Guidebook for Pre-Meeting Field Trip to Newark Basin

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Purpose of Field Trip

To provide a brief overview of the eastern North American (ENAM) rift system by observing the structure, stratigraphy, and igneous rocks of the Newark rift basin. We will discuss the influence of pre-existing zones of weakness on rift-basin development, the considerable spatial and temporal variability of syn-rift deposition near the border-fault zone, and the absence of rift-related igneous activity except for that associated with the short-lived CAMP (Central Atlantic Magmatic Province).

List of Stops

STOP 1. Durham Furnace, PA. Highly deformed Cambrian carbonates (pre-rift rocks) exposed in the footwall of the border-fault zone of the Newark basin.

STOP 2. Kintnersville, PA. Small normal faults near the border-fault zone of the Newark basin; playa-lacustrine syn-rift strata with evaporites in the Passaic Formation.

STOP 3. Ringing Rocks County Park, near Upper Black Eddy, PA. Diabase sheet related to the Central Atlantic Magmatic Province (CAMP); shallow-water lacustrine syn-rift strata of the Passaic Formation affected by contact metamorphism (hornfels) and fracturing.

STOP 4. (Optional) Pebble Bluff, near Milford, NJ. Alluvial-fan and deep-water lacustrine facies of the Passaic Formation in hanging wall of border-fault zone.

Introduction

Eastern North America is a natural laboratory for studying rift basins and passive-margin development. It hosts one of the world’s largest rift systems (the eastern North American rift system), one of the world’s oldest intact passive margins, and one of the world’s largest igneous provinces (the Central Atlantic Magmatic Province, CAMP). Additionally, seismic-reflection profiles, field exposures, drill-hole data, and vitrinite-reflection data provide a wealth of information about the tectonic and depositional processes associated with rifting, breakup, and
During early Mesozoic time, a massive rift zone developed within the Pangean supercontinent (insert, Fig. 1). The breakup of Pangea splintered this rift zone into extinct fragments, each now separated and preserved on the passive margins of eastern North America, northwestern Africa, and Europe. The fragment on the North American margin, called the eastern North American (ENAM) rift system, consists of a series of exposed and buried rift basins extending from northern Florida to the eastern Grand Banks of Canada (e.g., Manspeizer and Cousminer, 1988; Olsen et al., 1989; Schlische, 1993, 2003; Withjack et al., 1998) (Fig. 1). It is a large rift system, affecting a region up to 500 km wide and 3000 km long. Withjack and Schlische (2005) and Withjack et al. (2012a) divided the eastern North American rift system into three segments based on tectonic history (Fig. 1). Rifting was underway in all three segments by Late Triassic time. The end of rifting (and presumably the beginning of seafloor spreading), however, was diachronous, occurring first in the southeastern United States (latest Triassic), then in the northeastern United States and southeastern Canada (Early Jurassic), and finally in the Grand Banks (Early Cretaceous) (Withjack et al., 1998, 2012a; Withjack and Schlische, 2005; Schettino and Turco, 2009).

**Newark rift basin**

The Newark rift basin lies within the central segment of the ENAM rift system (Fig. 1). It is one of the largest and most thoroughly studied of the ENAM rift basins with abundant field, seismic, core, borehole, and vitrinite-reflectance data available to constrain its development (Fig. 2).

**Stratigraphy of Newark rift basin**

The stratigraphy of the Newark rift basin consists of the Stockton, Lockatong, and Passaic formations of Late Triassic age and the overlying basalts and interbedded sedimentary rocks of latest Triassic to Early Jurassic age (i.e., the Orange Mountain Basalt, Feltville Formation, Preakness Basalt, Towaco Formation, Hook Mountain Basalt, and Boonton Formation) (e.g., Olsen et al. 1996a; Fig. 3). Most syn-rift strata accumulated in a lacustrine setting and exhibit a pervasive cyclicity in sediment fabrics, color, and total organic carbon (from microlaminated black shale to extensively mudcracked and bioturbated red mudstone) (e.g., Olsen, 1986, Olsen et al., 1996a). We will see evidence of these sedimentary features at Stops 2, 3 and 4. Individual members of the stratigraphic units have great lateral extent and continuity and have been traced throughout much of the Newark basin (e.g., McLaughlin, 1948; Olsen, 1988); a prominent example is the Perkasie Member of the Passaic Formation (Fig. 2) (Stop 4). Biostratigraphy indicates that the preserved syn-rift strata in the Newark basin range in age from Carnian (Late Triassic) to Hettangian (Early Jurassic) (e.g., Cornet and Olsen, 1985; Olsen et al., 2011). Igneous rocks (e.g., basaltic lava flows, diabase sheets, and dikes) in the Newark basin are associated with the Central Atlantic Magmatic Province (CAMP), one of the world’s largest igneous provinces (e.g., McHone, 1996, 2000; Marzolli et al., 1999; Hames et al., 2003) (Fig. 4). CAMP-related igneous activity occurred during the very latest Triassic and earliest Jurassic (~200 Ma) (see Olsen et al., 2003, 2011 and references therein). We discuss additional aspects of CAMP at Stop 3.
Structure and tectonic evolution of Newark rift basin

A series of NE-striking, SE-dipping, right-stepping faults bound the Newark basin on the northwest (Fig. 5a). The bounding faults are subparallel to thrust faults present in pre-rift rocks surrounding the basin. Several large intrabasin faults also dissect the basin. Most syn-rift strata dip 10 - 15° NW toward the border-fault zone. Near many of the border and intrabasin faults, however, the syn-rift strata are warped into a series of anticlines and synclines whose axes are mostly perpendicular to the adjacent faults (i.e., transverse folds; e.g., Wheeler 1939; Schlische 1992, 1995). The Newark basin, like many other rift basins of the eastern North American rift system, underwent significant post-rift deformation including much of the tilting and folding of the syn-rift strata (e.g., Sanders, 1963; Faill, 1973, 1988; Withjack et al., 1998; Schlische et al., 2003; Withjack et al., 2010). Furthermore, the basin underwent significant erosion (locally more than 6 km) after rifting (e.g., Steckler et al., 1993; Malinconico, 2010; Withjack et al., 2012b).

Seismic line NB-1, located near the route of this field trip, images the subsurface geometry of the Newark basin. The seismic line shows that a major SE-dipping fault zone with normal separation bounds the basin on the northwest (Fig. 5b). The fault zone, characterized by a series of high-amplitude reflections, is relatively planar and has a dip magnitude of ~ 30°. Using core data, Ratcliffe et al. (1986) demonstrated that this fault zone is a mylonitic Paleozoic thrust fault reactivated during rifting; this is consistent with the relatively low-angle dip of the border fault. The seismic data show that the syn-rift strata dip ~10 - 15° toward the northwest. Furthermore, the Stockton Formation (exposed at the surface) and an unexposed older unit (which onlaps Paleozoic pre-rift strata) thicken toward the border-fault zone, indicating that faulting and deposition were coeval (i.e., these units are growth deposits). Field and core data indicate that the Lockatong and Passaic formations also exhibit subtle thickening toward the border-fault zone. Furthermore, all sedimentary formations contain conglomeratic facies where present adjacent to the border-fault zone (see material for Stop 4).

As the Newark rift basin developed from Late Triassic to Early Jurassic time, its geometry changed substantially (Fig. 6; Withjack et al., 2012b). Initially, the basin was narrow (< 25 km) and asymmetric, bounded on one side by a border-fault zone. The older syn-rift strata show significant thickening toward the fault zone. As rifting progressed, the basin, although still fault-bounded, became much wider (possibly > 100 km), deeper (up to 10 km), and less asymmetric; syn-rift strata exhibit subtle thickening toward the border-fault zone. Subsequent post-rift deformation and erosion (up to 6 km) significantly reduced the size of the Newark basin.
Fig. 1: Tectonic setting of the Mesozoic eastern North American rift system showing the main segments of the rift system (southern, central, and northern). The geometry of the offshore rift basins and those below the post-rift coastal plain is schematic. The boundary between the southern and central segments is diffuse; the boundary between the central and northern segments corresponds to the Newfoundland fracture zone and the large fault zone that bounds the Fundy basin on the north. Modified from Withjack & Schlische (2005). Inset shows rift zone within the Pangean supercontinent (modified from Olsen 1997).
Fig. 2. Geologic map of the Newark rift basin showing distribution of sedimentary formations, lava flows, and diabase intrusions; locations of borehole and core sites; and seismic-line NB-1. Only the largest Paleozoic contractional faults are shown. Box shows area of field-trip stops. Modified from Withjack et al. (2012b) based on Schlische (1992), Olsen et al. (1996a), and Schlische & Withjack (2005a).
Fig. 3. Stratigraphy of the Newark basin.
The lithologic column is a composite section based on seven Newark Basin Coring Project cores (see geologic map for locations) and several cores from the Army Corps of Engineers (ACE). For the core-based magnetic-polarity stratigraphy (Kent et al., 1995), black represents normal polarity. In all cored sections, all sedimentary formations (with the exception of parts of the Stockton Formation) are lacustrine, and exhibit a pervasive cyclicity related to lake-depth fluctuations (black is deepest water, red is shallowest). Based on global correlations, the Triassic-Jurassic boundary is currently placed in the lower Felville Formation. Previously, it was placed just below the Orange Mountain Basalt, coincident with the level of the end-Triassic mass extinction (see Olsen et al., 2011 for a full discussion). The geologic ages are based on radiometric dates of the lava flows coupled with Milankovitch cyclostratigraphy. Modified from Withjack et al. (2012b) based on Olsen et al. (1996a, 2011), and Olsen and Whiteside (2008).
**Fig. 4a. Map of Early Jurassic diabase dikes in eastern North America.** Dikes in the north trend NE-SW, and were intruded during syn-rift extension. Dikes in the south trend NW-SE and N-S, cut across many rift basins, and likely post-date syn-rift extension. Modified from Withjack & Schlische (2005) based on McHone (2000) and McHone et al. (2004).

**Fig. 4b. Map of the distribution of CAMP intrusive and extrusive rocks in North America, South America, Africa, Iberia and Europe plotted on a Pangea reconstruction.** Abbreviations are: A=Argana basin; BP=Blake Plateau; C=Culpeper basin; CHA=Central High Atlas; D=Deerfield basin; F=Fundy basin; H=Hartford basin; N=Newark basin. Modified from McHone (2000) and Whiteside et al. (2007).
Fig. 5a. Simplified geologic map of Newark basin showing location of seismic line NB-1 and highlighting folds adjacent to the border-fault system and intrabasinal faults. Modified from Withjack et al. (2012b).

Fig. 5b. Interpretation of seismic line NB-1 from Newark basin. Modified from Withjack et al. (2012b).
Fig. 6. Restoration of the Newark basin, showing the progressive widening of the basin during rift- ing. See Figure 3b for basin geometry after post-rift deformation and erosion. From Withjack et al. (2012b).
ROAD LOG and STOPS (see Figs. 7 and 8)

**START. Hyatt Morristown, 3 Speedwell Ave., Morristown, NJ 07960.** The hotel is located adjacent to the Ramapo border fault of the Newark basin, which separates Early Jurassic syn-rift rocks from Proterozoic pre-rift rocks. The border fault is marked by a fault-line scarp visible on shaded-relief maps.

<table>
<thead>
<tr>
<th>Road log to Stop 1. Travel time: ~1 hour, 8 minutes</th>
<th>Go…</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Head south on Speedwell Avenue</td>
<td>0.2 mi</td>
<td>0.2 mi</td>
</tr>
<tr>
<td>2. Turn left onto County Road 510</td>
<td>0.8 mi</td>
<td>1.0 mi</td>
</tr>
<tr>
<td>3. Slight left onto Madison Avenue</td>
<td>0.1 mi</td>
<td>1.1 mi</td>
</tr>
<tr>
<td>4. Slight right to merge onto I-287 South</td>
<td>14.4 mi</td>
<td>15.5 mi</td>
</tr>
<tr>
<td>5. Take exit 21B to merge onto I-78 W toward Easton, PA</td>
<td>18.9 mi</td>
<td>34.5 mi</td>
</tr>
<tr>
<td>6. Take the exit for NJ-173W, bear left at end of ramp for NJ-173W</td>
<td>0.2 mi</td>
<td>34.7 mi</td>
</tr>
<tr>
<td>7. At traffic circle, take 2nd exit onto Pattenburg Road / County Road 614. We are now traveling southwest, parallel to the border fault located &lt;1 km to the NW.</td>
<td>4.1 mi</td>
<td>39.8 mi</td>
</tr>
<tr>
<td>8. Turn left onto Route 631 / Little York Mt. Pleasant Road which becomes Spring Mills Road</td>
<td>0.4 mi</td>
<td>40.2 mi</td>
</tr>
<tr>
<td>9. Bear right onto County Road 614 / Spring Mills Road</td>
<td>2.3 mi</td>
<td>42.5 mi</td>
</tr>
<tr>
<td>10. Turn left onto County Road 519 / Milford Warren Glen Road</td>
<td>2.3 mi</td>
<td>44.8 mi</td>
</tr>
<tr>
<td>11. Turn right on Bridge Street and cross Delaware River</td>
<td>0.3 mi</td>
<td>45.1 mi</td>
</tr>
<tr>
<td>12. Turn right onto PA-32 North / River Road</td>
<td>4.5 mi</td>
<td>49.6 mi</td>
</tr>
<tr>
<td>13. Turn right on PA-611 North / Easton Road / River Road. Lehnenberg Road marks the location of the border fault. After passing Route 212 (Durham Road), continue 0.2 miles to parking area for Delaware Canal (gas station is just north of parking area). Walk south along the canal path to view the outcrop.</td>
<td>2.0 mi</td>
<td>51.6 mi</td>
</tr>
</tbody>
</table>

**Stop 1: Pre-rift rocks (Cambrian carbonates), Route 611, Durham Furnace, PA**

Outcrop-scale folding affects the Cambrian carbonate sedimentary rocks at Stop 1 (Fig. 9). The lithology and sedimentary features (i.e., mudcracks) indicate that the rocks were deposited in shallow marine conditions, likely associated with an early Paleozoic passive margin. Anticlines and synclines with steeply dipping and overturned limbs are present. Cleavage is widely spaced and converging downward in the massive competent units and closely spaced and diverging downward in the less competent units. This deformation is related to shortening produced during one or more of the Appalachian orogenies that preceded rifting.

Stop 1 is within the footwall of the Newark rift basin about 2 km to the NW of the NE-striking, SE-dipping border fault of the basin. As we proceed to Stop 2, we will travel from the footwall into the hanging wall of the Newark rift basin, crossing the basin-border fault (Fig. 10). Seismic data (NB-1, Fig. 5b) together with core data (Ratcliffe et al., 1986) show that the border fault of the Mesozoic Newark rift basin dips ~25 to 30° to the SE and parallels Paleozoic thrust faults.
The anomalously gentle dip of the basin-border fault and its orientation relative to that of the adjacent Paleozoic thrust faults suggest that it is a reactivated pre-existing structure. Restorations (Fig. 6) show that the border fault of the Newark rift basin had more than 10 km of displacement during rifting from Late Triassic to earliest Jurassic time.

### Road log to Stop 2. Travel time: ~4 minutes

<table>
<thead>
<tr>
<th>Go…</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>3.1 mi</td>
<td>3.1 mi</td>
</tr>
</tbody>
</table>

14. Turn around and head south on Route 611. After ~2.0 miles, bear right to stay on PA-611 South. After passing Traugers Crossing Road, pull off onto the wide shoulder on the right. Large exposure is on the left (northbound side) of road. Be careful crossing the road.

### Stop 2: Normal Faults in Passaic Formation, Route 611, Kintnersville, PA

A set of meter-scale normal faults (Fig. 11) cuts red mudstone of the middle Passaic Formation. The normal faults strike ~030° and generally dip 40°-50° SE. Slickenlines are steeply raking, indicating predominantly dip-slip movement. Like most of the larger intrabasinal faults in the Newark rift basin, these small faults are oblique to the strike of segments of the border-fault zone (the strike of the nearest segment of the border-fault zone is ~060°). This fault pattern is indicative of oblique extension (e.g., Schlische et al., 2002), i.e., the extension direction was not perpendicular to the strike of the border-fault zone. The geometry of the intrabasinal faults and the strike of the earliest Jurassic CAMP-related diabase dikes suggest that the extension direction was WNW-ESE.

Fault 2 has the smallest displacement and narrowest zone of breccia and gouge; fault 4 has the largest displacement and widest zone of breccia and gouge. These faults obey an approximately linear scaling relationship between fault-zone thickness and fault displacement (e.g., Hull, 1988; Knott, 1994; Knott et al., 1996; Fig. 11d). The sequence going from fault 2 to 3 to 1 to 4 likely reflects stages in the evolution of normal faults with increasing displacement; this involves the linkage of originally isolated segments and the widening of the fault zone.

According to Withjack and Olsen (1999), the exposure belongs to the upper part of Member K of the Passaic Formation (nomenclature of Olsen et al., 1996a). Deposition occurred mostly in playas. A prominent bed contains vugs that were once filled with evaporite minerals. Silt bands likely represent slightly deeper or more permanent shallow lakes. Red beds similar to those outcropping here account for more than 80% of the Passaic Formation.

Although this outcrop is only about 3 km from the border fault, the sedimentary rocks are remarkably fine grained. Two possibilities account for this observation: (1) The hanging-wall block and axial sources contributed more sediment than the footwall block (Fig. 12a), as in many modern rift basins (e.g., Gawthorpe and Leeder, 2000). (2) The present-day border fault of the basin was not the outermost border fault during deposition (Fig. 12b). In Late Triassic time, coarser sediments accumulated in the hanging walls of border faults located to the NW of the present-day border fault. Subsequent erosion removed these coarse-grained strata and exposed the Paleozoic and Precambrian rocks. Vitrinite reflectance data indicate that 4 - 6 km of erosion
occurred in the vicinity of this outcrop (Steckler et al., 1993; Malinconico, 2010; Withjack et al., 2012b; Fig. 12c).

Road log to Stop 3. Travel time: ~11 minutes

<table>
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<tr>
<th>Step</th>
<th>Description</th>
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</tr>
</thead>
<tbody>
<tr>
<td>15.</td>
<td>Continue south on PA-611</td>
<td>0.7 mi</td>
<td>0.7 mi</td>
</tr>
<tr>
<td>16.</td>
<td>Turn left (at traffic light) onto Center Hill Road</td>
<td>3.2 mi</td>
<td>3.9 mi</td>
</tr>
<tr>
<td>17.</td>
<td>Turn right on Ringing Rocks Road. Entrance to Ringing Rocks park is on the left. Follow the trail on foot to the boulder field. Then continue down trail to the waterfall.</td>
<td>0.6 mi</td>
<td>4.5 mi</td>
</tr>
</tbody>
</table>

Stop 3: Ringing Rocks County Park, Upper Black Eddy, PA (Fig. 13)

The boulder field in Ringing Rocks County Park contains rocks of the Coffman Hill diabase (dolerite). The boulders exposed to abundant sunlight do “ring” when struck with a hammer! The Coffman Hill diabase is the erosional remnant of a folded intrusive sheet. The geologic map (Figs. 2 and 8) shows that strata consistently dip toward the diabase, indicating that the diabase sheet and intruded strata define a doubly-plunging syncline (or basin). Contact metamorphic rocks of the Passaic Formation underlying the intrusive sheet are exposed at the waterfall (at the end of the hiking trail). These gray rocks are relatively fine-grained (mostly mudstone with some sandstone). Mudcracks and ripple marks suggest that these strata accumulated in very shallow lakes. Although gray rocks are typically associated with deeper-water deposits, in this case, the gray color results from contact metamorphism. The hornfels contains well-developed subvertical joints.

The Newark rift basin contains many other diabase sheets (Fig. 2), many of which, like the Coffman Hill diabase, are folded adjacent to the border-fault system. The most famous intrusion is the Palisades sill. At its northern termination, the Palisades intrusion becomes dike-like and feeds one of the lava flows (Ratcliffe, 1988). The Newark basin also contains three extrusive formations (Orange Mountain Basalt, Preakness Basalt, Hook Mountain Basalt), each consisting of multiple flow units (Fig. 14a). Although each basalt formation has a distinct geochemistry, all extrusive (and intrusive) rocks are quartz-normative tholeiites (Fig. 14c). Cyclical lacustrine strata with Milankovitch periodicities preceding, interbedded with, and succeeding the extrusive formations indicate that extrusive activity occurred in less than 600,000 years (Olsen et al., 1996b, 2003). This duration likely applies to other Mesozoic rift basins in eastern North America because these basins contain basalts with the same geochemistry as those in the Newark basin (Fig. 14c). As noted in the introduction, radiometric dates indicate that all igneous activity (intrusive and extrusive) occurred at ~200 Ma (see Olsen et al., 2011, and references therein).

Latest Triassic/earliest Jurassic igneous activity occurred throughout eastern North America. Diabase dikes are present from the southeastern United States to maritime Canada (Fig. 4a) (e.g., May, 1971; McHone, 2000). Most dikes in the southeastern U.S. strike NW-SE and N-S, and cut across the rift basins. In the northeastern U.S. and maritime Canada, the dikes generally strike NE-SW, and were intruded while lava flows accumulated in the actively subsiding rift basins (e.g., Schlische et al., 2003). These intrusive and extrusive rocks in eastern North America are
part of a vast igneous province (>10,000,000 km$^2$; Marzolli et al., 1999; McHone, 2000, 2003), known as the Central Atlantic Magmatic Province (CAMP), that also covers parts of South America, Africa, and Europe (Fig. 4b).

Seaward-dipping reflections (SDRs) are present at the continent-ocean boundary of eastern North America from the southeastern U.S. to southeastern Nova Scotia, Canada. They are, however, absent for the remainder of maritime Canada. The SDRs likely represent a volcanic and/or volcanoclastic wedge at the continent-ocean boundary (and account for the East Coast Magnetic Anomaly) (Fig. 1). It is unclear whether the SDRs are associated with CAMP or a second pulse of igneous activity (for a full discussion, see Schlische et al., 2003). Although the southeastern part of the ENAM continental margin is magma-rich (i.e., SDRs are present) and the northwestern part is magma-poor (i.e., SDRs are absent), CAMP-related igneous rocks are present along the entire ENAM continental margin. For example, the northwestern Scotian and Newfoundland segments of the ENAM margin lack SDRs, but the Fundy, Orpheus, and Jeanne d’Arc rift basins all contain CAMP-related intrusive sheets and/or basalt flows (e.g., Olsen, 1997; Withjack and Schlische, 2005; Withjack et al., 2012a).

<table>
<thead>
<tr>
<th>Road log to Stop 4. Travel time: ~10 minutes</th>
<th>Go...</th>
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</thead>
<tbody>
<tr>
<td>18. Exit the park and turn left onto Ringing Rocks Road</td>
<td>0.5 mi</td>
<td>0.5 mi</td>
</tr>
<tr>
<td>19. Turn left onto Bridgeton Hill Road</td>
<td>1.5 mi</td>
<td>2.0 mi</td>
</tr>
<tr>
<td>20. Turn right onto PA-32 / River Road.</td>
<td>0.2 mi</td>
<td>2.2 mi</td>
</tr>
<tr>
<td>21. Turn left onto River Road and take bridge over Delaware River to Milford, NJ</td>
<td>0.2 mi</td>
<td>2.4 mi</td>
</tr>
<tr>
<td>23. Turn left onto Church Street</td>
<td>&lt;0.1 mi</td>
<td>2.5 mi</td>
</tr>
<tr>
<td>24. Turn left to stay on Church Street</td>
<td>&lt;0.1 mi</td>
<td>2.5 mi</td>
</tr>
<tr>
<td>25. Take first right onto Spring Garden Street which becomes / County Road 627. After ~1.25 miles, you will pass the junction with Spring Garden Road. After this, look for railroad mile marker 37, and park in the large pull-out on the right. Proceed to the main outcrop by walking west along the unused railroad tracks.</td>
<td>~1.8 mi</td>
<td>4.3 mi</td>
</tr>
</tbody>
</table>

**STOP 4: Perkasie Member of Passaic Formation at Pebble Bluff near Milford, NJ**

These outcrops consist of thick sequences of red conglomerate and sandstone alternating with cyclical black, gray, and red mudstone and sandstone of the Perkasie Member of the Passaic Formation (Fig. 15a). Depositional environments ranged from deep perennial lakes (black shales) to debris-flow deposits of alluvial fans (red poorly sorted conglomerate) (Olsen et al., 1989). The sequence of strata above the 12-m-mark in Figure 15a represents the progressive flooding of the distal toes of an alluvial fan during rising lake levels, followed by lake highstand and regression.

Individual lake-level (Milankovitch) cycles (see Fig. 16a) of the Perkasie Member in this area average 7 m thick, as compared with a mean of 4.4 m at New Brunswick, NJ, and Pottstown, PA, and 5.3 m in the Titusville core (Fig. 15b; Olsen et al., 1996a). These thickness trends (Fig. 16b)
show that subsidence rates increased from the hinged margin of the basin toward the border-fault zone as well as from the lateral edges toward the center of the basin (Schlische, 1992).

<table>
<thead>
<tr>
<th>Road log to Morristown Hyatt.</th>
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<th>Go...</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>26. Head west on County Road 627.</td>
<td></td>
<td>1.1 mi</td>
<td>1.1 mi</td>
</tr>
<tr>
<td>27. Turn right onto Crabapple Hill Road</td>
<td></td>
<td>1.0 mi</td>
<td>2.1 mi</td>
</tr>
<tr>
<td>28. Turn right onto Church Road</td>
<td></td>
<td>2.4 mi</td>
<td>4.5 mi</td>
</tr>
<tr>
<td>29. Turn right onto Milford Warren Glen Road / County Road 519</td>
<td></td>
<td>&lt;0.1 mi</td>
<td>4.5 mi</td>
</tr>
<tr>
<td>30. Turn left onto Spring Mills Road / County Road 614</td>
<td></td>
<td>2.5 mi</td>
<td>7.0 mi</td>
</tr>
<tr>
<td>31. Continue onto Little York Mt. Pleasant Road / Route 631 / Route 614</td>
<td></td>
<td>0.2 mi</td>
<td>7.2 mi</td>
</tr>
<tr>
<td>32. Turn right onto Little York Pattenburg Road / County Road 614</td>
<td></td>
<td>4.9 mi</td>
<td>12.1 mi</td>
</tr>
<tr>
<td>33. Turn right onto Baptist Church Road (following signs for I-78)</td>
<td></td>
<td>0.1 mi</td>
<td>12.2 mi</td>
</tr>
<tr>
<td>34. Turn left to merge onto I-78 East</td>
<td></td>
<td>18.2 mi</td>
<td>30.4 mi</td>
</tr>
<tr>
<td>35. Take Exit 29 for I-287 toward US-202 / 206 / I-80 / Morristown / Somerville</td>
<td></td>
<td>0.6 mi</td>
<td>32.0 mi</td>
</tr>
<tr>
<td>36. Keep left at the fork and merge onto I-287 North. We will pass outcrops of Preakness Basalt containing columnar jointing.</td>
<td></td>
<td>15.8 mi</td>
<td>46.8 mi</td>
</tr>
<tr>
<td>37. Take exit 36B for County Rt 510 / Lafayette Avenue</td>
<td></td>
<td>0.2 mi</td>
<td>47.0 mi</td>
</tr>
<tr>
<td>38. Merge onto County Rt 510 / Lafayette Avenue</td>
<td></td>
<td>0.5 mi</td>
<td>47.5 mi</td>
</tr>
<tr>
<td>39. Turn right onto Morris Street</td>
<td></td>
<td>0.2 mi</td>
<td>47.7 mi</td>
</tr>
<tr>
<td>40. Take the 2nd right onto E Park Place</td>
<td></td>
<td>&lt;0.1 mi</td>
<td>47.8 mi</td>
</tr>
<tr>
<td>41. Continue straight onto Speedwell Avenue. Hotel is on right.</td>
<td></td>
<td>0.2 mi</td>
<td>47.9 mi</td>
</tr>
</tbody>
</table>

References


Ratcliffé, N.M., Burton, W.C., D’Angelo, R.M., Costain, J.K. 1986. Low-angle extensional faulting, reactivated mylonites, and seismic reflection geometry of the Newark basin margin in eastern Pennsylvania. Geology, 14, 766-770.

Sanders, J.E. 1963. Late Triassic tectonic history of northeastern United States. American Journal of Science, 261,
501-524.
**Fig. 7a.** Shaded-relief map of Newark basin and surrounding areas. Red box shows area detailed in (b). CP, Coastal Plain; DR, Delaware River; DWG, Delaware Water Gap; NB, Newark basin; NJH, New Jersey Highlands; NYC, New York City; PS, Palisades sill; RF, Ramapo border fault; VR, Valley & Ridge; WM, Watchung Mountains (lava flows). Assembled from 1/3 arc-second NED CONUS digital elevation model available from http://nmviewogc.cr.usgs.gov/viewer.htm.

**Fig. 7b.** Shaded-relief map showing location of field-trip stops (stars) and Morristown Hyatt (circled H).

**Fig. 7c.** Parts of the U.S.G.S. Allentown and Reading 15" topographic maps showing field-trip stops (stars).
Fig. 8. Geologic map of part of the Newark 1°x2° quadrangle, showing the northwestern Newark basin and adjacent prerift strata and basement in the vicinity of the Delaware River. Stars give field-stop locations. Map is from Lyttle & Epstein (1987). Note that the geology of the Lockatong and Passaic formations differs slightly from other versions in this guidebook, which reflect updated mapping utilizing the results of the Newark Basin Coring Project.
1.1. Age of stratigraphic unit: Cambrian

1.2. Distance from basin-bounding fault: 1-2.5 km (FW)

1.3. Description of sedimentary features:
Carbonate sedimentary rocks with mudcracks; shallow marine conditions

1.4. Description of structural features and tectonic environment:
Anticlines and synclines with steeply dipping and overturned limbs; cleavage is widely spaced and converging downward in massive competent unit; closely spaced and diverging downward in less competent units; related to shortening produced during Appalachian orogenies

Fig. 9. a. Photo of outcrop-scale fold in the Cambrian Leithsville Formation at Stop 1. Photo by Roy Schlisce. b. Interpretation of photo in (a); bedding is red; cleavage is yellow. c. Close-up photo of anticline with interpreted bedding and cleavage. Photo by James Grieshaber.
1.5. Age of stratigraphic units: Late Triassic
1.6. Distance from border fault: <0.1 km (HW)
1.7. Apparent dip angle & direction of bedding: 15-20°N
1.8. Description of sedimentary features &
depositional environments: Cyclical black, gray, and red
clastic sedimentary rocks; fine to very coarse grained
(conglomerates); deep- and shallow-water lakes; alluvial fans
1.9. Description of structural features &
tectonic environment: Border fault of Newark basin;
fault dips gently about 25-30° to the SE and parallels
Paleozoic thrust fault zone; structures related to
ripping and extension

Fig. 10. Aspects of the border-fault region at
Monroe, PA. a. Outcrop photo by James
Grieshaber. b. Exposed section showing cyclical
black, gray, and red clastic sedimentary
rocks. c. Geologic cross section based on core
data (after Ratcliffe et al., 1986).
2.1. Age of stratigraphic units: Late Triassic (Passaic Formation, Member K)
2.2. Distance from border fault: 3-4 km (HW)
2.3. Apparent dip angle & direction of bedding: ~5-10° N
2.4. Description of sedimentary features & depositional environments:
   Red, mostly massive mudstone with evaporites; very shallow-water
   lake deposits
2.5. Description of structural features & tectonic environment:
   NNE-striking, SE-dipping normal faults produced by extension; multiple
   joint sets with plumose markings

Fig. 11. a. Sketch of outcrop cut by multiple normal faults with variable displacements. b. Photo of fault 1 by Roy Schlische; Alissa
   Henza and Martha Withjack for scale. c. Hypothesized evolution of normal faults in cross section, showing the linkage of originally
   isolated segments and widening of the fault zone. d. Log-log plot of fault displacement versus fault-zone thickness (breccia and
gouge) for faults 2, 3, 1, and 4; the data are comparable to other measurements for faults cutting sedimentary rocks. Modified from
Schlische & Withjack (2005b).
**Fig. 12a. Inferred topography and fluvial inputs for a rift basin crudely similar to the Newark basin.**
Most of the footwall slopes away from the basin; most of the hanging wall slopes toward the basin. Consequently, direct sediment input from the footwall is limited (except at relay ramps between overlapping fault segments). This may account, in part, for the relatively fine-grained strata adjacent to the border-fault system. Modified from Schlische & Withjack (2005a).

**Fig. 12b. Schematic cross sections showing border-fault development during deposition.** (i) Model with multiple active faults. Coarse-grained sediments preferentially accumulate in hanging walls of outer border fault. Later erosion removed these sedimentary rocks. (ii) Model with basinward migration of border faults. During the early stages of rifting, the outer border fault was active, and coarse-grained sediments accumulated in its hanging wall. During the later stages of rifting, the inner border fault became active, and coarse-grained sediments accumulated in its hanging wall. Later erosion removed the coarse-grained sedimentary rocks. Thus, the present-day edge of the basin has shifted basinward from its position during deposition of the Passaic Formation. Modified from Schlische & Withjack (2005b).

**Fig. 12c. Estimated amount of post-rift erosion for transect along seismic line NB-1.** Red bars show eroded syn-rift section predicted by vitrinite-reflectance analysis; grey area shows potential error (±30%). The magnitude of erosion varies from 4 to 6 km. Vitrinite-reflectance data are from Malinconico (2010); figure is modified from Withjack et al. (2012b).
Stop 3: Ringing Rocks County Park, Upper Black Eddy, PA (N40°33.639' / W75°07.735')
3.1. Distance from border fault: 3-5 km (HW)

Part A: Boulder field; boulders composed of Coffman Hill diabase
3.2. Origin and likely age of source of boulders: Intrusive sheet of diabase of latest Triassic / Early Jurassic age (~201 Ma) (Coffman Hill diabase)
3.3. 3D geometry of diabase body: Folded sheet; sedimentary layers surrounding intrusion define a doubly plunging syncline.

Part B: Waterfall
3.4. Type of rock(s) present: Thermally metamorphosed rocks of Passaic Formation below diabase sheet; gray color regardless of composition; ripple marks and mudcracks are original sedimentary structures.
3.5. Strike and dip of fractures: Common strikes are 270° and 350°. The dip angle is steep (70-90°). The fractures are joints because there is no obvious shear offset across the fractures. Fractures in hornfels in Newark basin tend to be more closely spaced than in unmetamorphosed strata.

Fig. 13. Ringing Rocks County Park. a. Photo of waterfall; strata have undergone contact metamorphism from the overlying diabase sheet. b. Photo of boulder field; boulders consist of weathered diabase. Photos by James Grieshaber.
**Fig. 14a.** Stratigraphy of extrusive interval in the northern Newark basin based on the Martinsville and Army Corps of Engineers (ACE) cores. Cyclostratigraphy of lake deposits in sedimentary strata constrains the duration of the extrusive interval to approximately 600,000 years. Modified from Olsen et al. (1996b) and Whiteside et al. (2007).

**Fig. 14b.** Contact between Orange Mountain Basalt and underlying Passaic Fm. in quarry in West Paterson, NJ. Photo by Roy Schlische.

**Fig. 14c.** Correlation and geochemistry of extrusive rocks in various Triassic-Jurassic rift basins in eastern North America. Abbreviations for basalt geochemistry are: HTQ = high-titanium quartz-normative; HFQ = high-iron quartz-normative; LTQ = low-titanium quartz-normative; HFTQ = high-iron & titanium quartz-normative basalt. Modified from Schlische et al. (2003) based on Olsen (1997).
**Fig. 15a. Strata at Pebble Bluff:** LEFT: Measured section of lacustrine deposits interbedded with alluvial-fan deposits. Modified from Olsen et al. (1989). RIGHT: Photo of conglomerate by Martha Withjack.

- Gray well-sorted sandstone with tilted surfaces (shoreline)
- Black and gray laminated claystone and siltstone (deep lake)
- Gray well-sorted sandstone and gravel (shoreline)
- Red well-sorted sandstone with carbonate nodules (fluvial with wave reworking and soil formation)
- Red well-sorted conglomerate
- Red poorly sorted conglomerate (debris flow)

**Stop 4 (Optional): Pebble Bluff, near Milford, NJ**

4.1. Age of stratigraphic units: Late Triassic (Passaic Formation, Perkasie Member)

4.2. Distance from border fault: ~2 km (HW)

4.3. Description of sedimentary features & depositional environments: Mudstone, sandstone, and conglomerates

**Fig. 15b.** Measured sections of the Perkasie Member of the Passaic Formation from across the Newark basin. The sections generally thicken and coarsen toward the border-fault system and thin toward the lateral edges of the basin. Modified from Olsen et al. (1996a).
Fig. 16a. Hierarchy of Milankovitch lake-level cycles in the Passaic Formation. Depth rank uses color and sediment fabrics (left) to estimate relative water depth. Modified from Olsen et al. (1996a) and Olsen and Kent (1996).

Fig. 16b. Percent-change in thickness between correlative units of adjacent NBCP cores. Units generally thicken toward the center of the basin and toward the border-fault system. Modified from Schlische (2003) based on data in Olsen et al. (1996a).

Fig. 16c. Core-to-outcrop correlation of the two members of the Lockatong Formation. The units thicken subtly toward the border fault. A slope of <0.5° accounts for the differential thickening. Modified from Withjack et al. (2012b) based on Olsen et al. (1996a).