciofluvial gravel. Subsequent quadrangle mapping in the Delaware valley between Trenton and Camden (Stanford, 2004, 2008a, 2008b), and north of Trenton (Stanford, 1993a) demonstrates that the upper terrace at Trenton (the Spring Lake beds of Owens and Minard, 1979) is the downstream extension of the late Wisconsinan glaciofluvial deposit in the Delaware valley, that it is inset into the Cape May Formation south of Trenton, and that it projects below sea level south of the Burlington area. The lower terrace at Trenton (Van Sciver Lake beds of Owens and Minard, 1979) is a postglacial strath cut into the late Wisconsinan glaciofluvial deposit. Thus, the correlations of Owens and Minard (1979) and Newell and others (2000) are mistaken, and the terms “Spring Lake beds” and “Van Sciver Lake beds” are not used by the N. J. Geological Survey. Given these miscorrelations, and the confusing history of the term “Trenton gravel”, current NJGS maps use the descriptive terms “glaciofluvial deposit” and “postglacial stream-terrace deposit” to refer to materials younger than the Cape May Formation in the Delaware valley. This practice is followed in this paper.

Pensauken Formation

The oldest surficial deposit in the Trenton area is the Pensauken Formation (fig. 1). It is a fluvial braidplain deposit that consists of cross-bedded yellow to reddish-yellow arkosic quartz sand with quartz, quartzite, and chert pebbles, and trace amounts of sandstone, shale, and gneiss. The quartz, quartzite, and chert are mostly reworked from older late Miocene gravels that formerly veneered the entire Coastal Plain and much of the Piedmont. The Pensauken fills a broad valley along the inner edge of the Coastal Plain between the New York City area and the Delmarva Peninsula. In the Trenton area, the base of this valley is a narrow thalweg that extends to slightly below sea level (fig. 1). The plain itself averages about 10 miles wide and has a maximum elevation of 150 feet. Most of the surviving surface of the plain today is between 100 and 130 feet in elevation because it has been eroded. Paleoflow directions measured from cross beds (Owens and Minard, 1979; Martino, 1981; Stanford and others, 2002), and the regional slope of the plain, indicate that it was deposited by a large southwesterly flowing river that included the Hudson and, possibly, rivers from southern New England (Stanford, 2010). The Delaware was a tributary to this river, and the big bend in the Delaware at Bordentown is an inheritance from its junction with the Pensauken valley. In the Delaware valley upstream from Trenton, rock-cut terraces capped with quartzite-gravel lag about 120 feet above the modern river at Titusville, Raven Rock, Stockton, and Riegelsville, grade to the Pensauken plain at Trenton and mark the level of the valley in Pensauken time (Stanford, 1993a).

The Pensauken contains pollen indicating a Pliocene age (Stanford and others, 2002), and interfingers in the Delmarva Peninsula with the Beaverdam Formation, a Pliocene marginal-marine deposit (Groot and Jordan, 1999). The pollen content and plant fossils (Berry and Hawkins, 1935; Stanford and others, 2002) indicate that it was laid down in temperate climate, perhaps with estuarine influence. It is unconformably overlain by pre-Illinoian till of late Pliocene or early Pleistocene age in Somerset County, New Jersey. These relationships indicate that the Pensauken is a preglacial fluvial deposit that aggraded during the mid-Pliocene sea-level highstand at about 3.5 million years ago. This highstand is documented by marine deposits in the mid-Atlantic Coastal Plain south of New Jersey (Dowsett and Cronin, 1990).

The Pensauken river was diverted southwestward in the New York City area during the pre-Illinoian glaciation sometime between 2.5 million and 800,000 years ago. The Pensauken plain between New York City and Trenton was abandoned and a new local drainage network formed. At and south of Trenton, the Delaware now was the trunk river in the valley. During the early and middle Pleistocene (800,000 to 150,000 years ago), the Delaware and its tributaries eroded narrow inner valleys as much as 120 to 150 feet deep into the Pensauken plain. These inner valleys are the present-day stream valleys. They contain middle and late Pleistocene fluvial and estuarine deposits, and the modern estuary and floodplains. The fluvial and estuarine deposits at and south of Trenton are largely composed of material reworked, through multiple erosion cycles, from the Pensauken, with lesser contributions from first-cycle bedrock erosion.

Cape May Formation

The Cape May Formation is yellow to pale-brown quartz sand with minor silt and quartz-pebble gravel deposited in estuarine settings. Two phases of the Cape May occur in the Trenton area. The Cape May, unit 1 occurs as thin (generally less than 15 feet thick) erosional remnants on uplands and valley sides between 30 and 70 feet in elevation, southwest of the Columbus-Hedding area (fig. 1). The upper edge of the Cape May 1 laps onto Pensauken-capped uplands in places, and windblown sand commonly covers the contact, so the upper limit of this phase is poorly defined. The Cape May, unit 2 forms a well-defined valley fill as much as 50 feet thick within the Delaware valley at and south of the Burlington area, with a maximum surface elevation of about 35 feet. Shells from the Cape May 1 in Cumberland and Cape May counties yielded amino-acid ages older than 200,000 years, and shells from the Cape May 2 in Cape May County yielded amino-acid ages of about 125,000 years (Lacovara, 1997; Wehmiller, 1997; O'Neal and McGeary, 2002). The dates and the altitude of the deposits indicate that the Cape May 1 was likely deposited during the oxygen-isotope stage 11 interglacial about 400,000 years ago, when global sea level was about 70 feet higher than at present, or during the oxygen-isotope stage 9 interglacial at around 320,000 years ago, when sea level may also have been higher than at present. The Cape May 2 was deposited during the Sangamonian interglacial (oxygen-isotope stage 5e) at around 125,000 years ago, when global sea level was between 20 and 30 feet higher than at present.

Upper Stream Terrace Deposits

Broad stream terraces upvalley and inland from the Cape May 2 terrace in the Delaware valley and its Coastal Plain tributaries, with surfaces 20 to 50 feet above modern floodplains, are capped with yellow to yellowish-brown quartz sand and quartz-pebble gravel fluvial deposits. These sediments, which are generally less than 20 feet thick, are mapped as the upper stream terrace deposits. They grade to, or are onlapped by, the Cape May 2, and are inset into the Cape May 1, and so are between 400,000 and 125,000 years old. Their broad extent and variation in surface elevation suggest that they were laid down during several periods of alluviation, probably when sea level was high or when cold climate increased runoff and hillslope erosion. These periods of alluviation were separated by intervals

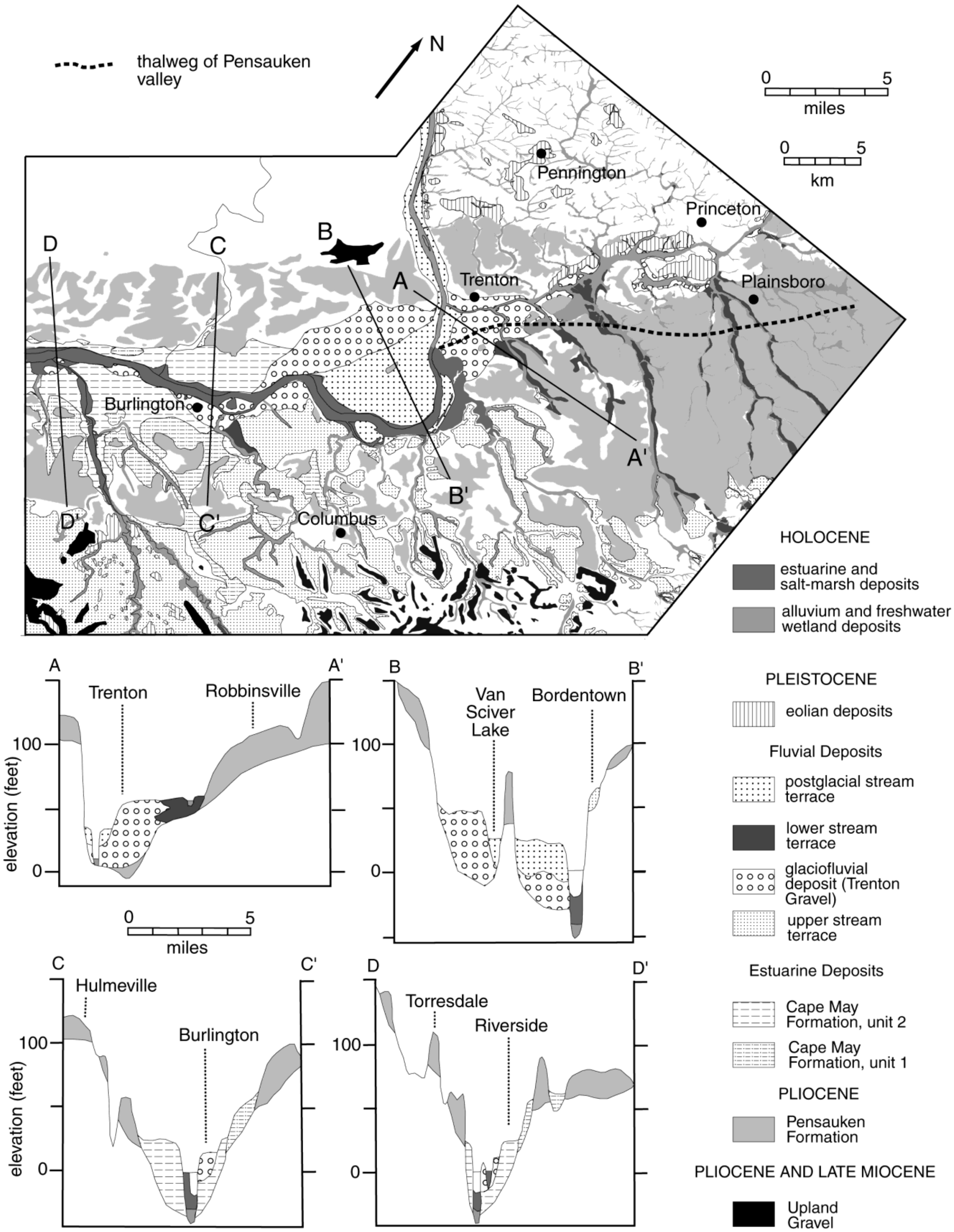

Figure 1. Map and sections of surficial deposits in the Trenton area. Compiled, with revisions, from Bascom and others, 1909; Owens and Minard, 1975; Berg and others, 1980; Newell and others, 2000; Stanford, 1993b, 2008a, 2008b; N. J. Geological Survey, 2007.

of shallow valley incision. Incision was not deep or long-lived because there are no distinct fluvial scarps or subterraces within these deposits. This baselevel stability may reflect the long period required for the Delaware River to incise and erode the Cape May 1 fill following the sea-level highstand 400,000 years ago. Headward incision of the Delaware into the Cape May 1 may not have reached the Trenton area until the lowstand during the Illinoian glaciation between 200,000 and 150,000 years ago.

Glaciofluvial Gravel

Glaciofluvial gravel of late Wisconsinan age forms discontinuous terraces in the Delaware valley between Trenton and the terminal moraine at Belvidere (about 45 miles north of Trenton), with a surface about 50 feet above the modern floodplain. A more extensive and continuous terrace about 25 feet above the floodplain in the Delaware valley north of Trenton is a strath cut into the glaciofluvial deposit, capped by postglacial floodplain sand (see below). Where the river emerges from its narrow bedrock valley at Trenton, the glaciofluvial terrace broadens to a plain at an elevation of 55 feet. This plain underlies downtown Trenton, most of Chambersburg, and much of east Trenton. It extends down the Delaware valley, chiefly on the Pennsylvania side but also on the New Jersey side in the Roebling-Florence-Burlington area, narrowing and declining to below present sea level south of the Burlington-Bristol area (fig. 2). Downstream from Burlington the glaciofluvial deposit is entirely covered by Holocene estuarine sediments.

At Trenton, a narrowing portion of the plain also extends up the Assunpink valley to Port Mercer, where it crosses a low divide into the Stony Brook basin and continues as a terrace down the Millstone valley to the Raritan River at Manville. This extension of the deposit reflects isostatic depression to the northeast during the late Wisconsinan glaciation, which tilted the already low Millstone-Delaware divide sufficiently to allow partial diversion of the Delaware down the Millstone (Stanford, 1993a). Interestingly, the Delaware and Raritan canal uses the same divide to gravity-feed from the Delaware to the Raritan valley (Port Mercer is a locale on the canal in the divide area), and follows the same grade as the glaciofluvial plain.

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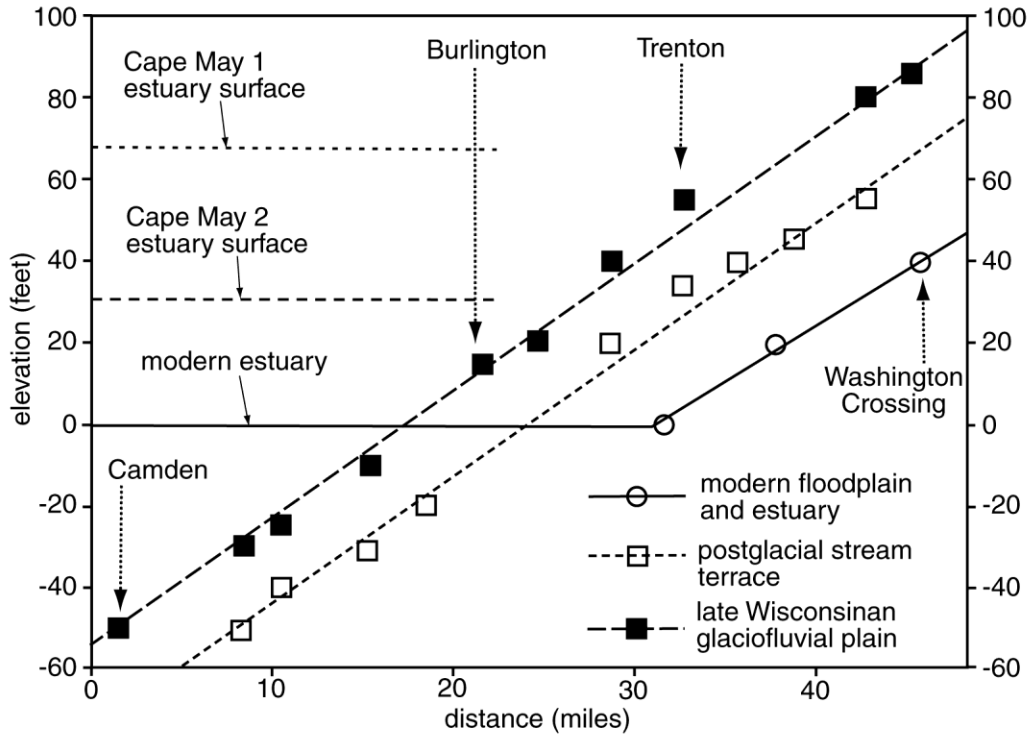

Figure 2. Topographic profiles of the glaciofluvial deposit, postglacial stream terrace, modern floodplain and estuary, and Cape May 1 and Cape May 2 estuaries in the Delaware valley around Trenton. Note projection of the glaciofluvial deposit and postglacial stream terrace beneath the modern estuary downstream from Burlington.

The glaciofluvial gravel is a grayish-brown lithic sand and pebble-to-cobble gravel, and is generally less than 50 feet thick. Gravel is chiefly gray, brown, and reddish-brown siltstone, sandstone, and quartzite, and white quartz pebbles reworked from the Pensauken Formation, with minor gray gneiss, diabase, dolostone, and chert. Dolostones are decomposed but the other clasts are unweathered or lightly weathered. Quartz-pebble content increases at and downstream from Trenton, where the Assunpink and Crosswicks creeks and other Coastal Plain tributaries delivered reworked Pensauken gravel to the deposit. In a few excavations in the Trenton area a more weathered gravel of similar composition underlies the fresher gravel. This weathered gravel is Illinoian glaciofluvial sediment. In the valley north of Trenton, Illinoian gravel is preserved in several places (Raven Rock, Frenchtown, and in the Phillipsburg and Belvidere area) as terrace remnants 10 to 20 feet above the late Wisconsinan terrace (Stone and others, 2002), indicating that a similar glaciofluvial deposit filled the valley during the Illinoian glaciation.

Lower Stream Terrace Deposits

In the Trenton area, narrow terraces in tributary valleys with surfaces 5 to 20 feet above modern floodplains, capped with fluvial sediment like that in the upper terrace deposits, are mapped as the lower terrace deposits. These deposits, which are generally less than 10 feet thick, are lithically similar to the upper terrace deposits, from which they are reworked, although they are generally more gravelly. They grade downvalley to the late Wisconsinan glaciofluvial plain in the Delaware and Millstone valleys, and so are largely of the same age. They document increased alluviation during the period of periglacial climate around the last glacial maximum. Permafrost during this period restricted infiltration of rainfall and snowmelt, thereby increasing surface runoff, and the absence or patchiness of tree cover made surface materials easier to erode. Thus, more sediment was washed into valleys, leading to terrace aggradation. Similar conditions during the Illinoian and, possibly, during earlier glaciations that did not reach New Jersey, likely contributed to deposition of the upper terrace deposits as well.

Lower terrace deposits in the Delaware valley below Burlington are somewhat older than those in the Trenton area. The terraces below Burlington are inset in the Cape May 2 and are in turn inset by the late Wisconsinan glaciofluvial deposit. Radiocarbon dates indicate that these terraces were deposited between 35,000 and 25,000 radiocarbon years ago (Jengo, 2006), during the middle Wisconsinan interstadial, when sea level rose to slightly below modern sea level in this area. Parts of the lower terrace deposit in the Trenton area may be of the same age.

Windblown Deposits

Cold climate also generates windblown sediment. Reduced tree and shrub cover, increased windiness due to katabatic effects of the ice sheet, and winter-dry conditions due to extreme cold all combine to erode and transport sand and silt from exposed sediment surfaces. In the Trenton area there are three classes of windblown deposits: 1) eolian loam on flat uplands adjacent to the Pensauken plain, 2) local sandy dune fields and patchy veneers of sandy loam on the surface of the Pensauken Formation, upper terraces, and Cape May Formation in the Coastal Plain, and 3) eolian loam on the lower valley walls in the Delaware valley north of Trenton, and in the lower Stony Brook and Millstone valleys near Princeton (fig. 1).

Class 1 deposits are best preserved on the flat shale uplands around Pennington and West Trenton that are topographically just above the level of the Pensauken plain, and just north of the edge of the plain (Stanford, 1993a). This distribution suggests that these deposits of silt and silty fine sand were blown from the Pensauken plain. Blow-off could have occurred either when the plain was active and exposed a broad expanse of sparsely vegetated sediment to the wind, or shortly after the plain was abandoned during the pre-Illinoian glaciation, when cold climate delayed the growth of forest cover.

Class 2 deposits have a patchy distribution suggesting local mobilization of silty and sandy surfaces rather than widespread deposition from a large source. The local patches may have been exposed by fire or drying of thaw ponds or, perhaps, grazing and congregating of herd animals. Since these deposits occur only on surfaces older than the lower terraces and the late Wisconsinan glaciofluvial deposit, they are of late Wisconsinan or older Wisconsinan age.

Class 3 deposits in the Delaware valley are best developed on the New Jersey side of the river to the east and south of broad segments of the late Wisconsinan glaciofluvial plain, for example, at Washington Crossing, New Jersey, across the river from a large remnant of the plain on the Pennsylvania side. They occur only on the valley wall immediately adjacent to the river. In Trenton and Hamilton, patchy windblown fine sand occurs atop the glaciofluvial deposit, notably at the Abbott Farm archeological site. This distribution indicates that they were blown from the unvegetated, actively aggrading plain, or the lower postglacial stream terrace, in the late Wisconsinan by prevailing winds from the west and northwest. This loam forms a veneer several feet thick atop the sandstone at the Wilburtha stone quarries, and was dug there for use as molding sand in the nineteenth century and earlier. The loam near Princeton is similarly situated on gentle valley slopes adjacent to the glaciofluvial plain in the Stony Brook and Millstone valleys (Stanford, 1993b).

Postglacial Stream-Terrace Deposits

As the glacier retreated northward from the terminal moraine, much of the glacial sediment delivered into the Delaware valley was trapped in glacial lakes that were dammed first by the moraine and then by heads-of-outwash laid down as the ice front retreated upvalley. Outflow of clean water from these lakes eroded the glaciofluvial deposit downvalley from the moraine. Later, as ice withdrew from the Delaware basin, no glacial sediment entered the valley and meteoric discharge further eroded the glacial valley fill. Most of the glaciofluvial plain in the valley north of Trenton was eroded, producing a strath terrace that today is about 25 feet above the modern channel. At Trenton, a four-mile-wide segment of the glaciofluvial plain, chiefly on the inside of the big bend at Bordentown, was eroded. This strath is at an elevation of 10 to 35 feet and includes the Van Sciver Lake area south of Morrisville in Pennsylvania, Duck and Newbold islands in New Jersey, and the 25-35 foot terrace along the river in Trenton, to the west of South Broad Street and Route 129. Waterfront Park, Sun Bank Arena, Trenton State Prison, and Riverview Cemetery are on this strath terrace. It consists of a capping of sand and reworked glaciofluvial gravel on the channeled and eroded surface of the glaciofluvial deposit. Like the glaciofluvial deposit, it narrows and declines downvalley and descends below sea level in the Florence area (fig. 2).

Radiocarbon dates from organic material at the base of modern floodplain deposits in the Trenton area range from 13,700 to 10,400 radiocarbon years old (Sirkin and others, 1970; Stanford, 1993a). These deposits are inset into the strath terrace and so provide a maximum age for its formation. Also, the strath terrace projects downvalley below Burlington to basal alluvial gravels in the bottom of the incised channel beneath the Holocene estuarine fill (fig. 2), indicating that the strath formed before Holocene sea-level rise. These observations indicate that the strath was cut between about 20,000 and 15,000 radiocarbon years ago, which corresponds to the timing of deglaciation of the Delaware basin (Ridge, 2004). This chronology in turn indicates that meltwater from ice in the upper Delaware valley was a significant contributor to strath erosion.

Modern Floodplain and Estuarine Deposits

Between 15,000 and 10,000 radiocarbon years ago the postglacial terrace in the Delaware valley was incised to form the modern channel and floodplain. At and north of Trenton the river incised about 25 feet before encountering bedrock, limiting further incision, but on unconsolidated Cretaceous deposits downstream from Trenton, in the vicinity of Duck and Newbold islands, the river channeled up to 60 feet below the postglacial terrace. Most of this depth is now filled with Holocene alluvial and estuarine deposits. This incision episode corresponds with the return of forest to the Delaware basin, as recorded by pollen records in peat bogs. Forest cover stabilized hillslopes, reducing sediment load in the river, and thereby favoring erosion over deposition.

The present floodplain of the Delaware and its tributaries has been in place since the beginning of the Holocene at about 10,000 radiocarbon years ago. Alluvium on the floodplain is generally less than 10 feet thick and includes pebble-to-cobble gravel channel deposits overlain or bordered by overbank silt and sand, with organic matter and peat. Along the Delaware north of Trenton, overbank deposits are narrow and patchy and in places restricted to small alluvial islands within the river, because the floodplain is not much wider than the river channel. The floodplain is narrow here because the gradient of the river is relatively steep, inhibiting lateral channel migration. The channelway and narrow floodplain along the Delaware at and north of Trenton appears to be adjusted to contain the 5 or 10-year flood; larger floods generally rise onto the postglacial strath terrace. The 1955 flood of record inundated much of the strath terrace in the valley north of Trenton. Coastal Plain tributaries have gentler gradients and so the floodplains are wider and overbank deposits more extensive. Floods rarely rise above the floodplains, except where they have been filled and urbanized, for example, along the Assunpink in Trenton.

The Trenton marsh, just south of Trenton, is a freshwater tidal wetland that marks the present inland limit of marine submergence. Peat and alluvial silt and sand have been aggrading in the marsh in step with sea-level rise for at least the last 9,000 radiocarbon years. Radiocarbon dates from peat cores in the marsh, made for a paleoecologic study (E. W. B. Southgate, personal communication, 2003), record a 16-foot rise in sea level between 8,600 and 3,900 radiocarbon years ago (about 1 mm/yr), a period which includes the final phase of melting of the late Wisconsinan ice sheets, and about 3 feet of sea-level rise since 3,900 (about 0.2 mm/yr). Over the past century, sea-level rise has accelerated to about 3 mm/yr, and will further accelerate in the coming decades (to perhaps a range of 8 to 15 mm/yr) as polar glaciers melt in response to global warming.

Groundwater and Economic Resources

Surficial deposits in the Trenton area, with the exception of the Pensauken Formation northeast of Trenton, are too thin to be aquifers. In the thalweg of the Pensauken valley between Mercerville and Plainsboro, the Pensauken Formation has not been deeply eroded by stream incision, and is as much as 100 feet thick. It includes a water-bearing basal gravel that overlies impermeable schist saprolite or Cretaceous clay. A number of domestic and agricultural irrigation wells were completed in the basal gravel in this area. Urbanization has eliminated most of the irrigation use, and the Pensauken aquifer is not thick or extensive enough for high-capacity public-supply wells.

Although they are too thin to be aquifers, the widespread distribution of surficial deposits in the Trenton area (fig. 1) makes them important in aquifer recharge, groundwater-surface water interactions, and contaminant transport. The glaciofluvial deposit is highly permeable because it is gravelly and generally unweathered. The Pensauken Formation, beneath the upper 10 to 15 feet of clayey weathered material, is also permeable, although, except for the basal gravel, it is dominantly sand and lacks the thick gravel beds of the glaciofluvial deposit. The Cape May Formation and stream terrace deposits are also predominantly sand or silty sand and so are generally permeable. Pebbly beds are thin and discontinuous in the Cape May and upper terrace deposits but are more abundant and thicker in the lower terrace deposits. Clay and silt beds are rare in all of the surficial deposits, except the Holocene wetland and tidal-marsh sediments, and overbank facies of Holocene floodplain deposits, all of which are organic-rich silt and silty fine sand, with a minor clay component.

The Pensauken Formation and the glaciofluvial deposit have been mined extensively in the Trenton area for sand and gravel. Van Sciver Lake in Pennsylvania south of Morrisville is a large former gravel pit dug through the postglacial stream-terrace material into the glaciofluvial deposit. Gravel is still mined from a smaller pit north of the lake. All of the other gravel pits in the Trenton area are now inactive.

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Chapter 11

Road Log

Saturday, October 10, 2010

Field trip 8:00 a.m. to 5:00 p.m.
Free parking is available in the Capital Parking Garage. Guards may ask for ID. Free parking also is available in parking lots near the Trenton War Memorial Theater and at the NJ State Museum.

Meet at Old Barracks Museum at 8:00 a.m.
Barracks Street, Trenton

8:00 to 9:30 a.m.--Walking tour of one block area around the Trenton Barracks
Leaders, Pierre Lacombe, Rich Volkert, Richard Hunter, Ian Burrow, Richard Patterson,

Prelude
Geology in an Urban Suburban Area

Most outcrops of metamorphic bedrock of the Trenton Prong in Trenton are covered by buildings, pavement, or fill. Many former outcrops likely were quarried to below land surface. Major outcrops of metamorphic rock still exist in the Delaware River and Assunpink Creek. Access to them is hazardous because of high water, cold water, or fast water. Generally the river outcrops are slick with algae in the summer and are covered with a black patina. We will visit three small outcrops that are not in the river.

Major outcrops of the sedimentary rocks of the Triassic Newark Basin are a few miles north of Trenton. The best outcrops are road cuts along I-95. Access to them is hazardous because of fast traffic. Former quarries of the Stockton and Lockatong sandstone are on private property or State property maintained by the N.J. Department of Corrections. Access to such property is by permission only. Minor outcrops of sedimentary bedrock are found in creek beds, local road cuts, and canal cuts and spillways. We will visit two small outcrops of the Lockatong Formation along the Delaware and Raritan (D&R) Canal Parkland at Scudder's Falls just north of the Scudder Falls Bridge. Rock core from a USGS Fracture Rock research site should be available for viewing the non outcrop rock in greater detail

Major outcrops of igneous rock (diabase) are of Jurassic age and form the Sourland Mountains in the Newark Basin. The diabase is extensively quarried just south of Lambertville and north of Pennington. We will visit the active quarry north of Pennington.

Major outcrops of Coastal Plain sediments of Cretaceous age are best exposed in sand and gravel quarries south of Trenton. Minor outcrops are in streams, gullies, and along the Delaware River. We will visit a former clay quarry that was active prior to the 1940s and a stream gully that reportedly has some Cretaceous fossils.

Major outcrops of the Pleistocene glacial outwash cover all the above geologic units. Generally, at each site we visit, the surfacial deposits with gravel are Pleistocene deposits. In many locations around Trenton, the mixture of sand and gravel at land surface is fill. Much of the fill was mined from nearby glacial outwash deposits.

Stop 1, Part A.
Retention Wall between Edison College and the Old Trenton Barracks

Leaders: Pierre Lacombe, U.S. Geological Survey
Rich Volkert, N.J. Geological Survey

The retention wall between Edison College and the Old Trenton Barracks **(fig. ft-1)** provides an excellent opportunity to view some of the indurated rocks that are found in the Trenton area. Rocks present in the wall are mainly reddish-brown, pink, light gray and dark gray sandstone facies of the Triassic age Stockton and Lockatong Formations **(fig. ft-2).** Also present are Mesoproterozoic age felsic and mafic gneisses and Cambrian age Chickies Quartzite (pebble conglomerate and quartz-sericite schist) that are representative of lithologies found in the northern and southern blocks of the Trenton prong**.** Present in minor amounts are fine-grained Jurassic diabase and rounded boulders of water-worn rock from the unconsolidated Trenton Gravel**.**

Figure ft-1. Retention wall between Old Trenton Barracks and Thomas Edison State College. Wall is mostly rocks from local outcrops.

Figure ft-2 Mesoproterozoic felsic and mafic gneisses, red purple and gray sandstone

Exotic lithologies include white, fine-grained, fossiliferous carbonate sandstone (Indiana limestone?) and white, fine-grained marble (Vermont Marble or Cockysville Marble) that is engraved and may be a memorial stone **(fig. ft-3).**

The eclectic nature of rock types present in this wall, and the variability in size and shape of the blocks, suggests that the material was scavenged from different sources. Some blocks display tool marks such as plug and feather from the quarrying process. **(fig. ft-a).** Some blocks show tool marks of hackers and masons who built the wall. All blocks are cemented by material consisting of coarse quartz sand containing rusty quartz pebbles that may be representative of the Pleistocene-age Trenton gravel or the Tertiary-age Pennsauken Formation, both of which form local deposits.

Stockton and Lockatong Formations in the wall here closely resembles the blocks that line the flood levee and hill slope along the west side of the Delaware River, south of the Calhoun Street Bridge at Morrisville and are probably from the same source.

Much of the material in the wall was likely quarried a relatively short distance away in Quarries on former quarry Street (now Hanover St), north of Trenton (Stockton and Lockatong Fm. and diabase), or in the southeastern Pennsylvania Piedmont (gneisses and Chickies). Rogers (1865) discusses the economic importance of the gneisses in providing "several valuable varieties of building stone, well adapted to structures demanding solidity and strength." Bascom et al. (1909) indicate that gneiss used for building stone was quarried chiefly at two locations in southeastern Pennsylvania, one operated by Jesse Darrah near Langhorne and the other by Charles T. Eastburn near Neshaminy Falls. These quarries were likely along the Neshaminy River and are about 6 miles west of Trenton. These same authors indicate that Wissahickon was quarried only very locally for building stone at Appleton's quarry, Wood's quarry, and Folkcold's quarry, all of which were near Byberry and Ford, Pa., where it was quarried mainly for use as road metal. See the section below under Part C for discussion of the Chickies Quartzite.

Figure ft-3. Part of memorial stone of local Cockeyville marble or Vermont marble

Figure ft-4a Mining features, Pin and feather rock breaking technique in dark sandstone.

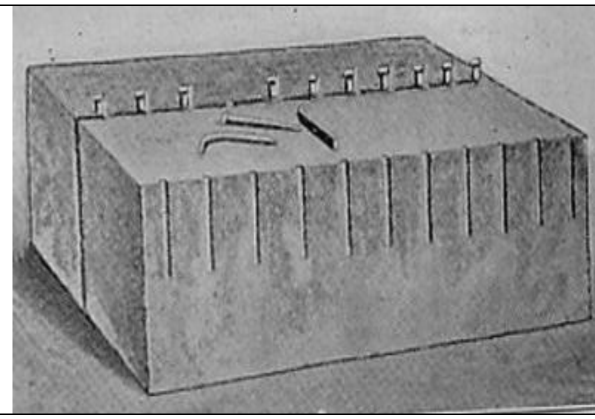


Figure ft-4b. Plug and feather method of quarrying. Block quarried by the plug (wedge) and feather (shim) method (Gage and Gage, 2005).

Rocks types in Retention Wall

Chickies quartzite, quartzite, quartzite sericite schist, quartzite conglomerate with blue quartz pebbles (sericite is fine grained mica)

Mesoproterozoic schist and gneiss

Amphibolites,

Cockeyville Marble (?) used for memorial stone

Trenton Gravel (boulders) pebbles in mortar,

Diabase from cooled margin

Stockton/Lockatong Sandstone White Pink, red, purple

Stockton Conglomerate

mining features,

plug and feather,

face smoothing features

Other rocks Indiana Limestone used for War Memorial,

Vermont Marble memorial stone

Stop 1, Part B.

Exterior walls, Old Trenton Barracks Museum
Leader: Rich Volkert, N.J. Geological Survey
Richard Patterson Old Trenton Barracks Museum

History of Barracks- Built in 1758, the edifice (fig. ft-5) documents the early commercial use of rocks of the Trenton prong as building stones. The Barracks first housed British, Scottish, and Irish soldiers. The officers were housed in the fancier section with the red brick front. During the Revolutionary War (1776-1781), the building was occupied by whoever controlled Trenton at the time. In about 1791, the middle section of the building was torn down and parts of the building became apartments, a school, and old age home. About 1915, Daughters of the American Revolution and the State bought the buildings and refurbished them in the attempt to make them look similar to when first constructed.

Figure ft-5. Old Trenton Barracks. Most stone work is original. Section between two wood barrels and five wood barrels are not original. Brick façade is not original.

The exterior walls of the Trenton Barracks are constructed almost exclusively from the Cambrian-age Chickies Quartzite. Original stonework includes the three major facies of the Chickies. Most stones are quartz-sericite schist, and less abundant conglomerate with small pebbles of blue quartz, and relatively pure quartzite (see Stop 3 for more detailed discussion of the Chickies). Thin tourmaline crystals are visible on selected blocks of sericite schist. The only other rock type seen consists of six blocks of Stockton Formation that form an archway above an upstairs window in the original stonework. The brick façade on the front of the officer's quarters is not original, but the original red brick façade would have been made at a local quarry south of Trenton.

During restoration work on the Barracks in 1915-1916, stone masons tried to match the new stone as closely as possible to the original. While the new stone used is Chickies, all of the new stone is of quartz-sericite schist and includes virtually no quartz pebble conglomerate or quartzite. Thus it is thought to be from a different quarry. The stone from the new quarry is more homogeneous facies of the Chickies than the original stonework.

Figure ft-6. Back wall of Old Barracks. Rock walls composed mostly of Chickies quartzite. Section with yellow bar is not original.	Figure ft-7. Exterior wall of Old Barracks Museum

While the blocks in the exterior walls of the Barracks have clearly been artificially shaped and sized, a thorough examination of the walls reveals an absence of tool marks on any of the blocks related to the quarrying process. Early quarrying methods since 1774 often utilized the plug and feather technique (Gage and Gage, 2005) that left distinct furrows in the face of the block (Fig. ft-3). Perhaps the blocks used in the Trenton Barracks were quarried by a different method such as hacking that utilized pry bars, or perhaps the craftsmen turned the blocks while constructing the walls so the imperfections were facing inward instead of outward.

Because the Chickies Quartzite does not crop out east of the Delaware River, the source for the material in the walls of the Barracks clearly was from the southeastern Pennsylvania Piedmont. A stone quarry in the Chickies at Morrisville attests to its local economic use. Rogers

(1865) mentions a laminated quartzose lithology containing mica that is likely a reference to the Chickies, indicating its very local use as a building stone in Trenton. Bascom et al. (1909) also report that Chickies Quartzite was extracted from quarries at Neshaminy Falls, Janney, and Oxford Valley in Pennsylvania principally for use as road metal, but they do not mention its use as a building stone. Yet, the walls of the Trenton Barracks are unquestionably constructed from the Chickies Quartzite. Willard et al. (1950) show nine quarries in the Chickies between Langhorne and Trevose in Bucks, County. The quarry at Morrisville raises this total to ten in just Bucks County. However, the exact source of the original material within the outcropping belt of Chickies remains unknown.

The interior of the building includes other local building materials such as reused redbrick, and river cobbles and less stately looking pieces of Chickies. Mortar used to cement the stone and brick likely came from burning oyster shells for the calcium carbonate mixed with local sand and gravel of the Trenton Gravel. Much of the building has been repointed and the original cement is covered.

For information on the history of the Barracks the interested reader is referred to the website www.barracks.org.

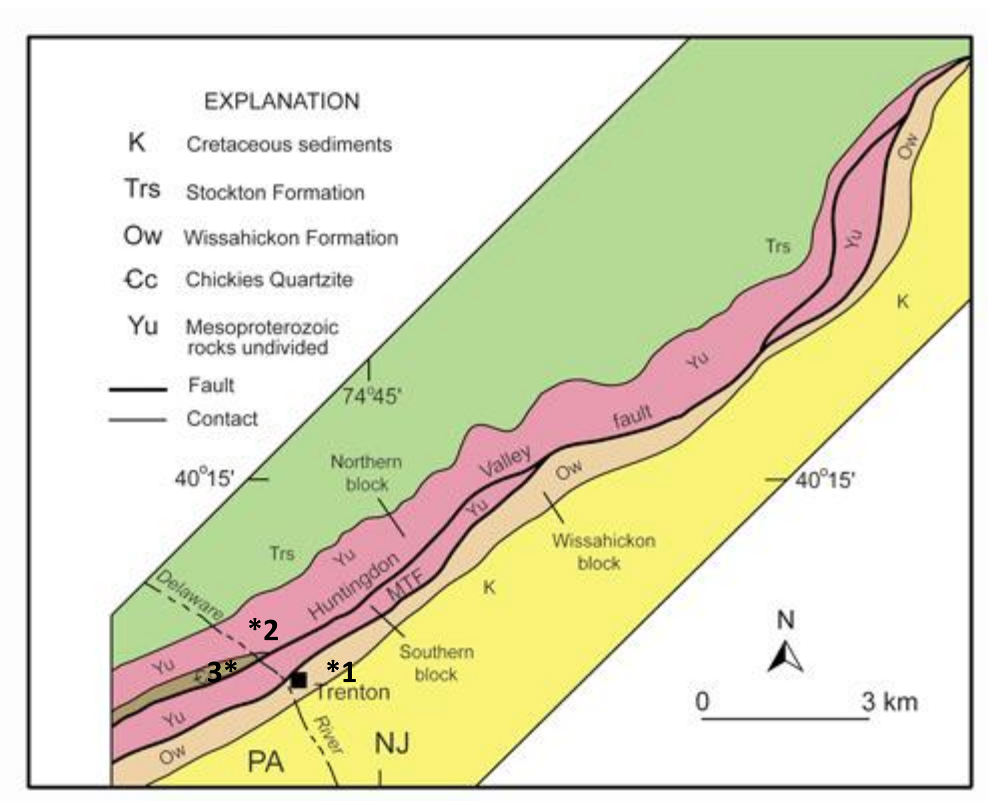


Figure ft-8. Simplified bedrock geologic map of the Trenton prong (modified from Volkert and Drake, 1993) showing locations of stops 1, 2 and 3. MTF; Morrisville thrust fault.

Stop 1, Part C. Mill Stones for the Ceramics industry.
Leaders: Pierre Lacombe U.S. Geological Survey
Richard Patterson Old Trenton Barracks Museum

In the back yard of Old Barrack Museum are nine massive mill stones used to grind rocks to a powder for the local ceramic industry. The mills stones were used during the late 1800's early 1900's. Six white mill stones are Silurian age **Shawangunk Conglomerate** likely from southern New York State. Three light brown mill stones are likely from granitic outcrops in New England

	
Figure 9a. Quartz pebble conglomerate mill stone lIkely silurian age Shawngunk conglomerate from southern New York State.	Figure 9b. Granite millstone lIkely from New England

Stop 1, Part D.
Petty's Run Archeological Excavation
Leaders: Richard Hunter, Hunter Research
Ian Burrow Hunter Research
Rich Volkert N.J. Geological Survey

The foundations and standing walls of the 1700 and 1800's industrial structures are currently protected by tarps and are therefore difficult to see. However, the main characteristics of the site are apparent when viewed from the south end, near the Barracks fence.

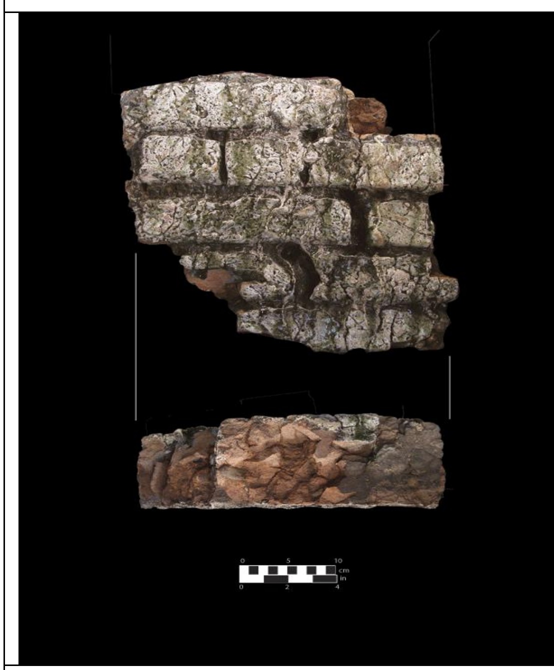
Most prominent is the **brick-roofed culvert** constructed over **Petty's Run** in about 1876, in part re-using earlier side walls constructed chiefly of gneiss. This runs from north to south across the site, reflecting the bedrock topography through a series of steps downwards. Inside is a spectacular cavern-like space with the stream rushing and tumbling over the bedrock.

On the west side of the culvert at the south end of the side is the impressive **wheel-pit of the 1827-1876 paper mill.** At the bottom of the pit still lies the massive oak framing structure put in place in the last years of the mill's operations, in order to channel water to two turbines that replaced an earlier iron wheel that was probably about 18 feet in diameter.

Partially destroyed by the wheel pit, but extending westwards from it, is the **furnace house of the 18th century steel furnace,** which extends over 35 feet to the west of the later wheel-pit and is about 30 feet north-south. Within the furnace house, close to its north wall, is the foundation of the **steel furnace** itself, about **ten feet square. Ingots of iron** came from the Iron province 30 miles upstream just south of Phillipburgh, NJ and Eaton, PA. Iron and carbon fused under high temp in the furnace made steel.

North of the furnace house the **gneiss bedrock** is extensively exposed. Several **drill holes** are apparent in this area, showing quarrying of the outcrop before 1876, probably including 1700's activity.

In the northeast corner of the site, adjacent to Thomas Edison State College, the standing walling is probably part of the early 1800's **cotton mill, overlying and incorporating parts of the 1743 plating mill** that drew water from Pettys Run to power a trip-hammer.

	
Figure ft-10a. Petty’s Run steel mill foundation	Figure ft-10a. Petty’s Run plating mill foundation
	
Brick from furnace with face melted to glass	

Stop 1, Part E.
Entrance to Thomas Edison College
Leader Pierre Lacombe, U.S. Geological Survey
Richard Hunter, Hunter Research

Terra cotta tiles on the entrance to the Kelsey building.
The School of Industrial Arts was established in 1890 to train artisans for the Trenton's booming pottery factories. The Kelsy building was completed in 1911.

Architect Cass Gilbert copied Florence Italy's Strozzi Palace for the building. Gilbert also designed Woolworth Building in NYC. The brick is local Coastal Plain red clay and sand. The foundation is highest quality Stockton Sandstone. Marble unknown, bronze plaque, likely a local atelier.

Herman Carl Mueller, noted Trenton tile manufacturer, designed the tilework frieze motif include the shield of the school, birds drinking from the vessel of knowledge, artist pallet and brushes, student portrait, and open book. The tile motifs were derived from Renaissance ornaments. Tile masters Mueller and Walter Lennox (Lennox china) were some of the school founders. From POTS webpage accessed Feb 2010

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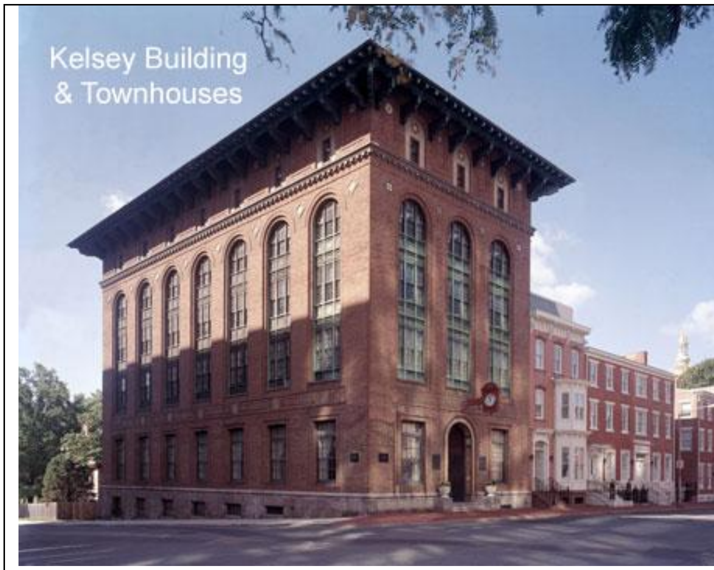
<tr><td>
</td><td></td></tr>
<tr><td>Front of Thomas Edison State College (local brick)</td><td>Terra cotta tile on former main entrance to Thomas Edison State College</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Trenton made ceramic sanitary ware</td><td>Bridge abutment ornament common on many older bridges of Trenton</td></tr>
</table>

Stop 1, Part E.

Intersection of Warren and State Street.

May pass this stop depending upon time

Planned center of 'Trentown' as designed by William Trent. Topographic high is a result of resistant amphibolites unit (Fig 1) similar to unit forming the rapids in the Delaware River.

Uphill (east) from intersection (east) at site of George Washington Monument, Geo Washington and American troops set up cannons on Christmas morning. During the First Battle of Trenton, the Americans shot cannon balls down of Broad Street and Warren Street (then Queen St & King St). The cannon balls skipping along the gravel streets mercilessly sprayed the mercenary Hessian soldiers with gravel (Trenton Gravel) and denied the foreign soldiers the ability to attack the insurgent Americans. (Oral communication Ralph Siegel 2009)

Stop 1, Part F.

Ceiling of Foyer to Trenton War Memorial

Description is from the Pottery of Trenton Society (POTS) web page.

Tiles produced by Mueller Mosaic Company

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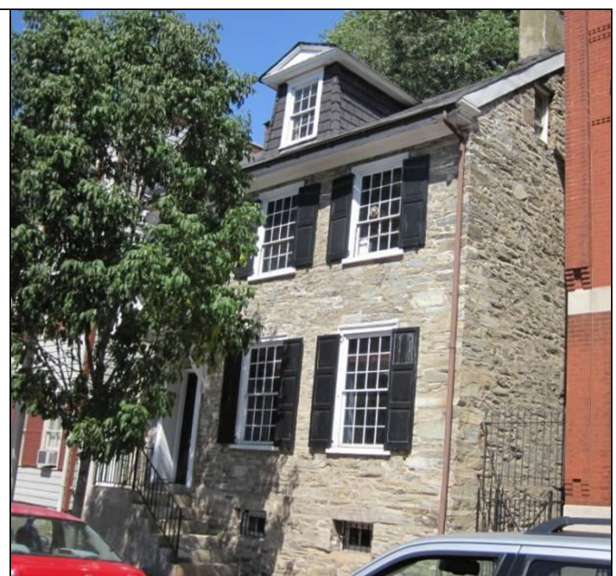
Terra cotta tiles on ceiling of foyer of Trenton War Memorial.

9:30 to 9:45 Board Bus: drive 1.1 miles west along West State Street to 383 West State Street.

0.0 mi – Front of Old arrack Museum
0.2 mi - Intersection of Lafayette and Broad Street 2nd Battle of Trenton fought over former bridge that cross Assunpink Creek at this intersection
Turn left up Broad Street, 1st and 2nd battle of Trenton fought on streets, Geo Washington shot cannon balls down street to spray Hessians with Trenton Gravel
0.3 mi - Turn Left onto West State Street
0.4 mi - Intersection of Warren and State Trent's original Center of Town on Topographic high of Amphibolite
0.6 mi- Pass NJ State Capital Building. Initially built in 1792, it was repeatedly expanded during the 1800's. Original basement stones have been white washed. It is unclear if original foundation is metamorphic rock or sandstone. Most foundation rock used after 1834 is Stockton/Lockatong sandstone and conglomerate. Stone was shipped to the site via the Delaware and Raritan Canal. Many hallways and legislative chambers are painted to look like rock.
0.8 mi -State Museum on left. Beautiful red sandstone building on right.
0.9 mi - Emlin House 222 West State Street residence constructed of Chickies quartzite
1.1 mi- **Stop 2** Feeder Canal for the Delaware and Raritan Canal. Water flows from intake Bulls Island and flow 42 miles to this point. In less than 1 mile downstream water formerly join the main D&R canal. Water was then directed northward to New Brunswick or southward to Bordentown. The south leg of the canal no longer carries water from this canal. Water in canal is used for drinking supply in New Brunswick.

	
NJ State Capital building foundation is metamorphic and sedimentary rock , interior is painted to look like rock	Emlin House built 1796 of Chickies quartzite and gneiss and schist

Stop 2: Metamorphic rock outcrops behind Catholic Charities and in Delaware and Raritan Feeder Canal Overflow channel.
NO HAMMERS, PLEASE

Leader: Rich Volkert, N.J. Geological Survey

Bedrock outcrops exposed near downtown Trenton along the edge of a paved lot, and in a drainage outfall from the Delaware and Raritan Canal, offer an exceptional opportunity to examine a heterogeneous sequence of Mesoproterozoic-age gneisses from the northern block of the Trenton Prong (Fig. 1) and some of the structural features associated with them. The gneisses in the drainage form part of an unnamed shear zone of unknown strike length, and the challenge here is to “see through” the deformational fabric and the high-grade metamorphism in order to interpret the protoliths and geologic history of the bedrock.

Entering the wooded area at the south end of the parking lot, outcrops are seen of medium-grained, foliated, grayish-black amphibolite composed of plagioclase, hornblende and minor clinopyroxene. Enclosed within the amphibolite is a thin layer of mafic metavolcanic rock that is texturally unlike amphibolites in the Trenton prong in that it contains abundant phenocrysts of hornblende up to 1 cm long in a matrix of plagioclase (see Chapter by Volkert, this volume for discussion of these mafic rocks). Entering the drainage and walking toward the northeast (upstream), one crosses a conformable contact between amphibolite and a sequence of medium-grained, layered and foliated metasedimentary, metavolcanic and possibly metavolcaniclastic gneisses. From south to north these include: 1) dark gray, quartz-poor gneiss composed of hornblende, plagioclase, clinopyroxene, biotite, and local sulfide; 2) light greenish-gray, quartz-bearing gneiss composed of clinopyroxene, plagioclase and local titanite; 3) dark grayish-black, hornblende-plagioclase amphibolite; 4) fissile, quartz-bearing gneiss composed of clinopyroxene, plagioclase, hornblende, and biotite; and 5) pale pinkish-white, massive gneiss composed of quartz, K-feldspar, plagioclase, biotite, and locally abundant sericite.

Contacts between the various gneisses are generally conformable, but the concordance reflects tectonic transposition rather than the preservation of original lithologic contacts. Foliation here strikes N67^{o}E and ranges in dip from 80^{o} toward the southeast to 83^{o} toward the northwest.

	
Stop 2 Multiple metamorphic rock outcrops in Delaware and Raritan Canal overflow wir	Outcrop of amphibolite showing metamorphic foliation and zones of weathering.”
	
Stop 2 Outcrop of phenocrystic amphibolite on Catholic Charities property.	

10:45 board bus for 5-mile ride to Graystone Monument and Chickies Quartzite outcrop, Morrisville PA

0.0 mi - Catholic Charities, drive west on West State Street to Parkside Avenue.
Note: W State Street is always within five blocks of the D&R Canal.
Note: Parts of many homes and churches constructed of Stockton Sandstone.

0.2 mi - Between Fischer St and Artisans Place, the small hill slope marks the northern limit of the metamorphic rocks and the southern limit of the Stockton Sandstone

0.6 mi - Dioceses of Trenton Episcopal Church. Stockton Sandstone. One alter is made a slab of rock from the Isle of Jersey in England. A rock on display in church is reportedly from the stone in front of Christ's grave. Stained glass window depicts in church the Brooklyn Bridge.

0.9 mi - Turn left on Parkside Street.

1.0 mi - Join Rt 29 South,

1.6 mi - Delaware River

1.9 mi - Trenton Water Works. Intake and water filtration plant. The plant can treat up to 50 million gallons per day and supplies water to 210,000 people in Trenton, Hamilton, Ewing, and Lawrence.

The 'Falls of the Delaware River' is the local expression of the Fall Line a geologic / physiographic line that separates the Coastal Plain sediments from the Appalachian piedmont. The rocks exposed in the river are the suite of Trenton Prong metamorphic. New Brunswick, Trenton, Philadelphia, Baltimore Washington DC, and Richmond all lay on the Fall Line.

2.2 mi- State Museum

2.3 mi - State Capital

2.8 mi - Market St Exit bear Left

2.9 mi - West Trent St Turn right

Note: William Trent house on right side of road. Built in 1716-19 of local brick and mortar from Coastal Plain Sediments. The basement is constructed of local stone. Likely metamorphic rocks of the Trenton Prong but all basement rocks are whitewashed.

3.1 mi - Right on to Bridge St

3.4 mi - on Trenton Makes Bridge

Note: TRENTON MAKES, THE WORLD TAKES, was first adopted by Trenton in 1910 to extol the industries of Trenton including steel, rubber, wire rope, linoleum, and ceramics. The original bridge was built in 1806 and the foundation piers are original on the upstream side of the bridge. The piers were extended on the downstream side of the bridge in 1874 to accommodate the railroad. The piers are made of Stockton Sandstone which rests on metamorphic bedrocks.

The Delaware River is tidal downstream. Average flow is about 100,000 cfs, maximum flow has been 295,000 cfs.
Tides on Saturday October 9 2010, High Tide 4:08 AM and 4:32 PM,
Low Tide 12:12 AM and 12:36 PM.

TRENTON MAKES THE WORLD TAKES Bridge over the Delaware River, note strike of rapids

3.6 mi- Right onto Delmarr Ave
Note: Flood levee restricts view of the Delaware River
4.4 mi - Left on East Trenton Ave.
4.5 mi - Right onto Crown Street.
4.8 mi - **Stop 3** Monument at intersection of Crown and Ridge Street.

Stop 3: Outcrops of Chickies Quartzite at Graystones Park, Morrisville, PA
NO HAMMERS, PLEASE

Leader: Rich Volkert

Outcrop of Chickies Quartzite "Graystones" marks the starting point of the initial land purchase the William Penn made from the Native Americans in 1682. A monument of Stockton Sandstone commemorates the purchase

The Chickies Quartzite, named for the type section in Pennsylvania at Chickies Rock along the Susquehanna River, derives its name from the Lenape word "chiquesalunga" meaning "place of crayfish." Outcrops of Chickies Quartzite are well exposed in the hill slope above the Delaware Canal at Gray Rock in Morrisville, Pennsylvania (Fig. 1). Lithologies here include an interbedded sequence of conglomerate and pebbly sandstone with clasts of blue quartz, quartzose sandstone, orthoquartzite, and quartz-sericite schist with disseminated, fine grains of black tourmaline, all of which have an estimated thickness of about 730 feet. The Chickies here locally displays graded beds and tabular cross-beds that indicate bedding is right-side-up and also confirm a sedimentary protolith for the unit. The presence elsewhere of *Skolithus linearis* burrows in the Chickies fixes its age as Cambrian (Bascom et al., 1909) and suggests that it is coeval with the Hardystone Quartzite in the New Jersey Highlands. The texture, bed forms, burrows, lithologic characteristics, and compositional maturity of the Chickies, indicate deposition in a marine environment, possibly estuarine, along a passive margin (Adams and Goodwin, 1975).

Much of the original bedding in the Chickies is parallel to, and overprinted by, well-developed schistosity that ranges in strike from N47^{o}E to N84^{o}E (average = N70^{o}E) and ranges in dip from 45^{o} to 76^{o} (average = 66^{o}) toward the southeast. To the north, the Chickies is in nonconformable contact with Mesoproterozoic gneiss, and to the south it is cut off by the Huntingdon Valley fault (Fig. 1). Near the Delaware Canal, a small abandoned quarry (Fig. 3) that was developed after 1950 is a reminder of the local importance of the Chickies as a building stone. An exceptional example of its earlier use may be seen in the walls of the Trenton Barracks. Careful examination of blocks forming the exterior walls of the Barracks reveals the presence of quartz-sericite schist with black tourmaline, conglomerate with blue quartz clasts and quartzite, all of which may be seen in the Chickies at this stop.

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<tr><td></td><td></td></tr>
<tr><td>Chickies Quartzite outcrop near Graystones monument that describes Wm Penn purchase of land from Lenne Lanape</td><td>Chickies Quartzite outcrops in Green Acres Park</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Chickies Quartzite outcrop and float in Green Acres park. Morrisville PA</td><td>Figure 3. Small abandoned quarry in the Chickies Quartzite at Morrisville, PA.</td></tr>
</table>

12:00 noon Board busses and drive to Scudder's Falls **8.2 miles total**
0.0 mi - Take Ridge Ave 1 block to North Pennsylvania Ave.,
0.1 mi - Turn Left, Drive North Pennsylvania Ave south
0.9 mi - cross Bridge Street
1.1 mi - take left onto Rte 1 North.

Cross Delaware on Route 1 Bridge.

Note: Kat-man-du Night Club on the New Jersey side of river is former Trenton Iron Works. Iron Works produced the first iron and steel rails for railroads (18xx), first rolled wrought-iron beams (1847) a 7–inch deep bulb-tee rail beam; first I-Beam (1848), artillery carriages and gun-metal for Civil War; first steel by open hearth in the United States. First steam boat in America made by John Fitch made successful trips between Philadelphia and Trenton and landed in front of building in 1790. Sadat Envirnmental Firm is in office complex next to Kat*Man*Du

1.7 mi - Exit bridge Take Exit for Rte 29 North,
1.9 mi - On Rte 29 North Drive 6 miles north,

Note: Route 29 follows the former Trenton Water Power Canal used from 1834 to 1890 for textile and iron industry and water supply until the 1950s. It was filled in for construction of Route 29 in 1950s.

2.2-mi - Bridge abutments made of Stockton sandstone
3.7 mi - Foot bridge, most northerly outcrop of metamorphic rocks of the Trenton Prong are in the river
4.8 mi - Sullivan Way intersection
5.0 mi - Rail road Bridge overhead
5.6 mi - intersection with wilburtha Road former Stockton/Lockatong sandstone mines along east side of Canal between Wilburtha rd and something road
7.1 mi - Villa Victoria Academy stone wall is from quarries less than 1 mile east of here.
7.8 mi - Scudders Falls Bridge for I-95.
8.2 mi - Turn Left onto Bernard Drive
8.2 mi - Turn left onto River Road, park, at Stop 5

Stop 4: Scudder's Falls section of the D&R canal

The Scudder Falls derives its name from Richard Betts Scudder, who purchased about 500-acre farm at this location in 1709. He and Hannah Reeder married in 1691 and had nine children.

Stop for Lunch;
View upper Tohekon Member of Lockatong Formation Outcrop along Delaware River
View upper Prahls Island Member of Lockatong along D&R canal.
View D&R canal
View Trenton Power Canal intake
View Scudder's Falls

Stop 4, Part A
Delaware and Raritan Canal Feeder Canal
Leader: Richard Hunter, Hunter Research

You are standing by the Feeder canal to the Delaware & Raritan Canal.

During the 1800s, when the United States entered into the industrial revolution, canals were built as transportation routes to link resources, manufacturing centers and markets. The D&R Canal was built across central New Jersey in 1834 to provide an efficient and safe route for transporting freight between Philadelphia and New York.

Boats from Philadelphia could navigate the Delaware River to Bordentown and boats from NYC could navigate the Raritan River to New Brunswick, therefore Bordentown and New Brunswick were selected as the two ends of the Main canal.

The Feeder Canal formerly supplied water to the Main Canal of the Delaware and Raritan Canal. The feeder canal starts at Raven Rock its highest point at about 70 to75 ft and flows to Trenton an altitude of about 58 ft. It is about 22 miles long, 60 feet wide, and 6 feet deep with a drop in water level of 12 to 17 ft a little more than 0.5 ft per mile.

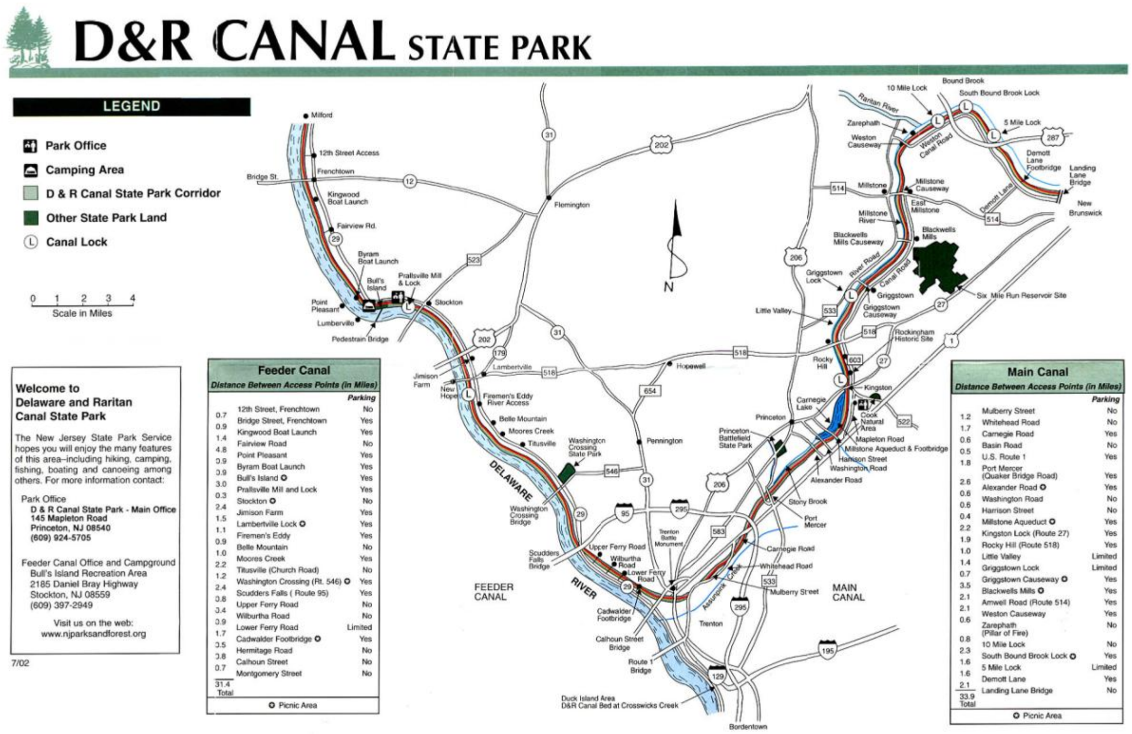
The Main Canal of the D&R is from Bordentown to New Brunswick. The Main Canal is 44 miles long, 75 feet wide and 8 feet deep and had 14 locks. The highest point of the Main Canal is 58 ft in Trenton. The lowest point is sea level in Bordentown and sea level in New Brunswick.

The canal today has a major function as an aqueduct transporting potable water from the Delaware Basin to the Raritan basin. The NJ Water Authority maintains it. In addition the canal coridore is actively used for recreation. The feeder canal is open and flowing from Bulls Island to Trenton and the Main Canal is open and flowing from Trenton to New Brunswick. The section of the Main Canal from Bordentown to Trenton is partly filled in and partly open. The filled part of the Main Canal is occupied by Rte 129 and Rte 1 . The open part of the Main Canal is near Duck Island and is open to the tide.

Irish immigrants dug the canal system by hand at an estimated cost of $2,830,000. The Feeder canal also was used to transport material, (80% of the freight was coal), from Pennsylvania coal country to NYC thus feeding the industrial boom during the 1860-80. Boats and barges were first pulled by mule teams then by steam-powered boats. The banks of the canal were reinforced with stone because the wakes of the steam boats eroded the shoreline.

The Belvidere-Delaware Railroad completed the laying of track alongside the feeder canal in 1855.

By 1890, canal use declined though boats continued to use the canal until 1932. The State of New Jersey took over the canal and rehabilitated it to serve as an aqueduct. Most of the D&R Canal system is (1) a State Park; and (2) an aqueduct managed by the New Jersey Water Supply Authority to transport drinking water supply from the Delaware River basin to the Raritan River Basin and serve about 600,000 people.



The USGS published a report (Gibs and others, 2001) on the quality of water in the canal. The USGS monitors flow in the canal at Port Mercer. Average flow is about 150 cfs.

Stop 4 Part B
Trenton Water Power Canal intake Feeder Canal:
Leader Richard Hunter, Hunter Research

The Trenton Water Power Canal was built in 1834. The Power Canal provided waterpower for industries of Trenton. The Power Canal was designed by Benjamin Wright who also designed the Erie Canal and Chesapeake and Delaware Canal. The canal was 60 ft wide 6 ft deep and the water level dropped only 18 inches between Scudder's Falls and the furthest industry downstream. The fall of water at industries near the War Memorial was about 14 ft to drive industrial water wheels. Mills south of Katmandu had almost 18 ft of drop with 575 gross horsepower. The Great Fall in Paterson produces 2,350 gross horsepower.

Two grist mills, two saw mills, a wood turning mill and oil mill and a cotton mill used the Power supply. Planned users include a paper mill, calico print mill, machine shop, and button works mill but the panic of 1837 hit and by 1844 it was bankrupt.

During about 1844-70, Trenton Iron Company rolling mills and almost 20 other industries in Trenton used water in the canal for hydro mechanical power supply. By 1852, the demand for more water caused the Trenton Iron works and other industries to obtain permission to deepen the canal to 8 ft and build a bigger wing dam at Scudder's Falls. When the canal owners Elevated the top of the wing dam at Scudder's Falls the decreased the flow of water to down stream reaches of the Delaware River. This lead to the Stone Hackers War. The New York Times article of August 9, 1852 describes the Stone Hackers War:

> RIOT AT TRENTON.--A party of about fifty stone hackers, men whose occupation is, we believe, the gathering of stones brought down by the current, yesterday proceeded from Trenton up the Delaware, armed with pikes and crows, to attack a dam of the Trenton Water Power Company, on the Delaware, which, they alleged, interfered with their occupation.
>
> The article goes on to describe fist fighting, swing rods and sticks and a show of a pistol. In the end, the stone hackers tore down part of the wing dam.

By 1870 coal power use caused the decline of the water power. The Power Canal was still used until about 1920 for some industries and for the Trenton Water Supply. By 1950 it was completely filled in by Route 29.

Stop 4, Part B
Tohekon Member of Lockatong Formation; red rock outcrop along former intake to Power Canal: Outcrop on the New Jersey shoreline by upstream of the kayakers playground.

The Lockatong Formation has been divided into 12 members (Olsen and Kent). Each member is a McLaughlin cycle and can be divided into five short modulating cycles. Each short modulating cycle can be divided into five Van Houten cycles. The traverse from this outcrop to the next outcrop 1000 ft north will cover one McLaughlin Cycle (one member). Only the upper indurated strata of the Tohekon and Prahls Island Member are exposed.

The 300 foot long Power Canal entrance outcrop along the east bank is the upper part (red rock part) of the Tohekon Member. The upper Tohekon Member is an indurated red and gray mudstone that resists weathering. The canal edge outcrop is a result of excavation in the 1830's. Blast holes can be found in about 10 locations along the outcrop. During construction, Nason found estheriae fish scales at Scudder's Falls, New York Academy of Sciences, Volume 23.

A second extensive outcrop of the upper Tohekon Member was created during I-95 construction at exit 2. The I-95 is about 1 mile east of here and we will view it at 60 miles per hour on our drive to Stop 5. The upper Tohekon Member also is the strata that form Scudder's Falls which today (as it was in the past) is a series of rapids that cross the Delaware River at this location. Olsen and Kent describe a Scudder's Falls Member of the Lockatong Formation but that is predominately sandstone and it is not the strata that forms Scudder's Falls.)

The Power Canal entrance outcrop is heavily water worn and much of it is covered with a patina of weathering which is less than 1 cm thick. The patina masks the true color of the rock. Most of the south end of the outcrop is red and purple mudstone and the northern 50 to 100 ft of it is dark to light gray mudstone. Typical Lockatong depositional features as seen in other outcrops are difficult to discern. Mudcracks, desiccation breccias, and salt crystal replacement vugs are evident. Thick indurated mudstone strata are intercalated with thin fissile mudstone strata. The fissile stratum weathers and erodes to form recessed bedding crevasses or short zones with no outcrop. The fissile zones generally are laterally extensive and generally form water-bearing zones. The fissile zones generally have many bedding plains partings in them and are the main conduit of groundwater flow.

Bedrock strike is N60^{o}W and dip is 15^{o} NE. The full thickness exposed is about 75 ft. Three major joint patterns are exposed. The most prevalent joint set is parallel with the basin boundary with a strike of N45^{o}E and a dip that is generally perpendicular to bedding. They are very planar joints. This joint set (NW joints) are generally strata bound and an individual joint is only .1 to 2 meters from top to bottom. They can be laterally extensive but generally a single joint extend from 1 to 10 meters. The less indurated strata show a higher frequency of the NW joints. In a single stratum, the joints appear to form in bundles with some sections of strata showing a high joint frequency while other sections of the same strata show low frequency of joints.

The second set of joints is equally pervasive in the rock but they are less planar. The second set have a strike of N10^{o}E roughly parallel with the flow of the Delaware and nearly perpendicular to the strike of the first set of joints These joints also are strata bound and run laterally from 1 to 3 meters.

The third set of joints is not very pervasive, with about 5 joints exposed in the full length of the outcrop. The third set of joint is sub parallel with the first set of joints with a strike of N 45^{o}E. Where the 1st and 3rd sets of joints intersect, the outcrop has an extensive fracture pattern. The vertical partings are highly fractured with a much closer spaced orthorhombic fracture pattern.

The bedding plane partings and the three joint sets were formed after lithification and at great depth during the Triassic and Jurassic. It was not until erosion and offloading allowed the bedding plain partings and the three joint set to open. As a result, the bedding plain partings that are laterally extensive and the joints that are strata bound and not laterally extensive exist from land surface to 2 or 3 kilometers. The bedding partings and the joints are only open from land surface to less than 100 meters and in this zone, they transmit water. Below 1000 meter the joints and bedding partings are not open.

Mapping the hydrogeologic framework based on bedding partings in this fashion removes much of the complexity of groundwater flow mapping. However, because the joints have limited lateral extent of and are bundled the mapping of groundwater flow remains complex.

Stop 4, Part D.
Prahls Island Member of Lockatong Formation; red rock outcrop at overflow of D&R Canal:

Upper Prahls Island Member outcrop is scoured infrequently when the D&R canal overflow. The rock is mudstone (a mixture of silt and clay) and shows many fine sedimentary rock examples:
Mud cracks: Indicative of intermittent wet and dry events on a single mud stratum
Desiccation breccia: Indicative of repeated wet and dry events on a single mud stratum
Indurated strata: likely shallow water silica rich deposits
Fissile strata: indicative of slightly deeper water clay rich deposits
Red strata: indicative of oxygen rich sub areal deposits oxygen mixes with the iron to form a red color
Dark gray and black strata: indicative of an oxygen poor sub marine deposits
Salt replaced by analcime: Indicative of saline water drying and growth of salt crystal in sediment, salt dissolves and is replaced by analcime in his area. Gypsum, calcite, and quartz fill the vugs in other area.
Bitumen, in fractures and joints: indicative of movement of oils form carbon rich strata to other location during the thermal metamorphism of the Lockatong as the Jurassic diabase is intruded and cools

Root cast: Tapered feature. During compression the root cast is squeezed
Animal burrow cast: tube like feature or circular features, during diagenesis compression caused the tube shaped casts to become squeezed.

Rheologic features of rock as a result of tectonics:
Close spaced strata bound joints not water bearing but store of DNAPL contaminants

Local multi strata joints wide spaced strata bound joints transmit water form one water bearing fissile strata to another.

1:30 p.m. Board busses and drive to Stop 5 Diabase quarry north of Pennington 9 **miles total**

0.0 mi - Drive South on River Road and under Scudder's Falls Bridge of I-95
0.3 mi - Turn left onto entrance ramp of I-95
1.5 mi - at exit 2

Note: Outcrop of Tohekon Member of Lockatong Formation at Exit 2 on both sides of road. U.S. Geological Survey Office of 85 people is 500 ft north of this exit.

U.S Geological Survey Fracture Rock Hydrology Research site at the former Naval Air Warfare Center is 1 mile south of Exit.

Note: Steep road banks but no outcrop between Exit 2 an exit 3. When roadway was first excavated, the black and dark gray fissile strata were exposed but it quickly breaks down to soil and plants soon cover the exposure.

2.4 mi - Newark Basin coring Project of Rutgers and Columbia Universities Nursery Road core is about 1000 ft north of here.
2.6 mi – Exit 3 interstate crosses from Lockatong into Passaic Formation.
4.0 mi – Take Exit 4 to Rt 31 North
4.3 mi – Left onto Rt 31 North, if you make a right in ~1 mile south is 'The College of New Jersey'. If you continue about 2 miles to Olden Ave and make a left onto Olden and a left onto Arctic Parkway then you are at the New Jersey Geological Survey Office.
5.6 mi – Pennington Traffic Circle continue on Rt 31 N
7.2 mi – at Pennington Market
7.7 mi – Ridgeline to the northwest is the Sourland mountains
8.7 mi – Intersection with Titus Mill Road
9.0 mi – Entrance to Trap Rock Industries Pennington Quarry. Rail Road overpass abutments are made of Diabase from quarry
This is an active mining site. Think Safety.

INSERT stop by Greg Herman

Diabase Quarry north of Pennington

Greg Herman (NJGS) Trip Leader
Must wear a hard hat to approach rock face. Conditions of rock face vary. Owner of quarry mine has complete discretion over the decision on which face we may approach if any.
See Chapter 9 for full description of Field stop

2:30 Board Busses for drive to Stop 6 Crystal Lake Park Part of Burlington county Park System to visit former clay quarry for brick industry and site of fossil zzzzz 20 miles
0.0 mi – Entracnce to Trap rock Industries Pennington Quarry turn Right onto Rt 31 south.
1.7 mi – Pennington Market
2.3 mi – RR bridge Greg Herman used outcrop near here in GANJ 1888 meeting
3.1 mi –Pennington Traffic circle stay on Rt 31 S
4.5 mi – Right onto entrance ramp to I-95East
If you continue on 31 S for about ½ mile Rider University is on the Right.
7.5 mi – if you take Exit 7 N on Princeton Pike about 4 mi you will be on Princeton University campus. A number of environmental consulting firms are in this area.
9.3 mi - Cross over Rt 1 and D&R Canal. I-95 north magically changes into I-295 south
10.8 mi - cross over contact from Stockton Formation to Trenton prong Metamorphic rocks
11.0 mi - cross Northeast corridor rail road tracks
11.7 mi - somewhere near here the NJ Coastal Plain Deposits Start
16.6 mi - Cross over I-195
16.9 Coal power plant on Duck Island driving over Trenton Marsh, Crosswicks Creek Marsh
18.3 mi- Delaware rive on Right
18.7 mi - Delaware River overlook
19.2 mi - Thomas Pine Bridge over Crosswicks Creek;
East side , Bordentown on bluff capped by iron cemented sandstone and
Entrance to D&R canal,
West side; GROSS landfill, Waste Management Inc piles garbage from NYC,
Philadelphia, and Mercer County and many northern N.J. Counties
19.6 mi – Cross over Delaware River, Line light rail tracks
20.0 mi – Take Exit 57B to Rte 130 South
20.6 mi – Dunn's Mills Road
21.5 mi – Housing tract on Left is built in former Clay quarry
21.6 mi – Crystal Lake on Left, rail road causeway that crosses the lake transported clay from the clay mine we will soon visit.
22.0 mi – view of Crystal Lake Park from Rte 130
22.5 mi – Turn Left onto Kinkora-Hedding road
23.4 mi – Hedding NJ, Center of town, make left onto Rte 660
23.7 mi – Bear left at Stop sign onto Axe Factory Road
23.8 mi – Turn Left into Crystal Lake Park
At last stop of the day

Bedrock Geology of Crystal Lake Park, Burlington County, New Jersey

Peter J. Sugarman[1] and Pierre J. Lacombe[2]
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This stop examines the sedimentary formations exposed in the farm fields and adjacent deep gullies at Crystal Lake Park (Fig. 1). The geology is well exposed in the small tributaries to the southeast of Crystal Lake. In the lower elevations of the tributary the Merchantville Formation is exposed. The gully adjacent to the west bank of Crystal Lake exposes the lower two-thirds of the formation. An abandoned clay pit just south of Crystal Lake exposes the uppermost beds in the Merchantville Formation.

Situated above the Merchantville at higher elevations of the tributary is the Woodbury Formation. These two formations (Merchantville and Woodbury) are composed of Upper Cretaceous fine-grained sediments that are part of a larger outcrop belt that trends to the northeast from the Delaware River up towards Raritan Bay and gently dips to the southeast. In the Crystal Lake area, the Merchantville strikes N45E and dips 42 ft/mile, and is about 45-55 feet thick, while the Woodbury also strikes N45E, dips 40 ft/mile, and is approximately 50 feet thick (Owens and Minard, 1962).

Detailed geologic mapping in this area is available from the geologic map of the Columbus quadrangle (Owens and Minard, 1962), and the bedrock geologic map of central New Jersey (Owens and others, 1998). Descriptions of the Merchantville and Woodbury formations presented here are modified from these publications. The Merchantville Formation (fig 1) consists of very clayey and silty glauconite sand with locally high concentrations of very fine to fine quartz sand. The outcrops are dark green to gray, but weather a lighter moderate brown to yellow brown color. The various colors depend on the degree of weathering. Marly beds weather to form an indurated, cinnamon-brown earth (Ries, Kummel, and Knapp, 1904).

The Merchatville Formation exhibits several lithofacies including the typical glauconite sand facies. The lower two-thirds of the Merchantville is a dark-gray clayey, micaceous glauconite quartz sand and silt. Minor sand components include vitreous lignite, and colorless and green mica. The best exposure of this stratum is in the gully just upstream of the wooden bridge.

The upper third (exposed in a 15-foot section at the abandoned clay pit, contains considerable more glauconite sand than the lower two-thirds of the Merchantville. A 5-to-10 foot bed of glauconite at the base of the upper section contains minor amounts of clay and mica. Also found in this bed is small masses of iron oxide and fine gypsum crystals. This bed grades upwards into a 5-foot thick dark, clayey, micaceous very-fined grained glauconite-quartz sand.

The contact of the Merchantville with the Woodbury is conformable (gradational). In general, the transition upward into the Woodbury is marked by a general decrease in glauconite and quartz sand and an increase in clay and mica.

Fig. 2. Outcrop of lower Woodbury Formation in a tributary to Crystal Lake.

The Woodbury originally received its name for an exposure in the railway cut at Woodbury, NJ. The Woodbury Formation is a massive, dark-gray clay silt. The best exposure of it is in the gully in the southeast corner of the park where a series of small slumps have exposed 10 to 20 foot high exposures. Where extensively weathered, colors display various shades of brown to pale gray. The Woodbury is generally massive bedded although the upper part can be crudely bedded.

The lowermost 10-15 feet of the Woodbury is dark gray micaceous, very fine-grained quartz, sandy to silty clay with a few percent glauconite, lignite, and pyrite (Fig. 2). Basal beds are commonly fractured, possibly due to desiccation, and the fractures are filled with light clayey material. The middle 20-25 feet is very micaceous clay which can also be fractured.

The upper 10-feet contains a small percentage fine quartz and medium glauconite, and near the very top are thin partings of very fine grained quartz sand interbedded with the clayey bed.

Economic Geology

In the Late 1800s to early 1900s, the Merchantville and Woodbury Formations were mined for clay, and termed the Clay Marl II (Woodbury) and Clay Marl I (Merchantville). The Woodbury clay and clay rich strata of the upper part of the Merchantville Formation were used as the raw material to manufacture bricks and draintile. The old causeway across Crystal Lake used to support a train track that led from clay mines near the wooden bridge to a brick making company less than 1 mile north.

In a permanent note on file at the NJ Geological Survey, Meridith Johnson wrote the following on April 8, 1958 to describe the now abandoned clay pit near Crystal Lake: "10 to 15 feet of weathered, brown, Woodbury clay here overlies the highly glauconitic Merchantville clay. The exposure is in the upper reaches of a small stream tributary to Crystal Lake and clay was evidently dug here many years ago."

The Woodbury clay is used by the county as the base of the Burlington County Landfill that is cut into the Merchantville Formation. The landfill is located 3 miles southwest of the park. The clay stratum is quite impermeable to water and in combination with the landfill liner acts as a shield to prevent contaminants in the landfill from reaching the county water supply. Permeability of the Woodbury clay has been measured from $9.9x10^{-10}$ to $1.5x10^{-7}$ cm/sec (Gill and Farlekas, 1976) to more permeable values of $4.4x10^{-8}$ to $1.9x10^{-5}$ cm/sec (Farlekas and others, 1976).

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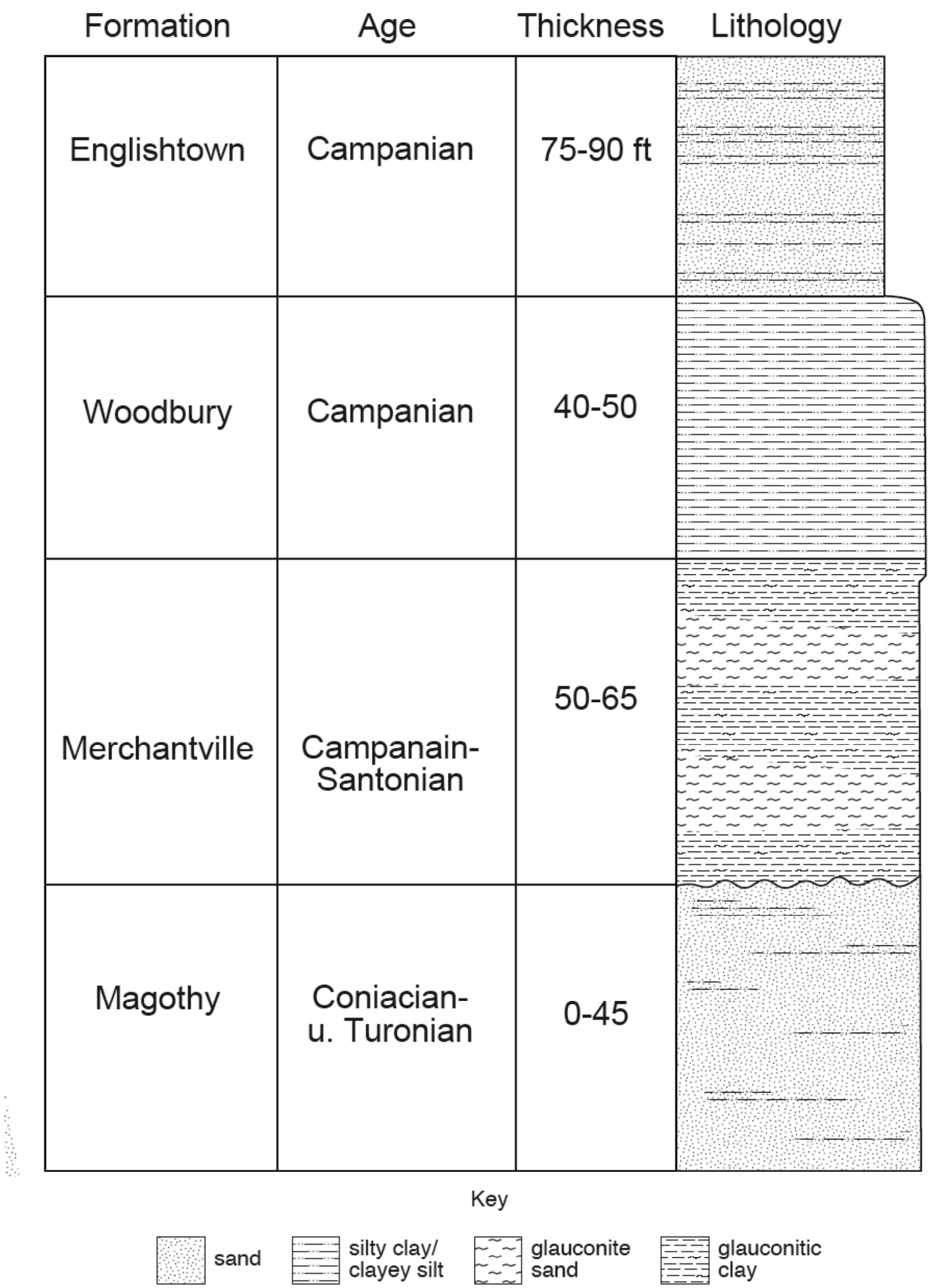


Fig. 1 Generalized stratigraphic section of the bedrock geology at Crystal Lake Park and vicinity.

Pensauken Formation, a fluvial sand and gravel of Pliocene age Crystal Lake Park

Scott D. Stanford[1]

[1]New Jersey Geological Survey, PO Box 427, Trenton, NJ 08645

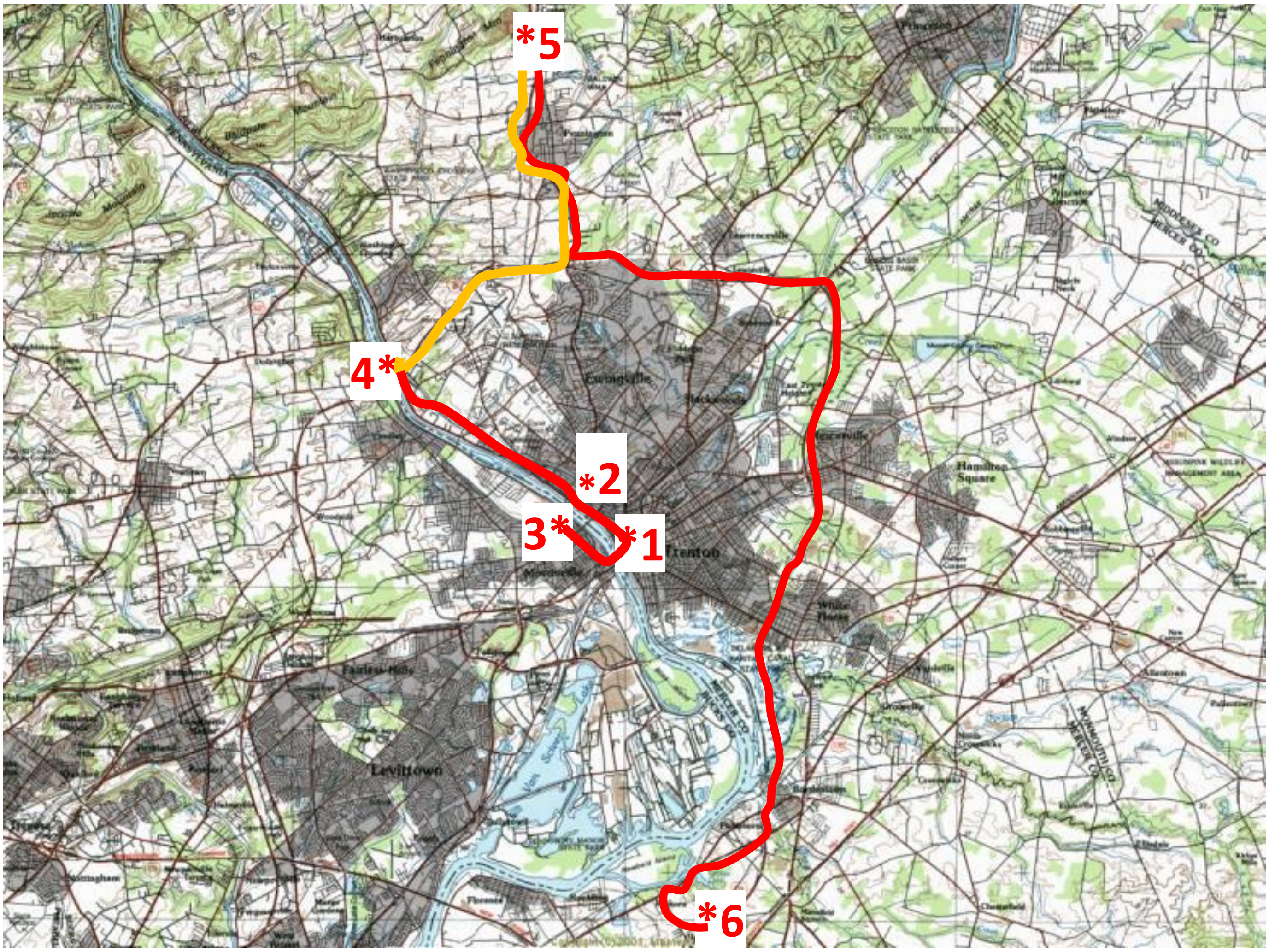
The flat surface seen in the fields along the entrance drive and parking lot for Crystal Lake Park is underlain by the Pensauken Formation, a fluvial sand and gravel of Pliocene age. The Pensauken is a fluvial deposit laid down by a large river that flowed southwesterly along the inner edge of the Coastal Plain between the New York City area and the Delmarva Peninsula (see chapter on "Pliocene and Quaternary geology of the Trenton area" in the proceedings). It is cross-bedded arkosic sand and pebble gravel (fig. 1). The gravel is composed mostly of yellow-stained quartz and quartzite pebbles and a few cobbles, with some chert and traces of gray and red siltstone and sandstone. These pebbles and cobbles are visible in fields and trails in the park, and the gravel was formerly dug throughout central New Jersey for construction material. The quartz, quartzite, and chert pebbles are largely reworked from late Miocene gravels that formerly veneered the Coastal Plain and Piedmont. The valley of this river was eroded during the late Miocene and early Pliocene, to a depth of slightly below modern sea level. The river system included the Hudson and, perhaps, rivers from southern New England. The Delaware was a tributary that entered the main valley at Trenton, and the big bend of the Delaware at Bordentown is an inheritance of the junction of the Delaware with the trunk Pensauken River here. Sand and gravel of the Pensauken Formation aggraded in the valley during a mid-Pliocene sea-level highstand centered around 3.5 million years ago. The Pensauken deposits filled and spread across the valley to form a broad plain about 10 miles wide, with a surface elevation of about 130 feet in the Trenton area. Between 2 and 2.5 million years ago, the Pensauken valley near New York City was blocked by the pre-Illinoian glacier and the Pensauken River was diverted southeastward to the Atlantic from the western end of what is now Long Island. The Pensauken plain between New York and Trenton was abandoned and the Delaware became the trunk stream in the valley southwest of Trenton. Through most of the Pleistocene (the past 2 million years) the Delaware and its tributaries have slowly eroded into the Pensauken plain, forming the modern valley network, which is inset about 100 feet below the original level of the plain. The Pensauken at Crystal Lake is an erosional remnant of the plain. A depth of about 30 feet of the deposit has been removed here. The local stream that was dammed to create Crystal Lake deposited a terrace during this erosion. It is visible as the small flat area in the lower agricultural fields near the lake, about 40 to 50 feet below the Pensauken deposit. This terrace may have been formed during a period of high sea level in the middle Pleistocene, when global sea level was higher than present at several times. High sea level would have temporarily halted incision of the Delaware and its tributaries, permitting terrace formation. Erosion resumed in the late Pleistocene (the last 100,000 years), and the stream cut another 40 feet or so into the terrace to form the present floodplain at the level of Crystal Lake.

Figure 1. Gravel and cross-bedded sand of the Pensauken Formation, Cinnaminson, New Jersey. Photo by Scott D. Stanford.

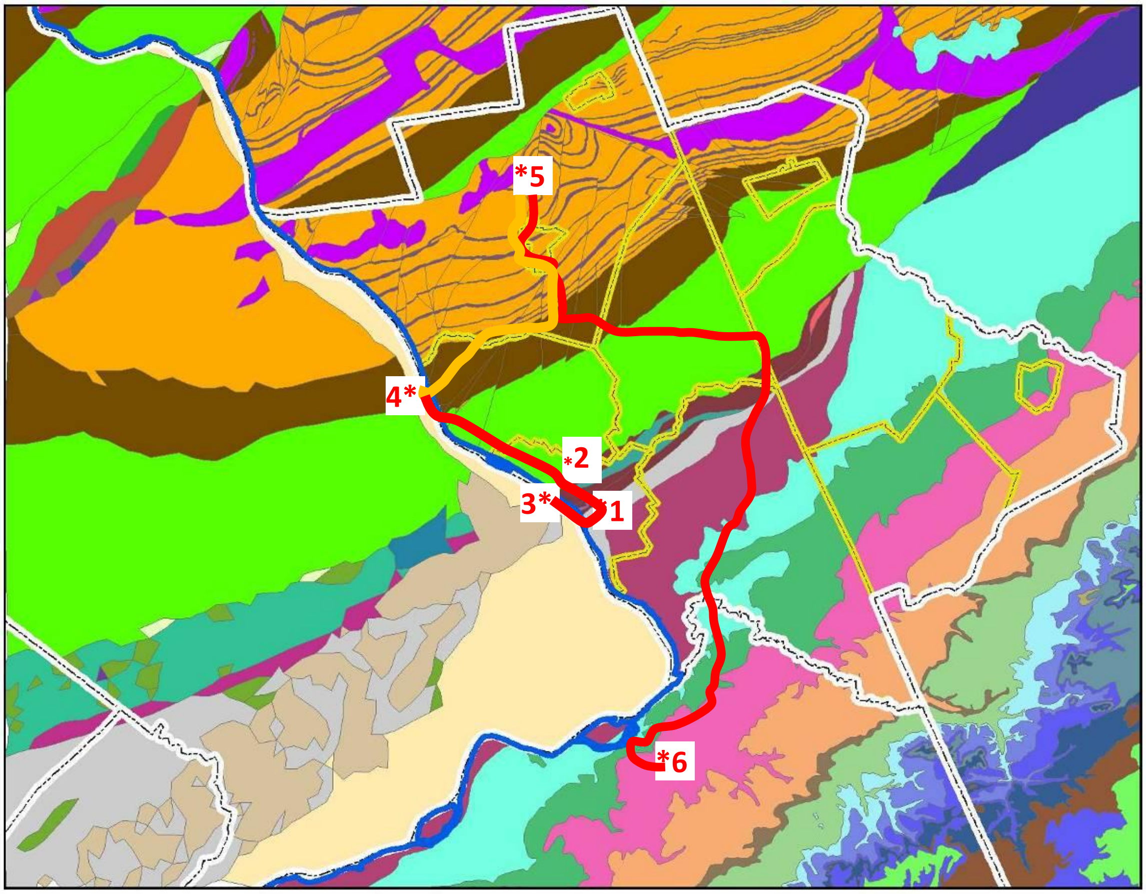
4:30 Board Busses to head back to Trenton

0.0 mi – At entrance to Crystal Lake Park Turn right onto Ax Factory Road
0.1 mi - Intersection of Ax Factory Rd and Rt 660 stay straight
0.5 mi – Turn right onto Kinkora-Hedding Road
1.3 mi – Turn right onto Rt 130 North
1.7 mi – Crystal Lake Park on right
2.1 mi – Crystal Lake on right
3.4 mi – Bear right for I-295 North
3.6 mi – Diabase riprap on embankments of entrance ramps
4.7 mi – Cross over confluence of Crosswicks Creek and Delaware River
5.1 mi – Governor's rest stop
6.8 mi – Bear left to take Rte 129 West
7.9 mi – Electric Power plant to the west
8.1 mi – Former Trenton Landfill now closed and covered
8.8 mi – Pond on right is likely a former clay pit for the brick and ceramics industry
8.9 mi – Follow road to Rte 129 N
9.4 mi – Driving in former D&R canal right-of-way with Light-rail tracks on edge of road
9.6 mi – All red brick buildings are part of former manufacturing industries of Trenton. Roebling Steel/wire rope mill is the a major industry
10.1 mi – NJ State Maximum Security Prison
10.3 mi – Bridge walkway constructed to show advantages of suspension bridges
10.6 mi – Turn left on to Hamilton Ave. Formely Sandtown Road. This was the escape route for Geo Washington on January 2 1977
10.8 mi – Monument on left commemorates the retreat of the American insurgents
10.8 mi – Turn right onto South Broad Street
10.9 mi – Abandoned Washington Inn, basement is made of local metamorphic rocks
11.0 mi – On right See NJ DEP Building in distance a 7-story building
11.1 mi – Crafts people of Trenton building built of local metamorphic rocks
11.2 mi – Cross Assuncunk Creek. Lots of metamorphic rock outcrop in creek. Bridge was fought over by British and Americans
11.2 mi – Turn left onto Lafayette Street
11.5 mi – Turn right onto Barracks Street.

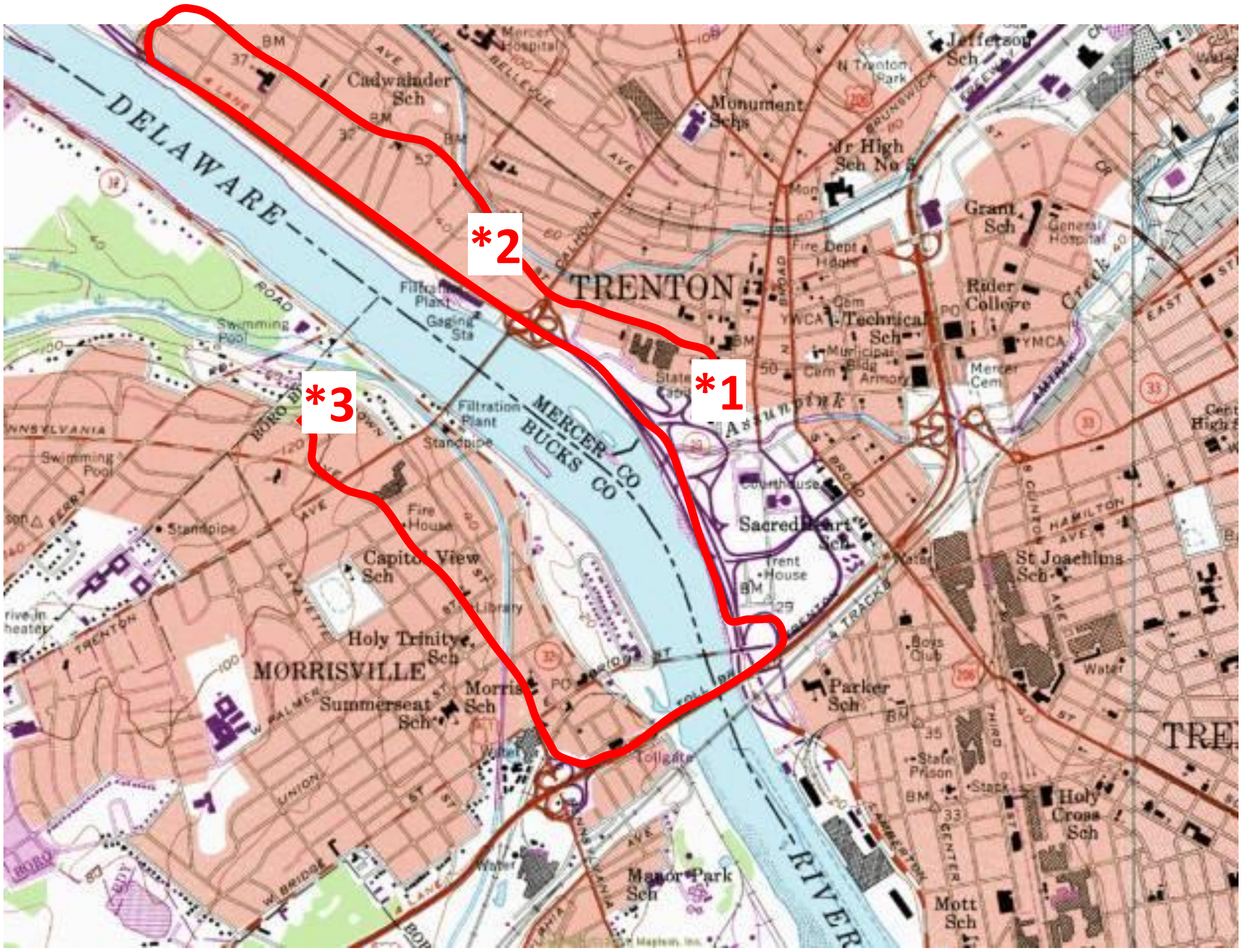
Home again. Hope you had a nice GANJ Field trip.



Non geologic map of Field Trip



Geologic map of the road log



Map of field trip in downtown Trenton

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