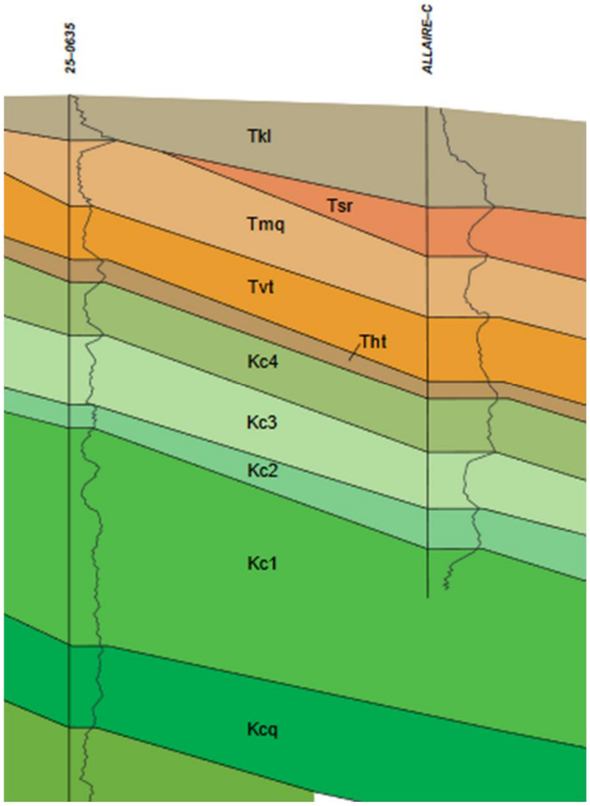
Geology and Paleontology of Monmouth County, New Jersey



2019 Conference proceedings for the 36th annual meeting of

the Geological Association of New Jersey

Edited by James Brown and Tim Macaluso

Hosted by Brookdale Community College

ACKNOWLEDGEMENTS TO GANJ XXXVI

James O. Brown, Ph.D., Retired, GANJ President
and
Tim Macaluso, Brookdale Community College, GANJ Past-President

Unlike previous GANJ field trips that have experienced bad weather, this trip could REALLY be challenging due to our need to transverse local streams that might be flooded. Therefore, it is our hope that if such a disaster occurs, it will be made up by the quality of conference speakers and this guidebook. Therefore, our first acknowledgement must go to the numerous sponsors listed in this guidebook who have helped us to alleviate the cost of this atypically large GANJ guidebook (and to Suzanne Macaoay-Ferguson, Mike Hozik and Bill Gottobrio of the GANJ Executive Board for contacting and coordinating with these sponsors).

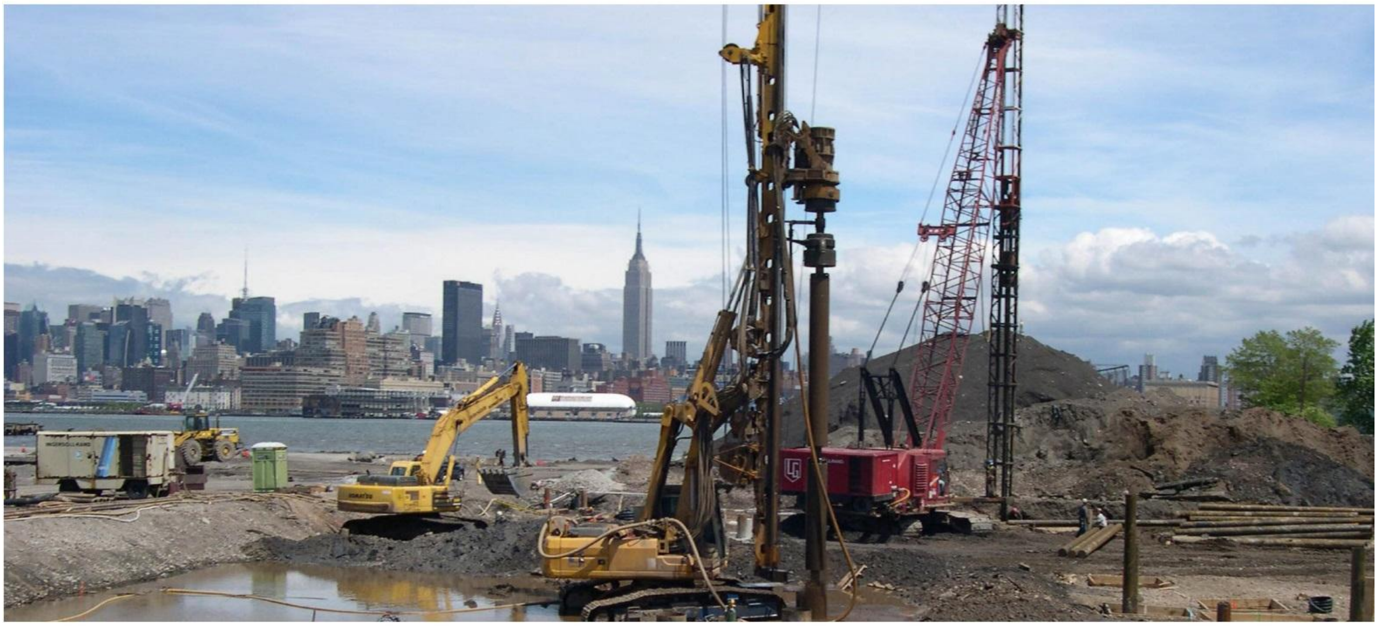
Our second thank-you is to the GANJ Executive Board for their assistance and guidance as we prepared this conference. Individuals of the Executive Board are listed at the beginning of this document: many have contributed to the preparation of the meeting or functioning of GANJ as a viable organization. However, we need to acknowledge Steve Urbanik of the NJDEP who is stepping down after 17 years of service as Recording-Secretary of GANJ. Although Steve held an annually elected position, we can attest to the fact that by having such dedicated individuals (such as Membership Secretary Suzanne Macaoay-Ferguson of PennJersey Environmental Consulting and Treasurer Alex Fiore of the USGS) to continue over long periods of time, helps to maintain stability with the operations of GANJ. Steve’s length of service is a testament to that dedication and our ability to function as a viable organization. Thank-you!

We would particularly like to thank Brookdale Community College (BCC) and the Brookdale Environmental Club for hosting our meeting site.

There are numerous people who have directly or indirectly collaborated with Jim B. in preparation of the conference and its guidebook. It started forty years ago with going fossil collecting with Wayne Cokeley (location unknown) and Ralph Johnson (MAPS). In the past year, various fellow members of the Monmouth Amateur Paleontologists’ Society (MAPS) have freely shared their ideas and field insights with J. Brown in regard to various aspects of Monmouth County’s paleontology and geology. This includes MAPS members Ralph Johnson, Steve Ballwanz, Wayne Callahan, Justin Andell, John Morano, and Bill Shankle. Additional field insights were obtained from Peter Sugarman and Scott Stanford of the New Jersey Geologic and Water Survey.

At New Jersey City University (NJCU) we wish to thank Professor Bill Montgomery, student Jena Richards, and technician Mark Zdziarski for preparing maps in association with the road log. Hun Bok Jung, Department Chair, was gracious in allowing Mark Z. to accompany Jena R. in the field for collection of GPS data. We would also like to thank the following for sharing field photographs: Mark Z. and Jena R. of NJCU; MAPS members S. Ballwanz and J. Andell; Bill Gottobrio of Golden Associates; Joanna Bednarek of the NJGWS; and Tom Mason of BCC.

Jim and Tim, August 2019



FIELD GUIDES & PROCEEDINGS OF PRIOR MEETINGS

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

GANJ II: Talkington, Raymond W., and Epstein, Claude M., eds., 1985, *Geological Investigations of the Coastal Plain of Southern New Jersey: Part 1 - Field Guide; Part 2A - Hydrology and Coastal Plain; Part 2B - Paleontologic Investigations*.

GANJ III: Husch, Jonathan, M., and Goldstein, Fredric R., eds., 1986, *Geology of the New Jersey Highlands and Radon in New Jersey*.

GANJ IV: Gallagher, William B., ed., 1987, *Paleontology and Stratigraphy of the Lower Paleozoic Deposits of the Delaware Water Gap Area.*

GANJ V: Husch, Jonathan, M., and Hozik, Michael J., eds., 1988, *Geology of the Central Newark Basin*

GANJ VI: Grossman, I. G., ed., 1989, *Paleozoic Geology of the Kittatinny Valley and Southwest Highlands N. J.*

GANJ VII: Brown, James O., and Kroll, Richard L., eds., 1990, *Aspects of Groundwater in New Jersey*.

GANJ VIII: Crawford, Maria L., and Crawford, William A., eds., 1991, *Evolution and Assembly of the Pennsylvania - Delaware Piedmont.*

GANJ IX: Ashley, Gail M., and Halsey, Susan D., eds., 1992, *Environmental Geology of the Raritan River Basin.*

GANJ X: Puffer, John H., ed., 1993, Geologic Traverse *Across the Precambrian Rocks of the New Jersey Highlands.*

GANJ XI: Benimoff, Alan I., ed., 1994, *Geology of Staten Island, New York.*

GANJ XII: Baker, John E. B., ed., 1995, *Contributions of the Paleontology of New Jersey.*

GANJ XIII: Dalton, Richard F., and Brown, James O., eds., 1996, *Karst Geology of New Jersey and Vicinity*.

GANJ **XIV:** Benimoff, Alan I., and Puffer, John H., 1997, *The Economic Geology of Northern New Jersey*.

GANJ XV: Puffer, John H., ed., 1998, *The Economic Geology of Central New Jersey*.

GANJ XVI: Puffer, John H., ed., 1999, *New Jersey Beaches and Coastal Processes from a Geologic and Environmental Perspective*.

GANJ XVII: Harper, David P. and, Goldstein, Fredric L., eds., 2000, *Glacial Geology of New Jersey.*

GANJ XVIII: Lacombe, Pierre, and Herman, Gregory, eds., 2001, *Geology in Service to Public Health.*

GANJ XIX: D'Amato, Dana, ed., 2002, *Geology of the Delaware Water Gap Area.*

GANJ XX: Hozik, Michael J., and Mihalasky, Mark J., eds., 2003, *Periglacial Features of Southern New Jersey.*

GANJ XXI: Puffer, John H., and Volkert, Richard A, eds., 2004, *Neoproterozoic, Paleozoic, and Mesozoic Intrusive Rocks of Northern New Jersey and Southeastern New York.*

GANJ XXII: Gates, Alexander E., ed., 2005, *Geology of the Central Newark Basin - The View from the 21st Century.*

GANJ XXIII: Macaoay, Suzanne, and Montgomery, William, eds., *Environmental Geology of the Highlands.*

GANJ XXIV: Rainforth, Emma C., ed., 2007, *Contributions to the Paleontology of New Jersey (II).*

GANJ XXV: Gorring, Matthew L., ed., 2008, *Environmental and Engineering Geology of Northeastern New Jersey.*

GANJ XXVI: Freile, Deborah, ed., 2009, *New Jersey Coastal Plain Stratigraphy and Coastal Processes.*

GANJ XXVII: Lacombe, Pierre, ed., 2010, *Geology of the Greater Trenton Area and Its Impact on the Capitol City.*

GANJ XXVIII: Rainforth, Emma C., and Uminski, Alan, eds., 2011, *Environmental Geology of Central New Jersey.*

GANJ XXIX: Alexander, Jane, ed., 2012, *Geology and Public Lands.*

GANJ XXX: Benimoff, Alan I., ed., 2013, *Igneous Processes During the Assembly and Breakup of Pangaea: Northern New Jersey and New York City.*

GANJ XXXI: Duzgoren-Aydin, Nurdan S., ed. 2014, *Global Environmental Issues and Local Consequences: Earth Surface Processes and Urban Environmental Quality.*

GANJ XXXII: Herman, Gregory C., and Macaoay Ferguson, Suzanne, eds., 2015, *Neotectonics of the New York Recess.*

GANJ XXXIII: Gagliano, Michael P. and Macaoay Ferguson, Suzanne, eds., 2016, *Shallow Subsurface Geophysical Applications In Environmental Geology.*

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

GANJ XXXV: Macaluso, Timothy, ed., 2018, *Water Supply, Hydrology and Hydrodynamics in New Jersey and the Delaware River Basin.*

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Copies of past guidebooks are available at www.ganj.org.

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CONFERENCE SCHEDULE

Friday, October 18, 2019 - Oral Presentations
Warner Student Life Center, Brookdale Community College

10:00	-	4:15	**Registration**
10:30	-	11:30	**Teachers Workshop**: **Amazing Discoveries and Fossil Hunting in Monmouth County, New Jersey** – Paul Kovalski, PhD., Research Associate, NJ State Museum
12:00	-	3:55	**Oral Presentations:**
12:00	-	12:15	**Opening Remarks** – James O. Brown, Ph.D., Retired, GANJ President
12:15	-	12:40	**Correlation of Aquifers and Bedrock Geology in Monmouth County, NJ** – Peter Sugarman, Ph.D., New Jersey Geological and Water Survey
12:40	-	1:05	**Surficial Geology and Geomorphology of Monmouth County** – Scott Stanford, Ph.D., New Jersey Geological and Water Survey
1:05	-	1:30	**Investigating the Geomorphic and Hydrologic Characteristics of the Big Brook and Willow Brook Watersheds, Monmouth County, New Jersey** – Josh Galster, Ph.D., Montclair State University
1:30	-	1:55	**Paleontology of the Campanian-Maastrichtian Boundary at Marlboro, Monmouth County, New Jersey – Taphonomy, Biostratigraphy, and Depositional Environments** – William B. Gallagher, Ph.D., Rider University
1:55	-	2:15	Break
2:15	-	2:40	**Late Cretaceous (Campanian/Maastrichtian) Vertebrate Fossils from the Holmdel Park Site, Monmouth County, New Jersey** – Wayne R. Callahan, NJ State Museum and Monmouth Amateur Paleontologists' Society
2:40	-	3:05	***Exogyra* Xenomorphs of the Atlantic Coastal Plain and the Environmental Influences of this Anomaly** – Justin Andell, Monmouth Amateur Paleontologists' Society and Raritan Valley Community College
3:05	-	3:30	**The Provenance of Sand and Lakehurst Titanium Ores Using Ilmenite Mg, Mn, and Nb Contents: Monmouth and Ocean Counties, NJ** – John H. Puffer, Ph.D., Professor Emeritus, Rutgers University
3:30	-	3:55	**Overview of Field Stops** – James O. Brown, Ph.D., Retired, GANJ President
3:55	-	4:15	Break
4:15	-	4:45	**GANJ Business Meeting**
4:45	-	5:45	**Keynote Presentation**: **You're Going to Need a Bigger Screen: The Fossil Sharks of Monmouth County** – Dana Ehret, Ph.D., Assistant Curator, Natural History Collection, New Jersey State Museum
6:00	-	?:??	**Dinner and Conversation:** Attendees are invited to gather at MJ's at 1213 Sycamore Street in Tinton Falls, NJ.

Saturday, October 20, 2019 - Field Trip

8:00	-	4:00	Starts at Parking Lot 1, Brookdale Community College

TABLE OF CONTENTS

Greetings and Introduction to GANJ XXXVI

James O. Brown, Ph.D., Retired RPG (AR#183), GANJ President

My first introduction of this year's field stop to Big Brook was back in the Spring of 1973. My St. Joseph's High School biology teacher, the late Francis Migliore, was the advisor to the Science Club and took a van of about a half dozen students on a field trip due to my "fossil enthusiasm". "Mr. Mig" helped me to expand my life-long interest in paleontology by assisting me "to get out in the field". We found shark's teeth and a few other fossil shells that day. Just before leaving we bumped into Jerry Case selling his fossil books: and what late 20th Century visit to Big Brook would be complete without meeting him or finding one of his brochures on your windshield?

Over the decades I would make numerous trips to Big Brook. Since the early 1990's this has included numerous visits with various Boy and Cub Scout groups. During this time, I would meet with Ralph Johnson and the Monmouth Amateur Paleontologists' Society (MAPS). Their enthusiasm for serious fossil collecting has led to numerous publications concerning fossils that would otherwise be overlooked by professional paleontologists due to the typical difficulties associated with collecting sites, specimen quantity and quality of preservation that characterize sediments of the Atlantic Coastal Plain. In the past decade my visits have also included taking students in my college Paleobiology class.

Despite all my numerous visits, notably to the Boundary Road exposures, I would find myself inspecting the outcrop and second guessing myself when looking at the visible outcrops. This brings us to one of the main themes of this year's field trip with regard to our journey through the Cretaceous:

1. Where's the Campanian-Maastrichtian Stage boundary?
2. Where's the Mount Laurel Formation?
3. Where's the upper Wenonah boundary?
4. Where's the lower Navesink boundary?
5. Where's the fossils? …and what do they tell us?
6. Where's the lag deposit(s)?, and
7. Finally, how laterally consistent are these features along strike and dip in the Monmouth County area?

Another significant theme for this year's meeting will also be looking at the surficial geology and geomorphology of the Coastal Plain. Water usage will also be reviewed in terms of watershed maintenance and hydrogeology. Beyond these technical perspectives, Big Brook, Ramanessin Park (also referred to as Hopp or Hop Brook), and Poricy Brook are fossil localities in Monmouth County that have various levels of accessibility to the general public for collecting. Therefore, in some ways this field trip is an extension of GANJ 29 (Alexander, 2012) that emphasized geology found on Public Lands. Our meeting this year will emphasize the first two fossil sites, as Poricy Brook was visited by GANJ in 2011 (Rainforth and Uminski, 2011). I go back to my opening statement about my high school science teacher getting his students into the field and the opportunities this leads to in science education. Then the reasons for my subsequent visits. All participants of this year's GANJ should appreciate how fortunate we, in overpopulated state such as New Jersey, are to have such places to introduce young people to science.

Cited References:

Alexander, Jane, ed. 2012. Geology and Public Lands. Field Guide to 29th Annual Meeting of the Geological Association of New Jersey, 110 p.

Rainforth, Emma C. and Uminski, Alan. 2011. Environmental Geology of Central New Jersey. Field Guide to 28th Annual Meeting of the Geological Association of New Jersey, 82 p.

Future geologists on a fossil hunt at Big Brook. (Photo by Jena Richards, NJCU.)

When “Layer-cake Geology” Leads to Debate: A Review of the Cretaceous Stratigraphic Units to be Visited for GANJ 2019

James O. Brown, Ph.D., Retired RPG (AR#183) [1,2]

[1]GANJ; [2]MAPS

ABSTRACT

In concept, geologists use formal names to define rock units as a way of communication with regard to stratigraphic and geographic position. In reality, different geologists have different criteria as to what defines a specific rock unit. The following attempts to review and to explain why the three Upper Cretaceous formations known as Wenonah, Mount Laurel, and Navesink that will be visited during the Geological Association of New Jersey’s 2019 meeting are defined differently by different researchers. As noted, and will be shown, a part of this is due to the criteria used by particular researcher, but added to this challenge is the natural tendency of these units to have varying facies over short distances, never mind across the strike and dip of the entire Atlantic Coastal Plain.

PURPOSE

In my introduction to this guidebook, I outlined several questions that led me to suggest and organize this years’ field trip:

1. Where's the Campanian-Maastrichtian Stage boundary?
2. Where's the Mount Laurel Formation?
3. Where's the upper Wenonah boundary?
4. Where's the lower Navesink boundary?
5. Where's the fossils? …and what do they tell us?
6. Where's the lag deposit(s)?, and
7. Finally, how laterally consistent are these features along strike and dip in the Monmouth County area?

In the process of getting participants and visiting the field with these individuals as well as others (please review the acknowledgements at the end of this paper), I’ve come away with an insight to these questions, but not necessarily “definitive” answers (see Figure 1 for a whimsical review of this). I hope that by sharing these insights you may better appreciate what you hear and see at this conference (whether or not you agree with me or other presenters) and that it leads you to new ways of future study of these formations. A recent conversation with Wayne Callahan, a contributor to this year’s conference, stated it as such: “to moderate a conversation that has gone on, in some form or another, for well over a hundred years (Weller doubted that the Mt. Laurel Formation was present in the Big Brook area)”. My take on that statement is that the debate will continue for another 100 years, but my hidden agenda is that this GANJ meeting *will force* collectors and researchers to be more definitive on where they collect their fossils and other data; not just say "Navesink" (which at this point has become useless in regards to litho-, time- and chrono- stratigraphic interpretations).

Therefore, based on the above considerations, the road log of this guidebook (see Brown *et al*., 2019) uses neutral terms instead of the stratigraphic names of Wenonah, Mount Laurel and Navesink. These neutral names refer to five different lithologic units called Beds A, B, C, D, and E. See the introduction of Brown *et al*. (2019, this volume) for a general description of each of these beds. In addition, a distinct lag deposit is commonly present between Beds C and D that is referred to as the Sequence Lag. These terms (Table 1) will be used and referred to within the following review.

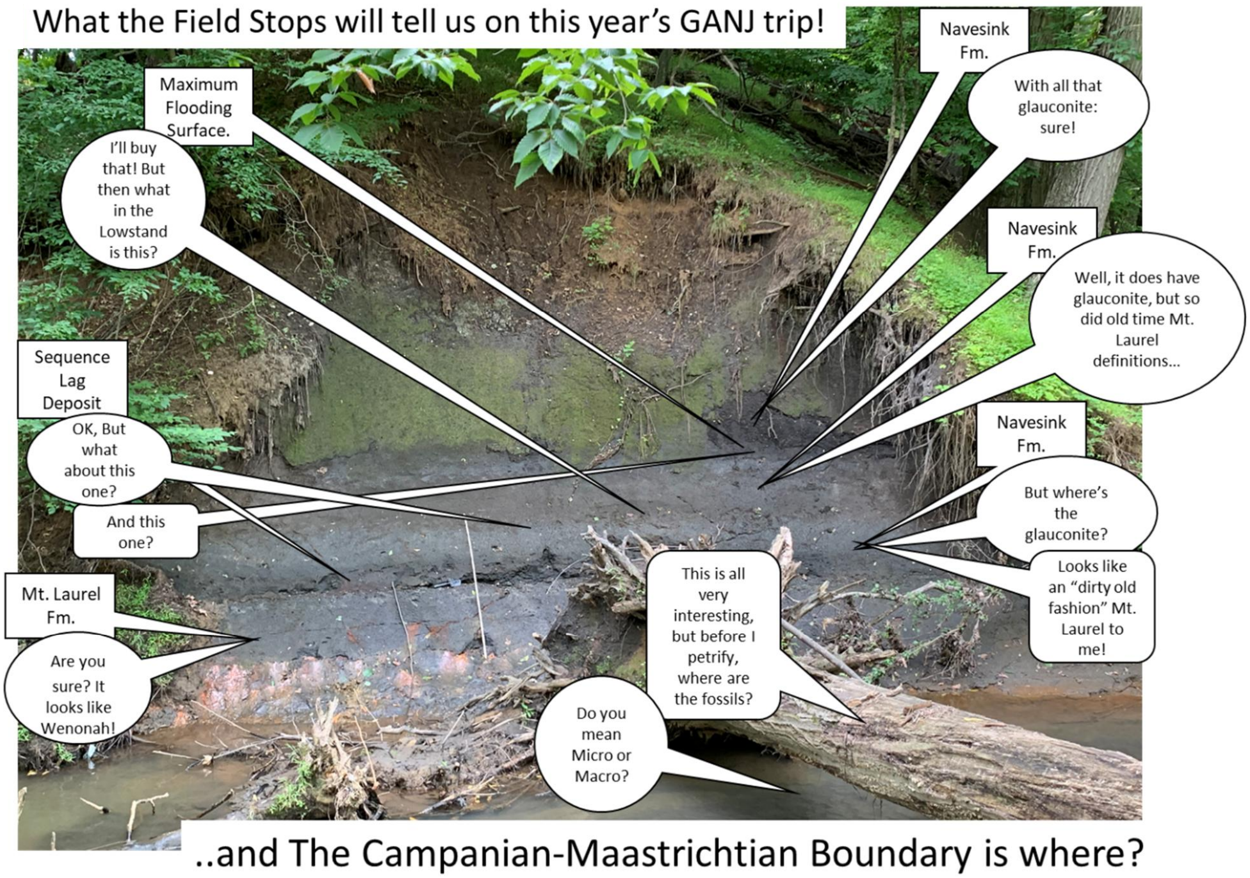

Figure 1. A whimsical summary of why there is a debate concerning Campanian-Maastrichtian sediments in Monmouth County, New Jersey. Photo facing south, at Big Brook, Colts Neck, NJ by Justin Andell, RVCC.

Disclaimer: This paper has many typographic errors and near contradictory statements. This is due to the haste of being the last thing written in preparation of this guidebook. In addition, as I visited exposures multiple times, notably with others, my "understanding" of what was present has changed. Add to this the various ways different geologists within different subfields classify the Cretaceous units of the Coastal Plain and one can, hopefully, excuse me for being inconsistent and contradictory with what is stated in this paper and parts of the GANJ road log. However, these are my mistakes and hopefully I've not mis-represented the findings of others.

INTRODUCTION

The semi-consolidated sediments of New Jersey's Coastal Plain have been studied for well over 150 years with major contributions by its first state geologist George Cook (of Rutgers' Cook College fame). Ramsdell (1958) summarizes Cook's work and that of others in terms of formal names used and is a good starting point for the "debate" that continues to this day. Ramsdell (1958) noted eleven formal formations and since then at least two others have obtained some level of recognition (see Sugarman and Owens, 1996 and Owens *et al.* 1998 for the various names of Cretaceous formations in Monmouth County with general lithologic descriptions of each).

Table 1. General Description of Neutral Names of Lithologic Units to be Inspected on Field Trip

Field Trip Unit	General Description
Bed E	Black marl ("glauconitic sand") with traces of quartz grains, but more commonly intercalated with gray clay.
Bed D	Well sorted (due to bioturbation?), fine quartz sand with common sand-size grains of the clay mineral glauconite; 2 to 5 feet thick gray and weathers to a light brown.
Other Lags	Not as distinct as what is referred to as the "Sequence Lag" are similar intervals with beds. These lags can be of similar composition or dominated by concretions of either phosphate, siderite, or calcarenite.
Bed C	Quartz sand bed approximately 2 to 3 feet thick with varying amounts of coarse versus fine size clasts. The base of this bed typically has the sequence lag. Belemnites are present. Big Brook: more silty, with only scattered pea-size (granule-size) quartz and gravel-size clasts. Hop Brook: the pea-size quartz clasts are quite abundant that can be a cemented as granule-size clast conglomerate. Willow Brook and other places: may be between the two extremes found at Hop Brook and Big Brook.
Sequence Lag	This disconformity boundary varies in recognizable abruptness. In some places gravel to cobble size concretions of calcarenite, siderite and phosphate plus rock fragments are abundant. At other exposures these coarse-size particles are rare whereby only finer granule to fine gravel-size particles of calcarenite, phosphate and siderite are found.
Bed(s) B	Thick, up to 2 feet, bed or combination of beds, gray clayey to silty fine to very fine sand with common to abundant mica and lignite. Upper part has burrows, typically of *Ophiomorphia*, that are sometimes filled with coarser sand size particles from the overlying unit. At some places a thin fine to medium quartz sand lens may be found between this bed and the base of the Sequence Lag. A lower, second clay dominated bed with abundant burrows is also sometimes found.
Beds A	Interstratified thin (0.1 to 0.5 foot) beds of clays, silts and sands. Mica and lignite are common in gray finer beds; quartz is main component of sand beds. Siderite concretions; ichnofossils, and body fossils are locally abundant.

Historically, the significance of using formal stratigraphic names was in terms of natural resources such as iron ore, clay, phosphate-sediment fertilizer, and water. Today, regarding these resources, water usage in terms of aquifer supply is the most significant for supporting the population of southern New Jersey (Hoffman, 2018) and continues to play a significant role in how these units are recognized. Regardless of the objective, researchers have noted some depositional cycles for the marine dominated sediment that vaguely follow the naming of stratigraphic units. The most simplistic way to look at these depositional cycles, whether as formations or hydrostratigraphic units, are as: 1. marl unit; 2. clay to silty sand unit; and followed by 3. a sand-dominated unit. The respective environments that these sediments would be: 1. Shelf; 2. offshore water; and 3. shoreface to beach. Generally, the marl, representing a sea level maximum flooding event, is the most consistently recognizable unit and used to define the beginning of a cycle. If the beginning of a cycle is determined by flooding event (highstand) as represented by a marl unit, then the three units being reviewed are in two different cycles where 1. clay to silty sand unit ("Wenonah"); is followed by a sand-dominated unit (Mount Laurel) and then 3. marl unit (Navesink). As will be discussed, even this simplistic model gets complicated by the "details" of lateral facies change at both a local and regional scale along with the question of "when" does the "flooding" begin? For example, associated with *the* clay-dominated marl may be glauconitic quartz sands and / or sand-size glauconite beds. Also associated with some depositional cycles may be underlying local beds that lack any significant glauconite. As will be inspected on the field trip, bioturbation also has mixed beds that may have had separate depositional histories.

Second, when looking at these sedimentary cycles and related depositional environments, we need to appreciate the several different perspectives and ways to emphasis how one can interpret their history and significance. Among the perspectives to appreciate are: 1. Paleontologic / Biostratigraphic; 2. Lithostratigraphic; 3. Sequence stratigraphic; 4. Sedimentological; 5. Hydrostratigraphic; 6. Structural geologic 7. Chronostratigrahic, 8. Allostratigraphic, and 9. Historic Geology to name a few. These different criteria lead to different levels of emphasis in defining the stratigraphic units and contacts as reviewed below. In terms of a Chronostratigraphic perspective, I believe there is a general consensus among all researchers that this "sandwich" of sediments *exposed in northeastern Monmouth County* has a lower slice recognized as the Wenonah Formation and an upper slice recognized as the Navesink Formation. Outside of northeastern Monmouth County there is exposed a quartz-dominated sand between these two Formations that historically has been referred to as the Mount Laurel Formation. The debate for northeastern Monmouth County exposures is how to define the boundaries of the upper Wenonah, the lower Navesink and whether a lateral equivalent of the Mount Laurel to the one in southeastern New Jersey is present. The next consideration is *what* is correlative to the subsurface.

1. Where's the Campanian-Maastrichtian Stage (CMS) boundary?

It has been less than 20 years that a "definition" for the CMS boundary has been agreed upon (of course not all stratigraphers "like it"). Odin and Lamaurelle (2001) note that the International Commission on Stratigraphy (ICS) has assigned the First Appearance Datum of *Pachydiscus neubergicus* as the defining biological marker for the start of the Maastrichtian Stage based on a stratotype in southwest France. Therefore, all historic and subsequent interpretations of "where" is the CMS Boundary need to reference this point. For New Jersey *P. neubergicus* is quite rare and has been tentatively identified in the basal Navesink Formation at the Atlantic Highlands (Cobban, 1974, p.18). Two layers ("lags") of fossils, equivalent to the layer of reworked phosphatized fossils noted by Minard (1969) were described by Cobban (1974) as the source of the unique ammonite fauna in this northeastern part of Monmouth County. These fossil layers are considered to be the northeast lateral equivalent of Beds D and E of the GANJ field trip based on lithic (glauconite, silt, and clay) and stratigraphic descriptions noted in Cobban

(1974). They are NOT considered to be equivalent to the Sequence Lag which, if exposed, would be at a stratigraphically lower interval.

Another biological event associated with the CMS boundary is the Last Occurrence (LO) of *Nostoceras hyatti* (Odin and Lamaurelle, 2001). At the Atlantic Highlands *N. hyatti* is known from the same basal-most Navesink Formation location *in abundance* (Cobban, 1974). However, Odin and Lamaurelle (2001, pp.236-237) note that based on Western Interior bentonites that "the geochronological calibration of this American series indicates that the LO of *N. hyatti* is in the interval 72.5–71.0 Ma". More recently, the ICS indicate the CMS boundary to be 72.1± 0.2 Ma (Cohen *et al*., 2013). This further suggests Beds D and E as the most likely candidates of having the actual CMS boundary.

From a historical perspective, Ramsdell (1958) did a limited review of stagal interpretations, however Richards (1958) in the same volume (Richards *et al*., 1958) stated that *in general* the Monmouth Group to be Maastrichtian while the underlying Matawan Group is Campanian. Richards (1958) further noted that despite their both having sand facies, the Wenonah (fine micaceous sand) based on its distinctive fauna should be placed within the Campanian Matawan Group, while the Mount Laurel (coarse glauconitic sand), likewise due to its fauna, should be assigned to the Maastrichtian Monmouth Group. However, as noted above the unique ammonite fauna from the Atlantic Highlands places the basal Navesink Formation at the Campanian-Maastrichtian Stage Boundary. For the "Wenonah Formation", ammonites collected at Monmouth County locations reviewed in this guidebook (Beds A and B) indicate a lower upper to upper middle Campanian age (Kennedy and Cobban, 1994a). Outside the GANJ field trip area, ammonites from the Mount Laurel Formation in Delaware indicate it to be Upper Campanian (Kennedy and Cobban, 1994b).

In other *general* studies that are post-1958 and pre-2001 with regard to the Campanian-Maastrichtian Stage boundary, the findings are quite diverse. For example, Sirkin (1986) made subsurface stratigraphic correlations of Long Island with New Jersey based on pollen palynology that indicated the Wenonah and Mount Laurel to be Campanian while the Navesink was either this or Maastrichtian. An opposite interpretation, Martino and Curran (1990, Figure 2) had all three units dated as Maastrichtian. Poag and Ward's (1993) allostratigraphic study of the Coastal Plain unconformity boundaries showed the Sixtwelve Alloformation (with lithostratigraphic equivalents that included the Wenonah and Mount Laurel Formations) as Campanian while the Allomac Alloformation (with the Navesink as a lithostratigraphic equivalent) was cited as Maastricthian. The geologic map of the Freehold-Marlboro Quadrangles, which has all the field stops, shows Wenonah and Mount Laurel as Campanian and the Navesink as Maastrichtian (Sugarman and Owens, 1996) as does the USGS bedrock geology map (Owens *et al*., 1998). For many of these studies, notably those of Poag and Ward (1993), Sugarman and Owens (1996) and Owens *et al.* (1998), it needs to be appreciated these are large scale regional investigations, where technically *most* of the Navesink *is* Maastrichtian.

Authors within this guidebook continue the trend of diverse interpretations for the CMS Boundary. Miller *et al.* (2019) cites the Mount Laurel/Navesink Formation contact as a "disconformable Campanian/Maastrichtian boundary" that "is poorly understood despite extensive study of its fossil beds". This would be the Sequence Lag at the base of Bed C. In their abstract, Callahan and Mehling (2019) refer to the basal Navesink as late Campanian, but within their paper they only review formational discrepancies regarding the definition of the Navesink. Gallagher and Hanczaryk (2019) refer to the Wenonah and Mount Laurel Formations as Campanian and the Navesink as "usually given a Maastrichtian age". They also review discrepancies with formational names, but come to opposite conclusions regarding the sequence lag than those of Miller *et al*. (2019) and Callahan and Mehling (2019). The definitions of formations noted by all of these authors relative to Beds A through E of the GANJ field sites are further reviewed elsewhere in this paper.

The above discussion emphasizes the chronostratigraphic location of the CMS boundary as a geologic event based on fossils. This brings up the time-stratigraphic question of how old is the CMS boundary? Sugarman *et al*. (1995) estimated the Mount Laurel Formation using belemnites analyzed for Sr-isotope values to be 70.1 Million Years ago (New Egypt, NJ) to 70.3 Ma (Mullica Hill, NJ) to 71.4 Ma (Delaware): this suggests a depocenter that moving towards the southwest over time. It also implies a lowermost Maastrichtian age for the Mount Laurel *along exposed strike* since the ICS indicate the CMS boundary to be 72.1± 0.2 Ma (Cohen *et al*. 2013). In comparison, Odin and Lamaurelle (2001, Figure 10) indicate it to be 72 Ma, while Miller et al. (2004, Figure 2) indicate it to be about 71.2 Ma and a more recent paper by Thibault *et al*. (2016 Figure 5) indicate it to be 72.2 Ma. This is another example of a lack of complete agreement among stratigraphers despite the amount of detailed information summarized in the cited example articles. It is also another reason why we might *see* the Campanian-Maastricthian boundary on this field trip even though we can't pin point exactly where it is at!

In summary (see Table 2), with the exception of Martino and Curran (1990), the general thought is that the Campanian-Maastrichtian stage boundary is located "somewhere" within the entire section of Beds A through E that we will visit during this field trip. As will be noted below through the following review of formational names, some would use the Sequence Lag (contact of Beds B and C) as the preferred boundary while ammonite biostratigraphy discussed in this section suggests it to be higher up section associated with Bed D or the base of Bed E. Finally, the potential amount of time represented by Beds A through E could be as much as 3 million years. This is based on a lower upper Campanian age (75 to 74 Ma) being established for Beds A and B while the overlying beds are as young as 72 Ma.

2.Where's the Mount Laurel Formation?

It should already be apparent that there are many different ways to define the Mount Laurel Formation in northeastern Monmouth County and elsewhere. Richards (1958) stated that the underlying Wenonah is a fine micaceous sand while the Mount Laurel is coarser and contains considerable glauconite. He later notes that from a lithologic perspective "they frequently cannot be separated". However, unlike the Wenonah, it is characterized by *Belemnitella americana* and other fossils found in the Navesink Formation. In the same publication, Ramsdell (1958) concurs with Weller's (1907) observation of these two formations being "readily distinguished lithologically" in Monmouth County, but further south, they are "almost indistinguishable". Based on these criteria, Bed B that will be observed on the field trip would be classify as Wenonah and the coarser sand Bed C immediately above with its belemnite "fossil clasts" would be Mount Laurel (or at least Navesink). However, it is also apparent from these statements why there has been debate with regard to identifying these two formations and that this debate, based on papers reviewed by Ramsdell (1958), has existed since the 1940's. It has also led to "re-classification" of "what" defines the Mount Laurel.

In contrast to the above statements regarding the northern New Jersey Coastal Plain, Owens and Sohl (1969) note that "some of the Mount Laurel beds are very micaceous and contain abundant thin layers of clay". They further note three lithofacies, only two of which we will see on the GANJ field trip:

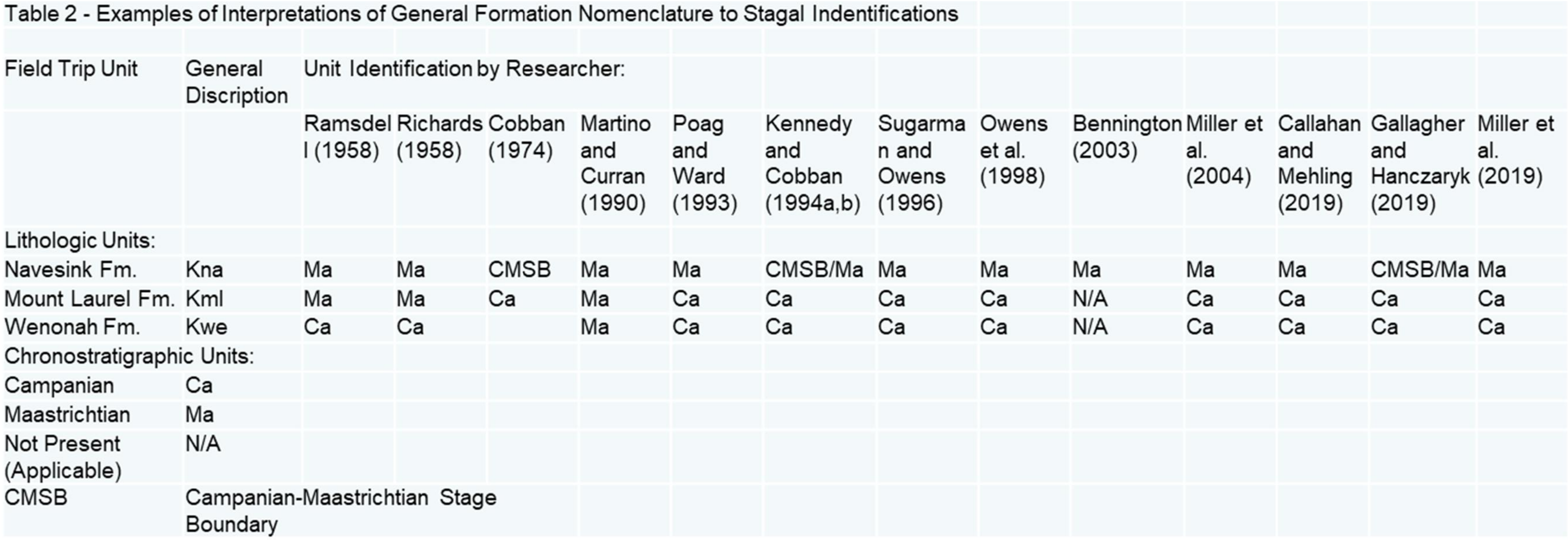

Table 2 - Examples of Interpretations of General Formation Nomenclature to Stagal Indentifications

Field Trip Unit	General Discription	Unit Identification by Researcher:												
		Ramsdell (1958)	Richards (1958)	Cobban (1974)	Martino and Curran (1990)	Poag and Ward (1993)	Kennedy and Cobban (1994a,b)	Sugarman and Owens (1996)	Owens et al. (1998)	Bennington (2003)	Miller et al. (2004)	Callahan and Mehling (2019)	Gallagher and Hanczaryk (2019)	Miller et al. (2019)
Lithologic Units:														
Navesink Fm.	Kna	Ma	Ma	CMSB	Ma	Ma	CMSB/Ma	Ma	Ma	Ma	Ma	Ma	CMSB/Ma	Ma
Mount Laurel Fm.	Kml	Ma	Ma	Ca	Ma	Ca	Ca	Ca	Ca	N/A	Ca	Ca	Ca	Ca
Wenonah Fm.	Kwe	Ca	Ca		Ma	Ca	Ca	Ca	Ca	N/A	Ca	Ca	Ca	Ca
Chronostratigraphic Units:														
Campanian	Ca													
Maastrichtian	Ma													
Not Present (Applicable)	N/A													
CMSB	Campanian-Maastrichtian Stage Boundary													

1. “A thin-bedded intercalated dark clay-light sand sequence” equivalent to Beds A.
2. “Massive sand beds” which is characteristic of south Jersey and not present at any of the field stops.
3. “An upper massive pebble sand” that is equivalent to Bed C of the GANJ trip. Owens and Sohl (1969) note this “interesting deposit” “is typically 4-8 feet, but may be as much as 12 feet thick locally”. They further note it to have “coarse sand, fine gravel and abundant disoriented fossils”, plus “many borings filled with glauconite sand extend down from overlying Navesink Formation”. Some of this description conforms with Bed C and its fossiliferous sequence lag while the “glauconite sand” facies concurs more with Bed D. The noted thickness also concurs with the combined thickness of these two beds.

For Owens and Sohl (1969) Lithofacies 1 (Beds A) is “the major Lithofacies in northern New Jersey” of the Mount Laurel. They further noted that its “dark beds contain large concentrations of mica, sand-sized carbonaceous matter”. This description fits Bed B of the GANJ trip. Thin beds containing siderite concretions are also associated with this lithofacies. Based on Owens and Sohl (1969), Beds A and B that were once called Wenonah Formation, are now recognized as Mount Laurel, *in addition to* Beds C and D. However, these observations have led to even further “re-classification” of “what” defines the Mount Laurel.

Sequence stratigraphic concepts have led to a new interpretation and understanding of the depositional cycles of the New Jersey coastal plain. Possibly one of the best papers to summarize this new understanding and interpretation is Miller *et al*. (2004). They recognized 14 Upper Cretaceous sequences and informally termed these “sequences after prominent basal (usually glauconite) lithostratigraphic units”. Apparently, due to its prominence, the (upper?) Campanian lag (as reviewed above) noted to occur between the contact of Beds B and C has been referenced by these authors and others to be the base of the Navesink Sequence. The use of the term Navesink Sequence versus Navesink Formation has not been strongly differentiated by these and other researchers. Both Beds B or C do not contain any significant quantities of glauconite when compared to Beds D and E. However, it has now led to the base of Bed C and its associated Sequence Lag to be called the Navesink Formation while Beds A and B are referred to as the Mount Laurel Formation.

As anticipated, authors within this guidebook present diverse interpretations of which of the “Neutrally-named Beds” should be called Mount Laurel Formation. (Note: none of the quoted authors have had an opportunity to review my interpretations of their formational assignments). Based on the position of the Sequence Lag in Bed C, Miller *et al.* (2019) would classify Beds A and B as the Mount Laurel Formation. In their abstract, Callahan and Mehling (2019) would refer to Bed C as the basal Navesink, but they also review within their text its history of being referred to as the Mount Laurel. There is no indication in Callahan and Mehling’s (2019) paper of whether they consider the underlying Beds A and B as either Mount Laurel or Wenonah. Gallagher and Hanczaryk (2019) would refer to Beds C and D as the Mount Laurel Formation with Bed B being the Wenonah Formation. Their Figure 2 shows the equivalents of Beds B through E, but also a 0.2 meter-thick, yellowish gray quartz sand between Beds B and C (not seen at the GANJ stops) that would also(?) be considered Mount Laurel.

In summary, depending on which criteria you use, the Mount Laurel Formation is:

a. not present;

b. represented by Beds A through D;
c. represented by Beds A and B immediately beneath the sequence lag;
d. a reworked part of the Navesink as indicated by Beds C and/or D;
e. Bed C but not Bed D; or
f. Beds C and D.

Table 3 summarizes some of the different interpretations made by others with regard to the different beds.

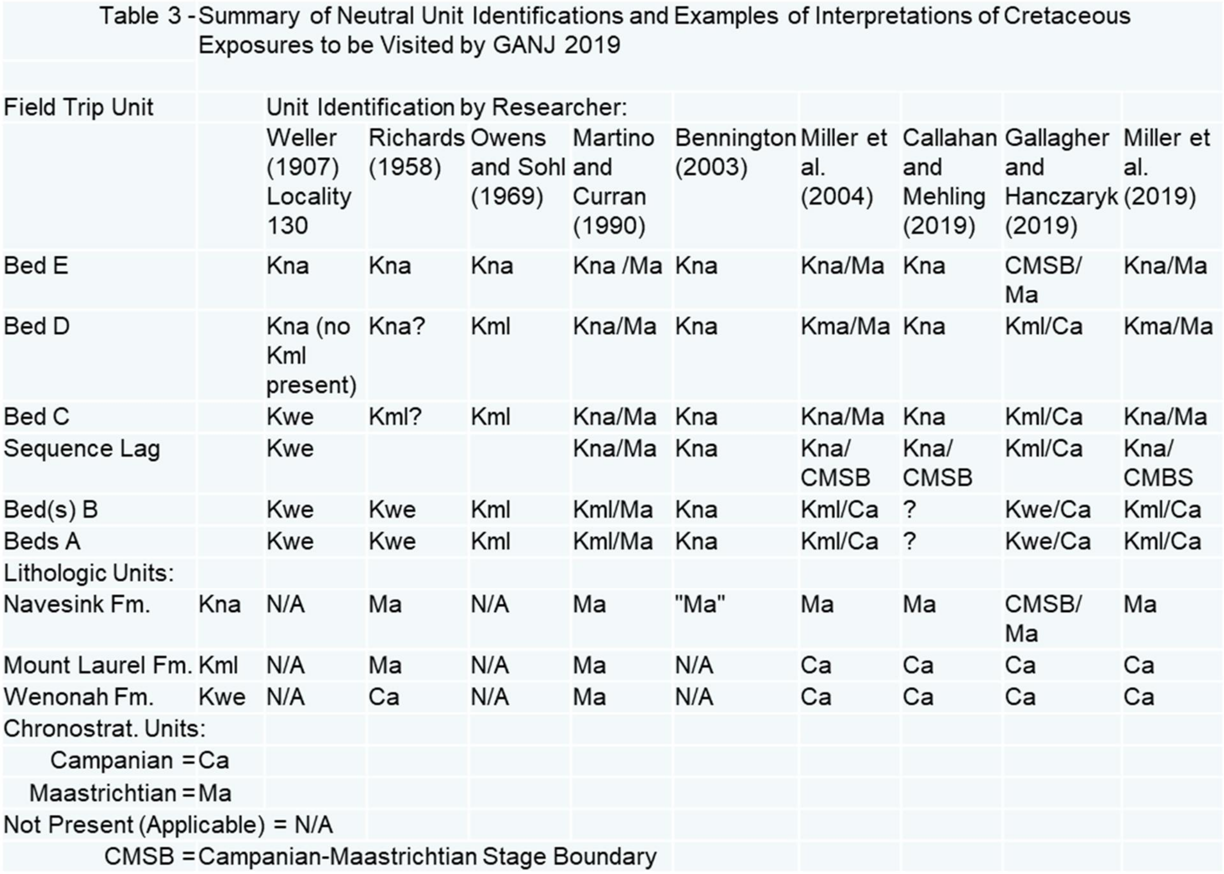

Table 3 - Summary of Neutral Unit Identifications and Examples of Interpretations of Cretaceous Exposures to be Visited by GANJ 2019

Field Trip Unit		Unit Identification by Researcher:								
		Weller (1907) Locality 130	Richards (1958)	Owens and Sohl (1969)	Martino and Curran (1990)	Bennington (2003)	Miller et al. (2004)	Callahan and Mehling (2019)	Gallagher and Hanczaryk (2019)	Miller et al. (2019)
Bed E		Kna	Kna	Kna	Kna /Ma	Kna	Kna/Ma	Kna	CMSB/ Ma	Kna/Ma
Bed D		Kna (no Kml present)	Kna?	Kml	Kna/Ma	Kna	Kma/Ma	Kna	Kml/Ca	Kma/Ma
Bed C		Kwe	Kml?	Kml	Kna/Ma	Kna	Kna/Ma	Kna	Kml/Ca	Kna/Ma
Sequence Lag		Kwe			Kna/Ma	Kna	Kna/ CMSB	Kna/ CMSB	Kml/Ca	Kna/ CMBS
Bed(s) B		Kwe	Kwe	Kml	Kml/Ma	Kna	Kml/Ca	?	Kwe/Ca	Kml/Ca
Beds A		Kwe	Kwe	Kml	Kml/Ma	Kna	Kml/Ca	?	Kwe/Ca	Kml/Ca
Lithologic Units:										
Navesink Fm.	Kna	N/A	Ma	N/A	Ma	"Ma"	Ma	Ma	CMSB/ Ma	Ma
Mount Laurel Fm.	Kml	N/A	Ma	N/A	Ma	N/A	Ca	Ca	Ca	Ca
Wenonah Fm.	Kwe	N/A	Ca	N/A	Ma	N/A	Ca	Ca	Ca	Ca
Chronostrat. Units:										
Campanian =	Ca									
Maastrichtian =	Ma									
Not Present (Applicable) = N/A										
CMSB =	Campanian-Maastrichtian Stage Boundary									

It will be interesting to see if in another 50 years a consensus can be achieved!

3. Where's the upper Wenonah boundary?

By starting with a review of the middle lithostratigraphic unit Mount Laurel Formation, the question of where the Wenonah boundary is and “if” we will be inspecting this formation has already been addressed.

In summary, the upper Wenonah Formation with regard to field trip stops, is:

a. not present;
b. represented by Beds A and B

However, a Wenonah **lithology** of a micaceous silty fine sand to clayey silt with lignite will be seen in parts of Beds A and all of Bed B. Time-stratigraphic data based on the presence of upper middle to lower upper Campanian ammonites (Kennedy and Cobban, 1994a) also suggest the lithofacies represented by Beds A and B not to be the lateral equivalent of the upper Campanian Mount Laurel along strike in southern New Jersey as suggested by Owens and Sohl (1969). This does not leave out the possibility that in the subsurface younger versions of the Wenonah lithofacies exist that are laterally equivalent to the exposed upper Campanian (see Kennedy and Cobban, 1994b) Mount Laurel of southern New Jersey.

4. Where's the lower Navesink boundary?

The above discussions already present the various levels of thought with regard to how to define the Navesink Formation. Despite being below the Sequence Lag and their distinct lithologies with only traces of glauconite, Beds A and B have, in a few cases in recent years, also been referred to as Navesink (see for example Bennington, 2003).

In summary, the three practical ways of lithologically defining the basal Navesink Formation is that it begins at:

a. the base of Bed C in conjunction with the Sequence Lag;
b. the base of Bed D due to its glauconite content;
c. the base of Bed E due to the phosphatic lag and/or its being a glauconitic clay (marl).

While a resolution with regard to the status of Bed C noted above in “statement a” may someday be achieved due to time-stratigraphic considerations, those noted above for Bed D versus Bed E may be a perpetual debate due to differences in opinion regarding lithologic criteria.

There are also questions in how to define the surface (versus subsurface) definition of the “Navesink Sequence” due to its time-stratigraphic connotations:

a. Does one use the Sequence Lag based on its widespread local recognition in this part of Monmouth County as a penecontemporaneous marker to the available subsurface data?
b. Does one use the “lesser lags” as a “correlative conformity” (sensu Mitchum *et al.*, 1977) to the subsurface unconformity, understanding that these lags are not always easy to recognized due to post-depositional bioturbation?
c. Does one use biostratigraphic data that suggests the base of Bed E and its discontinuous, phosphate dominated lag to be at the CMS boundary?

In regards to statement “a”, one needs to appreciate that surface exposures indicate the Sequence Lag to be a Campanian event whereby overlying sediments, up to at least the base of Bed E are also Campanian. Another hypothesis is that the Sequence Lag in conjunction with overlying sediments of Bed C and maybe Bed D representing a lowstand parasequence.

5. Where's the fossils? …and what do they tell us?

Despite the notion of “poorly fossiliferous outcrops” (Miller *et al.* 2004) by some, there is a lot of biostratigraphic data available regarding the time-stratigraphic relationships of lithostratigraphic, allostratigraphic and sequence stratigraphic units. Calcareous microfossils and macrofossils are of limited use due to diagenetic processes (see Brown and Morano, 2019, this volume): this hinders their potential use of nannofossils for isotope analysis along with this and other groups such foraminifera and ostracods for zonal correlations. However, molds and casts of ammonites, from either occasional occurrence or in concentration lagerstätten such as the Atlantic Highlands, are useful indicators. Probably the most useful macrofossil is *Belemnitella americana* whose occurrence is limited to the Mount Laurel and Navesink Formations (Richards, 1962) and gives a maximum age of Upper Campanian (notably for Bed C). I believe more attention to microfossils studied by palynologists for lateral and vertical correlations would potentially resolve some of the debate presented in this paper (most notably for the lignitic Beds A and B, but all of the other units as well).

In summary (and as reviewed in previous sections), macrofossils, notably ammonites and belemnites, but also bivalves (see Gallagher and Hanczaryk, 2019, this volume regarding Bed C) indicate the following:

1. Beds A and B to be upper middle to lower upper Campanian;
2. Beds C and D to be upper Campanian;
3. The basal part of Bed E to be uppermost Campanian to lowermost Maastrichtian;
4. Most of Bed E to be Maastrichtian.

A challenge to the future use of fossils is the need to compare historically collected fossil data with regard to ICS stratotype as reviewed by Odin and Lamaurelle (2001). A further challenge in regard to correlations is that collected fossils from a particular bed may be referred to a different lithologic unit by different collectors and geologists.

6. Where's the lag deposit(s)?

In summary, there are multiple lags of granule, gravel and larger size clasts associated with the respective contacts between Beds B-C; C-D; and D-E. This suggests such lags, in conjunction with oyster beds, to be a common occurrence. Some of these are potentially localized accumulations of shell and clasts, whereas a few may be more extensive in nature. As indicated at Big Brook, bioturbation may hinder the detection of such lag deposits (in the road log see and contrast Figure 6 with Figure 24 of Brown *et al.* 2019, this volume). However, the most distinct and laterally extensive lag to be seen during the GANJ 2016 field trip is between Beds B and C and is referred to as the “sequence lag” in this guidebook.

Of the noted lags, do they represent transgressive versus regressive versus maximum flooding events? Or, are they simply localized tempestites or coarse sediment sorted lenses between large submarine troughs? Consideration of the reviewed exposures to the paleostrandline of the Cretaceous needs to be considered where preserved lowstand deposits not found in subsurface deposits are present: thereby explaining multiple lags (disconformities) where in the subsurface only one is emphasized.

7. Finally, how laterally consistent are these features along strike and dip in the Monmouth County area?

In general, there is a lot of localize facies changes with each of the beds whereby it is difficult to present “definitive” characteristics of each. In particular. Beds B, C and D appear to have a very limited distribution outside the field trip area. During the field trip Bed C, associated with the Sequence Lag, will have the most diverse lithologic aspects where at Big Brook it will be more of a silty sand, while at Ramanessin Creek it will be a coarser granule clast sand. Its chronostratigraphic position with regard to Beds B and D along with the presence of the Sequence Lag is what “defines” this unit. Bed B also varies in regard to its thickness, degree of bioturbation, and content of silt versus clay versus sand. Bed B is fairly consistent with its “Wenonah lithology” of having visible quantities of mica and lignite, although actual concentrations vary. The lateral change for Bed D involves the amount of glauconite that varies as well the degree of bioturbation where both quartz sand and glauconite can be well mixed. The Sequence and other lags also laterally vary with abundance and types of clasts (phosphate versus calarenite, siderite, or quartz granules). Sometimes the clasts are barely visible while in other places they form a conglomerate type layer. Another problem with horizons that contain lags is that bioturbation disturbs its planar aspect. Beds A also vary greatly with regard to thickness and its quartz sand beds versus finer textured beds (although we will not get to inspect this on the GANJ field trip) whereby individual beds within this unit have a limited lateral distribution.

Other examples of lateral changes include, as previously noted, Gallagher and Hanczaryk (2019, in this volume) reporting a 0.2 meter-thick, yellowish gray quartz sand between Beds B and C that is not seen at planned GANJ stops. At Matawan, New Jersey, to the northeast of the field trip area, Miller *et al*. (2019, Figure 1) who show what appears to be Beds A (and B?) with a very thin sand that might be Bed C (or is the bed noted by Gallagher and Hanczayrk, 2019?), but no Bed D and then Bed E.

DISCUSSION

As previously reviewed, Miller et al. (2004) recognize the Sequence Lag at the base of Bed C as the basal Navesink Sequence (“Formation”). From a physical feature perspective, whether based on a glauconitic lithology or their poorly defined lags, either the basal contact of Bed D or Bed E would be better candidates to define the basal Navesink whether in terms of a lithologic formation. (As of this writing, I am undecided as to which of these beds would be a better candidate to define either Formation or Sequence for the Navesink.) Interestingly, Miller et al. (2004) does not reference the previously noted allostratigraphic study of Poag and Ward (1993). Would their physical stratigraphic, proposed allostratigraphic formational names based on unconfomities, in regard to “sequence names” be potentially less confusing than the use of lithostratigraphic terms?

A big question is whether the thinner near strandline deposits exposed in Monmouth County and elsewhere along the Coastal Plain represent depositional events not preserved (due to erosion or non-deposition) in thicker subsurface deposits? This could be due to near-shore sedimentation during a lowstand event. Another possibility is that such detail in these deposits does exist, but is difficult to collect. For example, six to ten feet of sediments is the seismic line that denotes a sequence boundary, although it might preserve one or two million years of history. It is also a difficult interval to collect core data from due to the irregular contacts associated with the coarse clasts found in a lag when compared to a surface exposure.

Possibly the greatest technical error that I have written in this paper is in reference to the lag between Beds B and C where I refer to it as the “Sequence Lag”. What if it is not? What if it is analog to the Maastrichtian-Danian Stage Boundary better known as the Cretaceous and Paleogene (K/Pg or K/T) Boundary? In New Jersey, stratigraphic data at the K/Pg boundary suggests an exotectonic (“impact”) event that caused sea level change from a large-scale tsunami. Maybe the noted Sequence Lag represents a similar type of eustatic event? (whether derived from a mega-earthquake or impact event). An immediate candidate is the Wetumpka impact structure in Alabama, although King (1997) suggests this to be early Campanian, making it much too old to be the source of the noted lag.

CONCLUSIONS (MORE STUDY!)

The use of the formation name “Navesink” to classify sequences is confusing and has led to miscommunication among various studies. This noted confusion has led to a new form of debate with regard to the identification of Coastal Plain sediments as suggested by the small number of examples found in this guidebook. A potential positive is that it has also forced the geologic and paleontologic communities to better focus on "where" their data is coming in terms of time and space along with "what" defines the Wenonah, Mount Laurel or Navesink formations. The historical use of formations was to identify lithologic units: albeit with paleontologic and depositional cycle connotations. New names, whether the allostratigraphic ones proposed by Poag and Ward (1993) or totally original names instead of "established" although "debated" lithologic names, are recommended for identifying stratigraphic sequences (see Owens et al. 1998 for one way to present this data using "Kc cycles").

A final thought: since the 1940's (see Ramsdell, 1958) there has been differences of opinion on how to define the various Cretaceous stratigraphic units reviewed here. This was in a time of geosynclines and the outrageous hypothesis of continental drift. Since then we have lost geosynclines while "discovering" plate tectonics, sequence stratigraphy and impact events as new ways to look at the environmental conditions that ultimately affect the deposition and distribution of sediments. I suspect, in another 80 years there will still be some degree of debate in how we communicate what we see in these sediments.

ACKNOWLEDGEMENTS

I've been visiting the noted Monmouth County locations, notable Big Brook, for some forty years and have discussed with many individuals what the exposures are trying to tell us (you know who you are). In the past two years, it has been many interesting discussions with fellow members of the Monmouth Amateur Paleontologists Society (MAPS), notably with (in alphabetical order) Steve Ballwanz, Wayne Callahan, and Ralph Johnson that led to the idea of the GANJ conference and this paper. Field visits with Peter Sugarman of the NJ Geological and Groundwater Survey (NJGWS) further helped me to understand the different opinions of the first three noted individuals. Some of these individuals, along with Ken Miller (Rutgers University) and Bill Gallagher (Rider University) contributed papers to the guidebook that greatly assisted me in understanding the current interpretations of the Cretaceous in Monmouth County. Tim Macaluso (Brookdale Community College) reviewed a draft and gave useful comments. It must be emphasized that these individuals do not necessary concur with everything that has been expressed in this paper.

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Geologic Control of Hydrostratigraphic Units in Monmouth County, New Jersey

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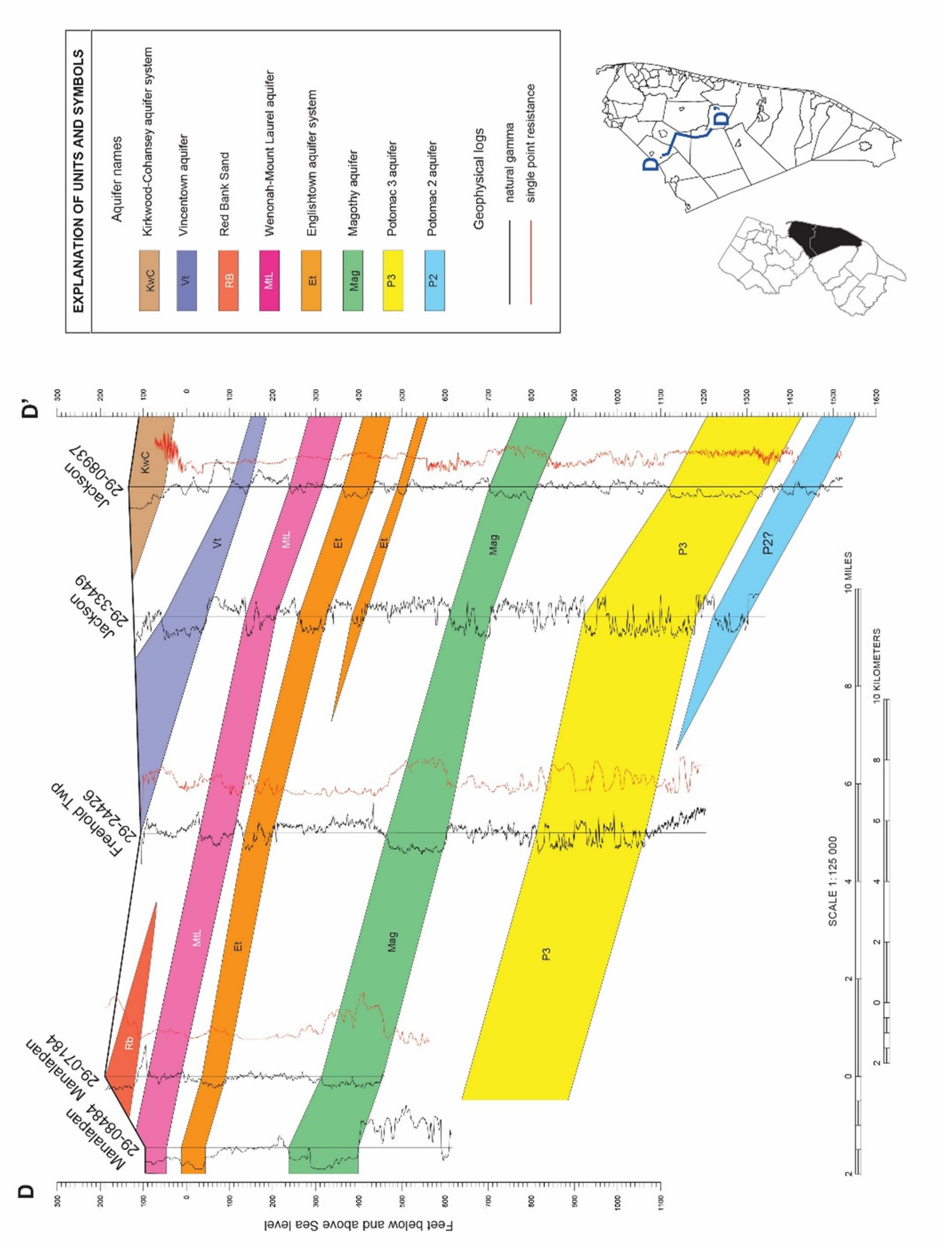
Bedrock geologic mapping coupled with corehole drilling and correlation of borehole geophysical logs has allowed better understanding of the hydrostratigraphic framework in Monmouth County, including the identification, extent, and connectivity of aquifer sands. Lateral facies changes in the subsurface and hydraulic interconnections between geologic formations have a pronounced effect on current water level distributions in aquifers. Twenty bedrock formations ranging in age from Late Cretaceous to Miocene contain four major aquifers: 1) Middle PRM/Farrington aquifer (PRM=Potomac-Raritan-Magothy aquifer system), 2) Upper PRM aquifer/Magothy, 3) Englishtown aquifer system, and 4) Wenonah-Mount Laurel aquifer; and three minor aquifers: 1) Red Bank sand, 2) Vincentown aquifer and 3) Kirkwood-Cohansey aquifer system. Non-marine sands in the Potomac Formation (part of Middle PRM) were deposited in upper and lower delta-plain environments, are isolated sands within floodplain confining clays, and stack to form a major aquifer that is a maximum 200 ft thick in Monmouth County (e.g. in the corehole at Freehold). The Middle PRM aquifer is correlative with the Potomac Formation, unit 3, based on pollen, and with the Farrington Sand Member of the Raritan Formation. The Upper PRM aquifer is dominantly a marginal marine estuarine – deltaic sand that is the most extensive and continuous of the PRM aquifers. It reaches a maximum thickness of 200 feet and is composed primarily of the Old Bridge Sand Member of the Magothy Formation and locally the Sayreville Sand of the Raritan Formation. The Englishtown aquifer system consists of an upper and lower sand unit that were deposited in delta front and shoreface environments. The sand varies from 40 feet thick near the outcrop to over 140 feet thick near Red Bank. The upper sand is the main aquifer sand in Monmouth County and is separated from the lower sand by a confining unit, which is 70 feet thick in the corehole at Sea Girt. The Wenonah-Mount Laurel aquifer varies in thickness between 60 and 80 feet in Monmouth County. Sands were deposited in variety of depositional environments including shoreface, delta-front and inner shelf. Rapid facies changes result in the variable thickness and grain-size variations of aquifer sands in the Wenonah-Mount Laurel. This is especially true in its outcrop belt where the Mount Laurel sand is not locally present. The Red Bank sand and Vincentown aquifer are minor aquifers that are thickest in outcrop (nearly 100 feet) and pinch out several miles downdip due to facies changes to finer grained clay-silt confining beds. The Cohansey sand component within the Kirkwood-Cohansey aquifer system is a thick, medium-coarse sand. The limited lateral continuity of the Cohansey owing to its “outlier” configuration in the outcrop belt, and the mostly fine-grained nature of the underlying Kirkwood Formation limits the productivity of the aquifer and thus its ability to supply large quantities of water in Monmouth County, in contrast to areas further south.


EXPLANATION OF UNITS AND SYMBOLS
Aquifer names
KwC Kirkwood-Cohansey aquifer system
Vt Vincentown aquifer
RB Red Bank Sand
MtL Wenonah-Mount Laurel aquifer
Et Englishtown aquifer system
Mag Magothy aquifer
P3 Potomac 3 aquifer
P2 Potomac 2 aquifer
Geophysical logs
natural gamma
single point resistance
D
D'
Manalapan 29-08484
Manalapan 29-07184
Freehold Twp 29-24426
Jackson 29-33449
Jackson 29-08937
KwC
Vt
Rb
MtL
Et
Mag
P3
P2?
Feet below and above Sea level
SCALE 1:125 000
10 MILES
10 KILOMETERS

What is a Lowstand Deposit in the Coastal Plain? The Mount Laurel-Navesink Formational and Sequence Boundary Contacts

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The Navesink/Mount Laurel Formation contact of the New Jersey Coastal Plain, which also contains the disconformable Campanian/Maastrichtian boundary, is poorly understood despite extensive study of its fossil beds. The underlying Wenonah Formation sandy silts coarsen upward in downdip coreholes from prodelta to shoreface. In updip sections (e.g., Hop Brook), differentiation of the two formation is more difficult because the Wenonah becomes sandier and the Mount Laurel also show tidally influenced delta front facies. The top of the Mount Laurel/base of the Navesink contains a lag unit that varies in thickness from a thin lag (<1 ft) of cemented calarenite nodules (Big Brook), to 2-3 ft coarsening upward lag (Rt. 34), to a 5+ ft lag (Hop Brook). This lag unit: 1) overlies an irregular, erosional, iron-cemented surface overlain by a phosphorite pavement that provides the largest gamma log signature in the coastal plain; 2) contains a lower section of rip-up clasts; 3) generally coarsens up; and 4) is overlain at an upper erosional surface by the Navesink. The Navesink is a clayey glauconite sand with a basal shell layer that fines up to a gypsiferous layer. The Navesink transitions in updip sections to a silt (Sandy Hook Member, Red Bank Formation) and an upper sand (Shrewsbury Member, Red Bank Formation) that progressively change upsection from swaley to hummocky cross-stratified beds (HCS, lower shoreface) to planar lamination in shallowing up shoreface environments. In downdip sections, the Red Bank facies are missing and chocolate glauconitic clays ("the New Egypt Formation") dominate. The complexity of lithostratigraphic units and facies can be simplified by considering the observations in a sequence stratigraphic framework: 1) the Wenonah silts and Mount Laurel shore facies sands and delta front interlaminated clays and sands are prograding, shallowing upward Highstand Systems Tracts (HST) of the Marshalltown sequence; 2) shoreface or delta front facies of the Mount Laurel Formation sensu stricto are disconformably overlain by the lag unit; 3) this disconformity is a sequence boundary (SB) that reflects a major global mean sea-level fall at the Campanian/Maastrichtian boundary (ca. 71.5 Ma); 3) the lag unit is a regressive Lowstand Systems Tract (LST) overlain by a Transgressive Surface (TS) a local erosional surface; 4) the Navesink Formation sensu stricto is the Transgressive Systems Tract (TST); and 5) the Navesink contains the Maximum Flooding Surface near its top at the gypsiferous layer.

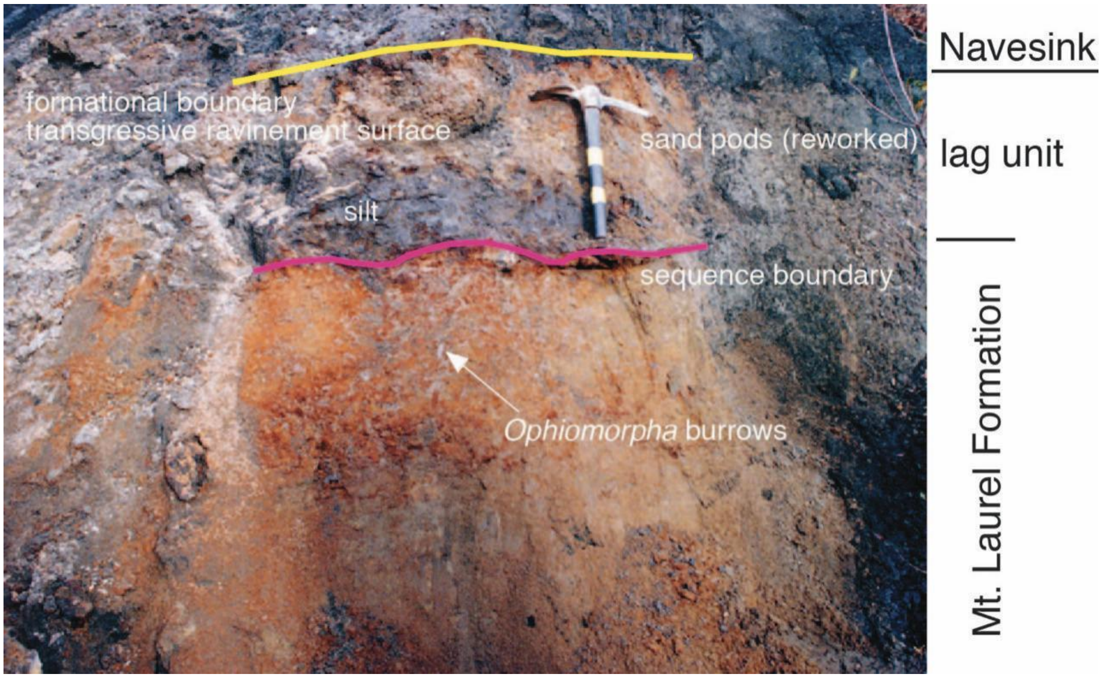

Figure 1. Navesink-Mount Laurel contact and sequence boundary, Route 34, Aberdeen, NJ.

Some of the Common Cretaceous Fossils of Big Brook and Ramanessin Creek

James O. Brown[1,2] and John Morano[2,3]
[1]GANJ; [2]MAPS; [3]Monmouth University

The three formations (Wenonah, Mount Laurel and Navesink) as found at Big Brook, Ramanessin Creek and elsewhere in Monmouth County (see elsewhere in this guidebook for locations) can yield a high diversity of fossils (see Richards, 1958 and 1962 for examples). However, in terms of "common" macrofossils, that can be found during any given visit to these and other nearby localities the list is quite small. It consists of several mollusks (*Exogyra, Pycnodonte, Agerostrea, Belemnitella*), a brachiopod *(Choristothyris*), a ghost shrimp (*Mesostylus* formerly known as *Protocallianassa*) and shark teeth. This observation is based on over forty years of collecting by one of the authors. Photographs of these and a few other "critters" that might be found during a casual collecting trip are presented in this paper[1]. Taxonomic identifications are based on visual inspections of illustrated specimens as presented in Richards (1958 and 1962) and Welton and Farish (1993) along with the use of https://paleobiodb.org and https://fossilworks. The New York Paleontological Society has a field guide on Big Brook (Rose, 2001) that shows additional fossils that one can also potentially find on any given field trip.

Biased in the Fossil Record

The reason for the abundance of the noted invertebrates is in part due to their being keystone species of their marine environments. A second, more significant, reason for all of the above noted fossil groups is due to their mineralogy in terms of crystalline structure and chemistry of the organisms' hard parts. This mineralogy enabled these hard parts to first survive Cretaceous ocean chemistry (whose water was much different than that of today as indicated by the abundance of glauconitic sediments) and sedimentary cycles (as discussed elsewhere in this guidebook). Then there are post-depositional diagenetic processes notably from bioturbation, biodegradation, groundwater circulation causing dissolution and mineralization. All of these biogeochemical processes suggest that many other "keystone species" and their representative environments are not well preserved.

Calcite versus Aragonite

The noted mollusks (Figures 1, 2, 3, 4) and brachiopod (Figure 5) are derived from and characteristic of the Mount Laurel and Navesink Formations (in Richards 1958 and 1962). Besides being keynote species representing "hard bottom" oyster bed environments (Figures 3 and 6), their preservation is probably due to calcite shells with low magnesium (Mg) content[2]. Railsback (2006) gives a summary of carbonate solubility that helps to explain this taxonomic bias. Two other bivalves commonly found, although usually in fragmentary form within these beds, that also apparently have low-Mg content calcite shells are *Spondylus* (*Dianchora)* (Figure 7) and "*Pectens*" (Figure 8).

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[1] Most of the photographed specimens by the late Jim Reme are examples from the Monmouth Amateur Paleontologists Society collection where the photographed examples shown may not have been directly derived from the two sites discussed in this paper.

[2] As far we are aware this hypothesis has not been tested regarding the geochemistry of these shells and is an example of one of many potential research projects highlighted by this GANJ trip.

Abundant Arms and Rare Bodies

Mesostylus (“*Protocallianassa”)*, is probably one of the most abundantly preserved megafossils to be found in all three formations at the two localities. However, most collectors don’t immediately find the arm fragments of this “ghost” shrimp. One reason, is due to the small size of their individual arm appendages of about 1 centimeter and rarely 1.5 cm length (Figure 9A). Less commonly found are articulated arms (Figure 9B) that can be about 4 centimeters long. A second reason these arm appendages are difficult to find is due to their dark color and general rock-like appearance (Figure 9).

Figure 1. *Exogyra costata* SAY

Figure 2. *Pycnodonte convexa* (SAY)

Mesostylus is referred to as a “ghost shrimp” in probable reference to its soft body (carapace). It is another example of bias in the fossil record albeit in terms of “what hard part” of the organism is preserved. Apparently the commonly fossilized arm appendages had more calcium phosphate than the rarely fossilized carapace. This difference in body chemistry is found in other crustaceans. Boßelmann *et al.* (2007) suggests that the arms are harder than the "body" due to mechanical requirements notably for burrowing in sediments. This would make sense, for *Mesostylus* is considered to be the source of the common ichnofossil *Ophiomorphia* (Figure 10) where the arms would be used in burrowing through sediment.

Shark Teeth

In general, several genera of sharks and rays (Figures 11 through 17) are represented by their erosion-resistant fluroapatitic teeth. Also present, due to their chemical and physical resistance to erosion and diagenetic processes, are bowl-shaped drum fish teeth (Figure 18). While these teeth are present in all three formations, they are more prevalent in the coarser textured lenses and beds of the Wenonah and Mount Laurel Formations.

Figure 3. *Agerostrea mesentrica* (MORTON). Several other species of this genus are also common.

Figure 4. *Belemnitella Americana* (MORTON). While the endoskeleton is common, the hardened clay cone-shaped phragmocone cast shown in the upper right corner is not always easy to find.

Figure 5. *Choristothyris plicata (*SAY). In general, when compared to mollusks, brachiopods are not diverse or very common. This particular species is the one most typically collected.

Figure 6. Oyster beds in the Navesink Formation at Big Brook. Colts Neck Township, NJ (Location BB-4 of GANJ XXXVI Road Log). Red circles highlight some of the shells. Photo by Bill Gottobrio, Golder Associates

Figure 7. *Spondylus (Dianchora) echinata* (MORTON)

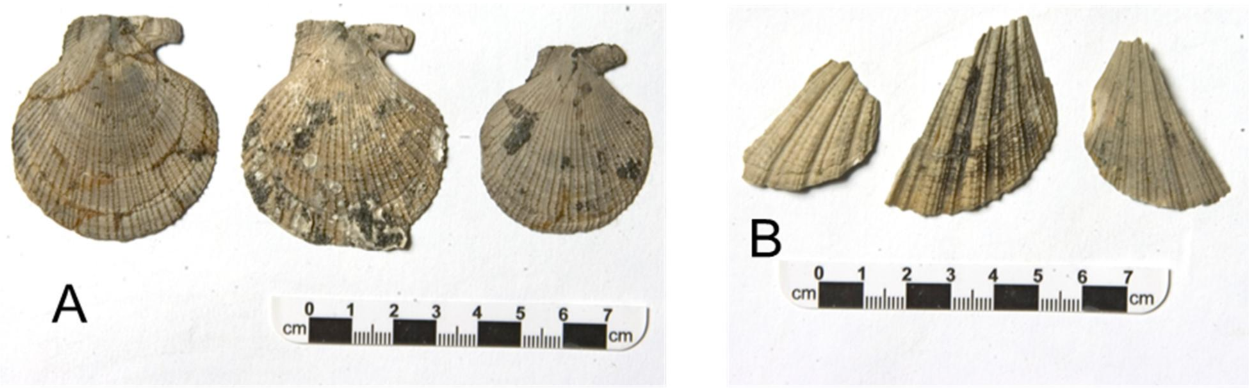

Figure 8. Pectens: A. *Pecten whitfieldi* WELLER
B. *P. craticulus* MORTON

Ichnofossils

There are three fairly common ichnofossils found that also contribute to the post-mortem bias of the fossil record. One is the previously noted *Ophiomorphia* (Figure 10) derived from the burrowing activity of crustaceans such as *Mesostylus* (Figure 9). A second is *Clionia* (Figure 19) which may also be consider a "body fossil" as it represents the occupied tissue area of a boring sponge. Figure 19 shows how original calcium carbonate shells are destroyed, but also replaced by the "cell-colony" of the sponge animal. A third ichnofossil commonly found on concretions (that may or may not have an organic origin such as mineralized wood) is *Gastrochaenolites* (Figure 20). These tear-drop shaped impressions are derived from boring[3] clams such as *Lithophaga carolinensis* (Figure 20).

"Almost" Common Fossil

Remains of both ammonites and gastropods are also commonly found, although typically as fragmentary molds and casts composed of clay minerals, surrounding sediments (such as quartz sand grains or glauconite) or siderite. This includes various species of the ammonite *Baculites* (Figure 21) from the Wenonah and Navesink Formations. The ammonite *Placenticeras* (Figure 22), notably individual septum, is also commonly found in the Wenonah Fm. Elsewhere in Monmouth County, at the Atlantic Highlands, an extensive ammonite fauna has been collected at the basal Navesink Fm. (see Cobban 1974). Internal casts (steinkerns) of gastropods are quite frequent, especially pieces of whorls. Two common genera are *Gyrodes* (Figure 23) and *Turretella* (Figure 24). However, less common are molds, casts or remineralized "original shell" preserving the exterior shell ornamentation and aperture that are useful in specific identification. This preservation-bias is also true for some bivalves such as *Inoceramus* (Figure 25), "*Cardium*" (Figures 26 and 27), and Cucullaea (Figure 28).

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[3] In terms of ability to drill through rock or wood and live there: not in terms of lacking a dynamic personality.

Figure 9. Ghost shrimp: A. Red circled cross-sections of appendages *in-situ*;

B. Articulated arm appendages of *Mesostylus mortoni* (PILSBRY)

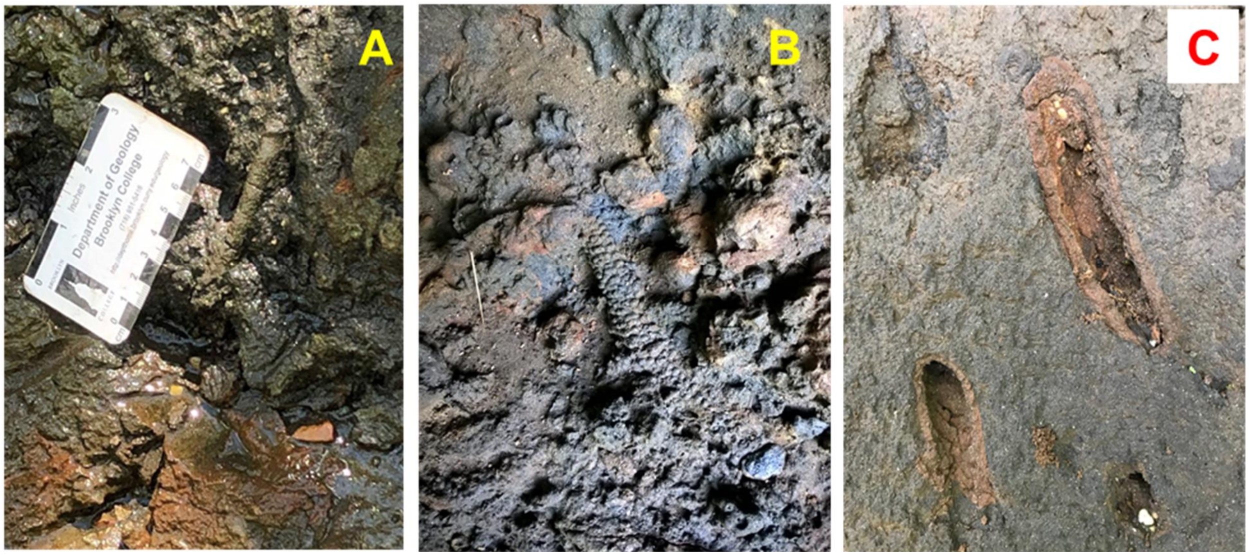

Figure 10. .Examples of the common ichnofossil *Ophiomorphia* and other burrows. These burrows commonly contain *Mesostylus* remains that are believed to be the source of this ichnofossil. Photo A shows the Contact of Beds B and C as discussed in the Road Log (Brown *et al*. 2019) while Photo C is in Bed B showing burrows with coarser particles from Bed C. Photo A from Big Brook. Colts Neck. NJ by Mark Zdziarski, NJCU. Photo B by Steve Ballwanz and Photo C by Joanna Bednarek, NJGW: both from Ramanessin Creek, Holmdel, NJ.

Figure 11. *Scapanorhynchus texanus* (ROMER): Goblin shark

Figure 12. *Cretoamna appendiculata texanus* (AGASSIZ): Mackerel shark

Figure 13. *Squalicorax pristodontis* (AGASSIZ): Crow shark

Figure 14. a. *Squalicorax kaupi* (AGASSIZ): Crow shark

b. *Cretolamina appendiculata pachyrhiza* HERMAN: Mackerel shark

c. *Odontaspis samhammeri* CAPPETTA & CASE: Sand shark

d. *Odontaspis hardingi* CAPPETTA & CASE: Sand shark

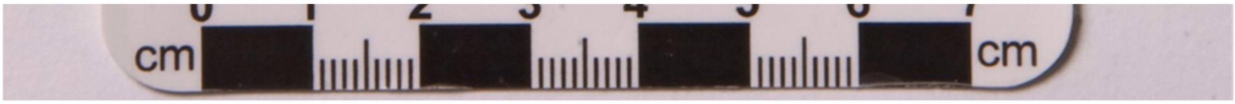

Figure 15. *Plicatolamna arcuata* (WOODWARD): *Mackerel shark*

Figure 16. *Ischyrhiza mira* LEIDY*:* Sawfish rostral teeth

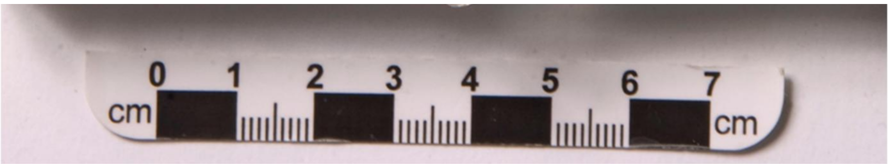

Figure 17. *Brachyrhizodus wichitaensis* ROMER: Ray Teeth

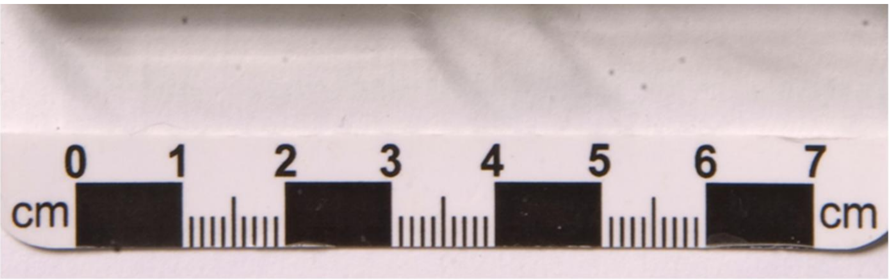

Figure 18. Pycnodontiform fish teeth (*Anomeodus*? Sp.)

Other Fossils

During any given collecting trip, one is sure to find other fossils beyond those discussed. These other fossils are typically found as molds and casts (see Figures 23 through 28 for examples) or as remineralized siderite (Figures 21 and 22). As indicated by Appendix D of Richards (1962), the diversity of gastropods ("snails") is almost equal to that of bivalves, yet "original shell" preservation such as that of an *Exogyra* is comparatively rare. What this *implies* for a majority of shelled organisms that "should be" as easy to find as fossils is that their hard parts were either aragonitic or intermediate to high magnesium – content calcite that dissolved shortly after deposition or subsequent diagenetic processes (see Railsback 2006 for a summary of carbonate solubility that helps to explain this taxonomic bias).

CONCLUSION

We have attempted to summarize some of the more common megafossils to be found at this year's GANJ field stops. In addition, we have also tried to explain why their presence may not just be due to their possibly being keystone species of past Cretaceous environments, but also due to their hard pasts being chemically and physically resistant to depositional, erosional and diagenetic processes.

Figure 19. Examples of shell replacement, from left to right, of *Pycnodonte*, a belemnite and two gastropods by *Cliona cretacica* FENTON & FENTON

A.

Figure 20. While the body fossil A. *Lithophaga carolinensis* (CONRAD) is not very common, its ichnofossil B. *Gastrochaenolites* sp. (LEYNERIE) is abundantly found in concretions.

Figure 21. Baculites texanus KENNEDY & COBBAN

Figure 22. Placenticeras minor KENNEDY & COBBAN

Figure 23. *Turrirella* sp.

Figure 23. *Gyrodes* sp.

Figure 25. *Inoceramus* sp.

Figure 26. *Trachycardium longstreeti* (WELLER)

Figure 27. *Granocardium* sp.

Figure 28. *Cucullaea neglecta* (GABB)

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Paleontology of the Campanian-Maastrichtian Boundary at Marlboro, Monmouth County, New Jersey; Taphonomy, Biostratigraphy and Depositional Environments

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ABSTRACT

The Late Cretaceous exposures along the banks of Big Brook and its tributaries have long been a source of significant fossil vertebrate remains and numerous invertebrate fossils. Most specimens have been found in the stream bed gravels that concentrate a variety of fossils from several different sources. Because of the difficulty and danger of digging in the steep streambank exposures, the origin of the vertebrate remains found in the stream placers has been poorly constrained. As a result of a recent construction project, we had the opportunity to sample and study a fossiliferous layer in the Mount Laurel Formation. Stream bed sampling for fossils done in conjunction with this excavation demonstrated that the bulk of vertebrate specimens are originating upstream and in the upper tributaries where the Wenonah and Mount Laurel Formations are better exposed. This establishes that the majority of the vertebrate remains found in the brook and its tributaries are probably Late Campanian in age, rather than Maastrichtian. Taphonomic studies determined the faunal composition of this bed, the relative fossil abundances, and orientation of fossils at several levels. The topmost fossils in this fossiliferous concentration are oriented with a northeast-southwest axis, parallel to the paleoshoreline. Vertebrate fossils from the Mount Laurel fossiliferous layers are durable elements that are commonly found in the stream gravel placers; invertebrate fossils from this bed are relatively underrepresented in the stream bed gravels because they are mostly delicate internal molds that do not withstand transport. Vertebrate fossils from the Matawan Group formations are more likely Judithian in age, and Monmouth Group fossils are Lancian in age.

INTRODUCTION

New Jersey figured prominently in the early development of the science of paleontology in North America, and although the fossiliferous deposits of the New Jersey coastal plain have been investigated for two centuries, new discoveries and ideas are still emerging from these classic sections. In the northern section of the coastal plain outcrop belt, the Newark Supergroup beds of the Piedmont Lowlands border the northeastern margin of the inner coastal plain, underlain by sediments of Late Cretaceous to Early Tertiary age. Especially in Monmouth County, the Upper Cretaceous beds are exposed along a number of stream courses; one of the distinctive sediments of the inner coastal plain, glauconite, is often seen in the stream bank outcrops. Glauconite is also known as greensand marl, and it was in the past widely dug in New Jersey for use as a soil conditioner. The town of Marlboro is named for the exposures of greensand marl in the vicinity which were mined here in the nineteenth century.

In 1865, George Cook, Professor of Geology at Rutgers College and the first State Geologist of New Jersey, obtained a set of fossil bones from a marl pit on the farm of the Reverend Schenck, along the banks of the Big Brook in Marlboro. Some of the bones displayed a hollow interior, like the leg bones of birds. Cook took these bones to Joseph Leidy of the Philadelphia Academy of Natural Sciences. Leidy made these remains part of the cotype of Coelurus antiquus, the first skeletal material of a carnivorous dinosaur described from North America (Leidy, 1865). The bones are essentially the foot and lower leg bones of a smallish coelurosaurian dinosaur, and are now reposited in the American Museum of Natural History as AMNH 2550, 2551, 2552 and 2553.

Since then Big Brook and vicinity have yielded numerous specimens for private and professional collectors (see Figure 1 for map). The usual method of collecting here is to sieve the stream bed gravels and point bars for their placer concentrations of transported fossils. The typical contents of such a sieve would be the mollusks *Exogyra, Pycnodonte,* and *Agerostrea,* belemnite pens (*Belemnitella americana*), the little brachiopod *Choristothyris plicata,* and shark teeth of several species (*Scapanorhyncus texanus, Squalicorax pristodontus, Cretolamna appendiculata),* plus perhaps a piece of fossil reptile bone. Another method is to dig into the steep stream banks. This is not recommended, however, because of the danger of collapse of the cliff. This practice has caused a series of serious accidents, including a slump in September 1999 that sent a private collector to the hospital for a week. For this reason, it is inadvisable to dig too deeply into the outcrop at this locality. Because of the difficulty in excavating the steep stream banks, the origins of the vertebrate fossils in the brook have remained poorly constrained; fossil assemblages from here have instead often been referred to the undifferentiated Mount Laurel-Navesink (see, for example, Richards *et al*., 1958, p. 24; Lauginiger, 1986; Becker *et al*., 2000).

The rapid pace of development in New Jersey sometimes results in the appearance of temporary outcrops in areas normally covered by soil and vegetation, and the opportunity to collect from these exposures is limited (Gallagher and Parris, 2004). We report here on one such site, Marlboro Manse, a development excavated in the Upper Cretaceous deposits in Monmouth County, NJ. As a result of housing construction, we had the opportunity to conduct taphonomic studies on a fossiliferous horizon in the Mount Laurel Formation, a level only normally seen in limited streambank outcrop in this area. Additionally, subsequent studies focused on streambed fossil concentration and outcrops near Marlboro Manse along a small tributary to Big Brook informally referred to here as Coelurus Creek (see Figure 1). Recent notable finds in the Big Brook drainage system and its beds include a portion of a hollow theropod tibia, the first lungfish jaw plate known from the Upper Cretaceous of North America (Parris *et al*., 2004), and a Cretaceous multituberculate incisor (Grandstaff *et al*., 2000).

STRATIGRAPHY

The section exposed along the banks of Big Brook includes the Wenonah, Mount Laurel, Navesink and Red Bank Formations, in ascending order (see Table 1). In addition, there are Plio-Pleistocene fluvial deposits lining the brook and its tributaries in some places, complicating the stratigraphic picture but also occasionally supplying the remains of Cenozoic mammals to the fossil mix in the stream gravels. The Cretaceous formations are the product of sea level fluctuations along a passive margin, reflecting transgressive, high stand, and regressive system tracts. Our study is concerned with the principal fossiliferous units: the Wenonah, Mount Laurel and Navesink Formations.

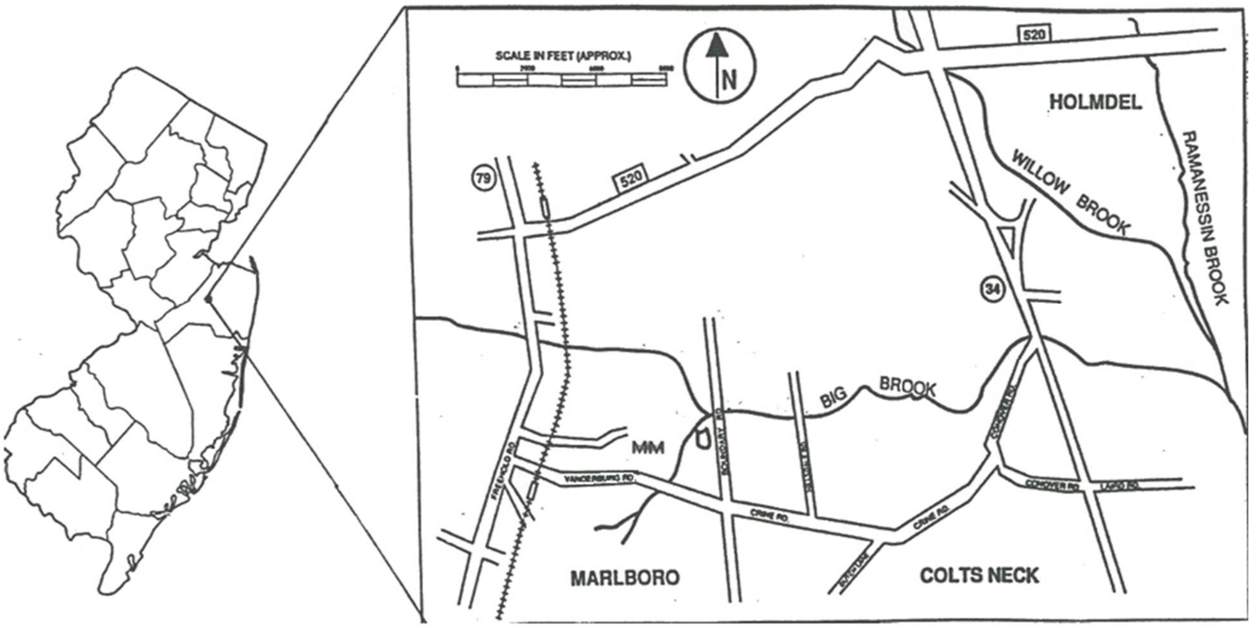


Figure 1. Map of Big Brook in Marlboro and Colts Neck, Monmouth County, NJ. MM = location of Marlboro Manse excavation site. Coelurus Creek runs between Vanderburg Road and empties into Big Brook at Boundary Road.

Table 1. Stratigraphy of section at Big Brook, Marlboro, Colts Neck, Monmouth County, NJ

Era	Epoch	Stage	Group	Formation
Cenozoic	Plio-Pleistocene			“Cape May” Fm.- alluvium
		Maastrichtian	Monmouth Group	Red Bank Fm.
Mesozoic	Late Cretaceous	Maastrichtian	Monmouth Group	Navesink Fm.
		Campanian	Matawan Group	Mount Laurel Fm.
		Campanian	Matawan Group	Wenonah Fm.

The Mount Laurel Formation at the excavation site is a poorly sorted silty fine to coarse quartz sand. Pebbles and lithic clasts of various compositions are found in the fossiliferous layer under investigation. Beneath the base of the fossiliferous layer, the sediments are micaceous, silty, lignitic fine sand, often displaying extensive burrowing, assigned here to the Wenonah Formation. The site is then in the lower part of the Mount Laurel Formation here.

Above the darker gray beds are the lighter quartz sands of the Mount Laurel Formation. Traditionally the Mount Laurel was regarded as Maastrichtian (Richards *et al.*, 1958; Martino and Curran, 1990), but recent practice has been to assign this unit a late Campanian age (Miller *et al.*, 1999). A widespread fossiliferous layer is found at the top of this unit, just under the formational contact with the overlying Navesink Formation (Krinsley and Schneck, 1964; Gallagher, 1984, 1993; Gallagher and Grandstaff, 1996). Although some authors have assigned this fossiliferous bed to the Navesink Formation, lithologically and paleontologically it has more in common with the Mount Laurel Formation. We will follow the usage of Miller *et al.* (1999) in assigning this layer to the Mount Laurel Formation.

The Navesink Formation is a well sorted medium-grained glauconitic sand darker green in color than the underlying fossiliferous layer of the Mount Laurel. The contact between the two formations is abrupt and irregular. The Navesink contains several discrete shell beds primarily composed of oyster fossils (*Exogyra, Pycnodonte, Agerostrea)*, the first of which is about 0.5 m above the bottom contact with the Mount Laurel Formation. The Navesink is usually given a Maastrichtian age.

Miller *et al*. (1999) have interpreted the Mount Laurel-Navesink contact exposed here and at other sites nearby as a sequence boundary caused by glacioeustatic sea level fall. They have concluded that continental glaciation was driving sea level change as far back as the Late Cretaceous. Certainly, our taphonomic work in this study supports the idea of falling sea level in the late Campanian, and the contact between the two formations is quite abrupt. The superjacent Navesink Formation is a transgressive unit containing several oyster bed assemblages in its greensand marl.

An interesting aspect of the contact between the formations is the seemingly abrupt appearance around the boundary of large numbers of *Belemnitella americana* guard shells in the Navesink above, and below in the Mount Laurel fossiliferous layer internal molds of phragmocones and guard shell external molds. *Belemnitella* is usually interpreted as a key indicator of the Cretaceous Boreal fauna, sweeping out of the Russian Platform in the beginning of Late Cretaceous time and moving consecutively across northern European chalk and glauconitic deposits, possibly arriving here via Greenland and Arctic Canada (Christensen, 1975). The arrival of *Belemnitella* here corroborates the idea of a coldwater influx associated with a eustatic lowering in sea level with associated unconformity. Since *B. americana* appears in the upper Mount Laurel Formation, the climatic change probably began in the Late Campanian.

METHODOLOGY

Excavations for construction in the vicinity of Big Brook in Marlboro have offered the opportunity for detailed taphonomic analysis of a fossil assemblage located stratigraphically in the Mount Laurel Formation. As a result of these excavations, we had the rare chance to study one of the main fossil-bearing beds in the area across a horizontal plain; usually the exposures are limited to steep vertical cliff sections which are dangerous to excavate because of the instability of the soft sediment. An area directly over the fossil bearing layer was cleared of vegetation Ten meter-square grids were laid out, quarried, and mapped through a three-decimeter thickness that yielded a concentration of Late Cretaceous fossils. Additionally, we carried out screen washing of bulk matrix samples from the layer of interest. Stratigraphic sections were measured at the excavation site, as well as at thicker sections both upstream and downstream to determine the larger stratigraphic relationships (see Figure 2). The area was originally discovered by Joseph and Sandy Camburn, and sampled from streambed and bank outcrops of the fossiliferous layer.

While mapping fossils in situ, compass orientations were taken on the long axis of the specimen, when possible (see Figure 5). Not all fossils are amenable to such treatment, since specimens such as the large round oyster shells or rounded bone pebbles do not have a readily determinable long axis. Long axis orientations were plotted on rose diagrams indicating two tails for the compass orientations. We divided the plots into top, intermediate and bottom decimeter intervals.

To determine the distribution of fossils in the stream bed gravels, we sampled the gravels at a series of points along Big Brook from Hillsdale Road bridge in Colts Neck Township to the tributary just upstream from Boundary Road bridge in Marlboro. In this way we could determine the patterns of fossil input into the commonly collected fossiliferous placer concentrations in the stream, and demonstrate biases resulting from collecting methods and erosional destruction of fossils.

Further sampling of the stream informally designated herein as Coelurus Creek (a.k.a. Kovalski Tributary) by students in Rider University classes, primarily in the GEO 168, MAR 210 and MAR 325 courses, has produced additional data regarding source and distribution of fossil clasts in the streambed placer deposits. Some of this more recent work is presented here to elucidate and corroborate the presented hypothesis (Grapski *et al.*, 2019, this volume). The Rider streambed sampling started as part of the Discovery Program for inquiry-based science education, and further publication of this aspect is planned for teachers' use (Gallagher, in prep).

FAUNISTICS

The *in situ* assemblage excavated at Marlboro Manse is predominantly composed of marine invertebrates with a mixture of marine and terrestrial vertebrate elements. The marine invertebrate fossils occur primarily in the form of fragile molds and internal casts. The vertebrate remains are almost always isolated single elements, often worn or abraded in appearance.

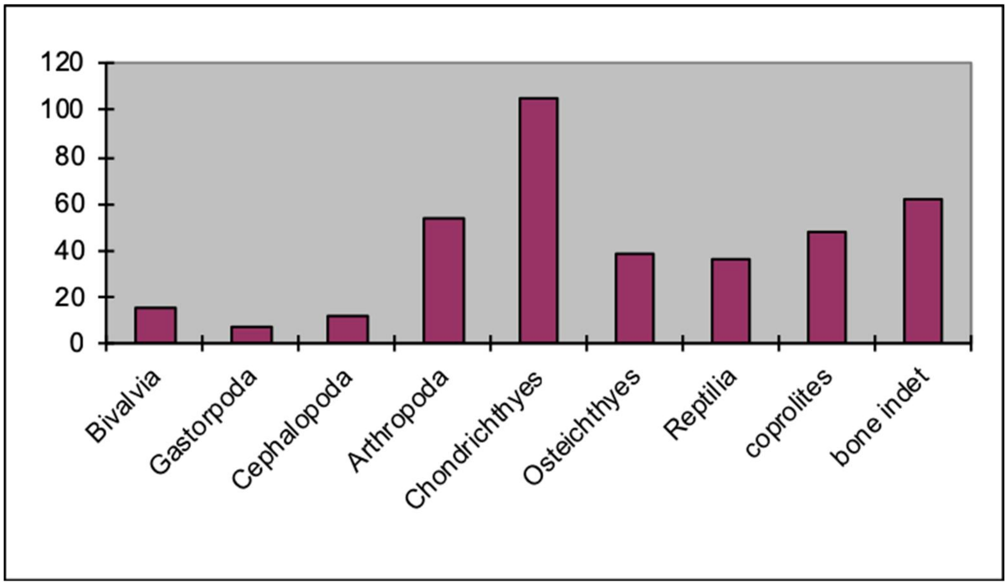
Among the invertebrates, the mollusks are most abundant. A conspicuous component of the fauna is the inoceramid *Inoceramus vanuxemi* (= *I. conferatim-annulatus* of previous authors; see Richards *et al.*, 1958). Richards *et al.* (1958, p. 98) reports this as a rare taxon in the Mount Laurel-Navesink interval of New Jersey, but it was unquestionably the most common larger bivalve in this excavation, and we have encountered it elsewhere along Big Brook in stacked clusters (NJSM 13890) from the Mount Laurel Formation. Other bivalves collected at the excavation site include fragile *Exogyra* shells, *Agerostrea*, and *Liopistha*. Gastropods make up a smaller part of the fauna. These are usually steinkerns (internal molds).

Cephalopods are numerous, with abundant belemnites of the species *Belemnitella americana* found in the assemblage. Heteromorph ammonites are preserved in excellent detail from some of the concretionary masses toward the bottom of the fossiliferous layer. One significant discovery made during the course of excavation was the delicate internal mold of a large baculitid, cf. *Baculites grandis*, which may be the largest specimen of its genus found thus far in New Jersey.

Crustaceans compose the remainder of the invertebrate fossils. The bulk of the crustacean fossils are in the form of claws of the ghost shrimp *Callianassa mortoni*. This is not surprising since tubes of the trace fossil form genus *Ophiomorpha* are found both in the layer under investigation as well as in underlying beds. There are also a few carapaces of true crabs.

Vertebrate remains are dominantly chondrichthyan, including abundant shark teeth of several species, shark vertebrae, chimaeroid jaw elements, batoid vertebrae, a rare and unusual batoid chondocranium, and sclerorhynchid rostal fragments and rostral spines. Other vertebrate fossils uncovered during the course of this investigation consist of bony fish remains (mostly *Enchodus*), turtle shell, crocodile teeth, mosasaur teeth, hadrosaur teeth, coprolites, and indeterminate bone pebbles. A multituberculate incisor was recovered by screen washing of matrix from the fossiliferous layer (Grandstaff *et al.*, 2000). See Table 2 for a graphic summary of faunal abundances of excavated taxa in the streambed outcrop at Marlboro Manse.

Table 2. Graphic Summary of Faunal Abundances of Excavated Taxa at Marlboro Manse

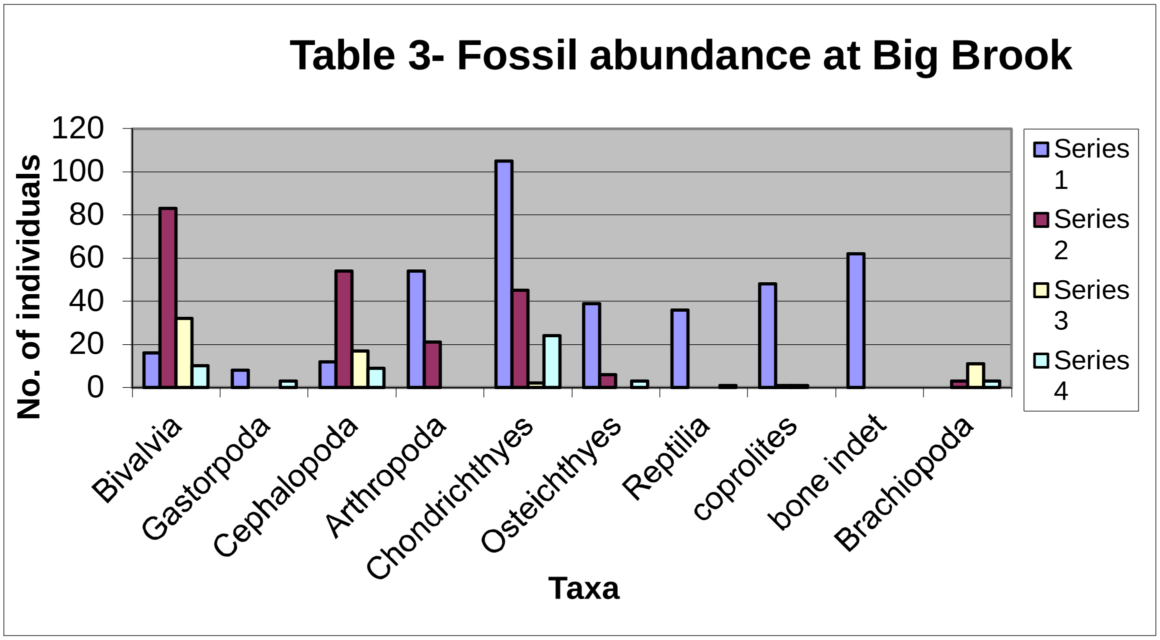


Based upon a sample size of several thousand specimens, the most common fossils found in the Mount Laurel bed were the remains of sharks, principally teeth. This bed and subjacent fossil concentrations in the Wenonah Formation appear to be the primary source of the vertebrate fossils found in the stream gravels of Big Brook. As recent studies have shown (Gallagher *et al.*, 2014), there is a mix of fossils from the Wenonah, Mount Laurel, and the Navesink Formations in the stream gravels. The bulk of the shell material is from the Navesink, while the Wenonah and the Mount Laurel are supplying most of the vertebrate remains. Additionally, Neogene alluvial deposits contribute reworked Paleozoic fossils in chert pebbles and rare Plio-Pleistocene mammal fossils (Gallagher and Grandstaff, 1996).

STREAM GRAVEL SAMPLING PROGRAM

Initial sampling of Big Brook was accomplished as part of a field exercise for the Paleontology (GEO 303) course at Rutgers University. As part of the program of sampling the stream gravels we were able to quantitatively demonstrate a progressive dominance of vertebrate remains upstream. Near Hillsdale Road Bridge in Colts Neck, the fossils in the stream bed and point bar gravels are unquestionably dominated by shell fossils; although some vertebrate remains are occasionally found, these are usually more resistant specimens such as shark teeth or stouter bone fragments. In our samples, the pattern of faunal dominance reverses from downstream to upstream (see Table 3); bivalves are the most common bioclast in the stream gravels downstream, while shark teeth and other chondrichthyan fossils are more common in the upstream gravel bars, where the Wenonah and Mount Laurel Formations crop out. The difference is that the downstream deposits are a mix of fossils from the Wenonah, Mount Laurel and Navesink Formations, but the upstream deposits are primarily derived from the vertebrate-rich Wenonah and Mount Laurel Formations.

Table 3. Breakdown of fossil taxa abundance along Big Brook: Series 1= Marlboro Manse streambed excavation of Mount Laurel Formation; Series 2= Big Brook stream gravel upstream from Hillsboro Road bridge; Series 3= Big Brook stream gravel at Boundary Road bridge; Series 4= Gravel in streambed at the mouth of Coelurus Creek, tributary to Big Brook just upstream from Boundary Road bridge.



Further sampling at Coelurus Creek was conducted by a series of classes from Rider University as part of GEO 168, MAR 210 and MAR 325 course work over the course of the last decade. Preliminary results show the same pattern observed in the Big Brook stream gravel sampling program in microcosm; stream gravels downstream below where input from the Navesink Formation comes in from the bench side tributary further downstream are richer in original shell material, primarily oysters and belemnites (*Pycnodonte, Exogyra, Agerostrea, Belemnitella, Choristothyris)*. Exposures at the head of Bench Run that empties into Coelurus Creek clearly display the source of such material in streambank outcrops filled with dense concentration of belemnites and fossil oyster shells in the basal part of the Navesink Formation associated with old 19th century marl pits. The dense belemnite bed at the base here in glauconitic sandstone is probably more likely a transgressive lag than the underlying Mount Laurel Formation.

Upstream in Coelurus Creek, past the mouth of Bench Run, the stream gravels have fewer pieces of original shell material in them, primarily small and highly abraded and broken pieces. Chondrichthyan teeth and bits of other vertebrate remains become more common as one goes upstream into outcrop areas of the subjacent Matawan Group exposures and toward the input from Marlboro Manse Run, a tributary coming in from the north on the righthand side of the stream (Grapski *et al*,2019). Clearing off an exposure of the stratigraphic section at the small cliff at the mouth of Bench Run will show a succession of beds from dark gray clay of the Wenonah facies at bottom through 1.5 m of lighter colored iron-stained Mount Laurel fine sand terminated by an abrupt and slightly wavy disconfomity surface above which lies the very differently colored dark green glauconitic clayey Navesink Formation (see Figure 2). This unconformity then represents the Campanian-Maastrichtian boundary in Marlboro.

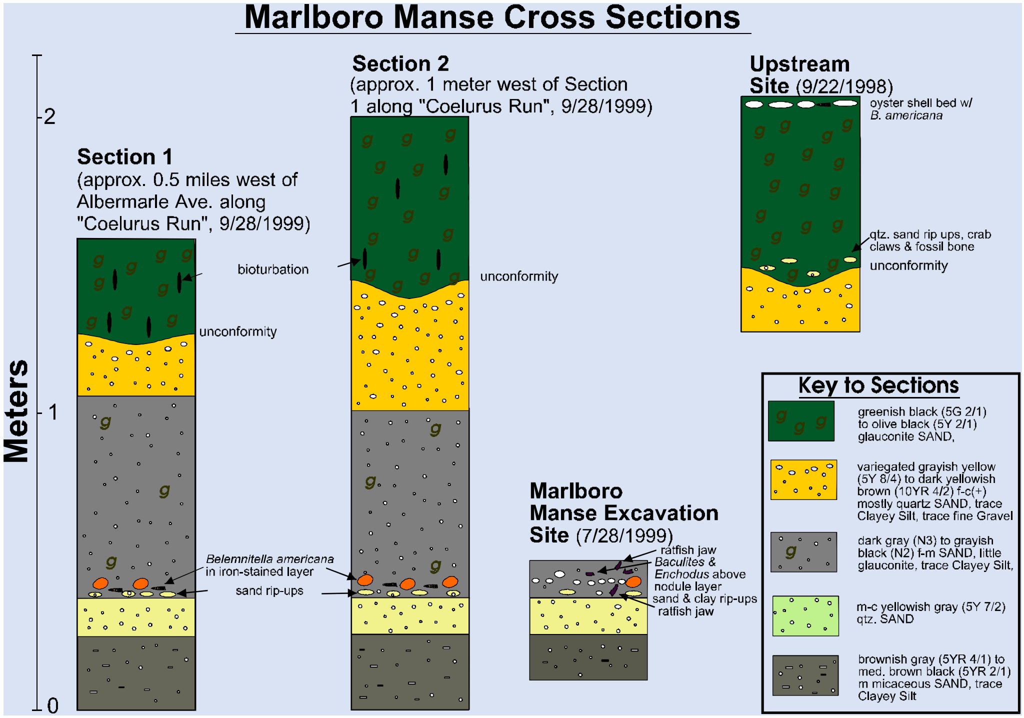


Figure 2. Stratigraphic sections at Coelurus Creek and Marlboro Manse, Marlboro, NJ.

TAPHONOMY

Virtually all of the vertebrate remains recovered during the Marlboro Manse site excavation were single isolated elements. The only possible exception to this was the opercular region of an osteichthyan (NJSM 19687; cf. *Enchodus*) in which several skull bones were associated. Most of the vertebrate material had a worn and abraded look, especially the numerous indeterminate bone pebbles that were uncovered. These taphonomically mature specimens display the highly weathered appearance of transported, reworked bone. From the size and appearance, much of this bone material seems to be from large reptiles, probably either mosasaur or dinosaur. A number of the indeterminate bone fragments are pitted by what appear to be the borings of marine organisms. These pits may be the result of boring by lithophagid clams, which prefer hard substrates for their burrows and which will bore into bone. The overwhelming majority of the identifiable vertebrate fossils were durable elements such as teeth or vertebrae that would survive long-term transport without too much damage. This is as true today as it was back in the Late Cretaceous, when this assemblage was first deposited; the resistant elements from this layer are now contributing to the placer concentrations of vertebrate fossils in the gravels of modern Big Brook.

However, the same is not necessarily true of the invertebrates. Many of the invertebrate fossils from the Mount Laurel layer at Marlboro Manse are delicate internal casts and molds in the loosely consolidated sediment (for example, the fairly common *Inoceramus* molds; see Figure 5); these specimens would be easily and immediately destroyed by erosion, and hence are underrepresented in the stream bed fossil concentrations. Still some of them manage to survive to indicate that this bed is the source of fossil input to downstream placers; smaller abraded specimens of the heteromorph ammonite *Nostoceras monotuberculatum* have been found at the excavation site and in the point bar gravels downstream from Marlboro Manse. *N. monotuberculatum* is only known from the Campanian elsewhere (Kennedy *et al*., 1995), and is not found in the Maastrichtian Navesink Formation.

The taphonomic grid work involved measuring compass directions on the long axes of fossil clasts in the upper Mount Laurel Formation. Orientations from different horizons within the foot-thick fossiliferous layer were plotted on rose diagrams. The data show that the specimens in the uppermost part of the fossiliferous horizon display a preferred orientation of clasts. In the deeper part of the foot-thick layer under study here, fossil clast orientations do not appear to show any preferred direction (see Figure 3). But the uppermost surface of the fossiliferous layer shows a preferred orientation of clasts with long axes directed in a northeast to southwest direction (see Figure 4). This is parallel to the presumed paleoshoreline at this time (Martino and Curran, 1990). Deeper horizons show more of a scatter of orientations. This trend upward suggests that shoreface currents associated with wave action became more important upward in this microstratigraphic section as sea level shallowed. Some of the current sorting effect may be due to increased effectiveness of storm-generated waves and currents as water depth decreased.

As a follow up to determine more completely the faunal composition of the fossil concentration, several grid areas were bulk sampled through the fossiliferous interval and the matrix sorted for small macrofossils and microvertebrate specimens. The original stream bed exposure was also bulk sampled and processed for microvertebrates, small invertebrates, and mineral and rock clasts. The results are presented in Table 4. The data illustrate the abundance of vertebrate specimens, mostly chondrichthyan vertebrae and teeth, that dominate each grid's yield of small fossil specimens from the upper Mount Laurel Formation.

A fossiliferous layer in the top of the Mount Laurel Formation is extensive in the Monmouth County area, and can be traced to other exposures in Holmdel and Matawan Townships (Gallagher, 1984, 1993; Gallagher and Grandstaff, 1996). Further south, the Mount Laurel becomes a thicker sandier unit that contains a mostly molluscan fossil assemblage, for example at old exposures (now largely covered) at Chestnut Run, Sewell, Gloucester County, New Jersey, or at the old Biggs Farm locality and at Reedy Point, both along the banks of the Chesapeake and Delaware Canal in New Castle County, Delaware (Gallagher, 1984). The formation thickens and changes lithology southward (Gallagher, 1993). The presence of the vertebrate-dominated fossiliferous layer at Marlboro and elsewhere nearby in Monmouth County, cannot be attributed to a transgressive lag model, since the Mount Laurel Formation is at the top of a regressive phase (Martino and Curran, 1990; Miller *et al.*, 1999). Wave and current action along a retreating, shallowing shoreline coupled with terrestrial input from a nearby river mouth, tidal inlet or bay could have supplied the conditions necessary for the genesis of the Mount Laurel Formation fossiliferous concentrations. This model is supported by the increasing degree of fossil clast orientation upward in the Marlboro Manse grid sections, and by the highly worn terrestrial and estuarine vertebrate component of the fauna. This model for the fossil concentration implies a time averaged assemblage, so some portion of the fossil material in this bed may have been exhumed and recycled from older deposits including the underlying units of the Matawan Group, all of which are known to contain Campanian fossils.

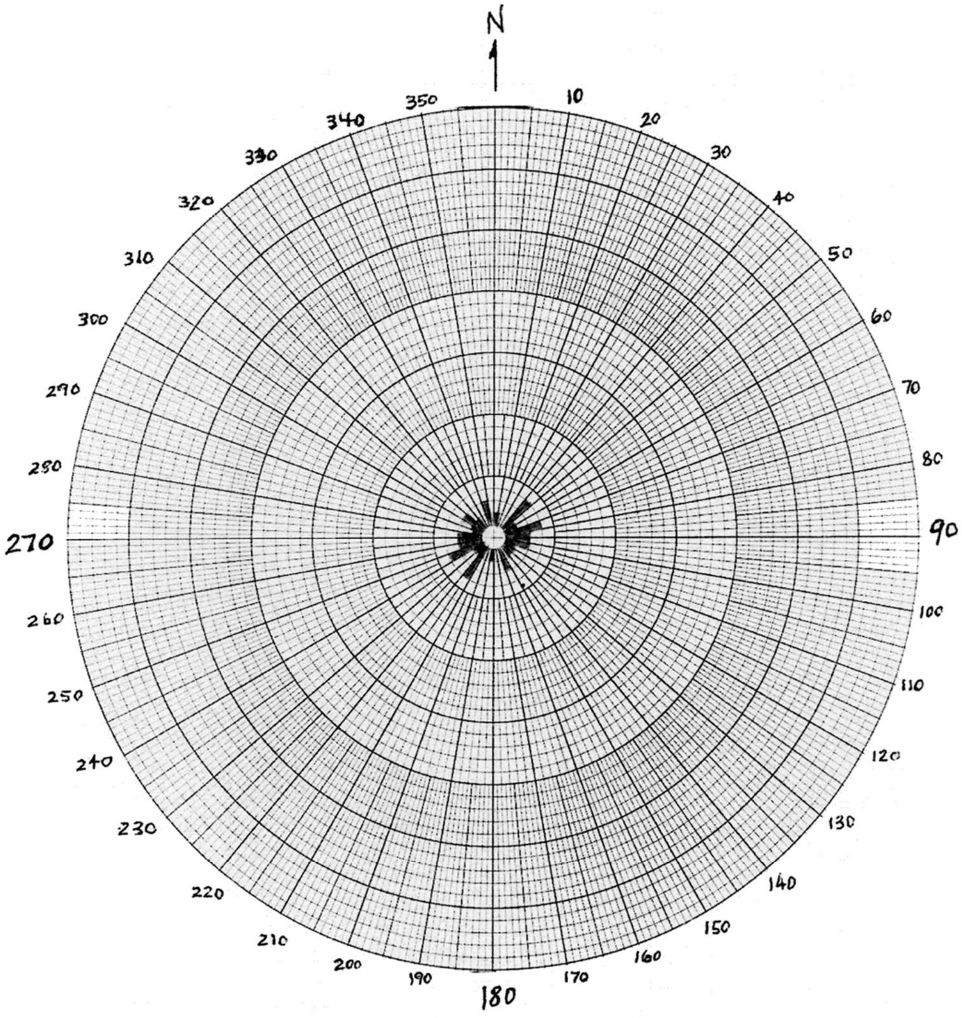


Figure 3. Fossil clast orientations for bottom layer of fossil concentration, Mount Laurel Fm., Marlboro Manse: Grids 1, 2 and 8. N=19.

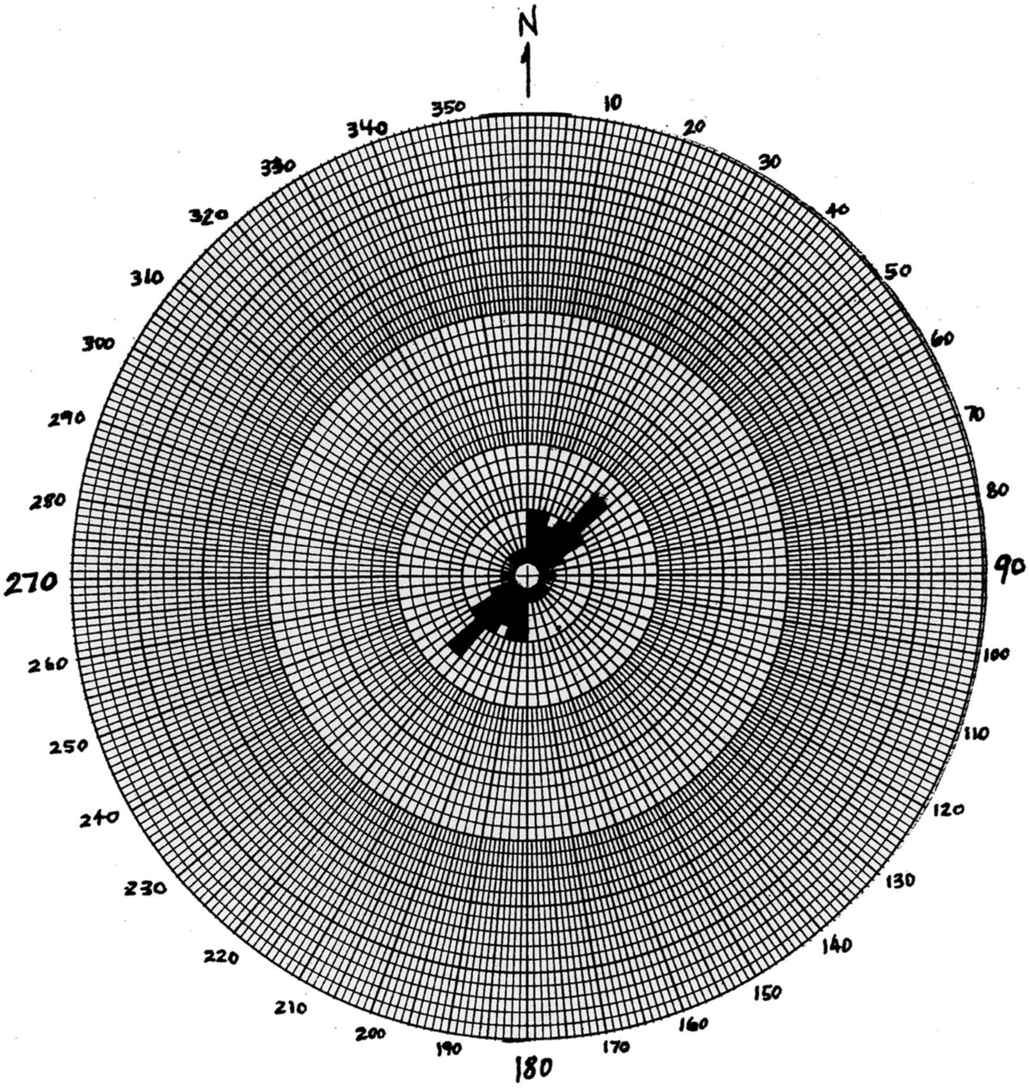


Figure 4. Fossil clast orientations for top layer of fossil concentration, Mount Laurel Formation, Marlboro Manse, all grids. N=35.

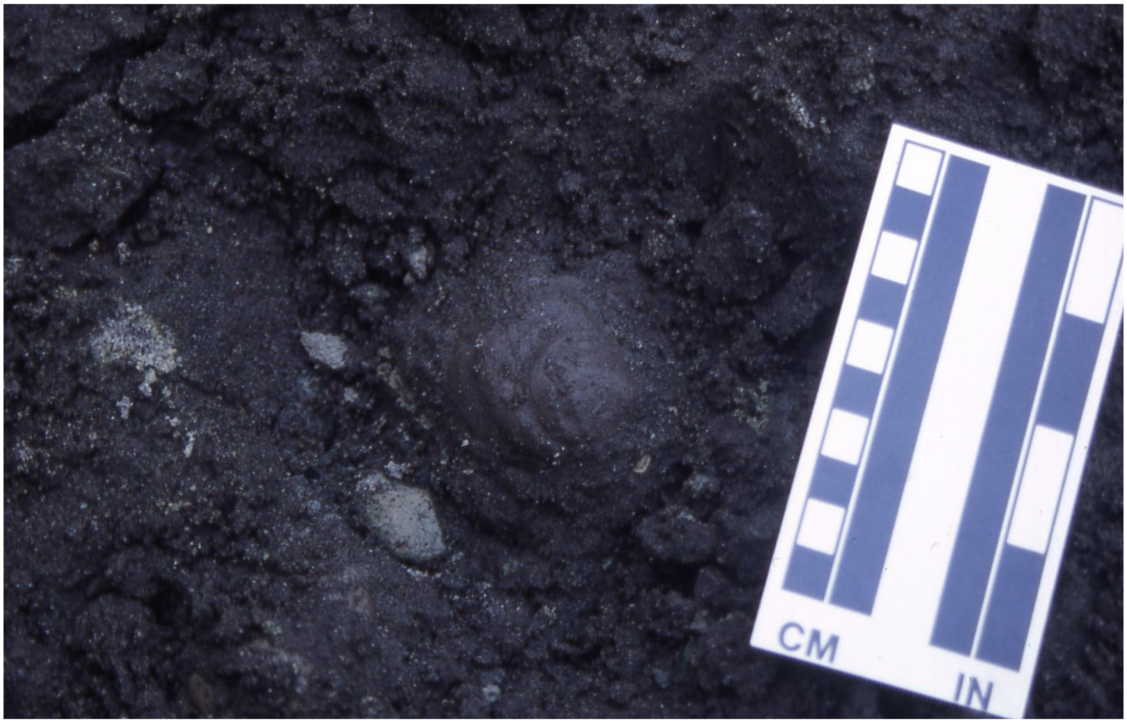


Figure 5. Internal mold of *Inoceramus vanuxemi* in situ at Marlboro Manse site. This is representative of the delicate invertebrate specimens that would not withstand erosion and transport into the downstream gravels.

Table 4. Number of vertebrate fossils, invertebrate fossils, and inorganic clasts recovered from several grids and streambed at Marlboro Manse.

	Grid 8	Grid 9	Grid 10	Streambed dig
Lbs. matrix sorted	32	31	16	105
Vertebrate fossils	355	440	309	1700
Invertebrates	63	30	0	191
Inorganic clasts	57	56	19	242

CONCLUSIONS

The primary sources for the numerous vertebrate fossils found in the stream gravels at Big Brook and elsewhere in the brooks of Monmouth County are the concentrations of fossils in the Wenonah and in the Mount Laurel Formations. These concentrations can be traced around Monmouth County to other brook exposures (Gallagher and Grandstaff, 1996) and to other previously existing outcrops. This is significant because in the past the Maastrichtian Navesink Formation has been assumed to be the primary contributor of fossils, including vertebrate remains, to the stream gravels. Where the Wenonah and Mount Laurel Formations are absent or poorly exposed, as at Poricy Brook in Middletown Township, Monmouth County, the vertebrate fauna found in the brook gravels is depauperate and original organic shell material from the Navesink Formation predominates.

An alternative explanation, advanced informally by some workers, is that the Plio-Pleistocene gravels along the brooks were the primary source of Cretaceous vertebrate material that had been secondarily reworked and concentrated into the Neogene fluvial deposits, and that were now contributing via exhumation to the fossil mix in the streambed and point bar gravels. While it is true that some Cretaceous fossils are present along with Pleistocene mammal remains in the Neogene deposits (Gallagher and

Grandstaff, 1996), these are relatively rare compared to the density of Cretaceous vertebrate remains found in the Mount Laurel Formation in places like Marlboro Manse, or in streamside outcrops at sites such as Willow Creek or Ramenessin Brook a short distance away.

The best exposures of the contact between the Mount Laurel and the Navesink were along Route 34 two miles south of Matawan; these clearly showed the uppermost quartz sand of the Mount Laurel packed with mostly vertebrate fossils and decapod claws (Gallagher, 1984). The only surviving remnant of these exposures is the Black Hill site in the Aberdeen section of Holmdel, and this is overgrown. The contrast between the very dark N1 Navesink glauconite and the much lighter quartz sand of the Mount Laurel was very sharp, and the main fossil producing layer here was the pebbly layer at the top of the Mount Laurel. The so-called lag unit should be part of the Mount Laurel since the fossils are found in the Mount Laurel lithology and the Mount Laurel is part of the regressive trend. The fossils in this uppermost lag layer are more closely related to the fossils found further down in the Mount Laurel and not similar to the oyster bed dominated fauna of the lower Navesink Formation. It is possible that this layer may be deposition in a lowstand system tract reflecting the further lowering of sea level in the regressive phase of the Vail cycle.

Moreover, orientations on the fossil clasts found in place in the Mount Laurel Formation suggest that wave or current orientation occurred in the shallow nearshore environment as sea level regressed toward the end of the Campanian Stage. While numerous marine invertebrate and vertebrate fossils imply a shallow marine depositional environment, supported by ichnofossil evidence (Martino and Curran, 1990), the discovery of terrestrial vertebrates (dinosaurs, mammals, and lungfish) in this bed suggests a more terrestrial input from nearby riverine or estuarine sources. The location of this significant fossil concentration does not fit into the standard transgressive lag model for such reworked beds, since the Mount Laurel is now considered to be part of the regressive phase of the Highstand Systems Tract in the Vail cycle (Miller *et al.*, 1999). Deposition was likely in a lower shoreface to inner shelf environment subject to wave and tidal action especially during storm conditions..

In terms of comparative taphonomy, the Marlboro Manse fauna is more marine in aspect than the Ellisdale Site, a similar time-averaged thin bed of predominantly vertebrate remains further down section and further south in Monmouth County; this is probably an estuarine environment with the fossils concentrated possibly as the result of storm deposition (Gallagher, 1993, 2012). However, the Marlboro Manse site has more terrestrial/estuarine faunal content than the well-known basal Hornerstown fossil concentration at the K/T boundary, which contains more complete specimens of a primarily marine fauna (Gallagher, 2012). Thus, it is intermediate in depositional environment between an estuarine setting and a deeper water fully marine seabed.

The significant time difference contained within the disconformity between the upper Mount Laurel bed and the basal Navesink is at least two million years (Miller *et al.*, 1999); this has important implications for the ages of some of the vertebrate material coming out of the brook sites. For instance, the determination of the primary fossil source bed as the Mount Laurel Formation helps to greatly increase the known occurrences of Campanian mosasaur specimens known from New Jersey Cretaceous outcrops (Gallagher, 2005), and establishes the outline of an East Coast Late Campanian terrestrial fauna for comparison to more famous Late Campanian land faunas elsewhere (for example, Alberta and Montana). The Mount Laurel and Wenonah vertebrate faunas then correlate to the well-known Judithian faunas from the Western Interior, and the Navesink and superjacent beds of the Monmouth Group are of Lancian age. This is an important difference especially since there is a well-known fossil fauna turn-over at the

Campanian-Maastrichtian boundary in the Western Interior linked to sea level change (Krsnak *et al.*, 2014).

ACKNOWLEDGEMENTS

We are indebted to the numerous people who assisted in this project. Sandy and Joseph Camburn helped initiate this project as volunteers at the New Jersey State Museum and were involved in all phases of the taphonomic excavation. David Parris and Barbara Grandstaff assisted with some of the excavation. The late Robert Ramsdell aided with the identification of some of the invertebrate specimens. The students of Rutgers Paleontology 303 performed much of the stream gravel sampling program in Big Brook as part of their field exercise. Students in several classes at Rider University have extended the stream gravel sampling program at Coelurus Creek and we acknowledge their efforts. Over the years, Ralph Johnson, Edward Gilmore, Dan Romeo, James Barnett, and Gudni Fabian have kept our interest alive in this area through their new discoveries of significant specimens. Our thanks go posthumously to the late Albert Wood of Cape May Court House, NJ, who identified the multituberculate incisor. This paper is a substantial revision and updating of Gallagher *et al.* (2014) with minor corrections and additions, primarily to include new work by Rider students. Thanks to the Geological, Environmental, and Marine Sciences (GEMS) Department of Rider University for their support over the course of this new work.

APPENDIX

Faunal List- Mount Laurel Formation, Marlboro Manse site, Marlboro, NJ. All specimens reposited in the collections of the New Jersey State Museum, Trenton, NJ.

Additional specimens from Coelurus Creek are in the GEMS Collection at Rider University.

Porifera
Cliona cretácea

Annelida
Longitubus lineatus

Mollusca
Gastropoda
Turritella sp.
Anchura sp.
Volutomorpha conradi

Bivalvia
Neithea quinquesostata
Glycimeris cf. microdentus
Inoceramus conferatim-annulus
Pecten venustus Morton
Unicardium umbonata
Pinna laqueta
Gervilliopsis sp.
Tachycardium sp.
Liopistha protexta
Cucullaea sp., cf. *vulgaris* or *neglecta*
Crassatellites subplanus

Veniella conradi
Trigonia mortoni
Exogyra sp.

<u>Cephalopoda</u>
Nostoceras monotuberculatum
Baculites cf. *ovata*
Baculites cf. *grandis*
Belemnitella americana

Arthropoda

<u>Crustacea</u>
Callianassa mortoni
Ophiomorha nodosa burrows

Vertebrata

<u>Chondrichthyes</u>
Chimaerid jaw plates- cf. *Edaphodon*
Cretolamna appendiculata
Sclerorhynchid rostrum
Ischyrhiza mira
Scapanorhyncus texanus
Squalocorax pristodontus
Batoid chondocranium and vertebrae
Squatirhina sp.
Pytchotrygon ?

<u>Osteichthyes</u>
Enchodus ferox
Anomoedus phaseolous
Gar teeth and jaw piece
Stephanodus sp.
Bony fish spines
Vertebrae and jaw fragments, indet.

<u>Reptilia</u>
Chelonian indet.
Plesiosauria- vertebra
Reptile bone indet.

<u>Squamata-</u> Mosasuroidea

Mosasaurus indet.
Halisaurus platyspondylus
cf. Leiodon sp.
<u>Dinosauria</u>
Hadrosaur indet..-teeth

<u>Mammalia</u>
Multituberculata- eucosmodontid incisor

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A Small Coelacanth (Sarcopterygii: Actinistia) from the Upper Cretaceous of Monmouth County, New Jersey

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ABSTRACT

The Late Cretaceous vertebrate scrap faunas of the New Jersey coastal plain have been the source of many major paleontological discoveries since the early 19th century. Even today, in spite of urban sprawl and the steady loss of classic collecting localities, new discoveries are made with relative frequency. Recently a partial quadrate of a small coelacanth was collected in situ at the Holmdel Park Site, a cooperative venture between the New Jersey State Museum and the Monmouth County Park Service. This site exposes a transgressive lag deposit from the Late Campanian, basal Navesink Formation. This is the second coelacanth fossil ever reported from the Cretaceous of New Jersey and, since it was collected directly from matrix, is the only New Jersey Cretaceous coelacanth that can be confidently dated. The specimen, though not complete, is well preserved with moderate to strongly ornamented bone above and on the sides of the condyles. The condyles themselves are approximately one quarter the size of those from the smallest quadrate assigned to *Megalocoelacanthus dobiei*. Since the newly found quadrate is quite robust in cross-section it does not appear to be from a juvenile and so does not likely belong to *M. dobiei*. The new specimen is from younger strata than the freshwater Cretaceous Gondwanan forms *Mawsonia* and *Axelrodichthys* and is considerably smaller than *Mawsonia*. We compare the new fossil quadrate to fragments of several small unidentified coelacanth specimens from the Late Cretaceous of Kansas and speculate as to the relationship of the new specimen to the European Cretaceous coelacanth *Macropoma*. Until additional material is found the exact status of the new fossil coelacanth is equivocal, however it does appear to represent a new small coelacanth in the Late Campanian of the Atlantic Coastal Plain.

INTRODUCTION

The state of New Jersey has played a key role in the history of vertebrate paleontology in America ever since the discovery of dinosaur bones on the John E. Hopkins farm in Haddonfield in 1838 and the subsequent description and naming of *Hadrosaurus foulkii* Leidy in 1856 (Weishampel and Young 1996). E. D. Cope and O. C. Marsh began their long productive paleontological careers, and their infamous feud, with the exploration and study of vertebrate fossils from the Late Cretaceous greensands and clays of the New Jersey coastal plain. Although most of the original localities collected by these early pioneers have long been abandoned and lost to urban development, super highways and the demise of greensand mining, important fossil finds are still being made in the state on a fairly regular basis (for example: Grandstaff et al., 2000; Parris et al., 2001; Landman et al., 2004).

The fossil record of coelacanth fishes from New Jersey includes the diminutive coelacanth *Diplurus (Osteopleurus) newarki* and the much larger *Diplurus longicaudatus* which are both known from rocks of the Late Triassic Newark Supergroup (Schaeffer 1952; Rizzo 1999). The coelacanth trail then disappears in North America for approximately 135 million years when the giant coelacanth *Megalocoelacanthus* *dobiei* makes its appearance in late Santonian and early Campanian marine sediments from Alabama, Georgia and (a coronoid assigned to *M. dobiei*) New Jersey (Schwimmer et al., 1994). The quadrate described here is the second coelacanth fossil from the Late Cretaceous of New Jersey and appears to be from a much smaller adult fish then *M. dobiei*.

The following institutional abbreviations are used: **AMNH,** American Museum of Natural History, New York City, NY, USA; **NJSM**, New Jersey State Museum, Trenton, NJ. USA.

DISCOVERY AND GEOLOGICAL SETTING

The coelacanth quadrate, NJSM 22481, was collected by the authors in April of 2008 at the Holmdel Park Site in Monmouth County, New Jersey. This site (hereafter referred to as the HP Site) is protected by a joint agreement between the Monmouth County Park System and the New Jersey State Museum and is an active research locality.

The site exposes a ≈1.5-meter-thick fossiliferous, highly bioturbated, poorly sorted, pebbly, slightly glauconitic quartz sand which is separated by a marked erosional disconformity from the subadjacent Campanian Wenonah Formation. This layer is a distinct but variable feature throughout much of northeastern Monmouth County and it has led to much confusion as to its proper place in the sequence. It has been variously referred to the upper part of the Mt. Laurel Formation by Krinsley and Schneck (1964) and as a lag related to the Navesink transgression by Owens and Sohl (1969). Olsson (1987) included it as part of the basal Navesink Formation, a procedure followed by Martino and Curran (1990) and Callahan et al., (2014). Gallagher (2014), following Miller et al. (1999), considers this layer to be a regressive unit in the uppermost Mt. Laurel Formation.

The problem of the exact nature of this unit is compounded by changes in the nature of its fauna from place to place. At the Marlboro Manse site, Gallagher (2014) reports an extensive invertebrate fauna in addition to common vertebrate remains, whereas Callahan et al., (2014) report an extensive vertebrate fauna with only a very few, poorly preserved invertebrate fossils.

The stratigraphic nature of this layer is discussed in some detail elsewhere in this volume.

The associated vertebrate fauna at the Holmdel Park Site is a mixed assemblage of predominately eurytopic marine taxon with a preference for shallow water. This fauna also includes some deep-water distal elements and a significant number of taxa of brackish, freshwater and terrestrial origin. Near-shore forms include, but are not limited to: abundant teeth of the lamnid shark *Scapanorhynchus*, the salmoniform teleost fish *Enchodus petrosis* several near shore rays including *Ptychotrygon vermiculata* and *Rhombodus laevis*, and the squamate *Mosasaurus conodon.* Distal deepwater forms include very rare teeth of the paleoniscid shark *Synchodus*, teeth of various Lamnid sharks, and rare teeth from the large predaceous teleost *Xiphactinus vetus.* Brackish and freshwater taxa are represented by the small hybodont *Lonchidion babulski*, an unnamed myleodaphid ray, the bonefish *Paralbula casei*, ganoid scales probably assignable to *Lepisosteus,* fairly abundant trionychid turtle bones, and crocodilian teeth and osteoderms. Entirely terrestrial taxa include abundant bits of petrified conifer wood (some exhibiting bivalve borings), common hadrosaurine dinosaur remains and a single theropod tooth. For a complete list of the fauna from this site see Callahan et al. (2014). The preservation of the vertebrate fossils in this fauna ranges from very well preserved to taphonomically very mature. This is not surprising considering that the fossils are found in a time averaged, transgressive lag deposit.

SYSTEMATIC PALEONTOLOGY

Class Osteichthyes HUXLEY, 1880
Subclass Sarcopterygii ROMER, 1955
Order Actinistia COPE, 1871
Family Coelacanthidae AGASSIZ, 1844

Genus and species indeterminate

Referred material: NJSM 22481**,** left quadrate, well preserved and almost complete; Late Cretaceous (late Campanian), basal Navesink Formation, Holmdel Township, Monmouth County, New Jersey, U.S.A. Figure 1.

Description: Quadrates, which are an element of the endoskeletal portion of the palate, are often well preserved in fossil coelacanths (Forey 1998). NJSM 22481 is an almost complete isolated left quadrate from a relatively small coelacanth. The bone measures approximately 10 mm across the condyles in the anteroposterior direction. The medial condyle measures slightly less then 10 mm in diameter while the lateral condyle measures 6 mm in diameter. The total height of the quadrate is 17.5 mm.

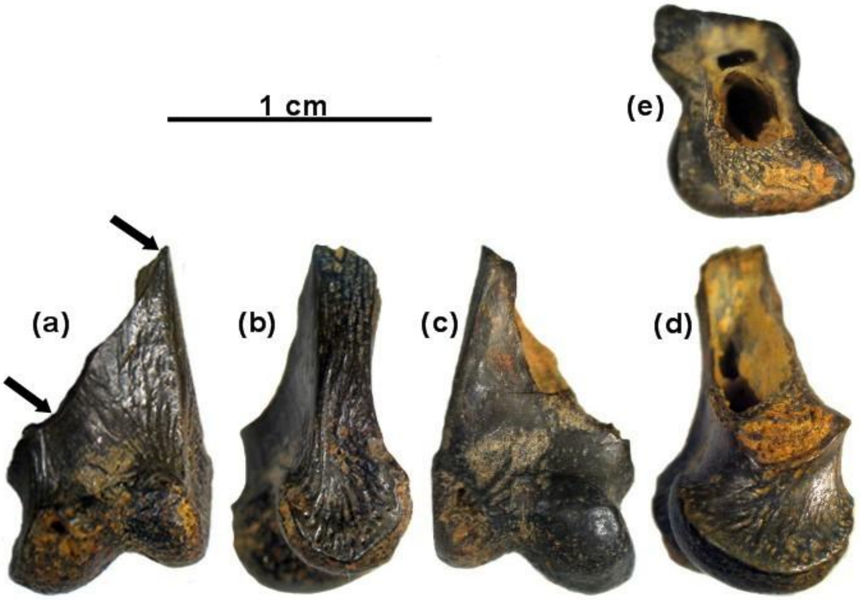


Figure 1. NJSM 22481, Left quadrate of a small coelacanth in (a) anterior view, (b) lateral view, (c) posterior view, (d) medial view and (e) dorsal view. Arrows indicate sutural surface of quadrate with pterygoid.

The anterior (Fig. 1a) and lateral (Fig. 1b) surfaces are strongly ornamented; having branching ridges which are separated by pronounced grooves. In medial view (Fig. 1d) the condyle displays more subdued ornamentation with fine radiating shallow ridges. In posterior view (Fig. 1c) there is no discernable ornamentation. Both condyles have a strong ridge along the margin of the bi-convex articular surfaces with the lateral condyle having a radial groove between the marginal ridge and another ridge marking the ventral limit of the ornamentation.

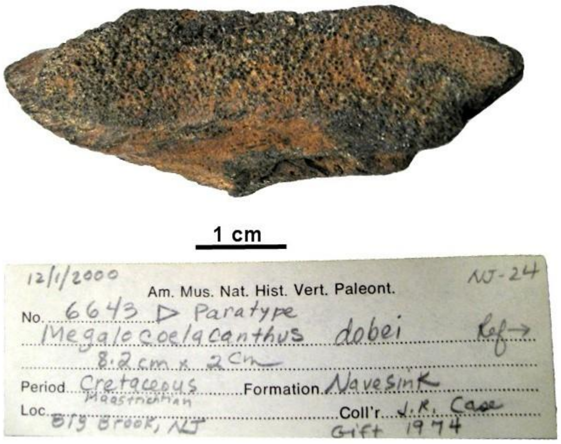
The medial condyle extends ventrally 2 mm below the lateral condyle. The shaft of the quadrate is compressed anteroposteriorly and has a central cavity that is approximately 2.5-3 mm in diameter. Another smaller, rectangular shaped cavity extends into the lateral condyle (Fig. 1e). One of the distinct features of the specimen is the almost complete, well preserved sutural surface which delineates the attachment of the quadrate to the pterygoid. The suture line extends from the dorsolateral tip of the shaft and terminates just above the medial condyle.

DISCUSSION

Coelacanths are rather rare in the Late Cretaceous with the latimeriid *Megalocoelacanthus* in North America, and indeterminate mawsoniids found in Europe and Madagascar (Cavin et al. 2005; Lionel Cavin pers comm. 2008). The giant coelacanth *Mawsonia* is known from the late Early Cretaceous (Apto-Albian) of Africa and South America (Forey 1998), and the smaller mawsoniid *Axelrodichthys* is known from the Apto-Albian Santana Formation of Brazil (Maisey 1991). Both of these predominately Gondwanan mawsoniids are interpreted to have inhabited freshwater environments. *Mawsonia* has also recently been reported from the Cenomanian (early Late Cretaceous) Bahariya Formation of Egypt (Grandstaff et al. 2002).

Macropoma, a marine coelacanth closely related to the extent *Latimeria*, is known from the Turonian of England and the Czech Republic (Forey 1998). Even though *Macropoma* and *Latimeria* show a close cladistic relationship they are found in environments that are very different, with *Macropoma* coming from shallow water deposits and *Latimeria* inhabiting water depths of 150 to 700 m.

Prior to the discovery of NJSM 22481 the only fossil coelacanth known from the Late Cretaceous of New Jersey was a single coronoid tentatively assigned to *Megalocoelacanthus dobiei* (Fig. 2). That specimen (AMNH FF 6643) was found as float among the stream lags at Big Brook in Marlboro, New Jersey (Schwimmer et al., 1994). Along its course of several miles, Big Brook transverses several fossil bearing formations and so the exact age of AMNH FF 6643 cannot be ascertained with certainty (Schwimmer et al. 1994). NJSM 22481 was found in-situ and can be confidently dated to mid-late to latest Campanian in age.



12/1/2000
Am. Mus. Nat. Hist. Vert. Paleont.
NJ-24
No. 6643 ▷ Paratype
Megalocoelacanthus dobei Ref →
8.2 cm x 2 cm
Period Cretaceous Maastrichtian Formation Navesink
Loc. Big Brook, NJ Coll'r J. R. Case Gift 1974

Figure 2. Medial view of stream worn left coronoid fragment (AMNH FF 6643) of a large coelacanth, possibly assignable to *Megalocoelacanthus dobiei*. The specimen was recovered as float along Big Brook in Marlboro, NJ by Gerard Case.

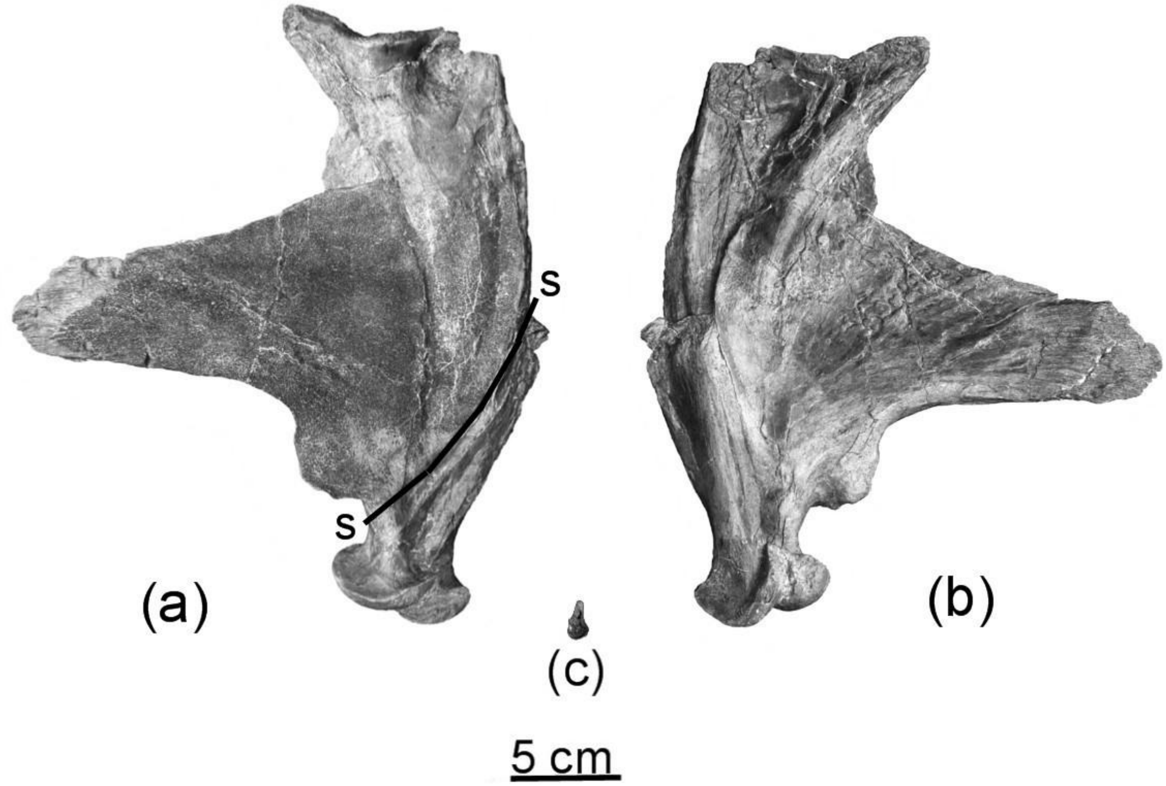


Figure 3. Right Palatoquadrate of *Megalocoelacanthus dobiei* (AMNH FF 20267) from the early Campanian Niobrara Formation, Lane County, Kansas, (a) medial view and (b) lateral view. NJSM 22481 (c) shown for size comparison. Line s-s delineates the suture between the quadrate and pterygoid. (Modified from Dutel et al., 2012)

We compared NJSM 22481 to quadrate specimens of *Mawsonia* (AMNH FF 11758) and *Axelrodichthys* (AMNH FF 11760, AMNH FF 12220 and AMNH FF 14026R) and to figured specimens of *Macropoma* and *Megalocoelacanthus* (Dutel et al., 2012; Woodward 1905; Forey 1998; Schwimmer et al., 1994). Although quadrates in general are not particularly diagnostic certain inferences could be made.

Carvalho and Maisey (2008) have estimated the overall length of specimens of *Mawsonia gigas* from the Areado Group of Brazil to be between 630 mm to 1.8 m. The largest known *Mawsonia* quadrate from Brazil with a condylar head length of 110 mm would represent a fish of 6.3 m in length. The overall lengths of *Axelrodichthys* specimens from Brazil reach 1-2 m (Maisey 1991). Schwimmer et al. (1994) estimate the overall length of *Megalocoelacanthus dobiei* to reach 3.5 m. Specimens of the European latimeriid Macropoma measure less then 600 mm long while the extent Latimeria reach a length of 1.5-2 m. Based on the condylar length of NJSM 22481 the fish would have been about 58-60 cm long which would place it in the smallest range for any of the known Cretaceous to recent coelacanths.

NJSM 22481 does not appear to represent *Mawsonia* or *Axelrodichthys* which, except for the recent discovery in southern France (Cavin et al. 2005), are restricted to fresh water deposits from South America, Africa and Madagascar. The quadrates of these coelacanths lack the ornamentation on our specimen and have a different geometry in the shapes of the condyles when viewed in posterior and anterior aspect. Fossil remains of *Megalocoelacanthus dobiei* (excluding AMNH FF 6643) have been recovered from marine sediments of late Santonian to early Campanian in Alabama, Georgia and Kansas. This makes them only marginally older than NJSM 22481 and from a similar environment. It is tempting and would be expedient to assign the new quadrate to *M. dobiei* considering the similarity in age and paleoenvironment. The great disparity in size could be explained by assigning NJSM 22481 to a juvenile. Comparisons of the New Jersey specimens to figured photographs of the quadrate of *M. dobiei* however show that the quadrate of *M. dobiei* does not display the type of ornamentation seen on the new specimen and there is a greater disparity in size between the two condyles of *M. dobiei* then are seen in NJSM 22481. Although these differences may be just artifacts of preservation or the result of ontogeny, it has been noted that in cross-section the shaft of NJSM 22481 is quite robust and not what would be expected in a juvenile (David Schwimmer pers comm. 2008). Several species of the genus *Macropoma* have been described form the Albien-Turonian of Europe (Forey 1998). These are very close in size to the New Jersey specimen and, like the NJ specimen, are found in sediments indicating a shallow marine environment (Maisey 1991). Unfortunately, published accounts of this genus are insufficient to make direct comparisons.

Additional small unidentified coelacanths have been reported from the mid-Turonian and Coniacian of Kansas (Stewart et al. 1991; Everhart et al. 1995). The quadrates associated with these finds are a close match in size and shape to the New Jersey specimen but are not as well preserved. These may represent additional material from the same or similar small coelacanth form North America. Another small coelacanth quadrate was found in Late Campanian sediments from Mississippi (David Schwimmer pers comm. 2008). This particular specimen is about the same size as NJSM 22481 but is very poorly preserved.

Until additional material is found the exact status of NJSM 22481 remains equivocal. It may represent a new small Late Campanian coelacanth from the Atlantic Coastal Plain or a relative of *Macropoma* that bridged the early Atlantic Ocean.

CONCLUSIONS

NJSM 22481 is the left quadrate of a small coelacanth from the Late Cretaceous (late Campanian) of Monmouth County. It was found in a transgressive lag deposit that represents a mix of shallow marine, brackish/freshwater and terrestrial environments. Since it is very well preserved it was likely not transported far from the place where it was buried and probably represents a shallow water marine fish, very unlike the preferred habitat of extent coelacanth *Latimeria*. Comparison to known fossil coelacanth remains is equivocal insofar as identification beyond Family is concerned although indications are that the new specimen shows closer affinities to the latimeriids then the mawsoniids. This discovery should encourage the search of existing museum and private collections from the Late Cretaceous of the Atlantic Coastal Plain for additional material that may have escaped notice by those looking for large shark bony fish and marine reptile teeth in the fossil bearing brooks, occasional construction sites and rare mining operations that expose Late Cretaceous sediments in Southern New Jersey.

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Exogyra and Other Ostreoida Xenomorphs of the Atlantic Coastal Plain

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[2]*Monmouth Amateur Paleontologists Society*

ABSTRACT

Xenomorph scars found on the left valves of the bivalve genus *Exogyra* are documented and reviewed from various localities and stratigraphic intervals within the Atlantic Coastal Plain. Three categories of xenomorphs are reviewed and illustrated. Category 1 will highlight xenomorph specimens on *Exogyra* that can be identified to the level of genus. Category 2 will outline xenomorph specimens on Exogyra with scars that are difficult to identify. The Author has found provisional evidence of the rapidity of *Exogyra* growth (calcification) which can be inferred by the sheer specificity of detail preserved in the valves seen in Category 1. It should be noted that this level of preservation can be compromised not by the rate of calcification but rather by a series of environmental factors both during *Exogyra* calcification and after, which will be discussed for Category 2. Category 3 will explore other genera of oysters that provide examples of xenomorphs to better demonstrate the phenomenon. Inferences of environmental conditions can also be made in the context of formational composition relative to the frequency of xenomorph specimens yielded from their respective sediments. Formations that provide larvae with inorganic firm substrates such as sand granules and pebbles tend to yield fewer xenomorph specimens due to the fact that the seafloor itself is providing these organisms with a substrate on which to calcify. In softer substrates comprised of silt and clay, xenomorph specimens occur much more frequently reflecting environmental pressures that push towards spats seeking out firmer, usually organic, substrates.

INTRODUCTION

The genus *Exogyra* is a widely recognized variety of Mesozoic oyster spanning the geologic interval from the Jurassic until the K/Pg boundary at the end Cretaceous. Throughout the New Jersey Upper Cretaceous sequence, various species of *Exogyra* have been described in a multitude of preservation conditions. Some of these conditions permit the preservation of calcareous shells, bioimmuring xenomorphic *Exogyra* can be yielded. These xenomorphs provide a record for hard-bodied biota that may otherwise be lost due to taphonomic biases preventing the preservation of certain biochemical make-ups, i.e. aragonitic shells being lost where calcitic shells are found en masse.

Xenomorphs (not to be confused with the arthropodal, multi-jawed icons of the “Alien” horror film made famous by Ridley Scott in 1979) were first described in 1971 by Stenzel (Taylor, 1990) as a phenomenon caused by substratum bioimmuration. All oysters begin their life cycles as soft-bodied larvae known as spats. In a microbial frenzy, the spats seek out a viable hard substrate on which to bind and which to calcify. Normally, the closest hard substrate to a larval oyster is another oyster, and this creates an oyster reef phenomenon seen in such contemporary locations as Chesapeake Bay, Maryland. However, oyster spats are not picky and will settle on any available hard object, often binding to organic substrates including, but not limited to: gastropod shells, marine worm shells, algal stalks, crustacean shells, other bivalves, and driftwood. They will also bind to inorganic substrates such as pilings, concrete, plastic tubing, etc. As the oysters' shells grow their "typical" body plan is altered to accommodate the new and different substrate – leaving scars or impressions of the substrate on their valves. Usually, this scar is more clearly defined on the left valve of the oyster near the beak which marks the initial attachment point of the spat.

For paleontologists, these impressions can provide evidence of species in ancient environments that would otherwise be lost due to preservation biases. For example, aragonitic gastropods are generally preserved as internal casts in strata where their shells have dissolved. Conversely, xenomorph impressions in calcitic oyster shells can record the external ornament with beautiful accuracy. This external molding process can help paleontologists infer a three-dimensional view of the specimens in question with detail comparable to finding the original shell itself. This process is so precise in fact, that it is able to fill in the arches and gaps of budding bryozoans with great accuracy (Taylor, 1990). This degree of accuracy can be diagnostic enough to see taxon defining ornamentation in the bioimmured specimen.

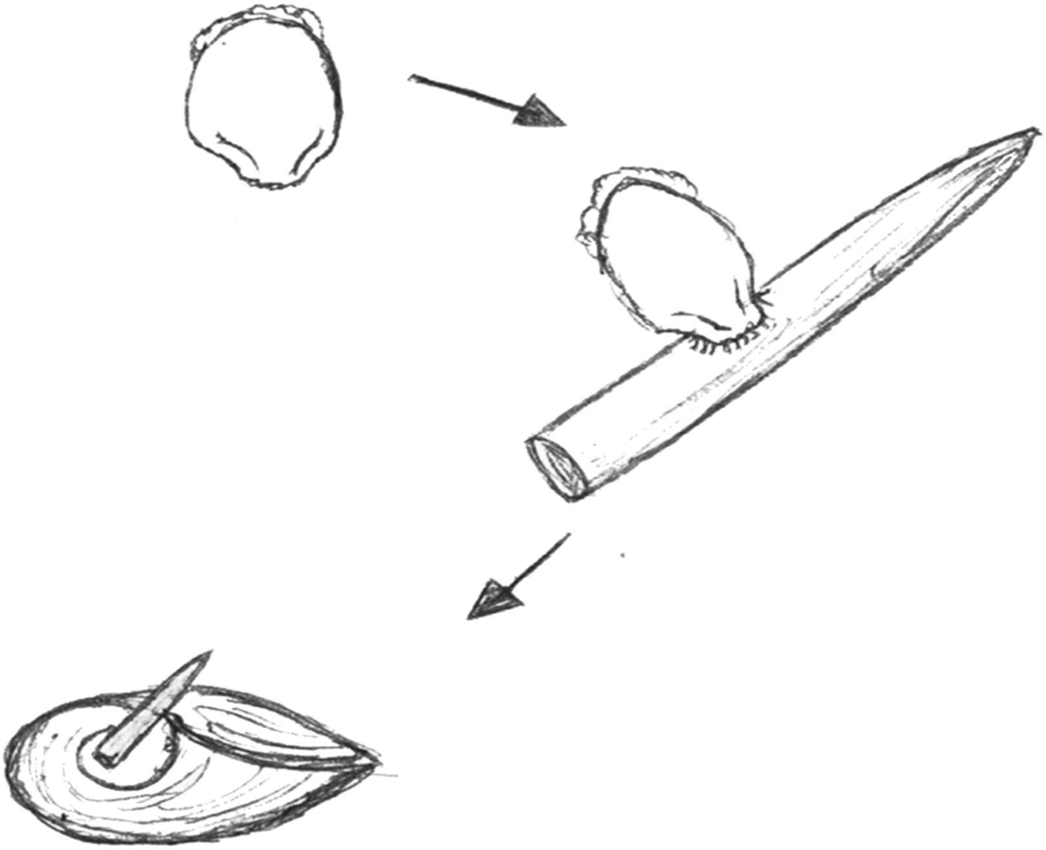

Figure 1. A larval spat attaches itself to the side of a belemnite and begins to calcify around it. Over time, the belemnite becomes attached to the lower valve of the oyster itself, creating a Xenomorph.

STRATIGRAPHIC OCCURRENCE OF *EXOGYRA* SPECIES

Three distinct species and two varieties of *Exogyra* are known to produce xenomorphs in the Cretaceous of New Jersey. The species are described below along with the formations in which they occur. Unless otherwise noted, these units are known to have produced large numbers of well-preserved calcareous specimens.

Exogyra costata (Say 1820)

- Lower New-Egypt Fm. (Upper Maastrichtian)
- Navesink Fm. (Lower Maastrichtian)
- Upper Mount Laurel Fm (Upper Campanian)

Exogyra costata var. spinifera (Stephenson 1941)

- Lower Navesink Fm (lower Maastrichtian)

Exogyra cancellata (Stephenson 1914)

- Mount Laurel Fm (upper Campanian)
    - Note *E. cancellata* is considered an index fossil for the Mount Laurel

Exogyra ponderosa (Roemer 1849)

- Marshalltown Formation (Middle Campanian)
- Merchantville Formation (Lower Campanian)
    - True *E. ponderosa* specimens are rare in New Jersey with the majority of well-preserved adult specimens coming from the Marshalltown with a few immature specimens known from the Merchantville.

Exogyra ponderosa var. erraticostata (Stephenson 1914)

- Lower Mount Laurel Fm. (Upper Campanian)
- Marshalltown Fm. (Middle Campanian)

E. costata and *E. costata var. spinifera* seemingly produce the highest number of xenomorph specimens. Although abundant, *E. cancellata* appears much less prone to attach itself to other *Exogyra* or neighboring substrates. However, it should be noted that the relatively few *E. costata* specimens found in the Upper Mount Laurel Fm. in the company of *E. cancellata* also seem to exhibit fewer xenomorph specimens.

METHODS

Exogyra specimens were collected from various localities on the Atlantic Coastal Plain, primarily from outcrops of the Navesink Formation. Specimens were either found as float in the stream bed or were found in situ in marl cut banks and prepared in a lab. Specimens described in this paper are from the Monmouth Amateur Paleontological Society's (MAPS) collection and the Author's personal collection. Category 1 illustrates xenomorph scars/overgrowths that can be identified to genus (Figures 2 through 42). Category 2 illustrates ambiguous xenomorph scars that are not identifiable to genus. Scars were identified using relevant literature and the MAPS collection.

CATEGORY 1 (FIGURES 2 THROUGH 27).

Figure 2. *E. costata* (Say 1820) that has overgrown *Belemnitella americana* (Morton 1830), Navesink Fm., Arneytown, NJ.

Figure 3. *E. costata* that has overgrown *B. Americana,* Navesink Fm., Colts Neck, NJ.

Figure 4. (left) *E. costata* with definitive *B. americana* scar Navesink Fm., Colts Neck, NJ (right); *E. costata* with likely *B. americana* scar, Navesink Fm., Cream Ridge, NJ.

Figure 5. (right) *E. costata* from Figure 4.

Figure 6. *E. costata* with *B. americana* scar, Navesink Fm., Colts Neck, NJ.

Figure 7. *E. costata* var. *spinifera* that has overgrown a *B. Americana*, Navesink Fm., Middletown, NJ.

Figure 8. *E. ponderosa* with *Arrhoges* sp. (Gabb 1868), Marshalltown Fm., Burlington County, NJ.

Figure 9. *E. costata* with *Turritella bilira* (Stephenson 1941) with scar and original shell of *T. bilira* still attached, Severn Fm., Brightseat, MD.

Figure 10. *E. costata* with *Turritella bilira* with scar and original shell of *T. bilira* still attached, Severn Fm., Brightseat, MD.

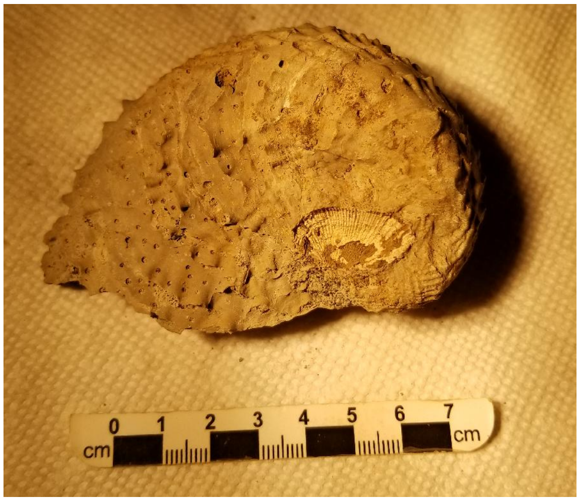

Figure 11. *E. costata* with scar and residual shell matter of *Arca* sp. (Linnaeus 1758), Navesink Fm., Colts Neck, NJ.

Figure 12. *E. costata* with scar and residual shell matter of *Arca* sp., Navesink Fm., Colts Neck, NJ.

Figure 13. *E. costata* with scar of *Gervilliopsis ensiformis* (Conrad 1858), Navesink Fm., Arneytown, NJ.

Figure 14. *E. costata* with scar of *G. ensiformis*, Navesink Fm., Arneytown, NJ.

Figure 15. *E. costata* with scar of *Legumen* sp. (Conrad 1858), Navesink Fm., Arneytown, NJ.

Figure 16. *E. costata* with scar of *Legumen* sp., Navesink Fm., Arneytown, NJ.

Figure 17. *E. costata* with scar of *Veniella conradi* (Morton 1833), Navesink Fm., Middletown, NJ.

Figure 18. *E. costata* with scar of *Pinna* sp. (Linnaeus 1758), Navesink Fm., Colts Neck, NJ.

Figure 19. *E. costata* calcified onto lower valve of *Pycnodonte convexa* (Say 1820), Navesink Fm., Middletown, NJ.

Figure 20. *E. costata* calcified onto lower valve of *P. convexa*, Navesink Fm., Middletown, NJ.

Figure 21. *E. costata* calcified onto lower valve of *P. convexa*, Navesink Fm., Middletown, NJ.

Figure 22. *E. costata* with scar of *Cyprimeria alta* (Conrad 1858), Severn Fm., Brightseat, MD.

Figure 23. *E. costata* with scar and residual shell matter of *Cucullaea* sp. (Lamarck 1801), Navesink Fm., Arneytown, NJ.

Figure 24. *E. costata* with scar of *Stantonella ripleyana* (Conrad 1860), Navesink Fm., Arneytown, NJ.

Figure 25. Cluster of *E. costata* left and right valves overgrowing one another, Navesink Fm., Cream Ridge, NJ.

Figure 26. Cluster of *E. costata*, Navesink Fm., Cream Ridge, NJ.

Figure 27. *E. costata* overgrowing echinoderm spine, Navesink Fm., Colts Neck, NJ.

CATEGORY 1 DISCUSSION

The detailed preservation of xenomorphs *Exogyra* shells is likely due to its rapid growth rate. The current record holder for fastest growing extant oyster is *Magallana cuttackensis* Newton & Smith 1912 at a rate of approximately .27 to .62 mm per day (Taylor 1990). The more rapid the rate of overgrowth by the bioimmuring organism, the more likely that details of the immured organism will be preserved before decomposition sets in. The rate of growth of *Exogyra* was likely analogous with *M. cuttackensis'* rate of growth because immured organisms not only leave their impressions along the beak but can occasionally have their original shells still attached to the beak. Figures 8 and 25 highlight just how detailed the scars alone can be, creating an external mold of the immured organism with details such as ridges and costae held in still-life.

- **Figure 26:** This cluster of *Exogyra* demonstrates just how prolific oyster reefs of the Cretaceous could be. This clustering is likely a by-product of the oyster's selective hermaphroditic reproductive strategy, more on this will be discussed in a later paper.
- **Figure 27:** This echinoderm spine is the first known to this study and helps exemplify how *Exogyra* spats were liable to grow on any and all available substrates.

CATEGORY 2 (FIGURES 28 THROUGH 33).

Figure 28. *E. ponderosa* var. *erraticostata* with scar of heteromorphic ammonite, Marshalltown Fm., Auburn, NJ.

Figure 29. *E. costata* with scar of potential bryozoan colony or coral, Navesink Fm., Colts Neck, NJ.

Figure 30. *E. costata* with scar of potential long bone, driftwood, or large rock, Navesink Fm., Colts Neck, NJ.

Figure 31. *E. costata* with tubular scar of potential baculite, Navesink Fm., Arneytown, NJ.

Figure 32. *E. costata* with scar of Scaphopod aka "tusk clam," Navesink Fm., Colts Neck, NJ.

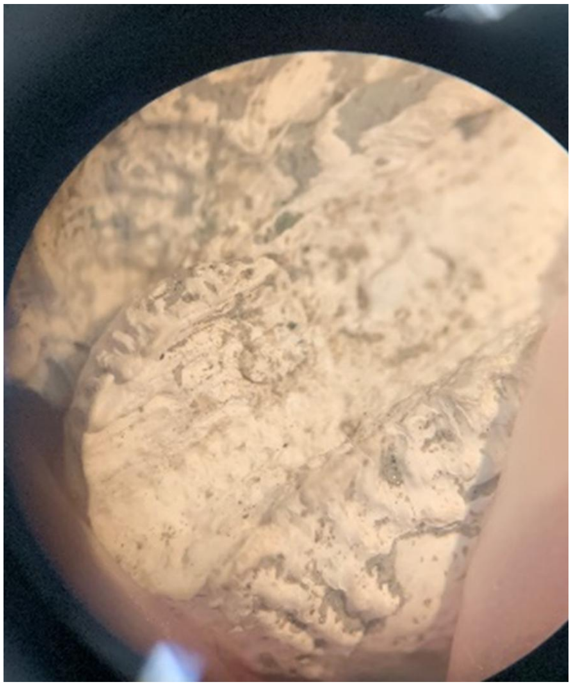

Figure 33. Closer view of probable scaphopod scar seen in Figure 32.

CATEGORY 2 DISCUSSION

The xenomorphs in this category are more ambiguous due to a variety of environmental circumstances. These include, but are not limited to: the shifting of immured substrate during growth; erosion of the scar following fossilization; multiple substrates being immured; organisms growing on the scar of the immuring organism; the substrate itself being ambiguous in shape without clearly defining ornamentation; or failure to completely enclose the substrate object.

- **Figure 28:** This is a very rare example of an immured heteromorphic ammonite. The detail of the shell is preserved well enough to allow for probable identification to species. This specimen is the subject of on-going research and will be described in a future MAPS publication. Based on the uncertainty of the taxon, this specimen is placed in category 2.
- **Figure 29:** The identification of this scar is uncertain due to lack of detail and incomplete immuration. Detail loss may be due to diagenetic instability. The author provisionally interprets the scar to be that of invertebrate colonial organism such as a bryozoan.
- **Figure 30:** The sheer size of the substrate scar makes this xenomorph difficult to identify. The surface detail is not diagnostic. A rock, a piece of driftwood, or even a long bone of a dinosaur has been suggested as possible suspects.
- **Figure 31:** The straight semi-cylindrical shape of this scar suggests the shell of the heteromorphic ammonite *Baculites,* however, damage (pitting) caused by the boring sponge *Cliona cretacica* (Fenton 1932) has obscured fine detail such as growth lines and made this identification tentative at best.
- **Figure 32/33:** This xenomorph is the smallest *Exogyra* detailed in this study. The scar was identified to be a scaphopod due to the shape and size, but most importantly, the negative image of the ornamentation of the scaphopod in the shell of the *Exogyra*. This specimen helps highlight the level

of detail an *Exogyra* can preserve along its shell. The second image detailing this specimen was taken under a stereoscope to better show the ornamentation.

CATEGORY 3 (FIGURES 34 THROUGH 38).

Figure 34. *Agerostrea monmouthensis* (Weller) with scar of *Longitubus lineatus* (Weller), Navesink Fm., Arneytown, NJ. **Note:** Right specimen has original shell material of *L. lineatus* still attached to valve.

Figure 35. *Pycnodonte convexa* with scar of probable baculite, Navesink Fm., Arneytown, NJ.

Figure 36. *P. convexa* with scar of probable baculite, Navesink Fm., Arneytown, NJ. Valve is flipped in this image to highlight the dramatic morphological effect overgrowing had on this *P. convexa*.

Figure 37. *Lopha panda* (Morton) with scar of probable marine worm, Marshalltown Fm., St. Georges Bridge, DE.

Figure 38. *L. panda* with scar of marine worm, Marshalltown Fm., St. Georges Bridge, DE.

CATEGORY 3 DISCUSSION

These xenomorph specimens were all collected from outcrops of the Marshalltown (Middle Campanian) and Navesink (Lower Maastrichtian) both of which are contemporaneous to the majority of *Exogyra* xenomorph specimens outlined in Categories 1 and 2. Implications regarding the locations of the sampled individuals will be discussed in the conclusion in depth.

- **Figure 34:** Both *A. monmouthensis* specimens demonstrate the overgrowth of the marine worm *L. lineatus*. Aside from being yielded from the same locality and calcifying over the same species of invertebrate, the *A. monmouthensis* specimens both appear to have grown in the same direction along the tube. This homogenous growth pattern is interesting, perhaps this shows that during calcification, the *A. monmouthensis* adjusts its position as it calcifies along the substrata that it may be growing around in order to ensure it is able to open its valves and feed.
- **Figures 35/36:** This *P. convexa* shows an intense level of distortion caused by what is provisionally identified as a baculite, however, another tubular object such as a long bone may also be possible. The distortion is so great that it carries over into the concaved side of the left valve.
- **Figures 37/38:** Both *L. panda* specimens were obtained from the same locality and exhibit similar worm tube scars seen in Figure 43. The scars, however, are different in both length and shape showing that *L. panda* was likely less particular in the direction and ways it grew along substrata when compared to *A. monmouthensis.* The discrepancy in the length and position of these scars may also be attributed to the *L. panda* overgrowing tubular objects other than worms or two different species of worm.

ENVIRONMENTAL CONSTRAINTS ON XENOMORPHS

The index fossil *Exogyra cancellata* and co-occurring specimens of *E. costata* in the Upper Mount Laurel formation seem to exhibit far fewer xenomorphs than populations of *E. ponderosa* var. *erraticostata* in the older Marshalltown Fm. or *E. costata* in the younger Navesink Fm. This discrepancy might better be explained by differences in the sediment substrate in which these populations lived rather than the habits of specific species. The Mount Laurel Fm. consists of a fine to medium coarse quartz sand that coarsens upward with ovoid phosphate grains near the top. These granules may have provided larval spats with a firm sediment substrate with which to calcify without pressure to seek out organic substrates. The specifics of depth and substrate composition relative to the frequency of *Exogyra* xenomorphs will be explored in greater depth in a later paper.

CONCLUSION

Xenomorphs are a fascinating and important but often overlooked and underutilized facet of invertebrate paleontology. On the Atlantic Coastal Plain, they give us glimpses of elements of the Cretaceous ecology that might otherwise go unrecognized. The author's work has been limited by; time constraints but most importantly the loss of classic sites such as the famous Swedesboro, New Jersey, (Marshalltown Fm. outcrops) and the Mount Laurel outcrops at Biggs Farm on the C&D Canal in Delaware. It is our hope that this publication will inspire future workers to be aware of and perhaps study these amazing fossils.

ACKNOWLEDGEMENTS

This paper could not have been done had it not been for Ralph Johnson and The Monmouth Amateur Paleontological Society for allowing me access to an amazing fossil repository to reference for this paper and help with any questions I had while working on it. It also could not have been written were it not for my dear friend Lina Rivetti who not only provided me with equipment necessary to continue gathering specimens for this paper, but who also taught me the ropes of formatting scientific papers as well as going through my work with a fine-toothed comb to ensure that what I was writing made sense not only to myself, but to others reading it. Special thanks to James Brown for aiding in the writing process and helping edit this paper.

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Surficial Geology and Geomorphology of Monmouth County, New Jersey

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ABSTRACT

Surficial deposits are the sedimentary record of the development of the landscape of Monmouth County over the past 15 million years in response to changing sea level, climate, and glacial river diversions. The oldest landscape element is a fluvial plain marked by the Beacon Hill Gravel, a quartz-quartzite-chert gravel that caps the highest hills in the county, above 300 feet in elevation. It was deposited by a south-flowing river system on the emerging inner shelf exposed as sea level fell in the middle Miocene after deposition of the Cohansey Formation. As sea level continued to fall, the river system shifted to a southwesterly course along the inner edge of the Coastal Plain, and Monmouth County became part of an upland separating this river valley from the Atlantic Ocean to the southeast. Local streams on this upland cut shallow valleys, reworked the Beacon Hill Gravel, and deposited the reworked gravel in the valley bottoms. These gravels today cap uplands and divides due to topographic inversion and are known as upland gravels. During a sea-level highstand in the Pliocene the Pensauken Formation aggraded in the main valley northwest of Monmouth County to form a plain. Some of the upland gravels in the northwestern part of the county grade to the Pensauken plain. During the first glaciation to reach New Jersey at about 2.5 Ma the Pensauken river was diverted southeastward to the Atlantic in the New York City area. This reroute led to the erosion of the New York Bight lowland to the northeast of Monmouth County, which in turn led to the reorientation of the streams in the eastern part of the county toward the northeast, forming the modern drainage pattern. This northeasterly drainage captured and replaced the previous southeasterly drainage marked by the upland gravels. Middle and upper Pleistocene fluvial deposits were laid down in these valleys, chiefly during periods of permafrost. Streams incised these deposits during interglacial periods and today they form upper and lower terraces. During two periods of higher-than-present sea level—one probably around 400 ka (+60 feet) and the other at 125 ka (+30 feet) estuarine and beach deposits of the Cape May Formation were laid down in marine terraces along the Atlantic coast. During the last glaciation between 25 and 18 ka the Raritan River was rerouted into what is now Raritan Bay. When the Hudson River, to which the Raritan was a tributary, was rerouted through the Narrows and deepened by erosive glacial-lake outflows between 18 and 13 ka, the Raritan and its tributaries in the county also deepened their valleys. Postglacial rise of sea level has submerged these valleys to form the present estuaries and bays.

INTRODUCTION

Monmouth County includes the northernmost unglaciated Coastal Plain in eastern North America and is directly bordered to the north by the terminal positions of three Pleistocene Laurentide glaciations. It is thus in a unique position to record the effects of changing sea level, climate, and glaciation over the past several million years of Earth history. These effects are recorded in the surficial deposits and landforms of the county. The Neogene and Quaternary surficial deposits (fig. 1), and the paleotopography they define, record an interesting history of river shifts in response to sea-level variations and glacial diversions extending back to 15 Ma. This paper will describe these deposits and landforms and outline their history in sequence from the middle Miocene to the present. The observations and interpretations provided here are based on 1:24,000 surficial geologic mapping conducted between 1990 and 2018 as part of the geologic mapping program at the N. J. Geological and Water Survey. This program builds on the earlier mapping and stratigraphic studies of R. D. Salisbury and G. N. Knapp (Salisbury, 1898; Salisbury and Knapp, 1917), who defined and named the principal surficial formations, and subsequent stratigraphic and geomorphic studies by Johnson (1931), MacClintock and Richards (1936), Owens and Minard (1979), and Newell and others (2000).

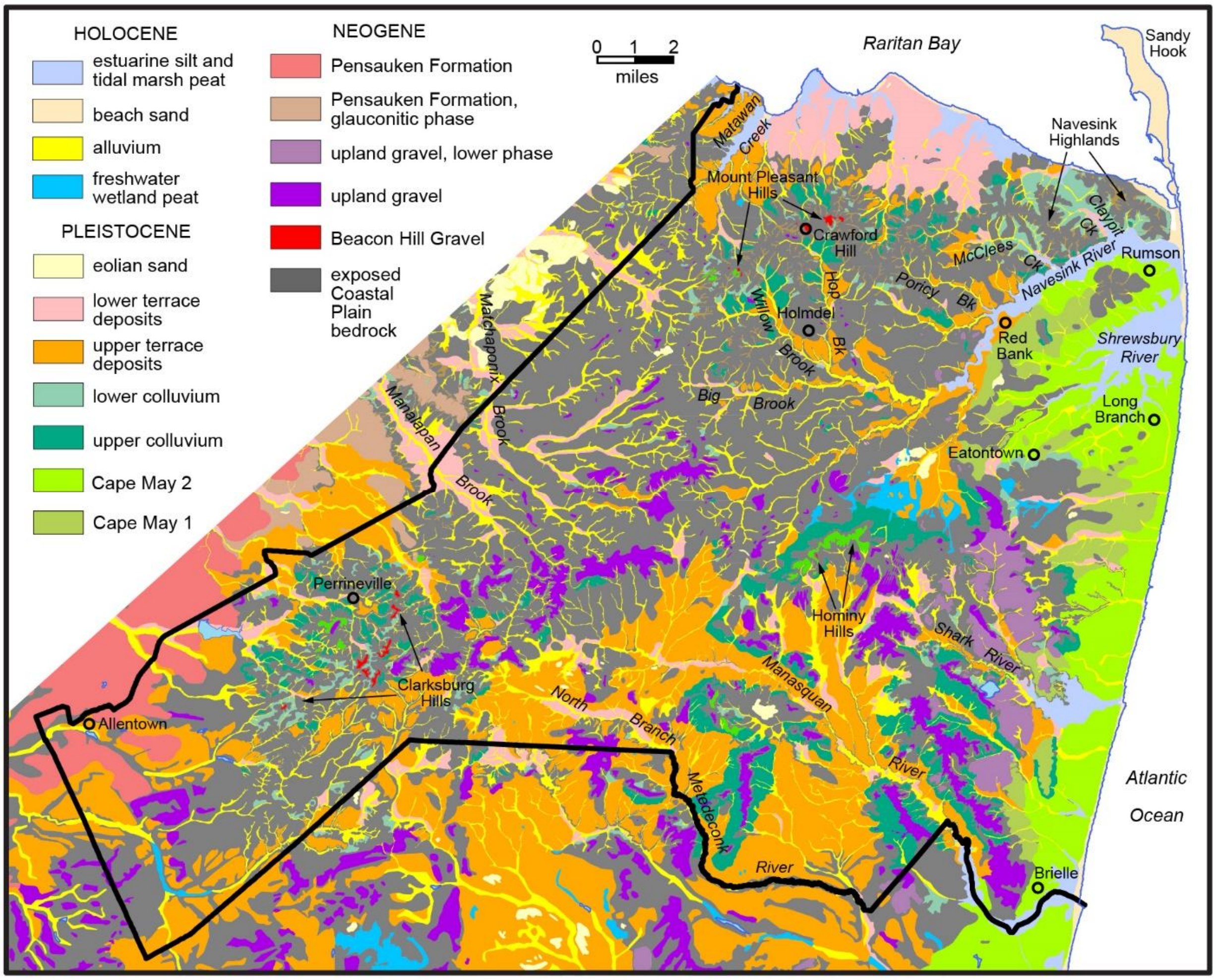

Figure 1. Surficial deposits of Monmouth County. From N. J. Geological and Water Survey digital data (Pristas and others, 2007).

COHANSEY FORMATION AND BEACON HILL GRAVEL

The youngest marine deposit in the New Jersey Coastal Plain is the Cohansey Formation, which consists of beach and nearshore quartz sand preserved on uplands and hilltops in the county, above elevations ranging from 30 feet to the southeast near Brielle to 290 feet in the Clarksburg Hills in western Monmouth and 220 feet in the Navesink Highlands in northeastern Monmouth. These elevations indicate that sea level was more than 300 feet higher than present when the Cohansey was deposited and that the shoreline was inland of the present edge of the Coastal Plain (fig. 2, panel A). The updip Cohansey is nonfossiliferous and so is difficult to date. Downdip in Cape May County the Cohansey contains dinoflagellates indicating an age as young as 8-9 Ma (deVerteuil, 1997) but lithostratigraphic relations suggest that the updip Cohansey is older. The updip Cohansey may be coastal facies of the upper Kirkwood Formation inner-shelf sediments downdip, such as the Kirkwood 2 and 3 sequences, dated by strontium stable isotopes to between 17 and 14 Ma (Sugarman and others, 1993). This age would agree with global sea-level records, which show a highstand between 17-14 Ma as much as 250 feet above present sea level (Hansen and others, 2013). At 14 Ma sea level begins a long decline through the middle and late Miocene as Antarctic ice sheets expanded, dropping to close to present sea level at times by 6 Ma (fig. 3).

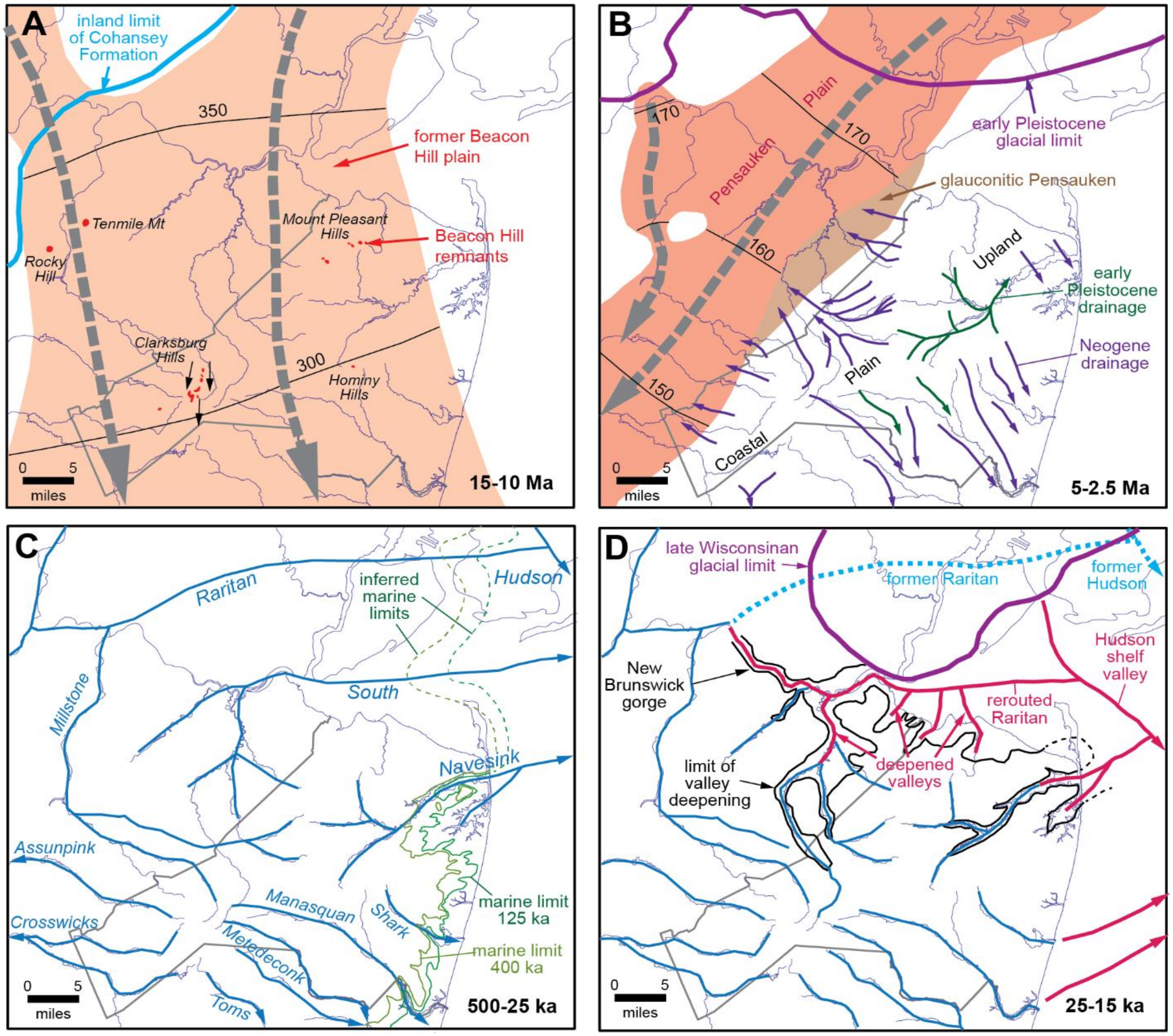

Figure 2. Events in the Neogene and Quaternary history of Monmouth County. A) Cohansey Formation and Beacon Hill fluvial plain. Thin numbered black lines are elevation contours (in feet) on the Beacon Hill plain. Black arrows are paleocurrent measurements. Thick dashed gray arrows show streamflow on plain. B) Pensauken fluvial plain, early Pleistocene glacial limit, and local stream drainage as marked by upland gravels (purple and green arrows). C) Stream drainage after early Pleistocene incision and limits of marine submergence during the Cape May highstands. D) Drainage changes and valley incision during the late Wisconsinan glaciation. Present streams and coast in light purple and county outline in gray on all panels.

In the early stages of this decline the inner New Jersey shelf began to emerge as a coastal plain. The Beacon Hill Gravel is a fluvial sand and gravel deposited on this plain (fig. 4). It caps the highest hills in Monmouth County, above elevations of 320 feet in the Clarksburg and Mount Pleasant Hills and above 290 feet in the Hominy Hills. It is generally less than 20 feet thick. The slope of the base of the gravel descends in a southerly direction, and paleocurrents measured on cross beds also show southerly flow (fig. 2, panel A). The gravel consists of quartz, quartzite, and chert pebbles, with rare fossils of Devonian coral in the chert, which indicate a source north of Kittatinny Mountain. Aligned wind gaps in northern New Jersey on grade with the Beacon Hill indicate that several south-flowing predecessors of the Delaware, Raritan, and possibly the Hudson, rivers supplied the gravel. The plain has a gradient of about 0.0008 (4 feet/mile), similar to the slope of the continental shelf today and in the Miocene (Steckler and others, 1999), indicating that it was deposited as the shelf was exposed, with little prior erosion.

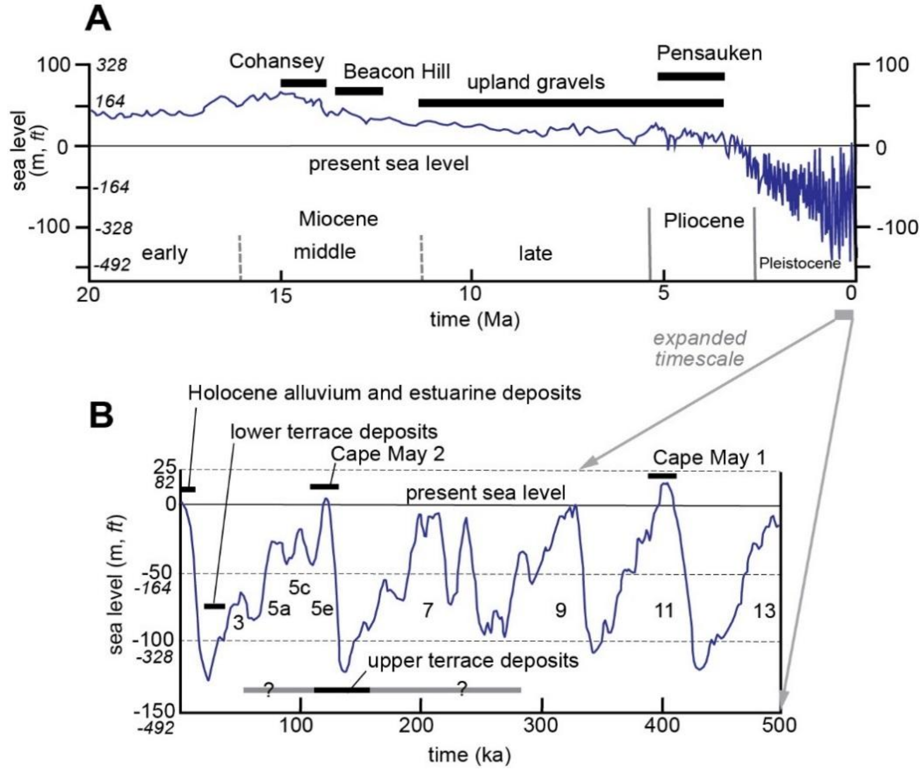

Figure 3. Global sea level and age of Monmouth County surficial deposits. A) Sea level for the past 20 million years, simplified from Hansen and others (2013). B) Sea level for the past 500,000 years, from Spratt and Lisiecki (2016), with marine isotope stages.

Figure 4. Beacon Hill Gravel over Cohansey Formation, Clarksburg Hills.

The small surviving remnants of Beacon Hill mark one of the oldest preserved land surfaces in North America (12-14 Ma). One of the Beacon Hill remnants caps Crawford Hill in Holmdel. Crawford Hill is also the site of the famous microwave “horn antenna” which in 1965 detected cosmic microwave background radiation from the Big Bang, a discovery for which Arno Penzias and Robert Wilson won the Nobel Prize in 1978. It is fitting that this discovery of the evidence for the ancient beginning of the universe was made on an ancient piece of the surface of that part of it that we inhabit.

UPLAND GRAVELS

As sea level continued to decline through the late Miocene the south-flowing rivers feeding the Beacon Hill became integrated into a trunk river that flowed southwesterly along the inner edge of the Coastal Plain between the Perth Amboy area and the Camden area. This reorganized river system then swung easterly across southern New Jersey to the ocean, depositing the Bridgeton Formation of southern New Jersey. The northern Coastal Plain, including Monmouth County, became an upland from which streams flowed northwesterly toward the trunk river and southeasterly toward the Atlantic (fig. 2, panel B). These local streams, responding to the gradually lowering sea level, cut valleys into the Beacon Hill plain. By the end of the Miocene these valleys had been cut to depths of between 100 and 200 feet below the Beacon Hill plain. The streams, and groundwater seepage and slope erosion on the valley slopes, eroded the Beacon Hill Gravel. Much of the chert in the Beacon Hill had weathered to clay-size material during the long exposure in the late Miocene and did not survive reworking, so the upland gravels contain less chert than the Beacon Hill.

Due to renewed valley deepening in the early Pleistocene (see below) the gravel deposits in the late Miocene valley bottoms became topographically inverted and today cap hilltops and interfluves between present-day valleys. This inversion happened because streams cut down faster in the sands and clays of the Coastal Plain bedrock formations along the valley sides than through the gravels flooring the floodplains. Eventually new valleys were cut at the sides of the original valleys, which became ridges between the new valleys. The former valley-bottom gravels now cap uplands and so are known as upland gravels.

Alignment and slope of the upland gravel remnants can be used to reconstruct the paleodrainage pattern. In eastern Monmouth County the drainage is southeasterly toward the Atlantic (fig. 5). The Atlantic coast was seaward of its present position, because the upland gravels are at elevations of 80 to 100 feet today at their easternmost occurrences along the present coast. In western Monmouth the drainage is westerly or northwesterly toward the trunk river in the Amboy-Camden valley. Upland gravels are generally absent from the northern coastal area of the county along Raritan Bay because this lowland was deeply eroded in the middle and late Pleistocene and any traces of the pre-Pleistocene land surface were removed.

Figure 5. Upland gravel in Brielle. Cross bedding shows flow to southeast (right in photo). Photo by M. E. Johnson, 1938.

PENSAUKEN FORMATION

By the end of the Miocene the trunk river in the Amboy-Camden valley had cut its valley to close to present-day sea level. During a period of high sea level in the Pliocene the valley aggraded with fluvial sand and gravel, which filled the valley thalweg to depths of as much as 120 feet and spread as a broad braidplain as much as 12 miles wide across the Amboy-Camden valley (fig. 2, panel B). This deposit is known as the Pensauken Formation. The surface of the Pensauken plain slopes downvalley to the southwest from about 170 feet in the South Amboy area to 150 feet near Allentown to 110 feet near Camden to 80 feet near Salem where the plain broadens, turns south, and exits to the ocean across what is now the Delmarva Peninsula. Paleocurrents measured from cross beds confirm this flow pattern (Owens and Minard, 1979; Martino, 1981; Stanford and others, 2002). In western Monmouth County, upland gravels mark the courses of local tributaries to the Pensauken draining from the Coastal Plain upland to the southeast. Sands of these tributary deposits contain glauconite reworked from outcropping Cretaceous and Paleogene formations on the upland, forming a glauconitic phase of the Pensauken along its southeast edge between South Amboy and Perrineville. Glauconite is otherwise absent from the Pensauken, which is chiefly arkosic quartz sand fed by a trunk river flowing along the inner edge of the Coastal Plain from southern New England and by the Hudson, upper Raritan, and Delaware rivers, which were tributaries to the trunk Pensauken River. This drainage eroded and redeposited the older upper Miocene gravels (Beacon Hill and Bridgeton formations and their former equivalents in New England) and middle Miocene marginal marine sands (Cohansey Formation and its former New England equivalent), so the Pensauken gravel, like the upper Miocene gravels, is largely quartz and chert.

EARLY PLEISTOCENE GLACIATION

The first Laurentide glaciation to enter New Jersey extended southward to the Somerville area and crossed the Pensauken plain in the New York City area (fig. 2, panel B). Deposits of this glaciation are magnetically reversed (Ridge, 2004), indicating that it occurred before 788 ka, and pollen associated with the deposits are indicative of Pliocene age (Stanford and others, 2001), suggesting that it may have been the first major Laurentide glaciation in North America, which is dated to 2.5 Ma in the Missouri River valley. This glacier had a significant effect on the geomorphology of central New Jersey and Monmouth County. It rerouted the Pensauken River seaward to the southeast in the New York City area, breaching the Coastal Plain upland in what is now western Long Island. In the early Pleistocene, after the glaciation, sea level progressively lowered due to growth of ice sheets in the northern hemisphere, and a new northeasterly local drainage network developed in central New Jersey and Monmouth County that was tributary to the rerouted Hudson-Pensauken River to the east. This new local drainage included the lower Raritan, lower Millstone, the South River basin, and the Navesink and Shrewsbury basins (fig. 2, panel C). As the Hudson incised its valley into the former Coastal Plain upland, the tributaries likewise deepened their valleys into the former Pensauken plain and the Monmouth County upland. The former southeasterly drainage to the Atlantic from the upland, marked by the upland gravels, was captured by the Navesink and turned northeasterly. A lower set of upland gravels in the Navesink basin marks an early phase of this turned drainage (fig. 2, panel B, green arrows). The southeasterly trend of the headwater reaches of Navesink tributaries like Big Brook, Willow Brook, and Hop Brook, and southeasterly trending abandoned valleys on Rumson Neck that align with the southeasterly trending valleys of Poricy Brook, McClees Creek, and Claypit Creek in the Navesink Highlands to the north across the Navesink estuary, are inheritances of this Neogene drainage. The southeasterly trend of the Shark, Manasquan, and Metedeconk rivers farther south are also Neogene inheritances, although these rivers have shifted laterally a little during the inversion process as they incised. These rivers were more distant from the incising Hudson to the northeast and so did not experience the northeasterly captures like those in the Navesink basin. The downstream ends of the valleys, and their extensions on the inner shelf (Lugrin, 2016), do turn northeasterly, indicating that captures likely occurred seaward of the present shore.

Through the early Pleistocene and into the middle Pleistocene (2.5 Ma-150 ka), the northeasterly drainage cut valleys between 50 and 150 feet deep into the Neogene landscape. Groundwater emerging in seeps and springs at the base of uplands eroded scarps that retreated into the uplands, widening the valleys. This process of seepage erosion can be observed today at the upland margins of floodplains. The efficacy of seepage erosion and hillslope erosion increased during periods of permafrost, when more water was retained near the surface during thaws by the impermeable permafrost, increasing runoff and seepage flows. By about 150 ka the valleys had reached their present size and the overall inland landscape looked much as it does now.

PLEISTOCENE DEPOSITS

Pleistocene valleys contain upper and lower stream terrace deposits, colluvium graded to the terrace deposits, eolian sands, and, along the Atlantic coast, marine terrace deposits of the Cape May Formation. Upper terraces have top surfaces 20 to 50 feet above the present floodplain and are the dominant landform in most valleys. The terrace deposits are generally less than 20 feet thick and cap straths cut into Coastal Plain bedrock formations (fig. 6). They grade downvalley to, or are onlapped by, the Cape May 2 marine deposit, which was laid down during the sea-level highstand during marine isotope stage (MIS) 5e at 125 ka, also known as the Sangamonian interglacial stage in North America. A single radiocarbon date of >36 ka on peat in an upper terrace deposit near Perrineville (Stanford and others, 2002) is the only direct date. The deposits are chiefly horizontally stratified sand and pebble gravel indicative of shallow braided channels, which suggests that the terraces were laid down primarily during cold periods when permafrost increased the volume of sediment washing into valleys from uplands. The peak cold during the middle Pleistocene was likely during the Illinoian (MIS 6) glaciation at around 150 ka, when ice advanced to northern New Jersey and Long Island. Most of the upper terrace deposits are probably of Illinoian age.

Figure 6. Upper terrace sand (above shovel) over Red Bank Formation in bank along Swimming River Reservoir. Middletown.

Lower terraces have top surfaces 5 to 20 feet above the present floodplain. They are of smaller extent that the upper terraces except along the Raritan Bay shore and in the South River basin (Matchaponix and Manalapan Brook valleys) in the northern part of the county. These valleys were deeply eroded when the Raritan River was glacially diverted into the Raritan Bay lowland during the late Wisconsinan glaciation at 25 ka (see below) and so are younger than the other valleys in the county and contain few to no upper terraces. Radiocarbon dates on peat and wood in lower terrace deposits at several places in the county indicate that they were deposited between 36 and 18 ka (Stanford and others, 2002). This age range encompasses the last glacial maximum, when the late Wisconsinan glacier advanced to, and began to retreat from, its terminal position at Perth Amboy and Staten Island. Like the upper terrace deposits, the lower terrace deposits are braided-stream sands and gravels laid down under permafrost conditions. Eolian sand was also deposited at this time, and perhaps during earlier peak glacial periods. These deposits, which are of small extent in Monmouth County but more extensive elsewhere in the Coastal Plain, form dunes and sand sheets. Dune morphology and the position of the sand sheets indicate they were deposited primarily by winds blowing from the northwest.

Both the upper and lower terraces have correlative deposits of colluvium that form aprons at the base of steep hillslopes. The aprons grade valleyward to the terrace surface. The colluvium is weakly stratified sand, silty sand, and gravel laid down by sheetwash and solifluction. Most of the hillslopes are stable under forested conditions, so the colluvium, like the terrace sediments, was likely laid down when permafrost was present.

During at least two interglacial periods in the middle and late Pleistocene, sea level was higher than at present in the New Jersey area, and beach, nearshore, and estuarine sediment was deposited along the Monmouth County Atlantic coast. These deposits comprise the Cape May Formation and today form two marine terraces (fig. 3, panel C). The deposits consist of horizontally bedded sand and gravel, with minor thin interbeds of silt and clay and rare peat and organic silt (fig. 7). They are as much as 50 feet thick but generally less than 30 feet thick. The highest terrace (Cape May Formation, unit 1) has a top surface at an elevation of 60 to 70 feet. It forms bench-like erosional remnants along the shore from Brielle to Long Branch and a more extensive terrace in the Shrewsbury and Navesink valleys between Long Branch and Red Bank. In southern New Jersey the Cape May 1 is dated by amino-acid racemization to either MIS 9 (330 ka) or MIS 11 (400 ka) (Lacovara, 1997; O'Neal and others, 2000). Global sea level during MIS 11 was at a similar height as that marked by the Cape May 1 while MIS 9 sea level was lower (fig. 3), suggesting that the Cape May 1 is mostly of MIS 11 age. The presence of the Cape May 1 in the Navesink and Shrewsbury valleys indicate that these valleys had been eroded to roughly their present size by 400 ka.

Figure 7. Cape May Formation, unit 2, exposed in beach cliff in Deal.

The lower terrace (Cape May Formation, unit 2) has a top surface between 25 and 35 feet in elevation. It forms a continuous terrace along the shore from Brielle to Rumson and extends up the Shrewsbury valley to Eatontown and up the Navesink valley to Red Bank. Amino-acid racemization dates from southern New Jersey (Lacovara, 1997) indicate that the Cape May 2 is MIS 5e age (125 ka). Organic clay from the Cape May 2 in Long Branch yielded a radiocarbon date of >40 ka (Stanford and others, 2002).

Neither of the Cape May terraces extend into the Raritan Bay lowland. As noted above in the discussion of the upper terraces, this lowland was deeply eroded during the late Wisconsinan glaciation. Because the two Cape May highstands preceded this erosion, any Cape May deposits in this area were removed, as was the case for most of the upper terrace deposits. Marine deposits (Gardiners Clay) of MIS 5e and earlier age on western Long Island (Wehmiller and others, 1988) are Cape May equivalents and indicate former shorelines extending north-northeast of the Rumson area (fig. 3, panel C).

LATE WISCONSINAN GLACIATION

Although there are no glacial deposits in Monmouth County, with the exception of glaciofluvial gravel beneath thick postglacial estuarine sediment in Raritan Bay and beneath Sandy Hook, the late Wisconsinan glacier had a significant impact on the landscape of the county. As the glacier advanced to its terminal position at 25 ka it blocked the preglacial Raritan valley, which drained northeasterly from the

Bound Brook area around the north end of Staten Island (fig. 3, panel D). The Raritan adopted a new course to the southeast from Bound Brook across a low shale upland in the New Brunswick area and into the South River valley at Sayreville, which it followed easterly through what is now Raritan Bay. The Raritan at this time carried not only its meteoric discharge but also outflows from glacial Lake Passaic, several glacial lakes in the Rockaway basin in Morris County, glacial Lake Bayonne in the Arthur Kill lowland, and, later, part of the outflow from glacial Lake Hackensack in the Hackensack valley. After the glacier began to retreat from the terminal moraine, sediment was trapped in these lakes and the water draining into the Raritan was largely sediment-free and therefore erosive. It cut a gorge into the shale upland from Bound Brook to New Brunswick and deepened the South River, which was floored by Cretaceous clay and sand. While ice stood at the terminal moraine, and during the early stages of deglaciation until about 18 ka, the Raritan Bay lowland and the present inner shelf off the south shore of Long Island, were occupied by an outwash plain sloping away from the moraine. Based on drillhole data from Raritan Bay (MacClintock and Richards, 1936) and recent coreholes on Sandy Hook (Miller and others, 2018), which penetrated the outwash gravel beneath postglacial estuarine sediments, this plain was at an elevation of about 0 on the south shore of Staten Island, sloping down to -150 feet beneath Sandy Hook. This plain, which extended upvalley to the Perth Amboy area, limited the depth to which the Raritan could incise during this time.

POSTGLACIAL VALLEY INCISION AND ESTUARINE DEPOSITION

During the early stage of deglaciation water in the Hudson valley was blocked from draining southward by the terminal moraine. After an early period of draining out through the Lake Bayonne spillway along the Arthur Kill into the Raritan, Hudson waters flowed out to the east into a glacial lake in the Long Island Sound lowland (Stanford and Harper, 1991). At around 18 ka a large glacial lake in the Wallkill valley drained rapidly into the Hudson valley when retreating ice uncovered Skunnemunk Mountain and Storm King south of Newburgh, New York (Stanford, 2010). The resulting flood breached the moraine dam at the Narrows between Brooklyn and Staten Island. This breach opened Hudson drainage to the south and initiated incision of the Hudson shelf valley seaward of the Narrows. This shelf valley is west of the former pre-late Wisconsinan Hudson egress, which was across Queens, and so brought the Hudson closer to Monmouth County (fig. 2, panel D). Between 18 and 13 ka, outflows from glacial lakes in the Hudson valley, and from large glacial lakes in the Ontario basin that drained into the Hudson valley via the Mohawk River, and, later, from the Champlain valley, exited through the Narrows and deepened the shelf valley to as much as -350 feet east of Sandy Hook (Schwab and others, 2002). The Raritan was a tributary to the Hudson shelf valley and this deepening allowed the Raritan and its tributaries to incise deeply also. The South River valley, Cheesequake and Matawan Creeks, and the Navesink and Shrewsbury valleys, which were also Hudson tributaries, all deepened their valleys in step with the Hudson.

This deepening provided much accommodation space for estuarine deposition as sea level rose in postglacial time. The postglacial sediments are as much as 275 feet thick beneath the north end of Sandy Hook (Miller and others, 2018), 110 feet thick at Perth Amboy (Stanford, 1999), 100 feet thick in the Navesink estuary at Rumson (Stanford, 2000), and 70 feet thick in the Matawan and Cheesequake Creek estuaries (Stanford, 1995, 2002). Estuarine deposition began as early as 13.4 ka at Sandy Hook (Miller and others, 2018). Sea level had risen to within about 25 feet of its present height by about 6 ka, by which time the coastline and estuaries of the county were close to their present size and shape. Within the past 6 ka northward longshore drift built the Sea Bright-Sandy Hook spit, which continues to grow northward.

The Sandy Hook lighthouse was built close to the north end of the Hook in 1764; today it is 1.5 miles from the north end and would be further if the ship channel around the tip of the Hook had not been kept open by periodic dredging.

FLOODPLAIN DEVELOPMENT

Radiocarbon dates on peat and wood (Minard, 1969; Sirkin and others, 1970; Stanford and others, 2002), and a mastodon skull (Harbour and others, 2014), in floodplain alluvium indicate that incision and erosion of the lower terraces to the base of modern floodplains was completed by about 15 ka. By this time permafrost had melted and pollen records show that closed spruce and pine forest had replaced the more open tundra and spruce parkland vegetation present through the late Wisconsinan glacial maximum (Sirkin and others, 1970; Watts, 1979). The resulting reduction of sediment washing into valleys, and the deepening of the Raritan and Hudson shelf valleys after 18 ka at the downstream end of streams in the northern part of the county, allowed streams to incise. Alluvium in the floodplains includes channel sand and gravel overlain by overbank silt, fine sand, and clay and backswamp peat. Floodplains typically consist of the main channel, perhaps bordered by low sandy natural levees, and seepage-collector channels or wetlands where groundwater discharges along the base of the upland bordering the floodplain.

Figure 8. Incised alluvium (above shovel head) over Wenonah Formation, Hop Brook, Holmdel.

In many floodplains, primarily in the northern and eastern parts of the county (Matawan, Navesink, Shark, and Manasquan basins) the main channel is inset as much as 10-15 feet deep into the floodplain alluvium, and in places has eroded into the underlying Cretaceous or Paleogene formation (fig. 8). Radiocarbon dates on wood and peat at four sites in the lower parts of the alluvium exposed in these incisions are between 2.2 and 2.7 ka (Stanford, 1992, 1995, 2001), indicating that most of the alluviation, and then the downcutting, has occurred within the past 2 ka. Possible causes of the incision include breaching of beaver dams after beaver extirpation, land use change from forested to agricultural to suburban that altered sediment influx and runoff intensity, filling and breaching of mill ponds or agricultural irrigation ponds, or ongoing up-basin migration of stream incision from the postglacial deepening of the Hudson shelf valley. This last possibility seems too remote in time but would explain the geographic pattern of the incisions, which are in basins draining to the Raritan and Hudson shelf valleys.

CONCLUSIONS

The surficial deposits and landforms of Monmouth County are the record of the interplay of sea level, glaciation, climate, and river dynamics over the past 15 Ma. Decline of global sea level in the middle and late Miocene between 15 and 5 Ma due to growth of Antarctic ice led to the transition of Monmouth County from an inner continental shelf to low-relief fluvial plain to, in the Pliocene, an upland with local streams draining both to the west and to the southeast. Glacial blockage and diversion of the Pensauken river during the first Laurentide glaciation at 2.5 Ma, and a second period of declining sea level in the early Pleistocene, caused streams in Monmouth County to reorient to a more northeasterly drainage and incise into the Neogene landscape. In the middle and late Pleistocene between about 500 and 15 ka fluvial terrace deposits were laid down in the valleys during cold periods and estuarine and beach sediments were deposited in the downstream reaches of valleys and coastal parts of the county during highstands of sea level at 400 ka and 125 ka. Glacial blockage and diversion of the Raritan and Hudson rivers during the late Wisconsinan glaciation between 25 and 18 ka caused renewed incision and erosion of valleys in the northern and eastern parts of the county. Postglacial sea-level rise after 14 ka flooded coastal valleys to create the present bays, estuaries, and coastline. Future rise of sea level due to anthropogenic global warming will, if unabated, return the coastline to the level of the previous Pleistocene highstands.

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Investigating the geomorphic and hydrologic characteristics of the Big Brook and Willow Brook watersheds, Monmouth County, New Jersey

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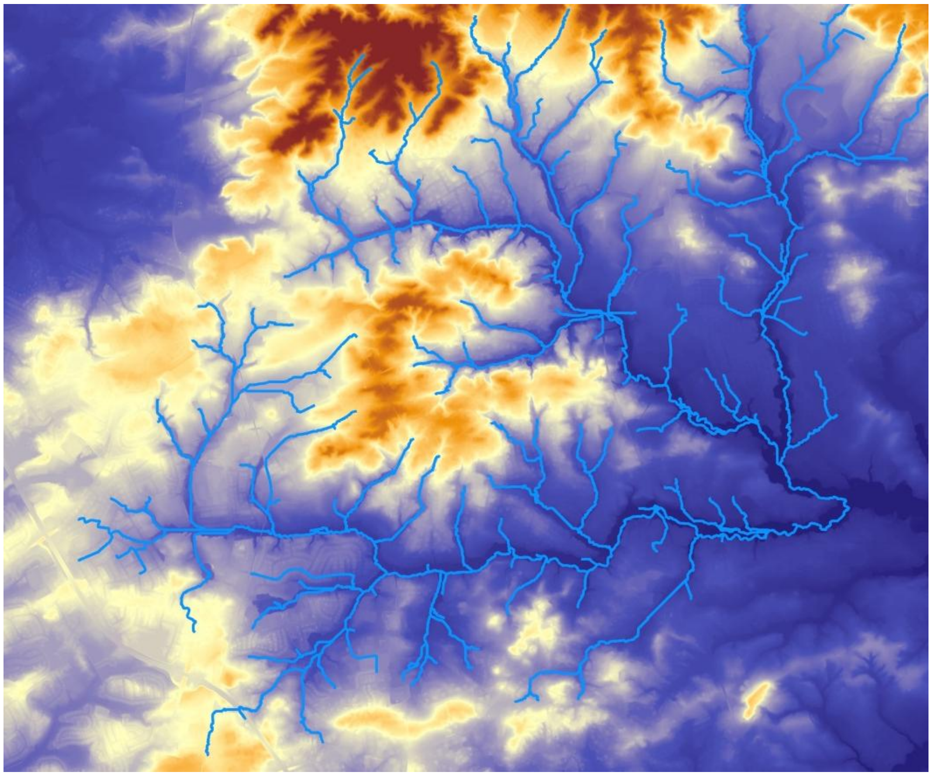


ABSTRACT

I analyzed two watersheds in northeastern New Jersey, Big Brook and Willow Brook, by examining their various hydrologic, geomorphic, and geographic characteristics. These characteristics included precipitation patterns, changes in the magnitudes/frequencies of annual floods, longitudinal profiles of the mainstems and tributaries, and changes in the land use of the watersheds. There was a significant increase in average annual precipitation following 1970, going from 44.4 +/- 5.8 inches per year before 1970 to 47.3 +/- 7.1 inches starting in 1970. The flood magnitudes/frequencies analysis produced mixed results. The two nearest USGS gages (but not within either watershed) displayed conflicting results, with the gage on the Swimming River having increasing floods but the gage on the Manasquan River displaying decreasing floods after 1970. There were also differences in the longitudinal profiles of the streams and their tributaries. In the Willow Brook watershed the mainstem and tributaries had similar gradients for their longitudinal profiles, while the tributaries for Big Brook were all much steeper than the mainstem. This may be driven by differences in the surficial deposits that the rivers are draining, but the cause is not entirely clear. There have all also been recent changes in the land use for both watersheds. The two watersheds both experienced increases in urbanization from 1972 to 2012, with the Big Brook watershed now having more than 50% of its land classified as developed.

INTRODUCTION

The adjacent watersheds of the Willow Brook and Big Brook in Monmouth County, New Jersey (Figure 1) are an excellent opportunity to use recently-acquired digital elevation models (DEMs) and other techniques to compare the two. These watersheds flow into the Swimming River Reservoir, an important local water resource, so understanding the behavior of these watersheds is important for proper management of the reservoir and for improved understanding of the recent geomorphic and hydrologic history of the area. In this paper I will discuss changes in precipitation patterns, flood magnitudes, river longitudinal profiles, and land use/land cover and how these changing characteristics influence the watersheds and their rivers.

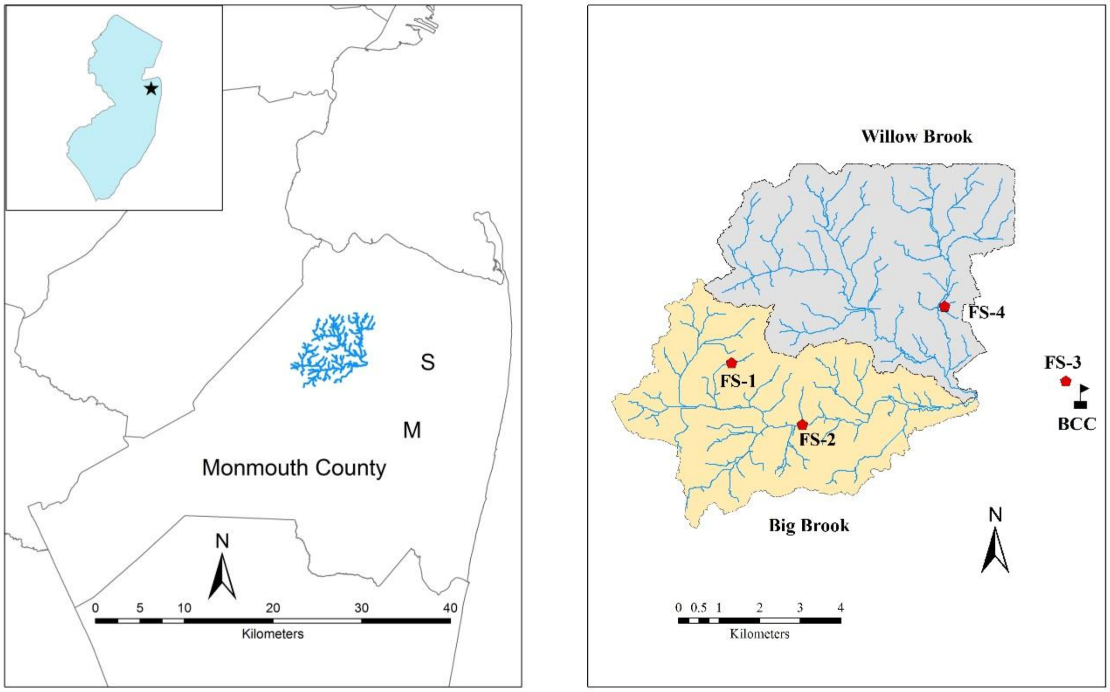


Figure 1. Location map of the two studied watersheds, located in northeastern New Jersey in Monmouth County. "S" designates the approximate location of the USGS gage on the Swimming River and "M" the location of the gage on the Manasquan River. The second map shows the Willow Brook and Big Brook watersheds and their tributaries in more detail. The second map also includes the stops for the field trip (FS) and Brookdale Community College (BCC).

METHODS

Precipitation

I analyzed precipitation data for Monmouth County, New Jersey by first downloading annual precipitation data from the Office of the New Jersey State Climatologist (https://climate.rutgers.edu/stateclim/). These data contained monthly and annual precipitation values, grouped by calendar year (Jan 1 to Dec 31) not water year (Oct 1 to Sep 30). The annual data was compiled and analyzed for trends over time. Using timings previously used by others, including the NJ State Climatologist, the average annual precipitation before 1970 was compared to the average annual precipitation from 1970 and after. These averages from the two time periods were then compared in

Excel (Microsoft, v. 2010) using the T-Test to tell if they were statistically different. Linear regressions were also run on the data.

Flood Frequency

I also investigated whether regional river discharges had changed statistically. I analyzed the records from two USGS river gages: 01407500 Swimming River near Red Bank NJ years 1923-2017, and 01408000 Manasquan River at Squankum NJ years 1932-2017. These were the two nearest gages with records before 1970 to allow for statistical analyses.

The annual peak discharges for each gage were downloaded and loaded into the software program from the Hydrologic Engineering Center's (HEC) Statistical Software Package (HEC-SSP v. 2.2: https://www.hec.usace.army.mil/software/hec-ssp/). HEC-SSP was used to calculate the chance of annual percent exceedance for various size floods. Analysis followed the USACE Bulletin 17 instructions, and used a minimum of 30 years of analysis.

Longitudinal Profiles

The geographic characteristics of the Big Brook and Willow Brook watersheds were investigated using Geographic Information System ArcGIS (ESRI v. 10.1). To calculate the longitudinal profiles of the rivers numerous steps were needed first. I downloaded high-resolution LiDAR (Light Distancing and Range) data from the United States Geological Survey (USGS) National Map viewer (https://viewer.nationalmap.gov/basic/). The highest resolution digital elevation models (DEMs) were downloaded, which were the bare earth 1m USGS NED (National Elevation Dataset (USGS 2015). That is, the cell size (resolution) is 1m by 1m, and items like vegetation, buildings, bridges, and other infrastructure have been removed to have the elevations reflect the ground surface.

I created a hydrologically-connected grid using several steps in GIS. I first removed any closed-depressions (these would be internally-drained basins) using the "Fill" command in ArcGIS. Flow direction ("Flowdirection") and flow accumulation ("Flowaccumulation") commands were then executed to determine stream networks and watersheds boundaries. The conditional ("Con") was used to create a stream network from cells with more than 100,000 contributing cells, which equals 100,000 m^2 of area. Unnamed tributaries of both rivers were numbered, beginning with the farthest downstream tributary and moving upstream (Figure 2) in each watershed being assigned #1, the second farthest downstream #2, and so on.

I determined watershed boundaries for the Big Brook and Willow Brook watersheds by establishing pour points for each upstream of the Swimming River Reservoir. A pour point is the point to which the watershed will drain. Using the pour point and the Flow direction grid from above I was able to delineate the watersheds for each pour point.

I created longitudinal profiles of each river and select tributaries by individually selecting each tributary or the mainstem of interest. I selected nine tributaries of the Big Brook and four for Willow Brook as well as the main stem of each, resulting in 15 river segments to work with. I arbitrarily selected the larger tributaries in each watershed, and then used the "Stack Profile" command to generate a profile of distance vs elevation for each river segment. The tributaries were numbered beginning with the farthest downstream tributary and then moving upstream in each watershed.

LULC

Land use/land cover information was obtained from numerous websites, including state and local sources. 2012 land use/land cover was downloaded from the New Jersey Department of Environmental Protection NJDEP Open Data website (https://gisdata-njdep.opendata.arcgis.com/) during June and July 2019. Historic land use/land (LU/LC) cover data for the years 1972 and 1995 were downloaded from the Center for Remote Sensing and Spatial Analysis (CRSSA) at Rutgers University (https://crssa.rutgers.edu/projects/lc/lccap_72_84_95.html). These were completed as part of the New Jersey Land Cover Change Analysis Project (Lathrop 2000). The data for 1972 and 1995 are raster (grid) data, with 1972 having a grid cell size of 80 m and 1995 having a cell size of 30 m. The 2012 land use is vector (polygon) and has a considerable amount of information, including % impervious. However, to make the data comparable between 1972, 1995, and 2012 the land use characterization from 1972 was used, which is the coarsest of the three datasets. The 1972 classifies land use into six categories: Developed, Cultivated/Grassland, Upland Forest, Bare Land, Palustrine Wetland, and Water. Each land use/land cover database was clipped to the watershed boundaries using ArcGIS. The number of cells categorized as "Developed" for 1972 was counted and compared to the total number of cells in the watershed to determine the percentage of land use that was developed. Similar methods were used for the years 1995 and 2012.

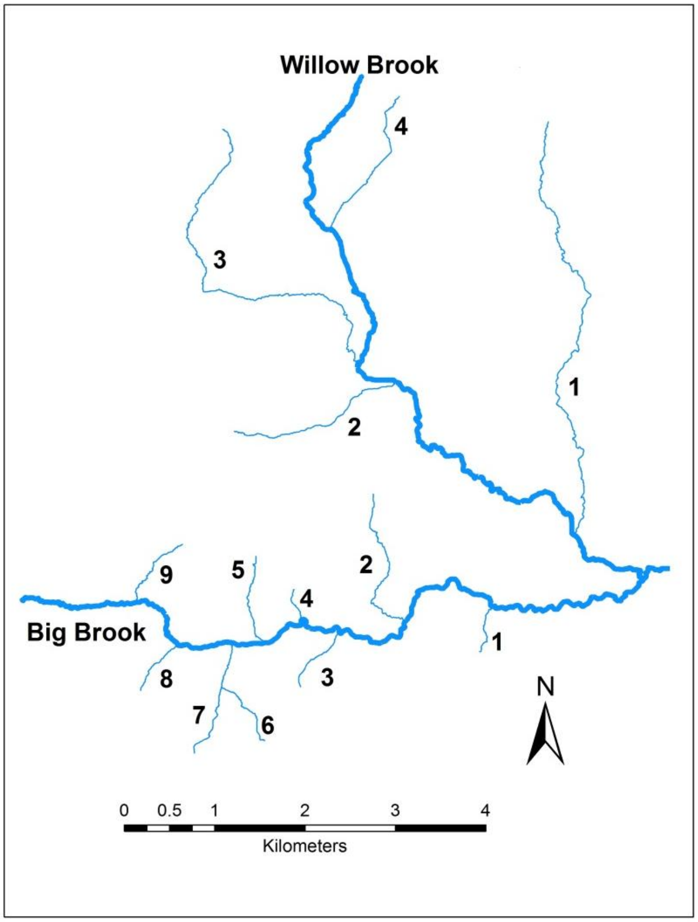


Figure 2. The location of the mainstems and tributaries for the Big Brook and Willow Brook watersheds. The unnamed tributaries were numbered starting going from downstream to upstream in each watershed.

RESULTS

Precipitation

The average annual precipitation increased significantly after 1970. The average annual precipitation for Monmouth County, NJ before 1970 was 44.4 +/- 5.8 inches. This average increased to 47.3 +/- 7.1 inches per year from 1970 and later. (Variation is reported as one standard deviation.) The averages for the two time periods are statistically different with a p value of 0.013. This means that there is a 98.7% chance that the difference between pre-1970 and 1970+ averages are not random. There were no significant trends in changes in annual precipitation when analyzed by linear regression or by looking at peak monthly precipitation values.

Flood Frequency

HEC SSP calculates flood magnitudes for floods with different recurrence intervals. While mathematically possible to calculate very infrequent flood discharges with SSP (e.g., the 0.2% annual chance, or the 500-year flood) I was not comfortable reporting such results from these records. I only reported the results from the 1% annual chance (100-year flood) to the 90% annual chance (1.1-year flood). The two rivers had opposite results comparing the pre-1970 flood discharges with those from 1970 and later. The Swimming River gage decreased in flood magnitudes, while the Manasquan River gage increased in flood magnitude (Table 1).

Table 1. The flood magnitudes for various frequencies for the Swimming and Manasquan Rivers, New Jersey. Flood magnitudes calculated for two different time periods (pre-1970 and 1970+) using HEC-SSP. Note the decrease for the Swimming River, but the increase for the Manasquan.

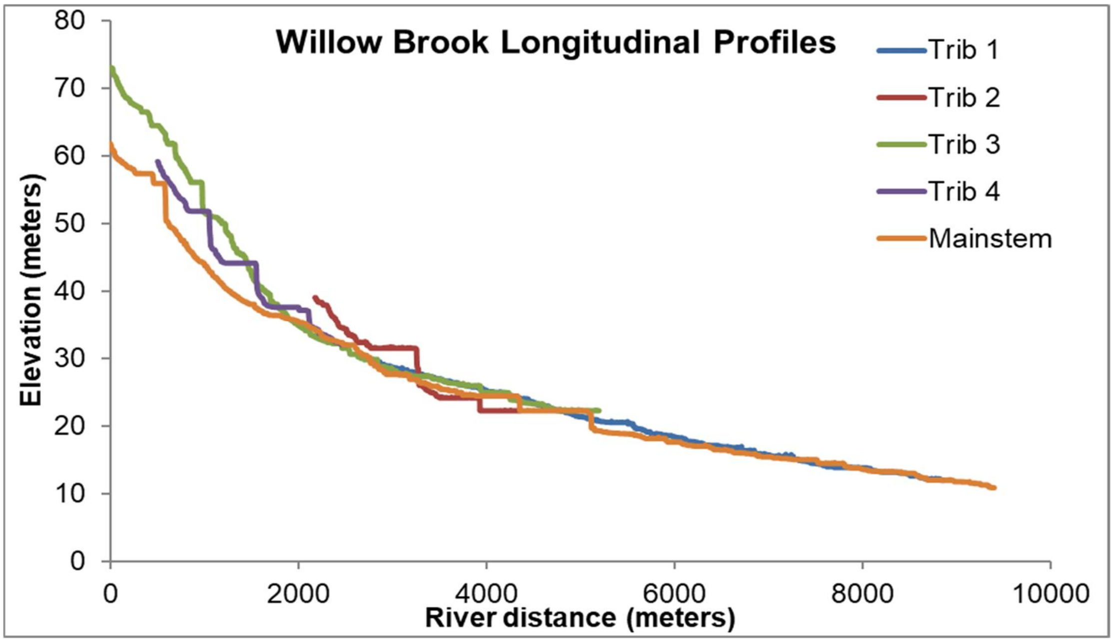
		Swimming River			Manasquan River	
% Exceedance	Recurrence Interval	Pre-1970 flood (cfs)	1970 and after floods (cfs)		Pre-1970 flood (cfs)	1970 and after floods (cfs)
1	100	13753	2897		2984	5687
2	50	9428	2254		2563	4527
5	20	5608	1571		2057	3276
10	10	3702	1158		1707	2503
20	5	2368	816		1377	1849
50	2	1185	441		941	1108
80	1.25	720	257		670	721
90	1.11	595	199		570	595

Longitudinal profiles

I calculated the longitudinal profiles for four tributaries and the mainstem of Willow Brook and nine tributaries and the mainstem of Big Brook (Figures 2 & 3) The profiles of Willow Brook and its tributaries have classic concave profile (Figure 3), in contrast to the profiles of Big Brook. For both watersheds the gradients of the main stem are lower than their tributaries (Figure 4, Table 2). The gradient (meter of elevation per meter of distance) for the mainstem of Willow Brook is 0.0051 m/m and for Big Brook is 0.0018. Only one tributary (Tributary 2 in Willow Brook) has a lower gradient than either of the mainstems.

LULC

The amount of developed land within the watersheds has increased over 40 years. The Willow Brook watershed went from 10.4% developed land in 1972 to 38.3% in 1995 to 45.2% in 2012. This represents a 4X increase in the amount of developed land in the Willow Brook watershed. There was a similar increase in the Big Brook watershed. Its developed land was at 19.8% in 1972, jumped up to 43.9% in 1995 and further increased to 53.5% in 2012. The relative increase is ~2.5X from where it was in 1972, less than Willow Brook, but it has over 50% developed land within its watershed.



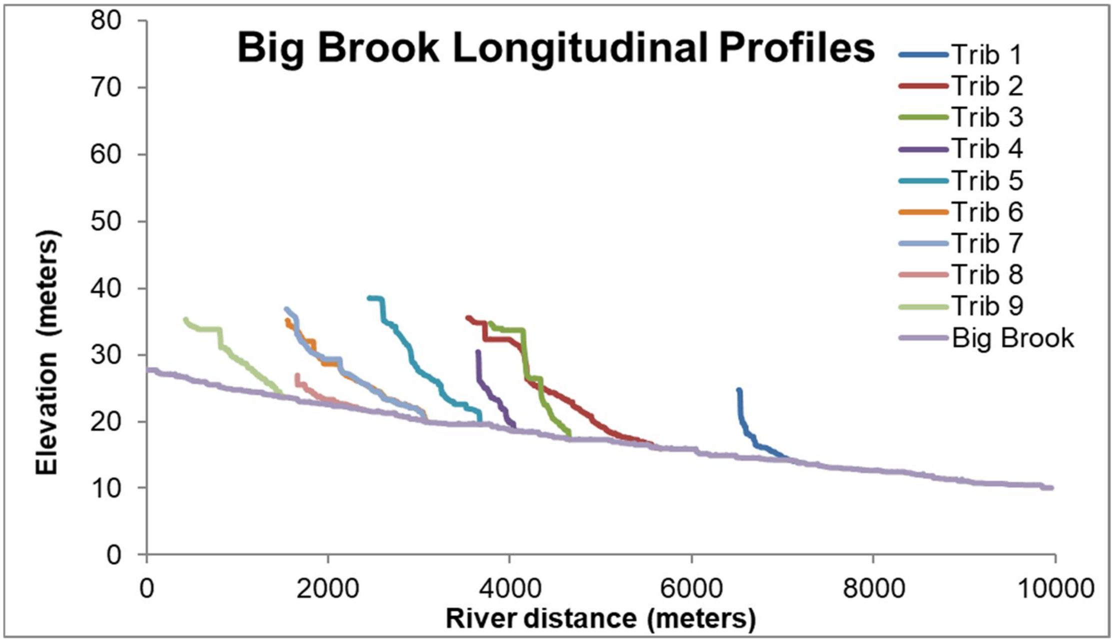


Figure 3. The longitudinal profiles for Big Brook, Willow Brook, and their tributaries. The tributaries in the Willow Brook have similar gradients to the mainstem, while the tributaries in Big Brook are much steeper.

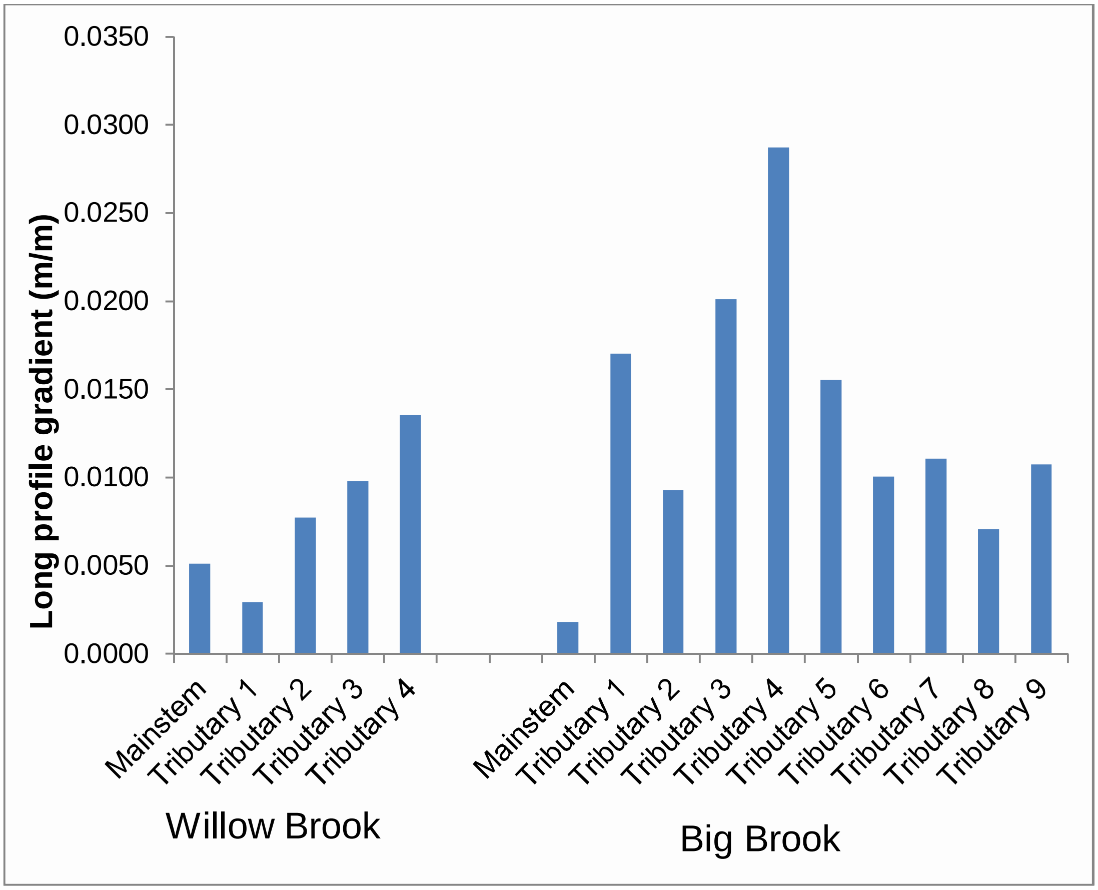


Figure 4. The gradients (m/m) for the tributaries and main stems of Big Brook and Willow Brook. The mainstems for both watersheds are generally lower than their tributaries, especially for the Big Brook.

Table 2. The gradients (meter/meter) for the 16 studied rivers in the Bog Brook and Willow Brook watersheds.

Willow Brook	Gradient (m/m)
Mainstem	0.0051
Tributary 1	0.0029
Tributary 2	0.0077
Tributary 3	0.0098
Tributary 4	0.0135

Big Brook	Gradient (m/m)
Mainstem	0.0018
Tributary 1	0.0170
Tributary 2	0.0093
Tributary 3	0.0201
Tributary 4	0.0287
Tributary 5	0.0155
Tributary 6	0.0100
Tributary 7	0.0111
Tributary 8	0.0071
Tributary 9	0.0107

DISCUSSION

There are both large-scale and small-scale factors that are affecting the Big Brook and Willow Brook watersheds. Some of these have affected both watersheds equally, while some have affected them differently.

There was a statistically significant increase in average annual precipitation experienced by the watersheds starting in 1970. This greater rainfall would be expected to increase river discharge and possibly metrics such as river channel width and depth. However, the physical size of the river channel would be slower to adjust to increases in precipitation, so the rivers may not exhibit that yet.

The precipitation patterns would have affected both the Willow Brook and Big Brook equally, as they are relatively small (both 4th order) and adjacent to each other. However, is it curious that the flood magnitudes for two nearby gages, the Swimming River and the Manasquan, display opposite trends (Table 1). This may be a factor of differing lengths of record, or highly localized convection-style intense precipitation, but the difference in their trends is unknown. Both of the gages are also downstream of reservoirs, which likely have some influence. However, both reservoirs are operated primarily as water resources (i.e., drinking-water reservoirs) and not flood control reservoirs, so their impact on downstream flooding may be minimal. The Swimming River Reservoir was constructed in 1901, while the Manasquan Reservoir was built in 1990.

Another change affecting both rivers is the increase in development within the watersheds. Both the Willow Brook and Big Brook basins experienced intense development between 1972 and 2012. Over half of the land within Big Brook is now considered developed, although for both watersheds the amount of impervious cover would be much lower. The increase in developed land would increase runoff and increase river discharge in the watersheds. This would likely increase river discharge, erosion, channel dimensions, and channel grain size.

The main difference between the two watersheds is their longitudinal profiles, especially with regards to their tributaries. The mainstems of both rivers have lower overall gradients (Figure 3), which is not that surprising given the concave profiles of many rivers in tectonically inactive areas such as New Jersey. The surficial deposits the rivers are eroding through are roughly the same, with large portions covered in weathered pre-Quaternary Coastal Plain sediments (Stanford, 1992 and Stanford, 2002). However, there are more exposed deposits of the Upper Terrace and Upper Colluvium units in the Willow Brook watershed than in the Big Brook. These differences may then be reflected in the behavior of the tributaries, with the steeper tributaries (Figure 4) in the Big Brook giving them, on average, more unit stream power and greater ability to transport sediment. It is also possible that the Big Brook has had greater anthropogenic influences, including for mosquito control (J. Brown, personal communication). However, more investigation, including on the ground, is needed to more confidently declare what is driving the differences between the watersheds.

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Pleistocene Mammals of New Jersey: a Twenty-First Century Retrospective

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In 1983, while the Geological Association of New Jersey was in its beginning phases, a review of New Jersey Pleistocene Mammalia was published (Parris, 1983) in the newly founded Journal of the Delaware Valley Paleontological Society THE MOSASAUR. It was intended to be a "benchmark" summary from which future research could be based. Since that time, most paleontologists from the region have put new discoveries on record in timely fashion, more especially if the specimens are in public museums. (Becker et al., 2010; Boulanger et al., 2015; Gallagher et al., 1989; Pallis, 2018).

It remains the greatest hope of vertebrate paleontologists that sites will yet be found with many taxa, particularly if microvertebrates can be found. It seems certain that such sites exist, especially in caves and fine-grained sediments. As always, the discoveries from amateur and avocational collectors are of the utmost importance in seeking such discoveries and donations to public museums will provide the best basis for future analysis.

Perhaps of greater significance is the depth of analysis that the many specimens have received. With the improvement of analytical methods of radiocarbon dating, many historical specimens can now be determined, even those which are small fragments of bones and teeth. (Boulanger et al., 2015). One of the most notable specimens is the skull of a juvenile mastodon (*Mammut americanum*) that could be accurately dated and also diagnosed for its paleopathology (Grandstaff et al., 2015). The specimen (NJSM GP23439) is currently on exhibition at the New Jersey State Museum, with its tuberculosis lesions noted. The care taken by collector/author Glenn Harbour was exceptional, preserving the Monmouth County specimen for sophisticated research and perpetual care at a public museum (Figure 1).

Monmouth County is notable not only for the number and variety of Pleistocene mammal specimens, but also for the protection of its paleontological resources. Few counties in America have established such high quality preservation areas, nor have many counties established suitable regulations for collecting, preserving, and studying the fossils. The Monmouth County Park System is partnered with the New Jersey State Museum in several projects that have assured the greatest recognition for paleontology.

Table 1 (below) is a revised list of the New Jersey Pleistocene 'megafaunal" species, gleaned from the bibliography.

Figure 1. Skull of a juvenile mastodon (*Mammut americanum*) that was diagnosed with tuberculous lesions and collected from Monmouth County, New Jersey.

Table 1
NEW JERSEY PLEISTOCENE MEGAFAUNA*

Megalonyx cf. *jeffersonii* Desmarest	Sloth*
Eremotherium mirabile (Leidy)	Sloth*
Castoroides ohioensis Foster	Giant Beaver*
Phocid indet.	Seal
Odobenus rosmarus Linnaeus	Walrus
Mammut americanum Kerr	Mastodon*
Mammuthus primigenius (Blumenbach)	Mammoth
Equus complicatus Leidy	Horse
Tapirus sp.	Tapir
Mysticeti indet.	Baleen Whale
Odontoceti indet.	Toothed Whale
Cervalces scotti Lydekker	Elk-Moose*
Rangifer tarandus Linnaeus	Caribou*
Symbos cavifrons (Leidy)	Musk Ox
Bison sp.	Bison
Trichechus sp.	Manatee

*Recorded from the mainland and beaches of Monmouth County.

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The Provenance of Lower Cohansey Sand and Lakehurst Titanium Ores Using Ilmenite Mg, Mn, and Nb Contents: Monmouth and Ocean Counties, NJ.

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ABSTRACT

The lower Cohansey Formation exposed throughout large portions of Ocean and southern Monmouth Counties is characterized by variable concentrations of ilmenite. Prospecting for titanium ore has focused on lowermost Cohansey sand with successful discoveries of commercial deposits near Lakehurst, New Jersey. The provenance of these lower Cohansey sands is, therefore, of interest to current and future prospecting ventures. The Mg, Mn, and Nb content of ilmenites are used to distinguish accurately among rock sources for sand provenance studies. Ilmenite in bedrock samples of each of the major ilmenite-bearing rock lithologies exposed throughout northern New Jersey are analyzed (1227 individual grain analyses) for major and trace element content. Four geochemical populations are identified: *High-MgO* containing >0.2 to <5.0 wt. % percent MgO; *Low-MgO* containing <0.2 wt. % MgO; *High-MnO* containing >4.0 to 12 wt. % MnO; and *High-*Nb_2O_5 containing > 0.2 wt. % Nb_2O_5. Altered ilmenites (averaging 65 wt. % TiO_2) from the Lakehurst, New Jersey, titanium sand ore deposits, are also analyzed (290 individual grain analyses) and compared with the ilmenite from the various bedrock samples. About 60 percent of the Lakehurst altered grains are *High-MgO* type and most closely match the *High-MgO* ilmenites from New Jersey Mesozoic basalt and diabase exposures. About 30 percent are *Low-MgO* and match ilmenites from Proterozoic granites and sodic gneisses; while about 10 percent are *High-*Nb_2O_5 type and match ilmenites from potassic gneiss and pegmatite interpreted as meta-rhyolite. The Mg, Mn, and Nb content of ilmenites are recommended as useful data pertaining to almost any future detrital sediment provenance study.

Keywords: ilmenite, Cohansey Fm., provenance, Niobium, Lakehurst ore.

INTRODUCTION

Ilmenite is a ubiquitous mineral found in most igneous and metamorphic rocks and in detrital sediment. McLimans et al. (2005) analyzed the major and trace element content of ilmenite grains from a wide variety of igneous and metamorphic rocks collected from worldwide locations in order to fingerprint the source rocks for sediment provenance determinations. They found that the Mg, Mn, and Nb content are particularly useful and varied across a very high compositional range. For example, 98 percent of the ilmenite grains separated from kimberlites contain > 10 wt. % MgO while 95 percent of the ilmenite grains separated from low metamorphic grade amphibolites contain < 0.2 wt. % MgO.

The international based conclusions of McClimans et al. (2005) agree with each of several local studies. For examples the ilmenite of mafic igneous rock is typically enriched in MgO including South African olivine gabbro (up to 6%, Cawthorn et al., 1985), South African picrite, (up to 11%, Cawthorn et al., 1988), the Siberian Flood Basalt Province, (up to 4.69%, Barnes & Kunilov, 2000) and kimberlite from Yakutia, Russia, (up to 18.60 %, Chakhmouradian & Mitchell, 1999).

In contrast, MnO enrichment was found to be a characteristic of low and medium grade metamorphic, hydrothermal, and granitic rocks such as Sullivan, British Columbian greenschist facies schists (up to 5.5%) and hydrothermal ore veins (up to 16.7%, Jiang et al., 1996), the Western Australian greenstones (up to 8.36%, Cassidy et al., 1988), and the granitic rocks of Southwest Japan (up to 19.8%, Tsusue and Ishihara, 1974).

Nb_2O_5 enrichment of ilmenite is not common, but seems to be a characteristic of felsic, highly fractionated or incompatible element enriched rocks such as Brazilian carbonatites (up to 3.36%, Gaspar & Wyllie, 1983); and the alkali quartz syenite from Cape Ashizuri, Southwest Japan (up to 4.4 %, Nakashima & Imaoka, 1998). Chakhmouradian & Mitchell (1999) found up to 12.5 % Nb_2O_5 in ilmenites from the same Yakutian, Russian kimberlite province that produced MgO enriched ilmenites; however they found that the Nb_2O_5 content of individual ilmenites was inversely proportional to their MgO content. Their niobian ilmenites were associated with a calcite-serpentine mineral assemblage that may not have formed in equilibrium with the primary kimberlite.

McLimans et al. (2005) determined that the MgO content of ilmenite is the most successful petrogenetic discriminating factor, but they also found that 83 percent of the ilmenites separated from felsic gneisses contain > 4 wt. % MnO and that alkali syenites are characterized by > 0.2 to > 1 wt. % Nb_2O_5 content in 87 percent of the ilmenite grains.

Previous studies, in addition to McLimans et al. (2005), have demonstrated the usefulness of ilmenite geochemistry for sediment provenance (Darby & Tsang, 1987; Darby, 1990; Grigsby, 1992; Schneiderman, 1995; Darby & Bischof, 1996; Schroeder et al., 2002; Lloyd & McLimans, 2003; Lloyd et al., 2005; Yang et al., 2009; Darby et al., 2015). A variety of sampling, analytical, statistical, and graphic methods were utilized in those studies. Those methods deserve careful consideration when designing a sand provenance study. However, the determination of the provenance of the lower Cohansey sand and related titanium ore deposits of Monmouth and Ocean Counties (Figure 1) is particularly well suited to the application of the Mg, Mn, and Nb approach utilized by Lloyd & McLimans (2003), Lloyd et al. (2005), and McLimans et al. (2005) because each of the four well documented rock types are represented where each of which crystallized under contrasting temperatures and geologic environments.

The four potential source rocks are the mafic igneous Watchung basalts and co-magmatic Palisades diabase, the Byram and Lake Hopatcong granites, a highly evolved REE enriched meta-rhyolite, and the Losee Gneiss, a metamorphosed calc-alkaline arc derived volcanic rock (Figure 2). Therefore, the approach here is to determine and compare the geochemistry of ilmenite in each of the potential source rocks to the ilmenites in the sand ore deposits on a grain by grain basis. The grain by grain application to the Lakehurst provenance question offers a distinct advantage over an average data approach. Averages tend to misrepresent the actual ilmenite composition contained within potential Lakehurst source rocks. Our grain by grain data indicate that many individual rock samples do not contain compositionally uniform ilmenites but instead contain more than one geochemical population. In many cases there is little transition from one population to the next. Instead, distinct compositional contrasts within single rock samples are common. Those complications are accommodated by defining geochemically the most abundant compositional clusters shared by the entire data-base and then graphically assigning defined compositional types to each individual sample with the use of bar diagrams. The methods used by this study should also apply to any future detrital sediment provenance study as a tested and successful approach.

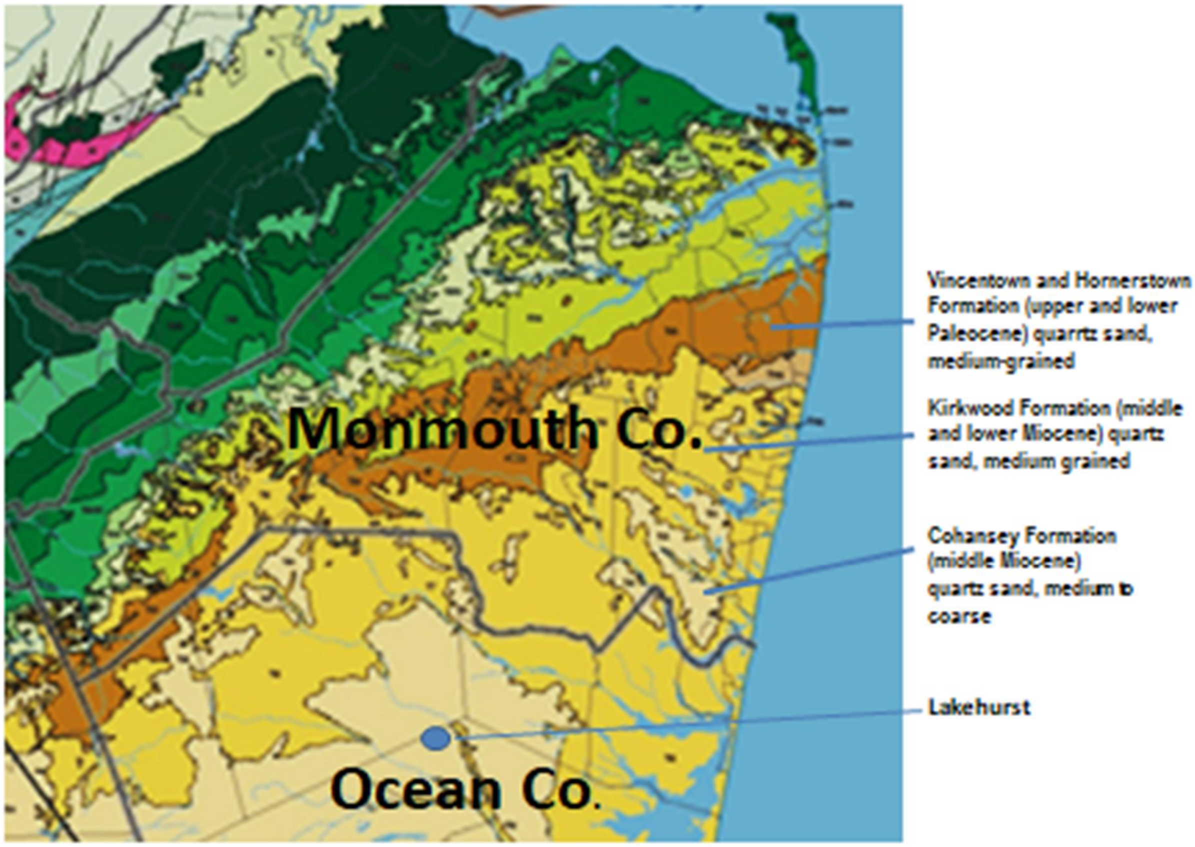

Figure 1. Geologic Map modified after Dalton et al. (2011) showing the distribution of Miocene Kirkwood and Cohansey sands. Prospecting for titanium was focused on the sands of the lower Cohansey and upper Kirkwood Formations with successful commercial discoveries near Lakehurst, New Jersey.

GEOLOGY

Ilmenite deposits of the Cohansey Formation

During the Miocene, marine regression controlled Cohansey Formation sand deposition across the New Jersey coastal plain (Figure 3). The Cohansey Formation is the host for titanium ore deposits that were discovered by Markewicz & Parrillo (1957) and mined extensively in the vicinity of Lakehurst, New Jersey from 1962 until 1982. Mining activity at the Gliden-Durkey, Inc. Jackson Township site extracted ore averaging 6 to 7 % ilmenite and at the ASARCO, Inc. mine in Manchester Township, the ore averaged 1.5 to 4 %. The Lakehurst deposits meet all the characteristics of the “Shoreline and Coastal Eolian” type of titanium mineral deposits (Force, 1991) together with Richards Bay, South Africa; Stradbroke Island, Australia; and Trail Ridge, Florida.

The ore is a pale buff colored, medium to coarse grained sand that is laminated and burrowed and is sparsely interbedded with lignite, or laminated clay and is described in detail by Markewicz et al. (1958); Markewicz (1969); Puffer & Cousminer (1982); and Puffer & Mullikin (1998). The ores contain 5 to 25 % heavy minerals with an average composition of 87% opaque Ti-Fe oxides, 7% zircon, 3% sillimanite, 1% staurolite, and traces of other heavy minerals (garnet, andalusite, chloritoid, epidote, kyanite, and titanite) (Puffer & Cousminer, 1982). The dominant Ti-Fe mineralogy is ilmenite that has been partially altered to pseudorutile (leucoxene) with a typical content of 65% TiO_2.

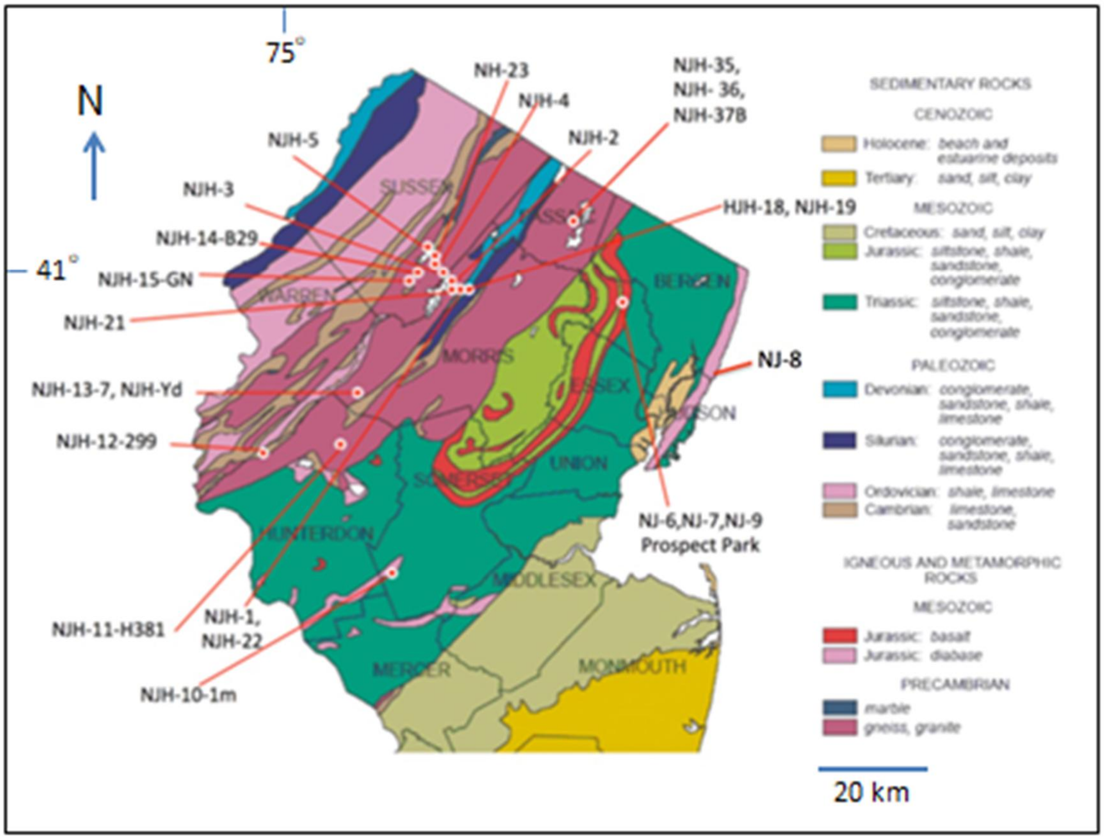

Figure 2. General geology of New Jersey and location of rock samples taken from Proterozoic New Jersey Highlands, and the mafic igneous rocks of the Mesozoic Newark Basin.

Sieve-size analyses of 31 samples of sand from the Lakehurst area (Puffer & Cousminer, 1982) indicate that the sand containing > 5% heavy minerals is better sorted (standard deviation = 0.65) than sand containing < 5% heavies (standard deviation = 0.95). Puffer & Cousminer (1982) also indicate a strong positive correlation of skewness with heavy mineral content. Positive skewness and high-degrees of sorting are characteristics of wind-blown sand in agreement with the general model proposed by Force (1991). His concentration process begins with fluvial detritus sorted in the swash zone of beaches resulting in coarse light minerals (principally quartz) deposited with fine heavier minerals (including ilmenite). The backwash then plucks the larger grains from the bed while the smaller heavy grains are left behind and accumulate in the upper part of the swash zone where they are exposed to eolian sorting processes.

Although the highest concentrations of titanium are located at the base of the Cohansey Formation that was deposited in a backshore beach and dune environment, the upper Cohansey was deposited in a fluvial and/or tidal channel environment (Puffer & Cousminer, 1982; Puffer & Mullikin, 1998). A late middle Miocene age for the Cohansey is based on an isotopic age of 12 million years for the uppermost beds of the underlying Kirkwood Formation (Sugarman et al., 1993) and on the pollen study of Owens et al. (1988).

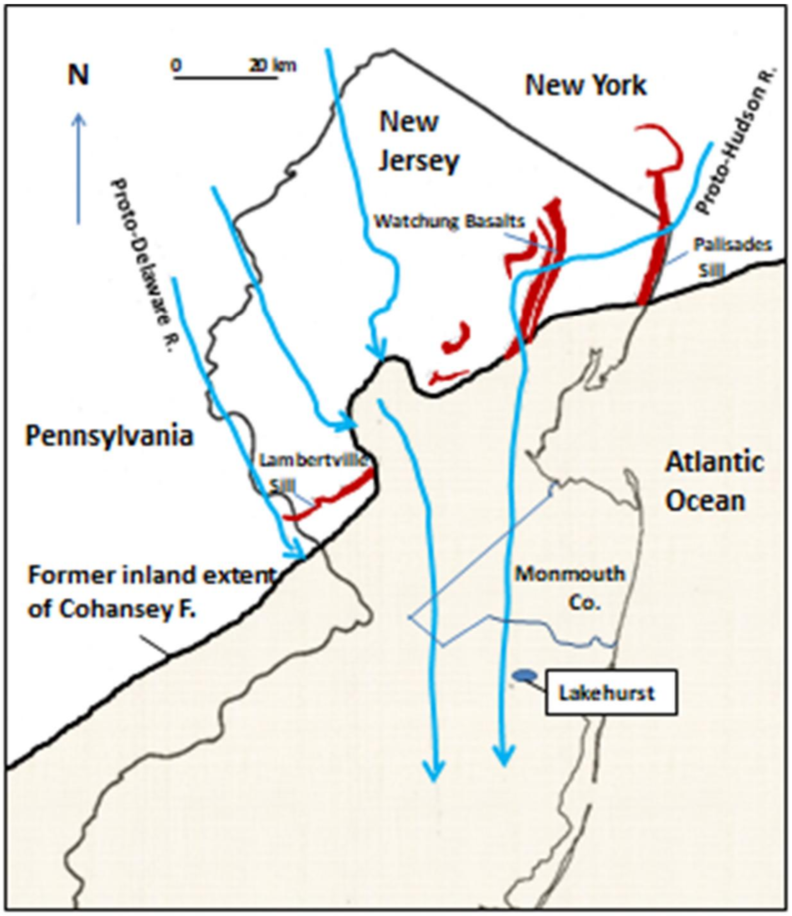

Figure 3. Areal extent of Cohansey sand deposition 10 million years ago and location of southerly flowing paleodrainage through wind gaps in the New Jersey Highlands and fluvial drainage on plains (blue lines) after Stanford (2009) and Harper (2013). The easternmost paleodrainage transects the Mesozoic Newark Basin (Figure 2) and flowed south to the Lakehurst area heavy mineral sand mines. Each of the major basalt and diabase bodies of New Jersey upstream from Cohansey deposition at their current level of exposure are indicated in red and labeled Palisades Sill, Watchung basalt, and Lambertville Sill.

Lakehurst titanium ore deposition

The fluvial drainage pattern across the New Jersey coastal plain during regressive deposition of the Cohansey sand is poorly constrained. However considerable constraint on the emergent southward flowing fluvial drainage pattern at about 10 Ma (Figure 3) is provided by the position of wind-gaps (notches in ridges where rivers formerly flowed) studied by Stanford (2009). This drainage pattern is also interpreted by Harper (2013) as well established before the late middle Miocene and would have controlled southward drainage throughout the deposition of the Cohansey. These are the rivers that supplied sediment to the Cohansey beaches and to the upper Cohansey deltas and flood plains as they meandered across the coastal plain. Their placement on the coastal plain of Figure 3 is based on the paleocurrent and surface elevation measurements, and the topographic reconstructions of Owens & Minard (1979), and Stanford et al. (2002). It is, therefore, likely that drainage during Cohansey deposition was controlled by the large former trunk rivers that flowed south from northern New Jersey area sources. We will show that the chemical compositions of ilmenites deposited in Cohansey sand near Lakehurst correlate with a northern Proterozoic and Mesozoic provenance in agreement with this proposal.

Potential Ilmenite Source Area

The geology of Northern New Jersey includes Paleozoic rocks in the northwest, a Proterozoic area to the north, and a Mesozoic area to the northeast (Figure 2). The Paleozoic area is largely composed of Ordovician Kittatinny Limestone and Martinsburg Shale, neither of which contains viable quantities of ilmenite. The Proterozoic area is composed largely of ilmenite-bearing gneisses and granites, and the Mesozoic area is composed largely of siltstones and ilmenite-bearing basalt flows and diabase intrusions. Our search for potential ilmenite source rocks was, therefore, focused on the most widespread ilmenite-bearing Proterozoic and Mesozoic rock formations of northern New Jersey. Most of our potential sources are igneous (Byram Intrusive Suite, Lake Hopatcong Intrusive Suite, Palisades intrusive system, and the Watchung basalt formations) but also include some meta-igneous formations (Losee Gneiss and meta-rhyolite).

Proterozoic granite, sodic gneiss, and potassic rhyolite source rocks

The Proterozoic rocks of New Jersey (Figure 2) have been mapped by Drake et al. (1996) and are commonly referred to as the New Jersey Highlands. Those rocks and their correlatives in New York and Pennsylvania include several minor formations that are exposed over less than 2 percent of the area and are, therefore, not important sources of ilmenite. Other Proterozoic formations, such as the Franklin Marble, do not contain significant ilmenite. Major ilmenite-bearing formations include two granite formations, a quartz-oligoclase gneiss, and a quartz microcline gneiss.

Granites underlie approximately 55 percent of the New Jersey Highlands area (Volkert, 1995). The major granitic formations are the Byram Intrusive suite and the Lake Hopatcong Intrusive Suite. The Byram Intrusive Suite is the more widespread of the two and comprises about 30 percent of the New Jersey Highlands. The Byram suite is predominately granite but includes syenite and alaskite facies and common magnetite-bearing pegmatites and amphibolite lenses. The mineralogy of the pegmatite and amphibolite components of each of the Highlands rocks tend to match the mineralogy of the host rocks. Accessory ilmenomagnetite and ilmenite are consistently found in Byram suite rocks. Twenty-six representative samples of Byram suite rocks were analyzed (Volkert, 1995) and found to contain 0.10 to 0.91 wt. % TiO_2 averaging 0.46 wt. %. The CIPW normative ilmenite content ranges from 0.19 to 1.63 percent averaging 0.87 percent.

The Lake Hopatcong Intrusive Suite comprises about 25 percent of the New Jersey Highlands area and includes syenite, alaskite, and gneissic facies, although the granite facies is the most abundant. Pegmatites and amphibolites are also common. Most Lake Hopatcong samples contain ilmenite. Twenty-eight representative samples of Lake Hopatcong Intrusive Suite were analyzed (Volkert, 1995) and found to contain 0.14 to 1.14 weight percent TiO_2 averaging 0.55 wt. %. The CIPW normative ilmenite content was found to range from 0.27 to 2.17 averaging 0.99 wt. %, slightly higher than the Byram Suite.

The Losee Metamorphic Suite comprises about 30 percent of the New Jersey Highlands. The Suite consists of quartz-oligoclase gneiss, and biotite-quartz-oligoclase gneiss, and rock mapped as “Albite-oligoclase granite” (Drake et al., 1996). Amphibolites, magnetite enriched pegmatites, and veins of magnetite and quartz are commonly found within each facies of the suite. The facies mapped as Albite-oligoclase granite typically contains less than 2 volume percent potassium feldspar and is actually a trondhjemite. Puffer & Volkert (1991) interpreted the trondhjemite as a product of local anatectic melting and the gneissic portion as residual metamorphosed calc-alkaline arc volcanics.

Eleven samples representing the Losee Suite were analyzed (Puffer & Volkert, 1991) with TiO_2 concentrations ranging from 0.1 to 0.89 wt. % averaging 0.38 wt. %. CIPW normative ilmenite content ranges from 0.19 to 1.59 wt. %. Actual ilmenite content, however is estimated at only 0.12 percent on the basis of seven polished sections and is commonly absent.

The combined area underlain by rock units mapped as Potassium Feldspar Gneiss and less common oligoclase bearing Microcline Gneiss is about 7 percent (Drake et al., 1996). Those units are interpreted as meta-sediments by Drake et al. (1996), Baker & Buddington (1970), and Sims (1958) and more specifically as meta-arkose by Drake (1984) and Volkert & Drake (1999). However, Puffer & Gorring (2005) present geochemical and stratigraphic evidence consistent with a highly evolved, REE enriched, meta-rhyolite protolith, particularly Na_2O/K_2O data that plots outside the compositional range of typical arkose but directly within rhyolite compositional fields. Fourteen samples of Potassium Feldspar Gneiss from across the New Jersey Highlands were analyzed (Puffer & Gorring, 2005) and found to contain an average of 0.29 wt. % TiO_2 and 0.57 wt. % CIPW normative ilmenite. Five samples of Microcline Gneiss were found to contain an average of 0.21 wt. % TiO_2 and 0.39 wt. % CIPW normative ilmenite. Seven samples of high-grade magnetite ore from an iron deposit within the meta-rhyolite (The Edison Iron Mine) were also analyzed and found to contain an average of 0.99 wt.% TiO_2 and 1.89 wt. % CIPW normative ilmenite.

Mesozoic basaltic source rocks

The ilmenite-bearing igneous rocks of the Newark Basin (Figure 2) include three early Jurassic basalt formations (the Orange Mountain, Preakness, and Hook Mountain) and the Palisades intrusive system consisting of diabase. Those igneous units represent about 8 percent of the total area making up the Newark Basin but presumably stood out as four parallel mountain ridges during active Miocene erosion and were an important potential source of detrital ilmenite. Each of the basalts contain ilmeno-magnetite and ilmenite. Although the basalts have undergone varying degrees of weathering and hydrothermal alteration, a collection of unaltered samples was analyzed by Puffer (1992). The TiO_2 content of 38 samples of unaltered basalt from all three formations averages 1.11 wt. % with a range of 0.76 to 1.55 wt. %.

The Palisades sill is exposed as a prominent ridge along the northeast boundary of New Jersey and extends north into Rockland County New York. The sill is a 340 m thick diabase intrusion. The Palisades sill is interpreted by Puffer et al. (2009) and Blackburn et al. (2013) as comagmatic with the Orange Mountain and Preakness flows. The average TiO_2 content and normative ilmenite content of the Palisades is virtually the same as that of the extrusive flows and with a network of comagmatic sills and dikes located throughout the southern Newark basin including the Lambertville Sill (Figure 2).

Other potential sources

It has been suggested that the titanium anomaly that correlates with the lower Cohansey may have an extraterrestrial source which may explain its unusual chemical composition including radioactive elements. However thin ilmenite concentrations are actually very common in well-sorted quartz sand for sedimentological reasons. The principle concentrating factor as described by Force (1991) is the back-beach depositional environment and the resulting winnowing out of minerals that are not as dense, hard, or insoluble as ilmenite and some ubiquitous radioactive accessory minerals such as zircon and monazite. The principle reason why ilmenite concentrates (back-beach black sand) are so common is the very ubiquitous distribution of accessory ilmenite in igneous and metamorphic source rocks. Ilmenite is rarely absent from granitic (Puffer, 1970) or basaltic rock. The principal factor that made the Lakehurst district commercial was that the back-beach environment was sustained over a period of time long enough to develop an unusually thick deposit.

SAMPLING AND ANALYTICAL METHODS

The Northern New Jersey potential ilmenite source rock formations were sampled at well exposed outcrop locations (Figure 2, and Table 1). Sand samples from the Lakehurst area titanium mines (Figure 3) were also collected and processed to produce ilmenite concentrates for this study.

Table 1. Description and location of analyzed samples.

Sample #	Rock Name	Location (see Fig. 1)	Description	Grains analyze
Mafic ig. NJH-10-1m	Lambertville Diabase	Quarry 3 km west of Belle Mead NJ	Medium grained augite - plagioclase diabase	58
Mafic ig. NJ-9	Orange Mountain Basalt	Prospect Park Quarry, Paterson, NJ	Massive plagioclase-augite basalt	47
Mafic ig. NJ-8	Palisades Diabase	Henry Hudson Dr. near Ross Dock 7 m above base of sill	Medium grained augite - plagioclase diabase	60
Mafic ig. NJ-7	Orange Mountain Basalt	Prospect Park Quarry, Paterson, NJ	Altered albite augite chlorite basalt	12
Mafic ig. NJ-6	Orange Mountain Basalt	Prospect Park Quarry, Paterson, NJ	Massive plagioclase-augite basalt	63
Meta rhyolite? NJH-21-5a	Mesoperthite pegmatite	Richards Iron Mine 1 km north of Rt 80	Microcline quartz pegmatite with minor plagioclase	52
Meta rhyolite NJ-5	Meta rhyolite	Edison Iron Mine 2 km southeast of Ogdensburg, NJ	Microcline quartz biotite garnet magnetite gneiss	56
Meta rhyolite NJH-12-299	Meta rhyolite	Rt. 78 road cut 8 km east of Easton PA	Microcline quartz biotite garnet cpx gneiss	59
Gneiss NJH-36	Pyroxenite in Losee Gneiss	East of northern Wanaque Reservoir	Hypersthene plagioclase gneiss w minor hornblende	59
Gneiss NJH-15-GN	Pyroxenite in Losee Gneiss	1 km north of Wright Pond, 2 km south of Lake Mohawk	Hypersthene plagioclase hornblende quartz gneiss	59
Gneiss NJH-11-H381	Pyroxenite in Losee Gneiss	3 km south of Califon, NJ	Hypersthene plagioclase quartz hornblende gneiss	59
Lake H Granite NJH-2	Amphibolite in Lake Hopotcong Granite	Rt. 15 near north end of Lake Hopatcong	Hornblende plagioclase phlogopite apatite gneiss	61
Byram Granite NJH-35	Byram Granite	West of northern Wanaque Reservoir	Hornblende phlogopite quartz microperthite plagioclase	57
Byram Granite NJH-22	Amphibolite in Byram Granite	Rt. 15 0.2 km north of Rt 80	Clinopyroxene phlogopite hornblende plagioclase gneiss	57
Byram Granite NJH 1	Byram Granite	HY 15 at entrance to Picatinny Arsenal	Hornblende quartz microperthite plagioclase granite	57
Losee Gn NJH-23-515a	Losee Gneiss	South end of Rt 15 roadcut 2.5 km south of Sparta Township	Oligoclase quartz biotite gneiss	61
Losee Gn NJH-19	Losee Gneiss	Mount Hope iron mine 3.5 km northwest of Rockaway NJ	Oligoclase quartz biotite gneiss	47
LoseeGn NJH-18	Losee Gneiss	near Rockaway Mall exit 35 Rt 80	Oligoclase quartz biotite gneiss	22
Losee Gn NJH-3	Losee Gneiss	North end of Rt 15 roadcut 2.5 km south of Sparta Township	Leucocratic oligoclase quartz gneiss	59
Losee Gneiss NJH-4D	Hornblende enriched Losee Gneiss	North end of Rt 15 roadcut 2.5 km south of Sparta Township	Hornblende oligoclase quartz biotite gneiss	59
Losee Gneiss NJH-4C	Hornblende enriched Losee Gneiss	North end of Rt 15 roadcut 2.5 km south of Sparta Township	Hornblende oligoclase quartz biotite gneiss	58
Lakehurst NJ-GLD-5	Cohansey Formation	Glidden Titanium Mine	medium grained quartz sand	53
Lakehurst NJ-GLD-2	Cohansey Formation	Glidden Titanium Mine	medium grained quartz sand	55
Lakehurst NJ-ASR-5	Cohansey Formation	ASARCO Titanium Mine	medium grained quartz sand	59
Lakehurst NJ-1	Cohansey Formation	Lakehurst, NJ	medium grained quartz sand	62
Lakehurst NJ-LKH-5	Cohansey Formation	Lakehurst, NJ	medium grained quartz sand	61

Samples of sand from the Lakehurst area were screened to -1.4mm +75um size and an ilmenite concentrate obtained via a lift roll magnetic separator. Rock samples from Northern New Jersey were crushed to fine size in a jaw crusher, screened at -1.4mm +75um and an ilmenite concentrate obtained via a lift roll magnetic separator. Polished thin sections were then made of the ilmenite concentrates for optical and electron microprobe analyses.

The ilmenite grains in polished sections were analyzed on a grain-by-grain basis by electron microprobe at the Microbeam Laboratories, Department of Earth Sciences, Bristol University. A high beam current (50nA) was used in order to excite the heavier trace elements (V, Cr, Mn, Fe, Nb) and that also resulted in more counts from the light elements (Mg, Al, Si). Count times were 30 seconds on element peaks (except Ti = 10 seconds) and from 10 to 20 seconds on background. The instrument, a Cameca SX100, operating at 20kV and with a beam current of 50na, is calibrated using a range of well-characterized synthetic and natural minerals from the Bristol University collection. The trace elements selected for analysis are those present in sufficient amount to be detected with a high degree of precision. The instrumentation used, ilmenite trace element levels and detection limits, and a desire to minimize analytical cost led to a focus on Mn, Mg, V, Cr, and Nb. Those elements also show only marginal changes in their concentration in ilmenite grains altered to as high as 70 wt. % TiO_2 (Lloyd & McLimans, 2003) and hence are candidates for use in provenance determination. Correction procedures were applied for interference between the analysis lines for V and Ti. Detection limits and errors are given in Table 2.

Table 2. Electron microprobe detection limits and errors at 99% confidence limit.

Oxide	Detection Limit	Error (+/-) wt. % oxide
SiO_2	0.02	0.02
TiO_2	0.02	0.08-0.11
Al_2O_3	0.02	0.02
V_2O_3	0.01	0.02
Cr_2O_3	0.01	0.02
FeO	0.02	0.09-0.15
MnO	0.02	0.03
MgO	0.01	0.01
Nb_2O_5	0.01	0.02

ANALYTICAL RESULTS

Chemical analyses

Microprobe analyses of 1348 ilmenite grains from the bedrocks of Northern New Jersey (Supplementary Table A1[4]) and 290 ilmenite grains from Lakehurst titanium ore sand (Supplementary Table A2[5]) were completed with average values and standard deviation calculations presented in Table 3. The analytical results indicate that negligible quantities of SiO_2, Al_2O_3, CaO, and P_2O_5 are present (averaging 0.08, 0.05, 0.06, and 0.00 wt. percent, respectively, Table 3). Those elements are typically contained in micro-inclusions that may have generated background contamination when located close to probed locations. FeO and TiO_2 data (Table A1) show that all the analyzed grains in northern New Jersey bedrock samples are slightly altered to unaltered ilmenite. All of the ilmenite grains from the Lakehurst area deposits are

Table 3. Chemical compositions of ilmenites from Lakehurst Ti ore and potential source rocks.

	Losee Gneiss n=486		Meta-Rhyolite n=269		Granites n=232		Basaltic Rocks n=240		Lakehurst Ti Ore n=290	
	av.	st. dev.	av.	st. dev.	av.	st .dev.	av.	st. dev.	av.	st.dev.
SiO_2	0.06	0.38	0.16	0.45	0.04	0.23	0.02	0.02	0.10	0.08
TiO_2	49.05	2.14	50.75	2.89	48.75	2.53	47.93	2.30	57.52	6.39
Al_2O_3	0.04	0.15	0.15	0.41	0.03	0.07	0.06	0.05	0.40	0.24
FeO_t	46.81	2.98	42.37	4.77	46.75	2.40	47.78	2.40	33.24	8.03
Fe_2O_{3t}	51.49	3.27	46.61	5.25	51.43	2.63	52.56	2.64	36.56	8.83
MnO	2.51	1.85	5.01	3.63	2.10	1.15	0.96	0.84	1.00	1.02
MgO	0.06	0.20	0.06	0.24	0.20	0.47	1.29	1.08	0.43	0.59
CaO	0.01	0.02	0.02	0.04	0.03	0.15	0.03	0.04	0.03	0.20
P_2O_5	0.00	0.01	0.01	0.02	0.00	0.02	0.00	0.00	0.08	0.08
Cr_2O_3	0.01	0.02	0.01	0.01	0.05	0.06	0.03	0.03	0.02	0.02
V_2O_3	0.11	0.13	0.02	0.05	0.10	0.10	0.43	0.20	0.19	0.14
Nb_2O_5	0.05	0.07	0.38	0.38	0.10	0.18	0.04	0.05	0.10	0.16
Total FeO*	98.71	0.87	98.92	1.58	98.15	0.75	98.57	0.70	93.10	2.31
Total Fe_2O_3**	103.39	0.81	103.16	1.73	102.82	0.72	103.35	0.72	96.42	2.96

* Total assuming all iron as FeO

** Total assuming all iron as Fe_2O_3. Low Lakehurst totals due to unreported $H2O^+$ from iron and aluminium hydroxides.

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[4] Available upon written request to John Puffer: jpuffer@scarletmail.rutgers.edu

[5] Ibid.

slightly to highly altered ilmenite (Table A2). The FeO and TiO_2 contents of the ore ilmenite are largely a function of alteration effects with increasing TiO_2/FeO as iron is progressively leached out.

The Cr_2O_3 content of the 987 analyzed ilmenite grains from granite and gneiss samples and the 240 grains from basaltic rock samples average 0.02 and 0.03 wt. percent respectively (Table 3). The difference may be meaningful, although the precision is constrained by the detection limit of the microprobe. The V_2O_3 content of the 987 analyzed ilmenite grains from granite and gneiss samples and the 240 ilmenite grains from basaltic rock samples average 0.09 and 0.43 wt. percent respectively (Table 3). The V_2O_3 contents in the basaltic samples show a cluster close to the average of 0.43 weight percent, however, the V_2O_3 contents in granitic and gneissic samples show a high degree of scatter. Hence, for the New Jersey rock samples, the V and Cr data are not sufficiently diagnostic for ilmenite provenance determinations.

Four chemical populations

The data for Mg, Mn, and Nb for the samples in Table 1 are plotted in Figures 4 through 8. Mg, Mn, and Nb substitutions for Ti and Fe in the ilmenite lattice are particularly sensitive to environmental and rock compositional controls during crystallization and are particularly useful for provenance estimations. Clustering of Mg, Mn, and Nb data plotted in Figures 4 through 8 enable division into four populations (Table 4).

1. High-MgO. 0.01 Ilmenite grains containing more than 0.2 percent MgO but less than 4 wt % MnO constitute a unique population that does not overlap other data on Figures 4 through 8. In each case the MgO content plots inversely to MnO content; a consistent relationship among ilmenites collected from several international locations (McLimans et al., 2005). Except for two grains in one sample of meta-rhyolite (NJH-21x), all ilmenite grains in the High-MgO field contain less than 4 wt. % MnO.

2. High-MnO. All grains containing more than 4 wt. % MnO are relegated to a High-MnO field on Figures 4 through 8. High-MnO takes precedence over High-MgO for provenance estimations because elevated MnO fingerprints (correlates with) high temperature felsic compositions that may also be MgO enriched (McLimans et al., 2005).

Table 4. Generalized ilmenite class defined and correlated to host rock type.

Ilmenite Class	Qualifying Attribute	Most Common Host Rock
Low-MgO	<0.2 wt. % MgO, Nb_2O_5, MnO	Proterozoic granites and gneisses
High-MgO	>0.2 <5.0 wt. % MgO	Mesozoic basalt and diabase
High-Nb_2O_5	> 0.2 wt. % Nb_2O_5	Meta-rhyolite and pegmatite
High-MnO	> 4 wt. % MnO	not well represented

3. High-Nb_2O_5. Nb_2O_5 content is inverse to MgO content (Figure 6). Except for four grains in one sample of meta-rhyolite (NJH-21-5a) all ilmenite grains containing more than 0.2 percent MgO also contain less than 0.2 percent Nb_2O_5. Ilmenite grains containing more than 0.2 percent Nb_2O_5 constitute a High-Nb_2O_5 population. The High-Nb_2O_5 population is particularly diagnostic and takes precedence over High-MgO for provenance estimations because Nb_2O_5 correlates with alkaline rocks whether they are felsic or mafic (McLimans et al., 2005).

4. Low-MgO. The Low-MgO field (less than 0.2 percent MgO) is also defined by <4 wt % MnO and <0.2 wt % Nb_2O_5 on Figures 4 through 8 so that it can be distinguished from any of the other ilmenite types.

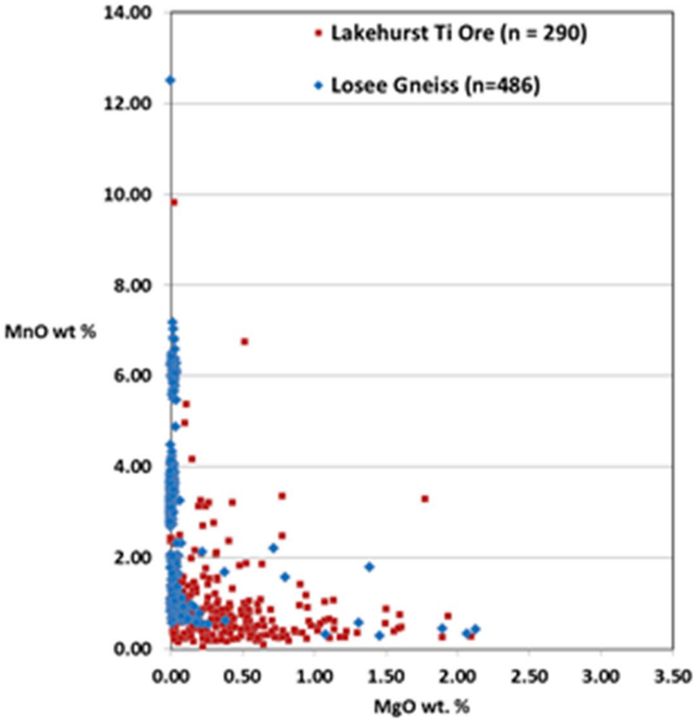

Figure 4. Plot of MgO and MnO content of ilmenite grains from the Losee Gneiss of Northern New Jersey and from sand samples of Lakehurst, New Jersey Ti ore.

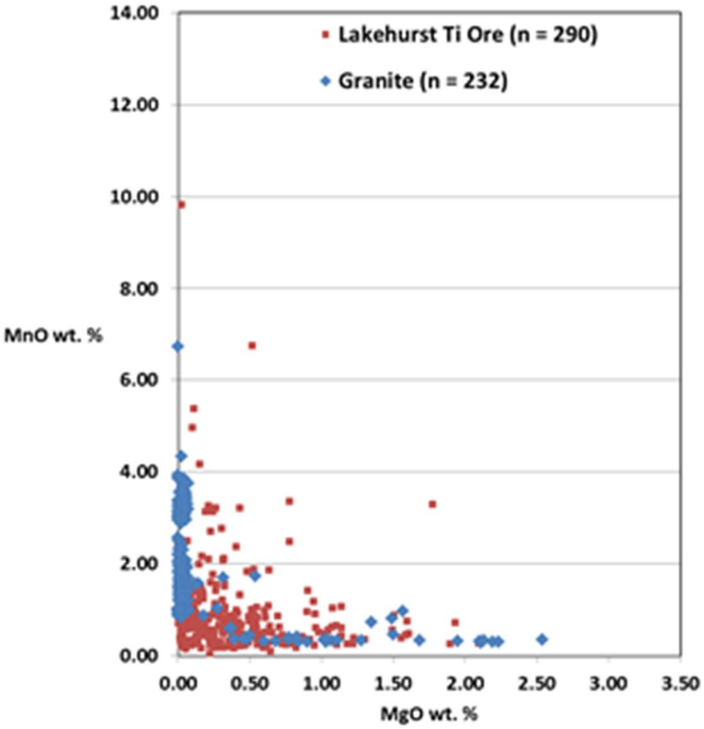

Figure 5. Plot of MgO and MnO content of ilmenite grains from the Proterozoic granites of Northern New Jersey and from sand samples of Lakehurst, New Jersey Ti ore.

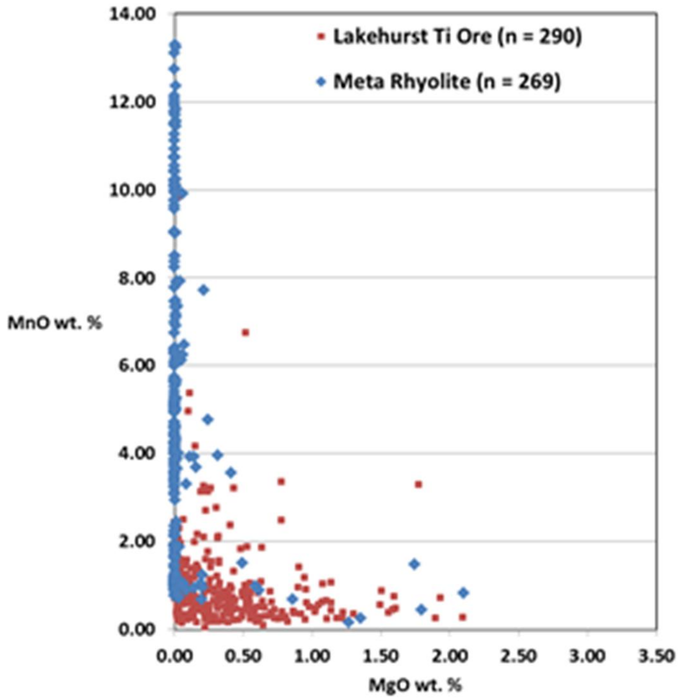

Figure 6. Plot of MgO and MnO content of ilmenite grains from potassic gneisses of Northern New Jersey interpreted as meta-rhyolite by Puffer and Gorring (2005) and from sand samples of Lakehurst, New Jersey Ti ore.

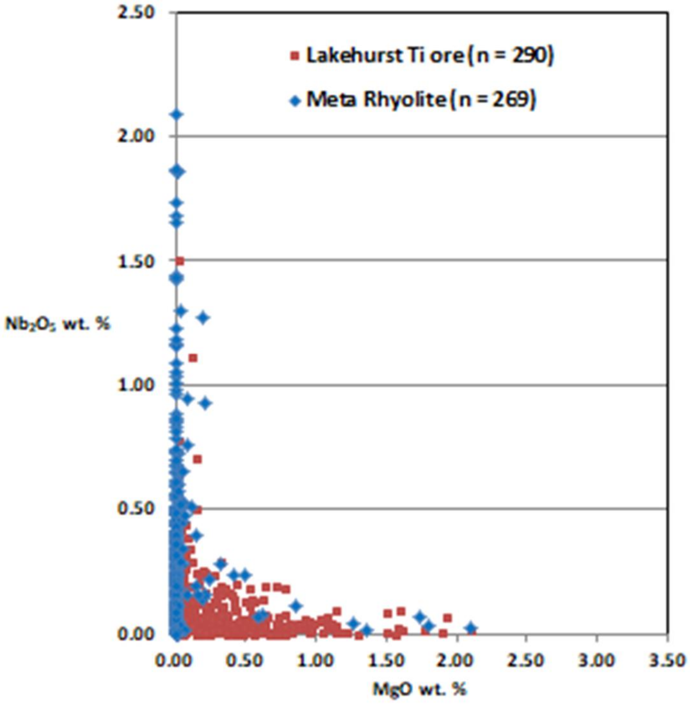

Figure 7. Plot of the MgO and Nb_2O_5 content of ilmenites grains from potassic gneisses of Northern New Jersey interpreted as meta-rhyolite by Puffer and Gorring (2005) and from samples of Lakehurst Ti ore.

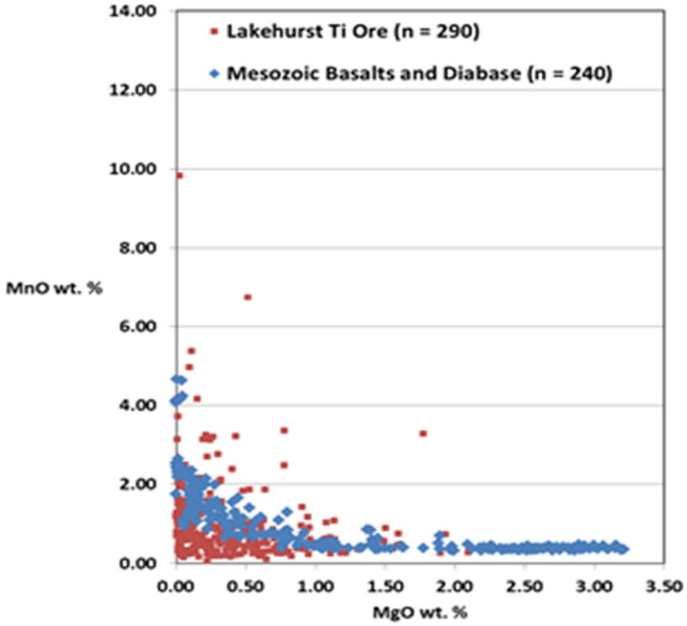

Figure 8. Plot of MgO and MnO content of ilmenite grains from the Mesozoic basalts and diabase of Northern New Jersey.

DISCUSSION

Geochemical controls on ilmenite composition

The minor elements typically found in ilmenite are Si, Al, Mg, Mn, Nb, Cr, P, V, and Zr. Some of these elements typically occur as fine-grained inclusions such as quartz (Si), clay or spinel (Al), monazite (P), or zircon (Zr). Other impurities are incorporated into nano-inclusions that fit into pore spaces created during alteration as iron is leached out. Elements that occur in solid solution as primary impurities include Mn, Mg, and Nb, which are the focus of our study. It is the extreme degree of the inverse Mn-Mg and Nb-Mg distributions seen in Figures 4 through 8 that is the basis of our provenance estimations.

These distributions are controlled largely by well-known contrasts in the ionic radii and electronegativity of Mg, Mn, and Nb; the relative availability of Mg, Mn, and Nb during ilmenite crystallization; and the response of the ilmenite lattice to the temperature and oxygen fugacity of crystallization (Buddington & Lindsley, 1964).

In addition to ionic substitutions during crystallization, weathering effects can also influence ilmenite composition. The process of leaching iron from ilmenite introduces other elements not present in unaltered ilmenite (Al, Si, P) and may alter the content of other elements initially present in ilmenite (Mg, Mn, Nb, Cr, V). However, studies of ilmenite alteration and provenance from several locations (Lloyd & McLimans, 2003; McLimans et al., 2005; Lloyd et al., 2005), found that the trace element signature of ilmenite successfully defined potential source rocks, even where alteration resulted in TiO_2 content up to 70 wt. %. In addition, the grain-by-grain microprobe methodology used here uses textural relations and data from SEM images to avoid issues such as inclusions within ilmenite and interference from near neighbor non-ilmenite grains.

Ilmenite composition of source rocks

Losee Gneiss. Compositional variations among the 486 analyzed ilmenite grains from the Losee Gneiss samples (Figure 4), particularly the wide range of MnO content, are the probable result of its complex geologic development (Puffer & Volkert, 1991). The ilmenite content of most Losee Gneiss is predominately Low-MgO (Figure 4) and is concentrated in thin mafic bands of gneiss mineralogically resembling amphibolite. The thin bands commonly thicken into distinct amphibolite layers and lenses. However, the Losee is a granulite-facies gneiss that has locally undergone low temperature anatectic partial fusion at the albite-quartz eutectic to form a very leucocratic trondhjemite melt (represented by sample NJH-3) plus an aqueous phase that carried away iron in solution (Puffer & Volkert, 1991). The iron, and presumably manganese with similar solubility, subsequently precipitated a network of magnetite veins. The magnetite/ilmenite ratio of the hydrothermal vein network is very high, but both phases are enriched in manganese. Only traces of High-Mn ilmenite remain in the trondhjemite, but enough grains were extracted from sample NJH-3 for analysis. The High-Mn cluster plotted onto Figure 3 at about 6 % 1MgO represents Losee trondhjemite sample NJH-3.

Compared to analyzed ilmenite from Lakehurst Ti ore (Figure 4), most Losee ilmenite contains either less MgO or more MnO, although there is some overlap at the low-MgO end of the range representing 22 percent of the analyzed Lakehurst ilmenites.

Granites. Figure 5 shows that most ilmenites from granite samples plot within the Low-MgO field and are therefore indistinguishable from most Losee gneiss ilmenites. However, one sample of granite from the Byram intrusive suite (NJH-1) is very anomalous and contains ilmenite that plots within the High-MgO field. Of the 57 analyzed NJH-1 ilmenite grains, 23 grains contain less than 0.07 % MgO as is typical of granites, but 1 grain contains 0.18 %, and 33 grains contain from 0.32 to 2.54 % MgO. The High-MgO content of over half the ilmenite grains from sample NJH-1 are also outside the MgO range of granite from the international rock collection analyzed by McLimans et al. (2005) and distorts the otherwise more typical range of MgO in the ilmenites of New Jersey Highlands granites. A plausible explanation for this anomaly may be the occurrence of a partially assimilated xenolith of mafic rock in sample NJH-1.

The usefulness of the grain by grain data presented in Figure 4 contrasts with the averages of Table 4. Without Figure 5, Table 4 might give the false impression that most grains of granite contain about 0.20 percent MgO. Figure 4 also shows that since most analyzed ilmenite grains from New Jersey granites plot within the low-MgO field they contrast with most analyzed Lakehurst ilmenites and are unlikely the major source rock.

Meta-Rhyolite. Figure 6 shows that the ilmenite grains from the Meta-rhyolite samples are characterized by Low-MgO and High-MnO compositions with only 13 out of 269 analyzed meta-rhyolite ilmenites falling outside either compositional range. In addition, note the extremely high MnO content of some of the meta-rhyolite ilmenites exceeding 13 weight percent.

Although the Low-MgO and High-MnO data overlap granite and Losee gneiss data, Figure 7 shows that most of the ilmenite grains from Meta-rhyolite samples also qualify as High-Nb_2O_5 ilmenite averaging 0.38 percent and containing as much as 2 weight percent Nb_2O_5. These values are exceptionally high and uniquely characterize the Meta-rhyolite ilmenites. Analyzed ilmenites from New Jersey granites and Losee Gneiss samples rarely contain more than 0.3 percent Nb_2O_5 (averaging 0.07 percent) and ilmenites from New Jersey basaltic rocks rarely contain more than 0.2 percent (averaging 0.04 percent) with the single exception of basalt sample NJ-7. Figure 7 also shows that 10 percent of the ilmenites from Lakehurst titanium ore plot within the High-Nb_2O_5 range and are, therefore, likely derived from meta-rhyolite source rocks.

Mesozoic basaltic rocks. Figure 8 illustrates the wide range in the MgO content of the ilmenites from potential Mesozoic igneous sources. The ilmenites are bimodal and plot as an MgO enriched population containing 2.2 to 3.5 percent MgO, and a relatively MgO depleted population containing 0.0 to 1.5 percent MgO, although both populations contain more than 0.2 percent MgO and qualify as High-MgO ilmenites. The MgO enriched population is derived largely from Palisades and Ladentown diabase samples and represent euhedral to subhedrial ilmenite grains that crystallized in equilibrium with plagioclase and pyroxene at high temperatures on the basis of thin section observations. The MgO depleted population is derived largely from subaerial flood basalt samples and represent fine grains associated with dendritic magnetites that crystallized as quench phases out of iron and titanium enriched residual melt following pyroxene crystallization. The extrusive ilmenites are hosted by a dark, almost black, glassy mesostasis (fine-grained groundmass) typically containing chlorite and evidence of deuteric alteration as described by Puffer & Laskowich (2012).

Figure 8 also shows a considerable overlap of the basaltic ilmenites with Lakehurst ilmenites. The degree of overlap exceeds that of Losee, granite, or meta-rhyolite ilmenites and indicates that basaltic rocks were a likely major source. However, the overlap of Lakehurst ilmenites with basaltic ilmenites does not extend into the MgO enriched population (Figure 8). The underrepresentation of the most MgO enriched ilmenites among Lakehurst samples may be due to some leaching of MgO from the ilmenites of the MgO enriched population during weathering.

Provenance of Lakehurst Ilmenite Ore

Although approximate provenance determinations can be estimated on the basis of Figures 4 through 8 a more quantitative approach is made with the use of bar diagrams that illustrate the common diverse ilmenite composition contained in individual rock samples. Figure 9, therefore, plots the source rock provenance data shown in Figures 4 through 8 as cumulative percent bar graphs of the ilmenite classes of Table 4 per rock type.

The same pattern emerges from examination of Figure 10, a strong correlation of Mesozoic mafic rocks with the High-MgO type and a strong correlation of Proterozoic granitic and gneissic rocks with the Low-MgO type except for meta-rhyolites that graphically correlate with the High-Nb_2O_5 type. These graphic correlations are supported by simple statistical analysis. Analysis of variance results using least square means for MgO in the 4 rock classes, with the Bonferroni ad hoc test show $p=<0.001$ for the premise that basalt + diabase distinguishes from Losee gneiss, granites and metarhyolite, and $p=0.009$ for the premise that Losee gneiss distinguishes from metarhyolite. Analysis of variance results using least square means for Nb_2O_5 in the 4 rock classes, with the Bonferroni ad hoc test show $p=<0.001$ for the premise that metarhyolites distinguish from Losee gneiss, granites and basalt + diabase, and $p=0.003$ that granites distinguish from Losee gneiss and basalt + diabase. The Bonferroni is a multiple comparison test.

Using the bedrock ilmenite type's data together with the average map area of each potential source rock in the Highlands and its average ilmenite content, the weighted average of the ilmenite types of each source are calculated. The results for each type are then grouped into Proterozoic (granites, gneisses, metarhyolite) and Mesozoic (basalts and diabase) and the average ilmenite types determined for each rock group. The results (Figure 10) are compared to the average ilmenite types for the Lakehurst area ore that are also presented in Figure 10. Visual inspection of Figure 9 indicates the significance of the Mesozoic basaltic rocks in sourcing ilmenite to the Lakehurst area deposits. A calculated mixture of 65% Mesozoic basaltic sources and 35% Proterozoic granite and gneiss sources accomplishes the ilmenite types distribution of the ore.

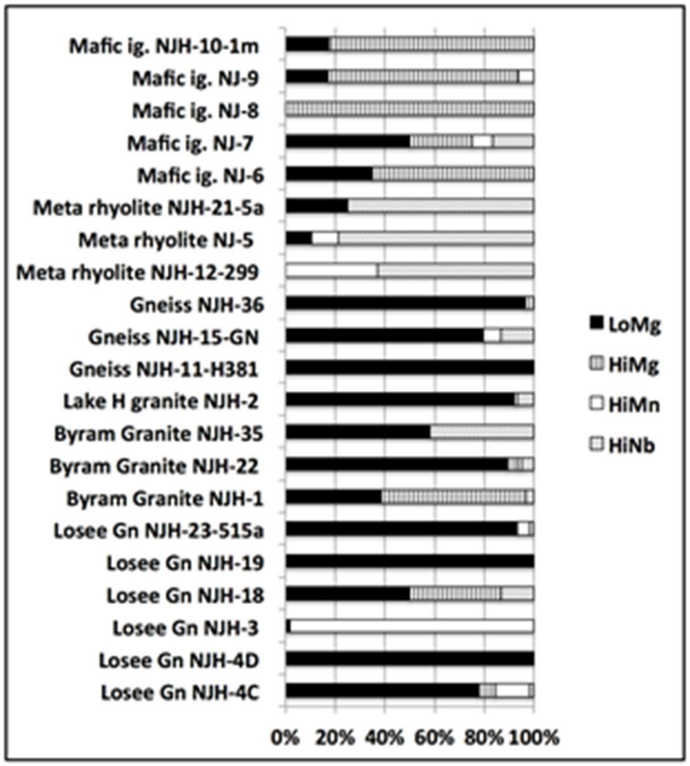

Figure 9. Bar diagram illustrating the distribution of the four ilmenite populations among the analyzed samples of northern New Jersey bedrock. The low-MgO type dominates among the widespread Proterozoic granitic rocks and sodic (Losee) gneisses but is not able to distinguish among them. The high-MgO type represents most Mesozoic mafic igneous samples. The high-Nb type is a characteristic of potassic meta-rhyolites.

The ilmenite MgO content is the key diagnostic parameter. The average MgO content of the 987 analyzed ilmenite grains in the granite, gneiss, and meta-rhyolite samples is 0.09 weight percent and strongly contrasts with the 1.29 percent MgO content of the average of 240 Mesozoic mafic igneous rocks (Table 4).

The likelihood that as much as 65 percent of the Lakehurst pseudorutile was derived from Mesozoic basaltic rocks, (Figure 8), strongly constrains the Miocene drainage pattern and provenance determinations. Stanford (2009) and Harper (2013) proposed southerly flowing rivers through wind-gaps along the northern New Jersey – Pennsylvania state line as the source of most Cohansey sand during erosion and deposition throughout a brief late middle Miocene interval. If any of the western rivers (Figure 3) were major sources of Lakehurst sand it is likely that much less than 65 percent of the Lakehurst ore would be High-MgO type. Instead, the hills and ridges of the Newark Basin drained by the eastern southerly flowing river (a proto-Hudson River, Figure 3) are composed of very thick exposures of flood-basalt and Palisades diabase that are characterized by the High-MgO type. A proto-Hudson River also agrees with the dominant influence of Hudson River sedimentation along most of the US Atlantic shelf as proposed by Darby (1990).

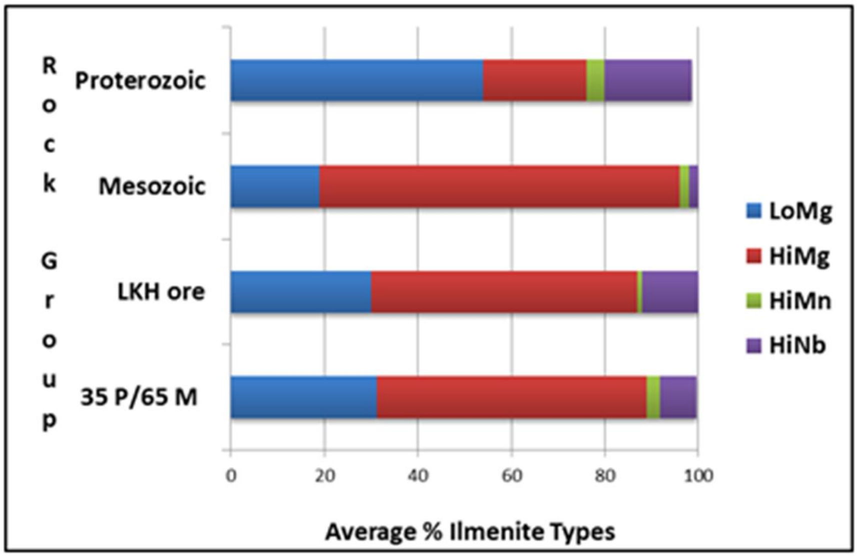

Figure 10. The weighted (source rock area % and % ilmenite) average ilmenite types for rock groups (Proterozoic = granites, gneisses, metarhyolite; Mesozoic = basalts, diabase) shown with the average for Lakehurst (LKH) ores (Lakehurst, Glidden, and Asarco) and the results for a 35% Granites and Gneiss and 65% Basalts and Diabase mixture for LKH ore.

The New Jersey portion of this eastern (proto-Hudson) drainage basin did not include any of the Proterozoic granitic terrain. However, significant mixing presumably occurred during marginal marine deposition as a result of longshore drift producing littoral sediment transport. Even if sand deposition at Lakehurst was sourced largely by the eastern trunk river it is likely that considerable sand carried by the western rivers was mixed in. Clear evidence of some mixing is provided by Puffer & Cousminer (1982). They observed an abundance of zircon and sillimanite in the Lakehurst sand. The Losee Gneiss is commonly enriched in zircon while the meta-rhyolite commonly contains abundant sillimanite.

Our data (Figure 10) suggests that at least 35% of the sediment deposited in the Lakehurst district was sourced from Proterozoic granites (Byram and Lake Hopatcong) and sodic gneiss (Losee) on the basis of the Low-MgO altered ilmenite portion of the sand. We do not have evidence bearing on the relative portion of granite versus sodic gneiss contribution because of overlap in the compositions of the ilmenites in the two rock types. The High-Nb ilmenite of the Proterozoic is likely contributed by metarhyolite and microcline rich gneiss that are about 7% of the total Proterozoic source areas. Figure 10 indicates that derivation of the Lakehurst ilmenite ore is, therefore, consistent with a 35% contribution from a Proterozoic mixture of granitic and gneissic rocks and 65% from Mesozoic basaltic rocks.

CONCLUSIONS

The conclusions of Figure 10 are based on the sorting of 1513 chemical analyses into 4 geochemical categories. The geochemical categories are based on graphically determined clusters of analytical data. The graphic clusters are data dependent and do not allow pre-determined bias but do reject anomalous data that plots outside the range of the geochemical categories that might otherwise distort chemical averages. The conclusions are the product of straightforward visually verifiable groupings. Arbitrary assumptions or data weighting applied to statistical modeling is therefore avoided. For example, multivariate statistical analysis treats each averaged analyzed element with equal potential usefulness and ignores implications based on the common wide range of variability of ilmenite compositions that were found within single samples.

It is concluded that ilmenite geochemistry is successfully applied to Lakehurst sand provenance determinations. The geology and drainage of the New Jersey-New York-Pennsylvania area indicates that the most likely source rocks for the Lakehurst heavy mineral deposits are those in Northern New Jersey. Ilmenites collected from the Lakehurst, New Jersey heavy mineral sand deposits and from probable source rocks in Northern New Jersey group into four populations based on the Mg, Mn, and Nb content. The MgO content is particularly diagnostic. Ilmenites from the Mesozoic basaltic rocks of the Newark Basin are characterized by a 0.2 to 5 wt. % MgO (High-MgO) population in contrast to the <0.2 wt. % MgO (Low-MgO) populations that characterize the Proterozoic granites and gneisses in the New Jersey Highlands. The various granites and sodic gneisses are indistinguishable on the basis of ilmenite geochemistry, however, the consistently low concentration of High-MgO ilmenite makes the Proterozoic group reliably distinct from the Mesozoic rocks.

The various ilmenite types found in the Lakehurst area heavy mineral sand deposits, together with the lithologies, volumetric proportions, and TiO_2 content of probable source rocks in Northern New Jersey, provide evidence that the provenance of the Lakehurst ilmenite deposits is 35% from Proterozoic rocks and 65% from the Mesozoic basic rocks. The interpreted provenance is consistent with a paleodrainage system, such that Miocene rivers flowed south from Northern New Jersey, transecting the Newark Basin, to the Lakehurst area in agreement with Darby (1990) and Stanford (2009).

The most diagnostic element for ilmenite provenance for the New Jersey samples is Mg. In this region, Mn did not prove to be useful, but elevated Nb content is a characteristic of metarhyolites. Minor amounts of Nb enriched ilmenite at Lakehurst were likely derived from these highly fractionated rocks of limited volume in the Highlands area of Northern New Jersey.

The successful application of the Mg, Mn, and Nb content of ilmenite to the Lakehurst provenance study implies a wide range of applications to sand provenance studies in general.

Supplementary materials (available upon written request to John Puffer)

The chemical compositions of 1227 individual grains of ilmenite from source rock (Losee Gneiss, Meta-Rhyolite, granites, and basaltic rocks) are presented in Table A1. The chemical compositions of 290 individual grains of ilmenite from Lakehurst Titanium ore are presented in Table A2.

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Keynote Speaker's Address:
You're Going to Need a Bigger Screen:
The Fossil Sharks of Monmouth County

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Chondrichthyan remains are among of the most ubiquitous vertebrate fossils known worldwide. Although their skeletons are primarily composed of cartilage which does not preserve well, shark and ray teeth are very common. Estimates range in the 10,000s for how many teeth an individual shark may produce and shed in its lifetime. If you couple this number with the almost 400 million year record of cartilaginous fishes, it is no wonder why they are so common.

The fossil record of Monmouth County, New Jersey is very rich in both aquatic and terrestrial organisms. Monmouth County is situated on the Atlantic Coast Plain in central with marine, tidal, freshwater and terrestrial exposures from the late Mesozoic (Cretaceous) and Cenozoic (Paleocene, Eocene, Miocene and Pleistocene). Fossils from the region have been collected for over 150 years, however new specimens and records and are still being reported today. The first comprehensive attempt at summarizing the fossil chondrichthyan and osteichthyan remains from the Cretaceous, Eocene and Miocene formations in New Jersey was by Henry Fowler in 1911. Although Fowler reviewed fossils from the entire state (and some sites outside of New Jersey), many of the localities he referred to are in Monmouth County. Earlier work by Weller (1907) referenced the occurrence of 'shark's teeth' from various stratigraphic units and localities in the state, but Fowler (1911) is the first comprehensive review of the fossil sharks and fishes. Researchers and amateur fossil hunters still refer to Fowler's seminal work and in light of continued population growth in the state, it remains the only record of early localities and outcrops that no longer exist.

Cretaceous units exposed in Monmouth County include the Raritan, Magothy, Merchantville, Woodbury, Englishtown, Marshalltown, Wenonah, Mount Laurel, and Navesink formations as well as the Red Bank Sand. Although earlier units are present and have some exposures in the county, fossil chondrichthyans become abundant in the Campanian Marshalltown Formation. Arguably, the most well-known Monmouth County locality for Marshalltown vertebrate fossils is the Ellisdale locality in Upper Freehold.

The Ellisdale locality represents one of the most diverse, late Cretaceous faunas in the eastern United States. The site occurs within the basal portion of the Marshalltown Formation (Middle Campanian) and represents a marine transgression with at least four depositional settings. Environmental indicators, including a robust fossil assemblage and lithology, indicate terrestrial, lagoonal, barrier beach and open ocean settings. For further reading on the geologic setting of the Ellisdale Locality, refer to Gallagher et al. (1986), Grandstaff et al. (1992), Denton et al. (1996), and Denton and O'Neill (1998). Renewed collecting efforts at the site resumed in 2018 and continue in 2019 as a collaborative effort between the New Jersey State Museum and the National Museum of Natural History.

Chondrichthyans from the Ellisdale locality include teeth, vertebrae, denticles, cephalic claspers and prismatic cartilage. Their diversity includes approximately 24 marine and freshwater taxa, representing the: Hybodontiformes (ex. *Meristodonoides* and *Lonchidion*), Squatiniformes (ex. *Squatina*), Lamniformes (ex. *Scapanorhynchus*, *Squalicorax*, *Cretalamna* and others), Rajiformes (ex. *Pseudohypolophus*), Myliobatiformes (ex. *Rhombodus*), Sclerorhynchiformes (ex. *Ischyrhiza* and *Ptychotrygon*) and Chimaeriformes (ex. *Ischyodus*). A preliminary faunal list was published by Gallagher and Parris (1996) and a more thorough review is currently in preparation by Ehret and Claeson (2019). Grandstaff et al. (2006) proposed that the Ellisdale locality could represent a paleo-nursery area for the extinct goblin shark, *Scapanorhynchus texanus*, based on the small size of most teeth recovered.

The most well-known fossil localities in the state, and arguably the northeastern United States, are the Monmouth brooks, including Big Brook, Ramanessin, Hop Brook and other tributaries, in and around Marlboro, New Jersey. The region of Big Brook most visited by collectors, near the Boundary Road Bridge, cuts through the Marshalltown, Wenonah and undifferentiated Mount Laurel-Navesink formations with more recent Pleistocene alluvium deposits interspersed (Lauginiger, 1986; Parris et al., 1996). The majority of the fossils are Cretaceous, late Campanian through Maastrichtian, in age and are dominated by marine invertebrates and vertebrates. Cappetta and Case (1975) published an overview of the fossil chondrichthyans of the Matawan and Monmouth groups in New Jersey, including collections from Big, Hop and Willow brooks in the Marlboro region. Taxa reported include members of the Hybodontiformes, Squatiniformes, Orectolobiformes, Lamniformes, Rajiformes, Myliobatiformes, Sclerorhynchiformes and Chimaeriformes (Cappetta and Case, 1975; Lauginiger, 1986). The taxonomic composition of species is similar throughout the localities in Monmouth County, and is also similar to other Late Cretaceous, shallow marine sites along the east coast of the US. Dominant taxa include *Scapanorhynchus texanus*, *Squalicorax pristodontus*, *Cretalamna* cf. *appendiculata* and *Archaeolamna kopingensis*.

Nearby Ramanessin Brook exposes the Wenonah and Navesink formations (Gallagher and Grandstaff, 1996; Callahan et al., 2014). This regressive-transgressive sequence is also marked by a disconformity, with the Navesink Formation sitting unconformably on top of the Wenonah (Callahan et al., 2014). The Mt. Laurel Formation is completely absent. A transgressive lag in the basal Navesink is the likely source of late Campanian vertebrate fossils in the brook (Callahan et al., 2014). A working faunal list for the chondrichthyans at Ramanessin Brook was first published by Gallagher and Grandstaff (1996). Callahan et al. (2014) published an updated list from a tributary of Ramanessin Brook in Holmdel Park that includes similar taxa to those found in the Marshalltown Fm. at Ellisdale and the Marshalltown/Wenonah/Mt. Laurel/Navesink fms. at Big Brook and other nearby tributaries. These include the Hybotdontiformes (*Meristodonoides* and *Lonchidion*), Heterodontiformes (*Heterodontus*), Squatiniformes (*Squatina hassei*), Orectolobiformes (*Ginglymostoma*, *Chiloscyllium* and *Cantioscyllium*), Lamniformes (*Scapanorhynchus*, *Cretalamna*, *Squalicorax*, etc), Rajiformes (*Rhinobatos*), Myliobatiformes (*Brachyrhizodus* and *Rhombodus*), Sclerorhynchiformes (*Ischyrhiza*) and Chimaeriformes (*Ischyodus*). For taxonomic lists of chondrichthyans from the Navesink Formation in and around Ramanessin Brook see Gallagher and Grandstaff (1996), Case and Cappetta (2004) and Callahan et al. (2014).

Outcrops of the Paleocene Hornerstown and Vincentown formations can be found along the Monmouth/Burlington county line in the areas along Crosswicks Creek in Upper Freehold, NJ (Dahlgren, 1977; Case, 1996). These formations are comprised of glauconitic sands and lie above the K/Pg boundary, giving a glimpse of faunas after the mass extinction event. Case (1996) published a small fauna from the Hornerstown Formation that includes: Hexanchids, a Squalid, Odontaspidids, an Otodontid, a Scyliorhinid, a Triakid, numerous Myliobatiformes and a Chimaeroid. Certainly, the Hornerstown and

Vincentown formations are more well-represented in Burlington and Gloucester counties with larger collections of chondrichthyans being reported.

The Eocene Manasquan and Shark River formations of Monmouth County are very fossiliferous. The Manasquan Formation represents an early Eocene, marine setting and is composed of glauconitic sands and clay. It is unconformably overlain by the middle Eocene Shark River Formation. The Shark River Fm. Is also a glauconitic sand that is more cemented that the underlying Manasquan Fm. and does include clay and silt (Sugarman and Stanford, 2006). Outcrops of both formations are well-known along the Manasquan and Shark Rivers in Howell Township, Farmingdale, Wall Township, Tinton Fall, and Long Branch in Monmouth County. Some compositional differences are apparent with regards to the chondrichthyan faunas of the Manasquan and Shark River formations, however many collections are made from river deposits that are temporally mixed making it difficult to discern which formation some species originated from. In some localities (such as Mingamahone Brook in Farmingdale) temporal mixing with an early Miocene, Kirkwood Formation lag deposit also occurs, further complicating faunal breakdowns (Maisch et al., 2015).

Fowler (1911) reviewed the Eocene faunas at a time where many fossils were still being mined from borrow pits and mines throughout the state that no longer exist today. Fowler's records along with contemporary collections from the Manasquan and Shark River formations exhibit a large chondrichthyan fauna. Comparisons can be made with other localities along the eastern seaboard, the Gulf Coastal Plain and the London Clay of the United Kingdom. Taxa found include (but are not limited to): Hexanchiformes (*Hexanchus*, *Notorynchus* and *Heptranchias*), Squatiniformes (*Squatina*), Heterodontiformes (*Heterodontus*), Orectolobiformes (*Nebrius*), Lamniformes (*Brachycarcharias, Carcharias, Hypotodus, Jaekelotodus*, *Macrorhizodus*, *Odontaspis*, *Otodus auriculatus*, *Striatolamia*, *Xiphodolamia* and others), Carcharhiniformes (*Abdounia*, *Carcharhinus*, *Galeocerdo*, *Negaprion*, *Physogaleus* and others), Pristiformes (*Pristis*), Rajiformes, Myliobatiformes (*Burnhamia, Dasyatis, Mobula*, *Myliobatis*, *Rhinoptera* and others) (Fowler, 1911; Gallagher et al., 1996; Maisch et al., 2015; Ehret pers. observ.).

As mentioned above, the early Miocene Kirkwood Formation lies unconformably on top the Shark River Formation in the area around Farmingdale in Monmouth County. A lag deposit at the base of the Kirkwood comprised of glauconite is extremely fossiliferous, yielding shark, fish, turtle and mammal fossils. Maisch et al. (2015) published a review of the chondrichthyan fauna from Mingamahone Brook, which includes temporally mixed Eocene, Shark River Fm. and Miocene, Kirkwood Fm. taxa. Distinctive Miocene taxa recovered from Mingamahone by Maisch et al. (2015) and Ehret (pers. observ.) include: *Carcharias* sp., *Isurus* cf. *desori*, *Otodus chubutensis*, *Alopias* sp., *Galeocerdo aduncus*, *Physogaleus contortus*, *Hemipristis serra*, and *Myliobatis* sp. The temporal mixing makes it especially problematic to identify some of the Odontaspidids to genus and species.

The most recent records of fossilized chondrichthyans from Monmouth County come from Pleistocene beach finds. While Pleistocene vertebrate fossils are regularly recovered by offshore dredging, they appear less commonly as beach wash. With the increased beach replenishment activities over the past 20 years, isolated shark teeth have been reported along the shore. During the summer of 2019, two white shark teeth (*Carcharodon carcharias*) were found in Monmouth County, Sea Bright and Sea Girt respectively (D. Ehret pers. observ.). With continued replenishment, it is likely that more taxa will be recovered.

Of particular interest to the author is the representation of the megatoothed sharks (Otodontidae) in Monmouth County. The Otodontidae is a family within the Lamniformes and includes the genera *Cretalamna*, *Otodus* (which includes *Carcharocles*), and *Parotodus* amongst others. The fossil record of Monmouth County arguably includes a nearly complete Otodontid record for the megatoothed lineage defined by *Otodus megalodon* (Fowler, 1911; Rapp, 1946; Maisch et al., 2015; Ehret pers. observ.) Taxa in this lineage reported from Monmouth County include: *Cretalamna* cf. *appendiculata*, *Otodus obliquus* (historic records, unverified), *Otodus sokolowi*, *Otodus angustidens*, *Otodus chubutensis*, and *Otodus megalodon* (historic records, unverified). *Otodus obliquus* and *O. megalodon* are reported in Fowler (1911) and Rapp (1946) but voucher specimens are unknown aside from the line drawings of Fowler. While not as common as other areas touted for their megatooth shark fossils (Aurora, North Carolina, Calvert Cliffs, Maryland, etc.), Monmouth County has an impressive representation!

In summary, the chondrichthyan fossil record for Monmouth County, New Jersey is extremely diverse. Records spanning the late Cretaceous through Pleistocene are reported. While much work has been done to identify and report on this diversity, there is still much work to be done to elucidate the diversity of chondrichthyans in geologic time.

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Monmouth Amateur Paleontologist's Society

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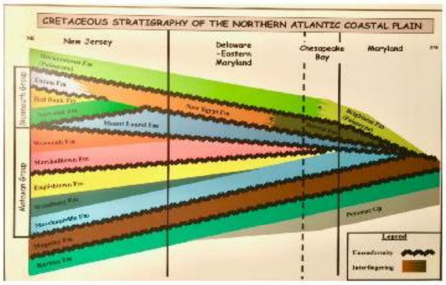
A HISTORY OF M.A.P.S

Monmouth Amateur Paleontologists' Society (MAPS) was founded in 1970 by Ralph Johnson and Anton Till for the express purpose of studying the Upper Cretaceous paleontology and stratigraphy of the Atlantic Coastal Plain geophysical province (ACP) which includes parts of New Jersey, Delaware and Maryland. In the process of conducting this study, the Society has assembled one of the largest and most comprehensive collections of Campanian and Maastrichtian invertebrate fossils from the ACP presently available to amateur, student, and professional researchers. Also a smaller but significant fraction of the collection consists of marine and terrestrial vertebrates. In total there are over 25,000 cataloged specimens representing 596 species. The collection contains numerous new species and occurrences not previously recorded from the ACP. For example, before MAPS was founded there were only about a dozen species of cephalopods known from the Cretaceous of the ACP. Now there are at least 68 species most of which were collected by MAPS members. Many of these are important zone and/or index fossils. Each field season continues to yield new surprises!



Over the years the MAPS membership roster has included students, teachers, professional paleontologists, and many amateur collectors. The Society has collaborated with professionals from institutions such as the New Jersey State Museum, the American Museum of Natural History, and the U.S. National Museum and MAPS members have co-authored or participated in a number of scientific publications (see bibliography). MAPS continues to further research in the field and assist all those who express a serious interest the Cretaceous of the ACP.

Ralph Johnson with ammonites from MAPS collection

Mount Laurel Oyster Bed Crosswicks Creek

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Stream Gravel Sampling Program and Stratigraphic Provenance of Late Cretaceous Fossils at Coelurus Creek, Marlboro, Monmouth County, NJ

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Marlboro is named for the deposits of Late Cretaceous greensand marl, known technically as glauconite, that were mined in the 19th century along the banks of Big Brook and its tributaries. One such tributary is informally known as Coelurus Creek, after the small theropod dinosaur bones and teeth found in this area. Coelurus Creek drains several old marl pits and cuts down through three Late Cretaceous Formations, in ascending stratigraphic order the Wenonah, Mount Laurel and Navesink Formations. The creek bed gravels and outcrops here are a prolific source of invertebrate and vertebrate fossils.

To determine the stratigraphic provenance of stream gravel fossils, we pursued a program of numerous sieving samples along Coelurus Creek, noting the stratigraphy of the surrounding banks. We divided our sampling process into several segments, including fossils from two tributaries, herein designated Bench Run and Marlboro Manse Run. Fossils from Bench Run, a northwest flowing tributary near the entrance to Big Brook Preserve, were overwhelmingly marine invertebrates, primarily original oyster, belemnite and brachiopod shells. Shark teeth were relatively rare in this stream bed. The banks of Bench Run, which drains a couple of old marl pits, are incised into the basal Navesink Formation that displays at least two fossil shellbeds.

In Coelurus Creek between Bench Run and Marlboro Manse Run, the pattern is reversed. The stream gravels in this segment have fewer marine invertebrate shells, and these tend to be smaller heavily worn fragments; internal molds (steinkerns) of gastropods, small bivalves, and ammonites are just as frequent as original oyster shell material in this stretch. The stream gravels here are relatively enriched in chondrichthyan teeth, bony fish material, ratfish remains and mosasaur teeth compared to Bench Run.

Further upstream, Marlboro Manse Run is an east-flowing tributary that drains the area of the Marlboro Manse housing development. The mouth of this stream where it enters Coelurus Creek and the gravels nearby are a third segment sampled, and here the placer concentrations are dominated by vertebrate remains. These are primarily shark teeth, but also include pycnodont teeth, *Enchodus* teeth and jaw pieces, and worn bone fragments probably from large reptiles. Last year a small worn possible theropod dinosaur was found in this segment by a Rider student. Marine invertebrate original shell material is rare. Upstream, the Marlboro Manse tributary incises and samples the Mount Laurel Formation fossil concentration reported on by Gallagher and Hanzcaryk (2019, this volume)., as well as cutting through the Wenonah Formation.

A superficial interpretation of the Marlboro streambed fossil placers might conclude they were all derived from one horizon, the basal Navesink Formation. Another hypothesis, thus far unsupported by quantitative data, is the speculation that they are secondarily recycled fossils eroded out of Plio-Pleistocene alluvial deposits which appear intermittently in the banks of Big Brook.

Our analysis strongly suggests that the majority of shellfish fossils are from the Navesink Formation, while most of the vertebrate fossils are from the underlying Mount Laurel and Wenonah Formations. This has important implications for the age of the fossils in the Monmouth County streams, since the Mount Laurel and Wenonah Formations are Campanian in age, and the Navesink is Maastrichtian.

Teacher's Workshop: Amazing Discoveries and Fossil Hunting in Monmouth County, New Jersey

Paul Kovalski

American Academy of Forensic Sciences; American Society of Forensic Odontology;
New Jersey Association of Forensic Scientists; Research Associate, New Jersey State Museum;
New York Paleontological Society

The Greensand Marls and Atlantic Coastal Plain of Monmouth County have been a hot bed of fossil finds for over a century. In 1865, Professor Cook of Rutgers University received bones from Marlboro, which became part of *Coelosaurus antiquus*, the first described carnivorous dinosaur in North America by Leidy in 1865 (Gallagher *et al.*, 2014).

Scientists from around the world have and continue to perform paleontological research here. Many specimens have been classified locally such as *Nucula marlborensis* and *Ostrea monmouthensis* (see Richards *et al.*, 1958 and 1962). The Cretaceous deposits yield a diverse fauna which include mollusks: *Exogyra*, *Pycnodonte*, cephalopods: belemnites, ammonites, vertebrates: a vast assemblage of shark species, mosasaurs, hadrosaurs, *Dryptosaurus*, giant turtles, crocodiles, bony fish and other marine fauna. More recently, the first Late Cretaceous lungfish specimen in North America, a dental plate, was found in 2000 (Halzer *et al*., 2018).

In western Monmouth County, the Ellisdale site since 1980 has produced hundreds of dinosaur remains including tyrannosauroids, and a spectacular vertebrate diversity including mammalian fossils. This site is a scientific trove currently worked by major institutions, including the New Jersey State Museum (Brownstein, 2018).

The Paleocene/Eocene outcrops on the Manasquan River, although difficult deposits to work, have produced marine vertebrate and invertebrate material including large gastropods: *Fasciolaria samsoni* and *F. hercules* of which State Geologist Robert P Whitfield described in 1892: “I know of no other Eocene shell in this country which closely resembles this one, especially in its great size and robust character” (Whitfield, 1892).

The Pleistocene has also gifted Monmouth County with a fossil vertebrate fauna including ground sloth, giant beaver, mastodon, elk moose, caribou and mammoth specimens (Parris, 1983). Off-shore fishermen have occasionally dredged up extinct Proboscidean molars with their clams and scallops. And recently, in 2015 a rare partial juvenile Mastodon skull was found here showing evidence of Tuberculosis (Grandstaff *et al*., 2015).

In 2012 a fossil Cretaceous turtle bone, *Atlantochelys*, discovered in Monmouth County was united with its fractured counterpart, which had been discovered 163 years earlier! (Parris *et al.*, 2014).

Monmouth County's rich paleontological resources provide educational opportunities for collecting and scientific studies. Parks such as Poricy Brook in Middletown, Ramanessin Brook Preserve in Holmdel, Big Brook Preserve in Colts Neck, Shark River Park in Wall Township and Big Brook Park in Marlboro allow collecting. There are other localities, but some require permission. It's advisable to check with any site for updated rules and regulations.

Besides exploring the field trip adventures we will discover fun projects that could be performed in the classroom or lab. Investigating fossil formation and identification by hands-on demonstrations will be covered. Students can be inspired to be "paleontological detectives" in examining the fauna, flora and ancient environments of the fossil remains. Other resources such as museums, universities, national and state parks and websites will be discussed.

Personally growing up in Marlboro, I have witnessed the encroachment of development and loss of fossil sites. I have lobbied for preservation and when elected councilman organized “Dinosaur and Environmental Awareness Day” to celebrate Earth Day and bring recognition to the significant paleontological resources in our back yard. Exhibitors from major museums, amateur collectors, local historical and conservation groups, and lately a realistic T-Rex all contributed to the success of this event which just celebrated its 20th year! I also worked with two Eagle Scout projects that developed an interpretive trail and descriptive sign. With the Marlboro Recreation Department, I lead several fossil collecting trips locally. In 2010, the Mayor and Council honored my preservation efforts by naming a portion of Big Brook the “Dr. Paul Kovalski Tributary” (Marlboro Township, 2010).

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Road Log: GANJ 2019 Field Guide

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GANJ 2019: SUMMARY OF FIELD TRIP TRAVEL ITINERARY

Time	Activity	Approximate Distance / Driving Time
08:00 AM	Leave Parking Lot 1 Brookdale Community College	7.2 miles / 18 minutes
08:20 AM	Arrive Stop 1: Big Brook Park, Marlboro, NJ	
08:50 AM	Leave for Stop 2	3.2 miles / 10 minutes
09:00 AM	Arrive Stop 2: Big Brook Preserve at Hillsdale Road, Colts Neck Township, NJ	
12:00 PM	Leave for Stop 3	6.4 miles / 15 minutes
12:15 PM	Arrive Stop 3: Thompson Park: Lunch (and Lecture?)	
01:15 PM	Leave for Stop 4	2.8 miles / 10 minutes
01:25 PM	Arrive Stop 4: Ramanessin Park (“Hop Brook”)	
04:00 PM	Leave for Brookdale Community College	3.7 miles / 10 minutes
04:10 PM	Return to Brookdale Community College	

INTRODUCTION

The location of the four main field stops of this field trip are shown on Figure 1 and are labelled FS-1 through FS-4. Also shown on Figure 1 are various Points of Interest (labelled "POI"): most of these locations are of limited access that inhibit visitation of a group as big as the GANJ meeting attendees. The Global Positioning System (GPS) data points indicated on this and several other maps in this road log were prepared by Jena Richards of New Jersey City University (NJCU) as a student's honor project under the supervision of William Montgomery and assistance of Mark Zdziarski of NJCU. Figure 1 is also useful in giving an idea of the degree of development of the Monmouth County in terms of current day land usage. All of the stops are associated with the Navesink River drainage basin that flows into the Swimming River Reservoir. Figures 2 and 3 respectively show the bedrock geology and surficial geology of the field trip area.

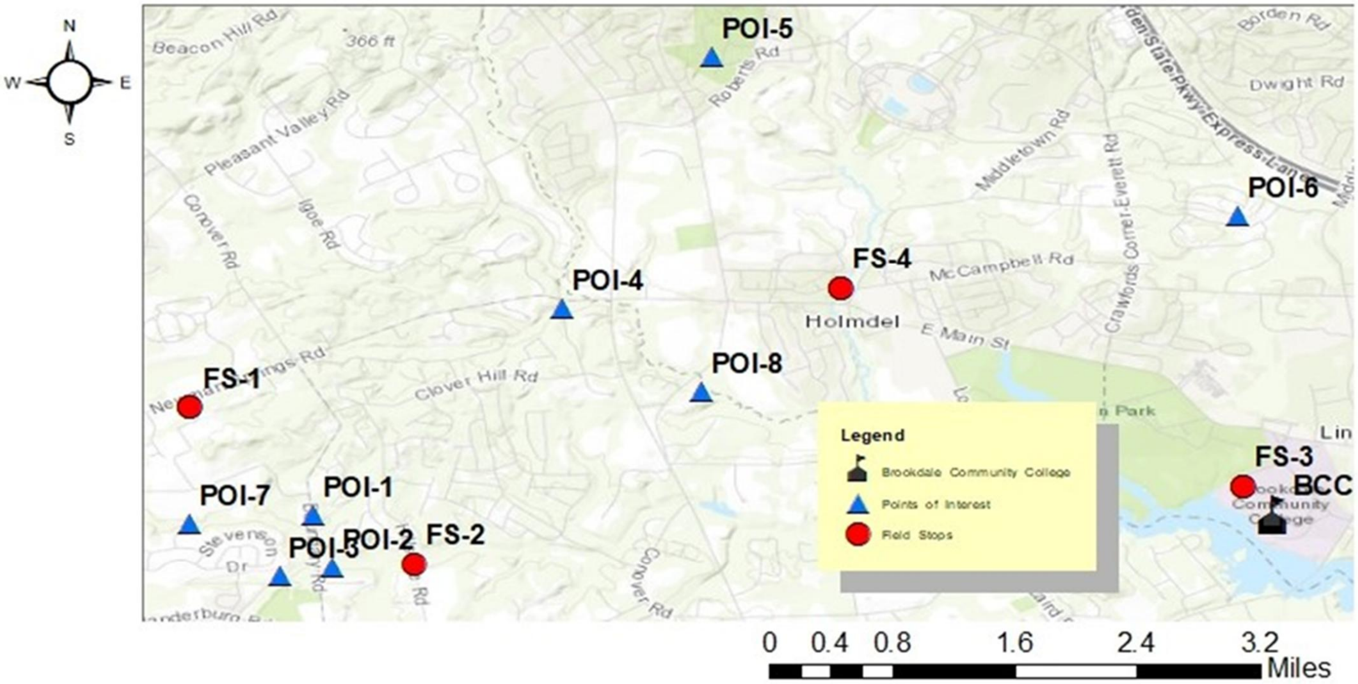

Figure 1. Overview of Field Stops (labeled "FS") and local Points of Interest (labeled "POI"). The noted POI's lack sufficient accessibility for inspection in a timely fashion and most except for POI-6, are on property that does not permit collecting or access. BCC = Brookdale Community College

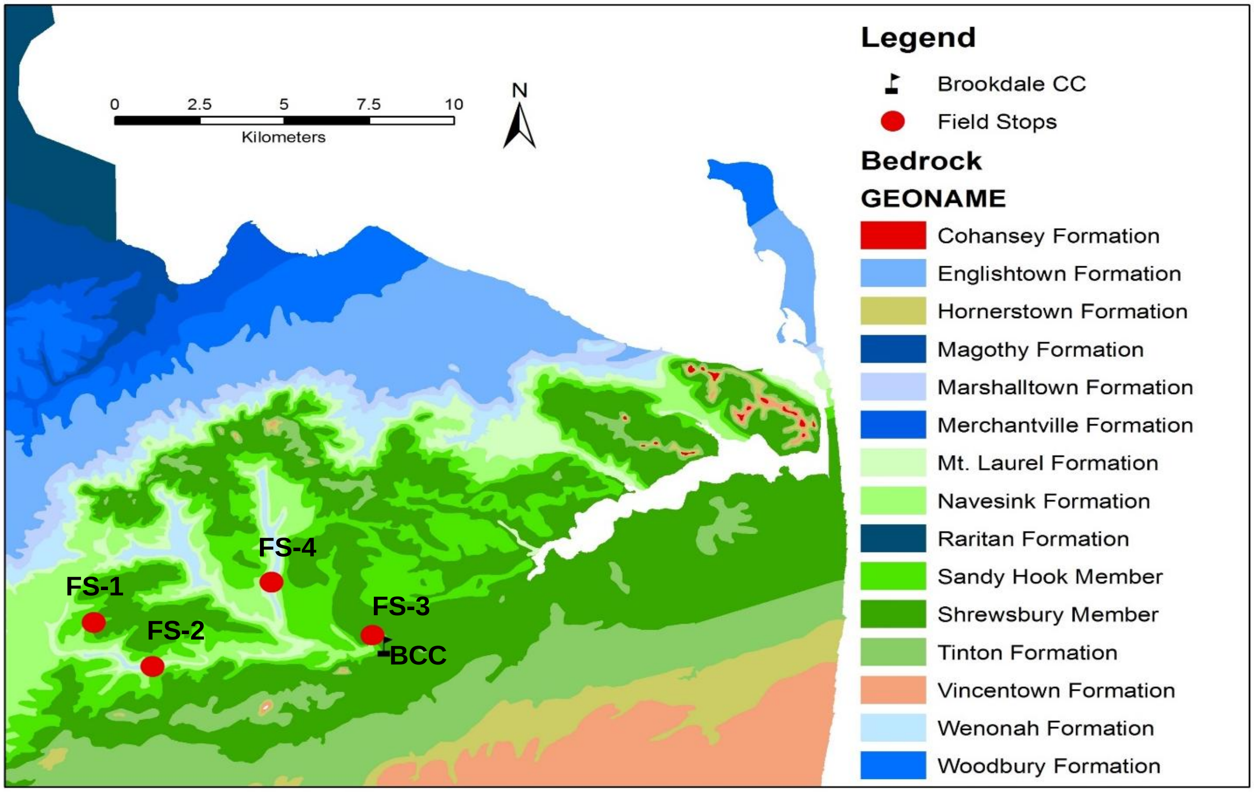

Figure 2a. Generalized Geologic Map of Monmouth County area. Note: “Geonames” on map are in alphabetical order *not* stratigraphic position: see Figure 2b where the cross-section shows stratigraphic position of named units. GPS/GIS preparations by Jena Richards, NJCU and Josh Galster, MSU. Source: Bedrock Geologic Map of Northern New Jersey, Drake et al., 1996.

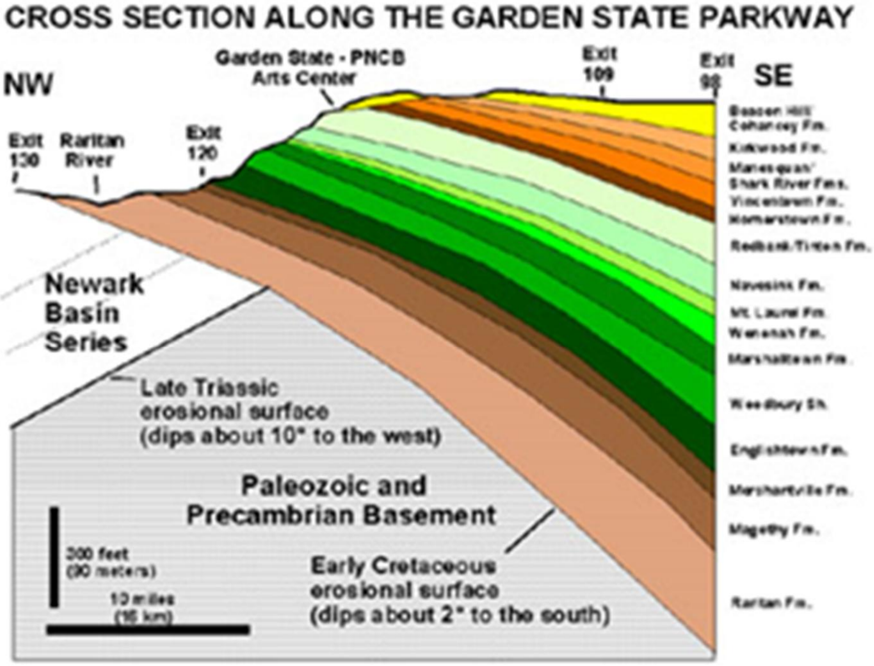

Figure 2b. Generalized Geologic cross-section of Monmouth County area.

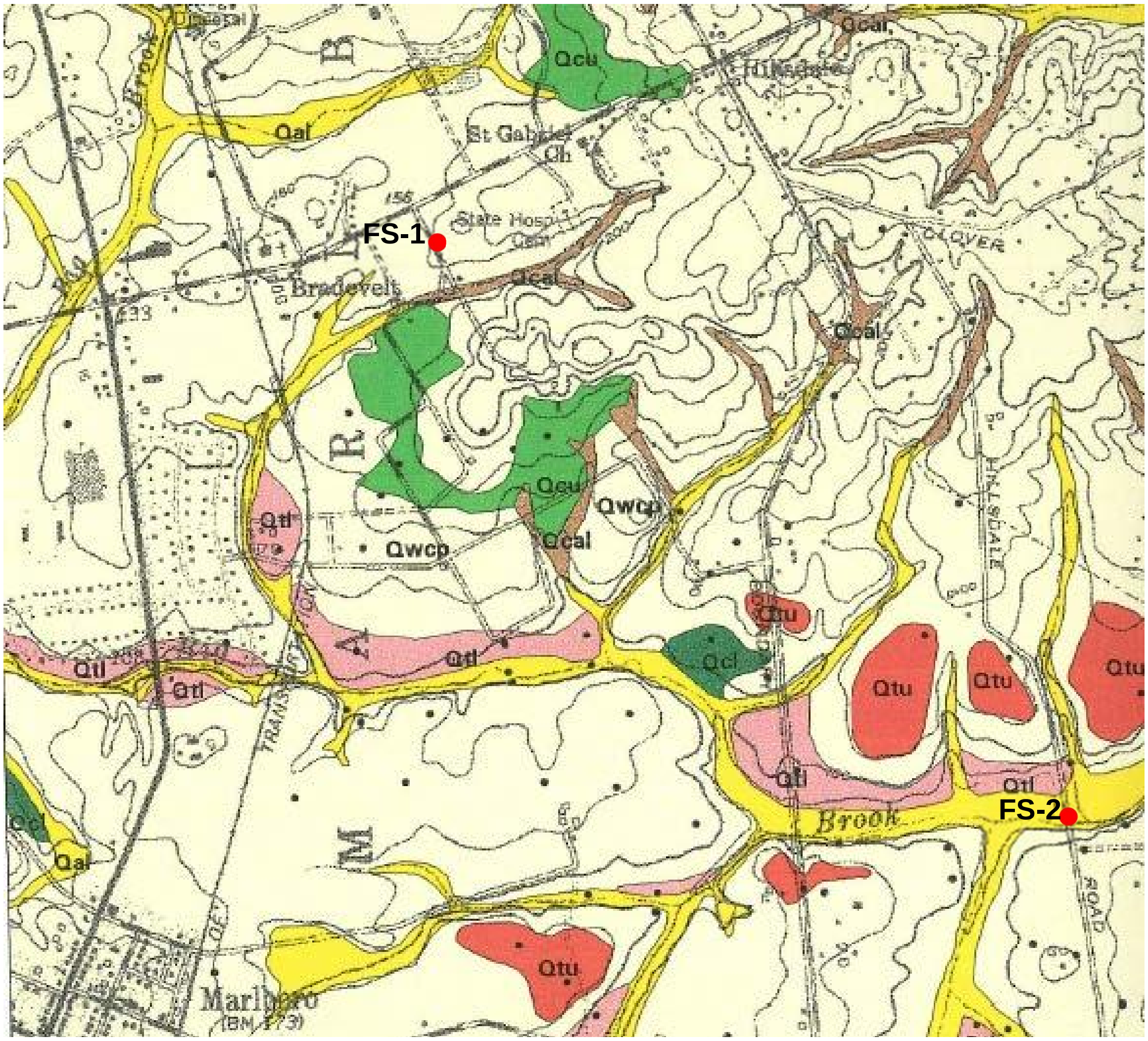

Figure 3. Surficial Geology Map of Field Stop Locations based on Stanford 1992. The locations of Field Stops ("FS") 1 and 2 are shown.

Neutral ("Uncommitted") Reference Names to Cretaceous Units to be Inspected on the Field Trip

Brown (2019) in this guidebook attempts to explain from a historic perspective the discrepancies between lithostratigraphers, paleontologists, hydrogeologists, and sequence stratigraphers with regard to the formal names of the semi-consolidated beds we will inspect on this field trip (probably to the dissatisfaction of all parties involved who study these units). Hopefully, different individuals will express their opinions of what these beds should be called and why during the field trip. In order to keep a "neutral" perspective regarding these subunits, the following "uncommitted" reference names will be used chronostratigraphically from lowest to highest position:

Beds A – These are interstratified thin (0.1 to 0.5 foot) beds of clays, silts and sands. Mica and lignite are commonly found in the gray finer beds while quartz is the main component of the sand beds. Siderite concretions are locally abundant along some horizons and sometimes contain fossil molds and casts. Trace fossils (see Martino and Curran, 1990) are present, but the organisms involved were not active to the degree to have totally destroyed bedding planes. These beds have been referred to the formational names of Wenonah or Mount Laurel.

Bed(s) B – This is a thicker (typically about 2 feet or more) bed of gray clayey to silty fine to very fine sand with mica and lignite. Its upper part has burrows, typically of *Ophiomorphia*. These burrows are sometimes filled with coarser sand size particles from the overlying unit. At some places a thin fine to medium quartz sand lens may be found at the top of this bed that appears below the Sequence Lag. A medium to coarse yellowish quartz sand (Gallagher and Hanczaryk 2019, this volume) is sometimes present between this bed and the lag, but will not be seen at any of the Field Stops. From a lithologic perspective, these beds resemble the Wenonah Formation, but due to their position relative to Beds A have also been referred to as the Mount Laurel Formation.

Sequence Lag – This disconformity boundary varies in recognizable abruptness. In some places gravel to cobble size concretions of calcarenite, siderite and phosphate plus rock fragments are abundant. However, along some exposures coarse-size particles are rare whereby only fine granule to gravel size particles of calcarenite, phosphate and siderite are found. The presence of this particular lag has been used to define a sequence boundary and the base of Navesink Formation, but it could also be used to recognize the base of the Mount Laurel.

Bed C – The base of this bed typically has the above noted sequence lag. It is a quartz sand bed approximately 2 to 3 feet thick with varying amounts of coarse versus fine size clasts. At Big Brook Bed C has more silt with only scattered pea-size quartz clasts. In contrast, at Hop Brook the pea-size quartz clasts are quite abundant. Where unweathered, Bed C has a lighter gray color than Bed B and weathers to a brown to orange or red color that at Hop Brook can be a cemented conglomerate. Lithologically, this bed, in conjunction with its basal lag is dominated by quartz sand particles whereby it would to be classified as a “dirty” Mount Laurel, but as noted, it is also based on its chronostratigraphic position considered to be Navesink.

Bed D – The contact between Beds C and D is not always distinct due to bioturbation. Bed D is a better sorted, fine quartz sand with common sand-size grains of the clay mineral glauconite. At some exposures, this gray bed is 4 to 5 feet thick gray and weathers to a light brown. This bed has characteristics of both the Mount Laurel and Navesink Formations.

Bed E – This is a black marl* (“glauconitic sand”) with traces of quartz grains, but more commonly intercalated with gray clay. Unlike the discrepancies associated with the underlying units, Bed E is recognized as the Navesink Formation. (**Marl* – is a geologic term with many different regional meanings: for the New Jersey Coastal Plain, Marl refers to a biochemically derived sediment dominated by the mineral glauconite where clay to sand size particles of this “clay mineral” are present. The degree of hardness, particle shape and cohesiveness of the glauconite grains has great variation. The color of glauconite varies from bright green to jet black when unweathered; versus a rust brown color when weathered: black colored glauconite grains are typical of the Navesink.)

Photographs of the above noted units are referenced throughout the remainder of this road log. It should be noted that with the possible exception of Bed E, the above beds have a limited lateral consistency and grade into coarser or finer sediments beyond the field trip stops.

POINTS OF INTEREST

POI-1: *Boundary Road at Big Brook, Marlboro and Colts Neck, NJ.*

Big Brook at this site (which we will travel by) was for many years a popular access area for fossil collectors. "Boundary Road" is a symbol in terms of public policy and public access where fossil collecting is allowed (Colts Neck side) and discouraged (Marlboro side) along Big Brook. However, due to limited parking and poor access to the stream, the Colts Neck Parks and Recreation Department prefers the public use the Hillsdale Road site for fossil collecting (Field Stop 2 of this trip).

A spring is located directly beneath the bridge at Boundary Road that probably represents a poorly sealed borehole associated with the bridge's construction. Groundwater seeping apparently has a high iron content as indicated by the iron oxide staining surrounding the spring (Figure 4).

A USGS water gauge[6] is located at Boundary Road, apparently a back-up to the gauge at Hillsdale Road (Field Stop 2), used when Hillsdale Bridge was under construction.

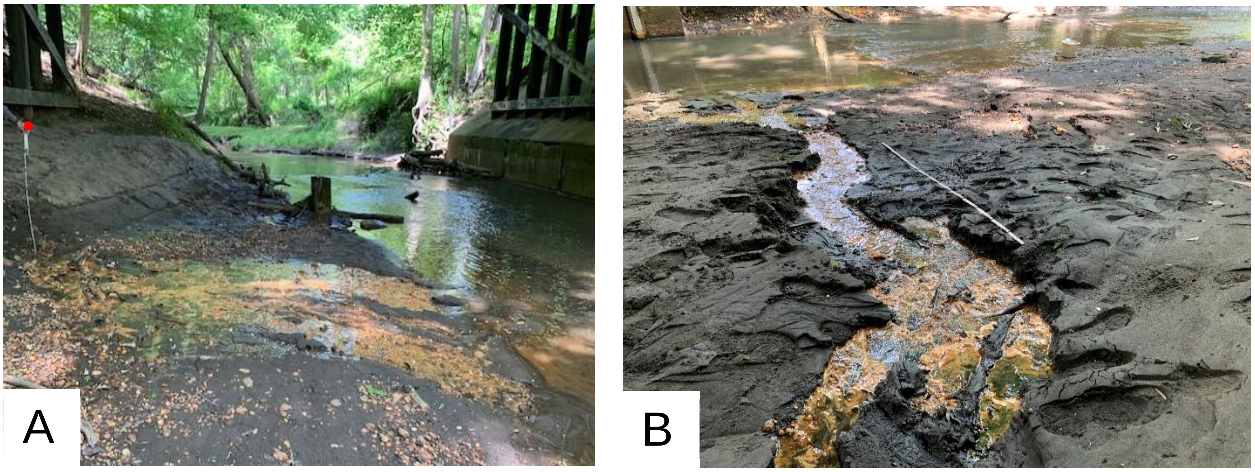

Figure 4. Spring located directly beneath the Boundary Road bridge. Is this a poorly sealed borehole associated with the bridge's construction? Note iron oxide staining surrounding the spring. Photo A: facing west, with red dot by 3.5-Foot Lufkin ruler at spring by Jena Richards, NJCU. Photo B: facing north with 6-Foot Lufkin ruler on ground; by Justin Andell, RVCC.

POI-2: *Exposure just east of Boundary Road at Big Brook, Colts Neck, NJ*

An excellent exposure (Figures 5 and 6) of Beds B through E is found here, but due to the noted access issues, we will not be able to visit. Unique to this section is the presence of three distinct lags based on the respective lower boundaries of Beds C, D and E. Bed B has a distinct Wenonah lithology, although as reviewed by Brown (2019, this document), the lithology of underlying Beds A along with location of the major "sequence" lag at its upper presence of large gravel to cobble size clasts of siderite, phosphate and/or calcarenite present at the boundary would define it as the Mount Laurel Formation by some stratigraphers. Beds C and D contain belemnite fossils and might be classified as either Mount Laurel or Navesink, but is not "typical" of either unit. Bed E is a glauconitic marl that is recognized as typical

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[6] https://waterdata.usgs.gov/nj/nwis/uv/?site_no=01407287&PARAmeter_cd=00065,00060,62614

Navesink Formation and the exposure of a lag here at its basal contact shows the "unconformity" discussed by Gallagher and Hanczaryk (2019, this volume).

Figure 5. POI-2: Exposure just east of Boundary Road at Big Brook, Colts Neck, NJ. The red arrow points to a bucket that indicates the approximate location of this cliff in the 1970's as remembered by J. Brown. It gives an idea of the degree of erosion and why study of Coastal Plain exposures are so challenging. The area above the arrow is highlighted in Figure 6. Photo facing southeast; by Justin Andell, RVCC.

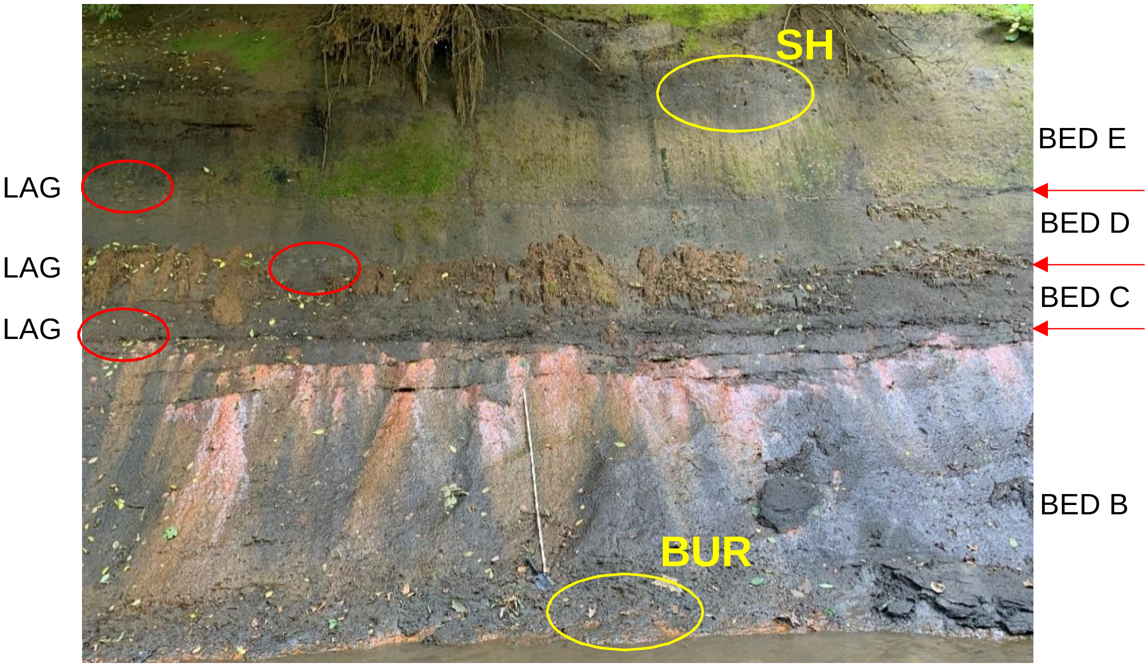


Figure 6. POI-2: Exposure just east of Boundary Road at Big Brook, Colts Neck, NJ. The red arrows point to contact boundaries of distinct beds. The red circles highlight clasts associated with these contacts indicating lag deposits. The lowermost lag is the most distinct and recognized as the sequence lag whereas the other two are not always easy to locate or recognize in exposures. The "SH" yellow circle indicates a calcitic shell bed. The "BUR" yellow circle indicates abundant burrows, notably of *Ophiomorphia,* that stand out in three dimensions due to differential erosion at the base of the cliff. Photo facing south with 6-Foot Lufkin ruler by lower yellow circle; by Justin Andell, RVCC.

POI-3: *Kovalski Tributary, Marlboro, NJ*

The Kovalski Tributary is named in honor of a local fossil collector, Paul Kovalski, who organizes annual "Dino Discovery Days with the Township of Marlboro". It is part of an athletic park operated by Marlboro Township that allows fossil collecting to permitted groups. This is another example of using geology and paleontology as an outreach to the general public and field-oriented education (see Kovlaski 2019, this volume).

Exposure at this locality (Figure 7) is poor when compared to the main stream trunk of Big Brook and of limited access for a large field trip. However, Bed B (referred to as the Wenonah Formation) in this area yielded ammonites indicative of Middle Campanian age (see Kennedy and Cobban, 1994). This locality is close to the Marlboro Manse study area of Gallagher and Hanczaryk (2019, this volume). Figure 7 shows a good example of the Quaternary outwash gravel sampled as part of the Gallagher and Hanczaryk (2019) study that commonly forms the bottom of local streams (see also papers by Galster, 2019 and Stanford, 2019, this volume). Also shown in Figure 7, and noted by these authors in this volume, is the gravel bed contact between Cretaceous sediments truncated by Quaternary Lower Terrace Deposits ("Qtl" as mapped on Figure 3).

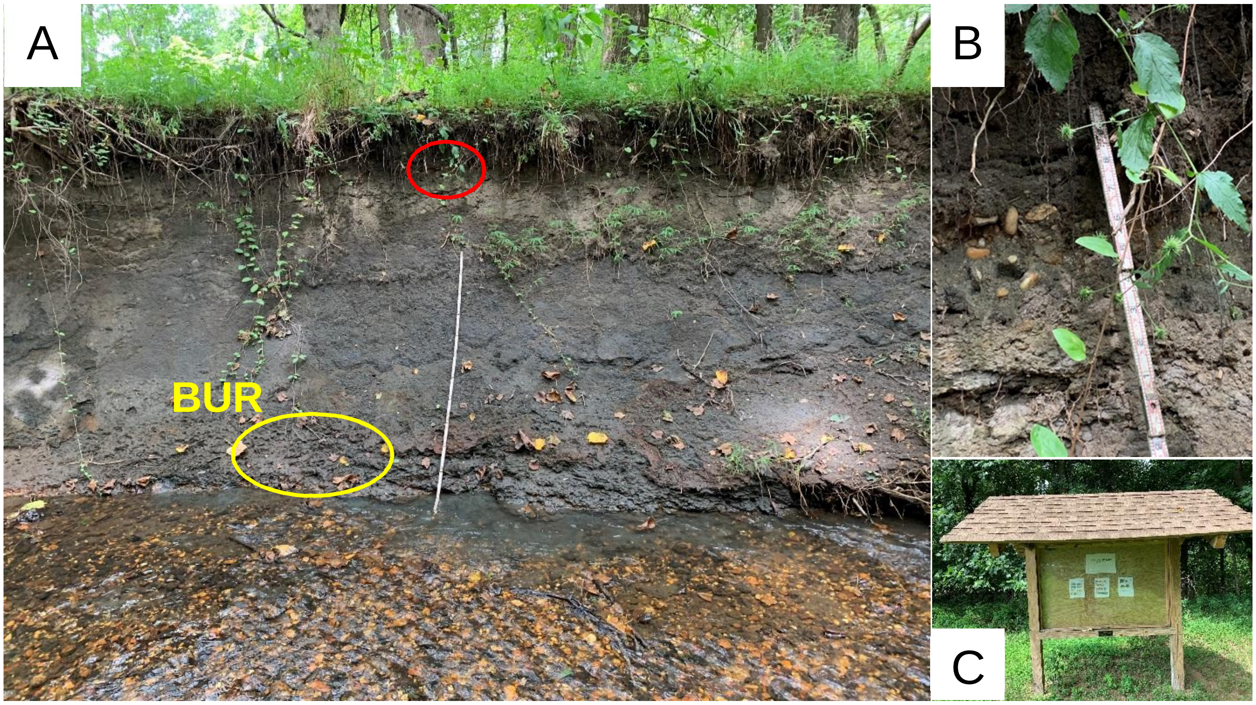


Figure 7. POI-3: Kovalski Tributary, Marlboro, NJ . Photo A shows Cretaceous Bed B truncated by Quaternary Lower Terrace Deposits (red circle is location of Photo B that shows the rounded quartz gravel of this bed). The "BUR" yellow circle indicates abundant burrows at the same stratigraphic location that is better shown in Figure 6 at POI-2. The common Quaternary outwash gravel found in many current coastal plain stream beds is visible just beneath the water surface. Photo C shows a billboard built as an Eagle Scout project with fossil identification charts. Photo A is facing north with 6-Foot Lufkin ruler scale; by Justin Andell, RVCC.

POI-4: *Tributary to Willow Brook by intersection of Newman Springs Road and Clover Hill Lane*

Access to this area is limited, but Beds A through D are present along this small stream.

As indicated in Figure 8, Bed C seems to have more pea size quartz (granule) clasts than found at Big Brook, but less than that observed at Hop Brook. In addition, Bed D is not as glauconitic and appears to have the characteristics of a coarse beach sand (poorly exposed in upper part of Photo A of Figure 8).

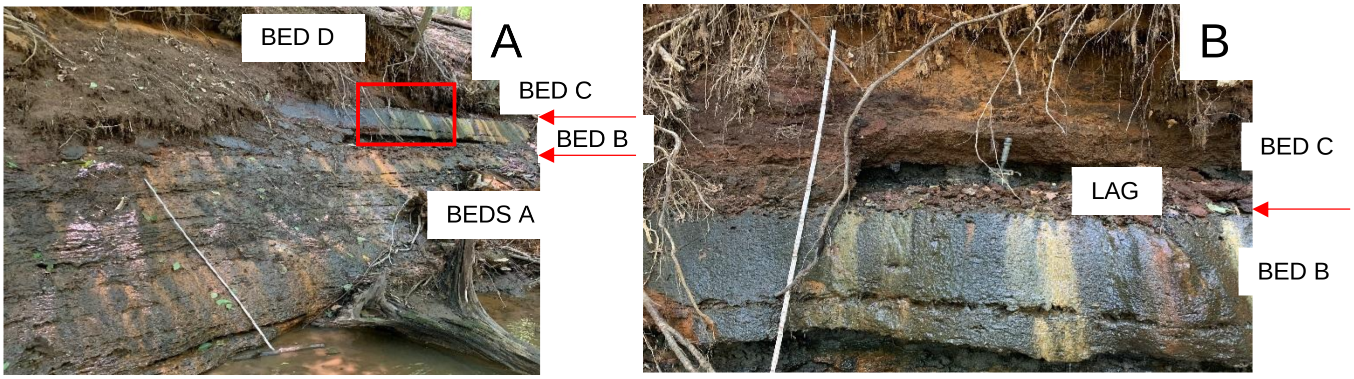


Figure 8. POI-4: Tributary to Willow Brook by intersection of Newman Springs Road and Clover Hill Lane. Photo A shows Beds A through C and poorly exposed D. Of note: Bed B is thinner here than at the Field Stop localities and at POI-2 shown in Figure 6. Red box indicates location of Photo B that shows weathered cemented aspect of Bed C. This is similar to the Ramanessin Creek exposure (see Figure 36). Photos facing southwest to south; 6-Foot Lufkin ruler; by Justin Andell, RVCC.

POI-5: *Holmdel Park area*

This is another area where fossil collecting is restricted as the property is managed by the Monmouth County Park System. Callahan *et al*. (2014) and Callahan and Mehling (2019 this volume) review some of the vertebrate fossils found in this area as well as Field Stop 4 (Ramanessin Brook).

POI-6: *Poricy Brook Fossil Beds, Middletown, NJ*

The Poricy Brook Fossil Beds at Middletown-Lincroft Road in Middletown, NJ are managed by the Poricy Brook Conservatory in conjunction with the Middletown Recreation Department (see their website https://ppc.wildapricot.org/). This is another example of a publicly accessible fossil collecting site that was recently visited by GANJ (Rainforth and Uminski 2011). The Maastrichtian part of the Navesink Formation is well exposed at this location, but not the Campanian-Maastrichtian boundary which is one of the topics emphasized as part of this year's conference.

POI-7: *Upstream Big Brook along south boundary of Monmouth County's Big Brook*

Most of Big Brook west of Boundary Road in Marlboro, NJ is managed by the Monmouth County Park system: as noted, fossil collecting is not allowed in county managed areas without special permit. This area has better exposures of Beds A (Figure 9) and sometimes Beds B through E. A review by Brown (2019 this volume) attempts to explain why some researchers refer to the beds shown in Figure 9 as the Mount Laurel Formation due to well sorted quartz sand beds. In contrast, others refer to these beds as the Wenonah Formation due to the lignite, micaceous silty sands and finer textured laminated beds.

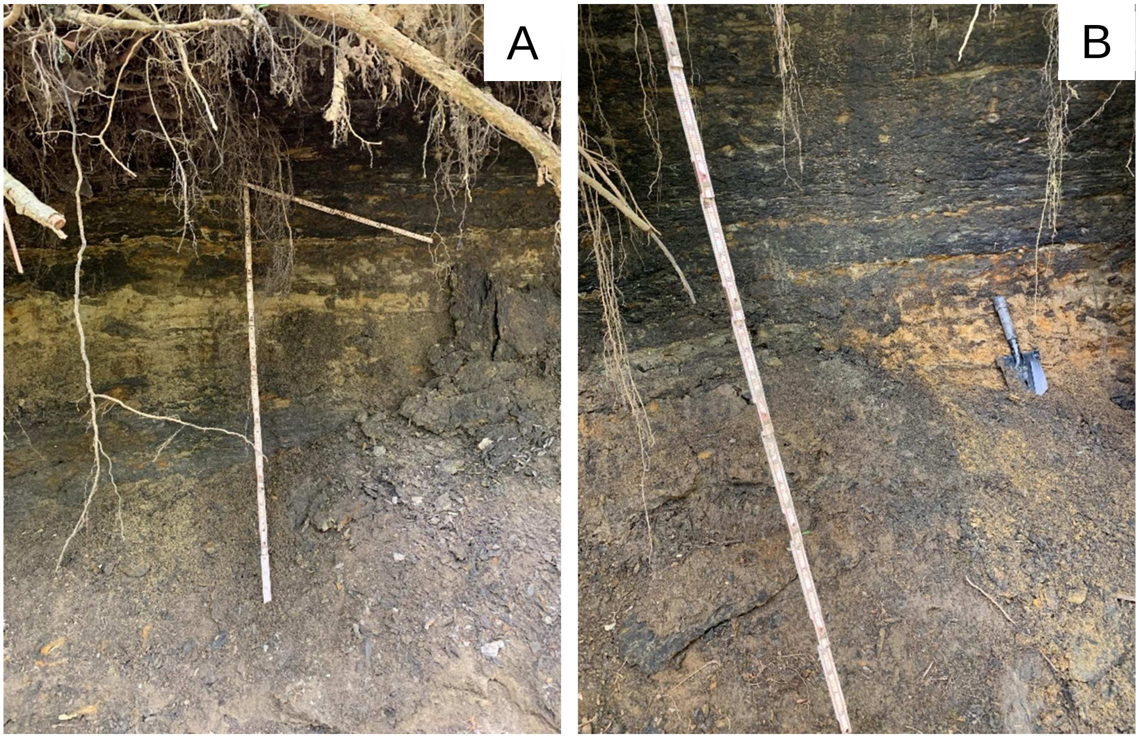


Figure 9. POI-7: Big Brook along south boundary of Big Brook Park, Marlboro, NJ. Beds A of intrastratified Cretaceous sediments: Lighter color beds consist of well sorted sands while darker beds are varied clays, some organic-rich, to silty sands with mica and lignite. The two red circles in Photo C show locations of close-ups in photos A and B. Scale: Lufkin ruler totals 6-feet but is not completely shown. Photo C facing south. Photos by Justin Andell, RVCC.

POI-8: *Willow Brook, Colts Neck Township, NJ*

It is unfortunate that logistics do not allow visitation to this area, as it a good example of why geologists can't agree with correlations, even on a local scale (Brown, 2019, this volume). The exposure here has a massive, erosionally resistant bed three feet thick of lignitic, micaceous fine sandy to clayey silt that lithologically characterizes the Wenonah Formation (Figure 10). It overlies a similar bed that has abundant ichnofossils (Figure 10). The area of POI-8 is mapped as Mount Laurel Fm. by Sugarman and Owens (1990) where mappable, Wenonah Fm. is exposed about 3000 feet further upstream (the amount of "typical" Wenonah exposed here is probably not of mappable extend). This "Wenonah" strongly resembles Bed B that will be inspected at Field Stops 2 and 4. However, at the noted Field Stops the sequence lag and coarser sand and gravel Bed C are present directly above Bed B. Here, no lag is visible and the overlying beds are interstratified and resemble Beds A. So, is this exposure all Wenonah based on the presence of Beds A and its stratigraphic position beneath Bed B? Or, is it all or part Mount Laurel, based on the presence of Beds A as mapped by Sugarman and Owens (1990). Or is this indeed Bed B where the overlying lag is not well defined and thereby making the overlying beds "Navesink".

Unfortunately, macrofossils that might help to clarify chronostratigraphic positions are scant at this location (it is unknown if palynologic samples have been taken).

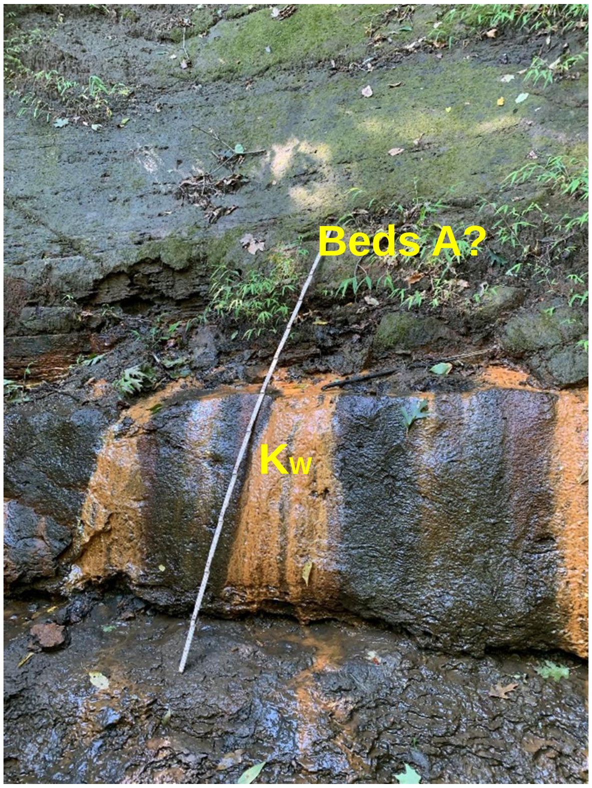


Figure 10. POI-8: Willow Brook, Colts Neck Township, NJ. Possible Beds A resting on Wenonah beds that *resemble* Bed B. This area is mapped as Mount Laurel by Sugarman and Owen (1990) with the mappable Wenonah exposed about 3000 feet upstream. Scale: 6-Foot Lufkin ruler. Photo facing west; by Justin Andell, RVCC.

Time	Activity	Distance
08:00 AM	Leave Parking Lot 1 Brookdale Community College	
	Drive 0.6 mile to Route 520 / Newman Springs Rd.	
	Go west on Route 520 6.6 mile to Big Book Park	
08:20 AM	Arrive Stop 1. Big Brook Park, Marlboro, NJ	7.2 miles

STOP 1. BIG BROOK PARK, MARLBORO, NJ

Presenters: Scott Stanford, Josh Galster, Jim Brown
Emphasis: Pleistocene Terrane and Geomorphology; Parkland Preservation

Big Brook Park in Marlboro, New Jersey is on property formally used as part of a state mental hospital. This land is now managed by the Monmouth County Parks system and consists of hiking and biking trails. It is a part of the Henry Hudson Trail which ultimately will connect with Raritan Bay. Elevations in the park vary from about 100 to 240 feet above sea level. The park is a part of the Big Brook watershed, a part of the Navesink River watershed. Big Brook ultimately drains into the Swimming River Reservoir with a water level elevation of about 35 feet Mean Sea Level (see: USGS 01407498, https://waterdata.usgs.gov/nj/nwis/uv?site_no=01407498).

At Stop 1 we are in the headwater part of the Big Brook valley (Figure 11). This part of the valley, like the valleys of Willow and Hop (or Ramanessin) Brooks, is south-draining. Just south of here the valley turns east and then, after connecting with Willow and Hop Brooks and becomes the Swimming River that flows northeast into the Navesink estuary. This change from south to northeast is an inheritance from the glacial diversion of the Pensauken and Hudson Rivers in the early Pleistocene (see Stanford's guidebook chapter). The south-draining upper valleys are relicts of the Pliocene drainage network which was captured in the early Pleistocene by northeast-flowing tributaries to the diverted Pensauken-Hudson Rivers.

Figure 11. Field Stop 1 – Big Brook Park, Marlboro, NJ. Gentle rolling hills of headwater part of the Big Brook valley. A tributary between the white car and hills (highest elevations of about 240 Feet MSL) drains to the west and south before connecting to the main trunk of Big Brook to drain eastward. Photo facing south; by Justin Andell, RVCC.

After this new drainage deepened and widened its valleys in the early and middle Pleistocene, sand and gravel alluvium was deposited during at least two periods of cold climate in the middle and late Pleistocene. At these times, permafrost was present, forest was replaced by tundra, and slope erosion delivered more sediment into valleys. These sand and gravel deposits today form upper and lower terraces. Both terraces are visible along Boundary Road south of Hampton Court on the drive to Stop 2 The surficial geology map (Figure 3) for this area show these terraces (pink and orange on map), which are of relatively small extent in this headwater part of the valley, and their relation to the present floodplain (yellow). Aprons of colluvium at the base of hillslopes (green on map) were also deposited at the same time as the terrace sediments.

The unexposed underlying bedrock geology (Figure 2) consists of the Red Bank Formation (Sugarman and Owens, 1996).

The southern border of the park includes the stream of Big Brook that consists of stratigraphic units that we will see at other locations on this trip. Fossil collecting is not allowed on this and other county-operated properties such as Big Brook Park.

Highlights:

1. Geologic features that do not "stand out" as is typical of most of the Coastal Plain;

2. The Elevated terrain represents a local drainage divide associated with Navesink River watershed;

3. Stream terraces are fossil floodplains. How does a floodplain become "fossilized"?

4. The terminal moraine of the last glaciation is about 10 miles to the north in Perth Amboy: is the local hilly surface representative of a peri-glacial (tundra) landscape? Or the aftermath? Or is it the result of pre-glacial events? Or all of the above?

5. An example of recreational public park and used for watershed conservation.

6. As we drive to Stop 2, we will travel south along Boundary Road and pass by Points of Interest (POI) 1, 2, 3 (see descriptions in Introduction to this Road Log).

Time	Activity	Distance
08:50 AM	Leave for Stop 2 Drive 0.2 mile back to Route 520; go east 0.6 mile to Boundary Rd., turn right; Go south on Boundary Rd 1.9 miles to intersection; turn left; Arrive Stop 1. Big Brook Park, Marlboro, NJ Head east on Crine Rd; Go 0.5 mile east to Hillsdale Rd.; turn left; Go 0.6 mile north on Hillsdale to Big Brook Preserve	
09:00 AM	Arrive Stop 2. Big Brook Preserve at Hillsdale Road, Colts Neck Township, NJ	3.2 miles

STOP 2. BIG BROOK PRESERVE AT HILLSDALE ROAD, COLTS NECK TOWNSHIP, NJ

Presenters: Scott Stanford, Peter Sugarman, Josh Galster, Jim Brown,
Emphasis: Quaternary and Cretaceous Stratigraphy & Paleontology;
Geomorphology; Structural Geology; Public Land Use

NOTE: *We will have approximately three hours at this field stop that will include an initial hike on both sides of Hillsdale Road along Big Brook. This will be followed by ample time for outcrop inspection and fossil collecting.* ***PLEASE BE BACK AT THE BUSES BY 12-NOON AS WE WILL BE PROMPTLY LEAVING AT THAT TIME.***

Safety Notes:

1. ***Anticipate walking a total of about 1.5 miles along "deer trail" type woodland areas with occasional fallen trees. In order to easily fossil hunt and to see a few of the exposures along the stream banks, it will necessary to get your feet wet by treading through approximately a foot of water.***
2. ***In addition to trip and fall in a wooded area, please be cognitive of ticks, poison ivy, and vegetation that can poke you in the eye.***
3. ***Be cognitive of undermined trees that can either fall or cause a landslide: especially along the stream banks.***
4. ***Wear proper footwear and clothing, especially in the streams to avoid cuts from rocks and broken glass in the stream as well as hypothermia.***

Background: Public Land Use and Watershed Protection

Big Brook Preserve is managed by the Colts Neck Township Department of Parks and Recreation (CNTDPR). It is an example of publicly accessible land that permits fossil collecting and thereby provides the opportunity of hands-on field orientation science education. In order for a group the size of the Geological Association of New Jersey to visit this site a paid permit was necessary. Such a fee helps to cover maintenance costs, such as the portable toilet located here. Smaller groups of individuals and families are allowed access for free without permit visitation requirements. In order to avoid over-collecting, the CNTDPR requests that no more than five fossils be taken during any single visit to the park.

As noted, the stream Big Brook is a part of the Swimming River Reservoir Watershed and existing land use of the Preserve helps to maintain low negative impact to this water body. A USGS water gauge is located here (USGS 01407290). At one point a golf course had been proposed for this area between Boundary and Hillsdale Roads, but was stopped to allow for the establishment of the present Preserve (personal communication, Hennessy, 2019).

Field Stop Highlights

Figure 12 shows locations (labelled BB-1 through BB-9) that will be inspected at this field stop. After exiting the buses and reviewing location BB-1 at Hillsdale Road we will proceed downstream (east) to BB-2 and then walk our way back upstream (west), past Hillsdale Road to location BB-9. Both east and west of Hillsdale Road we will be walking along trails on the northern floodplain for about a third of mile in each direction (with an approximate 1.5 miles total of hiking.) Please pay attention to your location relative to Hillsdale Road.

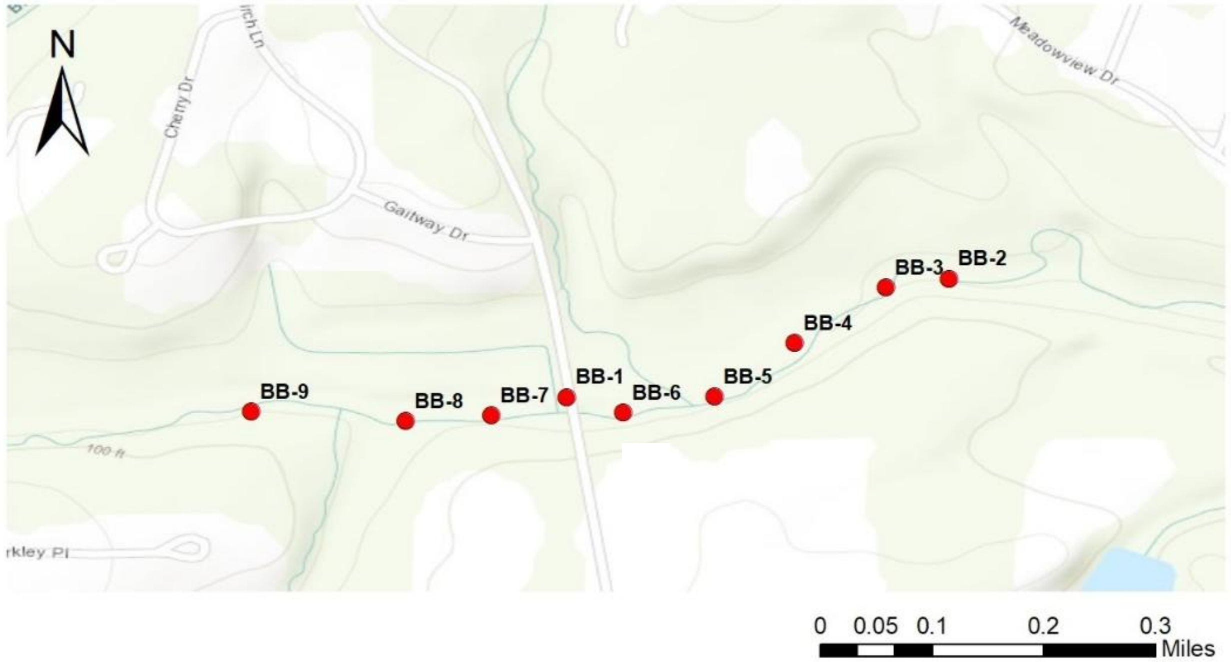


Figure 12. Field Stop 2 Locations of interest at Big Brook, Hillsdale Road, Colt Neck, NJ. Each of these numbers is referred to as “BB-1”, “BB-2”, and so on within the road log text.

Location BB-1: Hillsdale Road at Big Brook – From this location one can perceive the general geomorphic features. This includes Big Brook’s incised northern stream bank into the floodplain of Quaternary deposits that rest upon Cretaceous sediments. The typically higher terrane along the southern bank exposes Cretaceous sediments with a veneer of overlying Quaternary sediments. Figure 13 shows some of the public friendly aspects of the Big Brook Preserve, along with a water gauge (USGS 01407290) located on the western side of the Hillsdale Road Bridge.

Figure 13. Field Stop 2 at Big Brook Preserve, Hillsdale Road, Colt Neck, NJ. Photo A, facing NE showing park sign, parking, and toilet. Photo B, facing south, shows bulletin board with parking access; red circle indicates the USGS water gauge on the Hillsdale Rd. Bridge. Photos by Justin Andell, RVCC.

Location BB-2: Exposure of Cretaceous Beds – This approximately 20 feet of vertical exposure (Figures 14) shows the four main beds (B, C, D and E) of Cretaceous sediments that we will inspect during the field trip. Figures 15 and 16 show a close-up of beds B, C, and D at this location. As this is our first inspection of the Campanian-Maastrichtian beds we will see, a brief review of beds is presented below.

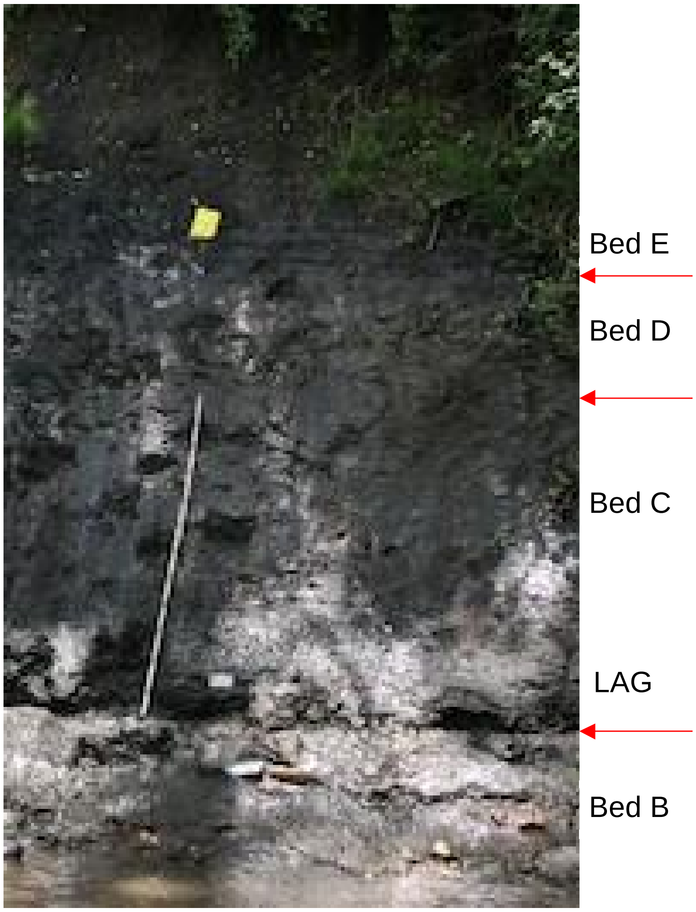


Figure 14. Exposure of Cretaceous at Location BB-2 where the combined thickness of Beds C and D is approximately 9 feet. Red arrow show bed boundaries. The Sequence Lag has a sharp contact with underlying Bed B (see Figure 16 for close-up) and is included as part of Bed C. (Right side is west.) Scale = 6-Foot Lufkin ruler. Photo by Mark Zdziarski, NJCU

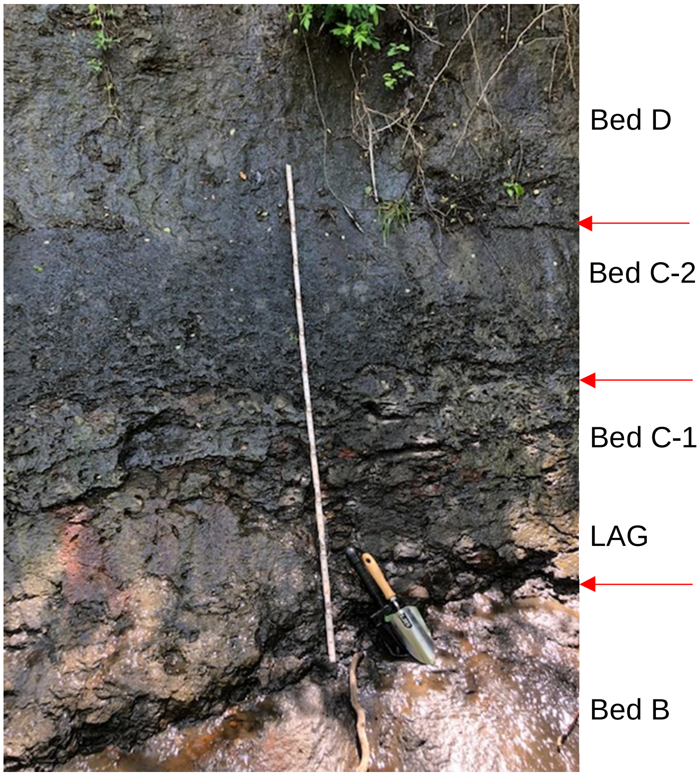


Figure 15. Close-up of Exposure at BB-2 immediately west of that shown in Figure 14. The weathered surface highlights the amount of bioturbation in Bed C which has been divided into two parts based on the darker color and weak bedding planes of Bed C-2. Scale = 6-Foot Lufkin ruler. Photo by Mark Zdziarski, NJCU.

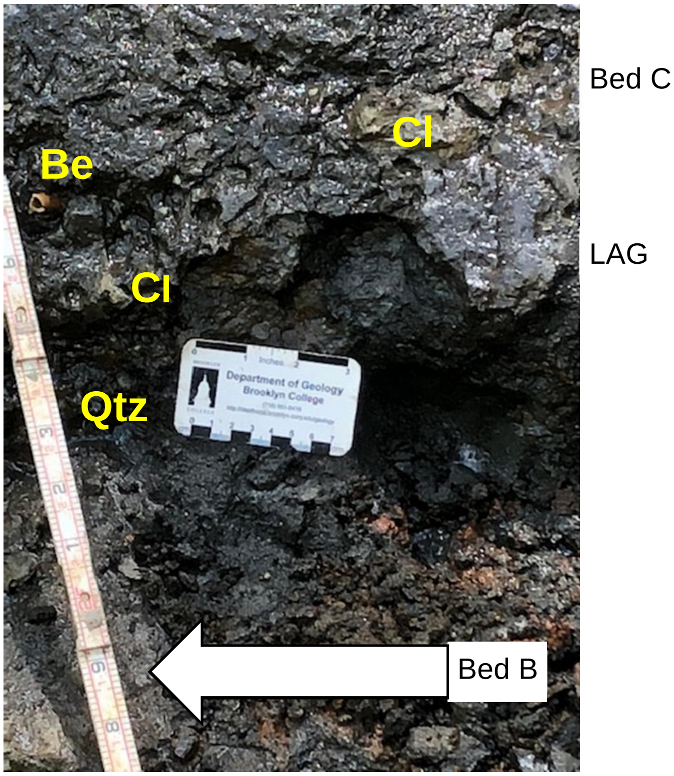


Figure 16. Close-up of Sequence Lag at Location BB-2. Be= Belemnite pen; Cl=Clast; Qtz = pea-size quartz grains. (Right side is west.) Scale = 2.5-Feet of visible Lufkin ruler and 7cm card. Photo by Mark Zdziarski, NJCU.

Bed B – At this exposure Bed B occurs at stream level and consists of a micaceous silty fine sand with some clay and trace of coarser sand-size particles (Figures 15 and 16). The upper part of the bed has some burrows, but are significantly less than what will be observed at other sites. This bed has "Wenonah" lithology, but its stratigraphic position, between Beds A (not shown at this location) and the Sequence Lag, would classify it as Mount Laurel (see Brown 2019, this volume).

Sequence Lag – The clasts representing this lag are not as abundant as will be observed at other exposures. Scattered clasts 2 to 4 inches in size of siderite and phosphate are present as are belemnites (Figure 16). Miller *et al.* (2004) would classify all overlying sediments as Navesink Sequence (see Brown, 2019 for historic perspective of this classification).

Bed C – At this exposure, Bed C is approximately 6 feet thick. It has been divided into two parts (Figure 15), although a case could be made that Bed C-2 is a subpart of Bed D. Bed C-1, as indicated in Figure 16, has the lag at its base. Bed C-1 contains belemnite pens and coarse sand to granule size quartz clasts: although this "coarse sand" aspect is not as abundant or "distinct" as will be seen at other exposures. The lithology present is atypical of either the Wenonah, Mount Laurel or Navesink formations. However, its stratigraphic position and the presence of quartz sand favors a "dirty", poorly sorted Mount Laurel lithology more than either a "Wenonah" or "Navesink" lithology. As a "clast", *Belemnitella americana* (Richards, 1962b) is known only from the Mount Laurel and Navesink Formations, therefore indicating the deposits immediately above the lag to be one of these two units. Distinct *Ophiomorphia* and other types of burrows are present in Bed C-1 and become more abundant all the way through Bed C-2 (Figure 15): this characteristic unites Beds C-1 with C-2, although Bed C-2 contains more glauconite as indicated by its darker color.

Bed D – The contact between Beds C and D (Figures 14 and 15) is where the burrows seem to stop for a more thoroughly mixed, bioturbated quartz fine sand with glauconite is present. This bed is highly bioturbated with some distinct burrows and fragments of *Microsytlus* (*Protocallianassa)* claws. It is not a definitive "marl" like Bed E: and therefore, has characteristics of both the Navesink and Mount Laurel Formations.

Bed E – At this exposure Bed E consists of dark gray to black, glauconitic marl with lesser amounts of gray clay. This unit is considered to represent the Navesink Formation. Its elevation above the stream bed at this location makes it hard to physically inspect.

So, where's the Campanian-Maastrichtian Stage Boundary?

A case could be made that it occurs anywhere between the base of the lag to somewhere within Bed E. Miller *et al*. (2004) would place it at the base of the lag. However, Sugarman and Owens (1996) notes "the Mount Laurel is assigned to the zone *Belembitella* [SIC] *americana* which is considered upper Campanian". Bed B does not contain this cephalopod. As noted above, it is found in both the Mount Laurel and Navesink Formations with a biostratigraphic range that straddles both the Campanian and Maastrichtian stages: so, is *B. americana*'s first occurrence in the Sequence Lag as part of Bed C (Figure 16) upper Campanian or younger?

At Big Brook, we will not encounter Beds B, C, D and E together at a single exposure again until we go west upstream across Hillsdale Road. However, recall what you see at Location BB-2 when we get to the next equivalent size exposure at Location BB-4.

Location BB-3: Exposure of Cretaceous Beds underlying Quaternary Floodplain Sediments (Figure 17) – This exposure is less than six feet high on the north side of Big Brook and illustrates the amount of Holocene channel incision relative to the floodplain surface. Quaternary gravel representing a stream bed similar to the current Big Brook overlies Cretaceous sediments. Question: is this new stream base level due to anthropogenic activities? The Sequence Lag at the contact of Beds B and C is among the exposed Cretaceous sediments at this location. Again, clasts and belemnites are found in the base of the Lag/Bed C while Bed B has less quartz sand. As we proceed upstream, this contact is not clearly visible again until near the Hillsdale Road Bridge.

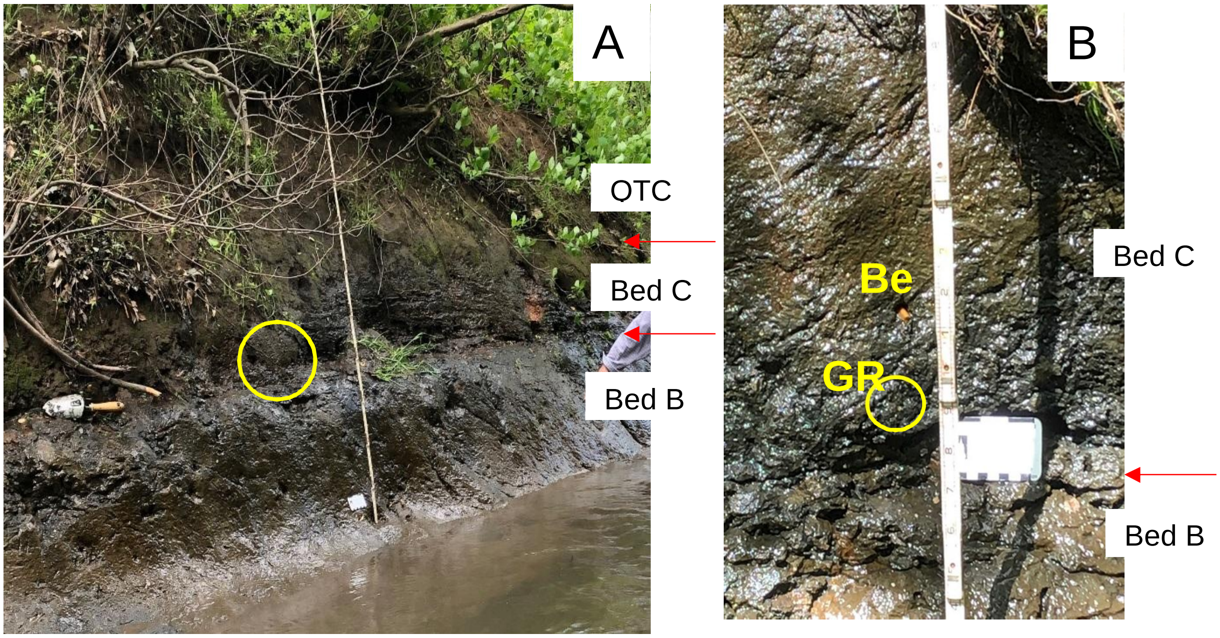


Figure 17. Location BB-3: Exposure of Cretaceous Beds underlying Quaternary Floodplain Sediments along north bank of Big Brook. Red arrows point to contact boundaries. Yellow circle in Photo A shows approximate location of Photo B. QTC = Quaternary deposits. Be = Belemnite; GR = coarse sand grains in yellow circle of Photo B. Larger clasts indicating the sequence lag are more dispersed than at other exposures. Scale = 6-Feet of visible Lufkin ruler and 7cm card. Photo right side is eastward; by Mark Zdziarski, NJCU.

Location BB-4: Unusually Thick Exposure of Navesink Formation ("Bed E") – This fairly large exposure (Figure 18) is due to recently fallen trees. Only "Bed E" or the Navesink marl is present and is at least 20 feet thick, if not thicker below stream level. None of the other three Beds (B, C or D) so far reviewed are present. Of note, stream gradient along the part of Big Brook visited as part of this GANJ 2019 trip is probably less than 0.5 foot where topographic elevation at stream level is approximately 79 feet Mean Sea Level (USGS 2014). The basically east to west exposures being examined at Field Stop 2 are relatively along strike (in contrast to the south to north "up-dip" exposures to be reviewed at Stop 4). So, is this a structural feature representative of a fault or slump block or a filled-in channel potentially associated with the low-stand erosion of the Sequence Lag? Unfortunately, a continuous exposure that might answer this question is not present. Subtle indicators of the latter explanation are noted further upstream.

Another interesting feature at Location BB-4 are the several *Exogyra*-dominated shell beds (Figure 19). An atypical horizontal bedding surface is also exposed slightly above stream level at the foot of this cliff that show possibly vertical settling fractures (Figure 20).

Figure 18. Exposure at Location BB-4 of the Navesink Formation ("Bed E") emphasizing its thickness. Photos A and B overlap but are at different angles. The lighter colored sands exposed in the right upper part of "Photo B" probably includes weathered Red Bank Formation overlying the dark gray to black Navesink Formation. (Right side is west.) Scale = 6-Foot Lufkin ruler. Photo A by Mark Zdziarski, NJCU; Photo B by Bill Gottobrio, Golder Associates.

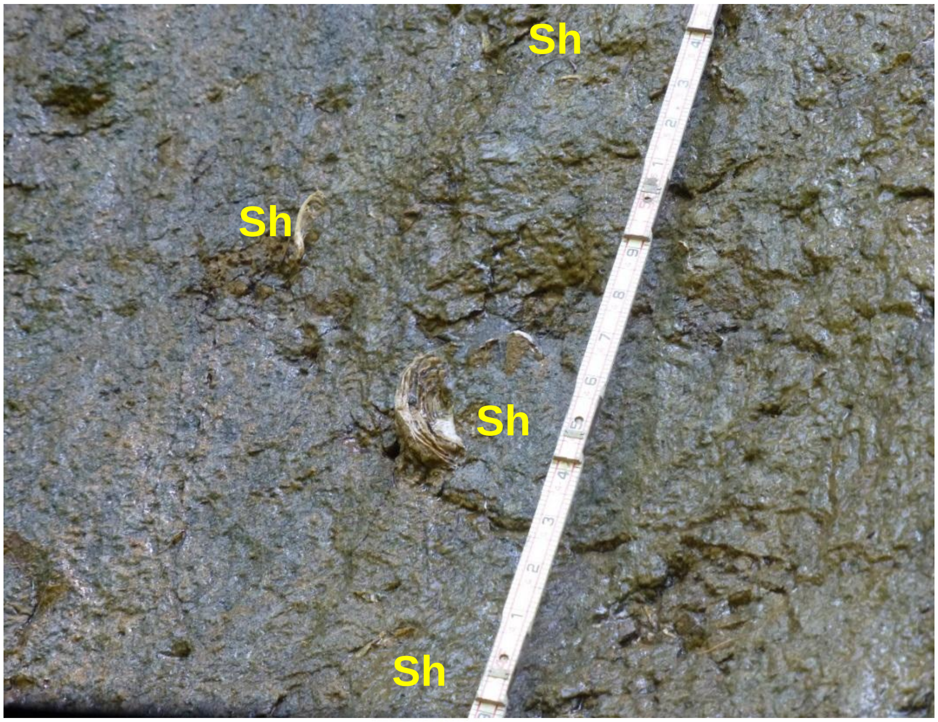


Figure 19. Close-up of exposure at Location BB-4 showing partly exposed *Exogyra* shell as well as other calcareous shells (all labelled "SHh") in glauconitic marl of Navesink Formation. (Right side is west.) Scale = 1.5 Feet of Lufkin ruler shown. Photo by Bill Gottobrio, Golder Associates.

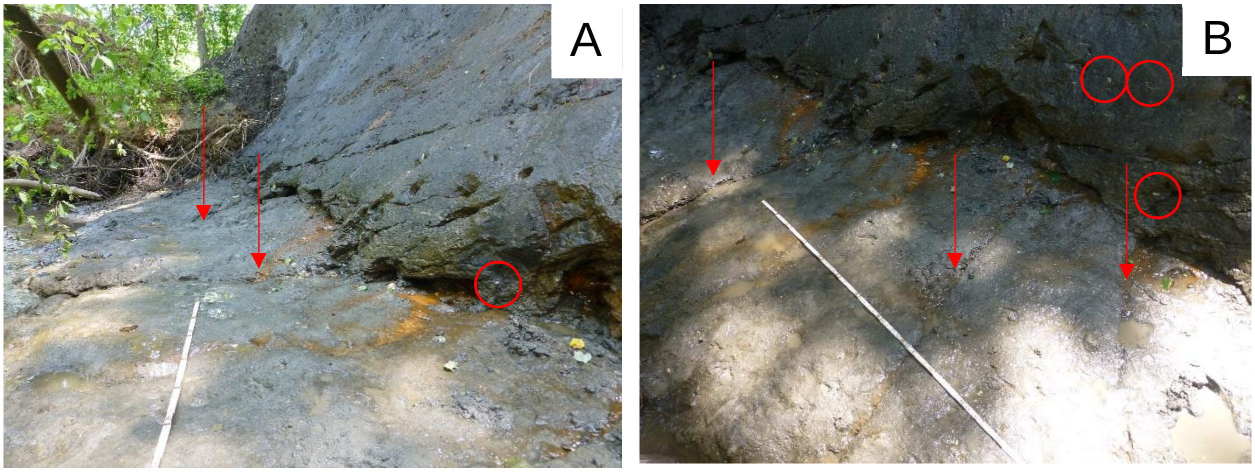


Figure 20. Exposure at Location BB-4 (Facing east) showing horizontal surface slightly above stream level (Photo A) at the foot of this cliff with possible settling fractures indicated by red arrows (Photo B). Red circles are examples of fossil shells dispersed throughout the outcrop (see Figure 19 for an example). Scale = 6 Feet Lufkin ruler. Photos by Bill Gottobrio, Golder Associates.

Location BB-5: Incised Floodplain and Terrace Boundary (Figure 21) – This area is immediately upstream of BB-4 (whose westernmost exposure is shown in the background of Figure 21). Big Brook's incised floodplain is easily recognizable on both banks of the stream showing a quaternary base level. Poorly exposed "Bed E" (Navesink Marl) is present at stream level on the right foreground.

Figure 21. Location BB-5 showing Big Brook's floodplain on both sides of the incised stream. Poorly exposed "Bed E" (Navesink marl) is present at stream level on the right foreground with better exposure downstream. (Facing east.) Scale = 6-Feet of Lufkin ruler shown under red dot. Photo by Bill Gottobrio, Golder Associates.

Location BB-6: Another Thick Exposure of Navesink Formation ("Bed E") – Our ability to see this exposure will be dependent on vegetation growth as it will be necessary to get off the main foot trail. Those who are in the water should be aware of "quicksand" at the foot of this exposure (Figure 22). The Navesink ("Bed E") appears to be 25 feet thick. While Beds B, C and D are not exposed in direct contact, Bed B (micaceous silty sand) and Bed C (quartz sand with cross beds) are present at stream level nearby. Weak cross beds appear to dipping eastward. After this location the Navesink Marl is no longer this thick and Beds B, C and D re-occur at similar elevations as observed at Location BB-2. The base of Bed E at these Locations (BB-7. BB-8 and BB-9) is at an elevation similar to the lower red arrow shown in Figure 22.

From this location we will re-cross Hillsdale Road and go to location BB-9 that is the western most part of our trip. From Location BB-9 we will backtrack to Locations BB-8 and BB-7 towards the buses on Hillsdale Road.

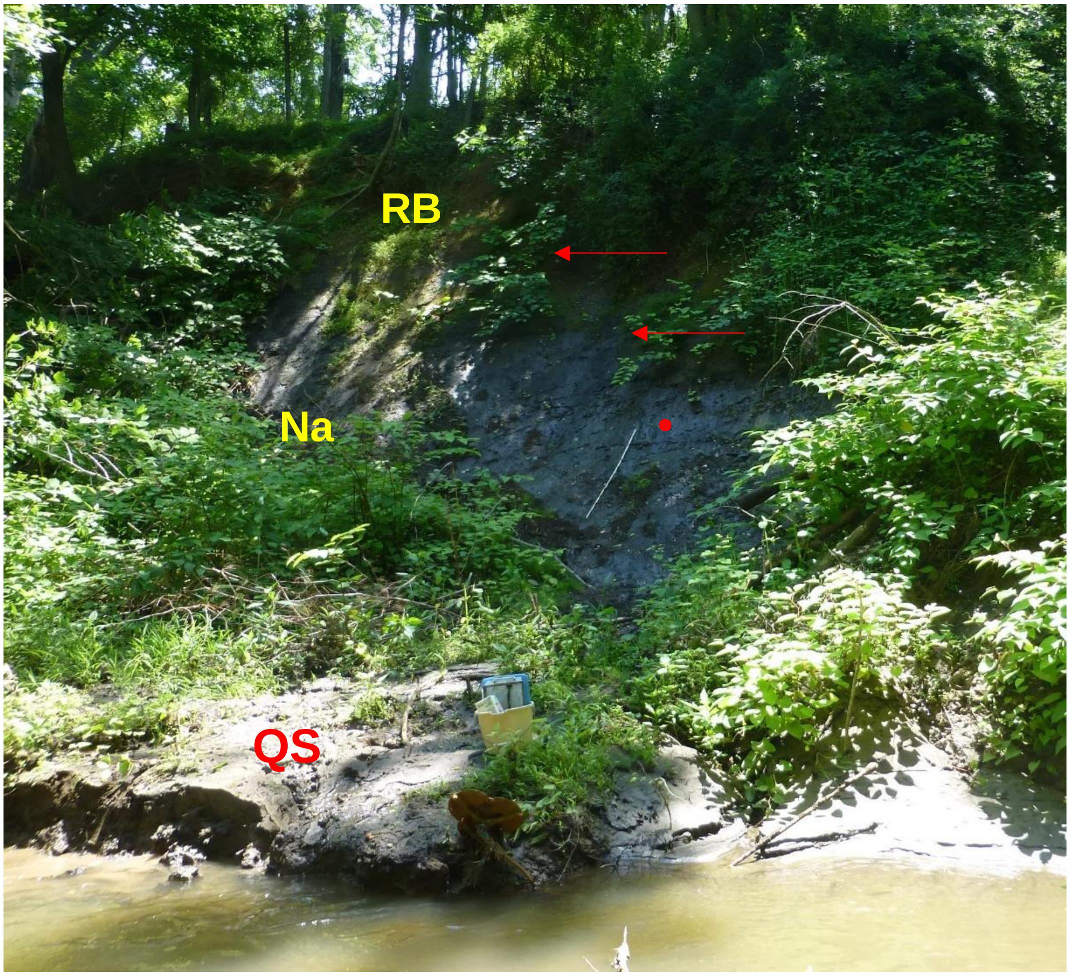


Figure 22. Location BB-6: Navesink Formation ("Bed E") immediately east of Hillsdale Road. Na = Navesink marl; RB = probable weathered Red Bank Formation; QS = quicksand of reworked sediments. The upper red arrow indicates contact between RB and Na while lower red line is distinct horizontal bedding surface: weak cross beds occur below this surface within the Navesink. (Right side is east.) Scale = 6 Feet of Lufkin ruler shown under red dot. Photo by Bill Gottobrio, Golder Associates.

Locations BB-7, BB-8 and BB-9 (plus POI–2): For a half mile, along approximate strike, between Hillsdale and Boundary Roads (Figures 1 and 12) are several exposures of Beds B, C, D and E along the south banks of Big Brook (compare Figure 6 of POI-2 to Figures 23 and 24). Bed B occurs at stream level as initially encountered at Location BB-2 (compare Figures 6, 15 and 23), but is missing at Locations BB-4 through BB-6 (see Figures 18 through 22) for nearly a half mile distance. Does this suggest a channel structure filled by younger Navesink lithology sediments?

The contact of Beds B and C showing the Sequence Lag is also exposed in this area on the north bank and is truncated by Quaternary sediments (Figure 25). Associated with the Bed B and Bed C contact, typically in the upper part of the Lag, are white to yellow calcarenite pods and burrows with interiors of well sorted quartz medium to coarse sand. These calcarenite clasts resemble the Mount Laurel of southern New Jersey (Figure 26). Does the sediment of these clasts represent a period of sedimentation at this location or are the clasts the result of intrabasinal transport? Collectors have also found large hard rock (schist) clasts referred to as “dropstones”. Is saltation, iceberg clasts, gizzard stones of swimming reptiles and/or entrapped in root masses of floating trees are potential sources for these unusually large clasts.

Figure 23. Exposure at BB-8 west of Hillsdale Road at Big Brook, Colts Neck, NJ. The red arrows on the right point to contact boundaries of distinct beds. Unlike the location farther west shown in Figure 6 (POI-2), only the contact between Beds B and C has a distinct lag. The red circles show the stratigraphic positions of clasts respectively labelled as A and B in Figure 26. Although clasts are present, both the upper and lower contacts of Bed D are irregular due to burrows. The red dot above the 6-Feet Lufkin ruler scale is in the center of the Bed D that has a lighter color and a better sorted sand texture than the two adjacent beds. Photo facing south; by Justin Andell, RVCC.

Finally, recall that Bed B is Campanian based on its sequence lag position and sporadic (“Wenonah” fossils). While *above the base* of Bed E as per its “Navesink” fossils is recognized as Maastrichtian, but “where” between these two points is the stage boundary? The presence of *Belemnitella americana* within Bed C (Figure 26) indicates at least an upper Campanian age if not Maastrichtian.

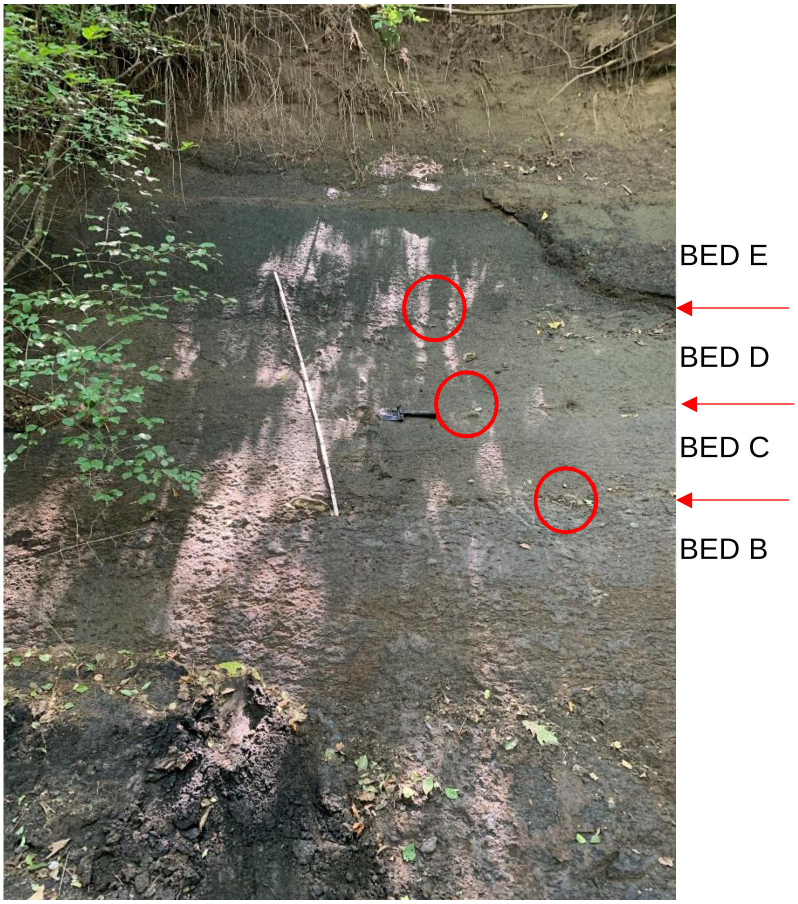


Figure 24. Exposure at BB-9 west of Hillsdale Road at Big Brook, Colts Neck, NJ. The red arrows on the right point to contact boundaries of the beds. Unlike the location farther west shown in Figure 6 (POI-2), only the contact between Beds B and C has a distinct lag. Although clasts are present, both the upper and lower contacts of Bed D are irregular due to burrows. Note differential weathering enhancing the burrows and bioturbation marks in Bed B. Scale= 6-Feet Lufkin ruler. Photo facing south; by Justin Andell, RVCC.

Figure 25. Exposure on the north (floodplain) bank of Big Brook by BB-8. Only the contact of Beds B and C showing the Sequence Lag is visible before being truncated by Quaternary (lower terrace deposits). Compare elevation relative to stream level and outcrop preservation to Figure 17 at BB-3. Scale: Lufkin ruler is 6-Feet. Photo facing south, by Justin Andell, RVCC.

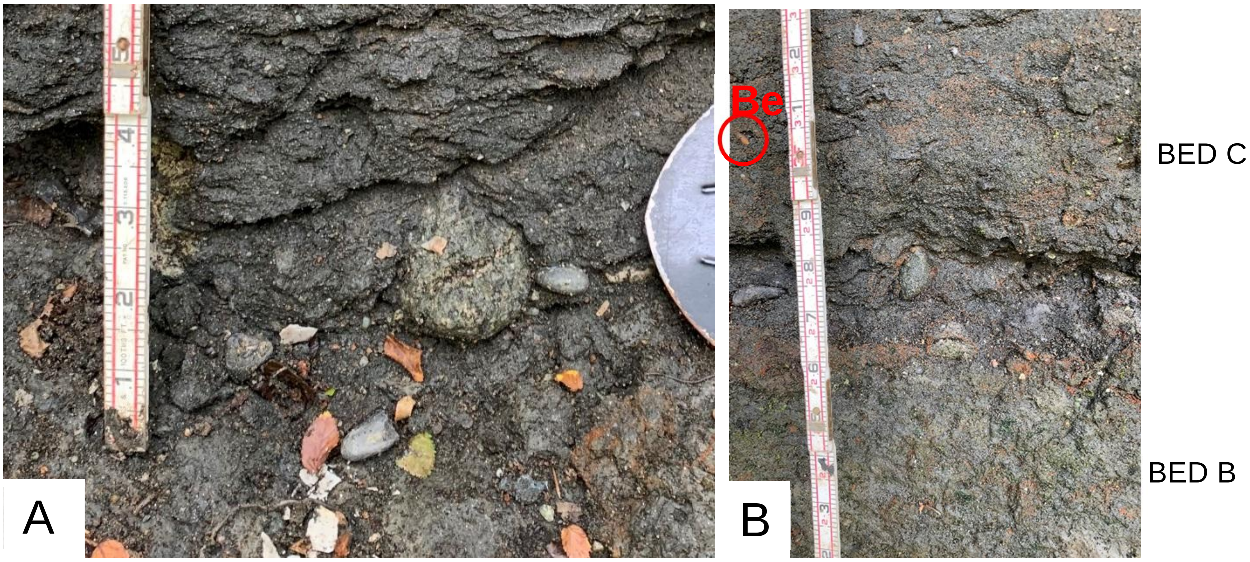


Figure 26. Clasts in the Sequence Lag. See Figure 23 for stratigraphic locations. The clast in Photo A was initially thought to be "dropstone" from an outside provenance but has been identified as a calcarenite. Differential weathering shown in Photo B also highlights the generally better sorted, finer grain, bioturbated aspect of Bed B in contrast to the coarser grain size clasts found in Bed C. The red circle "Be" is a pen of *Belemnitella americana* indicating Bed C to be either Mount Laurel or Navesink. Scale: Lufkin ruler is marked in 100ths of a foot where "1"= 1/10 or 10/100 of a foot. Photos by Justin Andell, RVCC.

Location BB-9: Westernmost Field Trip Boundary: We ask all field trip participants not go any further west then the trench shown in Figure 27 to avoid being left behind. Along the south bank are Beds B through E (see Figure 24) while approximately 50 feet upstream on the north bank is a deep excavated trench (Figure 27) that cuts through the Quaternary floodplain (Lower Terrace) deposits into the Cretaceous sediments (Figure 28). Some exposures in this trench show the bed load of past streams and indicate how the existing stream is at a new base level (Figure 28). This trench also marks the farthest west at Field Stop 2 that will we inspect today.

Figure 27. Location near BB-9: Shows Quaternary Floodplain of north bank of Big Brook and excavated trench. Dark gray sediments at stream level are Cretaceous Beds B and C. Red circle indicates location shown in Figure 28. Photo by Tom Mason, Brookdale Community College.

Figure 28. Location by BB-9: this is an excavated trench that drains south into Big Brook from its northern floodplain. Photo B is close-up of red box in Photo A and shows the lower terrace gravel deposit at contact between Cretaceous (K) and (Quaternary (QTC). Lufkin ruler is 6-Feet. Photos facing west; by Justin Andell, RVCC.

Time	Activity	Distance
12:00 PM	Leave for Stop 3	
	Continue north on Hillsdale Rd for 1.1 mile to Clover Hill Rd;	
	Go 1.1 mile to Clover Hill Lane make left (north); (Note: we will pass POI-4)	
	Go 0.5 mile to Route 520 / Newman Springs Rd.; make right (east) onto Route 520;	
12:15 PM	Go 3.4 miles to Thompson Park; make right into park and find parking	6.4 miles

STOP 3 THOMPSON PARK, LINCROFT, NJ: LUNCH BREAK

We intend to stay here for approximately an hour: unless announced otherwise we will be leaving at **1:15 pm**. There will probably not be enough time for some of us to inspect a location similar to Figure 6 of Stanford (2019, this document) that shows Quaternary upper terrace sand overlying the Cretaceous Red Bank Formation in a bank along Swimming River Reservoir.

Time	Activity	Distance
01:15 PM	Leave for Stop 4	
	Drive @ 0.2 mile through park to Route 520 / Newman Springs Rd; turn left;	
	Go 0.7 mile west on Route 520 to Everett Road; turn right;	
	Go 0.7 mile north on Everett Road to McCampbell Road; turn left;	
	Go 1.4 miles to intersection of McCampbell Road and Holmdel-Middletown Road;	
01:25 AM	We will disembark here (please be mindful of traffic if it is necessary to cross the road).	2.8 miles

STOP 4 - RAMANESSIN BROOK GREENWAY (“HOP BROOK”) CREEK, HOLMDEL, NJ

Presenters: Scott Stanford, Peter Sugarman, Josh Galster, Jim Brown
Emphasis: Pleistocene and Cretaceous Stratigraphy & Paleontology;
Geomorphology; Public Land Use

NOTE: *We will have approximately 2.5 hours at this field stop that will include a hike along Ramanessin Trail. This will be followed by ample time for outcrop inspection and fossil collecting.* ***PLEASE BE BACK AT THE BUSES BY 4 PM AS WE WILL BE PROMPTLY LEAVING AT THAT TIME.***

Safety Notes:

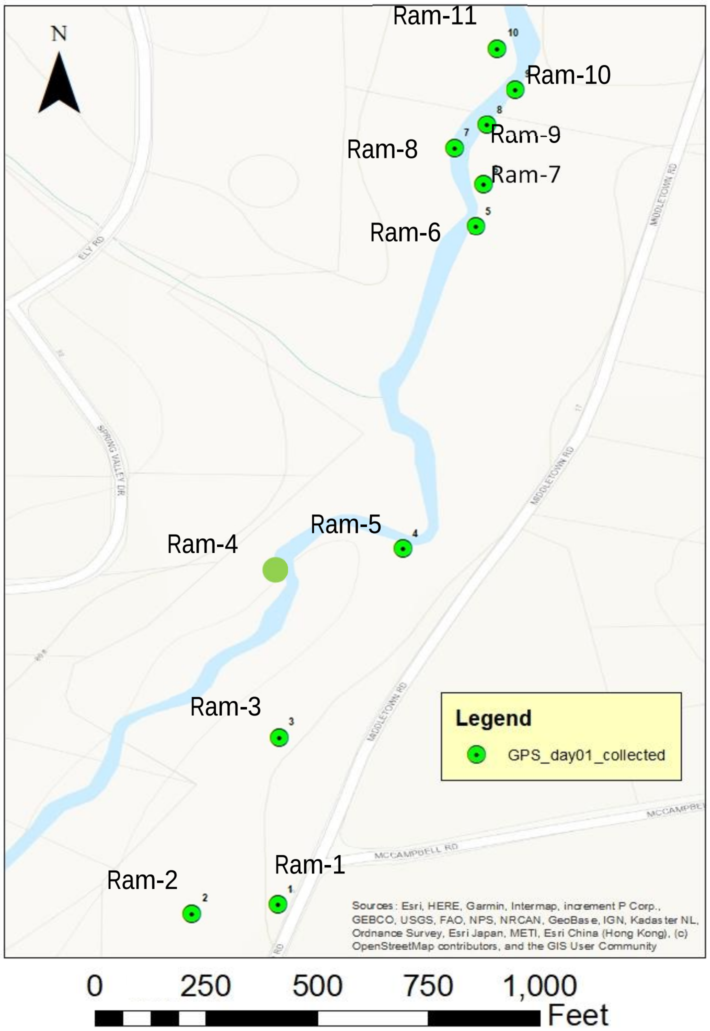
1. ***Anticipate walking a total of about 1 mile along “deer trail” type woodland areas with occasional fallen trees. In order to easily fossil hunt and to see a few of the exposures along the stream banks, it will necessary to get your feet wet by treading through approximately a foot of water.***
2. ***In addition to trip and fall in wooded area, please be cognitive of ticks, poison ivy, and vegetation that can poke you in the eye.***
3. ***Be cognitive of undermined trees that can either fall or cause a landslide: especially along the stream banks.***
4. ***Wear proper footwear and clothing, especially in the streams to avoid cuts from rocks and broken glass in the stream as well as hypothermia.***

Background: Public Land Use and Watershed Protection

We will be in the Ramanessin Brook Greenway of Holmdel Township. The stream that runs through this park is known by multiple names, notably Hop or Hopp Brook as well as Ramanessin Creek. The trail in the Greenway connects to the Ramanessin Brook Conservation Area managed by the Monmouth County Park system (Township of Holmdel, 2017). This watershed area ultimately drains into the Swimming River Reservoir Watershed (see Galster, 2019, this document). Fossil collecting policies vary on these managed properties where Monmouth County Park does not allow fossil collecting except to permitted research groups such as the New Jersey State Museum. In contrast Holmdel Township, with help from the Friends of Holmdel Open Space (FOHOS), will host recreational events to youth groups (Township of Holmdel, 2019).

Field Stop Highlights

Figure 29 shows locations (labelled Ram-1 through Ram-11) that will be inspected at this field stop. After exiting the buses at location Ram-1 (by intersection of Holmdel-Middletown Road and McCampbell Road), we follow a nature trail that includes several displays about local geology and hydrology that was completed as part of an Eagle Scout project. With regard to the Cretaceous formations we will be hiking approximately “up-dip” as we inspect exposures along the stream basically from south to north. It will be about a half mile walk each way along the Ramanessin Trail.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 29. Field Stop 3 - Points of interest at Ramanessin Brook Greenway ("Hop Brook"), Holmdel New Jersey. Each of these numbers is referred to as "Ram-1", "Ram-2", and so on within the road log text.

Location Ram-1: Entrance to Ramanessin Brook Greenway Trail – We will be loading on and off the buses from this area, so please be back on-time (otherwise it is a 3-mile hike from this point back to Brookdale Community College). We are on the surface of the upper terrace here and will be descending to the modern floodplain as we proceed to location Ram-3. The upper terrace is the former valley-bottom floodplain in the middle Pleistocene from about 150 to 125 ka. Streams began to incise into this surface as sea level lowered after the interglacial highstand at 125 ka (see Stanford 2019, this document).

Location Ram-2: Watershed Display – A billboard poster built as part of Boy Scout Eagle project explains the significance of the park for watershed protection.

Location Ram-3: Hydrogeology Display – This second notable display (Figure 30) show the geological formations. In terms of hydrogeologic units it combines the Mount Laurel and Wenonah Formations as a single unit (see Sugarman and Zapecza, 2019, this document). As we entered the floodplain, we crossed a small bridge spanning a "seepage collector" stream. These are common in Coastal Plain floodplains and form along the edge of the floodplain where groundwater from the adjacent upland discharges as seepage springs, feeding wetlands and back channels that eventually drain into the main channel.

Figure 30. Location Ram-3: Eagle Scout Project Display showing hydrogeologic units. Photo by Tom Mason, Brookdale Community College.

Location Ram-4: Beds A of Cretaceous Sediments (Figure 31) – This will be the only accessible exposure of sediments referred to as Beds A that will be inspected on the trip (but see Figures 8, 9, and 10 regarding the presence of these beds at other localities in Monmouth County). Beds A consist of interstratified thin (0.1 to 0.5 foot) beds of clays, silts and sands (Figure 31). Mica and lignite are commonly found in the gray finer beds while quartz is the main component of the sand beds. Siderite concretions are locally abundant along some horizons and sometimes contain fossil molds and casts. Ichnofossils (see Martino and Curran 1990) are present, but not to the degree to have totally destroyed bedding planes. These beds are interpreted to represent a shoreface environment as discussed by Martino and Curran, 1990) and have been interpreted to represent the Mount Laurel Formation (see also Miller *et al*. 2004; Owens and Sohl, 1969). As noted by Brown (2019, this volume) macrofossils reported from this unit and overlying Bed B represent a Wenonah Fauna. The stratigraphic debate of Mount Laurel versus Wenonah entails whether one prefers to emphasize the quartz sand (Mount Laurel aspect) or the lignite and mica silty sand (Wenonah aspect) of these beds. (If anyone finds belemnites *in situ* please alert the field guide leaders as this has potential significance with various correlations.)

Location Ram-5: Quaternary Fluvial Sediments and Stream Erosion – This exposure is along a recently developed meander in Ramanessin Brook as indicated by the park bench facing the stream. The stream bank is cut into the alluvial deposits forming the floodplain. Most of the bank exposes organic silt and fine sand that accumulated from overbank deposition during floods. Near the base of the bank is gravel that marks the former channel of the brook (Figure 32). The base of the gravel is in sharp contact on the Cretaceous bedrock formation. This contact is about a foot above the present channel, and shows

Figure 31. Location Ram-4 - Beds A of intrastratified Cretaceous Sediments: Lighter color beds consist well sorted sands while darker beds are varied clays to silty sands with mica and lignite. The two red arrows indicate a horizon with abundant white siderite concentrations. (Right side is north.) Scale = 6-Foot of Lufkin ruler shown under red dot. Photo by Joanna Bednarek, NJGWS.

that the bed of the stream was higher than it is now. This relationship indicates that the stream is incising into the floodplain. This is common for many streams in northern and eastern Monmouth County, but is rare elsewhere in the New Jersey Coastal Plain. A log in the basal gravel just upstream from here gave a radiocarbon date of 4730±30 years before present (Beta 529738), which calibrates to between 5.6 and 5.5 ka. At four other sites in the county, dates on organics in alluvium in similar incised floodplains range between 2.2 and 2.7 ka. These dates indicate that deposition of the overbank sediments, and then the incision into the underlying Cretaceous formation, occurred within the past 2000 to 6000 years. What might cause this? And why only in Monmouth County?

Locations Ram-6 and Ram-7: Geomorphology: Quaternary Erosion and Depositional Features: On our walk to location Ram-6 a tributary intersects the main trunk of the Ramanessin Creek. In this area both the upper terrace and the incised floodplain can be observed (Figure 33). This piece of upper terrace is lower than the main upper terrace that we saw at the parking area and probably represents a later position of the brook as it cut down after the 125 ka highstand. The photographs in Figure 33 were taken in early Spring in an elevated area on the opposite side of the creek from where we will try to appreciate these features in the area of Ram-6 and Ram-7.

Figure 32. Location Ram-5: Quaternary Fluvial Sediments – This exposure is at a meander in Ramanessin Creek that shows A. Gravel-size quartz grains of a former stream bottom; B. Round in-place wood (both above and below the hand trowel); C. Dark reworked Cretaceous sediments; D. Weak cross-beds. Photos: facing south: 1. by Tom Mason, BCC; 2. by Tim Macaluso, BCC.

Figure 33. Locations Between Ram-5 and Ram-6/7: Geomorphology: Quaternary Erosion and Depositional Features. UT = Upper Terrace; FP = Floodplain: CBL = Current Base Level of stream. Red circle shows person for scale. Both photos are facing north. Photos by Tom Mason, BCC.

Location Ram-8: Exposure of contact between Beds B and C – Only Beds B and C are clearly visible at this exposure (Figure 34). This exposure highlights both differential weathering and how different lithologies can be comingled due to bioturbation. Bed C and burrows within Bed B are a brown to rusty orange color. This reflects iron-dominated minerals most likely limonite (goethite) to be present within the coarser textured (sand to granule size) matrix. When the water table is high it is able to dissolve and transport iron that ultimately, when the water table is lower it cements the beds in the vadose zone together. (This is a counter-intuitive example of how younger sediments can be solidified into rock faster than older sediments and a phenomenon characteristic of New Jersey's Coastal Plain: see Hozik and Mihalasky (2003) in GANJ 2003 for additional field examples.) Ironically, once burrows such as those shown in Figure 34 are sufficiently cemented, they become more resistant to physical weathering in contrast to their surrounding matrix.

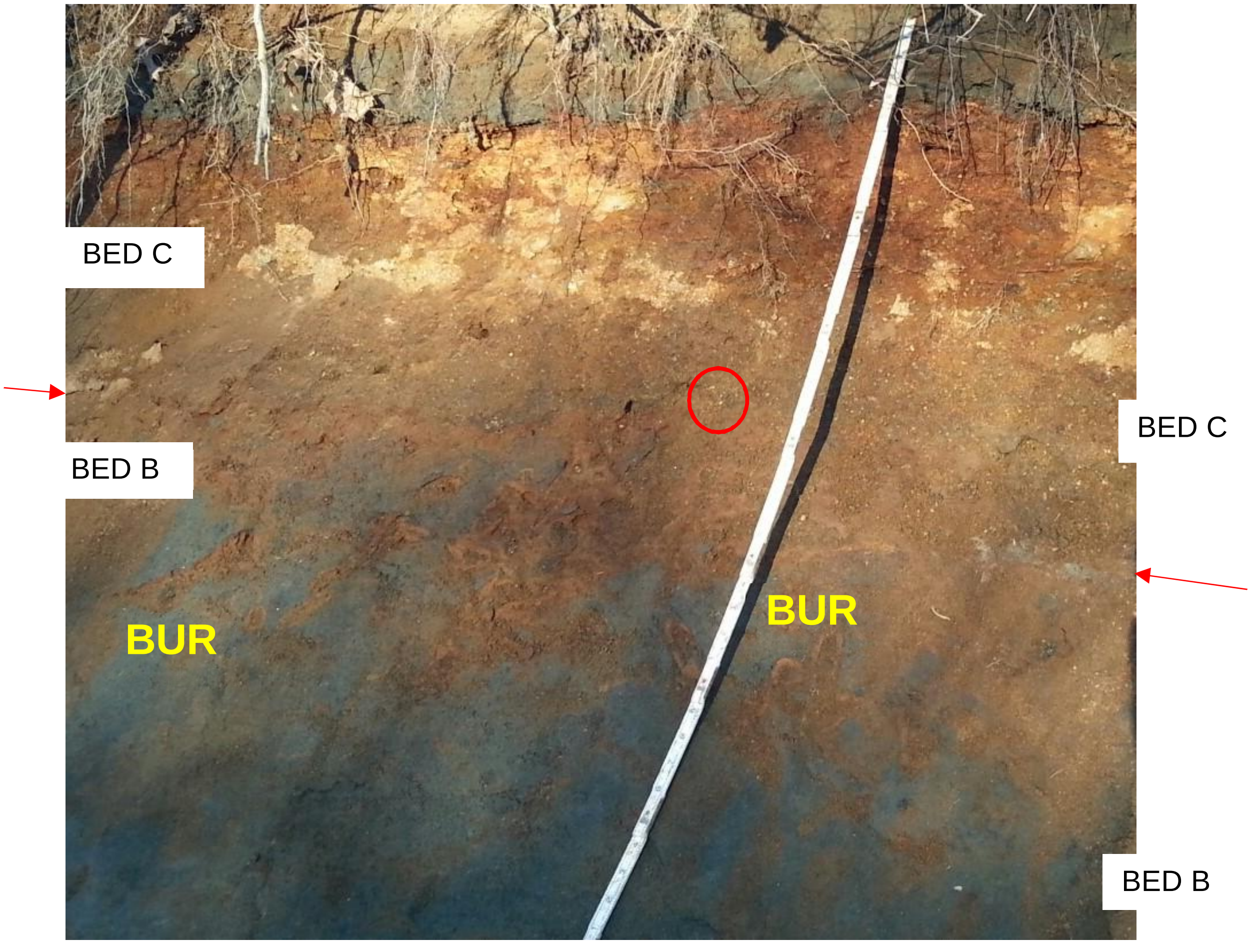


Figure 34. Ram-8. Exposure of contact between Beds B and C. Differential weathering due to grain size and mineralogy are exemplified at this exposure. Red arrows point to approximate contact boundary of the two beds whose contact has been disturbed by bioturbation: "BUR" indicates sand filled, limonite cemented burrows in Bed B. Red circle is one example of white granules that contrast against limonite cemented Bed C. The visible Lufkin ruler is 4 feet in length. Photo facing west; by Tim Macaluso, BCC.

The beds at Ram-8 are our first chance to compare lateral equivalents inspected at Big Brook. As at some spots at Big Brook, clasts indicative of the sequence lag are not very distinct here, probably due to the degree of large (crustacean?) animal bioturbation at this particular contact. Except where burrowed, Bed B is similar to what has been previously observed: it is a fine-textured (clay to silty sand) gray color with a fair amount of mica and fine lignite. In contrast Bed C is very different, with much, more coarse sand and granule quartz clasts. Despite the lithologic differences, Bed C at Ramanessin Creek represents chronostratigraphically equivalent sediments to those encountered at Big Brook as will be shown when we inspect Beds B through E at locations Ram-9 through Ram-11.

An exposure near Ram-8 shows Quaternary gravel truncating underlying Cretaceous sediments (Figure 35). This gravel bed which may represent lower terrace deposits indicates the location of a former stream bed and appears to contain reworked Cretaceous quartz granule grains characteristic of Bed C at Ramanessin Creek in addition to the reworked gravels characteristic of local stream beds (see Stanford 2019, this volume) from the Miocene Beacon Hill Gravel and younger gravel beds.

Figure 35. Location near Ram-8: Exposure of Quaternary gravel truncating underlying Cretaceous sediments. The finer quartz granules within this gravel might be derived from reworked Cretaceous sediments characteristic of Bed C, while the larger gravel size quartz clasts are more representative of younger reworked Coastal Plain gravels. Photo by Joanna Bednarek, NJGWS.

Locations Ram-9 and Ram-10: Extensive Exposure of Beds B through D. A good exposure of Beds B, C and D is present between Locations Ram-9 and Ram-10 (Figure 36). Bed E is also present, but poorly exposed due to vegetation growth. As noted at Location Ram-8, Bed B is basically similar to what was observed at the Big Brook locations and consists of clayey silt to fine sand with visible grains of mica and black lignite. What is notably different are ichnofossils derived from the downward movement of sediment due to burrowing activity; these burrows contain coarser sand and granule sized particles than surrounding sediment (Figure 37, but also see Figures 34 and 35). In deference to the naming of stratigraphic units, is this the Wenonah or the Mount Laurel?

Bed C is the most significantly different unit at Ramanessin Creek when compared to the Big Brook locations. This is due to the greater abundance of coarse sand to granule size quartz clasts (Figures 36 and 37). A prominent feature is the differential weathering of this bed where limonitic cement of its quartz clasts has locally created a conglomeratic rock (Figures 36 and 37). This approximate two-foot layer might be recognized as the sequence lag, although clasts composed of phosphatic, siderite and calcarenite concretions are sporadically present, notably at its basal contact. As indicated in Photo A of Figure 36 there may be multiple depositional events associated with Bed C, similar to what was also locally observed at Big Brook (notably Location BB-2). Historically, this unit would be recognized as Mount Laurel, but it has also been referred to as Navesink due to its location above the lag.

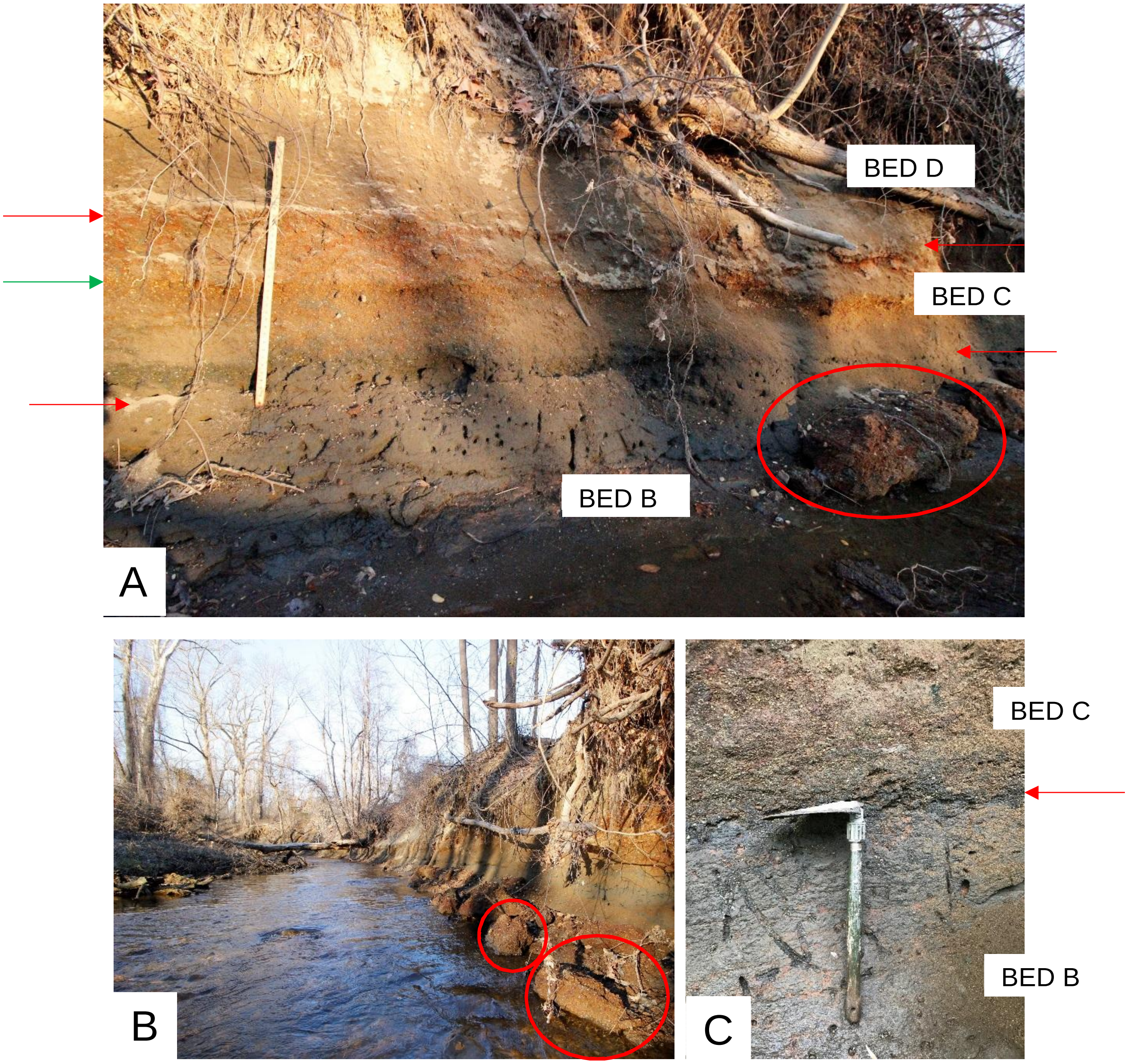


Figure 36. Locations Ram-9 and Ram-10: Photo A (facing about east) by Ram-9 shows good exposure of Beds B, C and D. Bed E is poorly exposed, but also present in this area. Red arrows indicate contact boundaries of the beds. The green arrow indicates a secondary bedding surface within Bed C that is similar to that observed at Location BB-2, but not a consistent feature. Red circle shows large boulder size erosional limonite cemented clasts of Bed C (see Figure 37 for close-up). Photos A and B were taken in early Spring 2019, by summer these clasts were nearly all gone due to erosional and human activity. Photo B (facing northeast from Location Ram-9) shows exposure between Locations Ram-9 and Ram-10. Photo C shows distinct bedding surface between Beds B and C in contrast to Location Ram-8 (see Figure 34). Scale in Photo A is 1 meter length. Photos A and B by Tom Mason, BCC. Photo C by Joanna Bednarek, NJGWS.

Bed D at Ramanessin Creek is fairly similar to its lateral equivalent at Big Brook and shows a relatively finer textured glauconitic quartz sand.

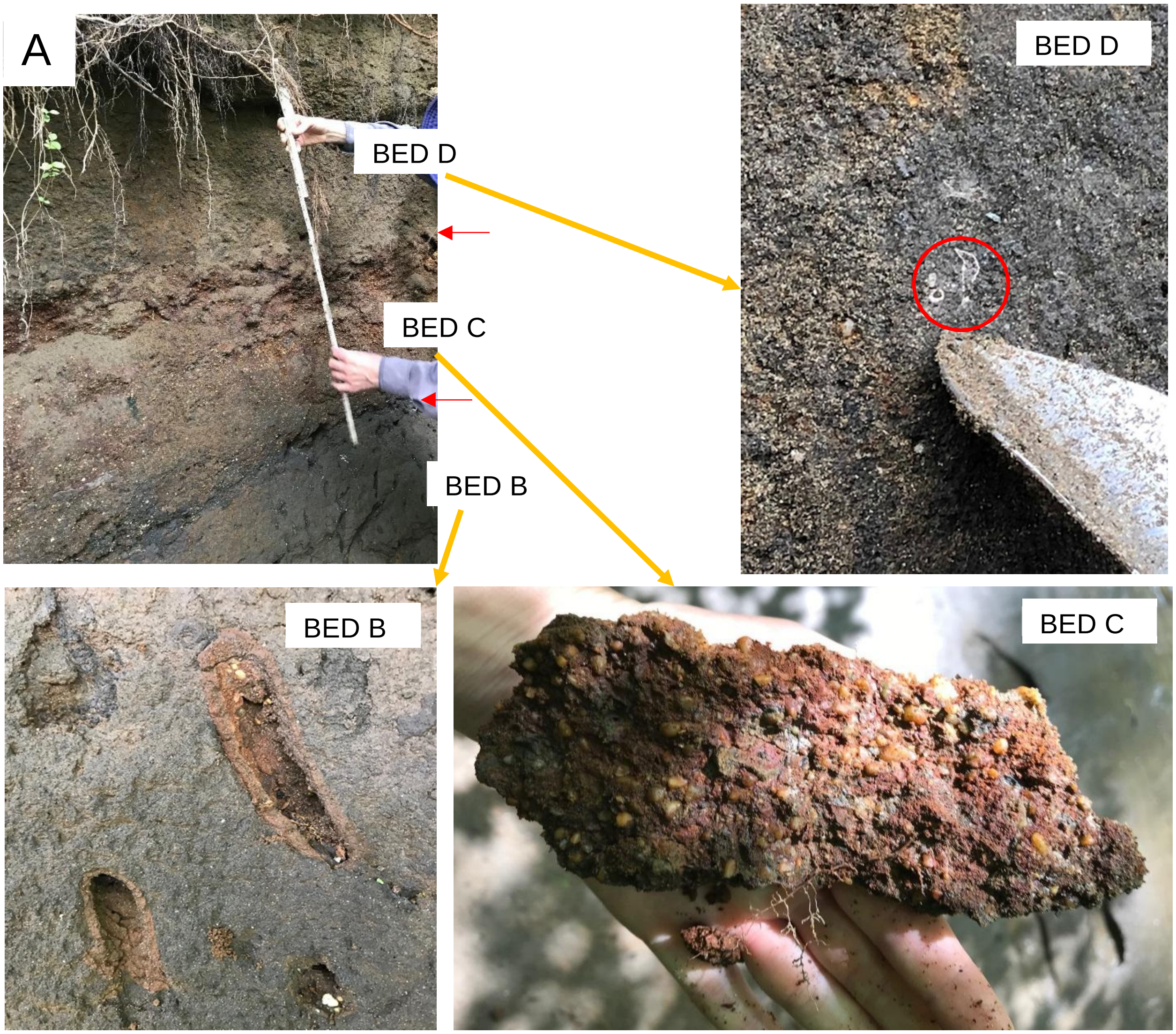


Figure 37. Close-ups of exposure between Locations Ram-9 and Ram-10: Photo A (facing about east) shows exposure of Beds B, C and D with 3 Feet of Lufkin ruler held by hand. Red arrows indicate contact boundaries of the beds. Other three photos are labelled by their representative bed as indicated by orange arrows. Bed B photo shows *Ophiomorphia* burrows of limonite filled with coarser sediment similar to Bed C. The hand-held example of Bed C shows its conglomeratic aspect due to differential weathering and limonitic cement of its quartz clasts. The close-up of Bed D shows a co-mingled glauconitic quartz sand: probably due to high amount of bioturbation derived from ghost shrimp whose fragmented remains are fairly common (red circle shows cross section example of these crustacean claws). Photo of Bed B by Mark Zdziarski; all other photos by Joanna Bednarek, NJGWS.

indicative of the amount of glauconite between these two beds, but a case could be made that both are the Navesink Formation. At the base of Bed E are phosphatic clasts that indicate the transgressive “lag” that is possibly equivalent to the disconformity noted by Gallagher and Hanczaryk (2019, this volume) at Big Brook. As previous noted, the general consensus of Bed E is it being the Navesink Formation in contrast to underlying Beds C and D which have been referred to as either Navesink or Mount Laurel.

After inspecting Ram-11, there should be ample time to collect fossils and re-inspect reviewed exposures. Please ***do not go upstream beyond Location Ram-11.*** *The area north of this location is managed by the Monmouth County Park system which requires fossil collection by permit under research institute supervision.*

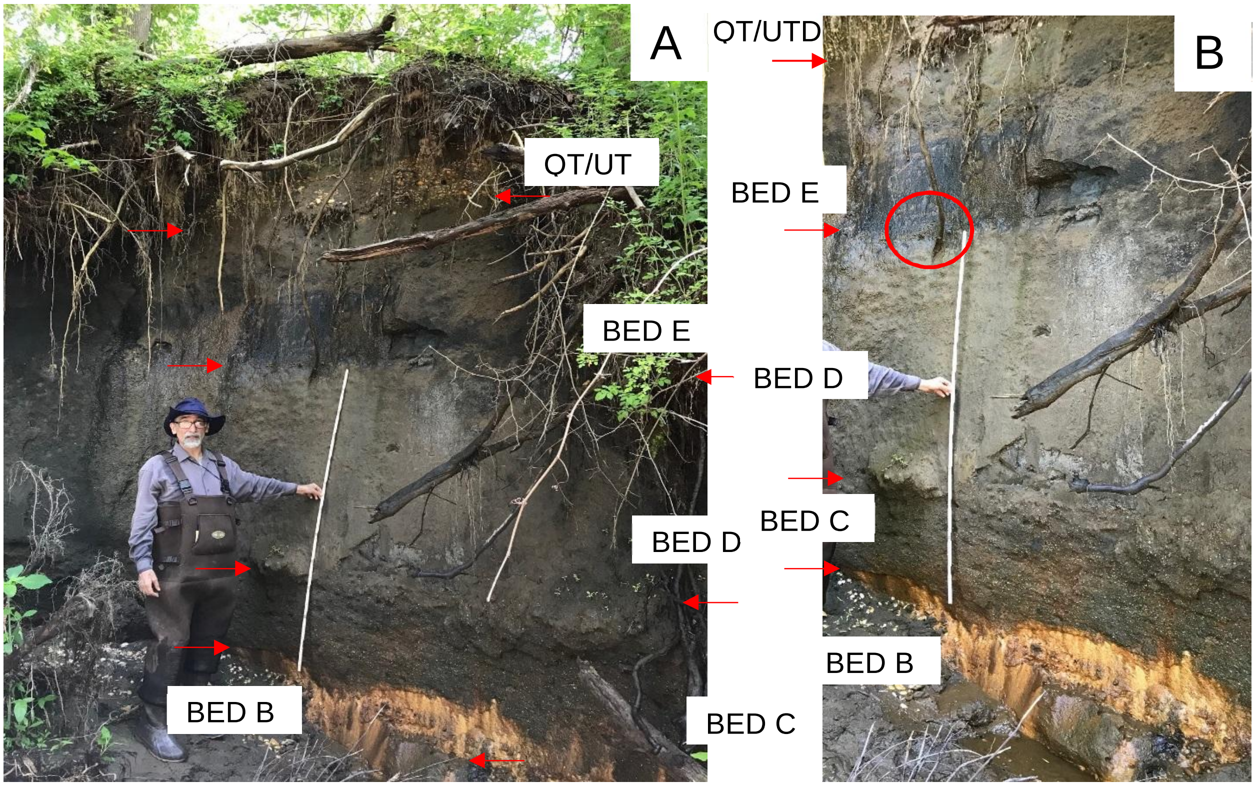


Figure 38 - Location Ram-11: Local Exposure of Beds B through E overlain by Quaternary Upper Terrace Deposit (QT/UTD). Lufkin ruler is 6 Feet and shows this to be combined thickness of the “sequence beds”, Beds C and D, at this location. The contrast in color of Bed D and Bed E is indicative of the amount of glauconite between these two beds. Red circle shows clasts indicating “lag” (“disconformity”) at base of Bed E. As previously noted, the general consensus of Bed E is it being the Navesink Formation in contrast to underlying Beds C and D which might be atypical Mount Laurel equivalents. Photos by Joanna Bednarek, NJGWS.

Time	**Activity**	**Distance**
04:00 PM	Depart for Brookdale Community College	
	Drive 1.4 miles east on McCampbell Road to Everett Rd; make right;	
	Drive 0.7 miles southeast on Everett Rd to Route 520 / Newman Springs Rd; make left;	
	Drive 1.0 mile to entrance to Brookdale Community College;	
04:10 PM	Go 0.6 mile on campus to Parking Lot 1 and disband	3.7 miles

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Several of the field maps were prepared under the supervision of Professor Bill Montgomery* from GPS field data collected by M. Zdziarski and J. Richards of NJCU. Alan Uminski*, Environmental Restoration, LLC proofed a draft of this document, but J. Brown takes responsibility of errors in terms of presentation and information of both the noted maps and text. Preliminary field visits, prior to this becoming a formal GANJ field trip, with MAPS members Ralph Johnson, Wayne Callahan, S. Ballwanz and J. Andell helped to establish stratigraphic and geographic locations. Insights on fossil collecting challenges, rules and regulations were obtained from conversations with R. Johnson (MAPS), W. Callahan (MAPS and NJ State Museum), former Marlboro councilman Paul Kovalski, and Thomas Hennessey, Jr. of the Parks and Recreation Department of Colts Neck Township.

(*denotes an active member of the GANJ executive board)

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USGS 01407287 Big Brook at Boundary Rd near Marlboro NJ.[9]

USGS 01407290 Big Brook near Marlboro NJ[10]

USGS 01407498 Swimming River Reservoir near Red Bank NJ[11]

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[7] https://www.holmdeltownship-nj.com/541/Map-of-Holmdels-Parks

[8] https://www.holmdeltownship-nj.com/DocumentCenter/View/1790/Holmdel-Monthly-Newsletter-May-2019

[9] https://waterdata.usgs.gov/nj/nwis/uv/?site_no=01407287&PARAmeter_cd=00065,00060,62614

[10] https://waterdata.usgs.gov/nwis/uv?site_no=01407290

[11] https://waterdata.usgs.gov/nj/nwis/uv?site_no=01407498