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Structural Geology of the Scottsville Mesozoic Basin, Virginia

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Structural Geology of the Scottsville Mesozoic Basin, Virginia

A thesis submitted in partial fulfillment of the requirement for the degree of Bachelors of Science in Geology from The College of William and Mary

By

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Accepted for Honors

(Honors, High Honors)

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April 23, 2012
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ABSTRACT

The Scottsville Basin in central Virginia is one of the westernmost Mesozoic sedimentary basins formed by continental extension during Pangaean rifting in eastern North America. Structural, stratigraphic, and aeromagnetic data are used to understand the structural geometry of the Scottsville Basin. The basin is developed across the Paleozoic Bowens Creek/Mountain Run fault zones that form the boundary between the Western Piedmont and eastern Blue Ridge. This small basin is a 130 km$^2$ half-graben structure bounded in the west by a segmented normal fault. The eastern boundary, previously interpreted as a shallow displacement normal fault, is an unconformable contact with prerift Paleozoic metamorphic rock. The basin is bounded at its northern and southern extent by a distinct “fish mouth” geometry that is likely related to normal faults that cut into the basin. Strata within the basin are tilted perpendicular to the western boundary fault, broadly increasing in dip angle from west to east. This trend suggests syndepositional rifting. A suite of north-northwest striking Jurassic diabase dikes cross-cut the region and are subparallel to the dominant extensional fracture set that cuts basin sedimentary rocks. The orientation of maximum extension appears to have rotated by as much as sixty degrees between basin formation in the Triassic and dike emplacement in the early Jurassic. Although several Mesozoic basins of the central Atlantic margin were tectonically inverted, structural and stratigraphic features in the Scottsville Basin are inconsistent with contractional inversion. It is possible that the magnitude of early Jurassic compressional stress waned from east to west, affecting the Scottsville Basin less than basins further east.
INTRODUCTION

Rift basins of Triassic age are among the most characteristic geologic features of eastern North America. This complex of sedimentary basins extends from the southeastern United States well into Canada (Figure 1). The Mesozoic basins of eastern North America record the breakup of Pangaea, a period of the earth’s history that has captured the interest and imagination of scientists for decades. The structure and stratigraphy of these basins preserve the full record of Pangaean rifting, from initiation through deposition and ultimately to tectonic quiescence along a passive margin (Schlische, 1993; Schlische, 1995; Olsen, 1990; Withjack, Schlische, and Olsen, 1998, LeTourneau, 1999). Understanding the process of continental rifting is not only of historical interest but also of modern pertinence, as mantle-driven crustal extension is presently active in contemporary environments such as the East African Rift System (Thiessen, Burke, and Kidd, 1979). In addition to documenting the breakup of Pangaea, Mesozoic rift basins are known to contain hydrocarbon deposits and have been mined since colonial time for their fuel-grade coal (Roberts, 1928). Studying the geology of North American Mesozoic rift basins will therefore contribute to a better understanding of the earth’s history and will potentially aid in the identification and extraction of valuable earth resources.

The Scottsville basin is located in the western Virginia Piedmont and is nucleated along the Bowens Creek/Mountain Run fault zone (Figure 2). This location places the Scottsville basin structurally west of almost all other North American Mesozoic rift basins. Consequently, this basin may represent the western extent of Triassic extensional stress. Many of the structural observations from other North American rift basins record
stresses applied to the North American continent from locus of rifting in the young Atlantic Ocean. Stresses therefore waned from east to west. One stress regime of particular interest is a NW-SE oriented period of compression that led to tectonic inversion and continental shortening in the earliest Jurassic (Withjack, Olsen, and Schlische, 1995; Withjack et al., 1998; Schlische and Withjack, 1999; Malinconico, 2003; Withjack, Schlische, and Baum, 2009; Withjack, Baum, and Schlische, 2010). Indeed, evaluating evidence for or against tectonic inversion in the Scottsville basin was one of the original motivations for this project. Studying the structural geology of the Scottsville basin will elucidate the processes active at the margins of Mesozoic rifting.

Presently, the Scottsville basin has received little scientific attention compared to the larger Mesozoic rift basins in Virginia. This project uses field observations and a synthesis of existing data to describe the basin’s structural geometry. The basin’s subsurface architecture is likely complex and will require detailed field mapping and analysis to properly identify. Understanding the Scottsville basin’s structural geometry will allow for a reconstruction of the regional kinematic history. By doing so, the orientation of paleostress fields can be determined. Describing the history of regional stress is the ultimate goal of this project. Detailed structural analysis of the Scottsville Basin will provide insight into the Mesozoic history of central Virginia.
Figure 1 – Map showing locations of Mesozoic rift basins (exposed and inferred) in eastern North America (modified from Olsen, 1990).
Figure 2 – Map of the Virginia Piedmont and Blue Ridge provinces (modified from Bailey, 1999 and Bailey, 2000). Mesozoic rift basins are outlined in teal. Major Paleozoic fault zones are traced in grey (F – Fries zone; R – Rockfish Valley zone; QR – Quaker Run zone; BC – Bowens Creek zone; MR – Mountain Run zone; B – Brookneal zone; Sh – Shores mélangé zone; CP – Central Piedmont zone; S – Spotsylvania zone; NC – Nutbush Creek zone; Ho – Hollister zone; Hy – Hylas zone)
REGIONAL HISTORY

The origin of the Scottsville Basin and other eastern North American Mesozoic basins began with the fusion of North America and Africa during the late Paleozoic Alleghanian orogeny, the result of which was the supercontinent Pangaea. During this and previous orogenic events, a series of transpressive faults were developed in the basement rock complex of the Appalachian Mountains (Gates, 1987; Conley, Henika, and Berquist, 1989; Withjack et al., 1998). The dominant stress regime was compressional in a NW-SE orientation (Schlische, 2003). The Pangaean continent was fully assembled by Permian time (Kent and Muttoni, 2003). Paleomagnetic data suggest that the continent was tectonically mobile over the period from 300 Ma to 175 Ma.

In the middle to late Triassic, a NW-SE oriented extensional stress regime initiated rifting of the Pangaean continent (Withjack et al., 1998; Schlische, Withjack, and Olsen, 2002). Direction of maximum horizontal elongation was parallel to \( \sigma_3 \), the direction of minimum principal stress (Schlische, 1993; Schlische, 2003). Transtensional normal and oblique strike-slip faulting was propagated along preexisting Paleozoic transpressive fault zones (Lindholm, 1978; Swanson, 1986; Schlische 1993; Withjack et al., 1998). The extent of slip along extension-related normal faults was in part a function of the orientation of the preexisting Paleozoic structural elements. Maximum displacement occurred on faults oriented directly perpendicular to the NW-SE extensional stress; such faults experienced pure dip-slip movement. Faults propagated on Paleozoic structures oriented subperpendicular or oblique to the direction of extension experienced a component of strike-slip. Greater obliquity to the stress direction led to
greater strike-slip movement and consequently less vertical displacement (Schlische, 1993; Schlische, 2003).

Continued normal faulting led to the formation of half-graben basin structures into which fluvial and lacustrine sediments accumulated (Smoot, 1991; Schlische, 1993; Schlische, 1995; Schlische, 2003; Schlische and Anders, 1996; Olsen, 1990; Olsen, Kent, Cornet, Witte, and Schlische, 1996; Olsen, 1997; Withjack, Schlische, and Olsen, 1995; Withjack et al. 1998). North-northeast striking normal fault zones formed the western boundaries of Mesozoic rift basins. These western margins are structurally complex and incorporate elements of dip slip, strike slip, detached hanging wall rider blocks, segmentation, and relay ramps (Schlische, 1992; Schlische, 1993; Schlische and Anders, 1996). As such, the western boundaries of CAM rift basins are referred to by the general taxonomy of “border fault systems” (e.g. Schlische, 1993). The dip angle of border fault systems is dependent upon the local Paleozoic fabric and is therefore widely variable within the set of CAM rift basins. Although the precise geometry of border fault systems is not well understood, the faults are listric at depth with detachments continuing into the shallow crust (Bell, Karner, and Steckler, 1988; Root, 1989).

Deposition of sediment into rift-related half-grabens was directly influenced by displacement along the border fault system. Maximum slip occurred at the center of the western margin and decreased roughly symmetrically outward until onlapping unconformably on prerift rock at the basin’s northeastern and southwestern boundaries (Schlische, 2003). This geometry produces a synclinal basin profile in cross-section perpendicular to the boundary fault system. Active slip in the western margin caused the basin to grow in length, width, and depth over time (Schlische and Anders, 1996).
Consequently, the basins are thickest in the west and gradually thin eastward, producing a wedge shape in cross-section perpendicular to the border fault (Figure 3). The eastern boundary of CAM rift basins is commonly interpreted as an unconformable ramping margin where synrift rock gradually thins out atop prerift rock (Schlische, 1993). This contact dips toward the boundary fault system (Schlische, 2003).

Faill (1973, 2003) has suggested that the majority of slip along the border fault system occurred after the predominant period of rift-related sedimentation. However, evidence supports the theory of synchronous faulting and basin filling (e.g. Schlische, 1993, 2003; Schlische and Olsen, 1990; Schlische and Withjack, 2005; Olsen, 1990; Olsen et al., 1996; Olsen, 1997). A series of stratigraphic observations synthesized by Schlische (2003) substantiate syndepositional fault movement. Foremost, strata nearest the border fault systems are dominated by boulder conglomerates both at the surface and at depth. Additionally, the widths of individual strata increase with proximity to the border fault system. Furthermore, the dip of strata is steepest at greatest distance from the border fault systems and becomes gradually less steep from east to west across the basin. This pattern suggests that basins grew over time with moderately consistent sedimentation. The oldest strata exposed at the surface are therefore at the eastern margin and the youngest are at the border fault system. These observations substantiate the theory that faulting occurred coevally with sedimentation in Mesozoic rifting.

Sedimentary analysis of the Taylorsville Basin, located approximately 100 km northeast of the Scottsville Basin, shows that sedimentation in the southern CAM rift basins (i.e. Virginia and points further south) ceased at some time from 208 Ma to 202 Ma, slightly predating the Triassic-Jurassic boundary (Malinconico, 2003). At some time
in the early Jurassic, the process of rifting gave way to continental drifting as Atlantic
seafloor spreading began in earnest (Withjack and Schlische, 2005; Schettino and Turco,
2009). However, sedimentary deposition in the northern CAM rift basins continued into early Jurassic time (Olsen, 1997). This evidence suggests that the initiation of the transition from rifting to drifting was not synchronous along the central North Atlantic margin, but rather occurred diachronously in a south-to-north progression (Withjack et al., 1998).

Active slip along the border fault system directly influenced development of the stratigraphy in CAM rift basins (Gibson, Walsh, and Waterson, 1989; Olsen, 1997). Capacity for sediment accumulation is a function of displacement along the border fault. As dip-slip movement increased, the basin’s capacity increased. Consequently, sedimentation changed from fluvial to lacustrine over time in a cyclical progression (Carroll and Bohacs, 1999). Olsen (1997) identified changes in accommodation space over time led to the creation of distinct tectonostratigraphic packages. The basal sequence, deposited early in the rifting history, consists of fluvial and eolian deposits. The upper strata are tripartite deposits recording a gradual change from fluvial to lacustrine and ultimately back to fluvial environment. Each tectonostratigraphic sequence is bounded by an unconformity. The distinct sequencing of sediment described by Olsen (1997) suggests that slip along the border fault system happened in a series of tectonic pulses in the late Triassic.

Many workers have described structures in CAM rift basins that are not consistent with a NW-SE extensional stress regime. Specifically, a suite of reverse faults and related folds indicate a period of contraction after Triassic extension (Withjack et al., 1995;
Withjack et al., 1998, Malinconico, 2003; Schlische 2003). In several basins, seismic reflection has shown reactivation along the border fault system in a reverse dip-slip orientation (Withjack et al., 1995). Tectonic inversion in CAM basins indicates a regime of NW-SE oriented compressional stress. Withjack et al. (1998) propose that NW-SE shortening began in the early Jurassic for southern CAM rift basins and progressed northward through the Middle Jurassic until the entire North American margin was subjected to compression. Though a clear causal mechanism for a change in stress regime has not been well established, researchers have proposed a ridge push process corresponding with plate movement (Withjack et al., 1998; Schlische, 2003). Inversion may have been facilitated by lithospheric thinning during the transition from continental rifting to drifting (Bott, 1992).

Early Jurassic magmatic activity in eastern North America drove the intrusion of diabase dikes into sediments at orientations controlled by the dominant stress regime (Schlische, 1993; Kelemen and Holbrook, 1995; Withjack et al., 1998; McHone, 2002). Dikes intrude in orientations perpendicular to the direction of minimum principal stress, \( \sigma_3 \). Dike orientation can therefore be used to reconstruct the regional paleostress field. In the central Atlantic margin, diabase intrusion is temporally constrained to approximately 200 Ma (Wilson, 1997; Marzoli et al. 1999, Marzoli et al., 2011). The short interval of magmatic intrusion therefore preserves a snapshot of active stress regimes in North America during the earliest Jurassic. Dike orientations in the southern basins are predominantly northwest-striking. Northern basins, however, contain dikes with northeastern strikes. This change in dike strike with respect to latitude suggests that the orientation of minimum principal stress in southern North America was rotated by more
than seventy degrees counterclockwise from the orientation of minimum principal stress in northern North America (Withjack et al., 1998).

Figure 3 – Schematic diagram of half-graben basin formation, a characteristic rift basin structural geometry. Displacement occurs on a preexisting plane of weakness. Sedimentary package is wedge-shaped in cross section and sits unconformably on prerift rock at the eastern margin. The hanging wall displays rollover geometry.
PREVIOUS WORK

The Triassic sedimentary basins of the Virginia Piedmont have been the focus of study since the early Nineteenth Century. The first detailed survey was conducted by Rogers (1836). This report describes rock outcrops in the Scottsville area composed of “fragments sometimes angular, sometimes more or less water-worn, cemented together by particles of sand, and occasionally a small admixture of carbonate lime.” Rogers (1836) also notes identifies the dominant clast composition as “derived from greenish-blue rock,” almost certainly a reference to the Catoctin greenstone. He concludes that this rock is the remnant of a high-energy period.

Detailed structural and stratigraphic analysis of the Scottsville basin is limited. Roberts (1928) identified the presence of a large normal fault at the western margin of the basin. He also divides the strata into three facies, described from oldest to youngest: a border conglomerate facies, a sandstone facies (the Manassas Sandstone), and a shale facies (the Bull Run Shale). In his interpretation, the sediments of the basin were deposited in a fining-upward sequence that was then downdropped and tilted by displacement on the western fault. Intrabasinal faulting supposedly placed the shale and conglomerate into contact. Roberts (1928) describes the eastern basin boundary as an unconformable contact between Triassic sediments and the older, surrounding rock.

Kingery (1954) provides the most thorough description of the Scottsville Basin. This study recognized three sedimentary facies in the basin, though their classifications and inferred depositional history differ from Roberts (1928). The Eastern Facies, inferred by Kingery (1954) to be the oldest of the three, is the most prevalent facies at surface exposure. Rock here consists of immature sandstones and siltstones rich in quartz,
feldspar, and epidote. The Fanglomerate Facies, located centrally within the basin, is predominated by boulder conglomerate bearing clasts of probable Blue Ridge provenance. In the westernmost extent of the basin lies the Western Facies, consisting of pebble conglomerates, sandstone, siltstone, and breccia. Mineralogy is mostly quartz, epidote, chlorite, sericite, and clays. Throughout the Scottsville Basin, twelve intrusive dikes were identified, each following a northerly trend. Dimensions of intrusive features average some two miles in length and fifty feet in width. Kingery (1954) also suggests the existence of an irregular hypabyssal body in the central west of the basin.

Through stratigraphic analysis, Kingery (1954) interprets the Scottsville basin as an erosionally dissected alluvial apron that formed when a system of isolated alluvial fans coalesced at their margins. This analysis is based upon the poor sorting and rounding of clasts, fining of strata from source to periphery, poor stratification in sediments, rarity of fossils, sedimentary texture suggesting a short transport distance from parent rock, and the basin’s fan like geometry in map view. Kingery (1954) describes a wedge-shaped basin geometry with beds dipping steeply in the east and gradually decreasing from east to west. To accommodate the observed stratigraphy, he proposes a kinematic model of contemporaneous faulting and deposition, rotating older beds toward the border fault. In the eastern margin, he observed evidence a low-displacement normal fault with slip magnitude decreasing to the northeast. To explain the “fish mouth” map pattern in the northeast and southwest basin margins, Kingery (1954) suggests two horsts that uplifted pre-Triassic rock. He suggests that these horst blocks are structurally related to the eastern boundary fault.
Though Kingery (1954) presents the most detailed description of the Scottsville Basin presently available in the literature, the findings proposed therein predate a great deal of research conducted in the latter half of the Twentieth Century. This research has greatly improved academic understanding of the Virginia Triassic basins as well as the greater regional history of eastern North America. Whereas Kingery (1954) assumes an essentially static geologic history in which landmasses including North America have been fixed in their present positions for long duration, a substantial amount of work over the past five decades has contributed to the modern kinematic model of global plate tectonics (e.g. Hess, 1962 and many others). These and other discoveries have expanded present understanding of Mesozoic geologic history. Though Kingery’s (1954) analysis is detailed and informative, further study in the Scottsville basin is necessary to better elucidate local and regional geologic history. The advances in geologic understanding made since the last detailed study of the Scottsville Basin justify a careful reanalysis of regional structure and stratigraphy.
METHODS

This study relies primarily on field data obtained through the Summer, Fall, and Winter of 2011/2012. Several research goals were addressed during field work. Foremost, observations were made to better identify the structural nature of the Scottsville Basin’s eastern boundary. Kingery (1954) maps this contact as a shallow displacement normal fault. Lines of supposed evidence include mylonitic fabric, slickenlines, drag folding, brecciated rock, vein quartz, mullion, intrusion of basin rock into underlying Paleozoic rock, and a decrease in foliation angle with increasing proximity to the contact (Kingery, 1954). It is possible, however, that many of the structural observations posited by Kingery (1954) are not the consequence of faulting but rather of rollover associated with the formation of a half-graben bounded in the east by a sedimentary contact. Structural evidence of rollover may be preserved in the present orientation of prerift fabrics. Defining the nature of the eastern boundary is an important step in reconstructing the Scottsville Basin’s kinematic history.

Using structural and stratigraphic data, I investigate the extent to which the Scottsville Basin experienced shortening in the early Jurassic. A reversal in stress regime from NW-SE extension to NW-SE compression would form transverse anticlinal folding through the basin. If no folding is present in the basin strata, it is then unlikely that the basin was tectonically inverted. Evidence of folding associated with shortening is examined though analysis of bedding data. Additionally, a compressional stress regime may have reactivated the boundary fault system in reverse orientation. I look for the presence of reverse slip indicators along the boundary fault to examine the possibility of tectonic inversion.
To determine the orientation of paleostress fields active during deformation of basin rock, this project quantitatively describes planar and linear features associated with brittle deformation. High angle extension fractures are the most common brittle deformation structure in the Scottsville Basin. The strike of extension fractures is oriented perpendicular to the direction of minimum principle stress ($\sigma_3$) at the time of formation. As such, extension fracture orientation can be used to estimate the direction of paleostress. I use fracture analysis to determine the orientation of extensional stress in the latest Triassic and earliest Jurassic.

In addition to fracture orientation, the trends of diabase dikes in and near the Scottsville basin are used as a paleostress indicator. In addition to field mapping of dikes, aeromagnetic and gravity data are used to infer the geometry of diabase intrusions at shallow depth. As with extension fractures, diabase dikes preserve the orientation of $\sigma_3$ at the time of their intrusion. Consequently, they are reliable paleostress indicators. The very well-constrained timing of Jurassic magmatism in the central Atlantic margin adds confidence to the use of diabase dikes for paleostress analysis. A preliminary review of existing literature suggests that fractures in the Scottsville Basin region have similar strikes to the diabase dikes. This similarity may implicate a temporal relationship between formation of the fractures and intrusion of the dikes. Placing temporal constraints on extension fractures allows for a more accurate paleostress analysis.
RESULTS

1:50,000 Scale Mapping

Field data was compiled in a 1:50,000 scale map that incorporates bedrock data with structural measurements from in and around the Scottsville basin (Figure 4). An accompanying stratigraphic diagram shows a simplified subsurface architecture for the basin and its surrounding rock units (Figure 5). The map is primarily drawn from field data and also incorporates data from maps drawn by Kingery (1954) and Ern (1968) as well as from unpublished data provided by Robert E. Weems. Aeromagnetic and gravity data were used to map the surface exposure of cross-cutting dikes. This new map redefines the location of several unit contacts and includes new structural interpretations which are discussed in this study.

Basin Boundaries

Field observations of structures in the Scottsville basin show evidence of basin-normal extension with slip localized along the western border fault system. A set of faults seen in outcrop near the northeastern margin of the basin show normal displacement (Figure 6a). Plotted stereographically, these faults can be assigned P and T axes that approximate the orientations of maximum and minimum principle stresses (Figure 6b). These data show that these faults formed in response to NW-SE oriented extensional stress. Normal faults in this orientation are characteristic of extensional basins (Withjack, Schlische, and Olsen, 2002). These data confirm the conclusion of Kingery (1954) and Roberts (1928) that the western boundary of the basin is a SE-dipping normal fault.
Figure 4 – Generalized geologic map of the Scottsville basin and surrounding units.
Figure 5 – Simplified stratigraphic section of the Scottsville basin area.
Figure 6a. – Outcrop of Triassic conglomerate in an abandoned quarry near the Hardware River. Normal faulting can be seen through the outcrop and is especially well exposed in the far right of the photograph (see arrow).

Figure 6b. – Stereogram of normal faults measured in the Scottsville basin and first motion diagram showing P and T axes. Stress during faulting was extensional and oriented NW-SE.
The western border fault system is clearly divided into three distinct segments in map view (Figure 4). This is a common geometry in normal-faulted rift basins. Larsen (1987) proposes a system in which initially separate extensional dip-slip faults connect over time via relay structures. Applying this model to the Scottsville basin, the border fault system likely began as three smaller faults in a left-stepping en-echelon progression (Figure 7a). Despite offset at the surface, the faults share a subhorizontal detachment surface at depth. As the faults converge upon one another, they conjoin at their tips via relay ramps (Figure 7b). After convergence, the faults experienced further displacement and basin growth (Figure 7c). Stratigraphic geometry in this kinematic scenario should resemble separate sedimentary basins that conjoin over time. This prediction is consistent with Kingery’s (1954) stratigraphic observations in the Scottsville basin. His report describes sedimentary structures indicative of coalescing alluvial fans. The stratigraphic architecture and segmented western boundary are preliminary evidence that the Scottsville basin’s border fault system was formed by the merger of three separate normal faults.

Though the nature of the western boundary is well confirmed as a listric normal fault zone, the eastern boundary remains enigmatic. Following from Kingery (1954), the eastern boundary is still shown as a faulted contact on most maps, including the most recent Virginia state map (VDMR, 1993). This interpretation suggests that the Scottsville basin is a graben structure. During field work, however, no structures were observed in the east of the basin that positively suggested faulting. Considering this lack of compelling evidence for graben geometry, a less structurally complex half-graben architecture is proposed. In this model, the basin is bounded in the west by a listric
normal fault and in the east by an unconformable contact where synrift rock onlaps prerift rock. The hanging wall rock rolls over along the western fault zone. This rollover geometry is characteristic of half-graben rift basins (e.g. Williams, 1987).

An analysis to determine the validity of the half-graben model involves measuring the present orientation of prerift fabrics in the hanging wall rock. Assuming a regionally consistent foliation orientation, rollover in the hanging wall would rotate existing fabrics some thirty degrees counter-clockwise. Hence, foliation orientations measured in the hanging wall of a half-graben should be less steep than those measured in the foot wall. By contrast, a full graben with a faulted eastern contact would not substantially alter
existing hanging wall fabrics from their initial orientation. It stands to reason, then, that a comparison of hanging wall versus foot wall foliation orientation would elucidate the structural geometry of the basin’s eastern boundary. To test this model, field data of foliation orientations in the hanging wall and the foot wall were combined with measurements compiled from Ern (1968). A study of fifty-two measurements in the hanging wall phyllite were compiled to determine an average foliation orientation at 020° 20° SE (Figure 8a). A similar study of foliation orientation in the hanging wall phyllite determined an average foliation orientation at 041° 50° SE (Figure 8b). The data do indeed show that existing fabrics dip less steeply in the hanging wall than in the foot wall, an expected observation in a half-graben.

The change in foliation orientation in the hanging wall preliminarily substantiates the rollover geometry model. To further analyze this model, it stands to reason that the thirty degree counter-clockwise rotation in the hanging wall can be artificially “undone” to approximately reconstruct the original fabric orientation. When the foliation orientation data from the hanging wall are “back rotated” by a factor of thirty degrees, the new average foliation orientation is 025° 51° SE (Figure 8c). This average orientation closely approximates the average hanging wall foliation orientation (Figure 8b). The consistency of this theoretical “back rotation” in the hanging wall, combined with shallow fabric orientation in the hanging wall and a lack of observed fault-related structures, supports a half-graben structural geometry in the Scottsville basin.
Figure 8 – Stereograms showing poles to planes of foliation orientations measured in the foot wall Candler Formation (a) and hanging wall Hardware Terrane (b) metasedimentary rocks. Back-rotation of measurements in the hanging wall by thirty degrees clockwise (c) produces an average foliation plane that is consistent with prerift fabric orientation.
Stratigraphic Geometry

Several research questions were addressed by describing the stratigraphic geometry of Triassic sediments in the Scottsville basin. Field measurements of strata orientations in the basin were combined with data from Kingery (1954) to construct a contoured bedding orientation map (Figure 9a) and corresponding bedding stereogram (Figure 9b). Broadly, strata dip homoclinal to the NW, perpendicular to the western boundary fault. The highest dip angles are located near the eastern boundary contact and approach 50° dip angles. The shallowest bedding planes dip less than 5° (often sub-horizontal) and are found along the western boundary fault. An average bedding orientation is estimated at 035° 22° NW. This stratigraphy confirms Kingery’s (1954) interpretation of syndepositional faulting. The oldest strata—those farthest east of the western border fault system—have experienced the greatest amount of tilting. The youngest strata—those nearest the western border fault system—have experienced comparably little tilting.

Though the stratigraphic geometry of the Scottsville basin largely resembles the expected architecture of an extensional basin, Figure 8a exposes one notable deviation from the predicted basin structure. Specifically, bedding planes locally reverse the east-to-west shallowing trend near the center of the basin. Here, strata dip thirty degrees or more. The homoclinal, NW-tilted geometry is preserved, suggesting that this steepness reversal is not related to folding of strata. Projected along strike, this zone of re-steepening is correlated with the irregular, “fish mouth” map pattern seen at the basin’s northeast and southwest margins. It is likely that the locally steepened strata and the
Figure 9 - Color contoured map of bedding dip angle in the Triassic strata (a) and stereogram showing poles to planes of bedding orientations. Strata dip homoclinal to the NW and decrease in steepness from east to west. The exception to the trend is observed in the center of the basin where strata are locally steepened. This re-steepening is correlated on strike with the “fish mouth” map pattern at the northeastern and southwestern margins.
abnormal map geometry are both results of a previously unrecognized normal fault that extends through the length of the Scottsville basin.

At depth, this fault separates the basin into two half-graben sub-basins. Plausibly, these sub-basins began as independent structures along separate normal fault systems. With sustained continental extension, the basins grew along their fault tips, increasing in length, width, and depth. Basin growth in this manner is substantiated by experimental modeling (Eisenstadt and Withjack, 1995; Clifton and Schlische, 2001; Withjack, Schlische, and Henza, 2007; Schlische and Withjack, 2009). In time, the sub-basins coalesced and began to grow as a singular basin. Erosional dissection has subsequently exposed evidence of separate sub-basins, particularly at the northeast and southwest margins. The “fish mouth” geometry shows two regions of Triassic sedimentary rock separated by phyllite (see Figure 4). Previous maps label this intervening phyllite as a horst block. That interpretation, however, presupposes a graben basin geometry that this study has demonstrated to be inconsistent with regional structural observations. It is more probable that this map pattern is created by two half-graben that rest unconformably atop prerift rock. The separate sub-basins are exposed at the basin margins where the sedimentary package is thinnest. The merger of these half-graben sub-basins into the can be seen near Dog Island on the James River in the southwest and near the Hardware River in the northeast.

**Tectonic Inversion**

Stratigraphic and structural data were analyzed to determine the impact—if any—of the NW-SE oriented compressional stress regime reported by workers in other
Mesozoic rift basins of the central Atlantic margin. In particular, stratigraphic architecture was analyzed for evidence of folding in the basin. A NW-SE directed period of continental shortening would result in broad anticlinal folding across the basin with SE-dipping strata disrupting the original homoclinal stratigraphic geometry (Withjack et al. 1998). Absent any compressional stress, the half-graben sedimentary package should be preserved in its original NW-dipping orientation. Between data collected in the field and from Kingery (1954), no SE-dipping strata are observed in the Scottsville basin (Figure 9b). Additionally, no clear structural evidence of reverse faulting was observed in or around the western border fault system. The preservation of the expected half-graben stratigraphic geometry coupled with the lack of reverse faulting suggests that the Scottsville basin did not experience a significant degree of continental shortening subsequent to basin formation in the Mesozoic.

It is unclear why the Scottsville basin lacks evidence of compression when other basins clearly show tectonic inversion and associated folding (e.g. Withjack et al. 1995). One plausible reason is the Scottsville basin’s west-lying structural position relative to other rift basins on the central Atlantic margin. Compressional stress may have been the result of initial continental resistance to ridge-push centralized at the nascent Mid-Atlantic Ridge (e.g. Bott, 1992). In this mechanical scenario, stress would wane with increasing distance from the ridge. Consequently, rift basins nucleated on east-lying fault zones may have experienced a greater magnitude of compressional stress. The Scottsville basin, however, was too far removed from the Mid-Atlantic ridge to experience shortening.
Fractures

Brittle fractures in the study area are characterized by high-angle extension fractures. Ninety-nine fractures were measured within the Triassic sedimentary rocks of the Scottsville Basin. The dominant set strikes NNW (337° - 340°) and is subvertical. A secondary set strikes NE (045°) and dips at an average of 76° (Figure 10). Fractures commonly occur in repeated sets across outcrops with average spacing ranging from 7 to 15 centimeters (Figure 11). The secondary set of NE-striking fractures do not propagate across dominant set of NNW-striking fractures. The dominant set therefore predates the secondary set. Both the dominant and secondary fracture sets are observed in diabase dikes of presumed Jurassic age.

Fractures in the adjacent Paleozoic metasedimentary units are also predominately high-angle extension joints. In the Candler Group phyllite to the west of the Scottsville Basin, forty fractures were measured. The dominant fracture set in the Candler Group phyllite strikes NW (300°) and is subvertical (Figure 12a, b). In the Hardware Terrane phyllite, metagreywacke, and quartzose schist unit, forty-eight fractures were measured. A dominant set strikes WNW (276° - 279°) and displays an average dip of 73° SSW. A secondary set strikes NE (077° - 080°) and dips 66° SE (Figure 12c, d). Fracture sets observed in these prerift metasedimentary units are not present in the Triassic basin rock and are therefore Paleozoic in age. Additionally, the NNW- and NE-striking fracture sets observed in the basin are not expressed in either of the adjacent metasedimentary units. This latter finding is unusual as the NNW- and NE-striking sets are Mesozoic or younger in age and are pervasive through the basin.
Figure 10 – Stereogram showing poles to planes of fractures in Triassic sedimentary rock (a) and rose diagram of fracture orientations (b). Fractures in the Scottsville basin are subvertical extension joints with a dominant set striking NNW at 337° to 340° and a secondary set striking NE at 045°.

Figure 11 – A set of extension joints in baked Triassic mudstone in the James River.
Figure 12 – Stereograms showing poles to planes of fractures and rose diagrams showing fracture orientations in the Candler Formation (a, b) and Hardware Terrane (c, d). Fractures in the Candler Formation are subvertical (a) and strike NW at 300° (b). Fractures in the Hardware Terrane are steeply dipping at ~070° SSW (c) and strike WNW at 276° - 279° (d).
Dikes

The igneous intrusions in and around the Scottsville basin are diabase dikes that are dated at approximately 200 Ma (Marzoli et al. 1999, Marzoli et al. 2011). Field data was combined with aeromagnetic data and gravity anomaly data from Johnson, Wiener, and Conley (1985) to map the dikes in the basin at high resolution. Multiple dikes extend through the basin, ranging in width from one to eighty meters. The most expansive intrusive in the Scottsville basin is three-pronged at the surface and forms the Goosby Islands in the James River. This dike is likely the thickest in the basin and produces a strong magnetic signature (Figure 13). This and other diabase dikes form knickpoints where they crop out in the James River (Figure 14a). Another major dike in the study area forms a rapid in the James River near Hatton. Though the largest continuous outcrops of diabase were observed in the James River, dikes were identifiable on land by their spheroidal weathering habit (Figure 14b).

The Jurassic diabase dikes that cross-cut the study area strike NNW (Figure 15). This orientation is subparallel to the dominant NNW-striking Mesozoic fracture set observed in the Triassic sedimentary rock in the Scottsville basin. This similarity in propagation orientation suggests that the extensional stress field active during dike emplacement was in the same orientation as the extensional stress field active during fracturing in the basin. Upon this evidence, it is therefore likely that diabase emplacement and basin fracturing are contemporaneous, i.e. ~200 Ma.
Figure 13 – Contoured aeromagnetic map of the Scottsville basin region. Notable magnetic highs include the major diabase dike that cross-cuts the basin and the Hardware Terrane; the body of greenstone situated on the western border fault; and the belt of Catoctin greenstone in the eastern Blue Ridge province.
Figure 14a – Diabase dike at the Goosby Island rapids in the James River. This outcrop shows the contact between the dike and basin rock; the head of the rock hammer sits on diabase and the base of the rock hammer sits on baked mudstone.

Figure 14b – Boulder of diabase in the north of the Scottsville basin. Diabase is readily identifiable by its characteristic spheroidal weathering.
Paleostress Reconstruction

Analysis of fracture and dike geometries was used to calculate paleostress orientation. Maximum principle stress ($\sigma_1$) during fracturing of the Candler Group phyllite was oriented at approximately 300° (Figure 16a) and extension was oriented at approximately 030° (Figure 16b). During fracturing in the Hardware Terrane phyllite, metagreywacke, and quartzose schist, maximum principal stress ($\sigma_1$) was oriented approximately 280° (Figure 16c) and extension was oriented at approximately 010° (Figure 16d). The orientation of maximum principal stress ($\sigma_1$) during the formation of the dominant NNW-striking Mesozoic fractures was approximately 340° (Figure 16e) and extension was oriented at approximately 070° (Figure 16f). During dike emplacement, maximum principle stress was oriented at approximately 347° (Figure 16g) and extension was oriented at 077° (Figure 16h).
Figure 16 – Rose diagrams of fracture orientations in the major units of the Scottsville basin region. Arrows represent the orientation of maximum principal stress $\sigma_1$ (left column) and the orientation of extension (right column) for the Candler Formation (a, b), Hardware Terrane (c, d), Triassic sedimentary rock (e, f), and Jurassic diabase (g, h).
The regional paleostress fields recorded in deformation features reveals a dynamic tectonic history for the Scottsville basin area. The fractures in the Candler Formation and Hardware Terrane may be as old as Cambrian in age, but are here interpreted as Alleghanian-age features. The orientation of extensional stress during Pangaean rifting and basin formation was NW-SE, normal to the basin’s border fault system. In the early Jurassic, emplacement of diabase dikes and fracturing of Triassic sedimentary rock occurred during a NE-SW oriented extensional stress regime. The orientation of early Jurassic extension relative to Triassic basin-normal extension shows a rotation in stress direction by at least sixty degrees. Though the regional tectonic cause for this rotation is enigmatic, it can be constrained in time between the Mid-Triassic when rifting is believed to have initiated and 200 Ma when the diabase intruded the basin.

**Greenstone History and Structure**

Exposures of greenstone/metabasalt lie directly adjacent to the western border fault system. Outcrops in the vicinity of the Rockfish River are comprised of both foliated greenstone as well as lithic greenstone breccias (Figure 17). The greenstone and greenstone breccias appear to be interlayered. Brecciated exposures are concentrated around the border fault system and are well exposed in the Rockfish River southwest of Howardsville. Foliation orientations are NE-striking and dip moderately steeply (~50° - 80°) to the NW. This orientation is notably different from nearby belt of the Catoctin formation, where foliation dips were measured as uniformly SE-oriented. The greenstone adjacent to the basin is discontinuous in map view, truncated at the zones of segmentation along the western border fault system. This likely reflects burial of greenstone by Triassic
sediments in the west of the basin, although it is equally possible that the greenstone is comprised of two or more separate bodies.

The history of this greenstone is not well established in the present literature. Numerous workers have proposed models to explain the age of this greenstone body, the timing of its emplacement and metamorphism, and its geometry at depth. Kingery (1954) describes the greenstone as a hypabyssal body of Triassic age. In his interpretation, the greenstone intruded into basin conglomerate strata, metamorphosing nearby rock to a low-grade, chlorite and epidote-rich metasedimentary body. The greenstone cements the conglomeratic sediments. This model, however, does not account for a mechanism by which this intrusive body was metamorphosed, nor does it explain why the other mafic
intrusives in the Scottsville basin—to which Kingery (1954) assumes the greenstone is temporally and genetically related—were not metamorphosed. Nelson (1962) mapped these exposures as part of the Paleozoic Catoctin formation, an interpretation that has been reproduced by subsequent maps (VDMR, 1993). For the purpose of this study, the greenstone body is assumed to be of Catoctin age.

Determining the timing and nature of brecciation in the Howardsville-area greenstone is important for understanding the regional kinematic history of the Scottsville basin. The close proximity of the brecciated rock to the western border fault may expose a relationship between brecciation and Triassic faulting. Indeed, this rock resembles a fault breccia in some outcrops. In this hypothetical model, the greenstone was largely consolidated prior to Mesozoic rifting and was deformed by tectonic activity. After an early examination of outcrops of greenstone breccias in the study area, this interpretation seemed appeared valid. Subsequently, however, an outcrop of Triassic conglomerate was found in the north of the basin that contains a boulder-size clast of brecciated greenstone (Figure 18). The inclusion of greenstone breccia in the sedimentary rock of the Scottsville basin is strong evidence that brecciation predates Mesozoic rifting. In an alternative explanation, this greenstone is a flow breccia that formed during Catoctin magmatism in the Neoproterozoic. Surface cooling of a basalt flow was disrupted by movement of lava at depth, fragmenting the solidified basalt into angular clasts. Flow brecciation has been documented in the Catoctin Formation (e.g. Reed, 1969).

If the greenstone and greenstone breccias are indeed of Catoctin age, their structure at depth remains unclear. This body of greenstone is discontinuous from the main belt of Catoctin in the eastern Blue Ridge, separated by three kilometers in map
Figure 18 – Outcrop of Triassic conglomerate containing a clast of greenstone breccia. This inclusion suggests that brecciation predates Mesozoic faulting.

view. Several hypothetical structural geometries may explain the presence of greenstone near the Scottsville basin. In one model, a shallow-angle normal fault displaced a block of the eastern Blue Ridge cover sequence, of which the Catoctin greenstone is now exposed at the surface (Figure 19a). However, no structural data was observed that suggests shallow-angle normal faulting in this area. A second proposed model assumes folding in the Blue Ridge cover sequence, in which the exposure of Catoctin greenstone is part of an anticlinal fold (Figure 19b). The NW-dipping foliation orientation measured in the Howardsville-area greenstones, compared with the SE-dipping foliation orientation measured in the main belt of the Catoctin Formation, may substantiate the folded model.
Figure 19a. – Cross-section of the Scottsville basin region depicting the normal faulting structural model. A block of Catoctin greenstone has been displaced from the main belt along the fault plane and has been subsequently exposed at the surface by erosion of overlying rock.

Figure 19b. – Cross-section of the Scottsville basin region depicting the folded structural model. The greenstone at the basin’s western margin is continuous with the main belt in the eastern Blue Ridge and has been exposed at the surface by anticlinal folding.
DISCUSSION

**Synoptic Basin History**

Prior to the Triassic, the geology of the Scottsville vicinity was dominated by metasedimentary rock that had been metamorphosed to greenschist facies and fractured during the Alleghenian orogeny. Through faulting, folding, or other tectonic processes, a body of Catoctin greenstone was exposed at the surface. At this time, North America was contiguous with southwestern Europe and northwestern Africa as part of the supercontinent Pangaea (Kent and Muttoni, 2003). Asthenospheric upwelling and resultant crustal thinning in the early to mid-Triassic initiated the breakup of Pangaea, with rifting centralized along reactivated Paleozoic fault zones. The Scottsville basin is nucleated along the Mountain Run/Bowens Creek fault zone, a major Paleozoic wrench fault and thrust fault that separates the eastern Blue Ridge and western Piedmont provinces in Virginia (Gates, 1987; Conley et al., 1989). Minimum principal stress ($\sigma_3$) in the early to mid-Triassic was oriented NW-SE at approximately 325°-330° (Figure 20).

Extensional stress in a NW-SE orientation was sustained through the Triassic, causing displacement along SE-dipping listric normal fault zones. The western boundary of the Scottsville basin likely consists of three initially separate normal fault-bounded basins. Homoclinal, NW-dipping strata are tilted in the east of the basin and sub-horizontal in the west, suggesting that slip along the western border fault was syndepositional. The basin formed as a half-graben with the eastern hanging wall rolling over along the western normal fault zone. As a result, existing fabrics in the hanging wall became shallower than those in the footwall.
Figure 20: Block diagram depicting the orientation of principal stresses active in the Scottsville basin region immediately prior to rifting in the mid-Triassic. Minimum principal stress $\sigma_3$ is oriented NW-SE, allowing the continental crust to extend in this orientation.
An abrupt shallowing of bedding dip angle near the center of the basin indicates a previously unrecognized normal fault spans the length of the Scottsville basin. In the incipient stages of rifting, two half-graben sub-basins formed along parallel border fault systems, both of which are nucleated on the Bowen’s Creek/Mountain Run fault zone (Figure 21). The intrabasinal normal fault was the western border fault of the east-lying sub-basin. Continued growth of the two separate border fault systems along their fault tips increased basin volume. Maximum displacement was accumulated at the center of the border fault system and decreased synclinally outward. In time, sustained growth led to the coalescence of the sub-basins into one continuous basin (Figure 22). The abrupt steepening of bedding orientation is a surficial expression of sub-basin linkage at depth.

Subsequent to Triassic rifting, the Scottsville basin entered a period of tectonic quiescence as evidenced by the preservation of unfolded, extensional basin stratigraphy. This sedimentary geometry suggests that the basin was not subjected to the NW-SE oriented compressional stress regime observed in other North American Mesozoic rift basins. The Scottsville basin’s west-lying structural position may explain why this stress regime is not evident in the basin’s stratigraphic architecture or in structural geometry. It is possible, however, that the basin did experience shortening with folding concentrated in the uppermost strata, which have subsequently been eroded.

By the earliest Jurassic, the process of continental extension gave way to drifting propelled by ridge push from the young Mid-Atlantic Ridge. As extensional stress waned, displacement along the border fault system ceased and the basin stopped growing. Shortly afterward (i.e. before the sediments had fully lithified), extensional stress caused high-angle jointing and faulting. The dominant fracture set in the basin is oriented
Figure 21 – Block diagram depicting initial stages of basin formation in the mid-Triassic. Two half-graben sub-basins nucleated along parallel border fault systems form along the Bowens Creek/Mountain Run fault zone.

Figure 22 – Block diagram depicting the coalescence of the half-graben sub-basins in the late Triassic during the final stages of continental extension.
NW/SE at approximately 340°, suggesting an extensional paleostress regime with σ₃ oriented NE/SW at 070°. This fracture set is oblique to the border fault system and does not propagate into adjacent Paleozoic rock. The NE/SW trending diabase dikes that cross-cut the basin are oriented subparallel to the dominant fracture set, suggesting that both are extensional features related to the same stress regime (Figure 23). Taken together, the diabase dikes and extension fractures in the basin suggest change in extensional stress orientation from NW-SE in the middle Triassic to NE-SW in the early Jurassic, a rotation of potentially sixty degrees.

After the magmatism ceased in the early Jurassic, eastern North America became a passive margin propelled westward by far-field stress from the Mid-Atlantic Ridge. High stands in sea level buried Mesozoic rift basins east of the fall zone in Cenozoic Coastal Plain sediments. Basins to the west of the fall zone remained exposed at the surface and experienced erosion through the Cenozoic. Consequently, modern basin morphology is only an erosional remnant of the original structure. In the Scottsville basin, Cenozoic erosion has exposed the separate tips of its two sub-basins at the northeastern and southwestern margins.
Figure 23 – Block diagram depicting emplacement of diabase dikes and the fracturing of basin rock in the earliest Jurassic. The orientation of minimum principal stress $\sigma_3$ has rotated more than sixty degrees from its orientation during basin formation. Based on their subparallel propagation orientation, magmatism and fracturing are assumed to be contemporaneous.
CONCLUSION

The Scottsville basin is a Mesozoic sedimentary structure that formed during continental extension associated with breakup of Pangaea. Rock type of the basin ranges from boulder conglomerate to mudstone and is predominantly derived from the Catoctin greenstone as well as other Blue Ridge cover and basement units. The area immediately surrounding the basin is primarily composed of Paleozoic metasedimentary rock, as well as a small and structurally unexplained body of Neoproterozoic Catoctin greenstone. Structurally, the basin is bounded in the west by a SE-dipping listric normal fault zone nucleated along the reactivated Paleozoic Bowen’s Creek/Mountain run fault zone. This fault system is segmented into three distinct zones, suggesting that it represents the union of three separate normal faults. As such, this boundary is referred to as the border fault system. Segments in this fault system are connected by relay structures. The eastern boundary of the Scottsville basin, historically identified as a shallow-displacement normal fault, is a hinged zone characterized by rollover in the hanging wall. The Scottsville basin therefore displays a half-graben structural geometry and is not a full graben as previously theorized.

Strata in the basin are oriented homoclinaly to the NW and are variably tilted, with the greatest magnitude of tilting near the eastern boundary and the least magnitude of tilting near the western boundary. This stratigraphy is indicative of syndepositional movement along the western border fault system. The re-steeping of strata near the basin’s center, correlated along strike with the distinct “fish mouth” map pattern at the basin’s northeastern and southwestern margins, reveals a previously unrecognized normal fault that runs through the length of the Scottsville basin. This fault separates the basin...
into two half-graben sub-basins that merged after sustained growth during continental extension. Throughout the basin, no SE-dipping strata are observed. The preservation of the expected extensional basin stratigraphic architecture indicates that the basin did not experience tectonic inversion in the Mesozoic. This is likely a consequence of the Scottsville basin’s west-lying structural position.

In the early Jurassic, the intrusion of diabase dikes cross-cut the Scottsville basin and surrounding Piedmont and Blue Ridge units. This intrusion is likely related to CAMP magmatism. The dikes in and around the basin trend NNW, subparallel to the dominant fracture set of subvertical extension joints in the basin rock. This similarity in orientation suggests that the features formed contemporaneously and in response to the same NE-SW oriented extensional stress field. This direction of extension deviates from the NW-SE oriented rifting stress field by at least sixty degrees. The cause of this rotation in the direction of extension is not yet well understood. After Jurassic magmatism and fracturing, the Scottsville basin was not significantly tectonically active, although isolated seismic events along the border fault system are not unlikely. Erosion throughout the Cenozoic has cut the Scottsville basin down from its original proportions, although the total extent of erosion—and, by extension, the pre-erosion dimensions of the basin—cannot be easily calculated. At the basin’s northeastern and southwestern margins, erosion has exposed the two half-graben sub-basins that compose the Scottsville basin.

To better understand the structural geometry and kinematic history of the Scottsville basin, better resolution structural mapping is imperative. The 1:50,000 scale map produced in this study provides a sufficient geologic overview of the basin and its surrounding rock, but cannot adequately address many of the structural complexities in
the study area. Mapping at the 1:24,000 scale may help substantiate the findings presented in this study. Particular focus in further mapping efforts should be placed on better imagining of the northeastern and southwestern basin margins, the intrabasinal normal fault, the eastern basin boundary, and the cross-cutting diabase dikes. Additionally, mapping to the southwest of the basin may help understand the structural relationship—if any—between the Scottsville basin and the zone of presumed Triassic rock near Midway Mills.

In addition to structural mapping, detailed stratigraphic analysis will help to better understand the structural geology of the Scottsville basin. Presently, the age of deposition in the basin is not well constrained; sediments can only be confidently described as mid- to late-Triassic in age. Though Kingery (1954) describes the Scottsville basin as distinctly fossil-poor, the identification of any paleobiological indicators would greatly aid in constraining the age of basin sediments. Understanding the age relationships between strata would allow for a better reconstruction of tectonic activity along the western border fault system. Specifically, stratigraphic analysis may identify the separation of sediments into the distinct tripartite tectonostratigraphic packages identified in other North American Mesozoic rift basins (e.g. Olsen, 1997). Additionally, paleomagnetic analysis of Triassic sedimentary rock and Jurassic diabase will help address tectonic and paleogeographic questions that persist in the Scottsville basin.
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