Basin Inversion in the Newark Basin Using Data From the Borehole Televiewer

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Abstract
Basin inversion occurs when a rift basin undergoes initial extension followed by shortening. Shortening and extension are believed to have the same principal axis of deformation. The later shortening phase of deformation is believed to result when ridge-push forces are activated, as the basin makes the transition from a rift to a drift (Withjack, et al., 1995). Data from a well-logging tool, the Borehole Televiewer (BHTV), was used to interpret the tectonic history of the Newark basin. The BHTV data indicates that basin inversion may have played a significant role in how the basin developed.

Introduction
During the early Mesozoic period, (Late Triassic-Early Jurassic), large-scale northwest-southeast (NW-SE), passive continental-margin rifting along the eastern seaboard of North America was associated with the break-up of the super-continent, Pangea (Corret, 1977). A modern analog of this form of rifting would be the East African rift.

The focus of this study is one of the largest of these rifts, the Newark rift basin (see Figure 1). Because the Newark basin’s rocks are well exposed, and the basin is conveniently located near most of the major universities on the east coast, it has been studied in great detail for over 130 years. Redfield (1856) provides an early study of the Newark basin.

Typically, extensional forces cause normal faults to form two opposing bounding faults. These bounding faults contain within them a down-dropped portion of the earth's crust called a "graben." The Newark rift basin, on the other hand, has a half-graben geometry because it is bounded by a fault on only one side. This series of major, normal faults in the Newark basin is oriented northwest and allows the rock units to drop in a hinge-like manner, with the units closest to the bounding fault having the greatest amount of displacement. These bounding faults are believed to be reactivated Paleozoic thrust faults.

The stratigraphy of Newark basin is dominated by five formations (see Figure 2). The Stockton formation consists of yellow-brown and red conglomerates, arkose, and sandstone units. These coarse-grained units are indicative of a fluvial environment, due to the high energy needed to erode, transport, and deposit the larger clasts in the rock units. These fluvial units are believed to have been deposited during the early phases of rifting.

The Lockatong formation, which consists of mostly gray mudstone, are believed to be deep, lacustrine sediments due to the low energy necessary for deposits and sedimentary structures found in the mudstones.

The Passaic formation, which is dominated by red and gray mudstone and sandstone, is interpreted to be a continuation of lacustrine sediments that grade into a more fluvial-dominated stratigraphy. The Orange Mountain basalt is an Early Jurassic sill, and the uppermost unit is the Feltville formation. These sedimentary units are believed to have been deposited syn-depositionally as the basin widened from rifting. The Lockatong and the upper part of the Passaic formation would have been deposited when the basin was hydrologically closed (meaning that the primary input/output components of the water budget were precipitation and evaporation, respectively). These formations were determined to be useful for studying climate cycles during the Early Mesozoic because they were deposited when the basin was hydrologically closed.
Newark Basin Coring Project

During an eight-month period in 1990–1991 and two months in early 1993, a grant from the National Science Foundation was presented to Paul E. Olsen of Lamont-Doherty Earth Observatory and Dennis V. Kent of Rutgers University to continuously core the entire stratigraphic sequence of the Newark basin. The eroded, half-graben geometry of the Newark basin allowed the cores to be collected by a method called offset drilling.

Offset drilling is a technique used when rock units are uplifted and steeply dipping. Geologically, a traverse of a basin with this type of geometry (half-graben) results in the youngest units positioned at one end of the basin, and the oldest units at the other end of the basin. With offset drilling, several shallow holes drilled across this traverse of the basin allows the entire stratigraphic sequence of the basin to be recovered.

The alternative to offset drilling is drilling one deep well to recover core for the entire stratigraphic sequence. This is much more expensive than offset drilling. These passive, continental-rift basins are abundant with igneous intrusions and faults. These structures take longer to core, and the faults can jeopardize the hole integrity. Setbacks of this nature mean an increase in costly rig time.

Offset drilling offers more flexibility in choosing drill sites that will cover the entire stratigraphic sequence without drilling into these costly structures. In order to continuously core the entire stratigraphic sequence in the basin, seven sites were needed to make a NW-SE transect of the basin, with the youngest units found in the NW and the oldest units to the SE. These seven sites are: Princeton, Nursery Road, Titusville, Rutgers, Somerset, Weston Canal, and Martinsville (see Figure 3).

Approximately 1000 m of continuous core were retrieved at each of these seven sites, totaling 6770 m of
There followed a Preakness diabase dike, and Jurassic formations names and lithology.

**Figure 2.** Composite section of the Newark Basin Coring Project cores with formation names and lithology.

**Figure 3.** Drill-site locations relative to their depth in the formation.

**NEWARK BASIN DRILLING PROJECT CORES**

<table>
<thead>
<tr>
<th>FORMATION</th>
<th>Main Correlation HORIZONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvale</td>
<td>Ukrainian Member</td>
</tr>
<tr>
<td>Passaic</td>
<td>Metlars Member</td>
</tr>
<tr>
<td>Lockatong</td>
<td>Perkasie Member</td>
</tr>
<tr>
<td>Stockton</td>
<td>Walls Island Member</td>
</tr>
<tr>
<td>Nursery Member</td>
<td>Princeton Member</td>
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</table>

<table>
<thead>
<tr>
<th>FORMATION</th>
<th>MAIN CORRELATION HORIZONS</th>
<th>UnCorrected Depths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvale</td>
<td>Ukrainian Member</td>
<td>1800 ft (55 m)</td>
</tr>
<tr>
<td>Passaic</td>
<td>Metlars Member</td>
<td>1500 ft (45 m)</td>
</tr>
<tr>
<td>Lockatong</td>
<td>Perkasie Member</td>
<td>1200 ft (35 m)</td>
</tr>
<tr>
<td>Stockton</td>
<td>Nursery Member</td>
<td>900 ft (25 m)</td>
</tr>
</tbody>
</table>

As each site was being cored, a string of downhole logging tools collected continuous, remotely sensed data. This data was used to measure a variety of rock and hole properties. Some of these geophysical welllogging tools include: sonic velocity, resistivity, gamma-ray, litho-density, neutron-porosity, caliper, temp/salinity, dip-meter, Borehole Televiewer (BHTV), susceptibility, and temperature logs.

Some of the properties measured by these tools include: density, sonic velocity, in situ temperatures, porosity, clay content, and fracture data. By concatenating the data from these seven holes and making corrections for rock-unit overlap and compaction/decompaction, a composite well log of each well-logging tool can be created to examine the various rock and hole properties of the entire stratigraphic sequence (6770 m total), as opposed to a hole-by-hole analysis of each logging tool used (1000 m each). Initially, the data collected from the Newark Basin Coring Project was used by Olsen and Kent (1995) and Reynolds (1994) to determine sedimentary basin evolution and climatic cycles preserved in the deep water, lacustrine units of the Lockatong and Passaic formations.

Dave Goldberg of Lamont-Doherty Earth Observatory of Columbia University saw promise in using the data collected from the Newark Basin Coring Project to piece together a tectonic history of the Newark basin.

**Research Goals**

After the Borehole research group processed the remotely sensed well-log data from the Newark Basin Coring Project, Goldberg recognized that the data from one of the seven sites drilled in the basin, Martinsville, was completely different from the data in the remaining six holes drilled in the basin.

The current model of the tectonic history of the Newark basin suggests that the basin underwent extension, with the principal axis of extension oriented NW-SE. There followed a long period of quiescence when the rift made the transition to drift (when
oceanic crust is made and a spreading center is established. This NW-SE oriented, principal extensional-stress direction would produce fractures with steep dips oriented NE-SW, or normal to this principal stress direction.

Stereo nets of the BHTV fracture data were plotted by Goldberg to examine fracture orientations and dips, and to try to determine how the data fit the current tectonic model of the basin. The stereo plots of the BHTV fracture data indicated that the six sites farthest away from the NW-SE trending-bounding fault in the basin fit this model perfectly. The fractures from these six holes (Weston Canal, Somerset, Rutgers, Titusville, Nursery Road, and Princeton) were oriented NE-SW and were steeply dipping (see Figure 4). However, the hole closest to the bounding fault, Martinsville, had a completely different character than the other six holes. At Martinsville, the fractures were dominantly shallow dipping, and half the fractures were oriented NW-SE (see Figure 5).

Other features that were unique to the Martinsville hole were an igneous intrusion, and a small reverse fault (Reynolds, 1994). Goldberg wanted to achieve three goals: First, “ground-truth” the BHTV data set to determine its accuracy or resolution; second, use this BHTV data to determine what type of past or current stress helped form the basin; and, finally, use this data to develop a model that would explain why Martinsville was so unique in the Newark basin.

Methods

The primary data set used to interpret the tectonic history of the Newark basin came from a relatively new logging tool, the Borehole Televiewer. The BHTV uses a rotating transmitter/receiver to send an acoustic pulse through the formation as it is being pulled up the hole. The BHTV provides an acoustic “image” derived from the amplitude and travel time of the acoustic signals reflected from the wall of the formation (see Figure 6). This data is useful in determining, among other things, fracture orientation, dip, and aperture. From the processed data, the orientations of the field that existed when these fractures were created during rifting can be inferred.

In order to use the BHTV data with any confidence, it was necessary to ground-truth it by comparing it with a data set that measures the same properties as the BHTV. To do this, a highly accurate second data set was required. The best data available to ground-truth the BHTV data was available from direct observation of the cores themselves. It would be time-consuming and inconvenient to create a data set from 6700 m of 4-inch core. Fortunately, when the core was being recovered it was photographed in 9-foot sections (see Figure 7). The core was marked every foot, so the photos allowed the core to be examined, with dividers, to get fracture locations, dips, apertures (how wide the fractures were open), and whether the fractures were open or closed (some fractures had mineral filling).

The first data set was created using the core photos from the anomalous Martinsville hole, and the second from the hole at Nursery Road. The Nursery Road site was selected because it best represented the BHTV stereo-plot data from the fractures in...
the six holes in the Newark basin that had the expected NE-SW trending, steeply dipping fractures. With these photos, a data set of the depth, aperture, dip, and whether the fracture was open or filled, was obtained and compared to the fracture depth, aperture, and dip obtained from the BHTV. In doing this we could determine the constraints of the BHTV data set by determining the accuracy and resolution of the BHTV.

When the core data sets from Martinsville and Nursery Road were completed, there were twice as many fractures as the BHTV. The core data set for Martinsville and Nursery Road had 3415 and 552 fractures, respectively. The BHTV data set for Martinsville and Nursery Road had 986 and 283 fractures, respectively. It was readily apparent that the BHTV was not "seeing" all of the fractures.

Obviously, the BHTV resolution was not as accurate as direct observations from the core. In order to determine which fractures the BHTV was not seeing, a series of fracture-density plots were created (see Figure 8). Fracture-density plots are essentially histograms of number of fractures vs. depth. In order to determine what elements of the data set were not being seen by the BHTV data set, comparison of these fracture-density plots with the elements measured (fracture dip, location, aperture, and open/filled) were filtered one-by-one. A fracture-density plot of the data set with these mix of elements filtered out correlated well with the fracture-density plot from BHTV data. When a fracture-density plot from the filtered, core data sets correlated with the fracture-density plot of the BHTV data set, we would know what the BHTV couldn't see by what was filtered out of these plots in order for them to correlate. This was done to help establish the limits of the BHTV data set. Correlations between the core data set and the BHTV data set were determined by number of peaks from the fracture-density plot of the filtered core data set compared to the peaks, at the same depth, of the fracture-density plot from the BHTV data set.

**Results**

Because the BHTV is an acoustic imager, we first hypothesized that the filled fractures would have played a crucial role in the resolution of the BHTV. These filled fractures had a much higher density than the open fractures, and we hypothesized that the acoustic pulse from the BHTV would not be able to see the filled fractures.

Surprisingly, the results showed that the BHTV could see open-and-filled fractures equally well. Fracture densities of both data sets, with respect to dip angles, didn't correlate well either. Finally, a fracture-density plot of the core data set with apertures between 3-6 mm correlated very well. It seemed that BHTV was aperture-controlled and, therefore, the wider the fracture was open, the

Figure 8. One of many fracture-density plots used to determine the Borehole Televiewer resolution by trying to correlate the fracture-density plot of the core data set with various apertures filtered out, (left three plots), to the BHTV fracture-density plot.

**Martinsville Fracture Density Composite**

![Figure 8](image-url)
more likely the BHTV would see it.

In order to pin down the minimum aperture at which the BHTV could image a fracture, we set up a proportion that allowed us to determine what aperture would have to be filtered out from the core data set so the number of fractures in the core data set equaled the number of fractures collected from the BHTV data set. An aperture of >=5 mm was calculated as the resolution of the BHTV from this proportion. By ground-truthing the BHTV data, it indicates that there are a significant number of shallow-dipping fractures throughout the basin that may not be imaged by the BHTV. This shortcoming must be taken into account when using the BHTV data set to interpret the tectonic history of the Newark basin.

To test this further, a query of the core data set was done. This query retrieved the fractures from data set with apertures >= 5 mm and with dips <= 45 degrees. This data was plotted next to a plot of all fractures >= 45 degrees, regardless of aperture. The plots were essentially the same. This indicated that most of the fractures in the Nursery Road hole with dips < 45 degrees had apertures of < 5 mm. Because a 5 mm aperture is the lower limit that the BHTV can image, this prevented the BHTV from recognizing these shallow-dipping fractures. This is an indication that Martinsville is not the only hole with shallow-dipping fractures in the basin, as the BHTV initially indicated. In summary, the ground-truthing demonstrated to us that with a resolution of >=5 mm, we could have confidence in the BHTV data as long as we take into account that many of the shallow-dipping fractures in the basin may exist in holes other than Martinsville.

**Discussion**

Ground-truthing the BHTV indicated that the stereo plots made from the BHTV of the Martinsville site did not fit the current model of passive margin, continental rift-basin evolution. Again, the current model suggests that the Newark rift basin underwent extensional stress during Late Triassic through Early Jurassic, followed by tectonic quiescence. The principal extensional stress direction was oriented NW-SE during rifting, and produced steep-dipping fractures oriented NE-SW, or normal, to the paleo-principal, extensional-stress direction of NW-SE. Every hole in the Newark basin except Martinsville had fractures consistent with this model. This model did not explain why the fractures at Martinsville were oriented NW-SE, which is not the usual principal, extensional-stress direction of NW-SE that would have created them. Also, Martinsville was dominated by shallow-dipping fractures, not the steeply dipping fractures normally associated with extensional stress.

A study of the Fundy basin in northeastern Canada (Withjack, et al., 1995) provided some very useful insights as to what may have happened in the Newark basin. The Fundy basin is part of the same series of passive, continental-margin rift basins as the Newark basin. Withjack, et al. (1995) determined that the Fundy basin underwent two separate episodes of deformation that he called basin inversion. Initially, rifting caused paleo-thrust faults to be reactivated extensionally, and the principal, extensional-stress direction was oriented NW-SE. As the rift basin made the transition from rifting to drifting, a later deformation event (Early Jurassic) was initiated and the basin was, and is still believed to be, dominated by shortening with the same principal stress direction (NW-SE). This is analogous to stretching a rubber band in the NW-SE direction and then letting it contract in the same NW-SE direction. Withjack, et al. (1995) suggests that ridge-push could be a viable mechanism for the change in stress fields when the basin progressed from a rift to a drift setting, or ridge-push may be an analogous force responsible for the rubber band being pushed back toward its original position. We believe this inversion of the stress fields, from extension to shortening, can explain the BHTV fracture data in the Newark basin.

As in the Fundy basin, Late Triassic, pre-existing Paleozoic thrust faults were reactivated, extensionally, in the Newark basin. We believe that the principal, extensional-stress direction was oriented NW-SE, and this early extensional stress caused the development of the steeply dipping fractures oriented NE-SW, normal to the principal, extensional-stress direction oriented NW-SE.

These fractures are dominant in all of the holes in the basin except Martinsville. At Martinsville, shallow-dipping fractures oriented NW-SE are dominant. We feel these fractures could not have been formed by this early extension, oriented NW-SE, that formed the fractures in all of the other sites in the basin where BHTV data was collected, except Martinsville. Martinsville may lack these early extensional fractures due to its proximity to the NW-SE oriented bounding fault. Goldberg suggests that during this early NW-SE oriented extension event, most or all of the strain could have been taken up by this bounding fault, and these early steep-dipping fractures did not develop. This may explain why Martinsville has a paucity of steep-dipping fractures. From this, we propose that these NW-SE oriented shallow-dipping fractures, which are dominant in the Martinsville site, originated from a second, and separate, deformation event.

As in the Fundy basin, this later episode (Early Jurassic/Early Cretaceous) of deformation had the same principal stress direction (NW-SE) as the early (Late Triassic), extensional stress that formed the steep-dipping fractures. The only difference between this early phase of deformation and the later phase is that the early phase was extensional, and this later phase of deformation is believed to be compressional. We believe this compression, or shortening, of the Newark basin formed the reverse fault (Reynolds, 1994), which was found at a depth of about 2200 feet, when the Martinsville hole was being cored (see Figure 9). This reverse fault was a function of the later shortening episode in the basin that may have locked up the bounding fault.
Figure 2. Composite logs of the gamma, density, porosity, and resistivity tools show how logs can be used to read the depositional character of the formation. From @ 800 ft.–@ 1200 ft., the low-gamma log signature represents the Orange Mountain basalt. The density log has a sharp-low @ 2200 ft. which is the approximate location of character @ 11,000 ft. This is the approximate location of the coarser fluvial units of the Stockton and Lockatong formations.

near the Martinsville site, and this created the reverse fault which helped in the development of the shallow-dipping, NW-SE oriented fractures found in the Martinsville hole. These shallow-dipping fractures exist in the other sites drilled in the basin, only shortening in the basin was taken up by the steep-dipping fractures formed during the earlier, extensional phase of deformation in the Newark basin.

**Conclusion**

The current model that a passive, continental-margin rift basin becomes quiescent after the basin has made the transition from a rift to a drift should be questioned. In both the Fundy and Newark basins, evidence suggests that two phases of deformation may have contributed to the tectonic development of these basins. The first event was extension and rift ing of the basin, which formed steep-dipping fractures. This is believed to have occurred during the Late Triassic. After the riftting progressed to drifting, a brief period of quiescence may have occurred from the Early Jurassic to as late as the Early Cretaceous. Thereafter, ridge-push forces may be responsible for shortening in the basin, which would have produced shallow-dipping fractures. Thus far this basin inversion model best explains the tectonic history of the Newark basin, based on the BHTV and data collected from the cores themselves.

Further work should include an analysis of the actual cores themselves at the fracture interface. Striations on the fracture interface, from shearing along the fracture planes as a result of shortening in the basin, and thin sections from the core may reveal microstructures (pressures solution, micro-cracks, etc.) that could provide further evidence for or against basin inversion. This was suggested by Grand Valley State University professor, Dr. John Weber.

Finally, core data sets should be created of the remaining five holes in the basin (Rutgers, Somerset, Titusville, Princeton, and Weston Canal) from the core photos, and a statistical analysis performed on these data to gain better understanding of the fracture distribution in the Newark basin.
Acknowledgements
I would like to thank my advisor at Lamont-Doherty Earth Observatory of Columbia University, Dave Goldberg, for all of his help and patience this summer. His remarkable ability to know when to let me go my own way, and when to pull back the reins when things were moving too fast, allowed me to realize my true potential in the area of research. I would also like to thank John Weber and Kevin Cole, two of my professors at Grand Valley State University for reviewing my paper and helping me develop my writing skills. All of this would not have been possible without Hazel Cochran. Not only did she initiate and develop the McNair Scholars Program at Grand Valley State University, which made this paper possible, but she expressed sincere interest in the research and always had time to point me in the right direction.

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