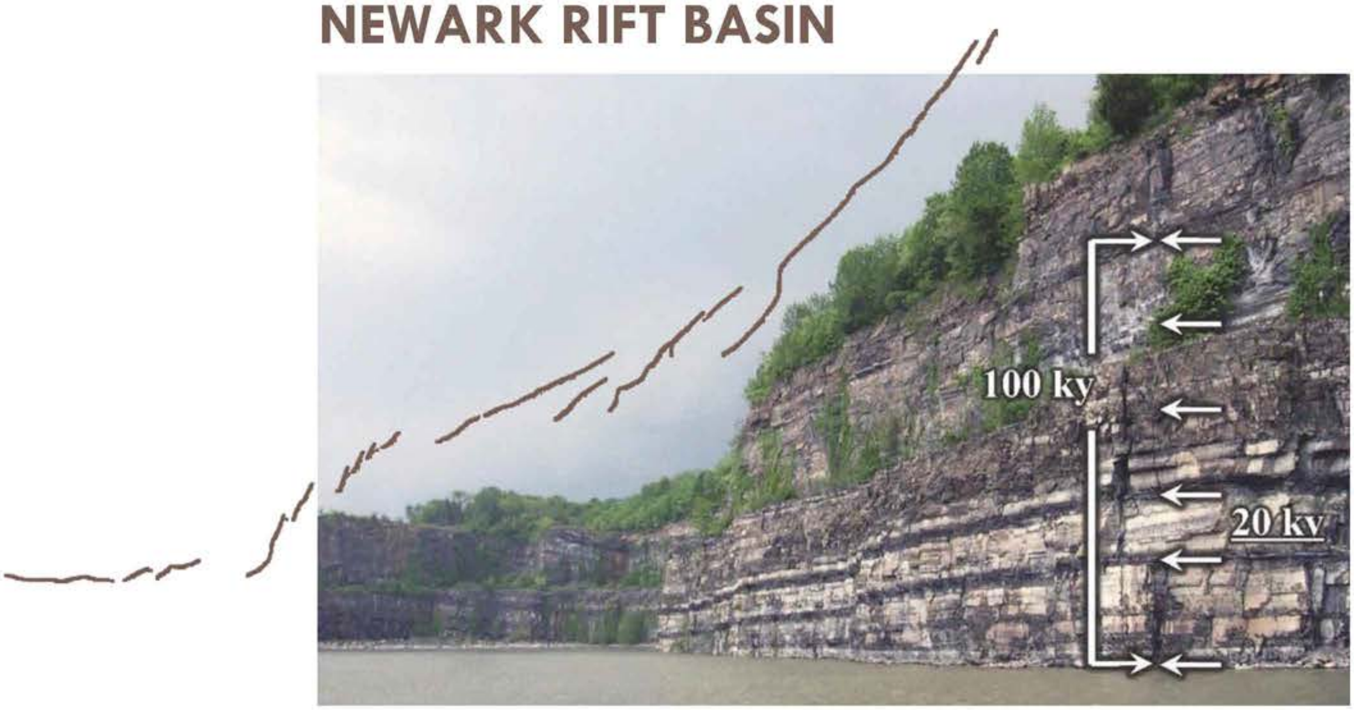
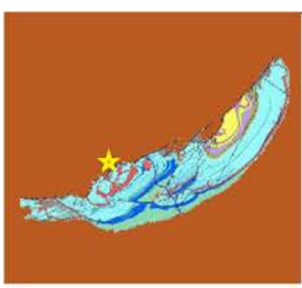
TEMPORAL, TECTONIC, CLIMATIC AND ENVIRONMENTAL CONTEXT OF THE TRIASSIC-JURASSIC RIFT SYSTEM OF EASTERN NORTH AMERICA: EMERGING CONCEPTS FROM THE NEWARK RIFT BASIN





83rd Annual Field Conference
of Pennsylvania Geologists
Center Valley, Pennsylvania
October 5 – 6, 2018

Trip Leaders: Paul Olsen – Lamont-Doherty Earth Observatory, Columbia University
Martha Withjack & Roy Schlische – Rutgers University
Frank Pazzaglia – Lehigh University

Hosted by the Pennsylvania Geological Survey

RAMAPO RIVER.

RAMAPO RIVER
by Jules Tavernier
from Picturesque America, Vol. II, 1874

Above: reproduced image of Jules Tavernier's Ramapo River (1874) from Van Houten, F.B., 1980, Late Triassic part of Newark Supergroup, Delaware River section, west-central New Jersey, in Manspeizer, W., (ed.), Field Studies of New Jersey and Guide to Field Trips: 52nd Annual Meeting New York State Geological Association, Rutgers University, Newark, NJ, p. 264-276.

Front Cover: Cyclic sedimentation in Lackatong Formation, Eureka Quarry (photo: Paul Olsen)

The Mesozoic Newark Basin stretches across southeastern Pennsylvania from the Delaware River to the northeastern tip of Lancaster County. This conference will focus on the basin in upper and central Bucks County where the sedimentary, igneous, metamorphic and tectonic history are well exposed in the local quarries. Topics to be discussed include the geometry and evolution of the basin, the distinct cyclic sedimentation related to climate history, and their relevance to environmental geology, groundwater and arsenic, and carbon sequestration. Additional stops will look at diabase related to Central Atlantic Magmatic Province (CAMP) and its associated contact metamorphism.

Oddly, the Newark basin has never been the focus of a field conference and it is hoped that this trip will spur additional interest, studies and mapping in one of the more rapidly growing parts of the state.

A variety of preconference trips are also planned. Excursions include a tour of the nearby 19th century Ueberroth & Hartman Zn mines, a caving trip, a look at the Quakertown diabase sill, a geo-biking tour of the Saucon Rail Trail, and a groundwater remediation study in fractured bedrock at a former military base.

Compiled by: Robin V. Anthony, Pennsylvania Geological Survey, FCOPG editor

Field Conference of Pennsylvania Geologists

Field Trip Guidebook

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Cyclical lacustrine strata of Lockatong Formation at Eureka Quarry (Stop 2). Photo by P.E. Olsen.

Introductory Materials

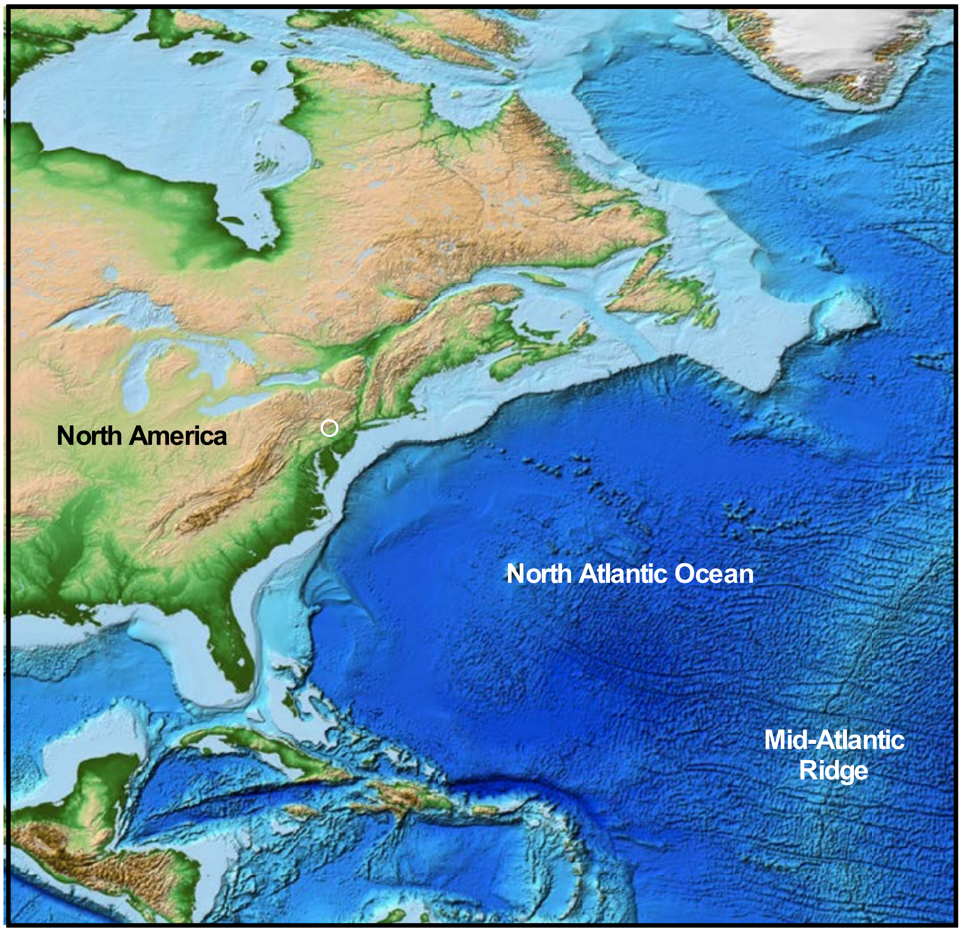


Figure I.1*: Shaded-relief map of eastern North America and adjacent regions of North America and the western North Atlantic Ocean. White circle shows field-trip region. From Etopo1: Global Relief Model (http://www.ngdc.noaa.gov/mgg/global/global.html).*

Overview of Rifting and Breakup in Eastern North America

Eastern North America (Figs. I.1, I.2) is a natural laboratory for studying rift basins and passive-margin development. It hosts one of the world's largest rift systems (the eastern North American rift system), one of the world's oldest intact passive margins, and one of the world's largest igneous provinces (the Central Atlantic Magmatic Province, CAMP). Additionally, seismic-reflection profiles, field exposures, drill-hole data, and vitrinite-reflection data provide a wealth of information about the tectonic and depositional processes associated with rifting, breakup, and the early stages of seafloor spreading.

During early Mesozoic time, a massive rift zone developed within the Pangean supercontinent (inset, Fig. I.2). The breakup of Pangea splintered this rift zone into extinct fragments, each now separated and preserved on the passive margins of eastern North America, northwestern Africa, and Europe. The fragment on the North American margin, called the eastern North American (ENAM) rift system, consists of a series of exposed and buried rift basins extending from northern Florida to the eastern Grand Banks of Canada (e.g., Manspeizer and Cousminer, 1988; Olsen et al., 1989; Schlische, 1993, 2003; Withjack et al., 1998) (Fig. I.2). It is a large rift system with multiple parallel and interconnected rift basins that affects a region up to 500 km wide and 3000 km long. Withjack and Schlische (2005) and Withjack et al. (2013) divided the ENAM rift system into three segments based on tectonic history (Fig. I-2). Rifting was underway in all three segments by Late Triassic time and may have begun as early as the Late Permian. The end of rifting (and presumably the beginning of seafloor spreading), however, was diachronous, occurring first in the southeastern United States (latest Triassic), then in the northeastern United States and southeastern Canada (Early Jurassic), and finally in the Grand Banks (Early Cretaceous) (Withjack et al., 1998, 2013; Withjack and Schlische, 2005; Schettino and Turco, 2009).

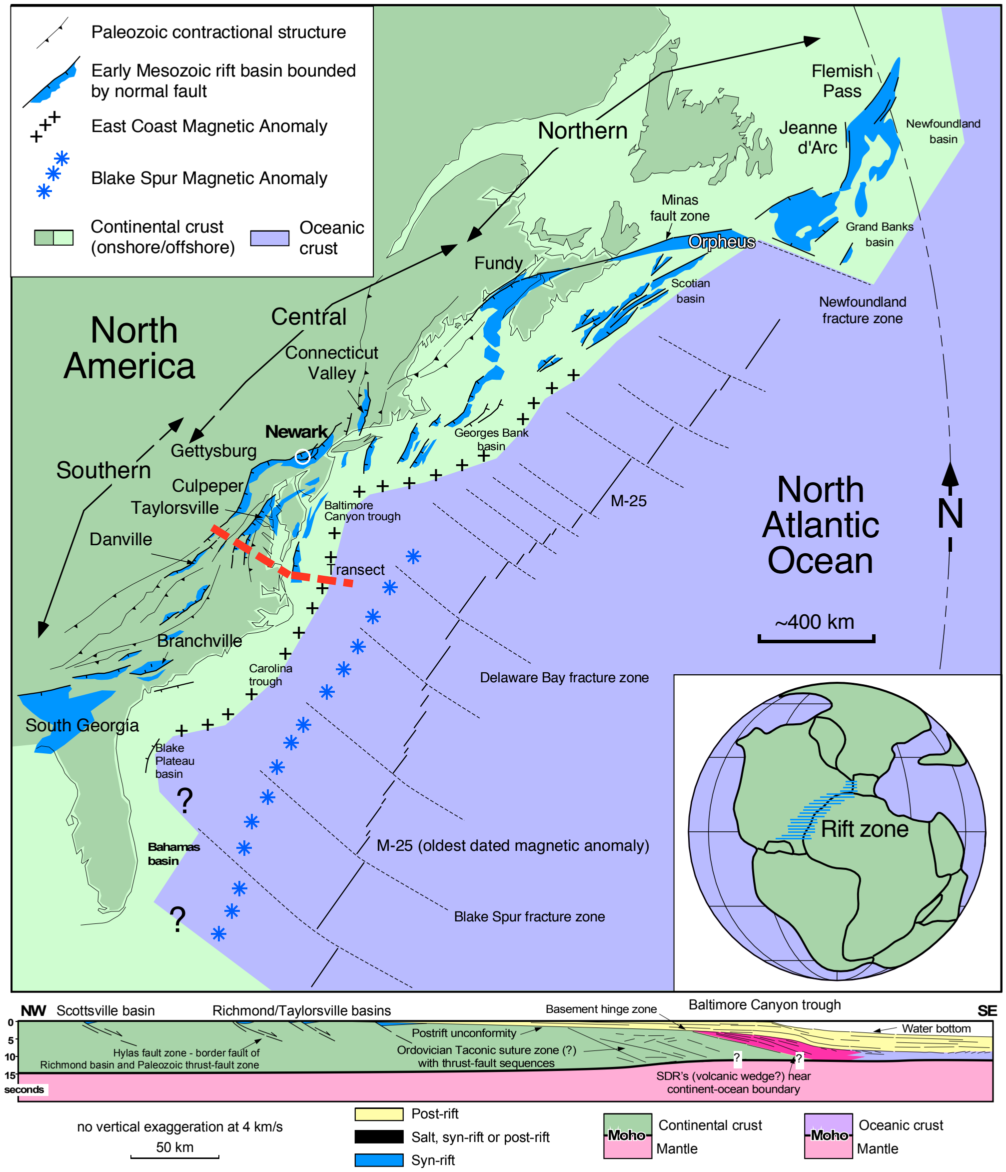


Figure I.2: *Tectonic elements of the eastern North American margin. The southern, central, and northern segments have progressively younger ages for the end of rifting and presumably the onset of seafloor spreading. The East Coast Magnetic Anomaly approximates the location of seaward-dipping reflectors near the continent-ocean boundary. The Blake Spur Magnetic Anomaly may be related to a ridge jump. Inset shows configuration of the supercontinent Pangea during the Late Triassic (Olsen, 1997), and highlights the rift zone between eastern North America and NW Africa and Iberia. Regional transect through southern segment of margin shows Triassic-Jurassic rift basins, seaward dipping reflectors (SDRs) at site of breakup, and Mesozoic/Cenozoic post-rift basins. Modified from Withjack & Schlische (2005).*

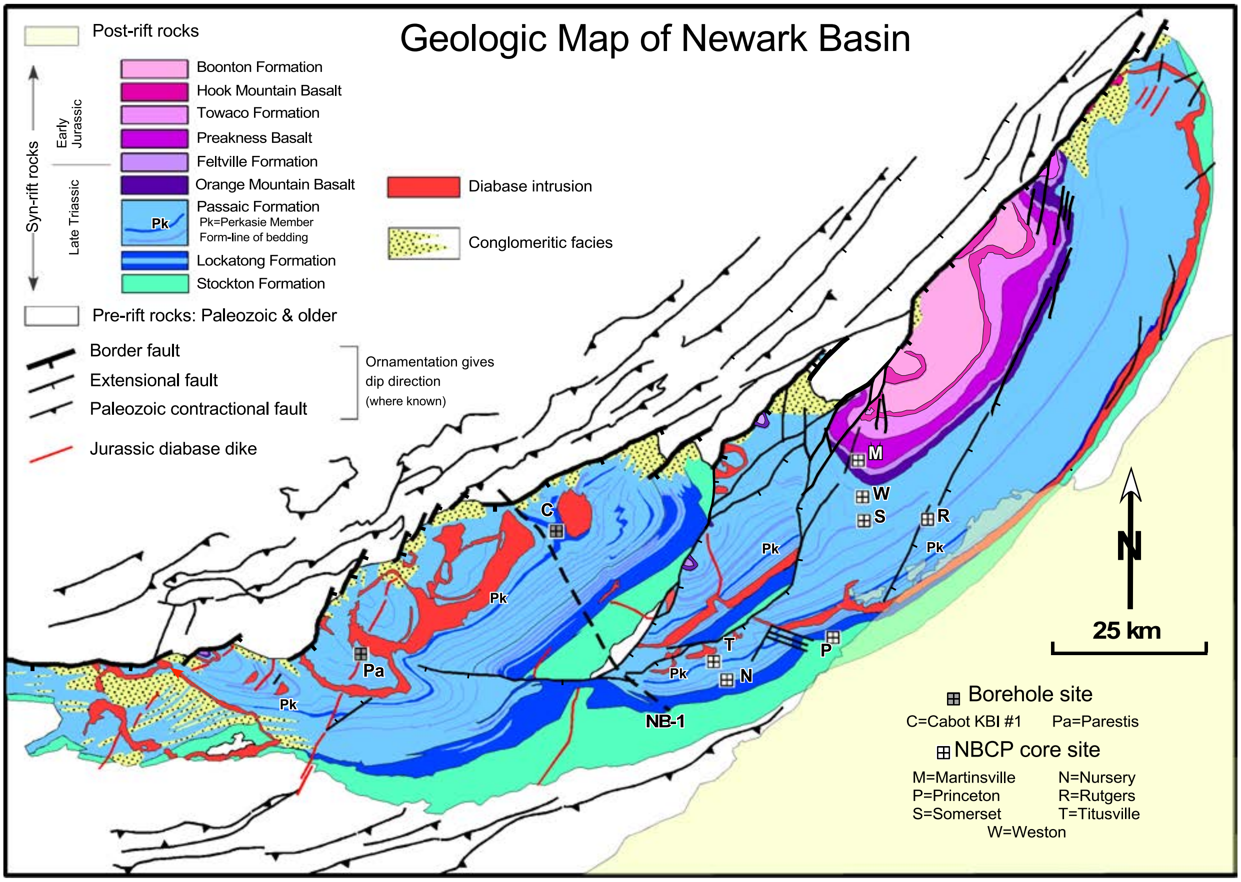


***Figure I.3a**: Detailed geologic map of Newark basin. NBCP=Newark Basin Coring Project. Modified from Withjack et al. (2013) and Schlische (1992).*

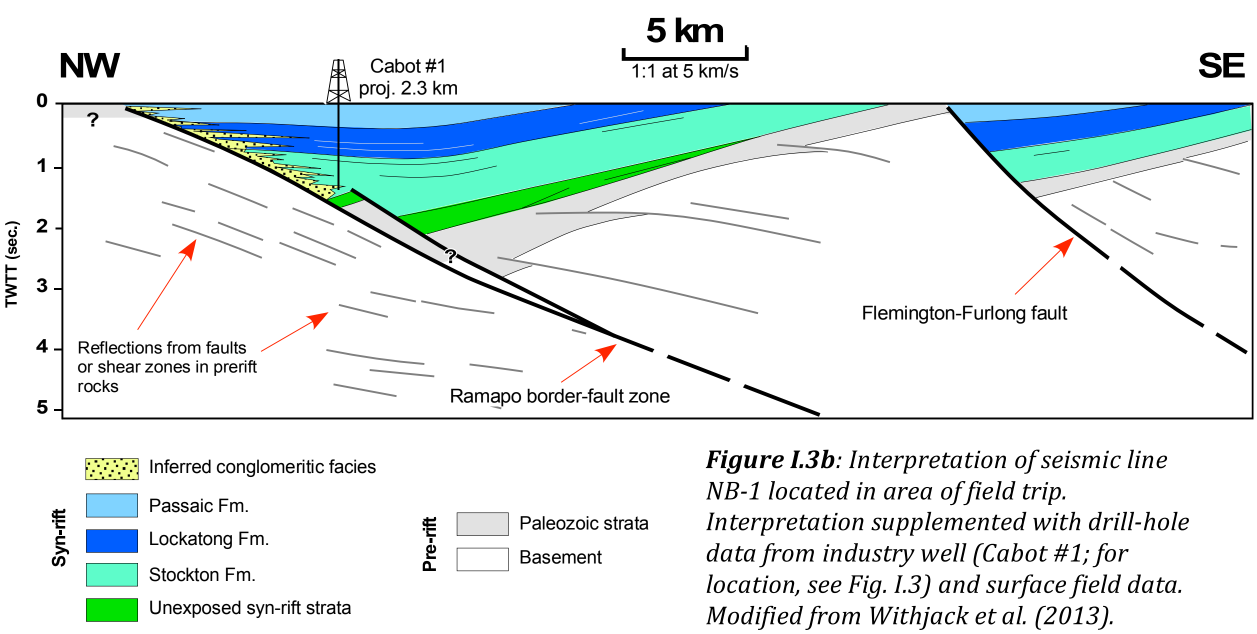


***Figure I.3b**: Interpretation of seismic line NB-1 located in area of field trip. Interpretation supplemented with drill-hole data from industry well (Cabot #1; for location, see Fig. I.3) and surface field data. Modified from Withjack et al. (2013).*

Structure and Tectonic Evolution of Newark Basin

A series of NE-striking, SE-dipping, right-stepping faults bound the Newark basin on the northwest (Fig. I.3a). The bounding faults are subparallel to thrust faults present in pre-rift rocks surrounding the basin. Several large intrabasin faults also dissect the basin. Most syn-rift strata dip 10 - 15° NW toward the border-fault zone. Near many of the border and intrabasin faults, however, the syn-rift strata are warped into a series of anticlines and synclines whose axes are at a high angle to the adjacent faults (e.g., Wheeler 1939; Schlische 1992, 1995; Fig. I.4). The Newark basin, like many other rift basins of the eastern North American rift system, underwent significant post-rift deformation including much of the tilting and folding of the syn-rift strata (e.g., Sanders, 1963; Faill, 1973, 1988, 2003, 2005; Withjack et al., 1998; Schlische et al., 2003; Withjack et al., 2010).

Seismic line NB-1, located near the route of this field trip, images the subsurface geometry of the Newark basin. The seismic line shows that a major SE-dipping fault zone with normal separation bounds the basin on the northwest (Fig. I.3b). The fault zone, characterized by a series of high-amplitude reflections, is relatively planar and has a dip magnitude of ~ 30°. Using core data, Ratcliffe et al. (1986) demonstrated that this fault zone is a mylonitic Paleozoic thrust fault reactivated during rifting; this is consistent with the relatively low-angle dip of the border fault. The seismic data show that the syn-rift strata dip ~10 - 15° toward the northwest. Furthermore, the Stockton Formation (exposed at the surface) and an unexposed older unit (which appears to onlap Paleozoic pre-rift strata) thicken toward the border-fault zone, indicating that faulting and deposition were coeval (i.e., these units are growth deposits). Field and core data indicate that the Lockatong and Passaic formations also exhibit subtle thickening toward the border-fault zone. Furthermore, all sedimentary formations contain conglomeratic facies where present adjacent to the border-fault zone (see material for Stops 9 & 10).

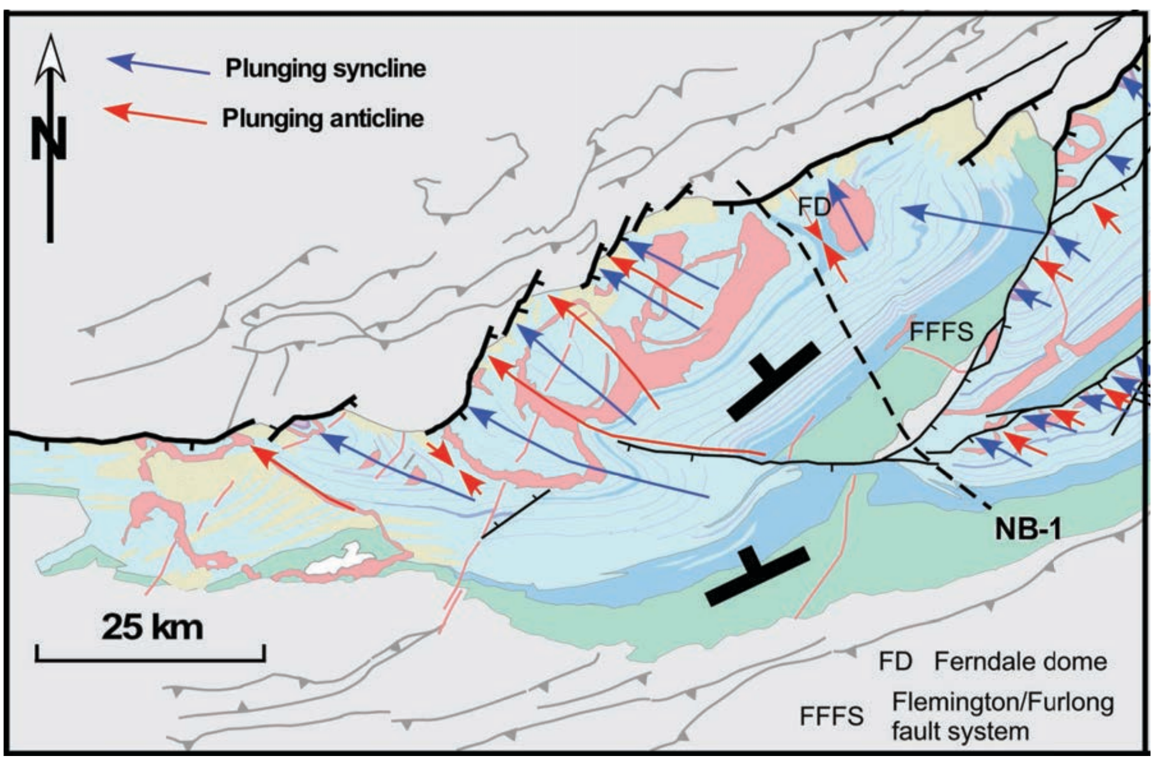


Figure I.4*: Geologic map of the southwestern Newark basin emphasizing the folds. A series of NW-plunging folds are present in the hanging wall of the border-fault system and the NE-striking intrabasinal faults. Modified from Withjack et al. (2013) based on Schlische (1992, 1995).*

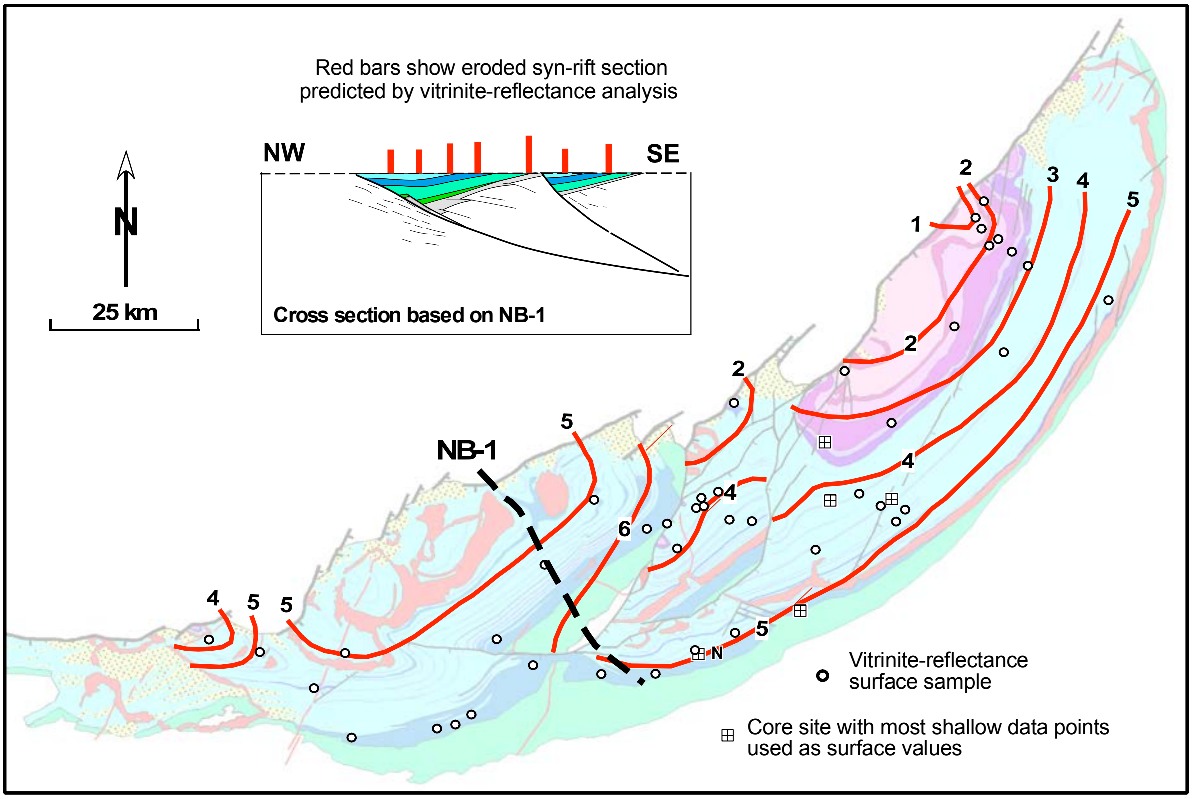


Figure I.5: *Estimates of eroded material based on vitrinite-reflectance data. Red lines are contour lines showing estimated amount of eroded syn-rift strata (km). N is the location of the Nursery core, used to calculate the reflectance/depth trend for all erosion estimates. In the area of the field trip, the amount of missing section is 5-6 km. From Withjack et al. (2013) and Malinconico (2010).*

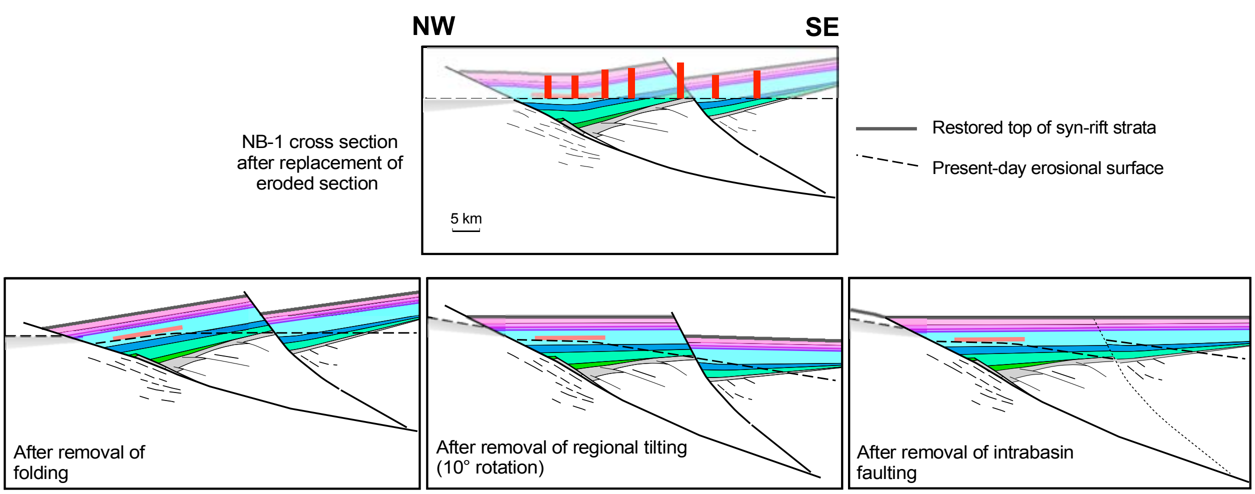
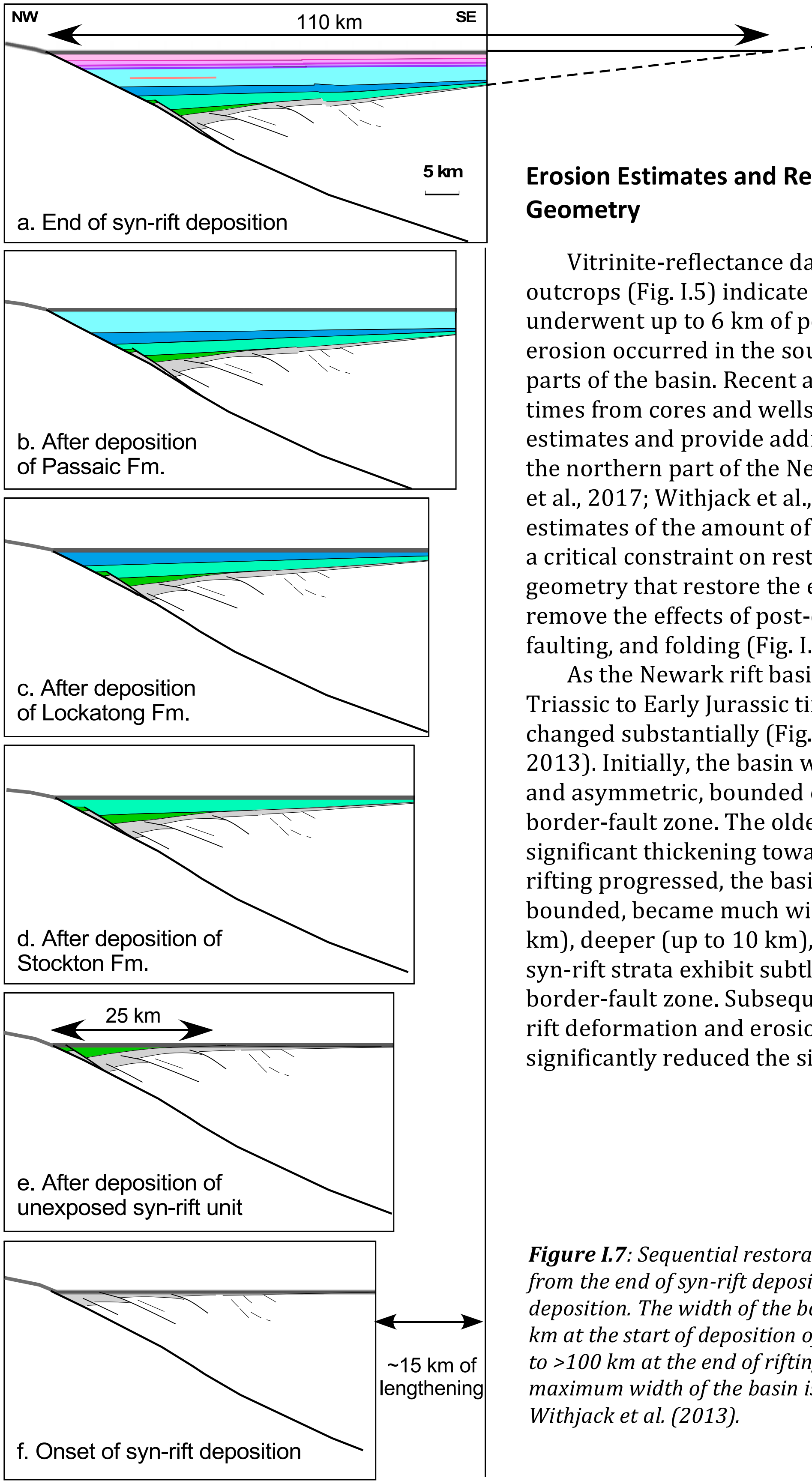


Figure I.6: *Restoration of cross section based on NB-1 to end of rifting. Restoration involves restoring eroded syn-rift section and removing post-depositional tilting, folding, and intrabasinal faulting. In the area of the field trip, the amount of missing section is about 5-6 km. From Withjack et al. (2013).*



Erosion Estimates and Restoration of Basin Geometry

Vitrinite-reflectance data from core and outcrops (Fig. I.5) indicate that the Newark basin underwent up to 6 km of post-rift erosion. Most erosion occurred in the southern and eastern parts of the basin. Recent analyses of sonic transit times from cores and wells support these estimates and provide additional constraints in the northern part of the Newark basin (Durcanin et al., 2017; Withjack et al., in prep.). The estimates of the amount of eroded section provide a critical constraint on restorations of basin geometry that restore the eroded section and remove the effects of post-depositional tilting, faulting, and folding (Fig. I.6).

As the Newark rift basin developed from Late Triassic to Early Jurassic time, its geometry changed substantially (Fig. I.7; Withjack et al., 2013). Initially, the basin was narrow (< 25 km) and asymmetric, bounded on one side by a border-fault zone. The older syn-rift strata show significant thickening toward the fault zone. As rifting progressed, the basin, although still fault-bounded, became much wider (possibly > 100 km), deeper (up to 10 km), and less asymmetric; syn-rift strata exhibit subtle thickening toward the border-fault zone. Subsequent late rift and post-rift deformation and erosion (up to 6 km) significantly reduced the size of the Newark basin.

Figure I.7*: Sequential restoration of the Newark basin from the end of syn-rift deposition to the onset of syn-rift deposition. The width of the basin varied from about 25 km at the start of deposition of the Stockton Formation to >100 km at the end of rifting. The present-day maximum width of the basin is ~50 km. Modified from Withjack et al. (2013).*

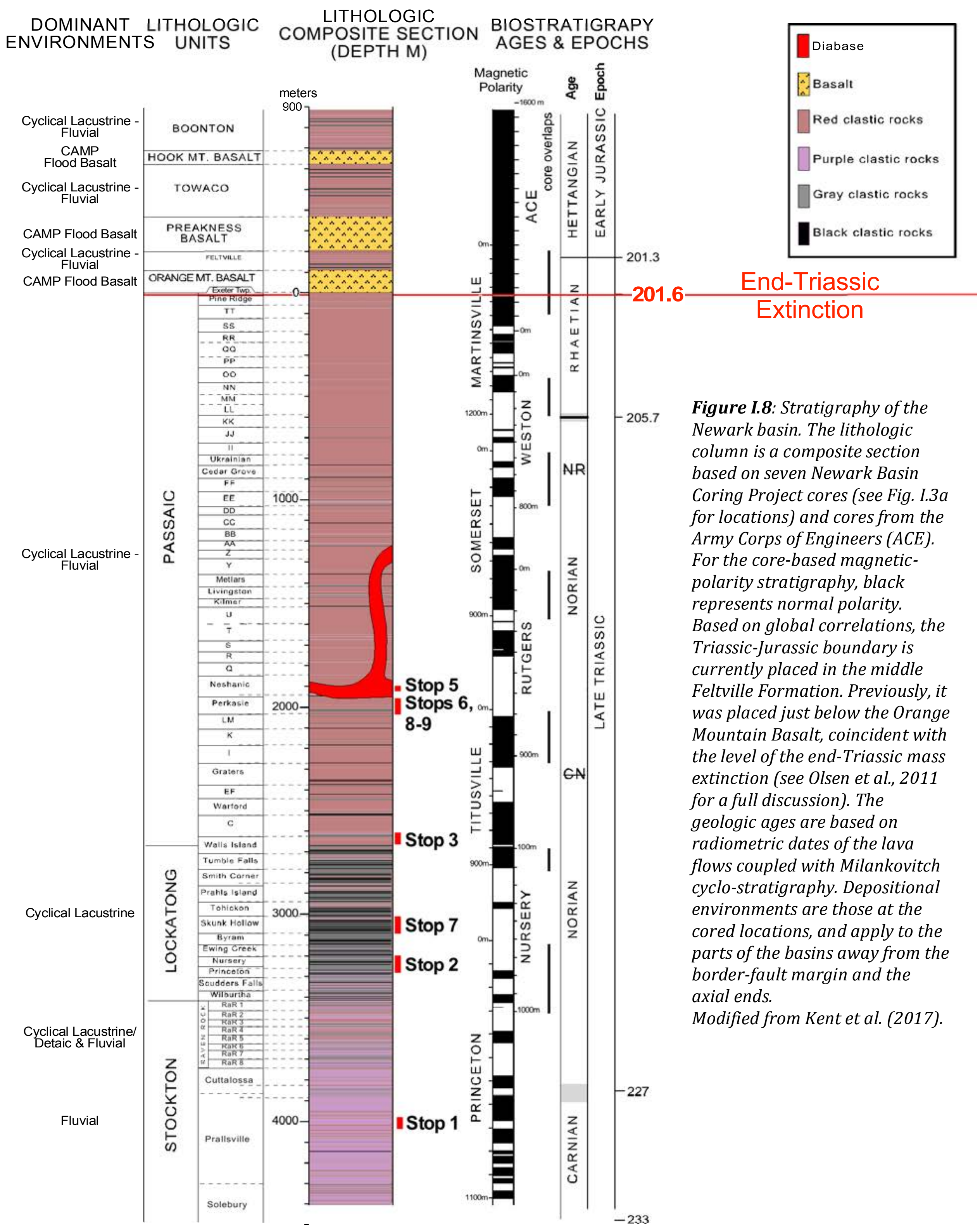


***Figure I.8**: Stratigraphy of the Newark basin. The lithologic column is a composite section based on seven Newark Basin Coring Project cores (see Fig. I.3a for locations) and cores from the Army Corps of Engineers (ACE). For the core-based magnetic-polarity stratigraphy, black represents normal polarity. Based on global correlations, the Triassic-Jurassic boundary is currently placed in the middle Feltville Formation. Previously, it was placed just below the Orange Mountain Basalt, coincident with the level of the end-Triassic mass extinction (see Olsen et al., 2011 for a full discussion). The geologic ages are based on radiometric dates of the lava flows coupled with Milankovitch cyclo-stratigraphy. Depositional environments are those at the cored locations, and apply to the parts of the basins away from the border-fault margin and the axial ends.
Modified from Kent et al. (2017).*

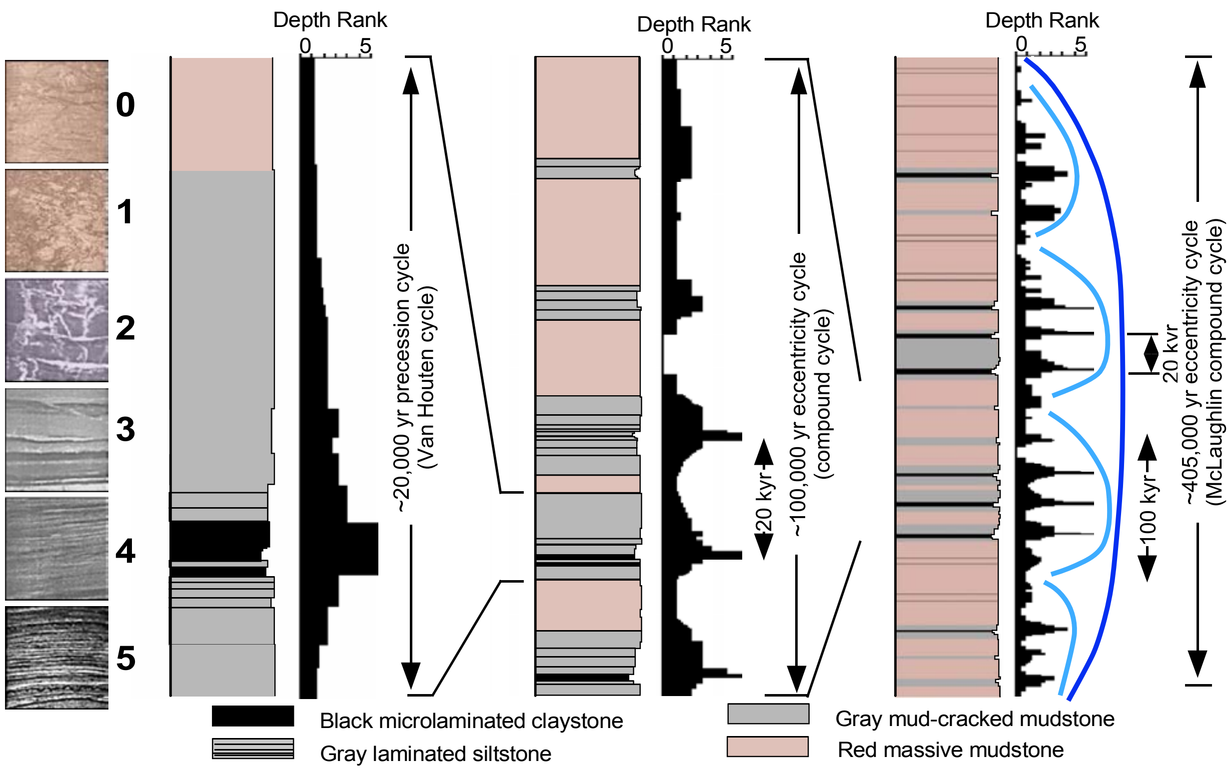


Figure I.9*: Hierarchy of Milankovitch-period lake-level cycles in the Passaic Formation. Depth rank uses color (red is shallow-water to subaerial; black is deep, anoxic water) and sediment fabrics (left) to estimate relative water depth. The basic cycle (Van Houten cycle) has a period of ~20,000 years. The two compound cycles illustrated here have periods of ~100,000 years and ~400,000 years. Orbital changes (precession and eccentricity) affected the amount of sunlight reaching a given point on Earth's surface, which affected rates of precipitation and evaporation, which in turn affected lake levels. Modified from Olsen et al. (1996a) and Olsen and Kent (1996).*

Stratigraphy and Cyclicity

The stratigraphy of the Newark rift basin (Fig. I.8) consists of the Stockton, Lockatong, and Passaic formations of Late Triassic age and the overlying basalts and interbedded sedimentary rocks of latest Triassic to Early Jurassic age (i.e., the Orange Mountain Basalt, Feltville Formation, Preakness Basalt, Towaco Formation, Hook Mountain Basalt, and Boonton Formation) (e.g., Olsen et al. 1996a). Most syn-rift strata accumulated in a lacustrine setting and exhibit a pervasive cyclicity (Fig. I.9) in sediment fabrics, color, and total organic carbon (from microlaminated black shale to extensively mudcracked and bioturbated red mudstone) (e.g., Olsen, 1986, Olsen et al., 1996a). Individual members of the stratigraphic units have great lateral extent and continuity and have been traced throughout much of the Newark basin (e.g., McLaughlin, 1948; Olsen, 1988); a prominent example is the Perkasie Member of the Passaic Formation (Fig. I.3a) (Stops 6, 8-9). Biostratigraphy indicates that the preserved syn-rift strata in the Newark basin range in age from Carnian (Late Triassic) to Hettangian (Early Jurassic) (e.g., Cornet and Olsen, 1985; Olsen et al., 2011).

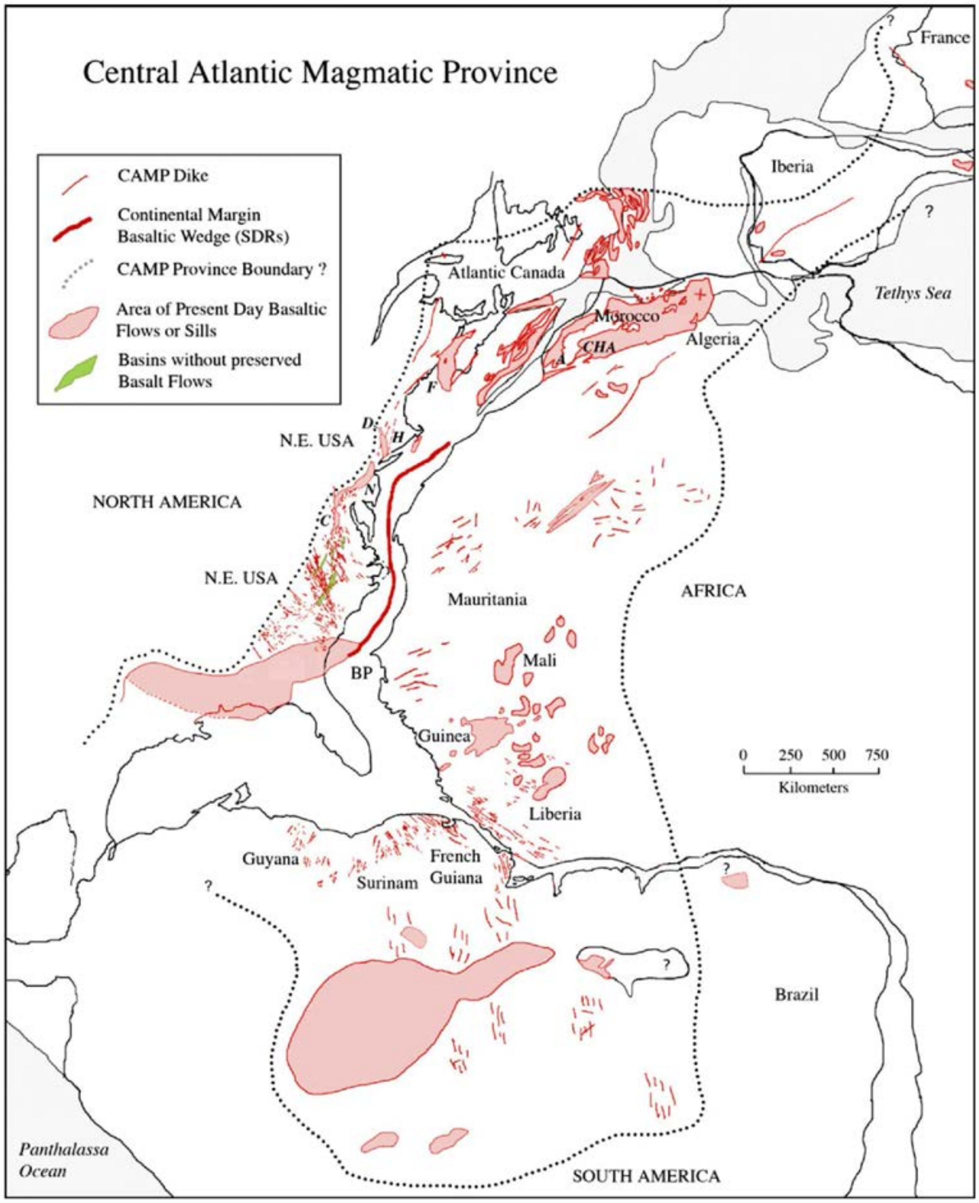


Figure I.10: Distribution of CAMP (Central Atlantic Magmatic Province) igneous rocks (red) shown on an early Mesozoic reconstruction. Modified from McHone (2000).

The tropical lacustrine cyclicity originated from fluctuations in monsoon intensity (Olsen and Kent, 1996) as it still does today. The monsoon varied in response to changes in sunlight modulating the intertropical convergence zone. The changes in sunlight intensity were (and are) caused by variations in the orientation of the Earth's spin axis driven largely by the sun and moon (precession) modulated by deformations in the figure of the Earth's orbit in response to the joint action of the planets and other Solar System bodies. This system is chaotic on timescales of hundreds of millions of years (Laskar, 2003) and detailed prediction or postdiction is quite impossible past 50 million years. The geological record, as in the case of the Newark Basin, has preserved a history of what the gravitational system actually did, and it is possible to recover a highly resolved record that passes stringent internal tests allowing calibration of Solar System behavior, thus escaping the confines of Chaos (Kent et al., 2018; Olsen et al., 2018b).

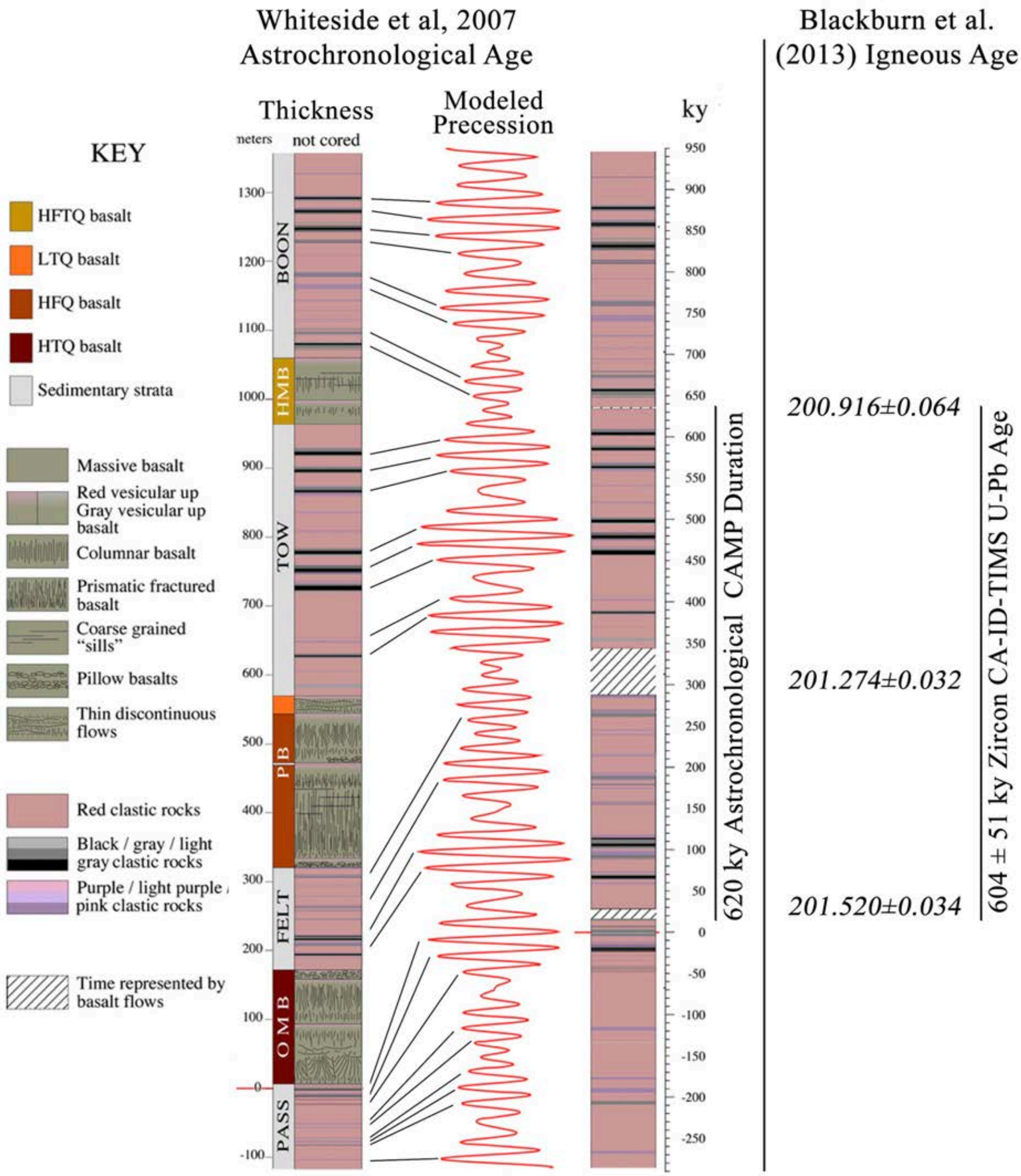


Figure I.11*: Stratigraphy and duration of the extrusive interval in the Newark basin based on ACE (Army Corps of Engineers) cores and the NBCP (Newark Basin Coring Project) Martinsville core. Basalt-flow units may be massive, pillowed, or columnar jointed. The flows have somewhat different geochemistry, although all flows are quartz-normative basalts. Intrusive rocks have the same geochemistry. HTQ = high-titanium quartz-normative basalt; HFQ = high-iron quartz-normative basalt; LTQ = low-titanium quartz-normative basalt; HFTQ = high-iron & titanium quartz-normative basalt. Interbedded sedimentary units are highly cyclical. These cycles indicate that the duration of the extrusive interval is ~600,000 years. Recent high-precision U-Pb isotope geochronology indicate that the oldest flow is dated at ~201.5 Ma and the youngest flow is dated at ~200.9 Ma (e.g., Blackburn et al., 2013). Modified from Whiteside et al. (2007) and Olsen et al. (1996b); also see Olsen et al. (2003).*

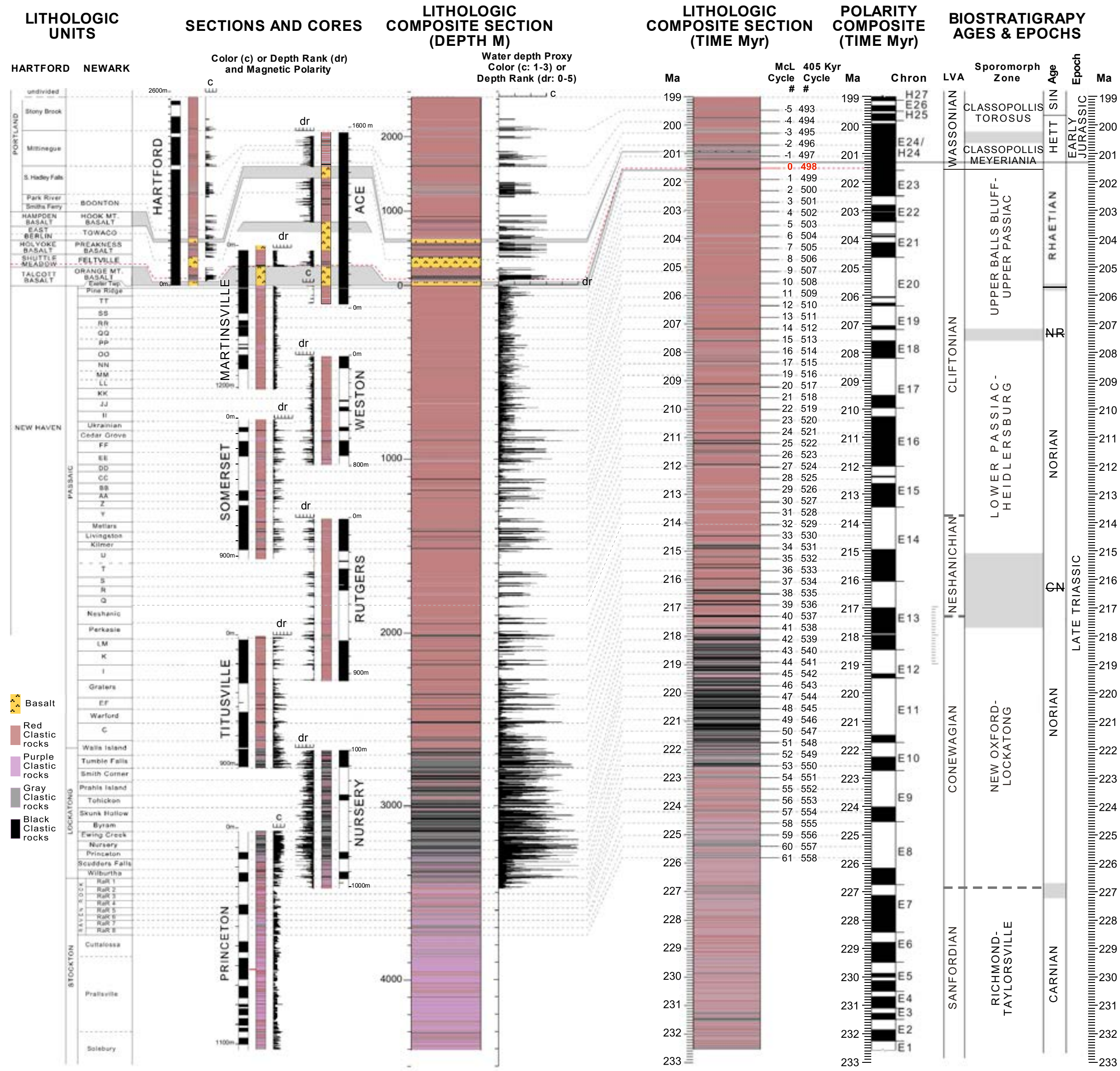


Figure I.12: *Stratigraphic and temporal framework for the Newark-Hartford timescale. Polarity chrons with prefix E based on the Newark basin section and H for the Hartford basin section. Earlier but no longer valid correlations to standard geologic age boundaries stricken through (~~NR~~ for Norian/Rhaetian and ~~CN~~ for Carnian/Norian). This time scale is now validated by U-Pb ages from the CAMP sequence (Blackburn et al. 2013) and from the Chinle Formation of the Cororado Plateau (Kent et al., 2018; Olsen et al., 2018b).*

Igneous Activity

ENAM rifting was generally amagmatic with one significant exception: the development of the Central Atlantic Magmatic Province (CAMP), one of the world's largest igneous provinces (e.g., McHone, 1996, 2000; Marzolli et al., 1999; Hames et al., 2003) (Figs. I.10 & I.11). CAMP-related igneous activity occurred during the very latest Triassic and earliest Jurassic (~201 Ma; see Blackburn et al., 2013, and references therein) (Figs. I.10 & I.11). This short-lived (Fig. 1.11), but intense, magmatic event led to the eruption of widespread basaltic lava flows and the intrusion of massive diabase sheets and dikes throughout the Newark rift basin.

Igneous activity also occurred during breakup. The ENAM margin, from Florida to southern Nova Scotia, is magma-rich, characterized by a wedge of seaward-dipping reflectors (SDRs) near the continent-ocean boundary (Fig. I.2). The SDRs, presumably of volcanic or volcaniclastic origin, formed during the rift-drift transition and are associated with the East Coast Magnetic Anomaly (ECMA) (e.g., Hinz, 1981; Benson and Doyle, 1988; Austin et al., 1990) (Fig. I.2). The remainder of the margin, from northern Nova Scotia to the Grand Banks, lacks SDRs and is, thus, considered magma-poor.

Timescale for the Triassic and Early Jurassic

The Newark basin and Hartford basin lacustrine record are the basis of a highly resolved and well tested timescale for the Late Triassic and earliest Jurassic. Largely based on the Newark Basin Coring Project, ACE cores, and new Hartford basin cores and outcrops, the timescale is based on the astrochronology of the lake cycles. Originally, this timescale was floating (Kent et al., 1995; Olsen and Kent, 1996; Kent and Olsen, 1999), that is, it was not well pinned in "absolute" time in terms of years. In a two-step process, the lava flows and associated intrusions of the CAMP provide a strong set of high-resolution zircon U-Pb tie points (Blackburn et al., 2013), and the pre-CAMP strata have most recently been calibrated by zircon U-Pb dates and magnetostratigraphy from the cores from the Triassic Chinle Formation recovered by the Colorado Plateau Coring Project (Kent et al., 2017; Olsen et al. 2018a; 2018b). These results unambiguously agree with the astrochronology supporting both the timescale and the empirical calibration of Solar System Chaos. This is the timescale we will use in this guidebook.

Field Stop Locations

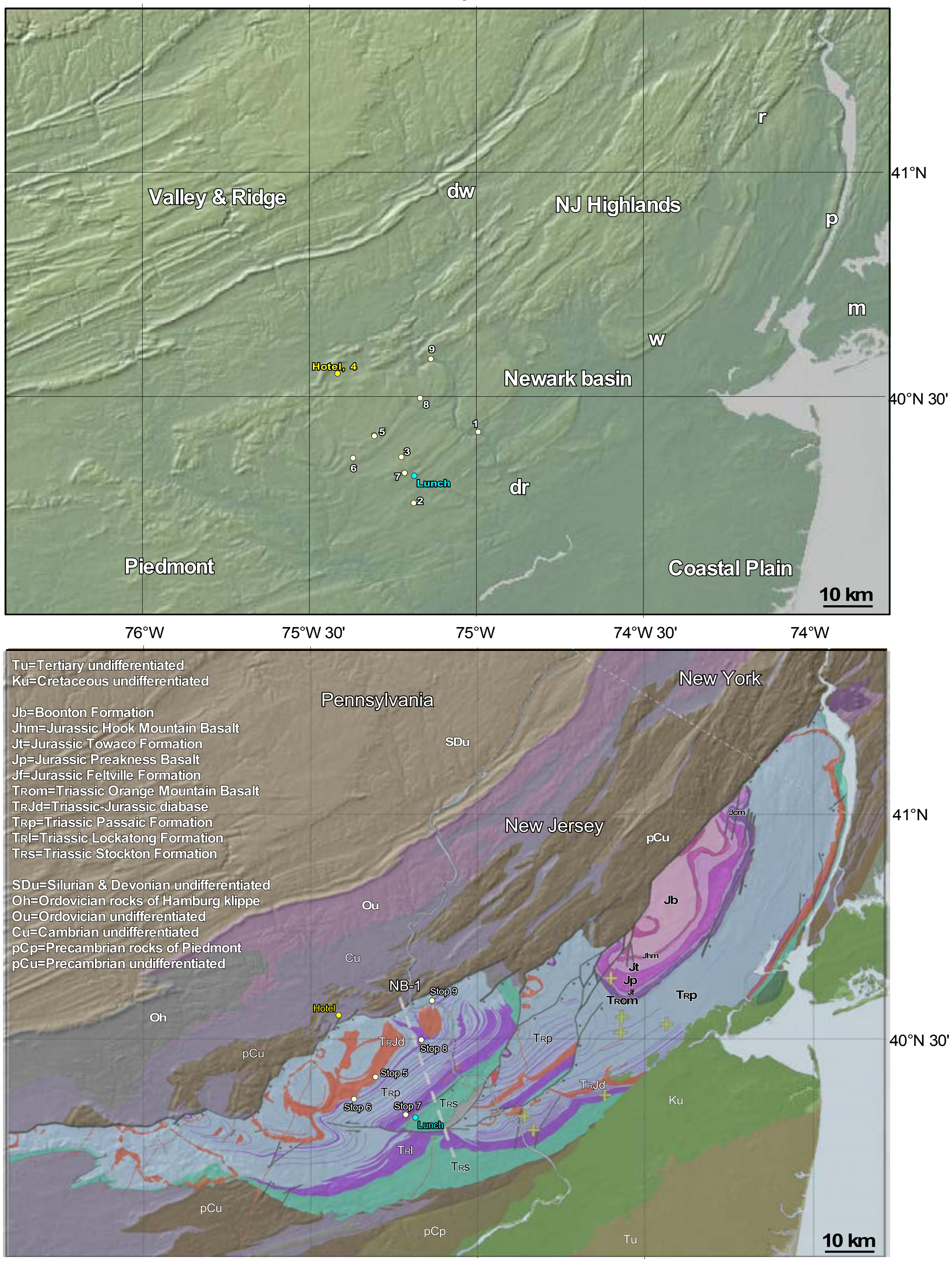


Figure I.13*: Shaded-relief map (with and without geology) of Newark basin and surrounding regions, showing physiographic provinces and locations of field sites, lunch spot, and conference hotel. Abbreviations on top map are: dr, Delaware River; dw, Delaware Water Gap; m, glacial moraine on Long Island; p, Palisades sill; r, fault-line scarp associated with Ramapo border fault. Shaded-relief map generated using GeoMap.APP. Geologic map compiled by P.E. Olsen based on Schlische (1992) and Lyttle & Epstein (1997).*

Field Stop Locations for Day 1

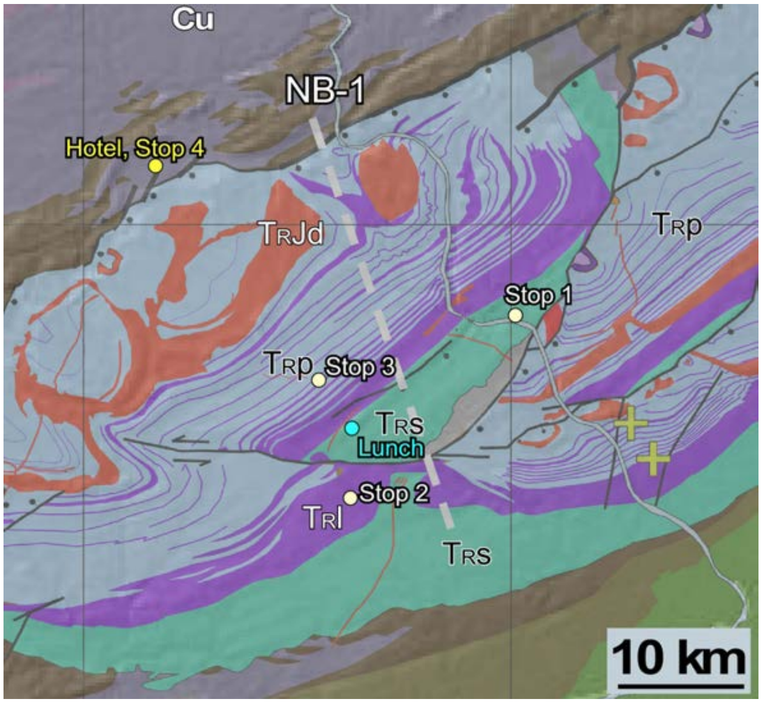
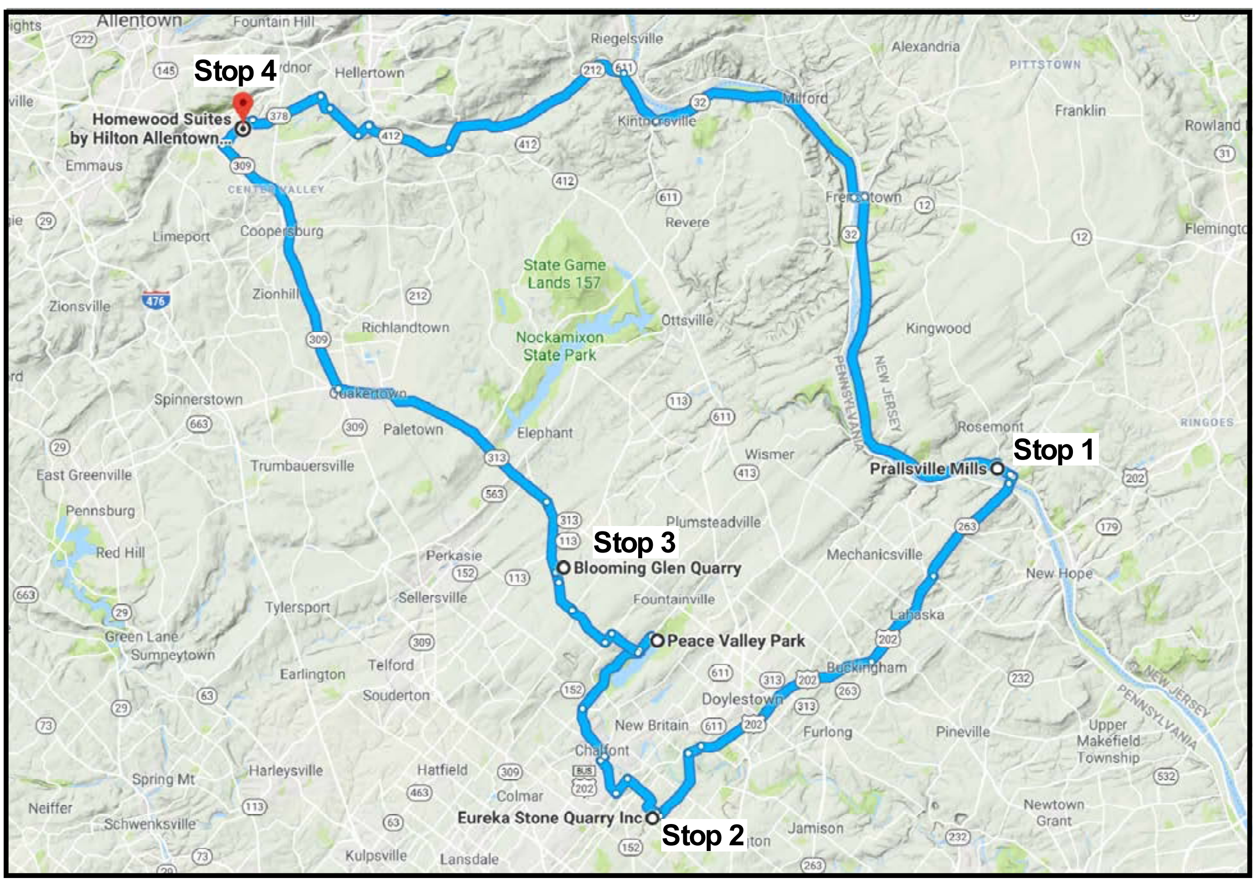


***Figure I.14**: Bottom: Google terrain map showing geography of Day 1 field sites along with lunch stop (Peace Valley Park) and conference hotel (Homewood Suites by Hilton Allentown).The blue line is a driving route for passenger cars; the buses will take a somewhat different route because of weight restrictions on some bridges. Left diagram shows field sites on geologic / shaded-relief map.*



Field Stop Locations for Day 2

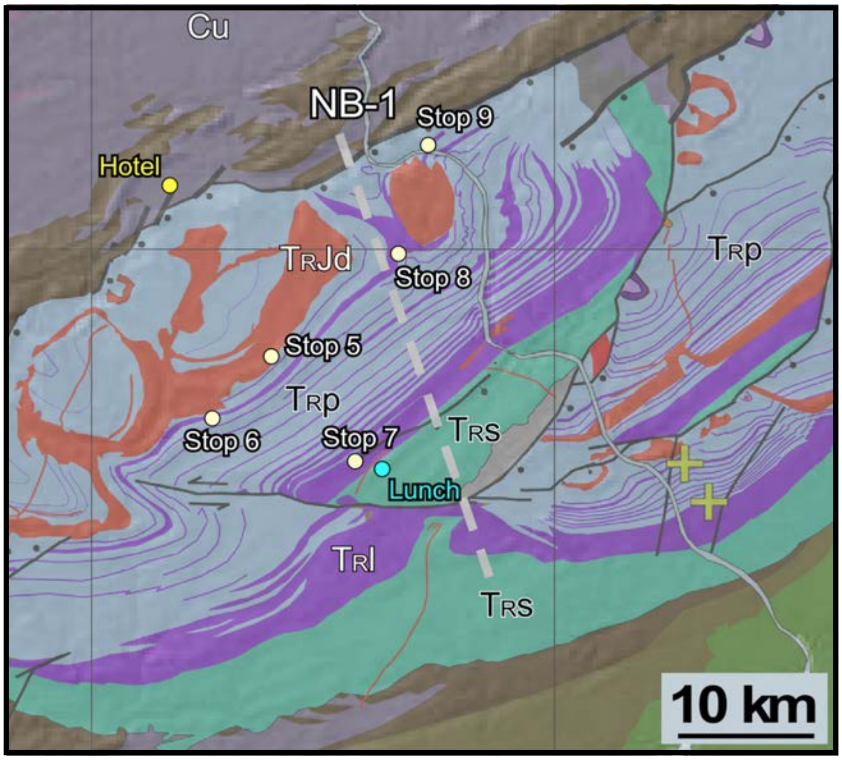
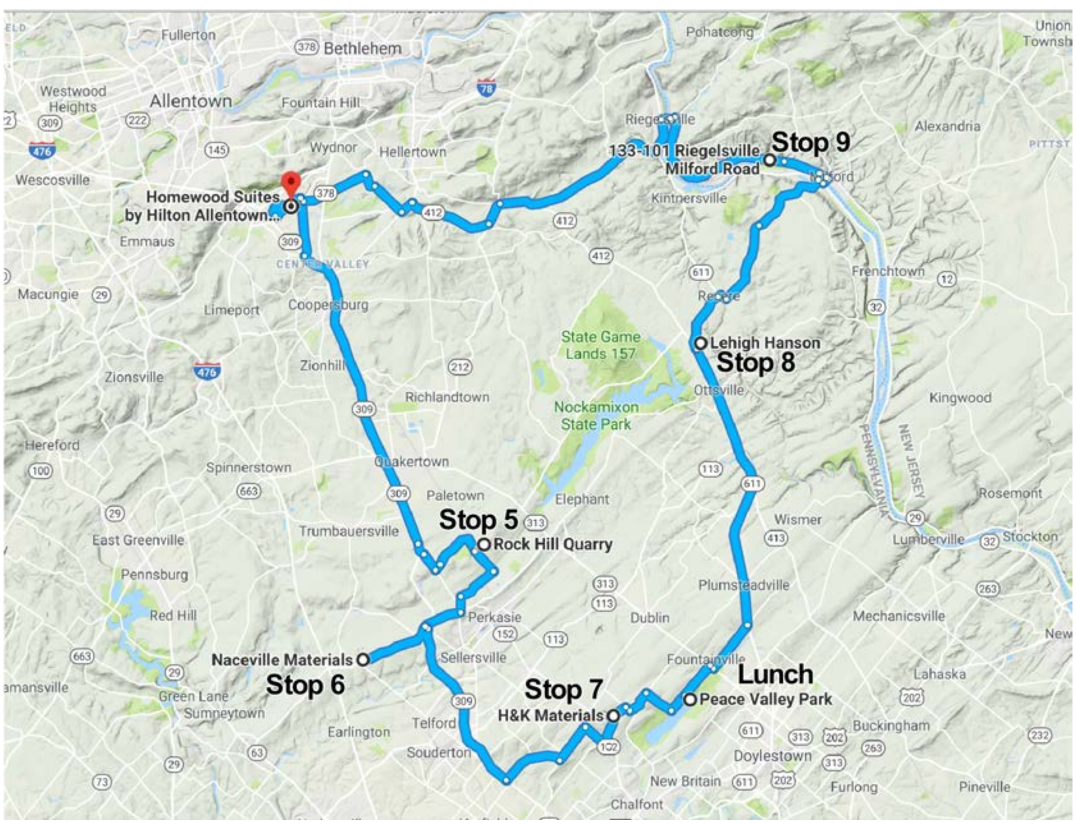


Figure I.15: *Below: Google terrain map showing geography of Day 2 field sites along with lunch stop (Peace Valley Park) and conference hotel (Homewood Suites by Hilton Allentown). The blue line is a driving route for passenger cars; the buses will take a somewhat different route because of weight restrictions on some bridges. Left diagram shows field sites on geologic / shaded-relief map.*



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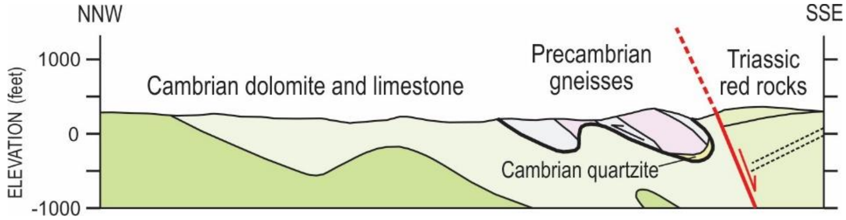
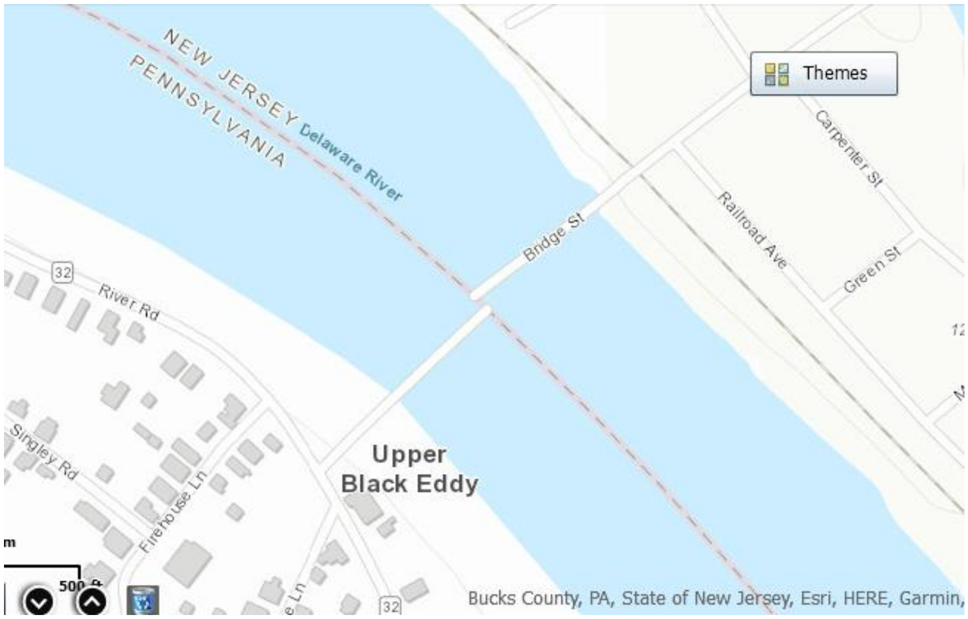
START	TURN	DIRECTIONS/COMMENTS/NOTES
0.0		Homewood Suites Hotel is located at 3350 Center Valley Parkway
0.1	R	Turn right onto Center Valley Parkway, PA 2044
2.6	R	Turn right onto Saucon Valley Road
4.3	R	Veer right onto Bingen Road
4.4	L	Turn left at "T" onto Apples Church Road
4.9	R	Turn Right at "T" onto Leithsville Road/PA 412 South
6.4		Cross Bucks County Line Marker
6.9	L	Veer left at "Y" onto Hellertown Road/PA 212 East/PA 412 South
7.1		Historical Marker - Walking Purchase Marker Text: Measured 1737, according to a supposed Indian deed of 1686, granting lands extending a day-and-a-half walk. Using picked men to force this measure to its limit, Thomas Penn reversed his father's Indian policy losing Indian friendship. https://en.wikipedia.org/wiki/Walking_Purchase
7.5	L	Turn left at "T" to stay on Springtown Road/PA 212 East/PA 412 South
9.3		Continue straight to stay on Main Street, Durham Road/PA 212 East
12.0		Historical Marker - Durham Furnace Marker Text: Built 1727. Original site at Durham. In blast until 1789, it made cannon and shot in the colonial wars and Revolution. One-time owners included James Logan and George Taylor. https://en.wikipedia.org/wiki/Durham_Mill_and_Furnace
13.8	R	Turn right onto Easton Road/PA 611 South, possible construction zone
13.8		Historical Marker - Delaware Canal (to north of intersection) Marker Text: Here is Lock No.21 in a series of 23 lift locks, numbered from Bristol to Easton. The aqueduct over Cooks Creek is one of nine which carried water and shipping across branches of the Delaware River. https://en.wikipedia.org/wiki/Pennsylvania_Canal_(Delaware_Division)
14.0		Outcrops of Grenville age basement gneiss -Reading Prong Alleghenian thrust of basement over lower Paleozoic carbonates. https://en.wikipedia.org/wiki/Reading_Prong
14.3		Monroe Border Fault Boundary fault between Triassic fanglomerate and red beds and Cambrian Leithsville Formation. A National Natural Landmark.  http://www.docs.dcnr.pa.gov/cs/groups/public/documents/document/dcnr_20032505.pdf

ROADLOG: Day 1 – Friday, October 5, 2018

START	TURN	DIRECTIONS/COMMENTS/NOTES
14.8		Triassic Passaic/Brunswick Formation, Delaware Canal on left
15.6	L	Turn left onto River Road/PA 32 South
16.1		Nockamixon Cliffs ahead. 300' cliffs of Passaic (Brunswick) Formation hornfelsed by Coffman Hill diabase intrusion. Top Rock provides panoramic views of the Delaware River valley. Cliffs offer habitat for unique arctic-alpine plant community, a wide variety of birds, and ice climbing in winter.  http://www.gis.dcnr.state.pa.us/topo/ogf/OGF_NockamixonCliffs.pdf
18.1		Move through one lane bridge over Falls Creek
18.3		Ringing Rocks
19.4		Milford Bluffs across river Passaic Formation siltstone and shale https://nj.gov/dep/njnlt/tfbreden.htm
20.1	L	Turn left crossing bridge over Delaware River and enter Milford, NJ

START	TURN	DIRECTIONS/COMMENTS/NOTES
		Crossing Upper Black Eddy - Milford Bridge  Recent tectonic movement along state boundary fault. From PAGeode - ESRI Topographic base map.  Hold on tight.
20.4	R	Turn right at "T" onto Frenchtown Road, Harrison Street/NJ 619
22.5		Roadside excavation Passaic Formation siltstone and shale. Well-bedded with mudcracks. Common trails, tracks and burrows most likely from small crustaceans.

ROADLOG: Day 1 – Friday, October 5, 2018

START	TURN	DIRECTIONS/COMMENTS/NOTES
23.2	L	Turn left onto 12th Street following sign for Truck Route/NJ 29
23.9		Route becomes Race Street, River Drive, Daniel Bray Highway, Risler Street
24.0	L	Turn left onto Trenton Avenue/NJ 29 South, tight roadway section
24.5		Historical Marker - Lower Argillite Alley Marker Text: Lenape tribes used this abundant Hunterdon mineral for spearpoints and tools. One of their trade routes followed the River Road (now Rte. 29) southwards towards Sanhican (Trenton). https://www.hmdb.org/marker.asp?marker=114648
28.3 - 28.9		Passaic Formation Lower part of Passaic Formation reddish brown siltstones and mudstones. Gray mudstone unit near southern end.
29.0		Contact of Passaic and underlying Lockatong about 600 feet south of Warsaw Road
29.6		Lockatong Formation Continuing downsection through basin. Predominantly gray sometimes dolomitic mudstones and siltstones. Some red beds.
30.3		Tumble Falls Group of waterfalls on flashy streams http://waterfalls.nature.st/NewJersey/Hunterdon.html
31.0 - 31.4		Abandoned quarry in Lockatong hornfels. Byram diabase sill at south end of outcrop.
32.3		Approximate location of contact between Lockatong and underlying Stockton Formation
32.7		Stockton Formation Bedded reddish-brown sandy mudstone and sandstone in uppermost Stockton Formation.
35.7	**R**	***Turn right into Prallsville Mills, 33 Risler Street, Stockton, Stop #1*** Just past “Entering Borough of Stockton” sign
		Doughnut & Coffee Break

Stop 1: Stockton Formation at Prallsville Mills

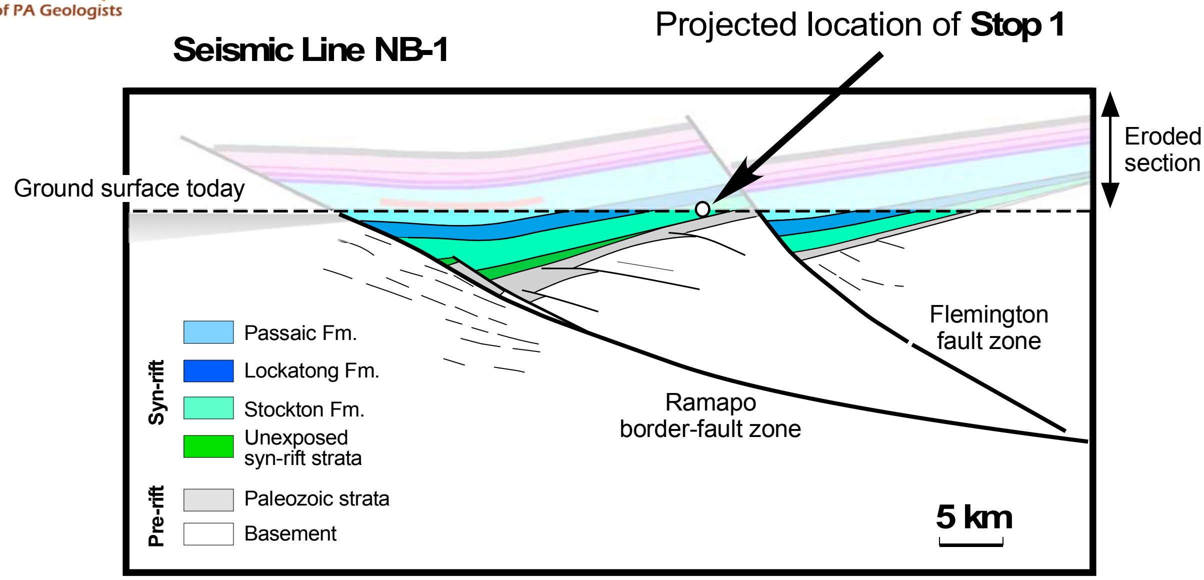


***Figure: 1.1:** Cross section of the Newark basin along seismic line NB-1 showing the projected position of Stop 1. Modified from Withjack et al. (2013).*

Location: Lat 40.409698, Long -74.987433: Prallsville Mills, 33 Risler St., Stockton, NJ 08559.

Key Points:

1. Exposures of Stockton Formation, basal synrift unit of Newark basin (~230 to 227 Ma in age)
2. Deeply buried (> 6 km) by end of rifting; now exhumed by uplift, tilting, and faulting
3. Deposited in meandering-stream environment near equator
4. Consists of interbedded sandstones, siltstones, clays with heavily bioturbated and soil fabrics
5. Long-term aquifer, plausibly charged with reducing fluids (hydrocarbons?) during deep burial
5. Orthogonal joints enhance ground-water fluid flow

Notes:

Stop 1: Stockton Formation at Prallsville Mills

An abandoned stone quarry at Prallsville Mills exposes a section of the Prallsville Member of the Stockton Formation (Fig. 1.1). Observations from a very similar section, present in the Skeuse Quarry (Olsen et al., 1989) (Fig. 1.2) which is no longer accessible, apply to Stop 1. The Stockton Formation is the basal syn-rift unit of the Newark basin. This section was once buried by more than 6 km of syn-rift section. Subsequent, regional uplift, NW tilting, and faulting produced significant erosion, exposing the Stockton Formation at this locality.

The Prallsville Member of the Stockton Formation consists of cycles of pale arkosic sandstone and conglomerate grading upward into red mudstone and red to purple sandstone with abundant burrows and root traces. Burrows are also present in the pale sandstones, but more difficult to see. No other fossils are known from the Prallsville Member of the Stockton Formation. The sedimentary structures in the fining-upward sequences are consistent with large, perennial meandering river deposits. In addition, lateral fining of cross-bedded units suggests the presence of lateral accretion surfaces on point bars. The implied large river systems indicate that the basin was hydrologically open.

Based on paleomagnetic data, the strata at this locality accumulated very near the equator (Kent and Tauxe, 2005). The heavy bioturbation suggests persistent humidity consistent with its near equatorial position. However, some soil carbonates are present and yield $p\mathrm{CO_2}$ estimates of ~5000 ppm (Schaller et al., 2015), suggesting very high evaporation rates, under climatic conditions with no modern analog.

According to Van Houten (1969), the Stockton sandstones exhibit interlocking grains resulting from pressure solution during their deep burial. The yellow patches in outcrop are intergranular zones of limonite replacing what was iron-rich carbonate. Abundant grains of specular hematite, supposedly replacing magnetite, are also present.

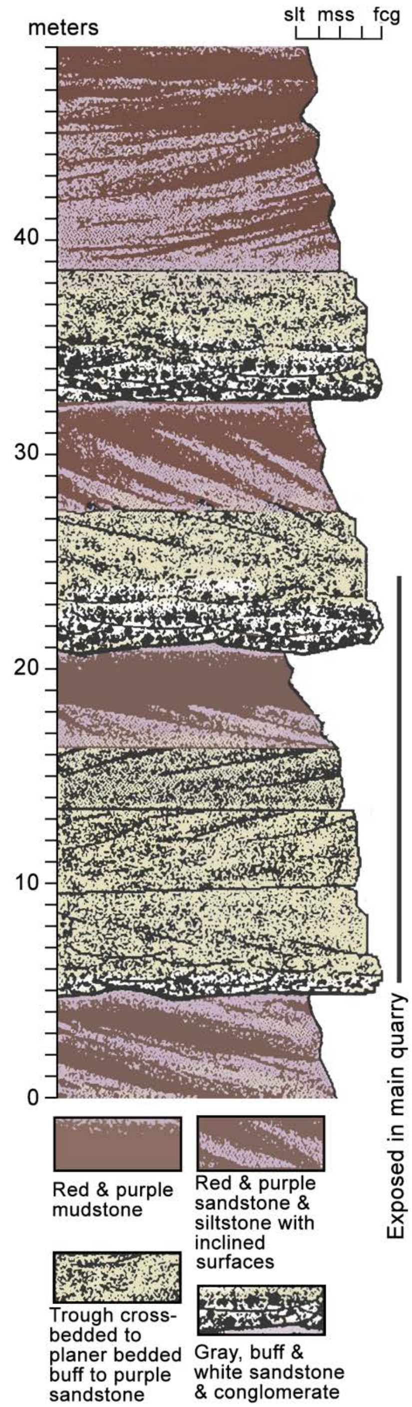


Figure 1.2: *Section at abandoned Skeuse quarry Stockton, NJ (modified from Olsen et al., 1989).*

There are no age-diagnostic data from this part of the basin section; however, it is below the Raven Rock Member of early Norian age. This part of the Stockton correlates to middle Carnian marine strata based on magnetostratigraphy (Muttoni et al. 2004); therefore, it is between 230 and 227 Ma in age. This means it is slightly younger than the still poorly constrained “Carnian Pluvial event” (Furin et al., 2006), which, if it exists, has been interpreted as due to a humid climatic interlude somehow related to CO_2 from the eruption of the Wrangellian oceanic plateau basalts (Dal Corso et al., 2015).

A prevalence of tan to white arkosic sandstones characterize the Stockton Formation, especially the Prallsville and older members. The mudstones in the same sequences tend to be red. Sandstones in younger parts of the basin section also tend to be red, notably in the vast Passaic Formation. This color difference may reflect the former presence of reducing fluids in the Stockton sandstones. Similar pale colors characterize sandstones of other ENAM rift basins, including the Pekin Formation of the Deep River basin, the Pine Hall Formation of the Dan River basin, the Otterdale Sandstone of the Richmond basin, the Newfound Formation of the Taylorsville basin, the New Oxford Formation of the Gettysburg basin, and the basal New Haven Formation of the Hartford basin (see Fig. I-2 for basin locations).

In the western U.S., particularly in the largely eolian Jurassic Navajo and Entrada sandstones, pale colored (white, tan, and yellow) sandstones have been interpreted as bleached because of reducing fluids, including natural gas, hydrogen sulfide, and oil (Chan et al., 2000; Beitler et al., 2003, Parry et al., 2004). The discordant, clearly diagenetic, color discontinuities are obvious at many outcrops (Fig. 1.3) in the Triassic-Jurassic sandstones of the Colorado Plateau. Diagenetic migration of iron by reducing fluids is a simple explanation for the light color of the Stockton sandstones. A source of hydrocarbons could be the overlying Lockatong Formation (see Stop 2) or a lacustrine sequence equivalent to the Stockton fluvial sequence present down-dip but not exposed (Reynolds, 1994). It is also possible that the sandstones were aquifers though most of their history and never developed the hematitic stains characteristic of younger Newark basin formations.

In the 19th and early 20th centuries, the Stockton Formation was a significant source of building stone, notably using the pale-colored sandstones which are nearly white when fresh. The one active quarry in the Stockton Formation, the nearby Delaware Stone Quarry in Lumberville, PA, still serves this use. Currently, the Stockton Formation is most important economically as an aquifer. Although sandstone porosities can be high (e.g., 22.5%; Sloto et al., 1996) compared to other formations in the rift basin, most ground-water flow is from fractures in the sandstone. Because of the widespread presence of mudstone intervals associated with the sandstones, as seen here, the ratio between horizontal to vertical transmissivities can be large, i.e., 100:1.

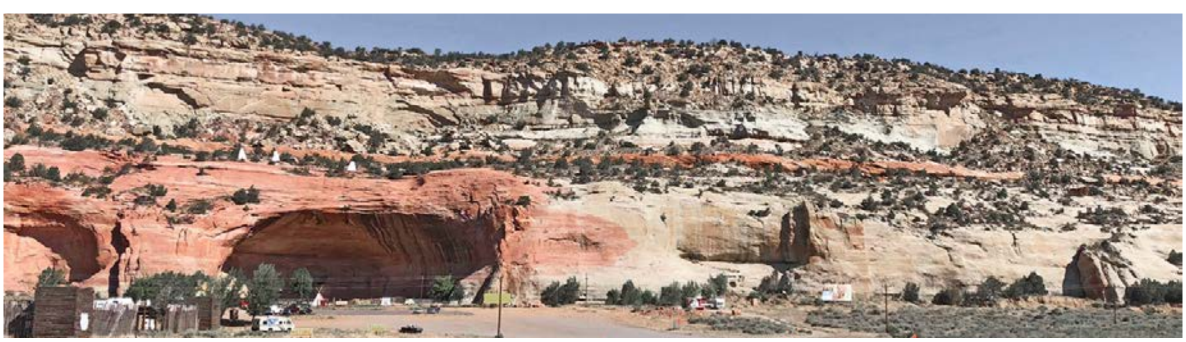


Figure 1.3: *Discordant color boundaries in the Entrada Sandstone just east of the NM/AZ border along 1-40 (35.369722°, -109.046028°), McKinley County, NM. Photo by P.E. Olsen.*

Two orthogonal sets of fractures are present in this area (Fig. 1.4) and elsewhere in the Newark basin. Plumose markings on fractures cutting fine sandstones indicate that these fractures are joints that formed perpendicular to the extension direction. One set consists of NE-striking, subvertical joints resulting from NW-SE extension. The other set consists of NW-striking, subvertical joints perpendicular to a local extension direction also responsible for the WNW-striking Solebury dike that presumably belongs to CAMP. Most other dikes in and near the Newark basin are NE-SW striking.

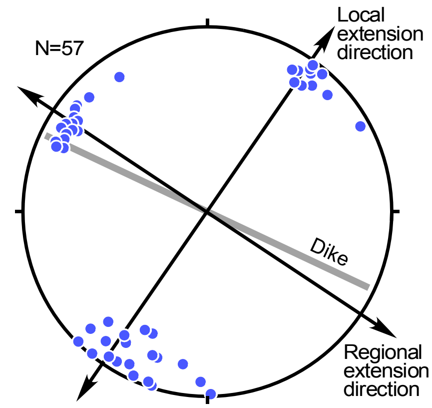


Figure 1.4: *Lower hemisphere sterographic plot showing poles to fracture surfaces at Skeuse Quarry and trend of Solebury dike. Fractures are subvertical and strike NE-SW and SW-NE. Olsen et al. (1989).*

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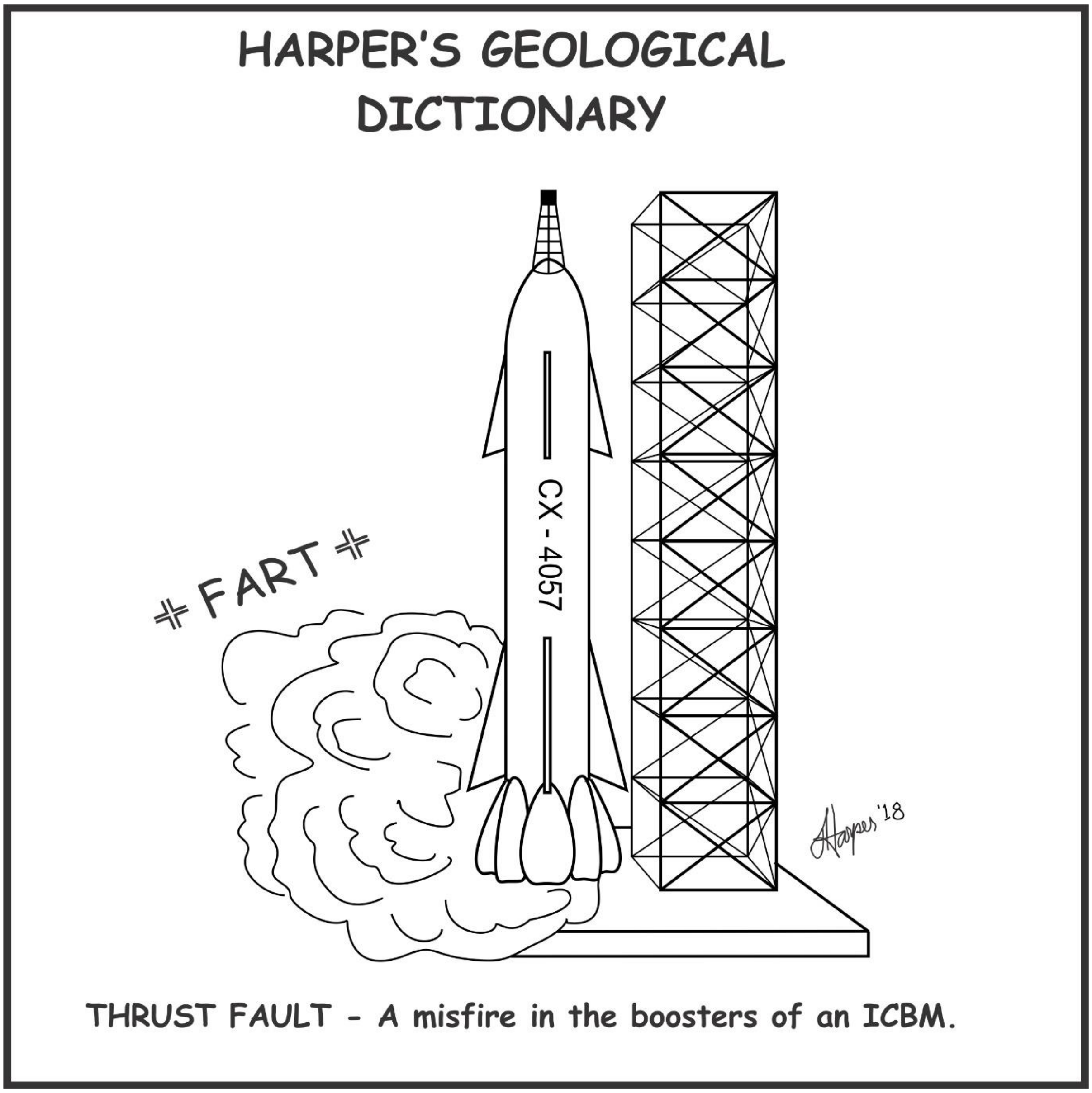
START	TURN	DIRECTIONS/COMMENTS/NOTES
35.9	R	Turn right out of Prallsville Mills onto Risler Road. NJ 29
37.2		Cross narrow bridge with "S" Shaped Approaches
38.7	L	Enter on ramp to NJ/PA 202 South to take bridge to return into PA
		Note Cemetery on right and tight ramp on left with no traffic signal
39.6		Pass through Toll Gate merging onto PA 202 South entering PA
		New Hope Lambertville Bridge
41.2		Following Lower York Road/PA 202, stay in Left Lane
46.3	R	Keep Right to stay on PA 202 South
52.3	L	Turn left onto Lower State Road/PA 3003
52.7	L	Turn left to stay on Lower State Road/PA 3003
54.9	R	Turn right onto Pickertown Road
55.0	**L**	***Turn left into Eureka Stone Quarry, 800 Lower State Road, Chalfont, Stop #2***



THRUST FAULT - A misfire in the boosters of an ICBM.

Stop 2: Lockatong Formation at Eureka Quarry

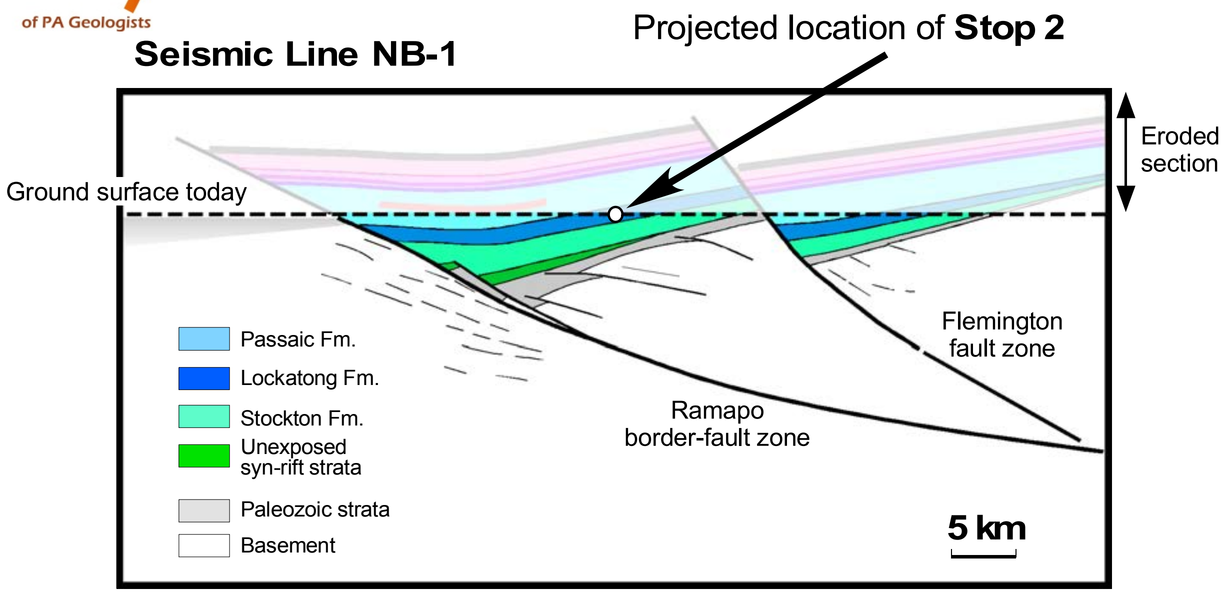


Figure: 2.1: *Cross section of the Newark basin along seismic line NB-1 showing the projected position of Stop 2. Modified from Withjack et al. (2013).*

Location: Lat 40.258880, Long -75.185419: Eureka Stone Quarry, Eureka, PA.

Key Points:

1. Synrift lacustrine Lockatong Formation (~222 – 218 Ma)
2. Deeply buried (~ 5 km) by end of rifting; now exhumed by uplift, tilting, and faulting
3. Mostly lacustrine depositional environment
4. Consists of orbitally paced cyclic black and gray shales
5. Accumulated at low latitudes at time of very high *p*CO_2
6. Fish fossils and clam shrimp
7. Oil stains
8. Detachment folding associated with bedding-plane slip
9. NE-striking, steeply dipping faults and joints

Notes:

Stop 2: Lockatong Formation at Eureka Quarry

The Lockatong Formation of Late Triassic age is a large lacustrine lens in the Newark basin and constitutes the most persistently deep-water facies of the Triassic part of the synrift section. This quarry exposes more than 200 m of cyclical black and gray calcareous mudstone of the lower Lockatong Formation including nearly all of the Nursery Member and the upper part of the Princeton Member (see Figure I.8) near the bottom of the formation and close to the center of the basin (Fig. 2.1). It is this part of the Lockatong Formation that has the highest frequency of organic-rich strata.

The Lockatong Formation was long thought to be Late Carnian in age. However, the last two decades have seen a major revision in age based on the combined astrochronology and magnetostratigraphic correlation to the European marine (Tethyan) sections (Muttoni et al., 2004). Consequently, the Lockatong Formation (and the Raven Rock Member of the Stockton Formation) are Norian in age (Kent et al., 2017). The paleolatitude was about N 6° (Kent & Tauxe, 2005), and $p\mathrm{CO_2}$ was very high: between 4000 – 5000 ppm (Schaller et al., 2015).

Van Houten cycles (see Fig. I.9) average about 6 m thick here and tend to be dominated by mudstone. Some are quite organic-rich (~4% TOC), including two prominent Van Houten cycles shown in Figure 2.2. The black shales in these two cycles are microlaminated, and produce abundant fossil fish (Fig. 2.3). Mudcracks are relatively uncommon, although present in every Van Houten cycle; burrowing is more common at this stratigraphic level than higher in the formation.

The section here in the Eureka Quarry was one of the first sections studied for its cyclically, both in terms of identification and counting of the cycles (e.g., Van Houten, 1964) and using Fourier analysis (Olsen, 1986) (Fig. 2.4). The original Fourier analysis used the Blackman-Tukey method, which is relatively low resolution. However, the results are completely consistent with later results based on the cored section (e.g., Olsen & Kent, 1996, 1999; Kent et al., 2017; Olsen et al., 2018) and reanalysis using the multi-taper-method (Fig. 2.4).

Detailed studies of the lateral facies relationships, paleontology, and chemical constituents of these two cycles (Olsen, 1980; Olsen, 1984; Olsen et al, 1989) suggest that the lower cycle accumulated during the rise and fall of a very large lake with dilute water during high stand. The upper cycle accumulated during the rise and fall of a very large lake with more solute (especially carbonate). The change between the two cycles is part of the trend through a ~100,000-year cycle in which the high-stand phases of the lakes are first dilute and large, then more saline but still large, and then finally shallow and smaller and more dilute again. Overall, this recapitulates the changes seen in the lower 400,000-year cycle. This recapitulation of a pattern at one scale to larger scales is characteristic of cyclical lake sequences.

The two cycles shown in Figure 2.2 are especially noteworthy because of their faunal content (Fig. 2.3) and their known lateral extent. The same cycles are recognizable laterally in the Newark Basin Coring Project (NBCP) cores ~30 km to the east (Fig. 2.2). Both cycles have a microlaminated, deep-water interval, and both contain well-preserved fish. The lower cycle (W-6), however, is relatively organic carbon- and carbonate-poor, whereas the upper cycle (W-5) is organic carbon- and carbonate-rich. The fish present (Fig. 2.3) are differ in each cycle with the lower cycle dominated by the gar-relative *Semionotus* and the upper cycle dominated by the distant sturgeon-relative *Turseodus* (Fig. 2.3).

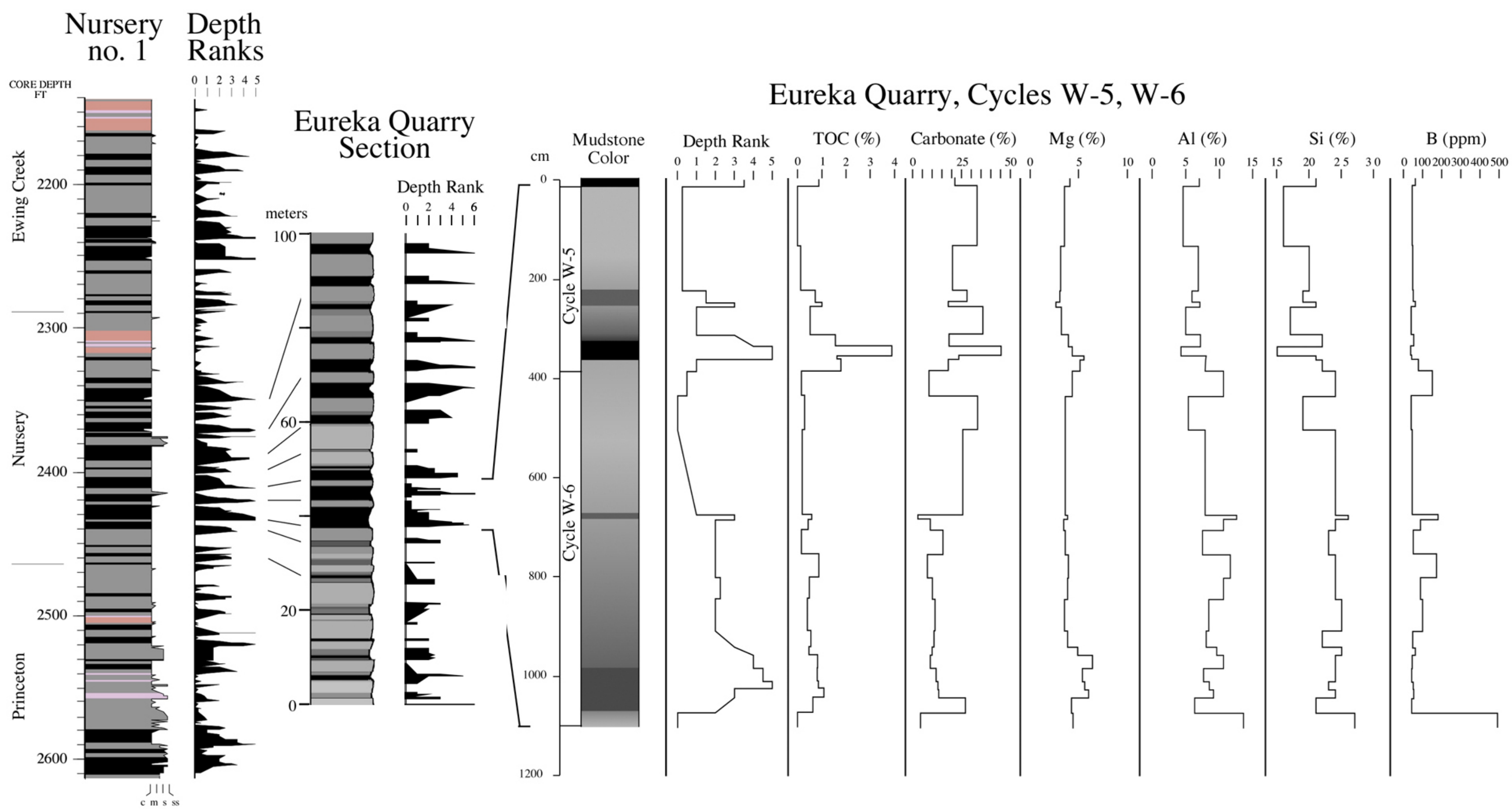


Figure 2.2: *Comparison of chemical and lithological data at Stop 2, Eureka Quarry (From Olsen, 1986), with the Nursery no. 1 core and depth rank section. We will be examining these two cycles (W-5 and W-6) in outcrop.*

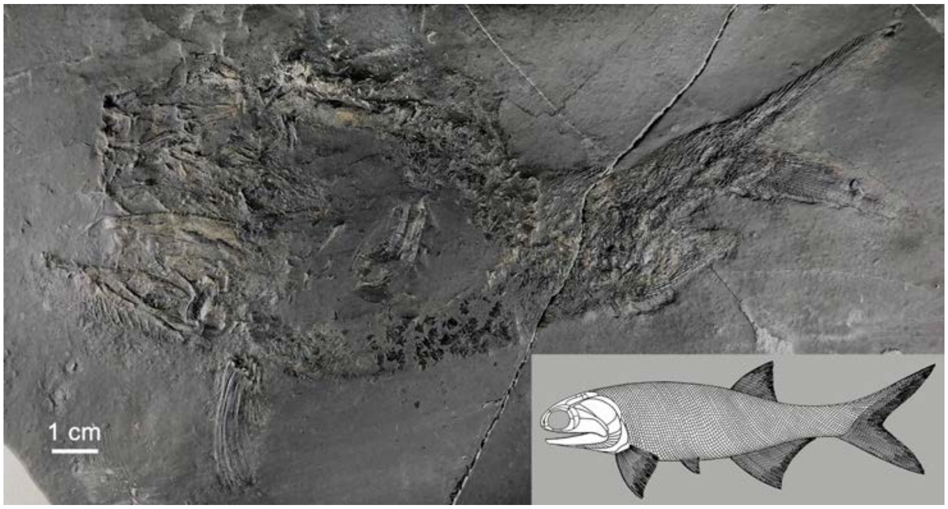


Figure 2.3: *The fish* Turseodus *from Eureka Quarry. This specimen is the holotype of* Gwyneddichtis *major Bock, 1959 (Academy of Natural Sciences of Drexel University 15655 Quarry (Bock 1959). Courtesy of Ted Daeschler.*

The lower cycle has mostly small clam shrimp, and the upper cycle has mostly large clam shrimp. These differences, maintained at all outcrops, must reflect basin-wide differences in lake chemistry affecting the fauna and organic-carbon preservation.

The microlaminated part of cycle W-5, represents the most extreme end-member of lake depths in these ancient lakes. In large tropical lakes, like those of the Newark basin, water depth is the main control on material distribution. This is because the main sources of energy for vertical and horizontal material transport are wind-driven turbulence and currents transmitted through the surface of the lake. Depth of wave base, one measure of this work, is a function of the distance over which the lake is exposed to wind (fetch) and the speed and duration of the wind (Fig. 2.5). Generally, a lake covering a larger surface area has a deeper wave base than a lake covering a smaller area. For two lakes of equal area, the deeper lake will have a smaller proportion of its water column affected by wave mixing than the shallower one. Assuming that the microlaminated strata at this locality were not exposed to wave base during their deposition, then the longest dimension of the microlaminated unit can be used to calculate a minimum lake depth using the unit's preserved length as the maximum potential fetch (Manspeizer & Olsen, 1981; Olsen, 1984, 1990). For the Lockatong Formation, this method yields depths of about 70, 100, and 130 m for medium wind speeds of 20, 30, and 40 m/sec, respectively (Olsen, 1990). Similar results are obtained using the model of Rowan et al. (1992) as interpreted by Smoot (2010). The absence of bioturbation in these layers together with the preservation of whole fish and reptiles suggest an anoxic bottom. Therefore, these estimates represent minimum depths to the chemocline, and the lakes could have been much deeper.

For this microlaminated unit, the deep water and resulting turbulent stratification greatly reduced the rate of oxygen transport to depth; consequently, bacterial respiration depleted the oxygen below about 100 m (based on Olsen, 1990). This had the effect of eliminating bioturbators, which increased the effective rate of burial of organic material and dramatically decreased ecosystem efficiency, sequestering organic matter from both metabolic enzymes and essential metabolic requirements. The result is increased preservation of labile organic matter. This is a general theme, applying to lacustrine and marine systems alike.

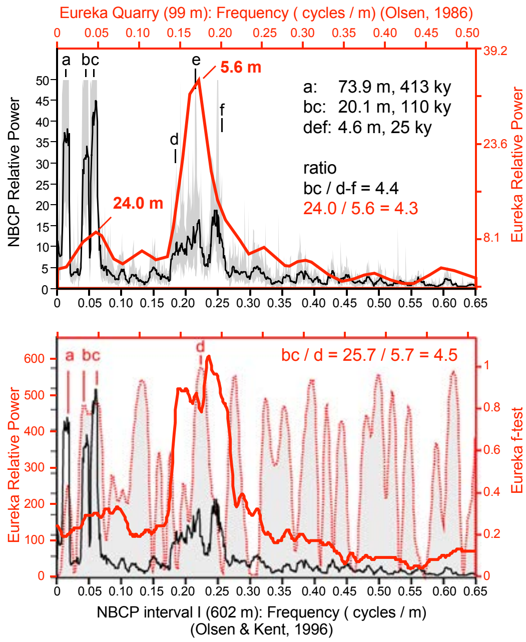


Figure 2.4: *Comparisons of power spectra for Lockatong Formation. (Top) Red line and labels show Eureka Quarry analysis from Olsen (1986) using Blackman-Tukey method, and black/grey line shows analysis from Newark Basin Coring Project (NBCP) cores (Olsen & Kent, 1996) using multi-taper-method (MTM). Note splitting of the ~ 100 ky cycle in the latter. (Bottom) Red line and labels show new MTM spectrum from original Eureka data. Notice the splitting of the f-test results for the new analysis showing that the Eureka results are representative of the Lockatong in general. For top and bottom, a is 405 ky cycle; b-c split is ~100 ky cycles; d-e-f is ~20 ky cycles. The accumulation rate is greater at the Eureka site than at the cored section, but the ratios between the ~100 kyr and the ~20 ky cycles are nearly the same.*

"Dead oil" staining and pyrobitumen-filled fractures are abundant at this site and in the Lockatong Formation in general. Although the present thermal maturity in the semi-anthracite to anthracite grade is 2.58 % R_0 (Malinconico, 2002) at this locality, the abundant staining attests to considerable petroleum migration earlier, and to the possibility of remaining gas, the economic value of which is unproven. The economic value of the Lockatong Formation is largely as crushed stone, the hardness of which is caused by the high content of silicate cements, deep burial (~ 5 km: Malinconico, 2002), and high thermal maturity. According to Rddad (2017) this same thermal cracking may have moved arsenic from organic matter into pyrite and bitumen where it can be further mobilized into groundwater, which is an issue in drinking water derived from Lockatong (and Passaic) bedrock aquifers (Serfes et al., 2010).

Melanges similar to those we will see in the core exercise (Stop 4) are present in cycle W-5. Olsen et al. (1989) termed them "dead horses" (see Stop 7). Generally, they are not present in the lower organic content of silty units, even when microlaminated. As discussed in the core exercise, these features have been misinterpreted as turbidites and surface erosional breccias (e.g., in the Eocene Green River Formation: Dyni & Hawkins, 1981), and both of these interpretations led to serious mistakes in the depositional context of source rocks, given that the breccias are actually early diagenetic features involving in situ liquefaction, brecciation, and shear.

Conspicuous in some cycles, especially W-5, is evidence of bedding-plane shear involving both folding and brittle failure with mineralized fault planes abundant at this site and in the Lockatong Formation in general. Although the present thermal maturity in the semi-anthracite to anthracite grade is 2.58 % R_0 (Malinconico, 2002) at this locality, the abundant staining attests to considerable petroleum migration earlier, and to the possibility of remaining gas, the economic value of which is unproven. The economic value of the Lockatong Formation is largely as crushed stone, the hardness of which is caused by the high content of silicate cements, deep burial (~ 5 km: Malinconico, 2002), and high thermal maturity.

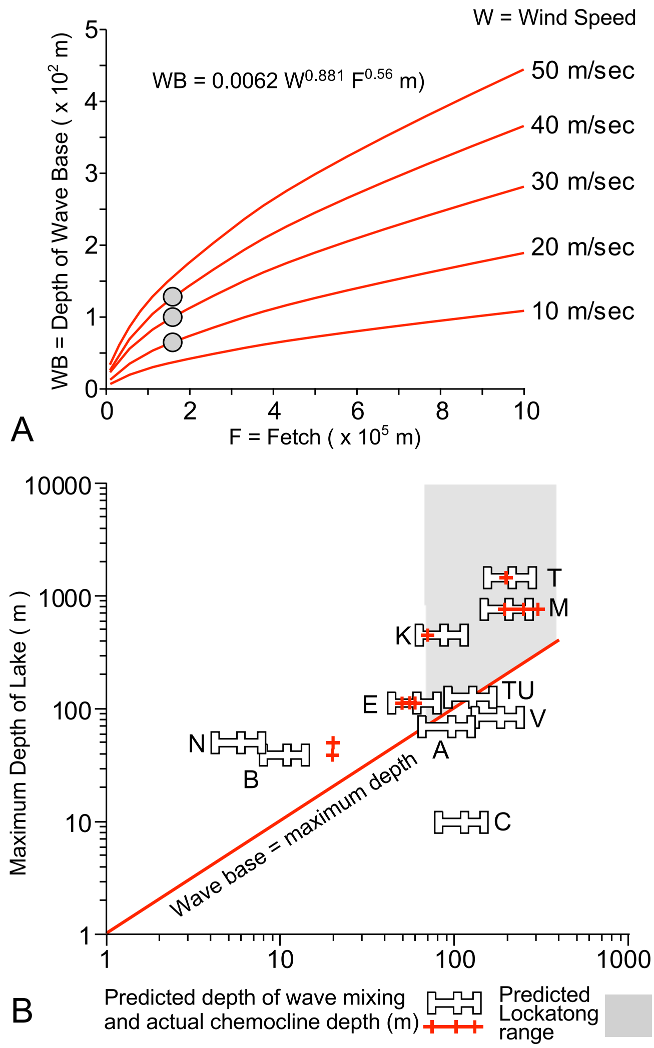


Figure 2.5: *Predicting the depths of lake with microlaminated, organic-rich units. A, Calculated relationship between maximum potential fetch of a lake and predicted wave base for winds of various speeds (Olsen, 1990). Gray circles show minimum depth estimates for Lockatong lakes. B, Predicted depth of wave base and actual depth of chemocline for several east African lakes. Abbreviations: A, Lake Albert; B, Lake Bunyuni; C, Lake Chad; E, Lake Edward; K, Lake Kivu; M, Lake Malawi; N, Lake Nhugute; T, Lake Tanganyika; TU, Lake Turkana; V, Lake Victoria. Predicted range for Lockatong microlaminated units shown in gray. Note that for modern lakes in which maximum depths are less than predicted depths of wave mixing, no chemocline exists, and oxygenated waters reach the lake bottoms. Note also that Lake Baikal would plot with Lake Tanganyika (T) in predicted depth of wave mixing, lake depth, and depth to the base of the measured turbulent layer; it presently has no chemocline, and oxygen reaches the bottom. During the Pliocene, however, with a longer growing season and higher productivity it evidently did chemically stratify and produced microlaminated diatomites. Calculated depth of wave mixing is based on A. Modified from Olsen (1990).*

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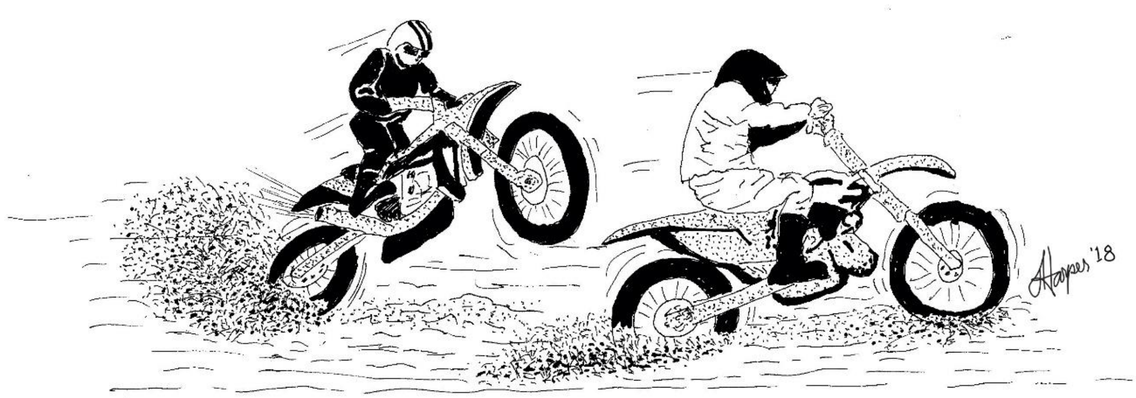
ROADLOG: Day 1 – Friday, October 5, 2018

START	TURN	DIRECTIONS/COMMENTS/NOTES
0.0		Zero out Odometer after touring Eureka Stone Quarry
0.1	L	Turn left out of quarry onto Lower State Road
1.0	L	Turn left onto Bristol Road
2.1		Get in Left Lane at PA 202 Intersection
3.3	L	Turn left onto West Butler Avenue
3.9	R	Turn right onto Main Street/PA 152 North
5.6	R	Turn right onto New Galena Road
6.4		**Enter Peace Valley Park for Lunch Stop**
7.0	R	Turn into Park Pavillions 3/4
0.0		Zero out Odometer before leaving Peace Valley Park
0.3	L	Turn left onto Myers Raod
0.8		Continue straight, Myers Road becomes Callowhill Road
2.1	R	Turn right onto Hilltown Pike
2.6	L	Veer left at "Y" to stay on Hiilltown Pike
3.1	R	Keep right to turn onto Blooming Glen Road
		Continue straight, Blooming Glen Road becomes Minsi Trail
4.0	**R**	***Turn right into Blooming Glen Quarry, 901 Minsi Trail, Perkasie, Stop #3***

HARPER'S GEOLOGICAL DICTIONARY



CYCLIC SEDIMENTATION - The process of accumulating sand, silt, and clay eroded from trail surfaces during bike races.

Stop 3: Passaic Formation, Blooming Glen Quarry

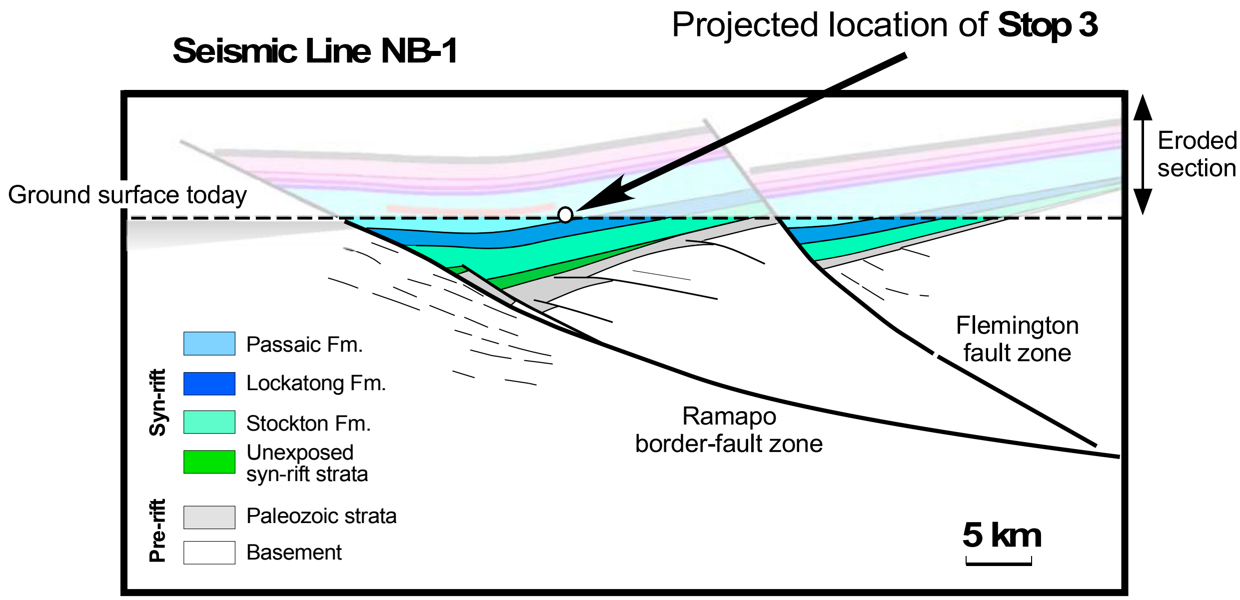


Figure: 3.1: *Cross section of the Newark basin along seismic line NB-1 showing the projected position of Stop 3. Modified from Withjack et al. (2013).*

Location: Lat 40.366371, Long -75.231750; 901 Minsi Trail, Perkasie, PA 18944.

Key Points:

1. Exposures of basal Passaic Formation
2. Deeply buried (~ 5 km) by end of rifting; now exhumed as a result of erosion, tilting, anl faulting
3. Mostly lacustrine depositional environment that accumulated at low latitudes during a time of high pCO_2
4. Orbitally paced cyclical red, gray, and black shales that accumulated in part of ~400 kyr cycle with little variability
5. NE-striking, steeply dipping strike-slip faults with normal and reverse separation
6. NE-striking, vertical fractures

Notes:

Stop 3: Passaic Formation, Blooming Glen Quarry

Red, gray, and black mudstones and sandstones of the basal Passaic Formation (Brunswick Group, undefined of Lyttle and Epstein, 1987) of Late Triassic age are exposed at the Haines & Kibblehouse, Blooming Glen quarry near the center of the Newark basin (Fig. 3.1). The age of the strata exposed here is Norian at 217 – 218 Ma, based on astrochronology (Kent et al.., 2017). The strata accumulated at about 10° N (Kent and Tauxe, 2005) under *p*CO2 concentrations of between 4000 and 5000 ppm (Schaller et al., 2015) and show the cyclicity typical of the lower three quarters of the Passaic Formation. The red mudstones accumulated primarily in playas with periodic purple, gray, and black strata reflecting deposition in progressively more permanent and deeper bodies of water. These cyclical strata are part of basal Member C (see Fig. I.8), which is exposed on the north side of the quarry) (Fig. 3.2). Desiccation cracks, some roots and burrows, and abundant scoop-shaped paleosol slickensides affect the more massive mudstones. Reptile footprints and invertebrate traces occur in the less intensely mudcracked red mudstones. Pinch and swell lamination is prevalent in the black and dark gray shales, indicating deposition above storm wave base. Although some mudstones are dark in color, they have rather low organic-carbon contents (<1%), and they comprise only a small fraction of the section. The organic-carbon content of the remainder of the section is very low, generally close to 0%, even in the gray beds.

The dark colored units high in the quarry wall are traceable for over 75 km laterally into different fault blocks. Correlation with outcrops and the NBCP cores show that even many of the shaley red intervals are traceable laterally over at least 30 km. This kind of lateral continuity is typical of Newark basin lacustrine strata and of lacustrine strata in general. Modern shaded-relief maps show the lateral continuity of bedding form lines produced by differential erosion of the cyclical strata (Fig. I.13 & I.14).

Fourier analysis of this section shows the hierarchy of cycles typical of Milankovitch-type climatic forcing. At this quarry, the mean Van Houten cycle thickness (i.e., the 20,000-year cycle of climatic precession) is 6.4 meters. The thickness of the short-modulating cycle (i.e., the ~100-kyr eccentricity cycle) is about 32 meters, and the thickness of the long-modulating cycle (i.e., the 405-kyr eccentricity cycle) is about 120 meters. This basal part of the Passaic Formation lies in the dry part of a long modulating cycle. Knowing this cyclicity, we can predict that organic-rich black shales will not occur within 40 meters of the ones exposed in the quarry. Those that do occur in the over- and underlying long modulating cycles are probably better developed -- and they are. Although the section exposed in the quarry is predominantly fine grained, beds of fine sandstone exist. Some of these beds have tilted surfaces and an overall geometry suggestive of very small deltas deposited during some of the shallower lake events. The transition from the mostly gray and black strata of Lockatong Formation to the mostly red strata of the Passaic Formation occurs just below the base of the quarry section.

This transition not only involves an upward change in the predominant color from gray to red, but also an upward increase in accumulation rate seen throughout the basin. This change may reflect an increased input of material. Such an increase could be due to the capture of a new drainage system or an increased eolian source. Smoot (2010) argues for the latter and notes that this transition occurs with a change in evaporite mineralogy from sodium salts to calcium sulfates. This evaporite transition could be due to a markedly increased eolian influx from the northeast (i.e., Scotian Shelf, Morocco) by the trade winds, bringing gypsum and clastic dust from evaporite basins in the subtropics receiving marine brines for the first time during continental breakup.

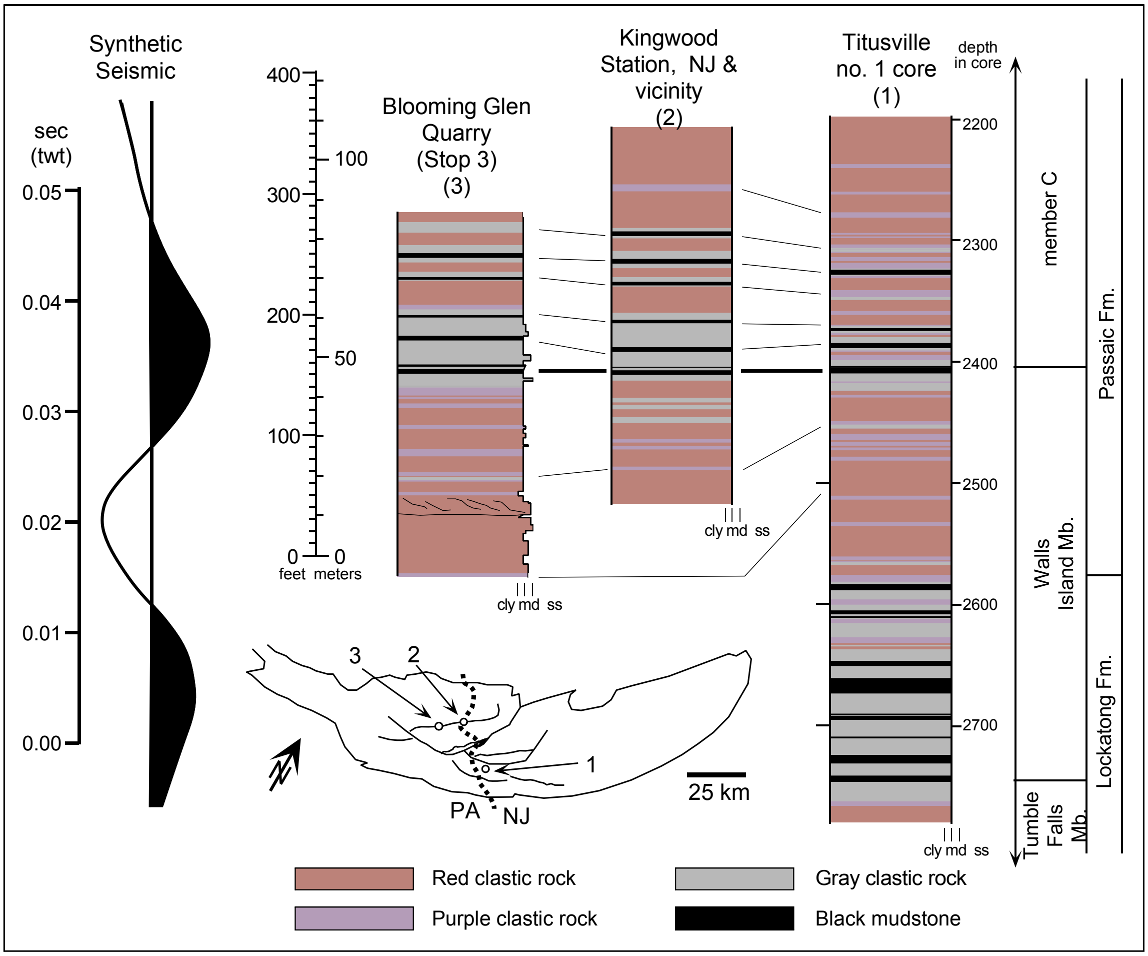


Figure 3.2: *Comparison between section at Stop 3 at the Haines and Kibblehouse Blooming Glen Quarry, outcrops along the Delaware River (Kingwood Station), and the Titusville no. 1 core of the NBCP and a synthetic seismogram derived from the nearby (16 km) Cabot no. 1 well from the correlative part of the section (after Reynolds, 1994).*

The lateral continuity discussed above helps produce the continuous, parallel character typical of lacustrine strata observed on seismic-reflection data. Thus, on seismic character alone, this part of the Passaic Formation might be identified as potential source rock like the underlying Lockatong Formation. It is, however, a very poor source rock. Scale is an important consideration when comparing field observations and geophysical data. Compare the section of the quarry to a synthetic seismogram of the same section from the nearby Cabot #1 well (Reynolds, 1994). The entire quarry is barely the scale of a single wavelet (Figure 3.2)!

Two high-angle, NE-striking faults cut the Passaic Formation in the quarry. One fault has normal separation, whereas the other has reverse separation. These faults appear to have formed late in the history of the Newark basin (i.e., after the deep burial of the Passaic Formation). Slickenlines indicate that they have a significant component of strike-displacement.

Groundwater flow occurs mostly in fractures in the fine-grained facies of Passaic Formation, with most flow occurring along bedding-plane partings, with high-angle fractures funneling flow toward the bedding-plane partings. Flow also occurs through zones of dissolved authigenic sulfates (gypsum and anhydrite) in the deeper subsurface (Michalski, 2010; Serfes et al., 2010). There are few signs of migrated hydrocarbons, but given the large ratio of red to gray and black strata, any hydrocarbons generated by the thin, more-organic rich rocks would be limited. However, the black shales are a potential locus of redox-concentrated metals, notably arsenic and lead (Serfes et al., 2010). The crushed stone produced here is largely used for ornamental purposes.

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Serfes, M., Herman, G., Spayd, S., Reinfelder, J., 2010, Sources, mobilization and transport of arsenic in groundwater in the Passaic and Lockatong Formations of the Newark basin, New Jersey. *Contributions to the Geology and Hydrogeology of the Newark Basin; New Jersey Geological Survey Bulletin 77*, E1-E40.

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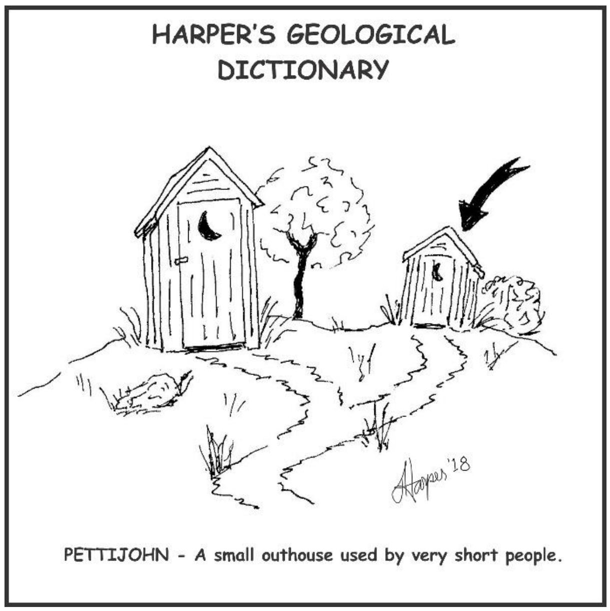
START	TURN	DIRECTIONS/COMMENTS/NOTES
0.0		Zero out Odometer after touring Blooming Glen Quarry
	R	Turn right out of quarry onto Minsi Trail
2.2	L	Turn left onto PA 313 West/Dublin Pike
7.6	R	Veer right onto East Broad Street/PA 313 West
7.9	L	Veer left onto East Broad Street/PA 313 West
9.6	R	Turn right onto PA 309 North
18.0	R	Turn right onto Center Valley Parkway
18.8	**R**	***Turn right to return to hotel, Last Stop for the Day***



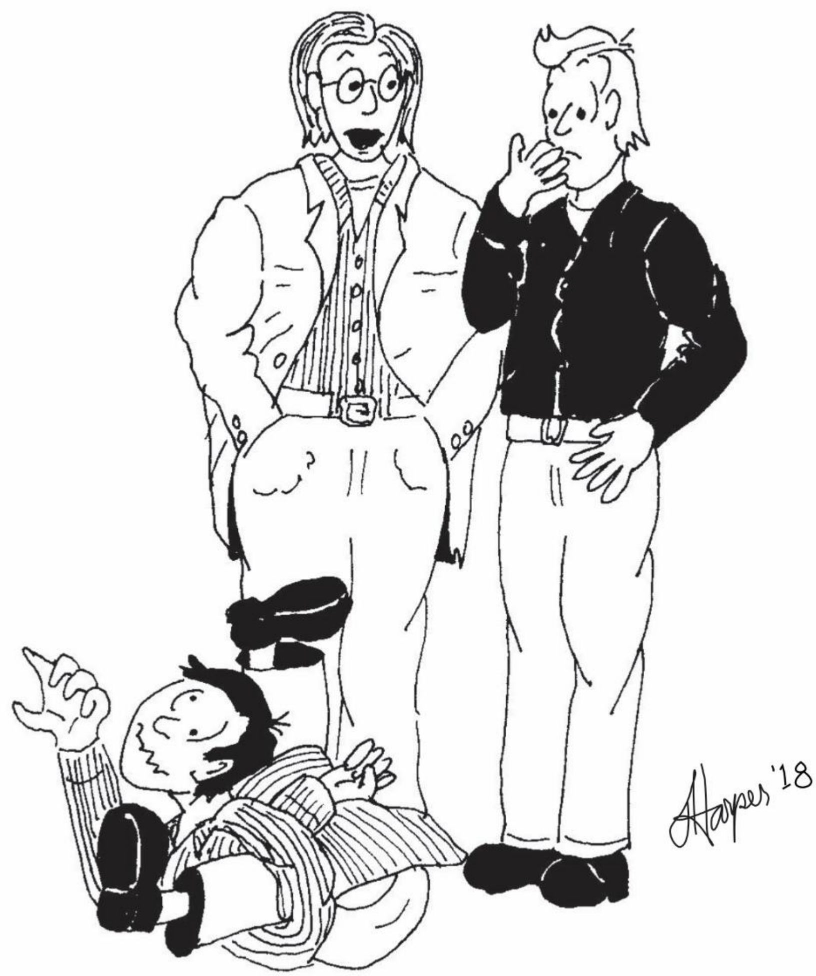
PETTIJOHN - A small outhouse used by very short people.

Homewood Suites Hotel is located at 3350 Center Valley Parkway


Sorry about the delay. I'm here to fix the computers. I hope you folks haven't been waiting too long!

85		**Total Mileage for Day 1, Friday, 5 October 2018**

ROADLOG: Day 2 – Saturday, October 6, 2018

START	TURN	DIRECTIONS/COMMENTS/NOTES
0.0		**Homewood Suites Hotel is located at 3350 Center Valley Parkway** **Cores and Seismic-Reflection Lines from Newark Basin, Stop #4**
		 **He was demonstrating some new karate moves he learned recently, and then there was this ominous "click"!**

Stop 4: Cores and Seismic-Reflection Lines from Newark Basin

Location: Lat 40.550690, Long -75.420517; Homewood Suites by Hilton Allentown Bethlehem Center Valley, 3350 Center Valley Pkwy, Center Valley, PA 18034

Key Points:

1. Seismic lines reveal subsurface geometry of Newark basin including variable dip of border fault (higher in north, lower in south) and saucer-shaped igneous intrusions
2. Seismic-reflection profiles, but not cores, provide large-scale geometry of synrift strata
3. Sedimentary and igneous fabrics in cores show detailed stratigraphic patterns and facies more clearly than outcrops
4. Representative cores of facies and stratigraphy of units seen at field stops and additional synrift units including Jurassic-age strata and CAMP-related lava flows
5. Lacustrine cyclicity is present in all formations except lower three-quarters of Stockton Formation
6. Sediment accumulation rate in syn-CAMP lacustrine strata is five times that of Lockatong and Passaic formations
7. Thermal maturity in syn-CAMP strata is much less than that at field stops and presently in oil window
8. Extremely unusual Pompton (air-fall) ash in Towaco Formation
9. Dead oil staining in Lockatong Formation and live oil in Feltville Formation
10. Various kinds of bedding-plane slip features including early melanges and brittle detachment faults
11. Various authigenic and vein-filling minerals
12. Datable zircon-bearing gabbroids in basalt

Notes:

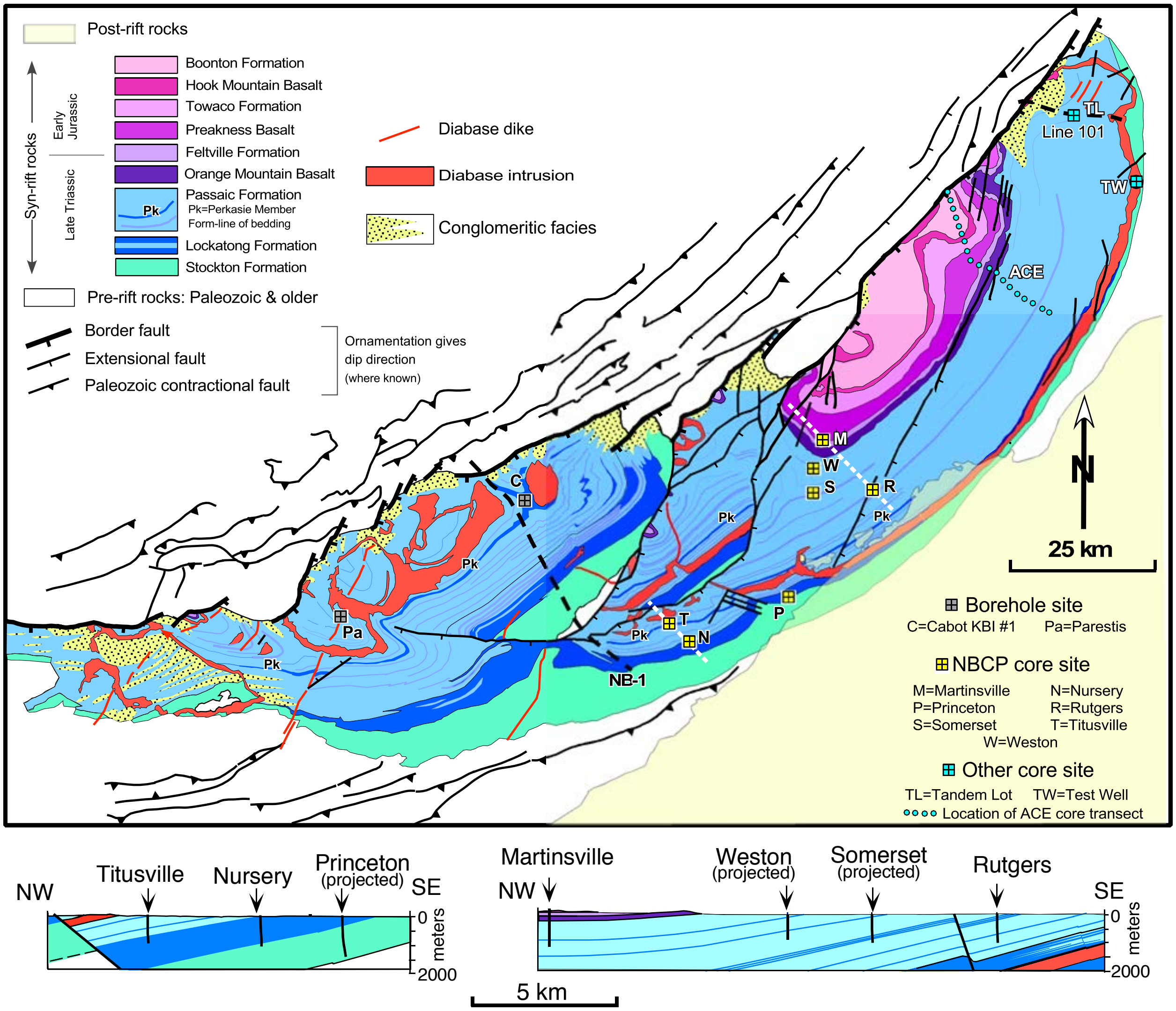


Figure 4.1: *Geologic map of Newark basin showing locations of seismic lines and cores on display. Cross sections show locations and projected locations of coreholes. The stratigraphy in the top of one core overlaps with the stratigraphy at the bottom of the adjacent borehole. This allows the construction of the composite stratigraphic section in Figure 4.2. Modified from Olsen et al. (1996), Withjack et al. (2013), and Olsen et al. (2016).*

Stop 4: Representative Cores of the Newark Basin

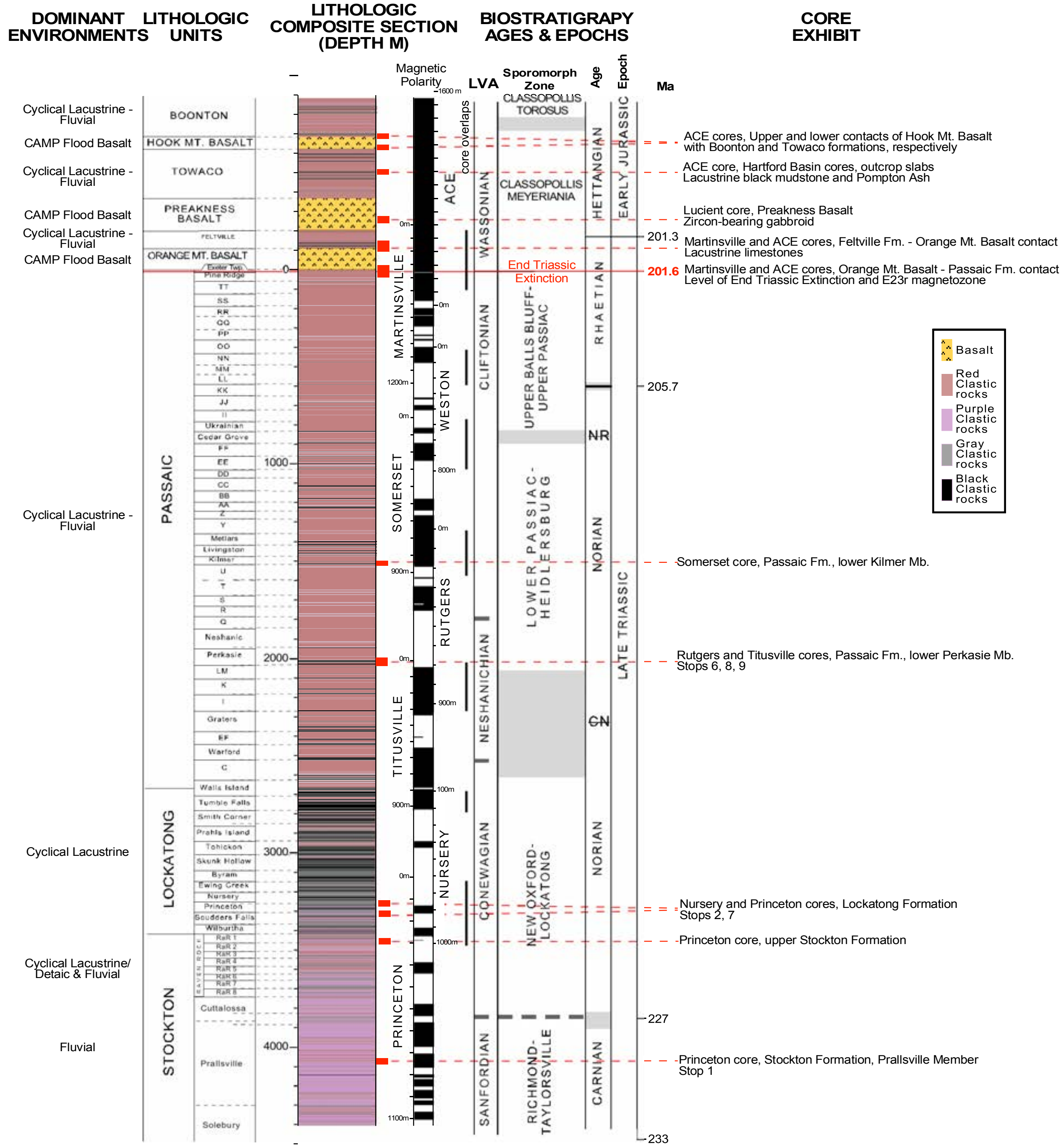


Figure 4.2*: Stratigraphy of the Newark basin. The lithologic column is a composite section based on seven Newark Basin Coring Project (NBCP) cores (see Fig. 4.1 for locations) and several cores from the Army Corps of Engineers (ACE). For the core-based magnetic-polarity stratigraphy (Kent et al., 2017), black represents normal polarity. Based on global correlations, the Triassic-Jurassic boundary is currently placed in the middle Feltville Formation. The geologic ages are based on radiometric dates of the lava flows coupled with Milankovitch cyclo-stratigraphy. Depositional environments are mostly those at the cored locations. Based on Olsen et al. (1996); Whiteside et al. (2007); Kent et al. (2017).*

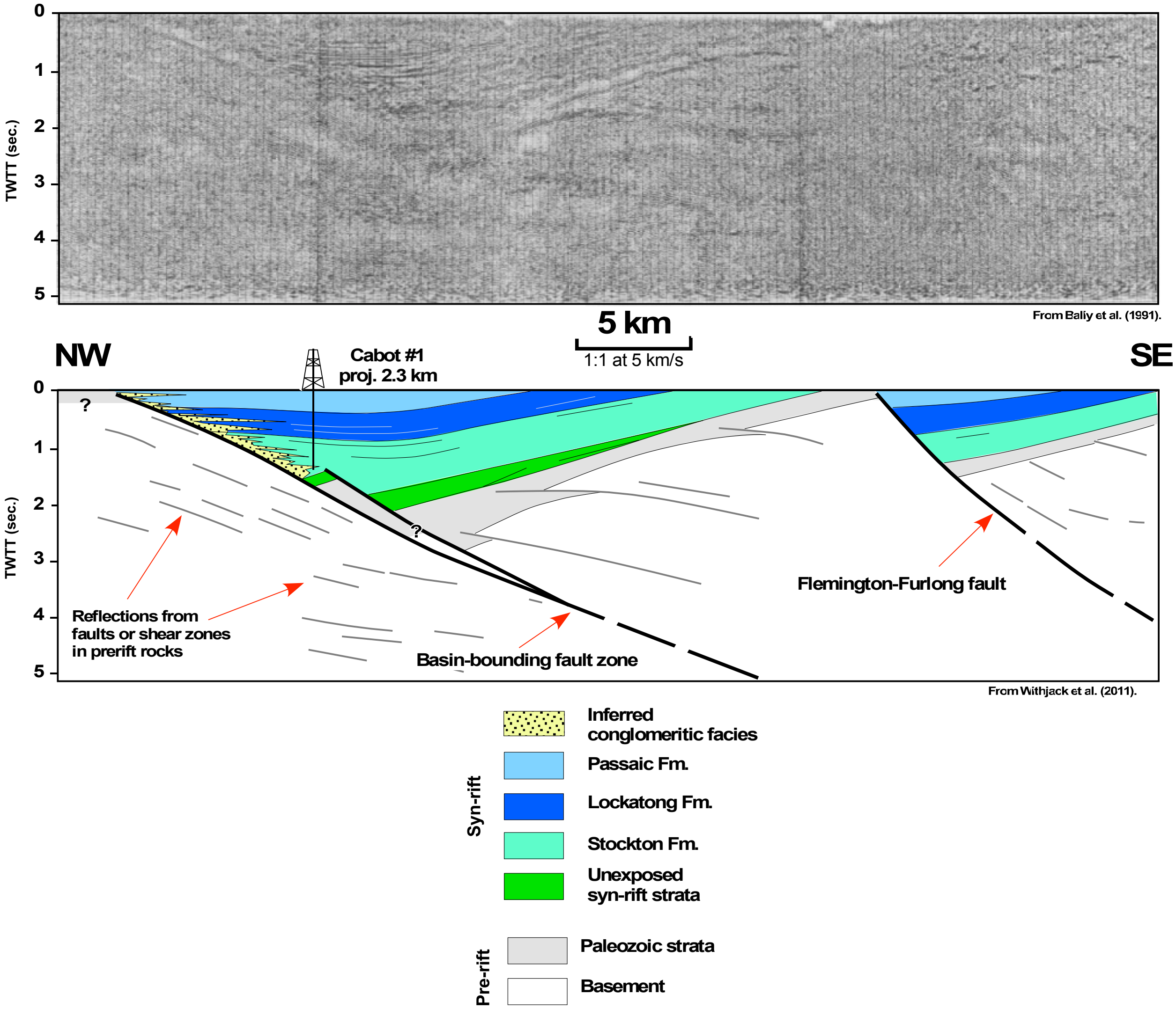


Figure 4.3: *Uninterpreted and interpretation of seismic line NB-1 located in area of field trip. Interpretation utilizes drill-hole data and outcrop data. Modified from Withjack et al. (2013). A large version of this line will be on display at Stop 4.*

The following discussion of seismic line NB-1 is largely from Withjack et al. (2013). The seismic line, acquired and processed by NORPAC Exploration Services in 1983, trends NW-SE across the central part of the basin (Fig. 4.3). The line shown in Figure 4.3, is time-migrated and displayed with no vertical exaggeration assuming a velocity of 5 km s^{-1}, a reasonable average velocity based on seismic-velocity analyses and sonic-log data from the nearby North Central Oil Corporation Cabot KBI No. 1 well (see location in Fig. 4.1) (Reynolds, 1994). Our interpretation of seismic line NB-1 (Fig. 4.3) honors the seismic data and all available surface geology (e.g., location of formation contacts and major faults) and drill-hole data (e.g., Ratcliffe *et al.* 1986; Olsen *et al.* 1996). The seismic line shows that a major SE-dipping fault zone with normal separation bounds the basin on the northwest. The fault zone, characterized by a series of high-amplitude reflections, is relatively planar and dips ~30° to the SE. Using core data (Stop 9), Ratcliffe *et al.* (1986) demonstrated that this fault zone is a mylonitic Paleozoic thrust fault reactivated during rifting. Similar high-amplitude reflections in the footwall of the basin-bounding fault zone are likely associated with Paleozoic thrust faults mapped northwest of the Newark basin, some of which were also reactivated during rifting (Fig. 4.1).

We propose that conglomeratic facies produce the narrow no-record zone in the hanging wall of the basin-bounding fault. Field data show that alluvial-fan conglomerates are present in all sedimentary formations in the hanging walls of the basin-bounding faults of the Newark basin, providing evidence of local footwall relief and syn-depositional faulting (see Stops 9 and 10) (e.g., Arguden & Rudolfo, 1986; Schlische, 1992; Smoot, 2010). The seismic data show that the synrift strata dip ~10° to 15° toward the northwest. Near the basin-bounding fault zone, however, the synrift strata are nearly flat-lying. This change in dip is associated with the transverse anticline (the Ferndale dome) whose axial trace is parallel to the seismic line. The seismic data also confirm that a major SE-dipping intrabasin fault with normal separation (the Flemington/Furlong fault) cuts the syn-rift strata in this part of the Newark basin.

The seismic data suggest that the Stockton Formation (exposed at the surface) and an unexposed older unit (which onlaps Paleozoic pre-rift strata) gradually thicken toward the northwest (i.e., toward the basin-bounding fault zone). The change in bedding dip is ~3° from the top to the bottom of the Stockton Formation. If sediment supply rates were sufficiently high to fill the basin (a reasonable assumption for the dominantly fluvial Stockton Formation; Schlische & Olsen, 1990), then this thickening toward the basin-bounding fault indicates that faulting and deposition were coeval (i.e., the Stockton Formation and underlying unit are growth deposits).

Seismic Line Sandia 101 is one of two high-resolution seismic-reflection profiles acquired in late March and early April, 2011 as part of the TriCarb Consortium for Carbon Sequestration Newark Basin characterization project (Slater et al., 2012; Tymchak et al., 2011; Olsen et al., 2011b; Collins et al., 2014). The following discussion of the dip-parallel line is mainly from Olsen et al. (2016). Source points were spaced at 36.5 m (120-ft) intervals and geophone accelerometers collected data at 3.05 m (10 ft) intervals. The seismic profiles were processed by Conrad Geoscience Corp. (Tymchak et al., 2011) to obtain depth-migrated images of the basin's subsurface geometry (Fig. 4.4). The NYSTA Tandem Lot no. 1 stratigraphic test well, along with the surface data, ground truths the seismic line. The most obvious features on the profile are the pair of strong reflections crossing the basin, making a trough- or scoop-shape (Fig. 4.4). Prior to drilling, these were interpreted as demarcating the Palisade sheet, which proved to be correct. The hole was spudded in middle Passaic Formation. Visible metamorphism and metamorphic minerals (e.g., epidote) were encountered at ~4500 ft. in reddish Passaic Formation. The Palisades sill was encountered at 4992.25 ft and the underlying metamorphosed Lockatong Formation was entered at 6567 ft. The drill hole reached total depth (T.D. = 6881 ft), still in the Lockatong Formation. The border fault is not imaged on the seismic profile, but it projects from the surface to depth to the west of the faint bedding reflections to the west of the Palisade sheet. At depth, strong discordant reflections demarcate basement structures, plausibly Paleozoic thrust sheets incorporating Paleozoic carbonates, as are imaged on other seismic lines across the basin (Fig. 4.3).

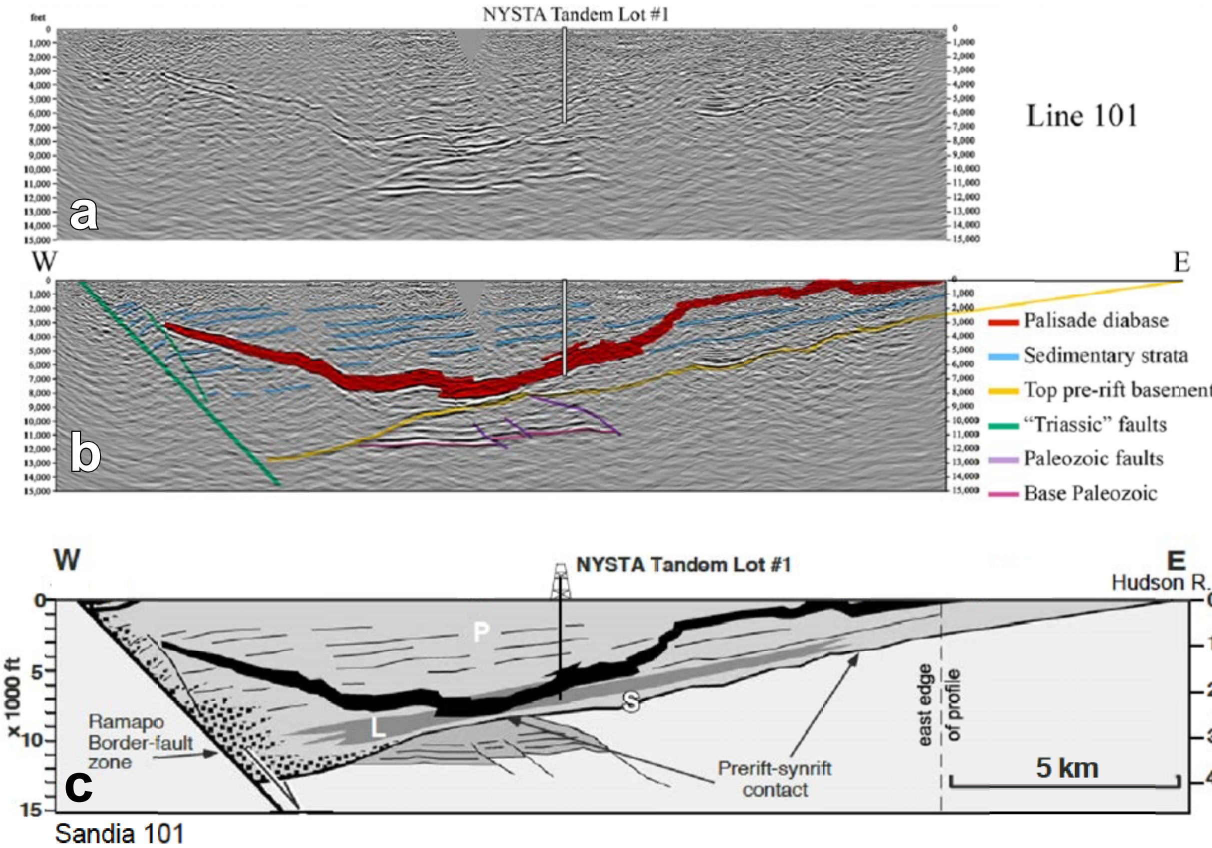


Figure 4.4*: Seismic line Sandia 101. a. Uninterpreted line. b. Interpreted line constrained by surface geology and the NYSTA Tandem Lot #1 well. c. Geologic cross section based on seismic line. S=Stockton Formation; L=Lockatong Formation; P= Passaic Formation. Note that the Palisade diabase is roughly saucer shaped, consisting of both concordant-to-bedding and discordant-to-bedding parts. Modified from Olsen et al. (2016).*

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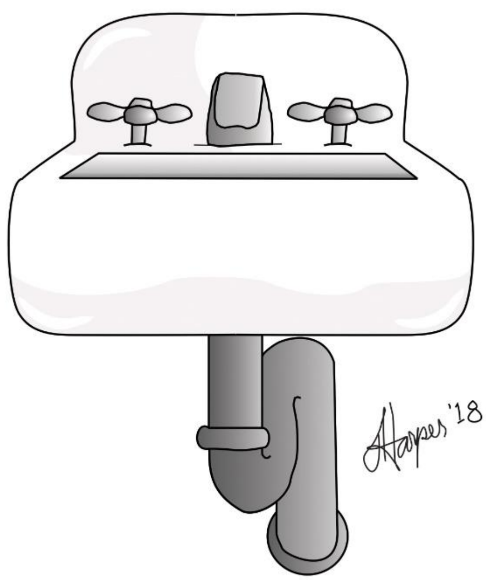
ROADLOG: Day 2 – Saturday, October 6, 2018

START	TURN	DIRECTIONS/COMMENTS/NOTES
0.0		Homewood Suites Hotel is located at 3350 Center Valley Parkway
0.2	L	Turn Left onto Center Valley Parkway
0.9		Use left two lanes to turn left onto PA 309 South
12.3		Take PA 309 South to Sellersville
13.1		Continue onto Bethlehem Pike/PA4013 South
13.4	L	Turn Left onto Weikel Road
		Continue onto East Rockhill Road
		Head southeast onto North Rockhill Road
15.1	**R**	***Turn right into Rockhill Materials Company, 2035 North Rockhill Road, Sellersville, Stop #5***

HARPER'S GEOLOGICAL DICTIONARY



NEWARK BASIN - A type of bathroom sink commonly found in New Jersey's largest city.

Stop 5: Quakertown Diabase Sheet, Rock Hill Quarry

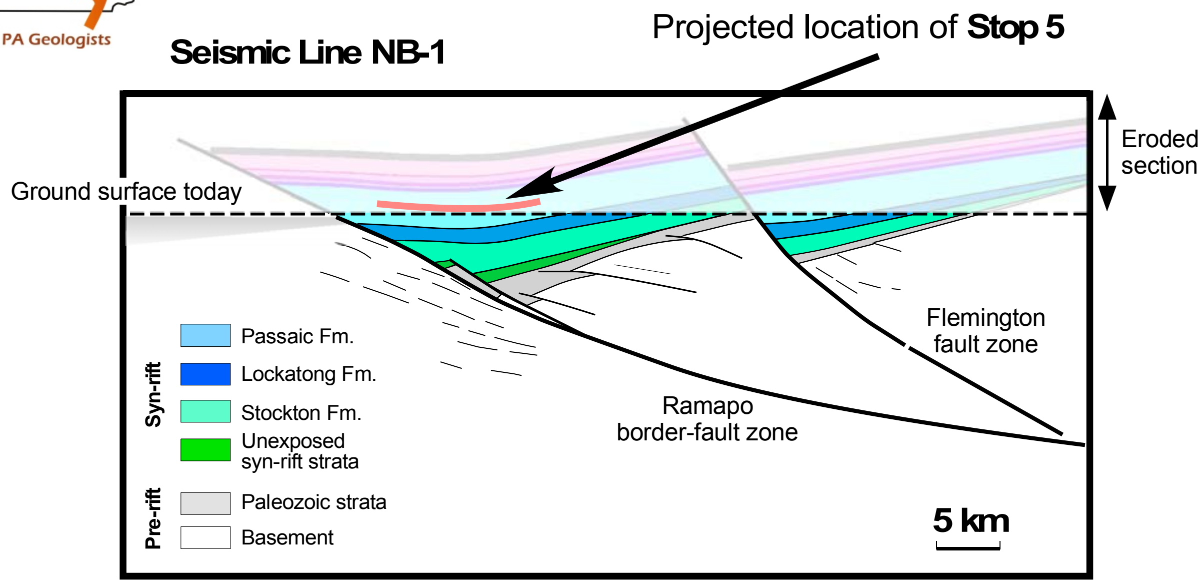


Figure: 5.1: *Cross section of the Newark basin along seismic line NB-1 showing the projected position of Stop 5. Modified from Withjack et al. (2013).*

Location: Lat 40.403892, Long , -75.300636: 2035 North Rockhill Rd., Sellersville, PA 18960.

Key Points:

1. CAMP-related Quakertown diabase intrusion associated with end Triassic mass extinction (201.5 Ma)
2. Intrusion has sheet-like form (i.e., its thickness is much less than its lateral extent); locally conformable to bedding
3. About 500 m thick and interconnected with other CAMP-related sheets and dikes in southwestern part of basin
4. Part of massive intrusive plumbing complex representative of earliest CAMP
5. Intrusion occurred at 4-5 km depth; now exhumed by uplift, tilting, faulting, and folding
6. Prominent flow banding at outcrop scale
7. Thermal contact metamorphism at Stop 6 caused by emplacement of Quakertown sheet

Notes:

Stop 5: Quakertown Diabase Sheet, Rock Hill Quarry

The recently reopened Rock Hill Quarry (Hanson Materials) exposes more than 20 m of the lower quarter of the Quakertown diabase (dolerite) sheet associated with earliest CAMP-related activity. In this area, the sheet is between 457 and 549 meters thick (Bascom et al., 1931). The diabase is mostly light gray and medium- to coarse-grained (especially at its center). Minerals include plagioclase (labradorite), clinopyroxene (augite), amphibole, biotite, magnetite, quartz, and orthoclase. Notably, olivine is absent. The chemistry of the Quakertown sheet on average places it in the High Titanium Quartz Normative (HTQ) group of Eastern North American tholeiites of Weigand and Ragland (1970) (see Fig. I.11) [1.04% TiO_2; 10.20% Fe_2O_3+FeO; 7.30% MgO; 0.85 Th/Hf; and 4.7 Hf/Ta, based on data in Gottfried et al. (1991)]. This is more or less the same group to which the chill zone of the Palisade Sill belongs. The simplest hypothesis relating the chemistry of these units of similar chemistry, based on map view and seismic lines, is that they represent a gigantic complex of interconnected intrusions formed at about the same time, termed the Palisade(s) Megasheet of Husch (1992). Based on zircon CA-ID-TIMS U-Pb dates, the age of the Palisade Sill is 201.520±0.033 Ma (Blackburn et al., 2013), and that date is probably representative of the entire complex, although needs to be further tested (for a different view see Block et al., 2015). Based on recent zircon CA-ID-TIMS U-Pb calibration of marine sections (e.g., Yager et al., 2017) and fixing the base of the Jurassic at a Global Boundary Stratotype Section and Point (GSSP) (Hillebrandt et al., 2013), this is a very latest Triassic date, but one that just postdates the end-Triassic extinction (Blackburn et al., 2013) with other CAMP units being synchronous or slightly predating the extinction (Blackburn et al., 2013; Davies et al., 2017).

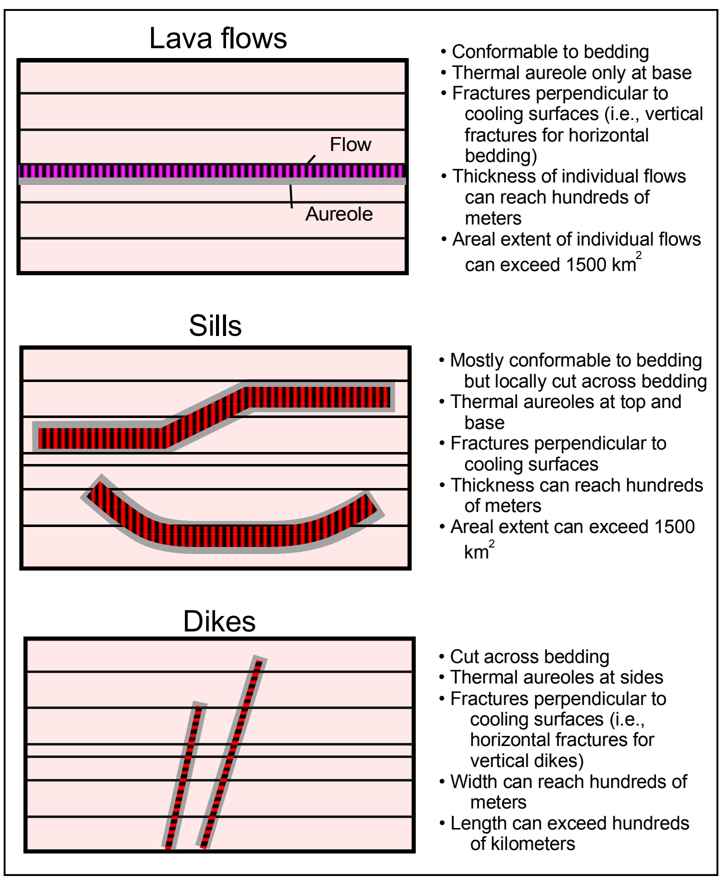


***Figure 5.2**: Characteristics of flows, sills, and dikes.*

Unlike the CAMP-related lava flows seen in cores (Stop 4), the CAMP rocks at this locality lack vesicular zones and its lower and upper contacts are with metamorphic synrift sedimentary strata in the Newark basin (as seen at Stop 6). While the southern edge of the Quakertown sheet is broadly concordant with surrounding strata, the northern extent of the sheet is discordant. Lava flows would be concordant to the strata everywhere. Thus, the Quakertown sheet has the key characteristics of an intrusive sheet rather than a flow (Fig. 5.2). Based on vitrinite-reflectance studies and independent sonic-transit time analyses (Durcanin et al., 2017), the intrusion depth was ~4-5 km, and the metamorphic aureoles are correspondingly thick as seen at Stop 6. Thermal metamorphism of intruded strata, with the release of thermogenic gasses such as CO_2, methane, SO_2, hydrogen halides, has been implicated to the end Triassic mass extinction (e.g., Davies et al., 2017).

The overall geometry of the Quakertown sheet is similar to that of many other diabase sheets in the Newark-Gettysburg-Culpeper rift system and others worldwide (Fig. 5.3). While in map view, the Quakertown sheet resembles a dish-shaped intrusion, like the famous dolerite intrusions of the Karoo basin, southern Africa, it was dish-shaped at the time of intrusion as shown by Hotz (1952) (Fig. 5.4). Unlike the Karoo basin, which is characterized by nearly flat or gently dipping strata, Newark basin strata dip at higher angles and, thus, the map view needs to viewed down-the-plunge. There is considerable variation in the geometry of diabase sheets in the Newark basin. Some such as the Morgantown sheet are not dish-shaped (Srogi et al. 2014, 2017), whereas others such as the Palisades sheet at the northern terminus of the Newark basin have a more dish-like shape (Fig. 5.2).

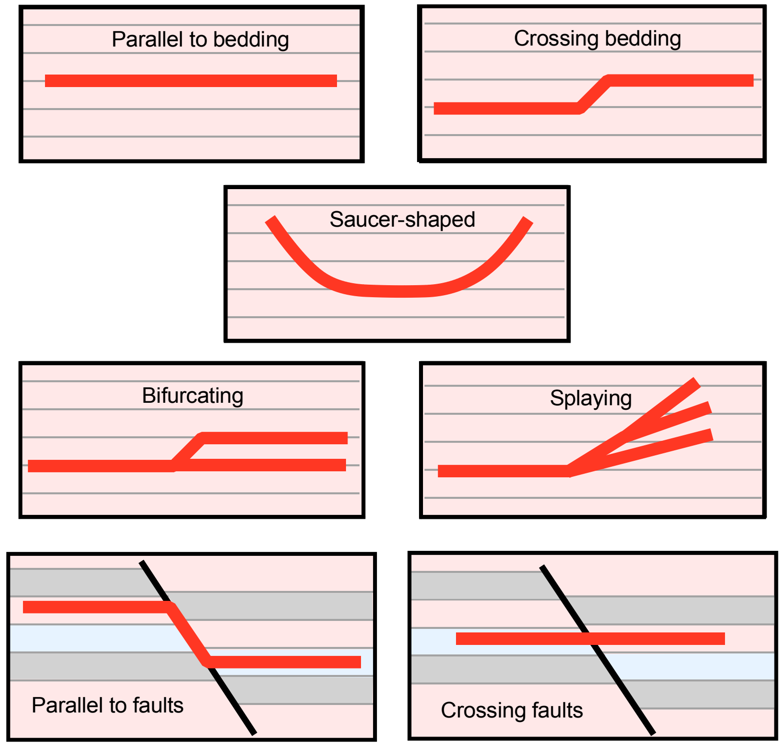


***Figure 5.3**: Geometry of intrusive sheets*

Prominent bedding-like features marked out by white crystals (~orthopyroxene-plagioclase) are visible in many quarried blocks. These are very similar to those described by Srogi et al. (2010, 2014) from the Morgantown sheet (Fig. 5.5). The apparent banding is generally parallel to the paleohorizontal, although we cannot see examples in place at this locality. In the Morgantown sheet, the banding and cross-cutting features suggest paleo-horizonal and paleo-vertical orientations, respectively (Srogi et al., 2014). They have subsequently been tilted toward the NW, like the surrounding synrift strata.

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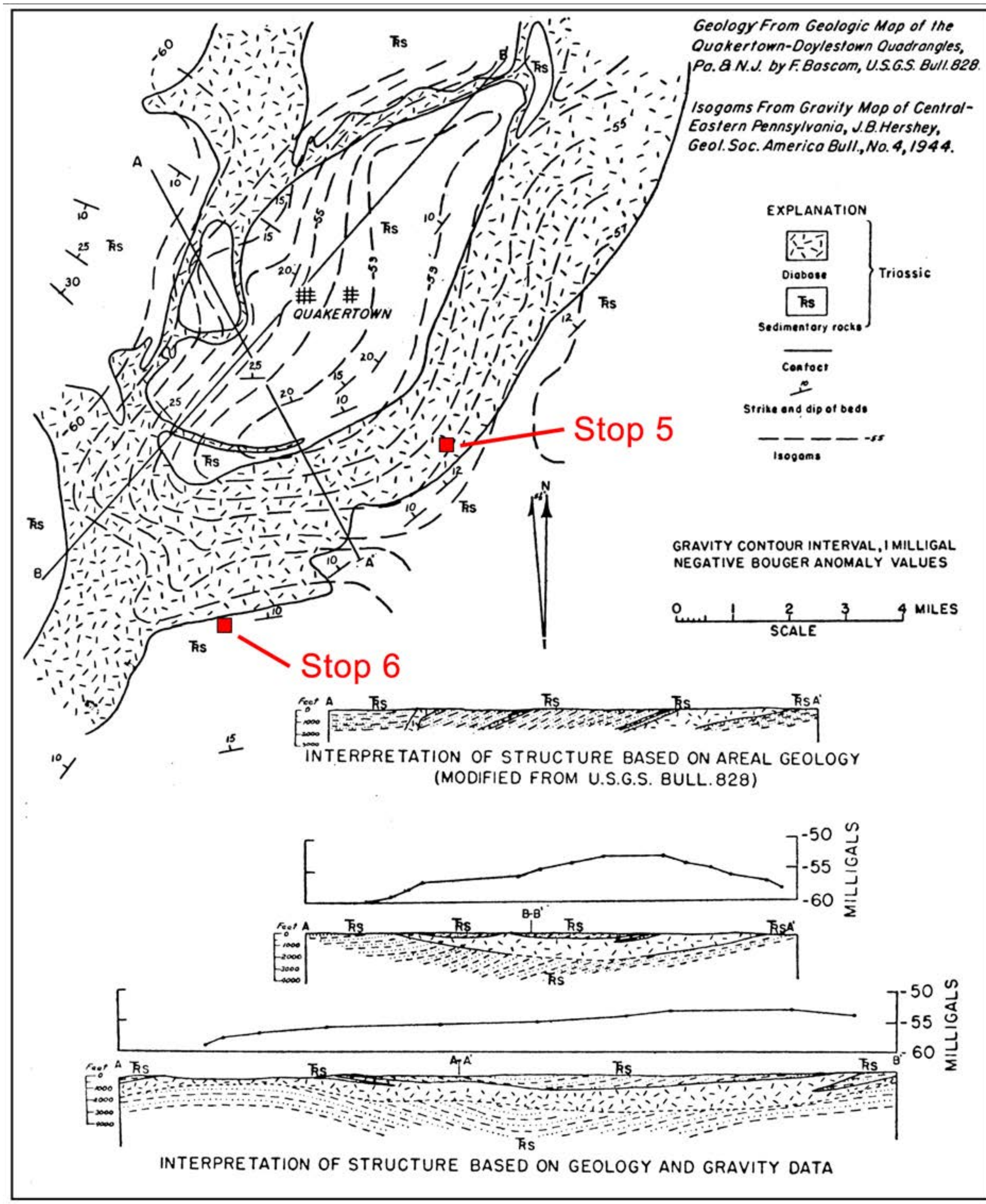

Figure 5.4: *Map and cross sections from Hotz (1952) with locations of this stop (Stop 5) and Stop 6. We have somewhat enlarged the cross sections from the original.*

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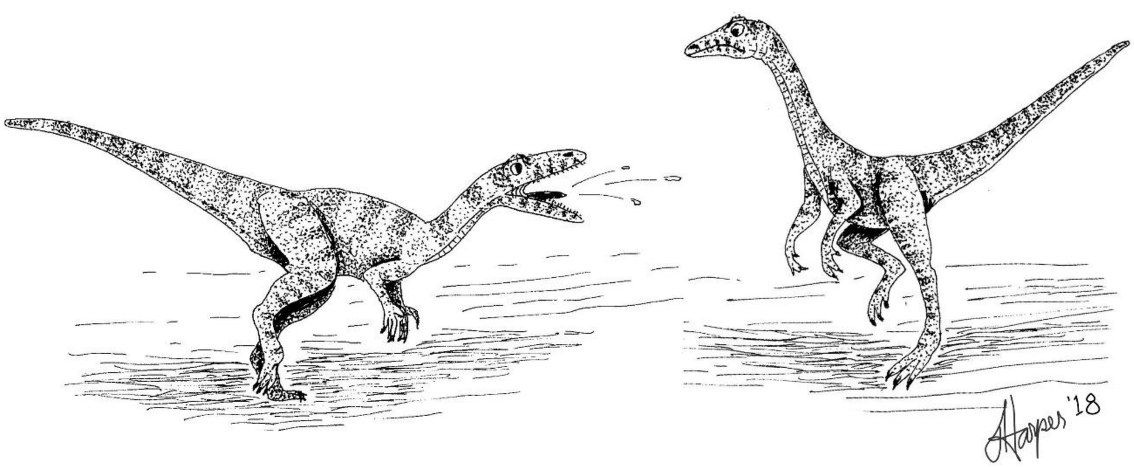
Figure 5.5: *Left, Plagioclase-rich and pyroxene-rich alternations in concave-upward shapes cut by diabase channels in the Pennsylvania Granite Quarry (from Srogi et al., 2014). Right, similar features on a weathered surface in a quarried block from The Rock Hill Quarry (Stop 5). Hammer head is 18 cm across.*

ROADLOG: Day 2 – Saturday, October 6, 2018

START	START	DIRECTIONS/COMMENTS/NOTES
		Zero out Odometer after touring Naceville Materials Company
0.0	L	Turn Left onto North Rockhill Road
1.6	L	Turn Left onto South Old Bethlehem Pike/PA 4052 South
3.3	R	Turn Right onto Ridge Road/PA 563 South
7.2	**R**	***Turn right into Naceville Materials Company, 2001 Ridge Road, Sellersville, Stop #6***
		Doughnut & Coffee Break

HARPER'S GEOLOGICAL DICTIONARY



MESOZOIC RIFT - Trouble in a 210 Ma paradise, when two or more cooperating partners have a falling out over a trivial disagreement.

Stop 6: Passaic Formation Hornfels at Naceville Materials Quarry

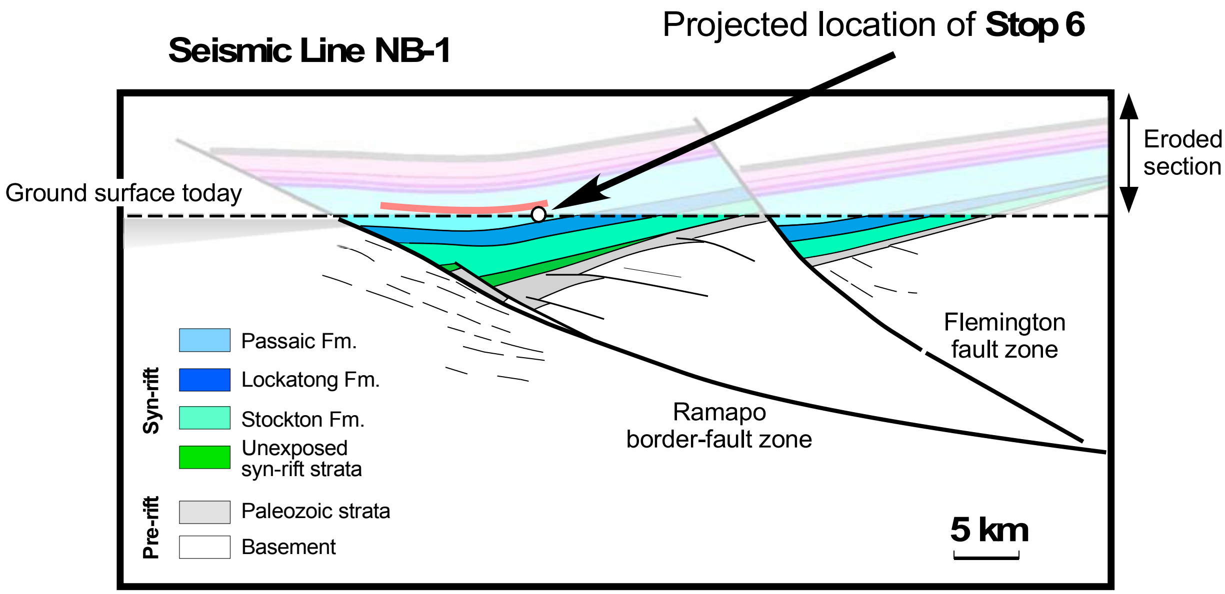


Figure 6.1: *Cross section of the Newark basin along seismic line NB-1 showing the projected position of Stop 6. Modified from Withjack et al. (2013).*

Location: Lat 40.364830, Long-75.335230; 2001 Ridge Rd, Sellersville, PA 18960

Key Points:

1. Passaic Formation of Newark basin
2. Metamorphosed (hornfels) by contact with overlying diabase sheet; dark color related to thermal contact metamorphism not depositional environment
3. Deeply buried (~ 5 km) at time of metamorphism; now exhumed by uplift, tilting, folding, and faulting
4. NE-striking, steeply dipping strike-slip faults
5. NE-striking subvertical joints; high fracture density
6. Epidote, hydrothermal metamorphism

Notes:

Stop 6: Passaic Formation Hornfels at Naceville Materials Quarry

The H&K Group's Naceville Materials Quarry in Sellersville, PA, exposes rocks of the Passaic Formation, stratigraphically in the upper part of the Perkasie Member. The rocks here lack any red color (unlike other known outcrops of the Perkasie Member), and have undergone epidote mineralization (Fig. 6.2). Given these features and the proximity of the quarry to the overlying Quakertown diabase sheet, the strata here have undergone thermal, plausibly hydrothermal, metamorphism. Nonetheless, sedimentary structures (like mudcracks) are still visible. Based on its apparent position within the upper Perkasie Member, the age of these strata is about 214.7 Ma (Kent et al., 2017), while the metamorphism caused by the HTQ CAMP the intrusive event is 201.5 Ma (Blackburn et al., 2013).

The quarry is located about 0.3 km southeast of the lower contact of the Quakertown sheet. Thus, assuming a stratal dip of 10°, the minimum stratigraphic thickness of the thermal contact metamorphic aureole is about 50 m. Thickness of metamorphic aureoles can be substantial (e.g., Raymond and Murchinson, 1991). For the diabase sheet at Coffman Hill exposed in Ringing Rocks County Park, PA, the visible aureole is about 60 m thick.

The rocks in the Naceville Quarry have a high fracture density, with predominantly NE-striking fractures. This is a common feature of hornfelses in the Newark basin including the rocks at the Douglassville Traprock Quarries in Pottstown, PA; Ringing Rocks County Park in Bridgeton, PA; and Dilts Corner, NJ. It is not clear if the high fracture density is related to intrusion-driven hydrofracturing (e.g., Schlische & Olsen, 1988; Olsen et al., 1989), the high rigidity of the hornfels, or both.

Many of the steeply dipping fractures likely originated as joints and were subsequently reactivated as strike-slip faults, based on the horizontal slickenlines on the fracture surfaces.

Figure 6.2: *Epidote-mineralized fractures in rocks from the Naceville Quarry. Photo by R. W. Schlische.*

References

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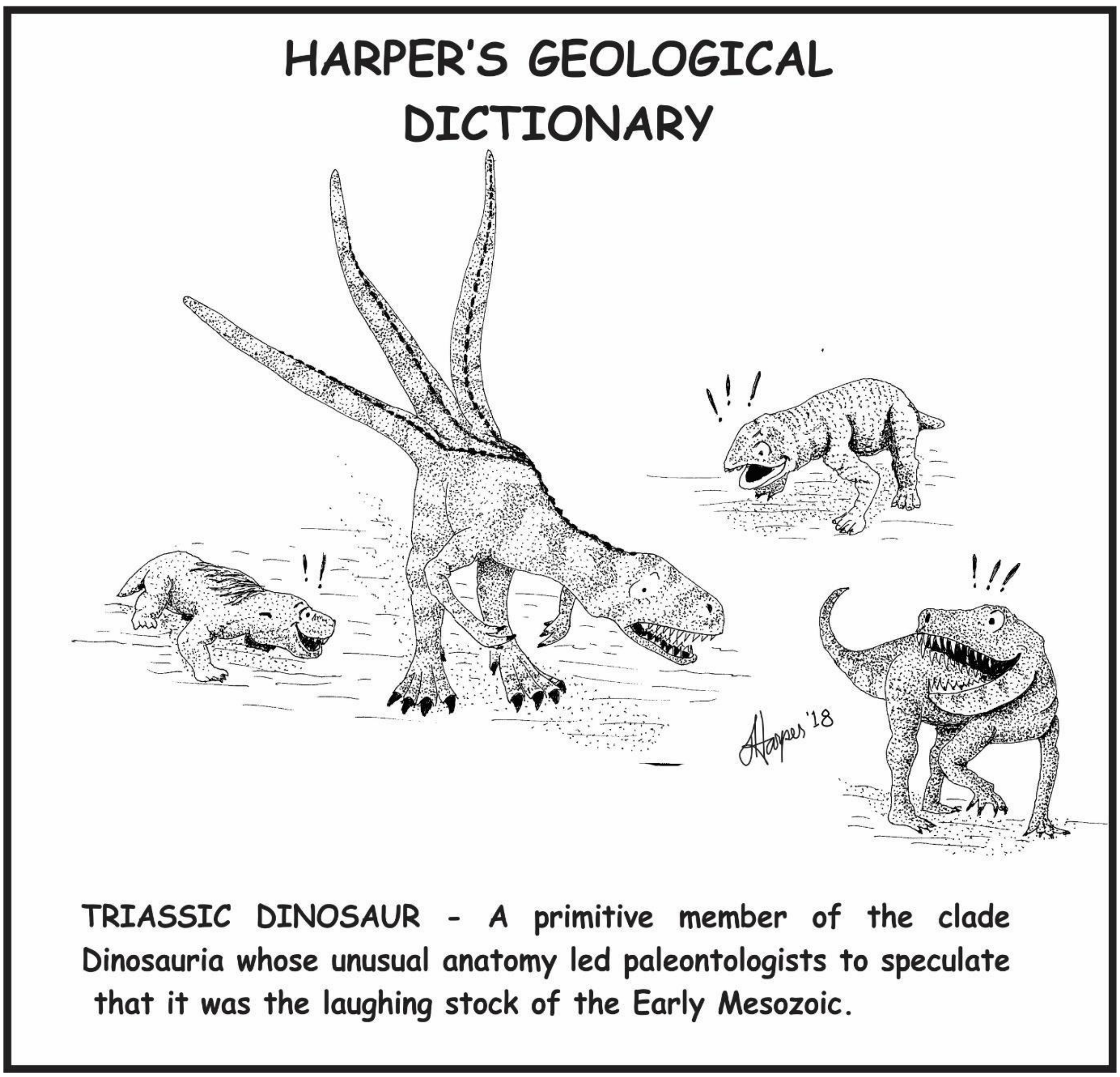
ROADLOG: Day 2 – Saturday, October 6, 2018

START	TURN	DIRECTIONS/COMMENTS/NOTES
		Zero out Odometer after touring Naceville Materials Company
0.0		Turn Left onto Ridge Road/PA 563 North
2.2	R	Turn Right onto Lawn Avenue
2.3	R	Turn Right to merge onto PA 309 South-Lesko Road-Sellersville Bypass
8.0-9.0		Get in Left Lane for upcoming left turn
9.4	L	Turn Left onto Hilltown Pike
		Continue straight, Hilltown Pike becomes Township Line Road
9.8	R	Veer Right to stay on Township Line Road
12.2	R	Turn Right onto Limekiln Pike/PA 152 South
12.5	L	Turn Left onto Skunk Hollow Road
13.4	**L**	***Turn right into H&K Chalfont, 300 Skunk Hollow Road, Chalfont, Stop #7***



TRIASSIC DINOSAUR - A primitive member of the clade Dinosauria whose unusual anatomy led paleontologists to speculate that it was the laughing stock of the Early Mesozoic.

Stop 7: Lockatong Formation at Skunk Hollow Quarry

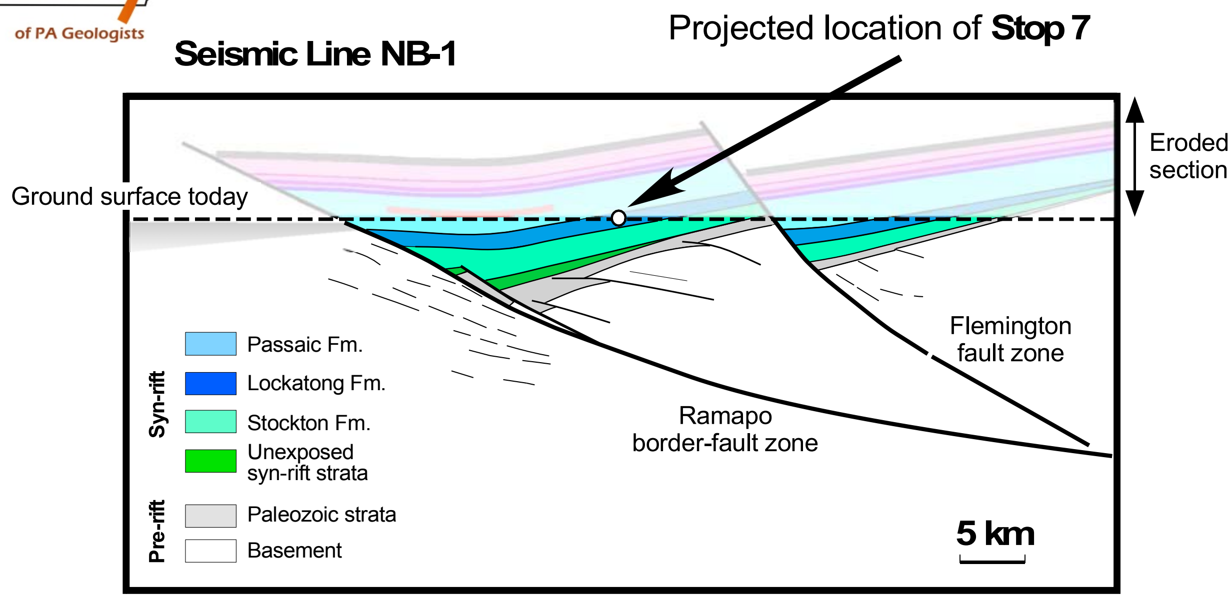


Figure 7.1: *Cross section of the Newark basin along seismic line NB-1 showing the projected position of Stop 7. Modified from Withjack et al. (2013).*

Location: Lat 40.328220, Long -75.226936; 300 Skunk Hollow Rd, Chalfont, PA 18914

Key Points:

1. Lockatong Formation of Newark basin; well exposed example of coarser facies of Triassic lake sequence
2. Once deeply buried (~ 5 km); subsequently exhumed by erosion, tilting, and faulting
3. Cyclical black and red lacustrine mudstone and sandstone
4. NE-striking, steeply dipping fault with wide fault zone and small normal separation; related to large strike-slip component of slip
5. Gilbert-style deltas
6. Fish and reptile fossils and coprolites
7. Microfaults
8. Sedimentary melanges

Notes:

Stop 7: Lockatong Formation at Skunk Hollow Quarry

The H&K Group's Skunk Hollow quarry exposes about 170 m of the middle Lockatong Formation (Fig. 7.2). It is in a basin position relatively close to a sediment source from the SE. Consequently, many of the shallow-water sequences exposed at Stop 7 consist of sandy dipping beds that make up deltas. The section is still strongly cyclical, however, and correlation with the mud-dominated sequences to the north and east is straightforward (Fig. 7.3). The sequence is about 1.5 million years younger than the Lockatong Formation at Stop 3 at 220 Ma (Kent et al., 2017).

At this locality, many cycles have overlying deltaic sands, some with 7-meter-thick foreset beds, overlying dark shales (Fig.7.4A). These sands were deposited as the lakes dried out and the deltas prograded out into the shrinking lake. The foreset height reflects the minimum depth of water during deposition. However, multiple foreset surfaces often have signs of exposure such as root traces showing that the lake rose and fell during the overall regressive phase. The short-modulating cycle (i.e., the 100,000-year eccentricity cycle) is about 30 m thick at Stop 7. This cycle is evident in the quarry walls as the alternation of mostly gray and black intervals with red intervals. The long-modulating cycle (i.e., the 400,000-year eccentricity cycle) is about 110 m thick.

At least two black shales at this stop consist of microlaminated calcareous units with elevated organic contents (+3%). These units preserve complete fossil fish (Fig. 7.4B). The estimated depth of water during deposition exceeds 100 m. The water depth during drying and deposition of the shallow-water deltas was at least 7 m at times. The presence of desiccation cracks, roots, narrow oscillatory ripples, and reptile footprints in many mudstones and sandstones from regressive portions of cycles shows that the lakes did dry out completely every 20,000 years. The lateral equivalents of the shallower-water units further to the north and east are almost entirely mudstones with extremely dense mudcracking, virtually no roots or burrows, and locally abundant pseudomorphs after sulfate evaporates suggesting deposition in evaporative playas, the margins of which are exposed in this quarry. The average water depth for this sequence was, thus, fairly shallow.

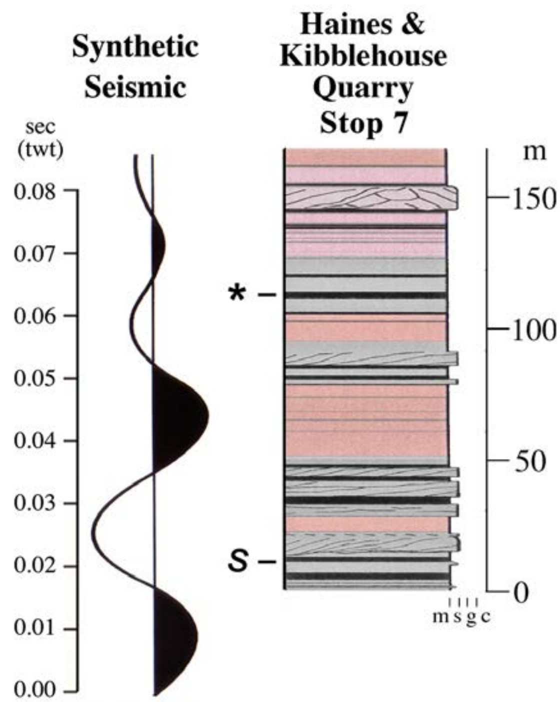


Figure 7.2: *Measured section at Haines and Kibblehouse Skunk Hollow Quarry, Stop 7, compared to a synthetic seismogram derived from the nearby Cabot # 1 well through the correlative section (from Reynolds, 1994). S, Skunk Hollow Fish Bed; * prominent black shale*

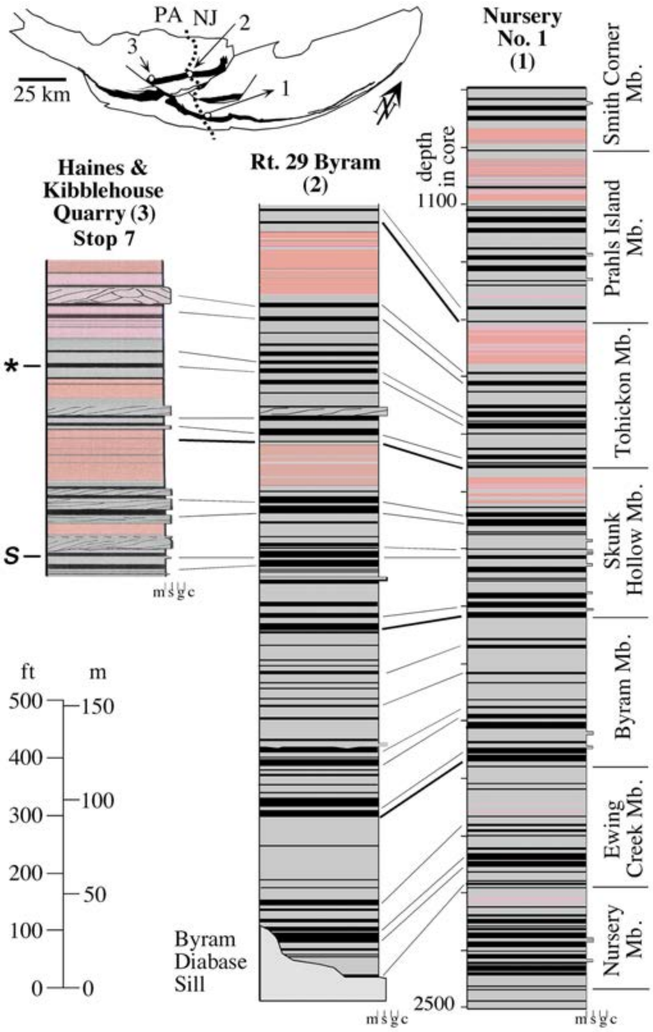


Figure 7.3: *Measured section at Haines and Kibblehouse Skunk Hollow Quarry, Stop 7, compared to finer grained exposure and core. S, Skunk Hollow Fish Bed; *, prominent black shale.*

An abundance of sedimentary and deformational features are displayed at this locality. The most obvious features are the numerous desiccation cracks of various kinds. Both oscillatory and current ripples are abundant as are numerous enigmatic structures that have yet to find an explanation. As at the Eureka Quarry (Stop 2), intra-bedding sedimentary mélange structures (a.k.a. “dead” horses related to bedding-plane shear: Olsen et al., 1989) are also present. (Fig. 7.5).

Fossils are particularly abundant, although not always easy to find. Most common are various trace fossils, such as burrows. But reptile footprints are common as well. Most abundant at this site are the lizard-like *Rynchosauroides* spp., but three-toed tracks of small dinosaurs or near-dinosaurs are present, typically lacking enough anatomical detail for identification. Quadrupedal forms are present, and these probably pertain to the phytosaurian track *Apatopus* and or tracks of stem-crocodile relatives *Chirotherium* and *Brachychrotherium,* but again the lack of anatomical detail precludes certain identification of the track taxon, not to mention the track maker. Nonetheless, the assemblage is as a whole is consistent with that known from the Lockatong Formation and also indistinguishable from that of the lower Passaic Formation as we will see at Stop 9.

Invertebrates are represented by freshwater crustaceans, specifically diminutive rice-grain shaped darwinulid ostracodes, and the larger bivalved spinocaudatans (“conchostracans” or clam-shrimp). The spinocaudatans are especially abundant in the microlaminated beds with fish, which sometimes are so common to make the whole surface appear crenulated (Fig. 7.4B).

Fossil fish are present in some of the units, most notably in the exposure of the Skunk Hollow fish bed exposed (but overgrown) on the south side of the quarry. Thus far, this bed has produced several examples of the primitive bony fish *Turseodus*, which we saw at Stop 2, including a beautiful example shown in Figure 7.4B. Isolated scales of the stem-gar, *Semionotus*, have been found in other less-well laminated dark gray strata in the quarry.

Figure 7.4: *Stop 7: A, tilted surface and wedge-shaped fine sandstones making up Gilbert-type deltas overlying dark gray shale (approximately at the 80 m level in Figure 7.2; B, Articulated fish (Turseodus) (above) and coprolite and partial articulated Turseodus (below) in microlaminated, organic-rich Skunk Hollow Fish Bed (from the level marked "**s**", in Figures 7.2 and 7.3). The surface of the fish-bearing unit is crenulated by the presence of abundant overlapping spinocaudatans (clam shrimp)*

Reptile bones are surprisingly common in the quarry, but usually hard to find. The best conditions for seeing them are when the rock is wet. In red strata, the bone is generally white, while in gray or black strata the bone is black, often weathering to a sky-blue. In sunlight, bones are nearly invisible. Most common are unidentifiable teeth that probably come from the amphibious phytosaurs along with bone fragments also probably phytosaurian in origin. However, one red mudstone interval low in the quarry near the 50 m mark in Figure 7.2 produces disarticulated remains of the tanystropheiid *Tanytrachelos* (Olsen, 1979). *Tanytrachelos* is known from abundant articulated skeletons from microlaminated black mudstones of the Cow Branch Formation of North Carolina and Virginia (Olsen et al., 1978) as well as the Lockatong Formation of the Newark Basin (Olsen, 1980), that are preserved flattened, like the fish are preserved. This little reptile is unusual because there is very strong sexual dimorphism in the pelvic and tail region allowing males and females to be easily distinguished (Olsen et al., 1978). The disarticulated remains from this quarry are unusual in being three-dimensional. While they have yet to be described, these specimens demonstrate that *Tanytrachelos* has a large sternal plate shaped rather like a bird breast bone. Why an aquatic form with rather weak looking and short forelimbs would have such a structure is utterly mysterious.

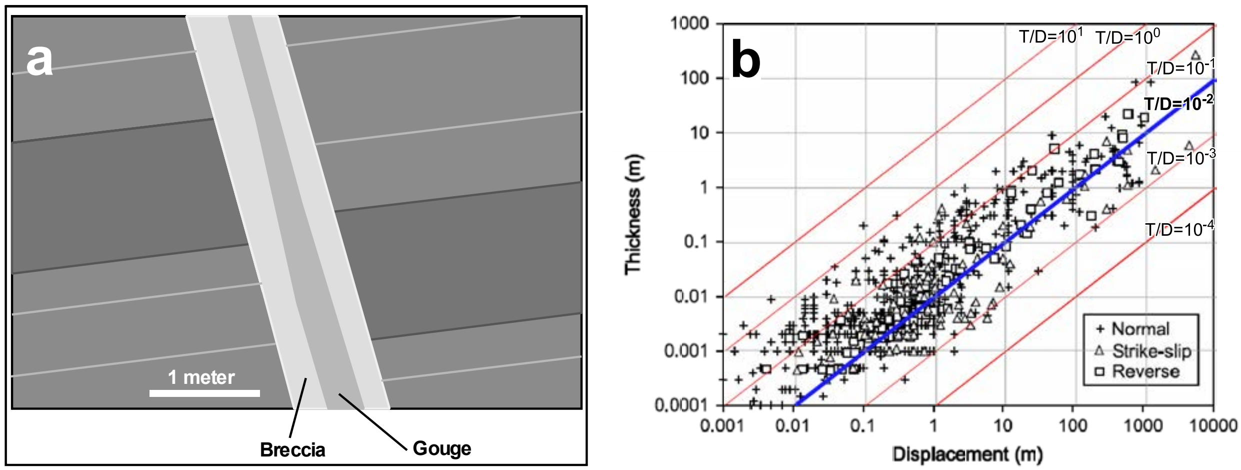
Plant material, apart from root traces, is rare but present. Identified forms include the horsetail Calamites and conifer shoots

Figure 7.5: *Example of intra-bedding mélange from Stop 7. Not clast with laminations diagonal to its boundaries and the fabric of the matrix.*

In terms of relating these outcrops to geophysical data, as at Blooming Glen (Stop 3) the scale of the quarry compared to a seismic line can be deceptive. Figure 7.2 compares the entire measured section of the H&K quarry (left) with a synthetic seismogram from the Cabot #1 well (right). The entire 560-foot (170-meter) section is roughly equivalent to two wavelets on the NB-1 seismic line.

One of the key structural features at Stop 7 is a prominent NE-striking fault zone that cuts across the quarry. The fault zone appears lighter than the adjacent unfaulted rock. The fault zone (see sketch in Fig. 7.6a) is about 1-m thick and has a stratigraphic separation of about 1 m. Its gouge consists of veins of white fibrous material with the texture of cardboard. The empirical scaling relationship between fault displacement (D) and fault-zone thickness (T) indicates that a fault with a fault-zone thickness of T=1 m should have a displacement of D=100 m (assuming T/D is 0.01; blue line in Fig. 7.6b). This predicted displacement value (100 m) is much greater than the observed stratigraphic separation (1 m). Thus, the fault must have a large horizontal component of displacement (i.e., it is a strike-slip fault). In fact, slickenlines from the gouge in the fault zone indicate that the last motion on the fault was predominantly strike-slip. The scaling relationship between fault displacement and fault length (Fig. 7.6c) allows us to predict the length of the fault. For D=100 m, we predict that L=10,000 m or 10 km.

Very small-scale normal faults (Fig. 7.7) are present in some dark gray to black units. These faults have a small amount of footwall uplift and hanging-wall subsidence; the maximum values occur near the center of the faults and decrease toward the tips. In plan view, faults with a preferred orientation superficially resemble ripple marks. In cross section, they produce geometries of loop bedding that resembles boudins. In the Skunk Hollow Quarry, faults have a preferred orientation, striking NE-SW. Similar features also occur in the deep-water lacustrine Cow Branch Formation of the Danville basin, Virginia and North Carolina (see Schlische et al., 1996; Ackermann & Schlische, 1997; and Ackermann et al., 2003).



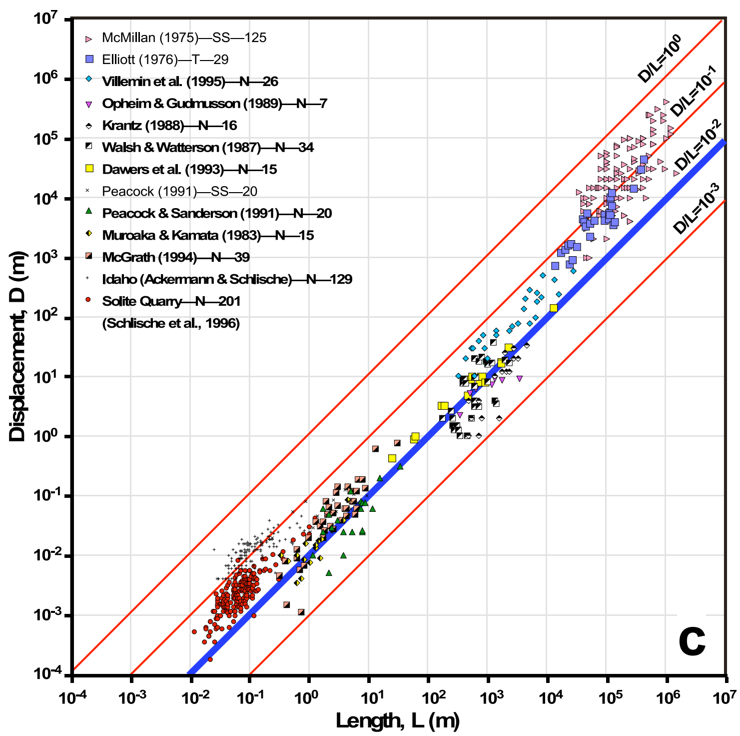


***Figure 7.6**: a) Sketch of fault zone in H&K Skunk Hollow Quarry, Newark basin, PA. The fault zone is about 1 m wide and has an apparent offset of ~ 1 m. b) Log-log plot of fault rock thickness (T) versus displacement (D). The T/D ratio for most faults is between 0.1 and 0.001. Modified from Childs et al. (2009). c) Log-log plot of fault length (L) versus displacement (D). The D/L ratio for most faults is 0.1 to 0.01. Modified from Schlische et al. (1996).*

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Figure 7.7*: Photo of bedding surface from Skunk Hollow Quarry cut by microfaults with normal displacement. The faults strike NNE-SSW. Photo by P.E. Olsen.*

Kent, D.V., Olsen, P.E., Muttoni, G., 2017. Astrochronostratigraphic polarity time scale (APTS) for the Late Triassic and Early Jurassic from continental sediments and correlation with standard marine stages. *Earth-science reviews*, *166*, pp.153-180.

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ROADLOG: Day 2 – Saturday, October 6, 2018

START	TURN	DIRECTIONS/COMMENTS/NOTES
		Zero out Odometer after touring H&K Chalfont Quarry
0.0	L	Turn Left out of Quarry onto Skunk Hollow Road
0.4	R	Turn Right onto Callowhill Road
0.8	L	Go Straight at Stop Sign, Road becomes Myers Road
1.4	R	Turn Right onto New Galena Road
1.6	**L**	**Enter Peace Valley Park for Lunch Stop**
1.9		Turn into Park Pavillions 3/4
		Zero out Odometer before leaving Peace Valley Park
0.0		Head South on New Galena Road
0.7	L	Turn Left onto Callowhill Road
1.5	L	Turn Left onto Ferry Road/PA 1006 East
6.4	L	Turn Left onto Silo Hill Road
6.7	R	Turn Right onto Easton Road/PA 611 North
16.7	R	Turn Right onto Quarry Road
17	**R**	***Turn Right into Lehigh Hanson Quarry, 262 Quarry Road, Ottsville, Stop #8***

Stop 8: Perkasie Member of Passaic Formation at Ottsville, PA

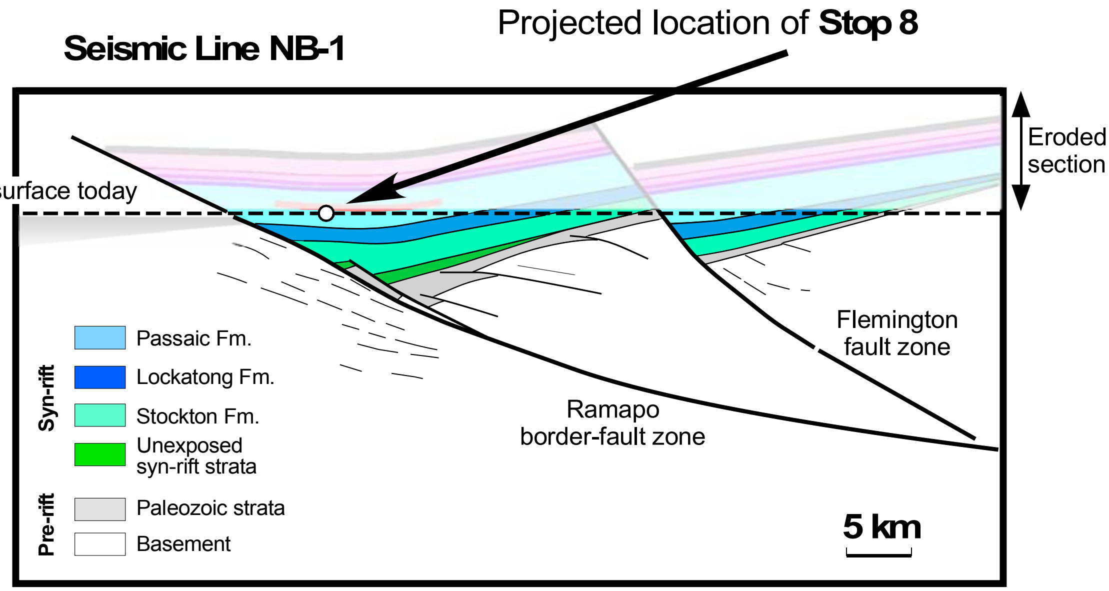

Figure: 8.1: *Cross section of the Newark basin along seismic line NB-1 showing the projected position of Stop 8. Modified from Withjack et al. (2013).*

Location: Lat 40.495010, Long -75.168159, -75.231750; 262 Quarry Rd, Ottsville, PA 18942

Key Points:

1. Exposures of lower-middle Passaic Formation
2. Deeply buried (~ 5 km) by end of rifting; now exhumed as a result of erosion, tilting, folding and faulting
3. Mostly lacustrine depositional environment; resembles Lockatong Formation because of massive expansion of grey units
4. Orbitally-paced cyclical red, gray, and black shales that accumulated at low latitudes during a time of high pCO_2
5. Overall, much finer-grained facies than at Stops 9 and 10 which are closer to the border-fault system

Notes:

Stop 8: Perkasie Member of Passaic Formation at Ottsville, PA

The Lehigh-Hanson Ottsville quarry on the west side of Rapp Brook exposes the Perkasie Member of the Passaic Formation. Stop 8 is located about 10 km south of the border-fault system of the basin, compared to the exposures at Milford (Stop 9) which are adjacent to the border-fault system. At Stop 8, the facies of the Passaic Formation is fine grained with extensive development of gray massive mudstones compared to the coarse grained facies at Stop 9. Crushed stone from the enhanced thickness of the gray strata of the Perkasie Member is the only current economic use of this unit.

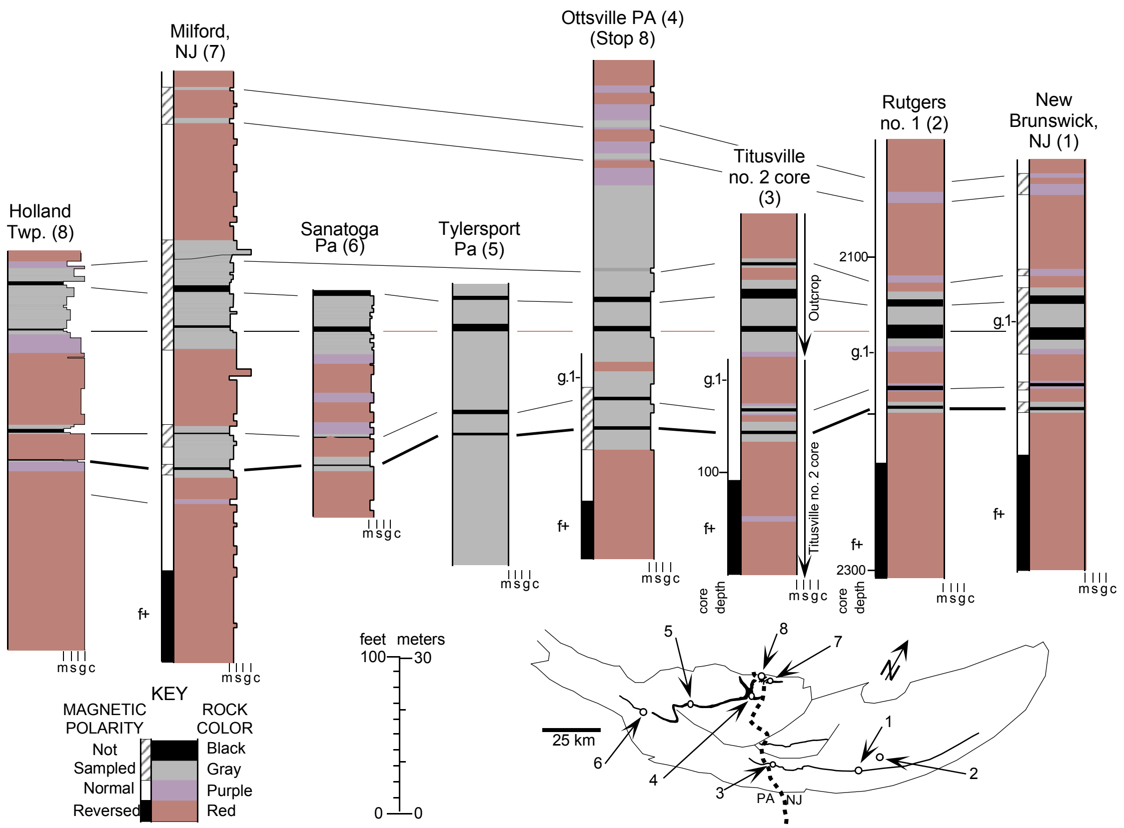

Figure 8.2: Basin-wide comparison of lower Perkasie Member and the upper part of member L-M. Section 4 is for Stop 8. Inset map shows locations of measured sections or drill sites. Paleomagnetic data for Stop 8 were recoded along the road cut adjacent to the quarry on Rt. 611, 2 km to the south, southeast (collected by W. K. Witte). From Olsen et al. (1996).

Deposited at about 12° N latitude (Kent and Tauxe, 2005) at 214.8 Ma (Tauxe and Kent, 2005; Kent et al., 2017), two prominent black siltstone-bearing cycles are exposed within the quarry. The high stand of these cycles shows intense bioturbation, pinch-and-swell lamination, and thin graded silt beds which are probably distal turbidites. The transgression phase of the lower cycle bears poorly-preserved dinosaur footprints. Other than the bioturbation and tracks, no fossils have been found at this locality as typical of the finer-grained intervals of the Passaic Formation. Fossils of all forms are much more common in the coarser-grained facies of the Passaic Formation.

The trend towards more abundant fossils in coarser facies is likely related to a higher short-term variance in sedimentation rates at the margins of the basin compared to the center, with intervals of rapid sedimentation resulting in a higher preservation potential in the marginal facies as the nutrient- and/or energy-rich tissue is buried beyond the reach of fast metabolizing ecosystems. In the Lockatong and Passaic formations in the more central parts of the basin, most sedimentation was by suspension, and the range in sedimentation rates was probably restricted, providing ample time for biological and chemical destruction of most organic and osseous material and even ichnofossils. In contrast, at the basin margins, even suspension deposition was probably more variable, dominating by other forms of deposition with much higher short-term rates of sedimentation. Biological remains might thus have been buried and protected more often and more quickly, even though the frequency of sedimentation events might be lower on the basin margins than in the center. A contributing effect, especially to the poor preservation of pollen and spores in the more central areas, might be the presence of corrosive interstitial alkali fluids, whereas the pore fluids near the basin margins might be buffered by spring water. We consider it less likely that the lack of fossils in the central basin facies reflects a lack of organisms.

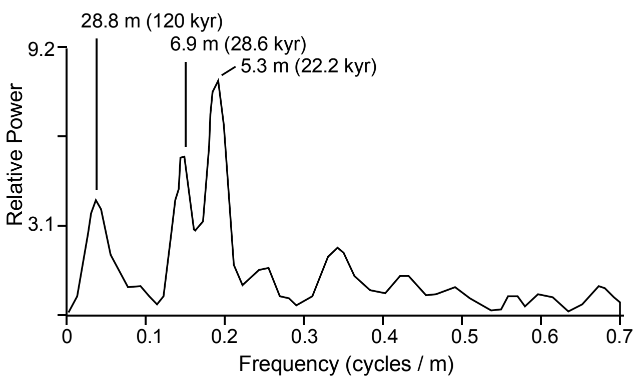

Figure 8.3: *Blackman-Tukey power spectrum of depth ranks from Ottsville, Stop 8 (from Olsen, 1986).*

The Perkasie Member consists of strata that exhibit Van Houten cycles and compound cycles showing the same pattern as the Lockatong Formation. It consists of two sequential ~100,000-year cycles, each containing two well-developed Van Houten cycles and one weakly developed red and purple Van Houten cycle, succeeded upwards by mostly red clastics that underlie the Coffman Hill diabase. The presence of these red strata at a higher stratigraphic level, closer to the diabase shows that the gray color is not due to metamorphism as at Stop 6. As with the Eureka exposures of the Lockatong Formation (Stop 2), these were some of the first strata to be examined using Fourier analysis (Olsen, 1986) (Fig. 8.3). The thickness of the ~20 kyr cycles averages 6.1 m and the ~100 ky cycle averages 28.8 m, showing the average 1:5 ratio of precession to short eccentricity.

Once thought to be the amongst the youngest strata in the basin, it is now clear that the Perkasie Member actually lies in the lower Passaic Formation far below the top of the formation. All of the overlying synrift strata (>5 km) have been eroded in this area (Fig. 8.1). Correlation of the strata in the Ottsville area with that in other fault blocks of the Newark basin where these younger beds are still preserved is afforded by magnetostratigraphy, lithological matching, and a palynological correlation web (Olsen et al., 1996).

References:

Kent, D.V., Olsen, P.E. and Muttoni, G., 2017. Astrochronostratigraphic polarity time scale (APTS) for the Late Triassic and Early Jurassic from continental sediments and correlation with standard marine stages. *Earth-science reviews*, *166*, pp.153-180.

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ROADLOG: Day 2 – Saturday, October 6, 2018

START	TURN	DIRECTIONS/COMMENTS/NOTES
		Zero out Odometer before leaving Lehigh Hanson Quarry
0.0	L	Turn Left out of Quarry onto Quarry Road
0.3	R	Turn Right onto Easton/Durham Road/PA 611 North
2.1		Continue Straight at "T" onto Marienstein Road/PA 1017
2.4	L	Turn Left to stay on Marienstein Road/PA 1017
4.5		**Note Diabase Boulders**
5.8		Marienstein Road becomes Bridgeton Hill Road
6.2		One Lane Narrow Bridge
6.8		View of New Jersey to East
7.6	R	Turn Right onto River Road/PA 32 South
7.8	L	Turn Left onto Upper Black Eddy-Milford Bridge
		Cross over Delaware River onto Bridge Street in Milford, NJ
8.1	L	Turn Left onto Church Street
8.2	R	Turn Right onto Spring Garden Street-River Road-Riegelsville Milford Road
8.4		Note Narrow Road Sign
8.9		**Pebble Bluffs Outcrop begins**
9.0		**Drop off, Approximate location, Traffic Control needed, loop and return**
		Pebble Bluffs Outcrop, Stop #9A

ROADLOG: Day 2 – Saturday, October 6, 2018

START	TURN	DIRECTIONS/COMMENTS/NOTES
		Loop for Buses, Alternate #1
12.3	R	Turn Right onto Phillips Road
15.3	R	Turn Right onto Church Road
15.5	R	Turn Right onto Spring Garden Street
17.2	R	Turn Right onto Spring Garden Street-River Road-Riegelsville Milford Road
17.4		Note Narrow Road Sign
17.9		**Pebble Bluffs Outcrop begins**
		Pick up, Approximate location, Traffic Control needed
		Loop for Buses, Alternate #2
12.3	R	Turn Right onto Phillips Road
15.3	R	Turn Right onto Church Road
18.9	R	Turn Right onto Milford Warren Glen Road
		Milford Warren Glen Road becomes Water Street
	R	Turn Right onto Bridge Street
	L	Turn Left onto Church Street
	R	Turn Right onto Spring Garden Street
	R	Turn Right onto Spring Garden Street-River Road-Riegelsville Milford Road
		Note Narrow Road Sign
		Pebble Bluffs Outcrop begins
		Pick up, Approximate location, Traffic Control needed
		Zero out Odometer before leaving Pebble Bluffs
0.0		Continue North onto Spring Garden Road
11.6	R	Right onto Phillips Road
		Approximate location, Traffic Control needed, Buses drop off people, loop or stay TBD
12.3		***Phillips Road Outcrop Stop #9B***

Stop 9: Perkasie Member of Passaic Formation at Pebble Bluff

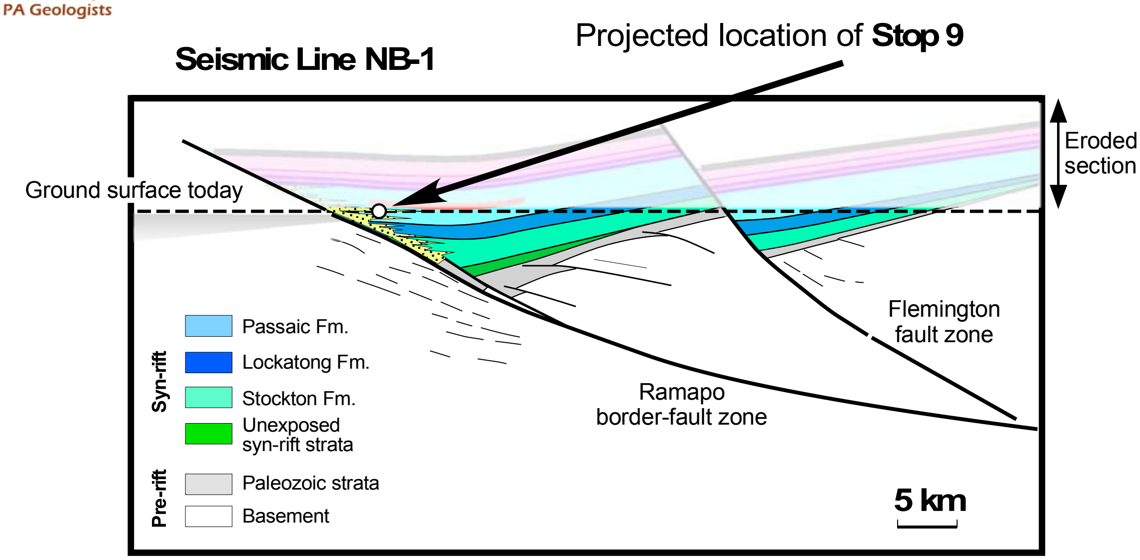


Figure 9.1: *Cross section of the Newark basin along seismic line NB-1 showing the projected position of Stop 9. Modified from Withjack et al. (2013).*

Location: Lat 40.575814, Long -75.129850: 100-132 Riegelsville Milford Rd., Milford, NJ 08848

Key Points:

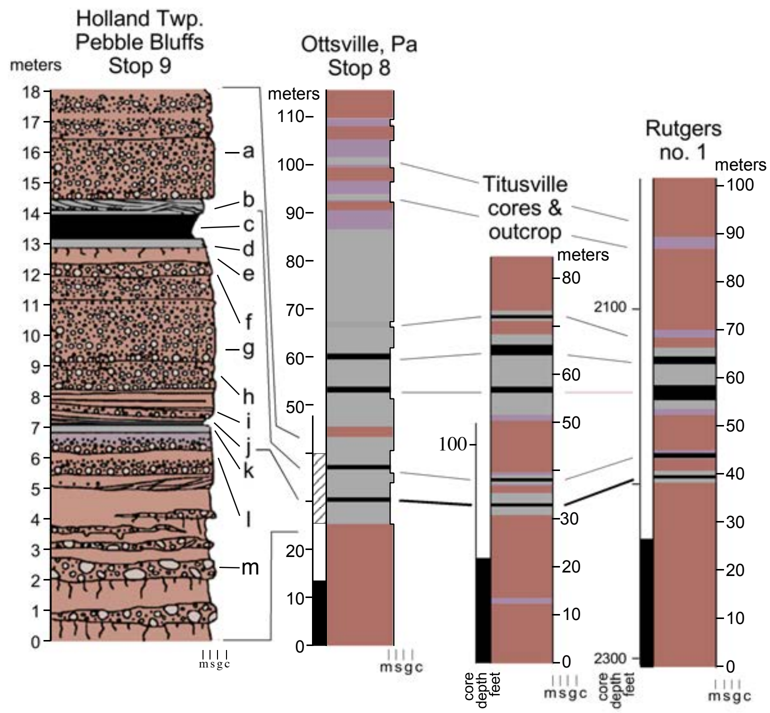
1. Exposures of basin-margin facies of Perkasie Member of Passaic Formation; excellent outcrops of faulted margin conglomerates and interbedded lacustrine units
2. Deeply buried (> 4 km) by end of rifting; now exhumed by uplift, tilting, folding, and faulting
3. Lithologies include black shale, gray sandstone, red sandstone and conglomerate
4. Caliche
5. Depositional environments include perennial lacustrine, marginal lacustrine, fluvial, and debris-flow
6. Footprints
7. Provide constraints on unroofing history of footwall

Notes:

Stop 9: Perkasie Member at Pebble Bluff

By Paul Olsen, Martha Withjack, and Roy Schlische

These outcrops, also described by Van Houten (1969, 1980), Arguden & Rodolpho (1986) and Olsen et al. (1989), are less than 2.4 km to the SE of the border fault and consist of thick sequences (>20 m) of red conglomerate and sandstone alternating with cyclical black, gray, and red mudstone and sandstone. Dips average 10-15° NW; several faults, downthrown to the east, are present between the largest outcrops.



Abbreviations*: a, poorly-sorted conglomerate (fluvial); b, well-sorted sandstone with tilted surfaces (wave & current–re-worked) delta and shoreline sequence with berm; c, lam-inated claystone & siltstone (perennial lake sequence); d, well-sorted sandstone & gravel (wave–reworked) shoreline; e, well–sorted sandstone with carbonate nodules (stream & wave reworking and soil formation & caliche); f, well-sorted conglomerate (fluvial); g, poorly-sorted conglomerate (debris flows?); h, well-sorted conglom-erate (fluvial); i, sandstone & conglomerate making up tilted surfaces with wave & current reworked sandstone and gravel (beach and deltas); j, siltstone and claystone (perennial lake sequence); k, well-sorted sand-stone & gravel (wave-reworked - beach); l, gravel & conglomerate (wave-reworked beach); m, poorly-sorted beds of conglom-erate and sandstone with nodular concretions (debris & mud-flows with soil formation & caliche).*

Figure 9.2*: Measured section of part of the Perkasie Member at Holland Township and detailed measured section at Pebble Bluff (Stop 9). Modified from Olsen et al. (1989) and Olsen et al. (1996).*

Conglomerates at Pebble Bluff occur in three basic styles (see Fig. 9.2)

1) Poorly-bedded boulder-cobble conglomerate with pebbly sandstone that are locally matrix-supported. The sandstones appear to be broad, shallow stream deposits that may include hyperconcentrated flow as indicated by flat layering defined by the orientation of granules. At this locality, this style of conglomerate occurs in the upper part of Member L-M.

2) Well-defined lenticular beds of pebble-cobble conglomerate separated by pebbly muddy sandstones with abundant root structures. The conglomerate beds are channel-form with abundant imbrication. Some internal coarsening and fining sequences are consistent with longitudinal bars (Bluck, 1982). Finer grained deposits resemble less-incised channels and overbank deposits. There are some

hints of thin debris flow sheets. Abundant root structures filled with nodular carbonate are soil caliche. Again, these types of conglomerates are here almost entirely within member L-M although some occur in the gray parts of the Perkasie Member.

3) Grain-supported cobble-pebble conglomerate with sandy matrix. Granules and coarse sand show high degree of sorting suggesting wave reworking of finer fractions (LeTourneau & Smoot, 1985; Smoot & LeTourneau, 1989). These are associated with gray and black shales and oscillatory-rippled sandstones in Van Houten cycles. No unequivocal bar-form structures or imbricate ridges have been observed. These types are here restricted to the gray parts the Perkasie Member.

Laterally-continuous black and gray siltstones and claystones within the high stand parts of Van Houten cycles contain pinch-and-swell laminae, abundant burrows, and rare clam shrimp. These are definitely lacustrine deposits, almost certainly marginal to the finer-grained facies more centrally located in the basin. These lacustrine sequences mark transgressions of perennial lakes over the toes of alluvial fans, much as LeTourneau and Smoot (1985) and LeTourneau (1985a) described in marginal facies of the Portland Formation in the Hartford basin of Connecticut. Division 2 of cycles comprising the Perkasie Member were produced by lakes which were almost certainly shallower than those which produced the microlaminated, whole fish- and reptile-bearing units in other parts of the Newark basin section. They evidently were deep enough, however, to transgress over at least the relief caused by the toes of alluvial fans.

The restriction of the conglomerate facies to the vicinity of the border fault and the association of debris flow and shallow stream deposits is consistent with an alluvial-fan model (i.e., Nilson, 1982). Channel-form conglomerates suggest flash-flooding streams that are still consistent with alluvial fans; however, the abundance of interbedded fine sandstone suggest lower slopes than for the debris-flow deposits. All of the deposits resemble distal low-slope fans or in the case of the coarse debris flow conglomerates, more distal parts of steep fans.

Intercalation of lacustrine shales with these conglomerates would appear to demand low slopes. Coarsening-up sequences of wave-formed deposits suggest intermittent introduction of material in receding lakes. This is probably a climatic as opposed to tectonic response because the shallowing is recognized basin-wide. Therefore, even the coarsest deposits accumulated on relatively low slopes. The requirement of low slopes means the present basin-margin fault does not necessarily mark the apex and more likely the fans extended several miles beyond the present basin boundary (Smoot, 1991). The fans could have extended away from the present basin as thin veneers on pediment surfaces on basement, with fan material being continuously recycled basinward. This is consistent with the observation that many of the clasts in the debris flow and poorly-sorted stream deposits are relatively well-rounded and mixed with highly-angular clasts. Apparently, very coarse-grained sediments with angular clasts accumulated in the hanging walls of boundary faults to the NW of the locally-present basin-margin fault during Late Triassic time. Later erosion removed these rocks, exposing Paleozoic and Precambrian rocks.

Individual Van Houten cycles of the Perkasie Member in this area average 7 m thick, as compared with a mean of 6.5 m for the same cycles at the Ottsville quarry (Stop 8). The thickness of the ~100-kyr cycles increase as well from 20.3 m at Ottsville to 28.1 m in this area (Fig. 8.2). At New Brunswick, NJ, near the east side of the basin, the Van Houten cycles have a mean of 4.4 m. This thickening towards the border fault is typical of most of the Newark Supergroup and dramatically illustrates the asymmetrical character of the half-graben.

As mapped by Ratcliffe et al. (1986) on the basis of surface geology, drill cores, and a seismic profile, the border-fault system in this area is a right-stepping system of normal faults that are reactivated imbricate oblique and thrust faults dipping 20 - 30°SE (Fig. 9.3). Core and field data reveal Paleozoic mylonitic fabrics of ductile thrust faults in Precambrian gneiss and early Paleozoic dolostone overprinted by brittle cataclastic zones of Mesozoic normal faults which form the border-fault system of this part of the Newark basin. Cores collected by the USGS confirm these dips and the fact that brittle normal-fault fabrics cut older ductile contractional (thrust) fabrics.

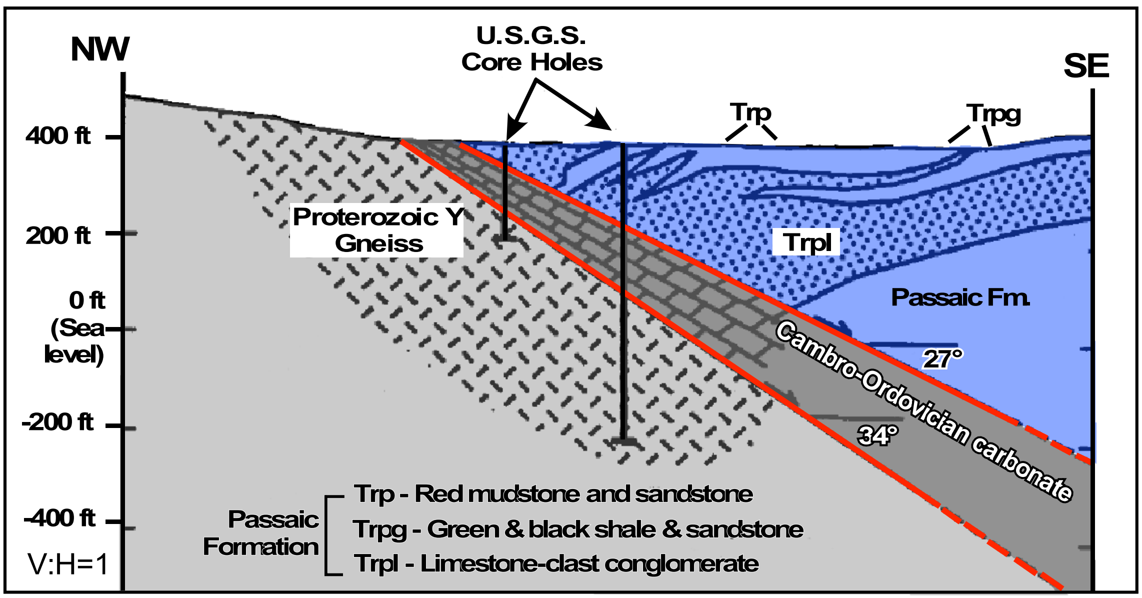


Figure 9.3*: Geologic cross section through border-fault zone of Newark basin (after Ratcliffe et al., 1986). Field and core data constrain the cross-sectional geometries. The average dip of the border-fault system is ~30°, which is more typical of thrust faults than normal faults.*

Quarries for flagstone operated in the 19th century in the vicinity of northern Milford to the east of Stop 9 in the sandy facies of the lower Perkasie Member have produced a suite of tetrapod footprints characteristic of the lower Passaic Formation in the Newark Basin and Norian track assemblages in eastern North America in general (Fig. 9.4). In totality, the Perkasie Member and underlying member L-M as seen at Milford, NJ, and Ferndale, PA, have produced the types and much associated material of *Rhynchosauroides brunswickii* (Ryan and Willard, 1947) (lizard like, lepidosauromorph), *Rhynchosauroides hyperbates* (Baird, 1957) (lizard-like lepidosauromorph or archosauromorph), *Apatopus lineatus* (Bock, 1952a) (phytosaur), the type of *Chirotherium lulli* (Bock, 1952a; Baird, 1954) (archosauromorph), the types of *Brachychirotherium parvum* (C. H. Hitchcock, 1889), *B. eyermani* (Baird, 1957) (archosauromorph),, the types of *Atreipus milfordensis*, *A. sulcatus* (Baird, 1957; Olsen and Baird, 1986) (non-dinosaurian dinosauromorph), and examples of brontozoiids (*Grallator* spp; Baird, 1957) (theropod dinosaurs). An indeterminate form, *Coelurosaurichnus* (Olsen and Baird, 1986), and a small stubby form of unknown status (Baird, 1957) have also been reported. Like most other North American Norian age assemblages, dinosaurs comprised only a small proportion of the fauna.

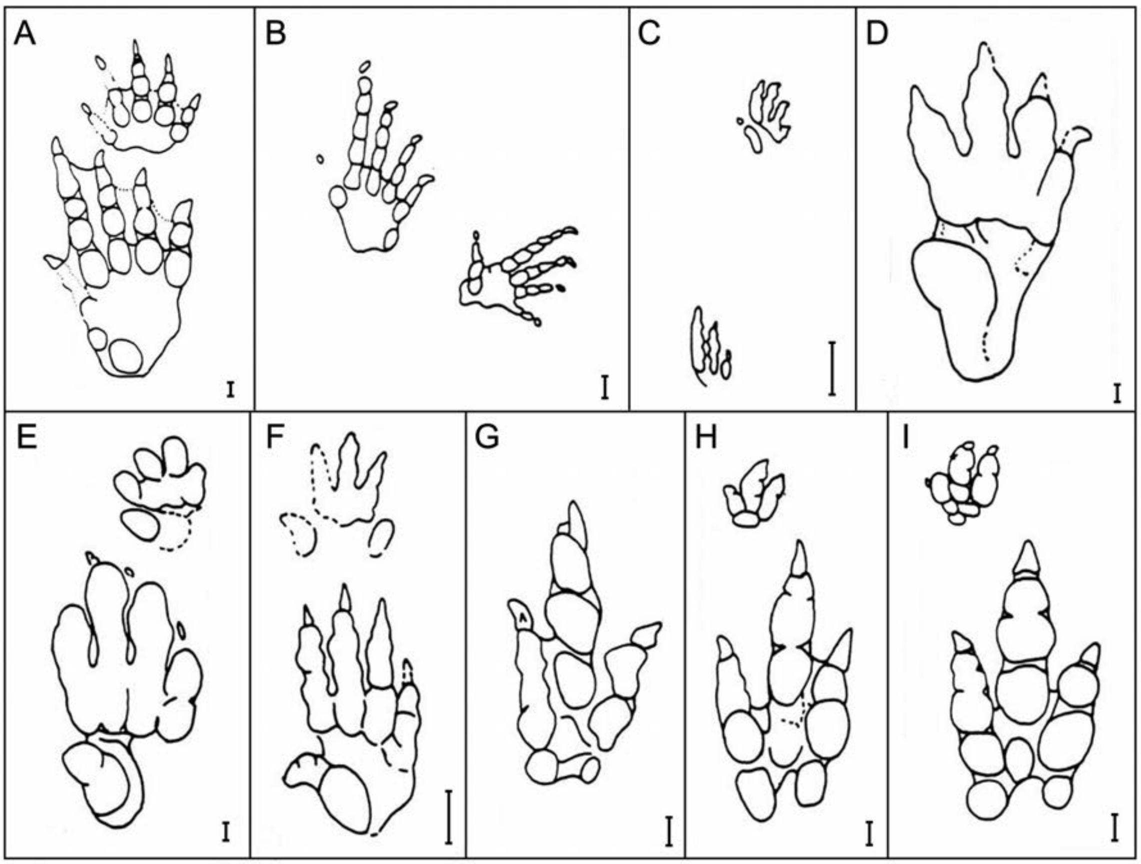


Figure 9.4: *Major ichnotaxa known from the Perkasie Member of the Passaic Formation: A,* Apatopus lineatus*; B,* Rhynchosauroides hyperbates*; C,* Rhynchosauroides brusnwickii*; D,* Chirotherium eyermani*; E,* Brachychirotherium parvum*;* Chirotherium lulli*; G, brontozoid,* Gralltor *sp.; H,* Atreipus sulcatus*; I,* Atreipus milfordensis*. A, D, E, G, from Baird (1957); F, from Baird (1954); A-C, from Olsen and Flynn (1989); H,I, from Olsen and Baird (1986).*

The Perkasie Member has also produced an important megafossil plant assemblage at Milford (Newberry, 1888; Bock, 1969) including *Glyptolepis playsperma* and *G. keuperiana* (Cornet, 1977), *G. delawarensis* (Bock, 1969), *Pagiophyllum* spp., (?) *Cheirolepis munsteri*, *Clathropteris* sp., and *Equisetites* spp. The interesting, unique specimen of the plant fossil *Ginkgoites miliordensis* Bock, 1952b (ANSP uncatalogued), from the Smith Clark quarry, was supposedly destroyed on loan in 1974 (Spamer, 1988), however material belonging to this taxon as well as many other of Bocks specimens have been rediscovered (Lendemer, 2002), making comparisons to other material possible. Axsmith et al., (2004) has redescribed some of this important material and concludes that the reproductive structure he assigns to *Pseudohirmerella* indicates a substantial but mostly undocumented, Triassic diversification of the extinct conifer family Cheirolepidiaceae.

The importance of these Perkasie assemblages is twofold: first is its general similarity to other Late Triassic age assemblages, and second in its similarity to older Passaic and Lockatong formation assemblages. In particular, the Perkasie footprint assemblages resemble those from the Lockatong of Arcola, PA, that is about 7 my. older (Olsen and Flynn, 1989) and the Lyndhurst, NJ, locality (Olsen and Rainforth, 2003) that is about 3 my younger, demonstrating slow rates of faunal change through the Late Triassic. When it was thought that the Carnian-Norian boundary was basically at the Passaic-Lockatong boundary it seemed clear that there was no apparent sign of the supposed Carnian-Norian extinction event. However, the marine Carnian-Norian boundary actually correlates with the base of the Raven Rock Member of the Stockton and the lack of a biotic break at the Lockatong-Passaic transition now appears completely expected.

Stop 9A: Conglomerates at Pebble Bluff

By Frank Pazzaglia, Lehigh University

This stop at Pebble Bluff exposes thickly-bedded, clast-supported quartzite-pebble conglomerate with medium to thickly-bedded sandstone and siltstone that are the proximal hanging-wall facies of the Perkasie Member of the Passaic Formation (214-215 Ma). There are three main goals in visiting this particular outcrop. First is to observe the sedimentology and stratigraphy of this mostly coarse-grained unit, discuss how it is consistent with an alluvial fan facies, and place this fan in the context of Perkasie Member lacustrine facies cycles observed in the basin center. Second is to observe the composition of the clasts and compare it to the next stop along Phillips Road. Third is to contemplate the provenance of this paleo-alluvial fan in the context of the detrital zircon geochronology described in Pazzaglia et al. (2018, this guidebook).

The Pebble Bluff exposures consist of several hundred meters of interbedded quartzite pebble conglomerate, sandstone, and siltstone (Fig. 9.5). No local source for the quartzite conglomerate pebbles are present in the abutting footwall of the Newark basin border fault, here represented by Blue Ridge rocks of Musconetcong Mountain. However, the quartzite-conglomerate facies is conformably overlain by a dolostone-breccia debris-fan facies that also contains clasts of gneiss and related crystalline rocks. The dolostone and gneiss do currently outcrop in the Musconetcong Mountain footwall suggesting that the footwall was exposed to its current structural level, at least locally, during or shortly following deposition of the Perkasie Member. These stratigraphic observations further suggest that a quartzite-pebble-bearing unit no longer present in the footwall was unroofed prior to exposure of the dolostone and gneiss.

Quartzite clasts of the Pebble Bluff paleo-alluvial fan are ~4-10 cm in diameter and generally well-rounded. They represent a range of white, red, and gray polycrystalline quartzites and minor quartz sandstone. The deposit also contains generally larger, subangular to subrounded clasts of vein quartz. The base of the fans is a dark red, sandy, fluvial quartzite-pebble and vein quartz-pebble conglomerate organized into 1-2 m thick beds interbedded with sandy siltstone and lesser amounts of dark gray mudstone. The middle part of the fans continues with fluvial quartzite-pebble and vein quartz-pebble conglomerate that locally contains sparse clasts of Precambrian granite and lower Paleozoic dolostone. In contrast, the upper part of the fans, ~300 m stratigraphically above the exposures at Pebble Bluff, is a dolostone and granite-clast debris-flow and mass movement fanglomerate and breccia. These observations are interpreted to represent an unroofing of the footwall block, starting with a vein quartz, quartzite or quartzite-conglomerate unit of unclear origin, but presumably formerly capping the Blue Ridge and proceeding down into Blue Ridge rocks and their Paleozoic cover that are presently exposed in the footwall block.

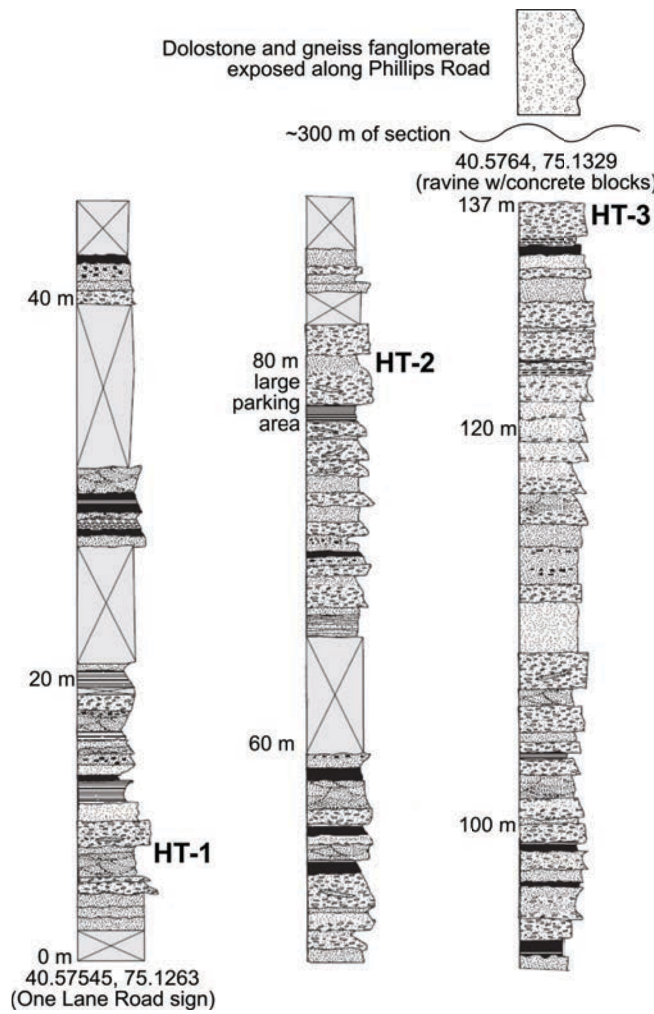


Figure 9.5. *Measured section of Perkasie Member of Passaic Formation along central part of Pebble Bluff, and relative stratigraphic position of overlying dolostone and gneiss fanglomerate. Detrital zircons were collected from three sandstone beds labeled HT-1, HT-2, and HT-3. Black indicates mudstone, not black color.*

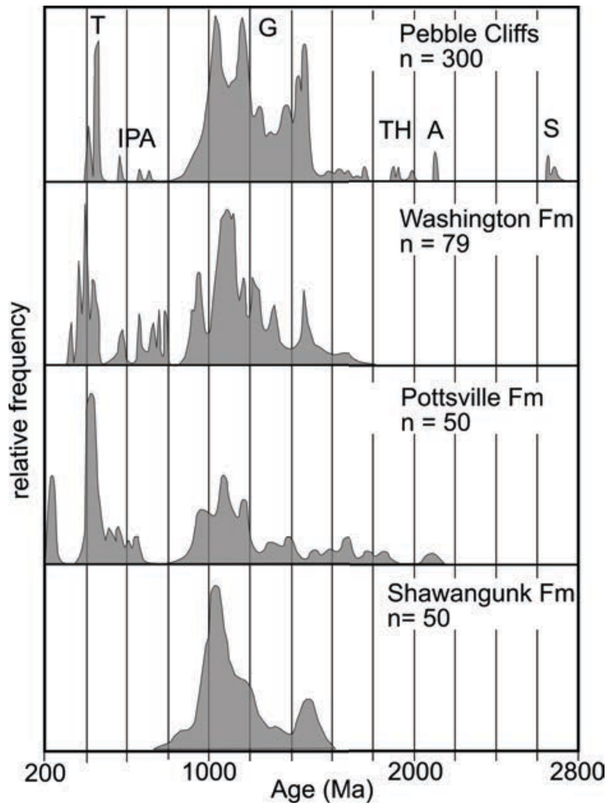


Figure 9.6. *The Pebble Bluff paleo-alluvial fan detrital zircon age spectra (n=300) compared to age spectra from the published literature illustrating possible sources of the zircons in the Blue Ridge and Appalachian foreland. T=Taconic, I=Iapetan, G=Grenville, IPA=Iapetan, Pan-African, TH=Trans-Hudson, A=Amazonia, and S=Superior. Washington Formation from Becker et al.(2005). Shawangunk and Pottsville formations from Gray and Zeitler (1997).*

Field work involved collection of ~24 kg of material from three sandstone beds labeled HT-1 through HT-3 (HT= Holland Township; Fig. 9.5). One hundred zircon crystals on all three sample mounts for a total of 300 zircons were randomly chosen and dated to generate a stacked probability age spectrum. The combined results of all three samples shows an age spectrum with main peaks at 450 (Taconic orogeny), 1050, 1200, and 1500 Ma (all Grenville orogeny with the latter probably granite-rhyolite province) (Fig. 9.6). There are minor peaks at 580 and ~700 (Iaptetan rifting or Pan-African), 1900 (Trans-Hudson), 2100 (Amazonia), and 2700 Ma (Superior Craton; Fig. 9.6).

There is considerable overlap of the Grenville and Appalachian (Taconic) peaks in the Pebble Bluff sample with other, published age spectrum from sandstones in the Appalachian foreland, but the > 1500 Ma, minor peaks are only present in the Pottsville Fm sample (Fig. 9.4). Qualitatively, the Pebble Bluff age spectra is most similar to the Permian Washington Formation sample, particularly in the details of two distinct Grenville peaks, minor Iapetan and Pan-African peaks, and a distinct Taconic orogeny peak. However, the Pebble Cliffs (and Washington Formation) age spectrum are essentially composites of the Pennsylvanian Pottsville Formation and Silurian Shawangunk Formation. The Grenville and Appalachian sources for all Paleozoic Appalachian foreland sandstones may not have varied significantly through time, leading to a composite age spectrum if these sandstones were in fact recycled back into the Newark basin.

Stop 9b: Conglomerates of Passaic Formation at Phillips Road

By Frank Pazzaglia, Lehigh University

Location: Lat 40.581616, Long -75.164835, Phillips Road, Holland Township, NJ

This stop along Phillips Road is adjacent to the border fault, located directly to the NW, separating the alluvial fan facies of the Newark basin hanging wall from Blue Ridge and lower Paleozoic cover sequence rocks in the Musconetcong Mountain footwall. The goal of this stop is to compare the texture, composition, and stratigraphy of these deposits to the quartzite-pebble conglomerate observed at Pebble Bluff, and to contemplate the unroofing history of the footwall, in the context of cutting the post-rift unconformity.

The outcrops along Phillips Road expose a thickly-bedded, matrix- and clast-supported, dolostone and granite-clast fanglomerate and breccia. The texture of this deposit is consistent with mass-movement deposition, such as landslides and debris flows. Compositionally, the dolostone and granite match the Cambrian Leithsville and Allentown formations and Grenville crystalline rocks currently exposed in the Musconetcong Mountain footwall. Accordingly, these observations strongly suggest that the footwall had been erosionally unroofed to its current structural level, more or less, by the end of Perkasie Member time (214-215 Ma). However, it is a bit difficult to reconcile that conclusion with the sedimentology and provenance of the Pebble Bluff quartzite fan conglomerate, unless recycling of a former late Paleozoic (Permian) molasse, from a footwall with ~ 500 m of relief is considered (Pazzaglia et al., 2018, this guidebook). Evidently both granite of the Blue Ridge and a capping quartzite-pebble conglomerate were both exposed somewhere in the footwall of the border fault during or shortly following Perkasie Member time.

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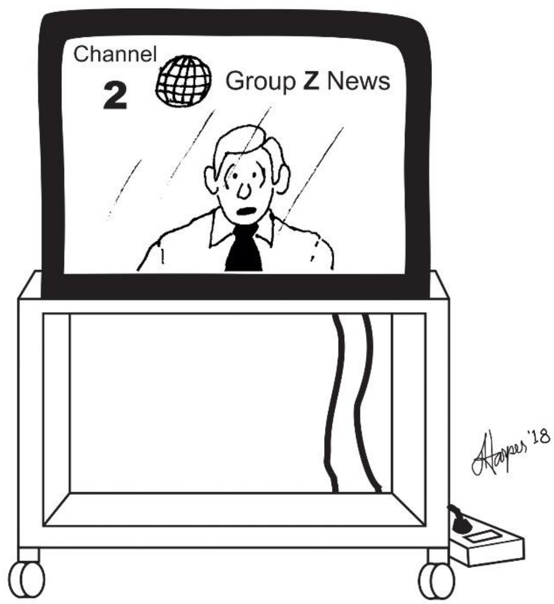
ROADLOG: Day 2 – Saturday, October 6, 2018

START	TURN	DIRECTIONS/COMMENTS/NOTES
		Zero out Odometer before leaving Phillips Road Outcrop
0.0	R	Continue North on Philips Road
0.2	R	Turn Right onto Church Road
3.2	L	Turn Left onto Milford Warren Glen Road
7.0	R	Turn Right onto Riegelsville Warren Glen Road/NJ 519 North
7.2	L	Turn Left to stay on NJ 519 which becomes Springtown Road, Enter Alpha Borough
10.6	R	Turn Right onto New Brunswick Avenue/NJ 122 East
11.7	R	Turn Right onto NJ 22 East
11.8	R	Enter Ramp for I-78 West
17.0		Pass through Toll Gate of I-78 entering PA
32.8	R	Turn Right onto PA 309 South
33.8	R	Turn Right to Exit for Saucon Valley Road
		Get in Middle Lane
34.0	L	Turn Left to stay on Saucon Valley Road
34.9	**R**	***Turn right to return to hotel, Last Stop for the Day***
		Homewood Suites Hotel is located at 3350 Center Valley Parkway



"According to geologists at Rutgers University, the entire mid-Atlantic coastline underwent something called 'isostatic readjustment' this morning, rising two feet above sea level. There has been no explanation of how or why this phenomenon occurred. In other news, former Governor Chris Christie left New Jersey this morning on the first leg of a European fact-finding mission . . . "

Field Conference of PA Geologists

Session Presentation: Zinc Mining in Lehigh Valley PA

Abstract:

Friedensville, an area in Upper Saucon Township, Lehigh County, PA, was the center of an active zinc mining industry from the mid 19th century until the end of the 19th century and, again, in the middle part of the 20th century. There are five separate mining pit remains, two of which are water filled quarries, substantial subsurface shafts and, most notably, the ruins of a unique 19th engine house which includes four standing stone walls with unaltered interior features. The engine house held a pumping engine called "The President" which was the largest single cylinder stationary steam engine ever constructed. The 19th century mine developers, engineers, skilled operators and supervisory staff were experienced Cornish mining talent who largely moved elsewhere to follow better opportunities when the mines began to economically fail in the later part of the 19th century. In the 1950s, the New Jersey Zinc Company opened its Friedensville mine. The ore body was an extension of that previously extracted through the Correll and New Hartman mines. The New Jersey Zinc mine used an open stope system in which the ore was removed with pillars left in place to support the hanging wall. Because this mining method was not selective, the average grade of the ore produced was approximately 5%. The mine was closed in 1981 because of declining metal prices and increasing costs. This presentation will consist of three parts: 1) a history of the 19th and 20th century Friedensville mines, 2) an overview of the President pumping engine and the engine house structure, and 3) a discussion of current activities to research, preserve and interpret the engine house and its surroundings including how Lehigh University students are being directly involved as part of their award winning innovative cross discipline Technical Entrepreneurship Capstone program.

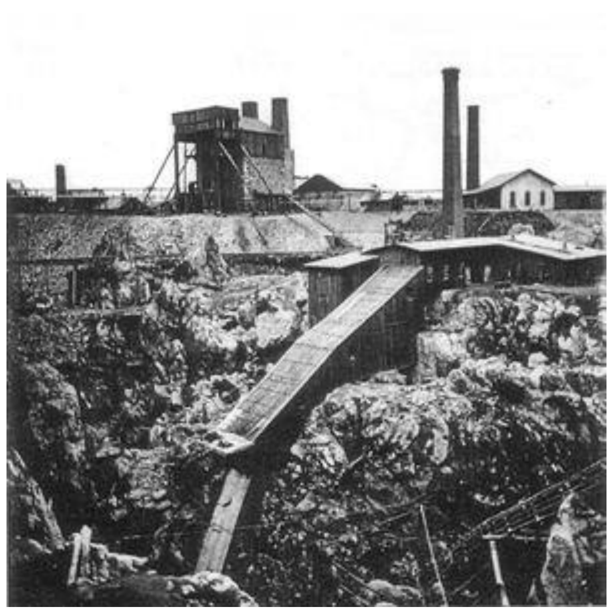


Figure SP.1: *Uberroth Mine with "The President" engine house (at the rear) ca. 1876. (Kaas, 2016)*

Biographical Statements:

Introduction

Mark W. Connar is a retired businessman with an AB degree in anthropology from Brown University with post graduate study in archeology at the University Museum, University of Pennsylvania. He has participated in archeological surveys in the United States and the United Kingdom. He also holds an MBA degree from Lehigh University. He is on the Board of Trustees, Historic Bethlehem Partnership and is a Founding Member of the National Museum of Industrial History. A Lehigh Valley native, he has a lifelong interest in the Friedensville mining area and, in particular, the engine house ruins. Consequently, he has extensively researched the subject and is currently working with Lehigh University, the property owner, and Upper Saucon Township officials to undertake steps to preserve this unique location as a heritage park or other suitable protective environment.

Speaker 1 – History of the 19th Century Friedensville Mines

L. Michael "Mike" Kaas is a retired mining engineer with a lifelong interest in mining history. His career included employment with the U.S. Bureau of Mines, Office of the Secretary of Interior, IBM Corporation and several mining companies including the New Jersey Zinc Company at their mine in Friedensville as a summer intern in the 1960s. He received a BS degree in mining engineering from Pennsylvania State University and a MS degree in mineral engineering from the University of Minnesota. He is a member and past director of the Society for Mining, Metallurgy and Exploration (SME). He is the author of numerous technical and historical papers, and serves as a volunteer docent at the Smithsonian Institution's National History Museum.

Speaker 2 – The President Pump

R. Damian Nance is Distinguished Professor (Emeritus) of Geology at Ohio University (Athens, Ohio). His field of expertise is structural geology and tectonics and the application of plate tectonics to ancient mountain belts and the role of supercontinents in Earth's geodynamic evolution. In addition to his extensive global geological studies, however, he has researched and recorded Cornish style engines and engine houses in the UK, United States and elsewhere. In this regard, he has co-written a definitive survey of engine houses in West Cornwall and is currently completing a pair of companion guides to engine houses elsewhere in Cornwall. He has also published numerous articles on beam engines in North America including the President pumping engine in Friedensville. Dr. Nance is a native of Cornwall and has a B.S. degree in Geology from the University of Leicester (UK) and a Ph.D. in Geology from Cambridge University (UK).

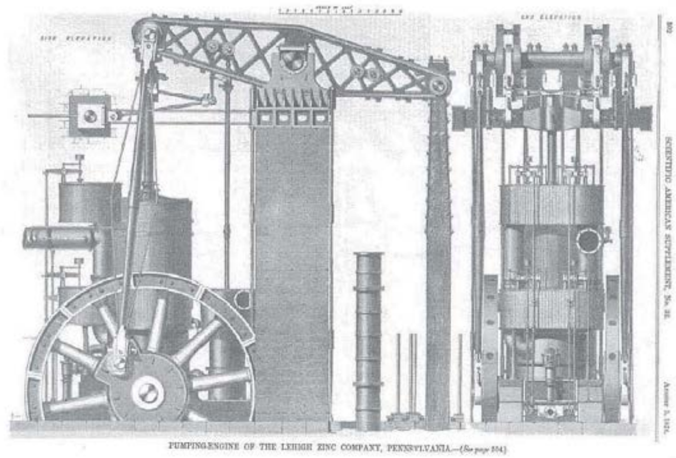


Figure SP.2: *Diagram of "The President" pumping engine (Kaas, 2016).*

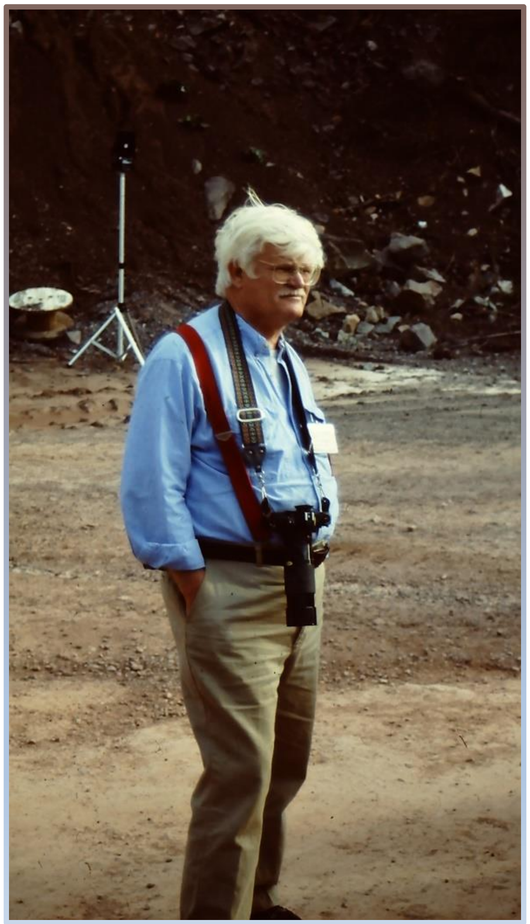
Speaker 3 – Current Activities to research and preserve the engine house

Dr. Gerard ("Jerry") P. Lennon is a faculty member of Lehigh University's Civil and Environmental Engineering department and he has conducted studies on groundwater hydrology and surface water hydraulics, surface water/groundwater interactions, and subsurface contaminant migration. He has published more than 70 papers in journals and conference proceedings, and he has received funding from the National Science Foundation, the National Oceanographic and Atmospheric Administration, the U.S. Environmental Protection Agency, New Jersey's Department of Environmental Protection, the U.S. Geological Survey, the Mellon Foundation and other agencies. Dr. Lennon's work includes field and laboratory studies as well as modeling ground and surface water flow, subsurface contaminant migration, effectiveness of containment and remediation alternatives including barrier walls, and estimation of fluid expulsion from geothermal vents in the Oregon Accretionary Prism in the Pacific Ocean. Dr. Lennon has also served as Lehigh's Deputy Provost for Academic Affairs. Dr. Lennon has a B.S. degree in Civil Engineering from Drexel University and an M.S. and Ph.D. from Cornell University.

References

L. Michael Kaas, "The History of Zinc Mining in Friedensville, Pennsylvania," in ''The Mining History Journal'' (Canon City, CO: Mining History Association, 2016), 17-42.

William David Sevon III 1933 – 2017



Dr. Bill Sevon passed away at the age of 84 in early October 2017, just after the end of the 2017 Field Conference of Pennsylvania Geologists. He had moved to Massachusetts to be near family in his last illness.

Bill joined the Pennsylvania Geological Survey as a field mapper in 1965, and his prolific career continued for 36 years. A native of Andover, Ohio, he was educated at Ohio Wesleyan University, the South Dakota School of Mines and the University of Illinois. He taught for several years at the University of Canterbury in Christchurch, New Zealand before coming to Pennsylvania.

Bill was best known for his work in Upper Devonian Catskill Delta rocks, the enigmatic origin of the Spechty Kopf Formation, mapping glacial geology in Northeast Pennsylvania, general Appalachian geomorphology and physiography, potholes in the Susquehanna River, the Hickory Run Boulder Field, and organizing field trips.

His geologic mapping is included in nine Pennsylvania Geologic Survey Atlas Reports and one County Report, covering 29 quadrangles. An additional 35 Quadrangles of Surficial Geology maps were Open-Filed. He was one of the primary compilers of the 1980 Geologic Map of Pennsylvania.

He was a firm supporter of the Field conference of Pennsylvania Geologists, leading 14 trips (more than any other single leader) and contributing to several others. For those and many other trips, Bill was the organizer of logistics. He wrote or checked the road logs, pre-ran the trips to catch any road or bridge closings and set the timetable for trips. His experience and attention to details established the tradition of solid, well run trips that the Field Conference still continues.

Bill was a Fellow of the Geological Society of America and rarely missed a Northeast Section meeting. He was sole author of 40 GSA abstracts, and coauthor of another 32, both at section and national meetings. He co-edited a GSA Special Paper on the Catskill Delta. He was Life Member Number 1 of the Harrisburg Area Geological Society, and ran or contributed to 12 of their annual field trips. He had scores of other publications, from journal articles to guidebooks for other field trips to major regional map compilations.

Bill was open to new ideas and to revisiting his own work as new information suggested alternate explanations. His influence on our understanding of the geology and geomorphology of Pennsylvania is significant.

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