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Kinematic reconstruction of the central US and conjugate northwest African margin

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Summary: The Early Jurassic margin of the East Coast of the U.S. is an excellent location to study the interaction between extension, mantle flow, and magmatism during continental breakup, because the crustal structure and stratigraphy of the subsiding margin are fairly well preserved. Modern geophysical tools such as those available on the R/V *Marcus Langseth* and arrays of land and ocean-bottom seismometers will allow us to image the deep structure better than before. Our understanding of the thermal state of the lithosphere during rifting and the magma flux in the young ocean basin depend on estimates of the oldest spreading rates. In this paper we review some constraints on the early opening history, and we present a plate reconstruction for the Central Atlantic. From this compilation we estimate that the Early Jurassic seafloor spreading half rate may have been as low as 5.5 mm/yr, if the Blake Spur magnetic anomaly (BSMA) was the result of an eastward ridge jump as suggested by *Vogt* [1973]. If this model is correct, a ~250 km wide ocean basin with two conjugate volcanic margins lies off the eastern seaboard of the U.S. If it is incorrect, initial seafloor spreading was highly asymmetric in the Atlantic for the first 30 million years [*Labails et al.*, 2010].

An interpretation of the Mesozoic and Cenozoic seafloor spreading magnetic anomalies allows for a fit of eastern North and South America, Europe and Africa [*Klitgord and Schouten*, 1986] by mid-Jurassic time (175 Ma, using the scale of *Gee and Kent* [2007]). This reconstruction is straightforward to anomaly M25 (153 Ma), but spreading rates during early opening of the central Atlantic (in the Jurassic Quite Zone) are unconstrained [*Vogt*, 1973], so the onset of seafloor spreading is uncertain. On the other hand, on-land geological and geophysical data [*Marzoli et al.*, 2011; *Schlische et al.*, 2003] allow for a relatively short period of rifting and CAMP magmatism around the Triassic-Jurassic boundary (200 Ma) in the northeastern US, by which time extension in rift basins in the southeastern US had already ceased.

The major magnetic anomalies along the central Atlantic margins may provide a time line for the initial opening of the Atlantic. The large negative Brunswick magnetic anomaly (BMA) has been interpreted as a rift-related feature in the southeast Georgia Embayment [*Lizarralde et al.*, 1994] though its landward continuation must be an Alleghanian structure [*McBride and Nelson*, 1988]. The large positive (350 nT) East Coast magnetic anomaly (ECMA) probably marks the continent-ocean transition zone on the American plate [*Austin et al.*, 1990; *Grow and Markl*, 1977], just as the weaker West-African Coast magnetic anomaly (WACMA) does on the conjugate margin [*Roussel and Liger*, 1983]. *Sahabi et al.* [2004] have dated the WACMA (and therefore also the ECMA) at 195 Ma (Figure 1a).

Since there is not a clear African counterpart to the ~50 nT positive BSMA, *Vogt* [1973] suggested it represents a sliver of West-African margin crust that was left on the American plate after the spreading center jumped east. This would also explain why the distance between ECMA and M25 is much wider than the distance between WACMA and M25 at the African side. In fact, M25 lies right between BSMA and WACMA at 153 Ma (Figure 1c), which may imply that the new spreading center parted these two anomalies. If we assume that the spreading half rate between M25 and M21 (18.5 mm/yr) is an acceptable average half rate between BSMA and M25, we obtain an approximate age of 173 Ma for the ridge jump to BSMA/WACMA, which is consistent with the age of Callovian (163 Ma) sediments drilled at DSDP Site 534 on Outer Blake Ridge [*Sheridan et al.*, 1982] east of the BSMA. Since the BSMA does not extend north of the New England seamounts, the ridge jump would have to be limited to the same distance. An important implication of the ridge jump hypothesis is that seafloor spreading between ECMA and BSMA (250 km over 22 Myr) occurred at a very low half rate of 5.5 mm/yr.

As an alternative to *Vogt's* [1973] ridge jump, *Labails et al.* [2010] suggested that all magnetic anomalies west of the Mid-Atlantic Ridge (MAR) have a counterpart on the east flank, though some of these would have to be much weaker in amplitude. More importantly, this model requires a much larger spreading half-rate on the North American margin than at the conjugate African margin prior to M25 because the distance from ECMA to M25 is much larger than from WACMA to M25. *Labails et al.* [2010] attribute this long-lived (~30 Myr) discrepancy to higher temperatures under the African continent.

In this paper we focus on *Vogt's* [1973] original hypothesis, and we develop a kinematic model that uses our best dates for the mentioned magnetic anomalies. To reconcile the opening of the Gulf of Mexico and the central Atlantic we must assume that the basement of the Bahamas and Blake Plateau is either (presumably stretched) continental crust or younger igneous rock. The original position of Florida is uncertain because of the possible existence of a major transform boundary [*Klitgord et al.*, 1984], and because of the early extension in the South Georgia Basin [*Salvador*, 1987]. To avoid a gap between North America, South America, and Africa in a reconstruction of Pangaea around 200 Ma, it helps to consider the Bahamas Platform and Blake Plateau as extended fragments of continental crust, though there is no good geophysical evidence for their origin yet. In Figure 1 we present three time frames from a global plate reconstruction using the oceanic magnetic and tectonic database of the UTIG PLATES project to illustrate the opening of the central Atlantic.

Future studies of the U.S. eastern seaboard may address the relationship between magmatism and rifting during continental breakup. The nature and timing of CAMP suggest that small-scale convection in response to continental rifting was responsible for the production of thick volcanic wedges at the eastern U.S. and northwest African margins [*Holbrook and Kelemen*, 1993; *McHone*, 2000]. Alternatively, a plume may have set the breakup of Pangaea in motion [*Wilson*, 1997], though there is no strong evidence for it. Either way, the early spreading history was unusual as it may have been asymmetric [*Labails et al.*, 2010] or very slow (this study).

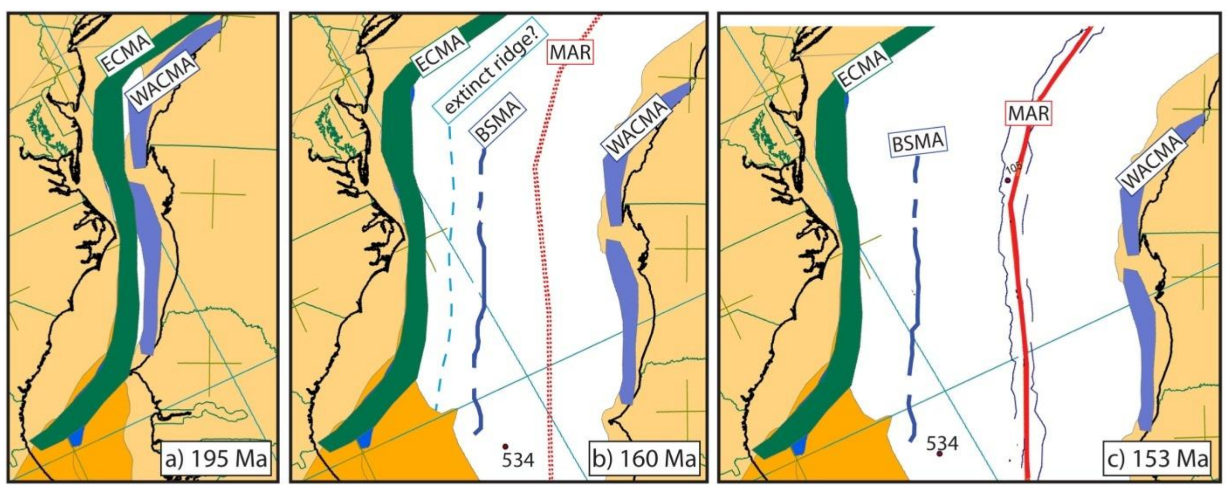

Figure 1. Plate reconstructions of the central Atlantic region. a) Onset of seafloor spreading. b) At roughly 173 Ma the spreading ridge jumped just east of the BSMA. c) Reconstruction at approximate age of M25. Note that the MAR here is equidistant between BSMA and WACMA.

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Deep-crustal seismic study of continental rifting in the Newfoundland Basin

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The generation, timing and manifestation of magmatism are key factors controlling the development of both rifted continental margins and seafloor spreading systems, yet the evolution of the magmatic system during the transition from rifting to mature seafloor spreading remains one of the least-studied problems in plate tectonics. A type example of a magma-poor rifted margin, where a seafloor spreading system was slow to develop [*Jagoutz et al.*, 2007], is the Newfoundland rifted margin. We suggest that characterizing the crust and mantle on the outer part of this slow, magma-poor system would illuminate the magmatic and deformational processes associated the transition from late-stage rifting to mature seafloor spreading. New studies should include 1) very long-offset seismic refraction data and/or passive seismic data to constrain deeper lithospheric structure, and 2) coverage of the oceanic crust produced by the earliest oceanic spreading center with active and passive seismic data. Magnetotelluric and deep-tow magnetic data may also provide critical constraints on these processes.

The magma-poor rifted margin of Newfoundland was the target of the deep-seismic SCREECH study in 2000 and ODP Leg 210 in 2003. As a result, the basement morphology and seismic velocity structure are constrained along three dip lines by deep-penetration multi-channel seismic reflection data and wide-angle seismic reflection-refraction data. The SCREECH project resulted in three deep-seismic transect across the Newfoundland margin. Whereas the northern line (SCREECH 1) crossed the edge of Flemish Cap [*Funck et al.*, 2003; *Hopper et al.*, 2004], SCREECH 2 [*Shillington et al.*, 2006; *Van Avendonk et al.*, 2006] and SCREECH 3 [*Lau et al.*, 2006a; *Lau et al.*, 2006b] ran from the Grand Banks to the Newfoundland Basin (Figure 1a). SCREECH 2 and 3 both showed wide zones of thinned continental crust and a portion of exhumed continental mantle. It appeared that oceanic crust of normal thickness (~6 km) was not even found at the seaward end of these profiles [*Lau et al.*, 2006a; *Van Avendonk et al.*, 2006], which led *Tucholke et al.* [2007] to suggest that true oceanic crust was only produced here at the Aptian/Albian boundary, which lies seaward of SCREECH lines 2 and 3. The deep structure of SCREECH 1 appears quite different, with a shorter transition from thinned continental crust to normal oceanic crust [*Funck et al.*, 2003; *Hopper et al.*, 2004].

Recent work on the SCREECH data includes a new interpretation of strong laterally continuous seismic reflections in the deep sediments of the Newfoundland continent-ocean transition [*Peron-Pinvidic et al.*, 2010], which appear to be post-rift magmatic sills [*Karner and Shillington*, 2005] that represent a phase of late-stage magmatism in the Newfoundland basin. Unfortunately, these sills obscure seismic reflections from the basement beneath them [*Shillington et al.*, 2008], so the basement morphology is not very clear in the continent-ocean transition zone of SCREECH 2. Given that the basement appears relatively flat and void of prerift sediments along this transect, *Van Avendonk et al.* [2009] suggested that it was formed by a west-dipping detachment fault that exhumed deep-crustal rocks. An analysis of seismic converted waves [*Eddy et al.*, 2011, in prep] confirms that rocks from the continental crust and upper mantle are both exhumed in the continent-ocean transition zone of SCREECH Line 2.

The previous work conducted in the Newfoundland Basin forms a great foundation for future marine geophysical work on cold rifting. The along-strike change in structural style of the rifted margin between SCREECH 1 and SCREECH 2 may have its origin in preexisting structures and far-field stresses during the early phase of the rift [*Sibuet et al.*, 2007], but it is nonetheless surprising that normal oceanic crust appears to have formed sooner off Flemish Cap than off the Grand Banks [*Van Avendonk et al.*, 2006], while extension of the continental lithosphere appears to have commenced in the south, and propagated north [*Tucholke et al.*, 2007]. The contrast in structural style, and its apparent influence on the delivery of melts to the incipient spreading center, makes the area between SCREECH Lines 1 and 2 the best location for a comparative seismic study (Figure 1). This area was also the site of ODP Leg 210, during which Site 1276 and 1277 were drilled [*Tucholke et al.*, 2007].

Given the results from SCREECH, we would expect that the crustal and mantle structure varies both along margin dip lines and along-strike over distances of several 10s of kilometers. These length scales can be resolved most efficiently with regional 2-D seismic reflection and refraction lines, so we do not advocate a 3-D seismic reflection survey. In Figure 1 we illustrate a possible strategy (blue lines) for new marine seismic profiles that would target the structure of the margin in its rift-to-drift transition. Although the SCREECH project successfully imaged the crustal and uppermost mantle structure of the margin, the depth of serpentinization of the mantle in the continent-ocean transition zone is not always constrained. It is also possible that mantle-derived melts are not extruded to the surface during cold and slow rifting [*Bronner et al.*, 2011]. It is therefore an attractive option to acquire very long-offset seismic refraction data along dip lines over crust produced by the incipient seafloor spreading center in the Newfoundland Basin, in the same manner as during the FAIM experiment [*Gaherty et al.*, 2004; *Lizarralde et al.*, 2004]. Other key offshore data sets that could address these questions include passive seismic data, MT and deep-tow magnetics.

New studies of the rift-to-drift transition in the Newfoundland Basin would meet key objectives of the Geoprisms science plan. Mantle melts probably play a large role in the style of deformation. The process of continental breakup, and the role of mantle melts is still not well understood [*Tucholke et al.*, 2007]. The thermal state of the lithosphere during and after the rift-to-drift transition controls the subsidence of rifted margins, which creates the accommodation space for evaporates and sediments.

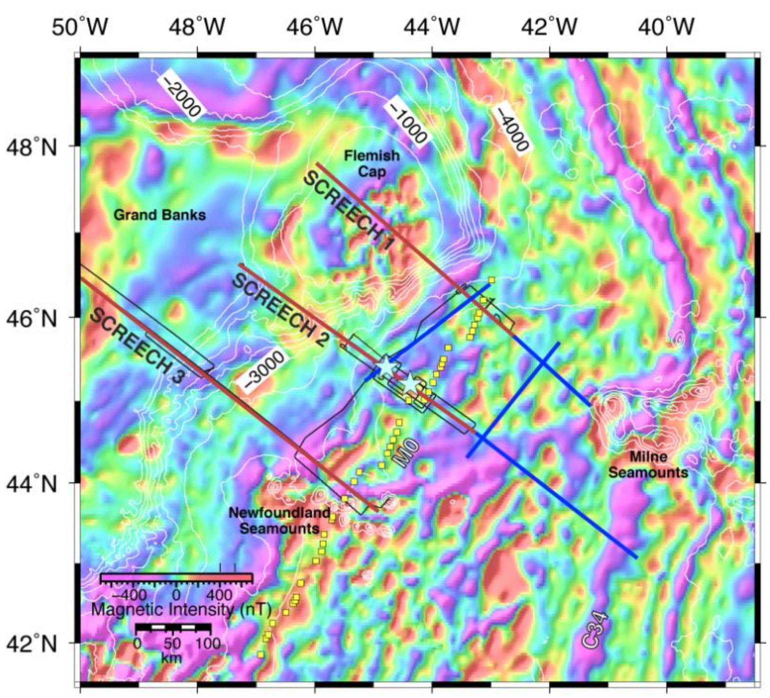

Figure 1. Magnetic map with existing (red) and proposed (blue) seismic lines at the Newfoundland margin. White contours represent depth intervals of 1000 m. White crosses mark ODP drill sites 1276 and 1277. Picks of magnetic anomaly M0, perhaps the oldest seafloor spreading anomaly in the Newfoundland Basin, are marked by yellow squares.

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A central Appalachian EarthScope transect in Virginia: Examining upper mantle interaction with Paleozoic sutures, Eocene magmatism, and modern seismicity

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Proposed site: *Virginia (Appalachian Valley & Ridge - Piedmont - Atlantic Coastal Plain)*

The central Appalachian orogen, with its well-developed foreland fold-and-thrust belt and paired metamorphic hinterland, is a classic example of an ancient collisional mountain belt. The orogen has been modified by Mesozoic rifting and, in western Virginia, Eocene volcanism. In addition, Cenozoic erosion and uplift, along with recent seismic events suggest a dynamic modern landscape influenced by crustal structures, some of which may link to upper mantle structures. This region of the central Appalachians, often considered a type section for a "passive margin", is quite dynamic.

To address the poorly understood dynamism of this region, we propose a 300 km transect across the Virginia Appalachians, extending from the Appalachian Structural Front in the northwest to the accreted terranes and Mesozoic rift basins buried beneath the Atlantic Coastal Plain in the southeast (Fig. 1). This is a superb locale for testing a number of hypotheses concerning lithospheric structure and dynamics in eastern North America using the EarthScope Transportable and Flexible Arrays. The Virginia transect crosses from thin-skinned foreland to a thick-thinned Laurentian basement massif to accreted terranes in the metamorphic hinterland that were later modified by Mesozoic Atlantic basin rifting and post-rift contractional reactivation. Although the Appalachians are a Paleozoic orogeny built upon a Proterozoic foundation, this section of the central Appalachians is particularly noteworthy as it experienced mantle-derived magmatism during the Eocene (Southworth et al., 1993; Furman and Gittings, 2003) and, as evidenced by the 2011 M_w=5.8 earthquake in central Virginia, is seismically active.

Key Scientific Questions and Background

Seismic refraction data indicate that the crust in the central Appalachians thins from ~50 km along the Appalachian Structural Front (western margin of the Valley & Ridge) to ~35 km at the Coastal Plain's westward edge (Fig. 1) (James et al., 1968; Taylor and Toksoz, 1982). Existing seismic reflection profiles are replete with east-dipping reflectors imaged to depths of 10 to 12 km (Harris et al., 1986). Deep crustal reflectors occur above the Moho (Pratt et al., 1988), however the origin and significance of these reflectors is less clear. Mantle anomalies in seismic velocity, discontinuity depth, and reflectivity indicate that variations in temperature and/or chemistry are present in the mantle beneath the study area (e.g. van der Lee et al., 2008; Courtier and Revenaugh, 2006). Shear wave splitting and receiver function analysis suggest subvertical mantle flow beneath the Piedmont and Coastal Plain, although the flow direction is unclear (van der Lee and Frederiksen, 2005; Long et al., 2010). Clearly, there is much work to be done to better image how structures throughout the crust and upper mantle may be interlinked.

The allochthonous Blue Ridge basement massif was thrust over early Paleozoic strata of the Valley & Ridge and structural relief across this boundary exceeds ~8 km in north-central Virginia (Fig. 1) (Evans, 1989). A major unresolved issue concerns the geometry of the Blue Ridge Fault zone (BRFZ) in the subsurface. Existing reflection profiles illustrate gently-dipping to sub-horizontal reflectors beneath Blue Ridge basement, which have traditionally been interpreted as Paleozoic shelf strata (Harris, et al., 1986; Pratt et al., 1988; Lampshire, 1994). However, mylonite zones exposed at the surface merge into these reflectors at depth (Bailey and Simpson, 1993; Chapman et al., 2003), suggesting that the BRFZ extends into the lower crust. Thus, the "thin-skinned" component of the orogen may not extend nearly as far eastward as previously thought.

The Virginia Piedmont includes a number of distinct terranes (e.g. the Hardware, Chopawamsic, and Goochland terranes) separated by dextral transpressive high-strain zones and faults (Fig. 1). Orogen-parallel displacement was significant, prior to the Alleghanian orogeny Virginia's Piedmont terranes were located from 100 to 500 km to the northeast in the north-central and northern Appalachians (Bobyarchick, 1981; Gates et al., 1988; Bailey et al., 2004). A number of distinct geophysical anomalies are imaged beneath Coastal Plain sediments (Fig. 1), although the significance and origin of these anomalies (Paleozoic sutures, Mesozoic mafic complexes, etc.) is uncertain (Snyder, 2005, Horton et al., 2010). The deep structure of these possible terrane-bounding zones and linkage to mantle structures is poorly resolved but can be addressed using the EarthScope Arrays.

The central Appalachians experienced rifting during the early Mesozoic, which reactivated Paleozoic structures and created the Culpeper/Barboursville, Scottsville, Richmond/Taylorsville basins (Fig. 1). The proposed Virginia transect crosses from an unrifted margin into the thinned crust beneath the Coastal Plain and would provide comparative data on basin geometry across the rift. Withjack et al. (1998) recognize post-Triassic tectonic inversion structures in many basins, but the magnitude and extent of inversion across the orogeny is unclear. Existing seismic data does not adequately discern whether basin-bounding faults are deep structures with an expression in the lower crust and mantle or are shallow localized structures consistent with an upper-plate rift setting.

Preliminary geochemical and petrographic analyses of alkaline Eocene volcanic rocks at Mole Hill in the central Shenandoah Valley indicate the presence of an Al-augite (clinopyroxenite) mantle with a temperature of ~1220° C at a pressure of 13 kbar, corresponding to a minimum Moho depth of ~39 km (Sacco et al., 2011). More detailed work on these enigmatic, young intrusive suites will test models of the thermal structure of the mantle and mechanisms of magma generation at passive continental margins. By matching crustal xenoliths to their parent rock formations through petrography and geochemistry (Kiracofe et al., 2011), existing structural models of the crust can be evaluated and provide a connection between surface observations and seismic data.

The proposed transect crosses the central Virginia Seismic Zone (CVSZ), a diffuse zone of moderate seismicity between Richmond and Charlottesville (Fig. 1) (Bollinger, 1973; Bollinger and Sibol, 1985). CVSZ earthquakes occur in the upper crust (<10 km) typically along moderately dipping reverse faults consistent with a subhorizontal σ_1 oriented northeast-southwest (Kim and Chapman, 2005). The magnitude 5.8 earthquake in August, 2011 was the largest seismic event in eastern North America in over a century and caused damage from central Virginia to Washington, D.C. The causative mechanism for seismicity in the CVSZ is poorly understood. Does faulting in the central Appalachians result from distal ridge-push stresses or from underlying mantle-derived stress fields?

Summary

The central Appalachians, and specifically the region of the proposed Virginia transect, demonstrate features not expected in a "typical" passive margin setting. Either this region is anomalous, or our preconceptions of old orogens and passive margins are too simplistic. In either case, we maintain that this central Appalachian transect has great potential to yield fundamental discoveries of the type that have characterized the best EarthScope projects to date. In addition, the Mid-Atlantic region has several large population centers, including Washington, D.C. Viewed from an education and outreach perspective, the recent D.C. area earthquake was a timely event that will enable us to highlight the arrival of the Transportable Array in the political center of the U.S. This will be a fantastic opportunity to showcase EarthScope science to policy makers. A focused project in the region, such as the one proposed here, has the potential to produce fundamental earth science discoveries and enhance public perception of our discipline.

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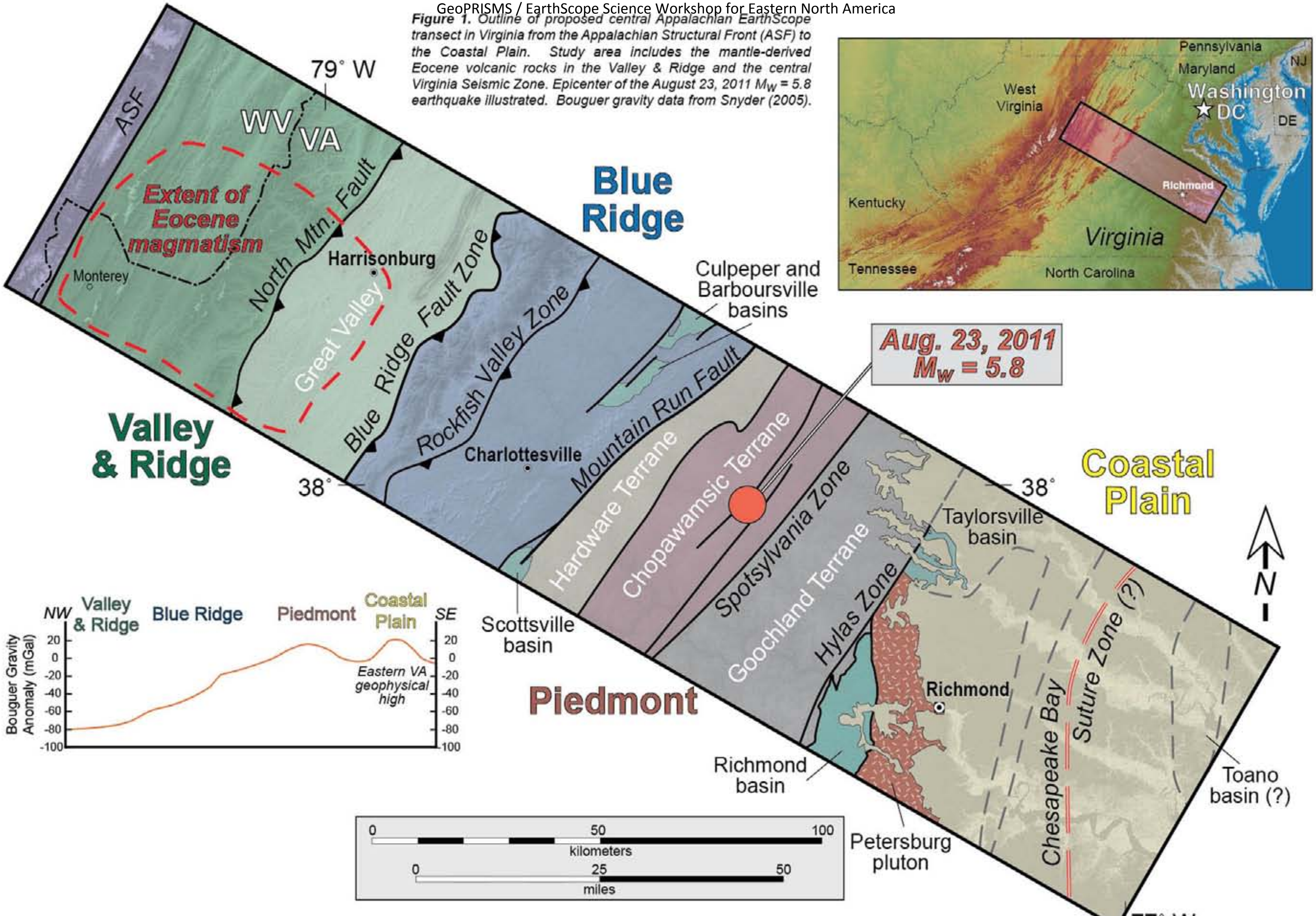

Figure 1. *Outline of proposed central Appalachian EarthScope transect in Virginia from the Appalachian Structural Front (ASF) to the Coastal Plain. Study area includes the mantle-derived Eocene volcanic rocks in the Valley & Ridge and the central Virginia Seismic Zone. Epicenter of the August 23, 2011 $M_W = 5.8$ earthquake illustrated. Bouguer gravity data from Snyder (2005).*

Testing the Lithospheric Counterflow Hypothesis

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In the past three decades since the publication of McKenzie (1978), which presented what is now termed the Uniform Lithospheric Extension model, significant quantitative advances have been made in understanding the structure of rifted continental margins using multiple geophysical, geochronological, petrological and geochemical techniques. Despite these advances, we have only a rudimentary understanding of the processes involved in the development of rifted continental margins, particularly the roles of depth-dependant lithospheric extension, inherited crustal weaknesses, flow of lower continental mantle lithosphere, and syn-rift sedimentation.

Huismans and Beaumont (2011) have advanced the new hypothesis that partly metasomatized (refertilized) lower cratonic lithosphere may be sufficiently weak (low viscosity) and chemically depleted (low density, $\Delta\rho$ = 10-80 kg/m^3, (Lee, 2003)) that it will flow toward the rift axis under gravity during rifting. If correct, this implies that the mid and outer regions of some continental margins will be underplated by thick lower cratonic lithosphere….'lost continent under the oceans'. Huismans and Beaumont proposed this model in the context of the flow of thick cratonic lithosphere and suggested that it applies to the west African margin outboard of the Congo craton and the Exmouth plateau margin outboard of the Pilbara craton.

More recently, Ings and Beaumont (2011) have generalized this hypothesis and propose that thick depleted continental mantle lithosphere in general, not just cratonic lithosphere, may flow in the manner proposed by Huismans and Beaumont (2011). They have termed this the Lithospheric Counterflow hypothesis because the lower lithosphere flows in the opposite direction from the motion of the overlying rifting margins (Figs 1 and 2).

The lithospheric counterflow hypothesis has several significant implications. It may explain: i) exhumed continental mantle lithosphere at rifted margins as noted above; ii) anomalous geochemical signatures in magmas contaminated when passing through this continental lithosphere and properties of xenoliths derived from this mantle (O'Reilly et al., 2009); iii) the paradox that both sides of many conjugate margins appear to be 'upper plate' margins; iv) a two-stage breakup in which crustal rupture occurs before that of the mantle lithosphere; v) a significantly longer syn-rift interval than previously indicated and a significant delay of up to 20 Ma between crustal rupture and final breakup of the continental mantle underplate and onset of ocean-floor spreading;
vi) anomalously shallow water syn-rift conditions at margins of this type owing to the reduced subsidence caused by low density underplate (Huismans and Beaumont, 2011).

Rifted continental margins are commonly divided into volcanic (magma-rich) and non-volcanic (magma-poor) types. There is general agreement that the east coast United States margin is volcanic, whereas the Newfoundland-Iberia conjugate margins and margins of Labrador and West Greenland are largely non-volcanic. The transition from volcanic to non-volcanic type occurs offshore Nova Scotia and represents a primary target for study in regard to the reasons for transitions between these two types (see Nedimovic et al., 2011, white paper, this volume)

Counterflow may also contribute to the difference between volcanic (e.g. US east coast) and non-volcanic (e.g. Newfoundland-Iberia) margins. We propose that margins subject to counterflow will be magma poor because the already depleted lower continental lithosphere will not yield decompression melts, and upwelling of asthenosphere, which normally produces magma, is inhibited by the counterflow. Melt infiltration will be therefore be delayed, consistent with observations (Jagoutz et al., 2007; Muntener et al., 2010) and potentially contribute to initially thin oceanic crust. Moreover, 3D lithospheric counterflow with a component of strike parallel flow may dam or absorb magma from a remote source that is flowing axially along the base of the lithosphere beneath the rift, e.g. CAMP magmatism.

In this ‘white paper’ we propose that GeoPRISMS–Earthscope evaluate and test the lithospheric counterflow concept. This is a proposal for a study in which the seismic and associated experiments can be tuned to test this hypothesis based on existing numerical results. From the arguments presented above, we suggest that non-volcanic margins are most likely to be underplated in this manner. An obvious choice is a detailed study of the Newfoundland conjugate of the Newfoundland -Iberia margins system, particularly focussed on the mantle lithosphere of the ocean-continent transition and the evidence for flow of the exhumed mantle lithosphere normal to the margin during rifting. A similarly good target is the volcanic to non-volcanic transition within Nova Scotian margin and the prolongation of the margin to the northeast.

We base this proposal on results from 2D thermomechanical upper-mantle scale finite element The models shown here contrast rifting of standard 125 km thick lithosphere (Fig. 1) with that of 200 km thick chemically depleted mantle lithosphere. Depending on the properties of the crust and mantle, two types of two-layer two-stage rift systems develop: Type I margins where the crust remains coupled to the mantle lithosphere during rifting producing narrow margins in which the crust necks before the mantle lithosphere; Type II margins where the crust is weaker allowing it to decouple from the mantle during extension producing wide margins in which the mantle necks before the crust finally rifts (Huismans and Beaumont, 2008, 2011).

When the mantle lithosphere is thick and chemically depleted, the hotter buoyant lower mantle lithosphere flows toward to rift axis during rifting and is exhumed toward the surface. Depending on the stretching width of the overlying crust (Type I vs Type II) and the run-out length-scale of the buoyant lower mantle lithosphere, the continental mantle will either underplate the crust or be exhumed in the ocean-continent transition. The combination of a Type I-rifting style with a long run-out results in the exhumation of wide tracts of continental mantle lithosphere, subsequently serpentinized owing to hydration (Fig.2).

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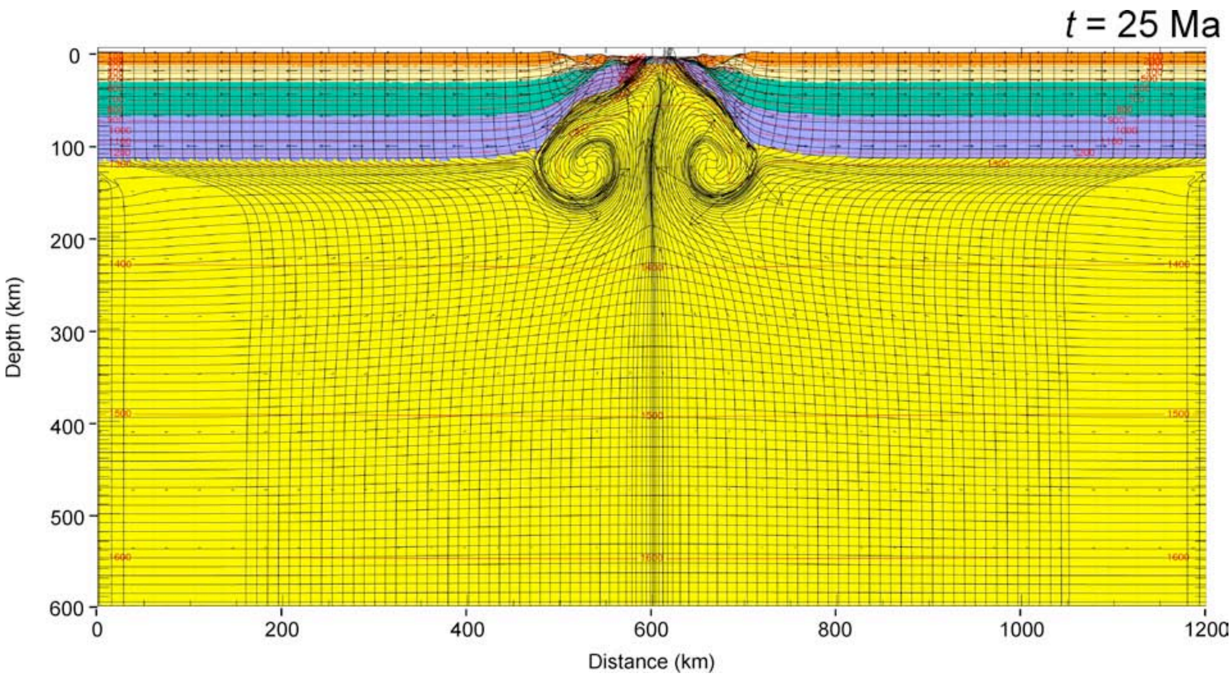

Figure 1. Post-rift configuration of a numerical model with 125 km thick lithosphere with no chemical depletion. The crust (orange and sand-color) and continental lithospheric mantle (green and light blue) have rifted at approximately the same time. Asthenosphere shown in yellow.

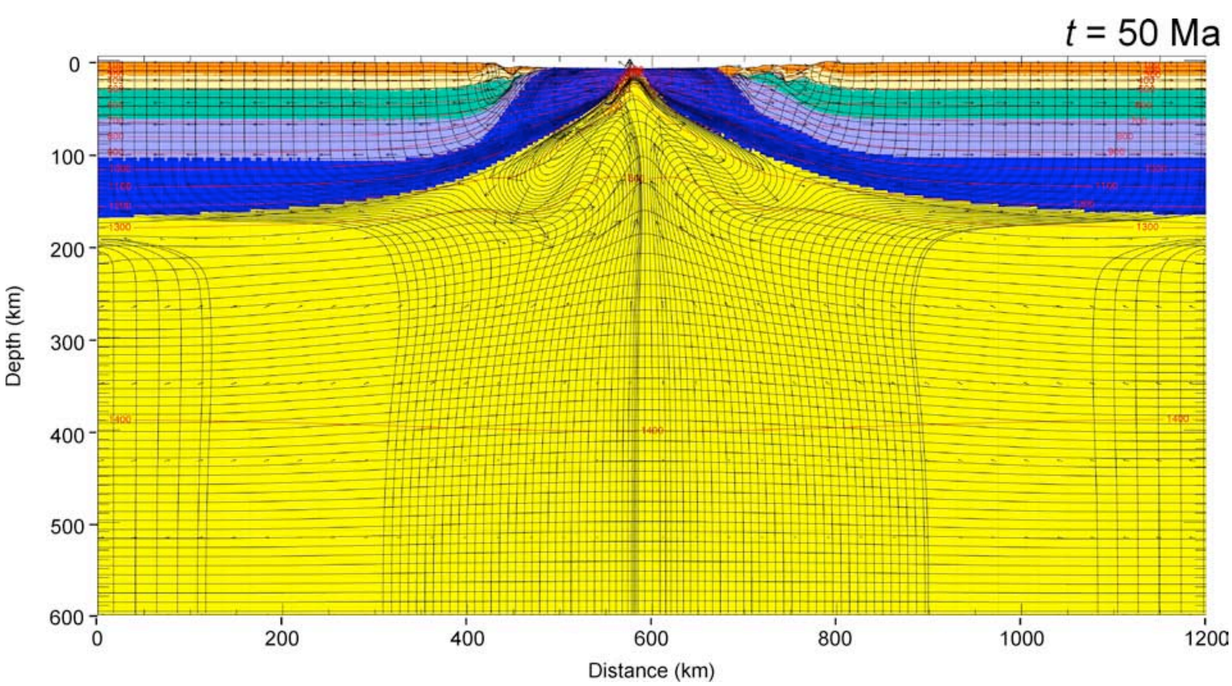

Figure 2. Post-rift configuration of a numerical model with 200 km thick lithosphere with 80 kg/m^3 chemical depletion. Other properties are as in Fig. 1. Rifting of the crust (orange and sand-color) occurred before the rifting of the buoyant continental lithospheric mantle (green, light, and dark blue). Hot, buoyant, low viscosity lower continental lithosphere (dark blue) flows toward to evolving mid-ocean ridge during rifting; counter to the tectonically driven movement of the crust and brittle upper mantle.

Integrating lithospheric structure, mantle dynamics, and surface processes to investigate topographic and lithospheric evolution of the southeastern US continental margin

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Several of the science questions outlined in the GeoPRISMS RIE implementation are inextricably linked to the science targets outlined in the EarthScope Science Plan for 2010-2020. Four areas of fertile overlap between these two documents include:

- Characterizing the broad-scale lithospheric structure of the eastern US margin and how it relates to the syn- and post-rift continental evolution
- Understanding the role mantle dynamics plays in controlling passive margin development and surface topography
- Investigating the role that magma and volatiles played during continental breakup and post-rift evolution
- Understanding the feedbacks and interplay between surface processes and tectonics in the evolution of the continent.

The most effective way to probe the structure and dynamics of the crust and mantle over a region as broad as the proposed ENAM focus site is to analyze seismic array data in the context provided by geochemical, geomorphological, and geodynamical constraints. Our preliminary analysis of existing broadband seismic data as well as new data collected by the TEENA array (Test Experiment for Eastern North America; Benoit and Long, 2009) suggests three main findings. First, we observed extremely sharp variations in crustal thickness (on length scales of ~25 km or less) that correlate with Precambrian structures and domain boundaries, suggesting that inherited pre-rift structures may have influenced rifting (Benoit et al., in prep.). Second, we identified evidence for magmatic underplating beneath the Appalachian Piedmont and Coastal Plain based on an analysis of lithospheric structure from receiver functions and gravity data (Benoit et al., in prep). Third, we identified lateral variations in SKS splitting patterns between stations located in the Appalachians and those located closer to the coast, which suggests a transition in mantle flow direction and/or a transition in lithospheric anisotropy structure at the southeastern edge of the North American continent (Long et al., 2010).

Our own preliminary work (Long et al., 2010; Benoit et al., in prep) as well as the recent work of others (e.g., Abt et al., 2010) suggests that there are intriguing variations in both crust and mantle structure trending perpendicular to the present day margin. Unfortunately, the 75 km EarthScope Transportable Array station spacing that is planned for this region is too sparse to fully sample the small-scale variations in structure across domain boundaries. Thus the densification of the TA with Flexible Array-style experiment(s) trending perpendicular to the margin, in combination with constraints from geodynamical modeling and geomorphological analysis, is necessary to address the science questions related to the role that pre-existing structures and mantle dynamics have played in rifting and evolution of the margin.

Variations in crustal and mantle structure can be linked to both surface processes (from geomorphological investigations) and mantle flow (from geodynamical models) to provide a vertically integrated picture of tectonic processes from the surface to the deep mantle. There is an ongoing interplay between erosion, topography, and lithology, and topographic change records a complex set of processes, including dynamic processes in the mantle and perhaps changes in the buoyancy structure of the crustal roots that underlie the mountains. It is not well understood how each of these factors contributes and better constraints on the history of topographic change and its relationship to the deep structure and dynamics are needed. Therefore, a collaborative interdisciplinary effort is required to constrain the nature of these relationships at the continents margin.

We suggest that a transect from the Virginia coastline westward past the Grenville Front in Kentucky (Figure 1) represents an ideal location for investigating these science questions. As a choice for the location of a margin-perpendicular transect, this region offers a number of advantages. The transect would sample a large number of physiographic provinces and domain boundaries, including those of the Appalachian Plateau, Appalachian Valley and Ridge, Blue Ridge Mountains, Pieldmont, and Coastal Plain. The region contains significant Proterozoic, Paleozoic, Mesozoic, and Cenozoic volcanic exposures and has exhibited recent seismic activity (the magnitude 5.8 earthquake in Mineral, VA, in August 2011, and subsequent aftershocks). The region is unique globally in that it preserves two overlapping large igneous provinces. The proposed transect exhibits relatively high, persistent topography and active surface processes. There is evidence for abrupt spatial variations in crustal and lithospheric structure in this region from the TEENA experiment (Benoit and Long, 2009). Finally, this choice of location offers the advantage that the Grenville Front is relatively close to the Atlantic coast compared to other locations along the margin, which makes the logistics of a linear seismic array that goes from the coast to the west of the front substantially easier.

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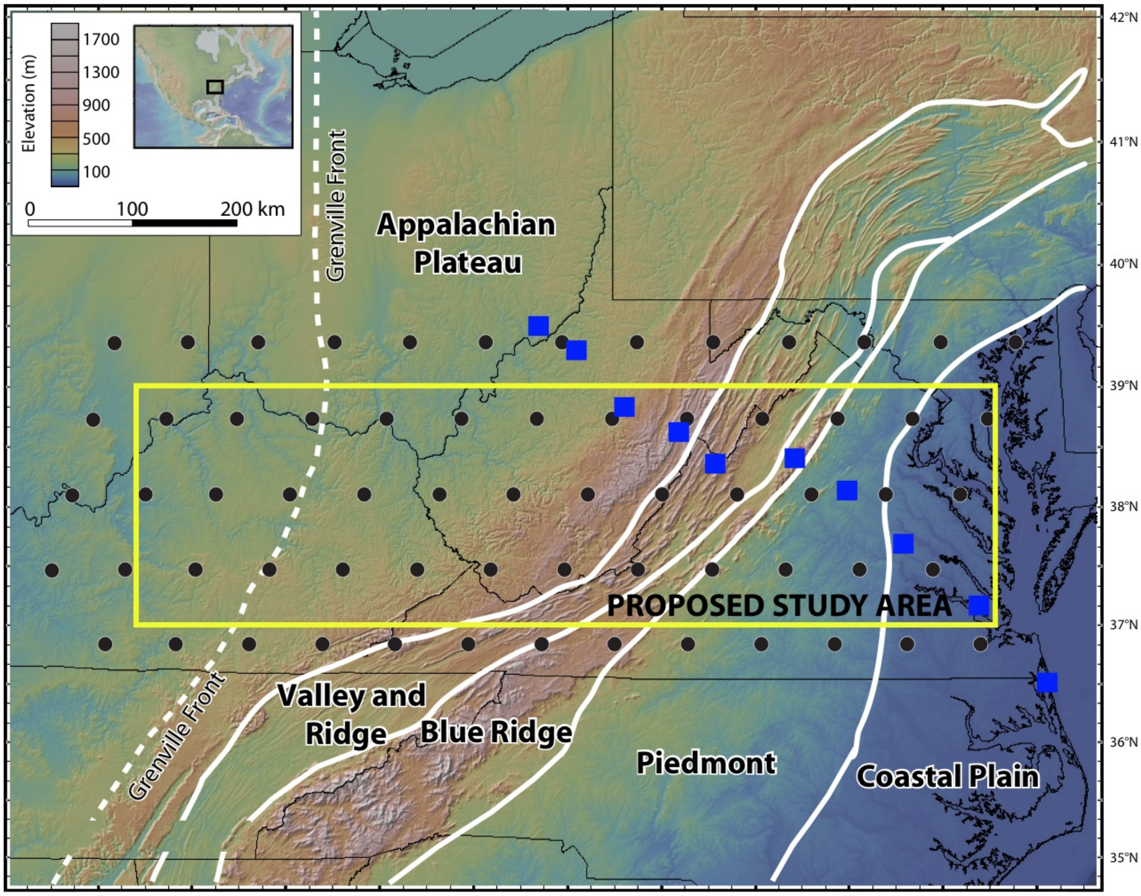

Figure 1. Map of proposed study area showing topography and physiographic provinces. Black circles show the nominal Transportable Array station locations in the region; blue squares show the locations of the TEENA experiment stations (Benoit and Long, 2009).

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EarthScope in the New England Appalachians: Structural inheritance and the long-term strength of continental lithosphere

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Introduction

Eastern North America is essentially the birthplace of the Wilson Cycle concept (Wilson, 1966). Since the Mesoproterozoic, the Appalachian region has undergone two cycles of supercontinent assembly and breakup. As a result, it is an ideal place to examine the problems of orogenic segmentation, structural inheritance, and the long-term strength of continental lithosphere, all of which are fundamental issues to orogenic belts worldwide. In the Appalachians, one long-standing hypothesis holds that 1) large, lithospheric-scale anisotropies were established during the Late Proterozoic–Early Cambrian rifting of eastern Laurentia and 2) these features have had a first-order influence on lithospheric behavior during subsequent contractional and extensional events. An evaluation of this hypothesis is essential, not only for understanding the origin of abrupt along-strike changes in the structure and tectonic history of the Appalachians, but also for determining the long-term (≥ 100 m.y.) strength and rheology of continental lithosphere.

Previous work in the northern Appalachians of Quebec and New England suggests that large, cross-strike fault systems in basement rocks partition the orogen into segments at scales ranging from 50 to 100's of km. These fault systems appear to have created long-lived zones of weakness that were reactivated repeatedly during the Paleozoic Taconian and Acadian orogenies and the Mesozoic opening of the Atlantic Ocean (Thomas, 2006). However, there is uncertainty about the size and spatial distribution of these features (Allen et al., 2009) and their possible effects on Appalachian tectonics. Much of the uncertainty comes from inadequate information on the structure of the deep crust and upper mantle beneath the New England Appalachians. Despite the recognition of large basement anisotropies, there is great uncertainty about their depth and character and how they may have affected the behavior of deforming continental lithosphere during a ≥ 500 million year period involving several orogenies and the opening of two ocean basins.

Specific questions include: 1) Are lithospheric-scale, cross-strike anisotropies present in the crust and mantle of the New England Appalachians, and, if so, do these anisotropies reflect segmentation inherited from the Neoproterozoic Iapetan rift margin of Laurentia? 2) What is the relationship between large, cross-strike anisotropies and the stratigraphy and structure of the upper crust, including Neoproterozoic rift and Cambro–Ordovician passive margin strata, Appalachian basement massifs, and early Mesozoic rift basins? 3) How did the geometry and spatial distribution of relic Neoproterozoic faults affect crustal and lithospheric strength and how did these variations affect subsequent orogenic and rifting events?

Possible long-lived crustal anisotropies beneath Vermont and Quebec

Using data collected from over 400 seismic lines and 120 wells, Theriault and Laliberte (2006) constructed several 3-D structural maps of Precambrian basement that underlies the St. Lawrence Lowlands Province of southern Quebec. The data reveal the presence of swarms of SSE-deepening normal faults that compartmentalize the crust and display an asymmetric, segmented pattern that is remarkably similar to the crustal- and lithospheric-scale segmentations observed in the East African rift system (Wolfenden et al., 2004; Mackenzie et al., 2005). Theriault and Laliberte (2006) also identified a second system of orthogonal E-W (cross-strike) faults that are interpreted to be genetically related to the formation of grabens and transforms during the drift phase of Iapetus. These faults typically form km-wide linear collapse zones and are postulated to have been reactivated during the early Paleozoic Taconian orogeny and again during subsequent rifting.

A similar reactivation of basement anisotropies also has been inferred for other parts of the New England Appalachians, including Vermont (Doolan et al., 1982; Crespi et al., 2010). In the Champlain Valley, abrupt changes in the thickness of synrift and postrift stratigraphy, facies transitions, and differential subsidence occur along the strike of the orogen (Dorsey et al., 1983; Cherichetti et al., 1998; Thompson et al., 2004; Kim et al., 2007). These zones appear to coincide with abrupt changes in depth to basement and thrust style (Doolan et al., 1982; Stanley and Ratcliffe, 1985), suggesting they represent long-lived basement anisotropies that partition the orogen into segments that differ in structure and tectonic history. Their apparent origin during or prior to the Late Proterozoic–Early Cambrian rifting of eastern Laurentia and influence on subsequent orogenic and rifting events suggest the heterogeneities are crustal or lithospheric in scale, making them prime targets for the USArray.

Basement massifs and inherited strength of continental lithosphere

In the New England Appalachians, Mesoproterozoic rocks are exposed in a series of basement massifs that lie along the outboard edge of Laurentia. The massifs are common in the New York promontory, disappear in the Quebec embayment, and reappear north of Quebec City, indicating that both their presence and behavior during orogenesis is spatially variable. Recent work in the Berkshire massif by Karabinos et al. (2008) suggests the massif behaved as a rigid block during the Middle to Late Ordovician Taconian orogeny. Previous workers (Stanley and Ratcliffe, 1985) suggested that the massif had undergone significant internal shortening via displacement along a network of Taconic-age thrust faults. However, new isotopic dates and field observations (Karabinos et al., 2008) contradict this interpretation and highlight this issue as an important problem to resolve.

The Berkshire massif and other basement massifs provide a window into understanding the mechanical behavior of the middle crust during orogenesis, and modern collisions can guide our understanding of these rocks, which commonly have long, complex histories. For example, in the active arc-continent collision in Taiwan, the Sanyi-Puli seismic zone marks the location of a partially subducted transform fault. The interpreted boundary between continental crust of normal thickness and transitional crust makes a leftward step across the transform, and the corner region of partially subducted, normal-thickness continental crust has low seismicity and acts as a strong indenter (Byrne et al., 2011). The Berkshire massif may have occupied an analogous structural location in the Taconic arc-continent collision. This can be tested by identifying the location of relic Iapetan transform faults in the New England Appalachians, and it has implications for understanding the heterogeneity and inheritance of crustal strength.

Importance of the New England Appalachians and links to processes in active rifts

Active rifts, including the East African rift system, show the important effects of lateral variations in lithospheric strength on rift processes. For example, in Kenya and northern Tanzania, the eastern branch of the rift is deflected and changes geometry where it encounters the thick, cold lithosphere of the Archean craton (Macdonald et al., 2001). Focused studies in the New England Appalachians that target lithospheric-scale, cross-strike anisotropies have the potential to illuminate the geometry of these anisotropies, their longevity, their effect on Appalachian contraction and Mesozoic extension, and their relation to lateral and vertical variations in strength of continental crust and lithosphere. Results of this work would further bear on seismic hazards and geothermal energy potential in the region.

Establishing a New England Appalachian *EarthScope* and *GeoPRISMS RIE* "Discovery Corridor" would build on and benefit from existing synergies such as strong state agency-university partnerships in the region that provide important undergraduate and graduate research opportunities. High-quality results are anticipated from the New England Appalachians for the following reasons: 1) On-the-ground geological work over the past 200 years has resulted in an excellent understanding of the Late Proterozoic–early Paleozoic rift-drift stratigraphy. 2) A collaborative effort between the Vermont Geological Survey and the USGS has resulted in a new bedrock geologic map of the entire state (Ratcliffe, 2010; Walsh et al., 2010). 3) Preliminary work has identified specific candidates for large, cross-strike faults. 4) Studies in the Quebec Appalachians have produced a superb geological and geophysical database, providing important context for understanding the New England segment of the Appalachians.

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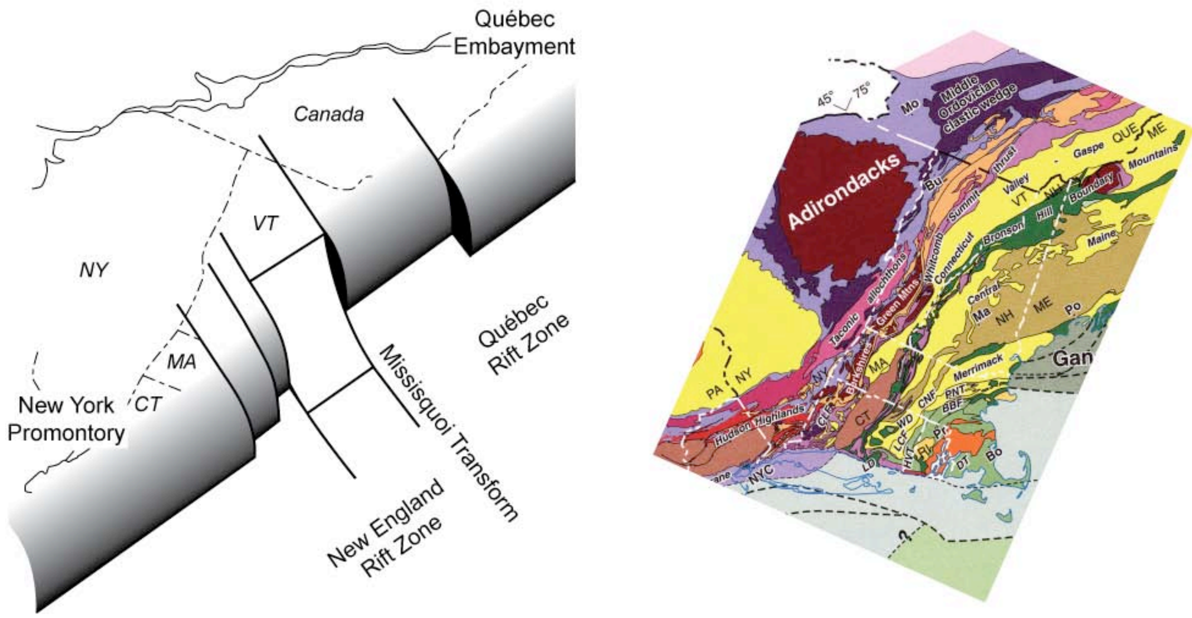

Figure 1. Interpreted segmentation of Iapetan rift margin and tectonic map of New England Appalachians. Modified from Fig. 3 of Allen et al. (2009) and Fig. 1 of Hatcher (2010), respectively.

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Submarine Groundwater Discharge: Linking the Continental and Oceanic Hydrospheres

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EarthScope Theme: Hydrosphere, Cryosphere, and Atmosphere
GeoPRISMS Theme: Mechanisms and Consequences of Fluid Exchange Between the Earth, Oceans, and Atmosphere

Summary
Onshore-offshore groundwater flow occurs over many temporal and spatial scales along the continental margin [*Younger, 1996; Moore, 1996; Cohen et al., 2010*], with significant implications for society (water supply) and a wide range of coastal ecosystems [Fig. 1] [*Moore, 2010*]. Observations document submarine discharge of fresh and saline groundwater along the entire US East Coast margin, exiting the seafloor from meters to nearly 100 km offshore [*Hathaway et al., 1979*]. Measurements and models show that modern processes (e.g., rainfall, tidal loading) can affect these flow systems locally and rapidly [Fig. 1] [*Michael et al., 2005; Taniguchi et al., 2006; Wilson and Gardner, 2006*], but also that long-term processes (e.g., sea-level change, glaciation) can affect these systems at a regional scale [Figs. 2,3][*Cohen et al., 2010; DeFoor et al., 2011*]. Many offshore flow systems are believed to be out of equilibrium with modern sea level and topography conditions and thus record previous conditions [*Person et al., 2003, Marksamer et al., 2007*]. Assessing the controls on submarine groundwater systems and their variations in time has important implications for understanding linkages between onshore and offshore flow systems, ocean chemical budgets, and human water supply [*Edmunds, 2001; Li et al., 1999; Slomp and van Cappellen, 2004*]. Accurate assessment of these systems: (1) requires detailed stratigraphic knowledge; (2) is a problem addressable along the US East Coast (a GeoPRISMS primary site); and (3) has societal relevance. These systems also link geological and climatological impacts that bridge EarthScope and GeoPRISMS and tie directly to the hydrosphere aspects of EarthScope and GeoPRISMS.

Scientific Addressability
Existing well and geophysical data provide ample information on the general distribution of offshore freshwater along the US East Coast margin [*Hathaway et al., 1979*]. Modeling studies of submarine groundwater systems constrain the basic behavior of many of these flow systems and submarine groundwater discharge, but they also indicate the importance of linking the long-term geologic evolution with the hydrologic cycle. The timing and type of sediments being shed from the continent and deposited on the shelf affects the pore pressure regime and the stratigraphic architecture, both of which affect the flow regime. Therefore it is crucial to understand the sediment inputs to the system over time, which is affected by the tectonic history of the continent and the structure of the margin. In addition, glacial history greatly affects subsurface hydrology along the margin due to its impact of fluid pressure [*Marksamer et al., 2007; Cohen et al., 2010*], but it also has topographic affects due to loading and flexure of the lithosphere [*Lemieux et al., 2008*]. This latter component is not well constrained but could be through EarthScope research that would feed into coupled ice sheet-sedimentation-fluid flow models [e.g., *Wolinsky, 2009*].

The low salinity of submarine groundwater presents an electrically resistive target that is suitable for geophysical imaging using controlled source electromagnetic (CSEM) technology developed during the past decade for offshore hydrocarbon exploration [e.g., *Key, 2011*]. Although this technology has not been applied to submarine groundwater study previously, an analogous well-tested application is CSEM mapping of resistive gas hydrate on the continental shelves [e.g., *Weitemeyer et al., 2011*]. CSEM mapping would provide vital constraints on the spatial distribution and concentration of submarine fresh water that could be integrated with seismic images of the stratigraphic architecture. CSEM imaging could also be used to map the lateral extent of groundwater identified from drilling studies.

Study Sites

Understanding large, offshore, non-equilibrium freshwater distributions requires knowledge of the emplacement mechanisms for the water in these systems and an understanding of the factors that have controlled these emplacement mechanisms through time [Figs. 1,2]. We propose two separate study areas to look at different temporal and spatial scales and at different driving mechanisms. The first study region is the New England continental shelf offshore Massachusetts and the second is the South Atlantic Bight offshore South Carolina. Models of the onshore-offshore hydrology offshore New England suggest that significant volumes of water are stored offshore and that glacial loading and sea level have impacted the long-term storage and discharge of continental freshwater into the ocean [Fig. 3][*Cohen et al., 2010*]. A combined EarthScope-GeoPRISMS study could help image the stratigraphy of the shelf, thus defining the hydrologic connectivity but also the deep earth structure that has affected the large-scale flexure and topography, which also influences the shallow fluid flow regime. CSEM studies will help define the distribution of this onshore-offshore freshwater resource. Thus we can address linkages between the cryosphere and the hydrosphere at the onshore-offshore transition.

The South Atlantic Bight study site provides an alternate end-member location with a very active modern, nearshore submarine groundwater discharge system. *Evans and Lizarralde* [2003] conclude that stratigraphically-controlled permeability enhancement has led to focused submarine groundwater discharge in the South Atlantic Bight. Offshore stratigraphy places important controls on the distribution, volumes, and recharge and discharge rates of freshwater in offshore environments. *Wilson et al*. [*2011*] show that nearshore (marsh) discharge in this region is tidally modulated, but also that stratigraphic distribution affects how the flow system responds to high-frequency water-level perturbations. The links between multi-scale flow processes, with temporal scales ranging from hours for tides to 100 ky for sea-level fluctuation, are very poorly constrained and depend strongly on an accurate understanding of stratigraphy and basin history. We have something like a zeroth-order understanding of these controls. A detailed study of stratigraphy and fluid type (freshwater, saltwater) through geophysics (seismic, CSEM) coupled with high-resolution monitoring of surface hydrology and subsurface hydrology and water chemistry will facilitate our ability to constrain linkages between fluid flux, local topography, and climate (rainfall) [Fig. 1] but also can be linked with continental controls of the stratigraphy linked to sediment flux from the Appalachians.

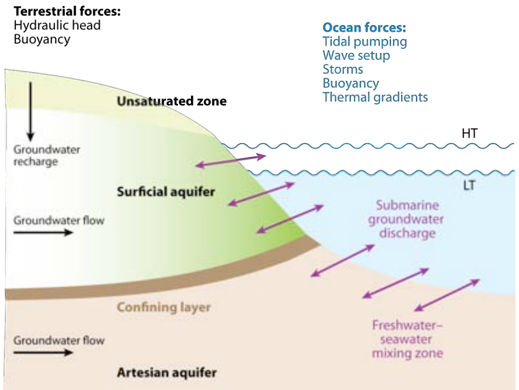

Fig. 1. Conceptual model of submarine groundwater discharge showing geologic components and terrestrial and oceanic forces. Figure from Moore [2010].

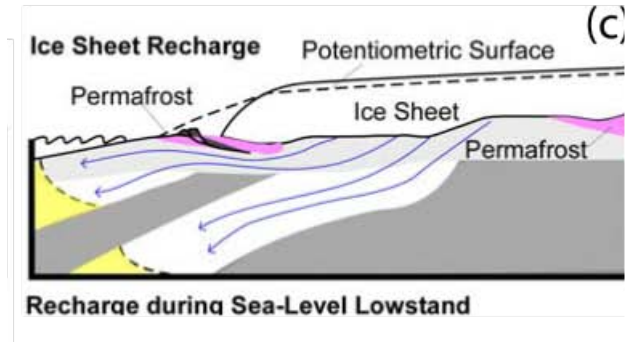

Fig 2. Example of impacts of glacial loading on submarine groundwater systems (blue arrows) including extending the freshwater zone and changing location and chemistry of SGD.

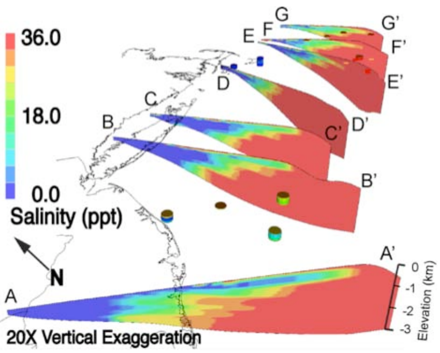

Fig. 3. Simulated salinity (in parts per thousand) along cross sections extracted from the three-dimensional finite element model of the Atlantic continental shelf. Cylinders depict concentration of offshore AMCOR, COST and ODP wells (well radii not to scale). The wells were raised 500 m above the sea floor in this image, so that the cross sections would not obscure them. Figure from Cohen et al. [2010].

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GEOPRISMS WHITEPAPER

TITLE: Slope Failure Control on Margin Morphology at the Cape Fear Slide

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I. Summary

Retrogressive submarine slide occur occurring on all of Earth's passive margins. These repetitive back-stepping failures record long-term instability (e.g., Micallef et al., 2008). They are wide-spread, they impact margin erosion and evolution, and they are a societal risk because of their potential to generate tsunamis. Their repetitive failure cycles make them both conducive for understanding failure conditions and for testing slope stability models and establishing what influences the size and rate of failure. Ultimately, these failure processes impact the large scale form of continental margins.

Why retrogressive submarine slides occur remains controversial (e.g., Dugan and Flemings, 2000, 2002; Maslin et al., 2004). Hypotheses for their occurrence invoke external drivers such as infrequent, strong earthquakes (e.g., Kvalstad et al., 2005). Others hypothesize that hydrate dissociation driven by sea-level fall or ocean warming drives slumping (*Paull et al.* 1991; *Rothwell et al.* 1998; *Maslin et al.*, 2004; Liu and Flemings, 2009)). Conversely, other studies hypothesize that sediment strength, slope geometry, and depositional history drive retrogressive slope failure (Dugan and Flemings, 2000; Lee, 2009; Locat et al., 2009) such that external drivers including sea-level fall or earthquakes are not necessary.

We propose an interdisciplinary multi-stage field-based study of slope stability focused on integrating in situ pore pressure measurements with high-resolution 3D seismic images and 3D fluid-flow/heat-flow observations and models to constrain key factors that cause instability at a retrogressive slide. Slope failure and associated tsunamis are a recognized geohazard for the East Coast of the United States and several studies link slope failure with climate change. Many studies have relied on empirical observations and correlations to estimate causes of slope failure on continental margins. We will test these hypotheses by providing a process-oriented understanding of failure based on direct observations. This study will elucidate the geotechnics of slope failure to understand how unloading due to slope failure can lead to a characteristic timescale of regressive failure. This timescale will be influenced in-part by the geotechnical properties of the slope. We will also directly address whether steady-state or dynamic (and therefore unstable) gas-hydrate stability conditions exist at a slide, and therefore, if methane hydrates are presently contributing to instability at these sites. Our study has the potential to define slide re-occurrence time-scales, slide size, and the process of slope failure by direct measurements of in situ time-dependent variables (e.g. pore pressure, stress), and how these variables affect margin stability with time. Our study is focused on the Upper Cape Fear Slide but the approach and expected results will be broadly applicable to retrogressive submarine failures around the globe.

II. Conceptual Model for Retrogressive Slope Failure

We propose a testable hypothesis for the processes that underlie retrogressive failure systems, which we term 'Pore Pressure Rebound'. When slope failure occurs, sediments near the headwall remain relatively strong because unloading has reduced the pore pressure: this limits further failure (Figure 1). Specifically, once an initial scarp forms, the lateral stress (σ_3) is reduced in sediments near the scarp face (figure 1B, figure 1E blue-to-green dot transition). The reduction in lateral stress increases shear (q) and drives the system toward failure (red dot Figure 1e). However, since fluids in headwall sediments are also no longer being squeezed laterally, fluid pressures are also reduced (the 'undrained poroelastic response') immediately following failure (figure 1B, 1E).

During failure, mean stress drops and therefore pore-pressure *drops*. At this point, the in situ shear stress (green dot, Figure 2C and E) is less than the failure strength at the same mean stress (the green dot is well below the failure line). Thus the in-situ stress is less than the failure stress and the system is stable. However, over time, lateral flow occurs toward the scarp face: pore-pressure begins to rise back towards its original values (figure 2C, figure 2E between green and red dot) (Bishop and Bjerrum, 1960; L'Hereux et al., in press; Leroueil, 2001). On the p'q plot, the stress path moves horizontally (green to red dot, Figure 1e). As it does, sediments near the headwall further weaken until failure again occurs (Figure 1e). Leroueil (2001) reports time scales from 50 years to 2000 years for ~40m high cliff faces, yet similar retrogressive submarine slides may be more stable (e.g. Rodriguez and Paull, 2000).

Retrogression will be controlled by four factors: (1) the magnitude of pore pressure drawdown due to unloading; (2) the coefficient of consolidation of the material which determines the rate of pore-pressure rebound; (3) the initial pressure conditions; (4) the failure properties of the material. Our research will lead us to (1) an understanding of the time scale of pore pressure equilibration (thus the timing of recurrent failure) (2) the current pore-pressure values at slide headwalls and (3) from this, if slides are near failure. Furthermore, by dating slide failure events, we can test whether pore-pressure rebound times generally match observed failure times, and from this, recognize if a link between pore-pressure rebound and slope failure exists.

To test whether pore-pressure rebound controls slope failure at retrogressive submarine slides, we must know (1) soil properties (e.g. undrained strength, porosity, permeability, friction angle), (2) sediment/slide geometry and thickness (to estimate overburden, pore-pressure, and stability near the headwall and extend sediment properties in space), and (3) the frequency of sliding, which we need to compare estimated pore-pressure rebound times with actual slope failure recurrence. To determine the timing of failure events across the slide, we will use C14 radiometric dating at the site in conjunction with seismic stratigraphy. To determine slide geometry and sediment/slide dip, we will use reflection seismology. To constrain soil properties, we will obtain and analyze long cores across the pre failure, failure, and post-failure surface, and interpolate these properties in two- and three-dimensions using seismic images.

III Study Area: The Upper Cape Fear Slide (CFS)

The Cape Fear Slide (CFS), perhaps the largest slide complex on the U.S. Atlantic margin, is located ~200 km southeast of Cape Fear, North Carolina, just seaward of the Carolina trough (Figures 2 and 3). Initial studies (Cashman and Popenoe, 1985) suggested the CFS may consist of only a few large slides. However, more recent multibeam studies have identified at least five (but likely many more) moderately sized (all >1 km^2) slide events [(Hornbach et al., 2007; Paull et al., 1996; Popenoe et al., 1993; Rodriguez and Paull, 2000; Schmuck and Paull, 1993)].

The upper headwall of the CFS has a crown-shaped morphology, is ~10 km long and ~20 m high (figures 2, 3). It is likely one of the youngest slides in the complex; old single-channel seismic lines indicate no other up-slope debris obscures the scarp and associated features (Carpenter, 1981). As the most landward component of a retrogressive slide, it also represents an area where future failure will likely occur.

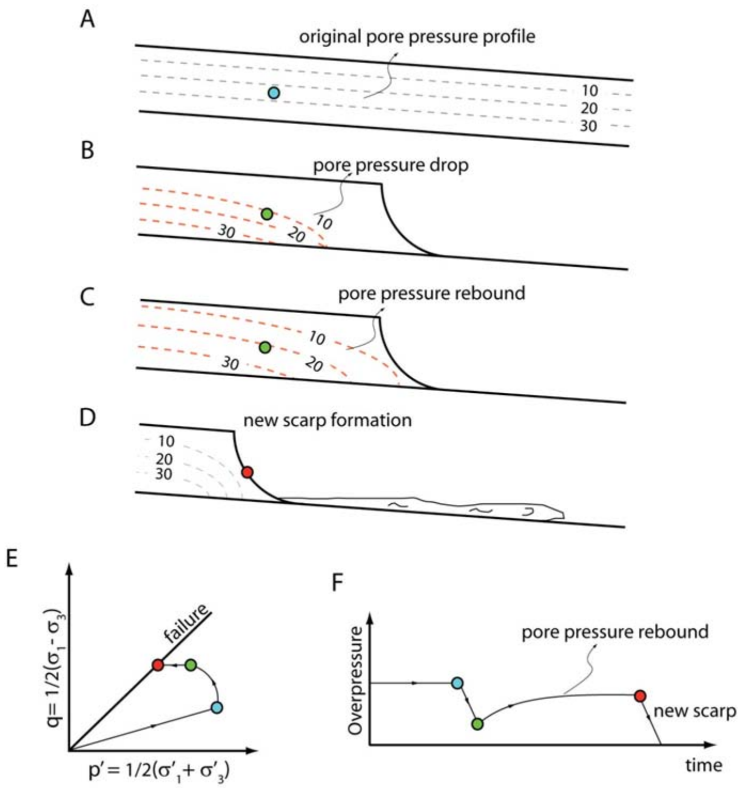

Figure 1. *Conceptual model for retrogressive failure.* ***A*** *Sediment is initially buried from seafloor to pre-failure depth.* ***B.*** *An initial slope failure unloads the lateral stress behind scarp. This increases shear stress but decreases pore pressure, keeping the slope stable in the short-term.* ***C****. Lateral flow causes pore pressures to rise gradually, which decreases effective stress over time and triggers subsequent scarp formation (****D****).* ***E.*** *Effective stress path plot illustrating the evolution of retrogressive failure.* ***F.*** *Overpressure vs. time showing pore pressure drop, rebound, and drop to failure.*

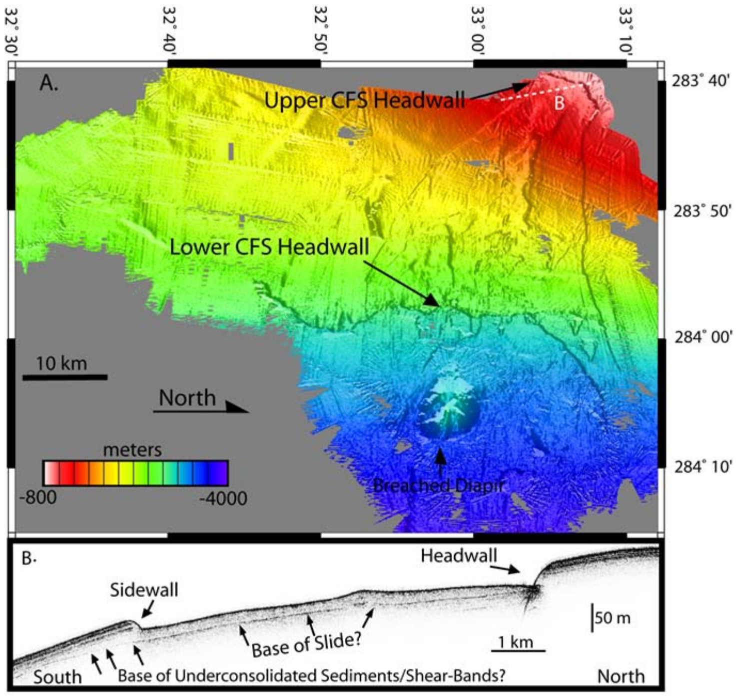

Figure 2.(**A**) Multibeam data collected at the Cape Fear slide complex during reconnaissance work on 2003 NOAA Ocean Exploration cruise (adapted from Hornbach (2007). (**B**) Single chirp seismic line collected across the headwall of Upper CFS. A continuous, variable amplitude reflector tracks across the section and may represent both the base of overpressure and base of the slide. No sediments onlap the sidewall or headwall, suggesting recent failure.

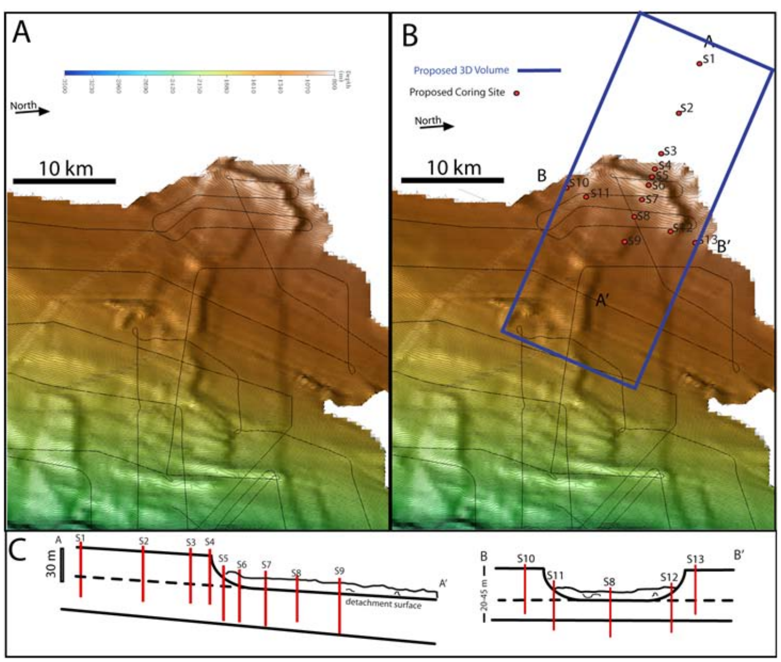

***FIGURE 3(A)** Basemap (same orientation as Figure 1) showing the multibeam data obtained in 2003 on the R/V Atlantis. Chirp lines are shown as thin black lines. (**B**) Proposed coring and seismic lines at the Upper headwall. (**C**) idealized 2D cross section of seismic data with core site locations in red. Chirp images and previous coring results near this area indicate long cores should penetrate below the proposed detachment surface.*

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The role of magmatism in rifting: insight from the lithospheric mantle

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Passive margins store the cumulative record of syn- and post-rift deformation, magmatism and sedimentation, and examination of these margins thus provides unique information on several key aspects of the rifting process highlighted in the GeoPRISMS science plan. Mature, evolved margins provide critical constraints on the distribution of deformation and magmatism throughout the lithosphere and the emergence during rifting of primary characteristics of mid-ocean ridges – for example, segment-centered magmatism focused at the ridge axis and the formation of tectonic segmentation. The locus of melting and associated deformation during rifting is located within the mantle, and the lithospheric mantle preserves structure inherited from and diagnostic of these processes, such as the patterns of melt depletion and shear deformation. The east-coast margin of the North American continent displays a remarkable diversity of syn- and post-rift structures, including failed rift basins, strong variations in apparent magmatic production, and correlation between margin structures and present-day mid-Atlantic ridge segmentation. Seismic imaging of the lithospheric mantle across and along the margin of east coast North America can thus provide us with knowledge of the basic magmatic and deformation processes that control rifting and its subsequent evolution.

The majority of the constraints on the volume and bulk composition of magmatism during rifting are derived from seismic studies of the crust, and therefore omit the magmatic processes that occur in the mantle. The generation of melts during rifting leaves behind a depleted mantle that is stronger and more buoyant, influencing development of the rift and the stability of continental lithosphere long after rifting. The mantle lithosphere also provides unique information on magma generated during rifting. Studies of mid-ocean ridges suggest that the extraction of melts to form new crust can be incomplete in very slow-spreading systems (which have a thicker, colder lithosphere), and at very magmatic ridges, where the volume of magmas can overwhelm the melt extraction system. Detailed estimates of shear and compressional velocities in the lithospheric mantle across regions of magmatic production provide a means to constrain the balance of melt production and extraction. Furthermore, anisotropy of the mantle lithosphere holds the record of pre-existing fabrics imparted prior to rifting, mantle deformation during rifting, and relationship of the deformation to magmatism. Traditional marine refraction experiments provide important but limited constraints on shallow mantle structure; expanding these constraints using far-offset mantle refraction and passive-source imaging are critical for extending these constraints to greater depths and more broadly across the margin system.

The east-coast margin of North America provides an excellent opportunity to investigate these processes. The breakup of Pangea to form the Atlantic margins was associated with one of the largest magmatic events in Earth's history: the Central Atlantic Magmatic Province, and the along-strike variation in magmatism associated with this event are clear from potential field data and crustal-scale imaging, with length-scales of segmentation ranging from 100-300 km. Three dimensional imaging experiments that span the crust and upper mantle will constrain the balance of melt production and extraction and its impact on extensional deformation under different magmatic conditions. Coupled with onshore instrumentation, these data will provide new contraints on the underlying differences between the extensive network of failed rift basins (e.g., Newark Basin, South Georgia basin) and the adjacent successful rift. Extending far offshore, this imaging will illuminate the magmatic and deformation processes across the transition from rifting to seafloor spreading, and will allow us to probe whether segmentation during the rift stage seeds to the dominant segmentation structure of mid-ocean ridges.

Imaging mantle structure across the margin requires far-offset active source work coupled with passive-source arrays. It is clear that a full program to understanding magmatism and deformation during rifting requires embedded higher-resolution surveys to characterize the crustal structure that is complementary to the underlying mantle.

GeoPRISMS Data Portal

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1) Introduction

The GeoPRISMS Data Portal of the Marine Geoscience Data System is funded by NSF under the IEDA Facility cooperative agreement to provide data services to the GeoPRISMS community. For each GeoPRISMS primary site, the data portal has been 'seeded' with a range of existing high-priority terrestrial and marine data sets. For the ENAM primary site, this includes, for example, Ewing multi-channel seismics cruises and links to USGS and Canadian LITHOPROBE surveys across the margin. The portal offers customised searches for GeoPRISMS-related data, and the GeoPRISMS bibliography database seamlessly links papers to the data sets and to funding awards.

GeoMapApp, Virtual Ocean and EarthObserver are map-based tools that provide rich data exploration, analysis and visualisation functionality (Figure 1).

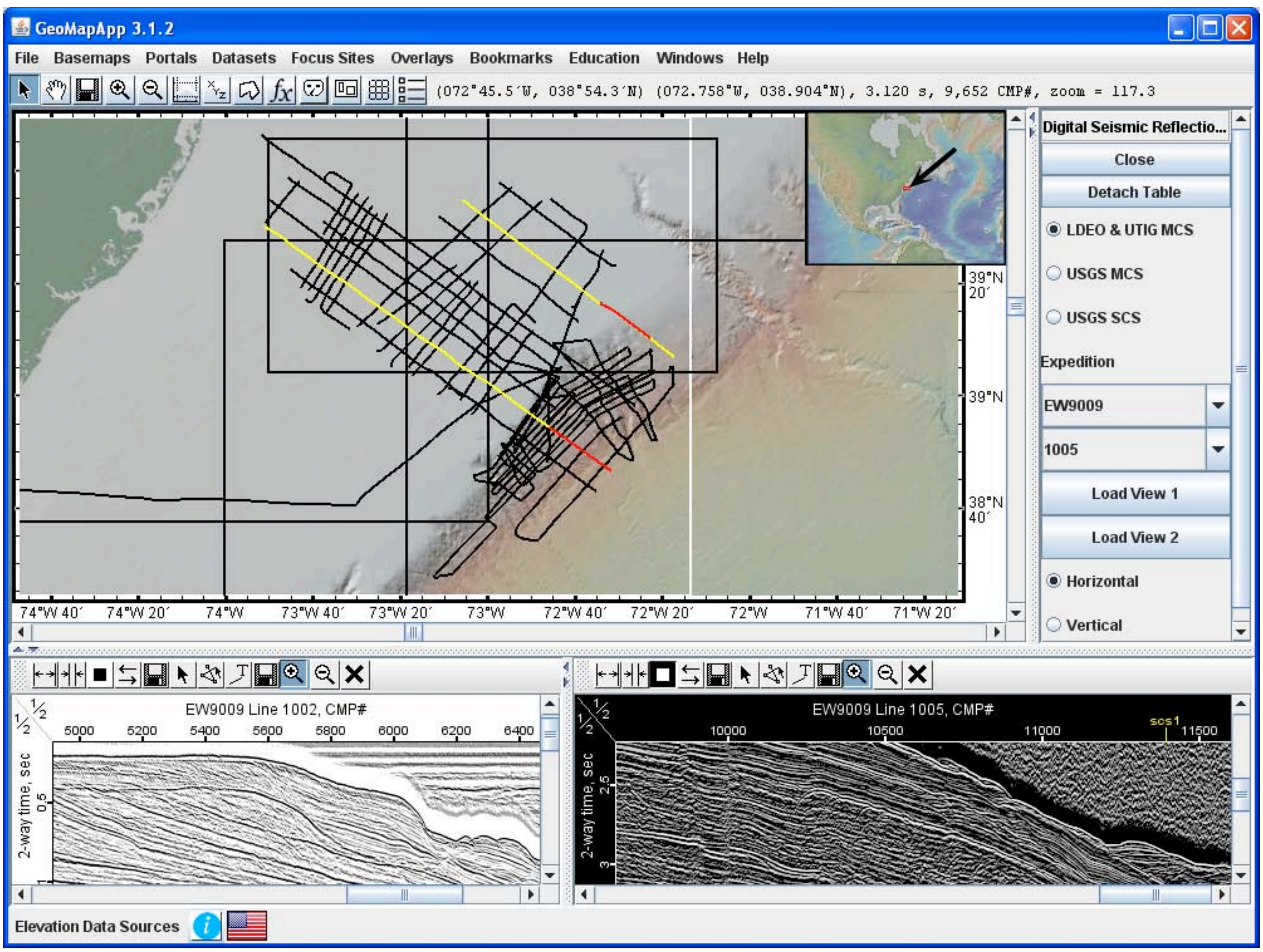

Figure 1: GeoMapApp screenshot showing Ewing EW9009 MCS lines 1002 (lower left) and 1005 (lower right, with inverse video turned on) across the New Jersey slope. The seismic lines are displayed on the map in yellow, with red portions representing the extent of the two profiles shown in the lower panes. A digitiser function allows horizons to be quickly delineated and saved to disk. The base map is the global multi-resolution topographic synthesis that offers 10m horizontal resolution of ENAM's on-land elevations and 100m or better resolution in the oceans and on the shelves.

2) Services

- **Data Portal**
  The GeoPRISMS data portal, like the predecessor MARGINS portal, is fully integrated with the wider Lamont database system and offers a compilation of pre-existing data sets of interest to the community. Links are provided to ENAM-related projects such as LITHOPROBE-FGP, and a simple search function, described below, provides user access to the data. As funding for GeoPRISMS research projects gets underway, the portal team will work with PIs, members of the community and the GeoPRISMS Office to ensure appropriate capture of marine and terrestrial field program information and derived data products.
  http://www.marine-geo.org/portals/geoprisms/

- **Search for Data**
  Data can be found (Figure 2) by searching on key words such as data or device type, name of field program or investigator, by geographic location, and even by award numbers. Filtered searches and auto-complete technology help speed users towards data.
  http://www.marine-geo.org/tools/new_search/index.php?initiative=GeoPRISMS

▸Field Data at MGDS

Click on title above to show/hide digital field data sets at MGDS

Data Set	Device Information	Event Information	Investigator	References
Navigation:Primary	R/V Endeavor Navigation	NotApplicable	Mountain, G.	NotProvided
Seismic:Active:Subbottom	Sled:CFAV Endeavour Seismic:Subbottom:CHIRP(EdgeTech,3200-XS, SB-0512i)	NotProvided	Mountain, G. McHugh, C.	McHugh et al., 2010
Seismic:Reflection:MCS	Array Seismic:MCS	Show/Hide	Christie-Blick, N. Mountain, G. McHugh, C.	McHugh et al., 2010

Figure 2: Example of data portal links to data for Endeavor cruise EN370 cruise (PIs Mountain, Christie-Blick, McHugh and Pekar) to the New York-New Jersey margin. Links at left take the user to MCS data files. Links at right display publications associated with the data sets.

- **Data Visualisation and Exploration**
  The GeoMapApp and Virtual Ocean tools offer a rich variety of options for users to plot, analyse and visualise their data in a geographical setting (Figures 1 and 3). EarthObserver, a recently-released app for the iPad™, iPod Touch™ and iPhone™ offers instant access from mobile devices to a large range of built-in data sets.
  http://www.geomapapp.org/ , http://www.virtualocean.org/ , http://www.earth-observer.org/

- **Bibliography**
  The GeoPRISMS references database provides an integrated, searchable resource that links publications to data sets and funding awards. Currently comprising more than 175 papers of direct relevance for GeoPRISMS science, the database can be searched on author, title, journal, year, and primary site. All displayed results can also be exported in EndNote™ format. The bibliography page provides a simple tool to allow anyone to submit references for inclusion in the database.
  http://www.marine-geo.org/portals/geoprisms/references.php

- **Data Management Plan Tool**
  Since January 2011, all proposals submitted to NSF must be accompanied by a Data Management Plan. With NSF input we created a simple web page that allows PIs to fill in information boxes and generate a data management plan in PDF format to be attached to the proposal.
  http://www.iedadata.org/compliance/plan

- **Data Compliance Reporting Tool**
  Currently under development, this tool will help PIs demonstrate compliance with funding agency data policies by allowing PIs to inventory their data contributions, with links to award numbers.

3) Data Policy

Led by Susan Schwartz, the GeoPRISMS data policy was compiled by a sub-committee of the GeoPRISMS Steering and Oversight Committee, with input from NSF and the database group.
http://www.geoprisms.org/data-policy.html

4) Community Outreach and Accountability

A representative from the database group plans to attend a number of GeoPRISMS meetings to act as a liaison with the community, to increase awareness about the data portal services, and to solicit feedback and advise on products and resources. A report on database activities will appear in the GeoPRISMS twice-yearly newsletter, and, at each GeoPRISMS Steering and Oversight Committee meeting, a report will be given and data-related discussions held.

The GeoPRISMS data manager, Andrew Goodwillie, and the database team are keen to help the community with any questions related to data, analysis tools or the GeoPRISMS bibliography.

5) References

GeoPRISMS Data Portal Status Report, *GeoPRISMS Newsletter*, Spring 2011, vol 26, page 26.
http://www.geoprisms.org/images/stories/documents/newsletters/issue26.pdf

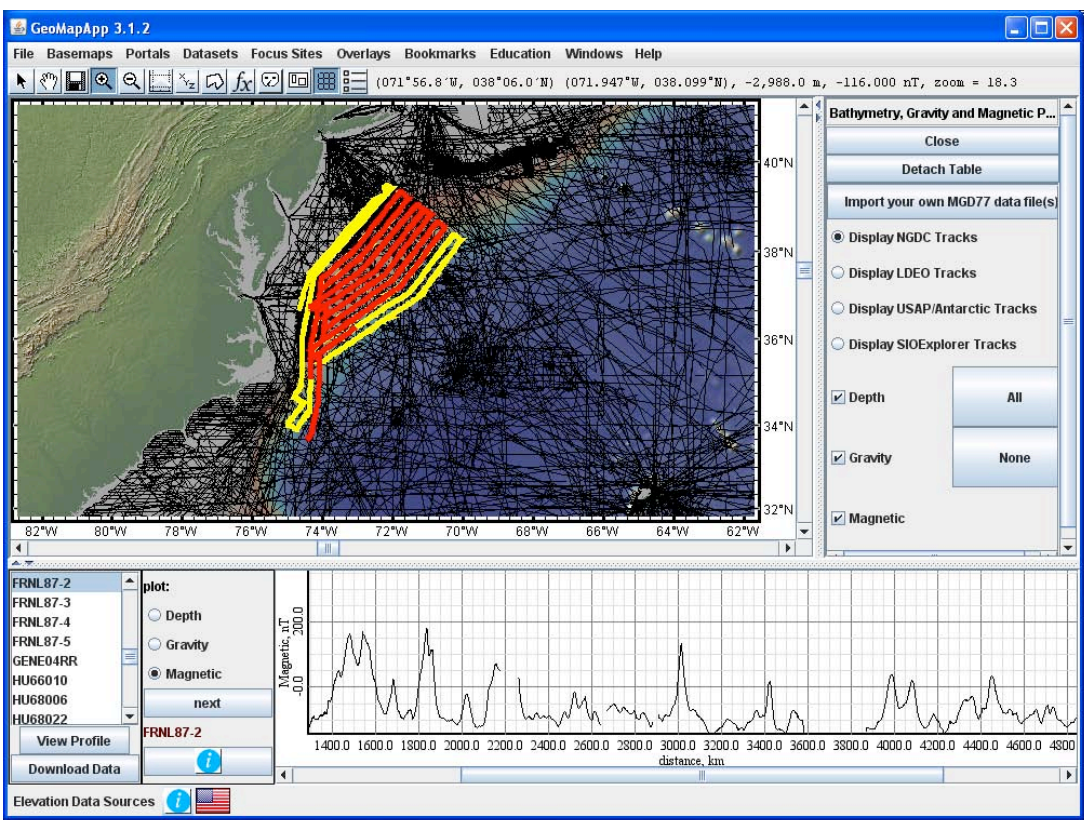

Figure 3: Magnetic anomaly profile for cruise FRNL87-2. Track lines for all available cruises in GeoMapApp are shown in black. Yellow indicates the FRNL87-2 cruise track, and red shows the extent of the profile displayed in the lower pane. Users can download the MGD77 file. The 10m grid of USGS NED on-land elevation data is illuminated from the NW.

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An REU site at James Madison University: Understanding the Rift-to-Drift Transition in Eastern North America and the North Atlantic

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We propose a Research Experience for Undergraduates (REU) program in the Department of Geology and Environmental Science at James Madison University (JMU) based on the scientific objectives of the GeoPRISMS Implementation Plan for Eastern North America. We envision JMU as one of several collaborative REU sites forming a GeoPRISMS-wide REU network. Our department will encourage young students from local community colleges to participate in the REU program and to transfer into a four-year degree in the Geosciences. JMU is a public, primarily undergraduate institution (PUI) located in the central Shenandoah Valley of Virginia and has an enrollment of ~19,000 students. JMU is among the top ten PUIs in terms of number of students who go on to earn doctorate degrees in STEM fields (Table 1) and has NSF-funded REU programs in Materials Science, Chemistry, and Mathematics.

Table 1: Science and engineering doctorates earned by graduates of PUIs (2000-2009)

1	**Carleton College**	**503**
2	**Oberlin College**	**497**
3	**Wesleyan University**	**466**
4	**Cal Poly U- San Luis Obispo**	**455**
5	**Swarthmore College**	**445**
6	**Williams College**	**419**
7	**Reed College**	**371**
8	**Wellesley College**	**370**
9	**James Madison University**	**344**
10	**Harvey Mudd College**	**343**

Data taken from NSF survey of earned doctorates: http://webcaspar.nsf.gov/.

Geology faculty and students have participated in the JMU Materials Science REU in the past, and we would like to expand on these experiences to create an REU experience specifically for Geosciences.

The Department of Geology and Environmental Science at JMU has 15 full-time faculty members and ~125 majors in two degree programs: the BS in Geology and the BA in Earth Science. Students in both programs are required to complete an independent research project as part of their degree requirements. We have laboratory facilities and field equipment, including 4 dedicated field vehicles, to support research projects.

The REU program at JMU would promote the Outreach and Education goals of GeoPRISMS by:

1) Providing research experiences that encourage undergraduate students to attend graduate school and continue in careers in the GeoPRISMS disciplines;
2) Providing pre-service teachers (BA in Earth Science) with research experiences that will help expand GeoPRISMS science into the classroom;
3) Strengthening existing research collaborations between JMU and other institutions in the region including the USGS (Reston), the Virginia Department of Mines, Minerals, and Energy, the Consortium for Ocean Leadership and the Integrated Ocean Drilling

Program (IODP), the Smithsonian Institution, Virginia Tech, the University of Maryland, and the Ohio State University;

4) Creating new collaborations and sharing instrumentation and equipment resources with other universities.

Student research projects undertaken at JMU will be aligned with questions posed within the GeoPRISMS initiatives for Eastern North America by working with one of the faculty members listed below:

Anna Courtier is a structural seismologist who investigates deep Earth indicators of mantle flow and patterns of thermal and chemical variability in the mantle. Variations in mantle discontinuity and reflectivity structure are indicative of heterogeneous thermal and chemical structure within upper mantle rocks. In particular, studies examining the distribution of water in the mantle beneath Eastern North America may yield insight as to how continental collision and rifting are initiated. In addition to documenting current plate motion, upper mantle and lithospheric anisotropy records the deformation history associated with major tectonic events.

Anthony Hartshorn is a soils scientist who studies biogeochemical cycles (carbon, nitrogen, phosphorus, silica) and the genesis of soils and soil-landscapes. His research will address these GeoPRISMS questions for Eastern North America: 1) As mass is removed from the Atlantic seaboard, how are uplift rates, and therefore soil residence times, affected? and 2) How does a lithologic gradient in silica content affect weathering processes and therefore delivery rates of silica and other elements to the Chesapeake Bay?

John Haynes is a sedimentary petrologist with research interests focused on the Paleozoic of the central and southern Appalachians. He uses lithostratigraphic, chronostratigraphic, and petrographic methods in the field and lab to investigate the early Paleozoic history of the central and southern Appalachians, in particular the origin and significance of (1) altered volcanic ash beds (K-bentonites) and associated quartz arenites and conglomerates of Ordovician age from Virginia to Alabama, (2), chemical trends in mudrocks of the central Appalachians, (3) facies relations in Silurian and Lower Devonian strata of western Virginia, and (4) the connections between stratigraphy and karst development in the region.

Elizabeth Johnson is an igneous petrologist who uses geochemical and spectroscopic techniques to 1) investigate the source and mechanisms of magma generation which produced the Eocene (35-48 Ma) volcanic field of western Virginia, and 2) determine the composition, volatile content, and structure of the crust and mantle underneath the Shenandoah Valley and Allegheny Plateau from xenoliths entrained within the Eocene magmas. These data will be used to constrain and test models of the structure of the crust and mantle in Eastern North America.

Stephen Leslie is a paleontologist and stratigrapher whose interests include the integration of paleontology with stratigraphy, Most of his current focus is using conodont biostratigraphy and isotope stratigraphy to examine the greenhouse–icehouse transition at the end of the Ordovician. One of his projects would examine the petrology and potential fossil content of the Paleozoic sedimentary rocks preserved as xenoliths in the Eocene volcanic rocks.

Kristen St. John is a paleoceanographer and paleoclimatologist. Her project would address the GeoPrisms Tectonics-Climate-Surface Feedbacks Theme (http://www.geoprisms.org/surface-feedbacks.html) by focusing on the ODP Site 908 post-rift marine depositional record on the Hovgaard Ridge, at the southern end of the Fram Strait. Opening of the strait and subsidence of this ridge allowed for water exchange between the Arctic and North Atlantic Oceans. Early low resolution investigations suggested no sea ice cover in the Oligocene sediments, however this is inconsistent with current understandings of regional (Greenland and Arctic) climate change. She will conduct a high resolution reinvestigation of the sea ice history of the Arctic gateway by examining the abundance, composition, and surface textures of the coarse sand fraction at Site 908.

Steven Whitmeyer is a structural geologist whose interests include 1) development of digital mapping techniques and 3D and 4D visualizations, and their incorporation into field geology curricula; 2) Bedrock mapping of the Blue Ridge - Valley and Ridge transition, including the semi-cryptic Blue Ridge thrust system; 3) Evolution of continental crust and basement development in orogenic zones, with recent focus on the mid-Atlantic region of the eastern United States.

South Georgia Rift Basin: Rift Initiation and Evolution (RIE) Assessment through Controlled Source Seismology

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The Eastern North American Margin (ENAM) has been identified as one of the primary focus areas for GeoPRISMS due to the complexity and regional extent of this mature Mesozoic passive margin rift system encompassing: (1) a large volume and regional extent of related magmatism, (2) a preserved complete stratigraphic column that records the post-rift evolution in several basins, (3) preserved lithospheric-scale pre-rift structures including Paleozoic sutures, and (4) a wide-range of geological, geochemical, and geophysical studies both onshore and offshore. The short-lived but most voluminous magmatic event associated with the initiation of rifting, the Central Atlantic Magmatic Province (CAMP), is one of the most significant magmatic events in North America.

The South Georgia Rift (SGR) basin is believed to be the largest and probably the most geologically complex Mesozoic graben of the ENAM (Popenoe and Zietz, 1977; Daniels et al. 1983; McBride et al. 1989) formed during crustal extension associated with the breakup of Pangea and later opening of the North Atlantic Ocean. The separation of the African and North American plates, the formation of the Atlantic Ocean and the associated zones of weakness in eastern North America have been stated as the initial events in the breakup of Pangea. Chowns and Williams (1983) and Swanson (1986) suggested that the formation of the Mesozoic basin was probably influenced by the presence or reactivation of these zones of basement weakness in the Southern Appalachians. McBride et al. (1989) and Petersen et al. (1984) have also described the basin to be a composite of smaller, Triassic basins. These basins, in most cases, appear to be bounded by high-angle normal faults some of which may have been reactivated in late Cretaceous and Cenozoic time as apparent reverse faults (Behrendt, 1986). Some of these sub-basins also contain interbedded basalt flows and diabase dikes and sills.

Tectonically induced rifting events also led to pronounced igneous activity within the SGR basin (Dietz and Holden, 1970). This igneous activity was characterized by the presence of surface basalt flows as well as the voluminous emplacement of diabase dikes and large-mafic and ultra-mafic intrusions (Daniels et al., 1983) as part of CAMP. These igneous deposits have been described by Phillips (1983) as normally magnetized materials, suggesting that they formed during the Late Triassic-Early Jurassic interval of predominantly normal polarity. Most radiometric ages for eastern North American Mesozoic basalt flows and diabase sills fall within the range of 180 – 200 million years (Phillips, 1983), thus supporting a Late Triassic-Early Jurassic age. The Jurassic ("J') basalt received considerable attention in the 1980's as a distinct, regional geologic marker that is widespread throughout the South Georgia Rift (SGR) basin, and that is either below or at the base of the Coastal Plain. One of our main interests in the "J" basalt reflector lies in its regional significance and potential to serve as seal for CO_2 storage in the underlying Triassic reservoir. The term originated from Schilt et al. (1983) based on seismic correlations with the Clubhouse Crossroads basalt flows (Figure 1) from three drill cores in South Carolina (Gohn et al., 1983, Gottfried et al., 1983). The age of the "J" basalt as determined by Lanphere (1983) on the Clubhouse Crossroads Basalt is early Middle Jurassic (184 Ma). Its emplacement resulted from the effects of pronounced igneous activity that is associated with the formation of the SGR basin and characteristics of the onset of sea floor spreading associated with continental margins (Holbrook and Kelemen, 1993). Also, it is known to be chemically similar to the Central Atlantic Magmatic Province (CAMP) basalt flows (Goldberg et al., 2010) and overlap with offshore basalt described seismically as "seaward-dipping reflectors (SDRs)". These SDRs were emplaced during the early opening of the Atlantic Ocean (Goldberg et al. 2010). The true geographical extent of the "J' horizon remains unknown in spite of previous efforts by Gottfried et al. (1983), McBride et al. (1989), and Chowns and Williams (1983) at delineating its areal extent. The postulated regional extent of the "J' basalt within the SGR was based on seismic correlations with limited and scattered drill-hole data.

Based on reanalysis of seismic and well data, Heffner et al. (in press) show the preserved extent of the "J"-horizon as being much more limited areally than previously reported and appears to correspond with the base of the Coastal Plain unrelated to the presence of basalt. This reinterpretation of the J-horizon has larger implications as to the timing of the opening of the Atlantic Ocean, and is also supported by re-processing and re-interpretation of the USGS' seismic reflection profile SeisData6 (Akintunde et al., in prep.).

The University of South Carolina has been funded by DOE to perform a feasibility study of geological storage of CO_2 within the Triassic sediments of the SGR basin (in South Carolina). Included in this ongoing effort are (1) acquisition of 240 km of 2-D seismic data (6 s two-way traveltime) (Fig. 1), (2) acquisition of a 6 km^2 3-D seismic data (Fall 2011), and (3) drilling and sampling of a borehole to ~4 km within the basin. These activities center around the Norris Lightsey deep well that provides lithological and petrophysical control down to ~3000 m. While these seismic data are most suitable for providing a good quality high resolution image of the SGR basin, the recording time is too short to provide reliable information from the lower crust and uppermost mantle.

Despite the panoply of controlled source seismic data recorded across the SGR basin (the majority of them being 6 s), there remain many critical questions that are suitable to address within the context of EarthScope targeting the lower crust/ upper mantle interaction. Some of these issues include: (1) the role of pre-existing structures/zones of weakness in the Triassic rifting including the style and timing of break-up and extensional deformation (orogenic belts, rheological heterogeneities, mechanical anisotropy of the mantle, thermal disturbances, and base-lithosphere pre-existing topography; Keranen & Klemperer, 2008), (2) the age of the CAMP basalts/diabase and how CAMP relates to the rift-drift transition of ENAM, (3) the controls on the architecture of rifted continental margins during and after breakup, (4) the nature, age, and geometry of the Brunswick anomaly that divides two different terrains with different orogenic imprints (Daniels et al., 1983), (5) the nature of the NE-trending SGR with NW-striking transfer faults, (6) the role of magmatic underplating in rift and post-rift evolution and relationship to slow lithospheric extension, in order to (7) better understand the regional SGR basin structure and asymmetric geometry and the role of a series of recognized transform faults and relationship to the suture zone shown now as the Brunswick anomaly. In addition, such an in-depth study can provide valuable information for the assessment of geohazards, in particular, the magnitude and frequency of rift-related earthquakes.

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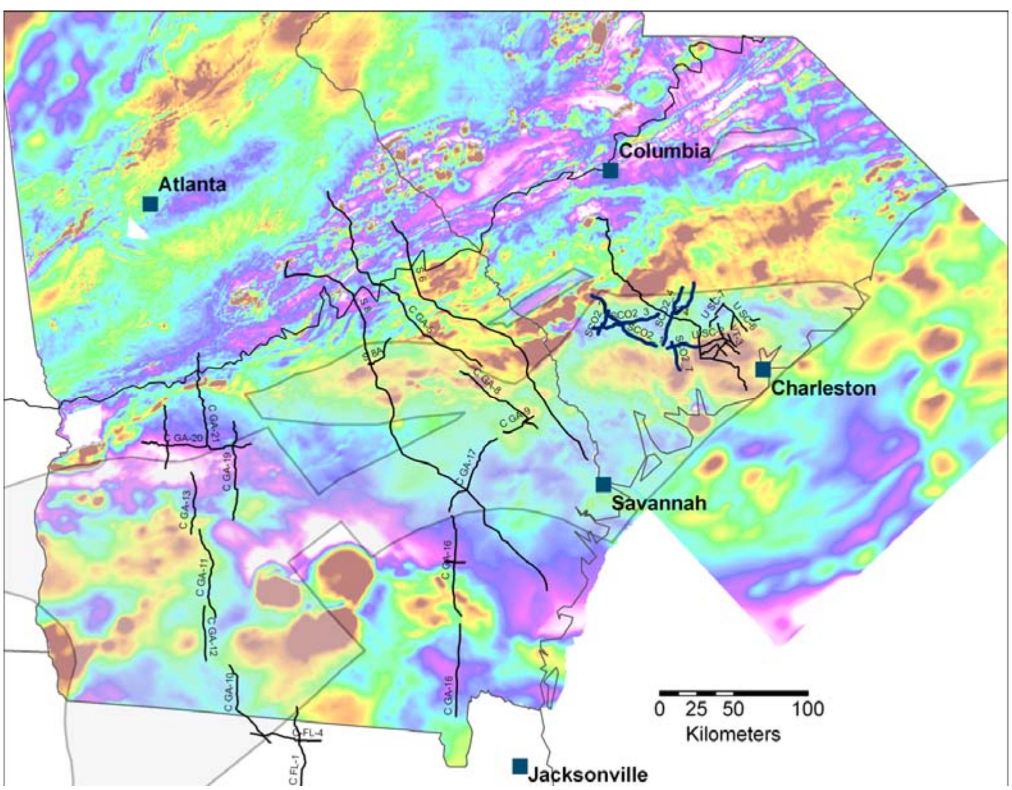

Figure 1. Location map of the South Georgia Rift (SGR) basin (light gray contour, after Chowns and Williams, 1983) in South Carolina and Georgia superimposed on the magnetic anomaly map. Existing deep seismic lines (USGS and COCORP) are shown as black lines together with newly acquired 2-D seismic lines (6 s TWT in bold) as part of the DOE CO_2 sequestration project.

Late Cenozoic stream incision in the Appalachian region

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EarthScope themes: Appalachian landscape evolution and neotectonics; impact of mantle flow on surface dynamics

The persistence of topography along the ancient Appalachian orogen remains one of the outstanding questions in landscape evolution. In particular, it is unknown whether Appalachian topography is in a state of quasi-equilibrium (e.g., *1, 2*), is decaying slowly over geologic time (e.g., *3*), or whether it has been rejuvenated during Neogene time (e.g., *4, 5, 6*). Pursuit of these hypotheses over the past century has led to numerous contributions to the discipline of geomorphology, but the fundamental question about why Appalachian topography still exists remains largely unanswered. In this white paper, we make the case that advances in our understanding of how to interpret topographic signatures of long-term landscape change (e.g., *7*), in our ability to measure erosion rates (e.g., *2*), and in our ability to model the influence of mantle flow on surface topography (e.g., *8*) allow us to re-evaluate the problem of Appalachian topography. The landscapes of eastern North America (ENAM) present a research opportunity that is both intellectually rich, in the interplay between deep earth and surface processes, and timely, in that both the EarthScope facility and GeoPRISMS community are beginning to focus on this region.

Perhaps the strongest line of evidence in support of steady, long-term lowering of Appalachian topography, modulated by isostatic rebound (*9*), is the broad coincidence between rates of erosion over Cenozoic timescales inferred from thermochronology, and rates of erosion measured over late Quaternary timescales with cosmogenic isotopes (*2*). Departures from this condition, in the form of rapid stream incision (*10*) and pulsed sediment delivery offshore (*6*), have been variously attributed to climate change (*5, 10, 11*), drainage divide migration and stream capture (*12, 13*), or tectonically driven rock uplift (*6, 14*).

The advent of mantle flow models raise the striking possibility that dynamic topography on the East Coast has contributed to as much as 200–300 m of surface uplift since ~30 Ma (*8*). To date, most of the geologic evidence for dynamic topography in ENAM consists of anomalous New Jersey sea-level curves (*15*) and deformed shorelines south of New Jersey (*16*). Eroding, upland landscapes inboard of these shorelines, however, typically do not preserve markers of subtle warping (cf. *17*) and therefore make it a challenge to determine spatial patterns of deformation. Moreover, late Cenozoic exhumation is sufficiently limited such that even very low-temperature thermochronologic systems are not particularly sensitive. In such settings, however, information may be extracted from the topography itself; stream profile analyses coupled with erosion rate data provide a potential tool for deciphering long-term landscape evolution. Here we present some preliminary results that motivate us to look more closely at the fluvial record as a means for testing hypotheses about Cenozoic landscape evolution in ENAM.

Preliminary analysis of that knickpoints in the Susquehanna River basin (Fig. 1) suggests that these features represent a fundamental boundary between faster incision downstream and slower incision upstream (*18*), consistent with models of transient erosion and local evidence for relict topography such as residual soils as old as Miocene (*19*). Analysis of streams draining upland plateaus revealed transient profiles, characterized by steep reaches incised into narrow, steep-sided valleys below knickpoints that are not associated with lithologic contacts or contrasts in rock strength (Fig. 2). When normalized for drainage area, channel gradients correlate with watershed-averaged erosion rates from cosmogenic ^{10}Be in detrital quartz (Fig. 3), indicating that steeper channels are eroding at rates two to three times greater than those atop the plateau.

Similar relationships between erosion rates and stream profile form have been observed in more tectonically active regions (e.g., *20*), and suggest that the techniques developed to interpret the history of tectonic forcing of landscapes of those regions (e.g., *21*) may be applicable here as well. Thus, we believe that we are able to begin to resolve rates of transient erosional responses and use increasingly sophisticated models of fluvial incision to constrain the timing (and perhaps magnitudes) of forcing. Reconstruction of relict channel profiles in the Susquehanna study area suggests that higher rates of incision are a response to ~200 m of relative base level fall. Stream profile models calibrated with erosion rate data suggest base level fall began in the range of 10–20 Ma. Although still somewhat imprecise, this combination of geomorphic and geochronological approaches allows one to establish 1) whether knickpoints are migratory (transient) or anchored to features of the drainage network (steady-state) and 2) to place constraints on the rate of knickpoint migration (and thus the timescales associated with transient incision). It also provides a framework for comparing observations against models to assess whether transient incision is tectonically or climatically driven (*22*). Such a combination of stream profile analyses, erosion rate measurements, and stream profile models may be applied over a larger part of the Appalachians.

These results draw attention to outstanding methodological and theoretical questions. Current methods for inverting rock uplift history from stream profiles make simplifying assumptions about erosion processes (e.g., *23*), but do the inverse solutions adequately state their uncertainties? Also, how best do we account for complex geology, and what is the quantitative relationship between lithology and erosion? How are transient erosion signals transmitted through fluvio-karst terrains? How can we separate and quantify the relative contributions of multiple factors that may each be driving transient erosion in a single basin (e.g., climate, tectonics, and stream capture)?

The results above also bring a number of regional research problems into focus. Volumes of Miocene and younger sediment in the Baltimore Canyon Trough indicate ~1 km of spatially averaged denudation across the northern and central US ENAM margin, generally consistent with estimates of exhumation since 20–30 Ma based on apatite fission-track thermochronology (*11, 24*). However, it is difficult to attribute this sediment to denudation in specific drainage basins. Are stream profile data consistent with the offshore record of sedimentation, and capable of giving us a more detailed picture of landscape evolution? Is the landscape adjusting similarly to external forcing (whether tectonic or climatic) across the ENAM region, or is transient deformation affecting different regions in different ways? Is late Cenozoic transient erosion in the Susquehanna basin unique along the ENAM margin? Do geomorphic variables correlate with imaged mantle structures, once lithologic or lithospheric structures have been factored for? Finally, is the long-term geomorphic record consistent with the record of deformation measured by classic and new geodetic tools (GPS, InSAR), or can the comparison between these two datasets (e.g., *25*) provide insight into how deep structures are evolving?

The upcoming deployment of US Array throughout the ENAM region, as well as the new focus of the GeoPRISMS along the Atlantic passive margin, presents a unique opportunity to begin to address these outstanding questions. Improved, high-resolution images of the velocity and density structure of the ENAM mantle will provide the basis for finer resolution of potential surface deformation. At the same time, a more comprehensive regional analysis of river profiles coupled with focused studies of erosion rates could elucidate spatial patterns in erosion over 10^4–10^5-year time-scales with resolution previously unavailable, and help calibrate landscape evolution models. Similarly advances in the cosmogenic and magnetostratigraphic dating of cave sediments (*26-28*), and of terrace surfaces (e.g., *29, 30*) afford the opportunity to provide quantitative constraints on the timing and rates of fluvial incision. Coupling of these data with the predictions of geodynamic models presents a real opportunity to test the role of dynamic topography in ENAM and discriminate other possible mechanisms driving transient landscape erosion in the Appalachians (*31*).

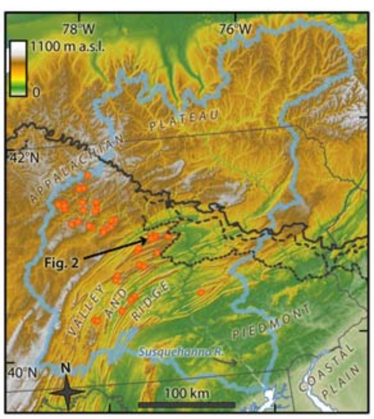

Fig. 1. Topographic map of Susquehanna River drainage basin (blue outline), showing analyzed tributary drainage basins (orange circles), glacial limits (dotted line—Wisconsin; dashed line—Illinoian; solid line—pre-Illinoian), and location of stream in Fig. 2.

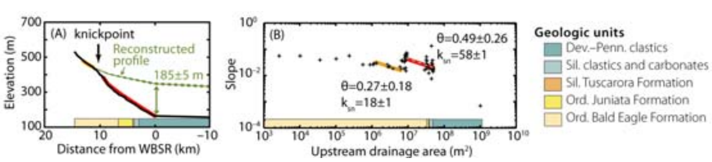

Fig. 2. Example stream profile (A) and slope-area plot (B) showing knickpoint separating two profile segments (orange and red). The stream shown is McElhattan Creek, a tributary of the West Branch Susquehanna River (WBSR) in the Valley and Ridge near Lock Haven, Pennsylvania.

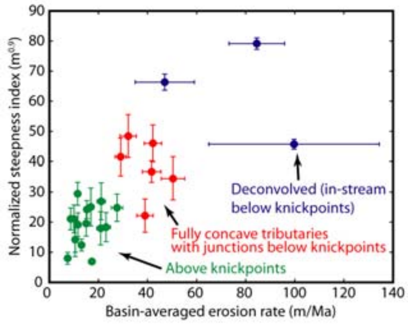

Fig. 3. Scatterplot of normalized steepness index, or channel slope normalized for drainage area, plotted against basin-averaged erosion rate (*32*). Data are from basins above knickpoints (green), basins with fully concave streams that join larger streams below knickpoints (red), and basins in which erosion rates below knickpoints have been deconvolved using erosion rates estimated above knickpoints on the same stream (blue).

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High-resolution marine magnetic anomaly data across the margin would delineate structures controlling lithospheric formation and rift localization

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Proposed sites: (1) Carolina/Avalon terrane boundary and ECMA offshore New Jersey; (2) Alleghenian suture and ECMA offshore Georgia

Forthcoming data: high-resolution, near-source, three-component, marine magnetic anomaly data

Onshore, magnetic anomaly data from airborne surveys clearly delineate geologic terranes along the entire length of the eastern North American margin (Figure 1). Similar magnetic data have been collected offshore, but deep water and thick sediments suppress short-wavelengths, making it difficult to map the continuation of these features across the shoreline or identify new boundaries offshore. High-resolution marine magnetic anomaly data can be collected from a variety of near-bottom instrument platforms, enabling detailed offshore mapping of sutures, dikes, sills, and small plutons—structures that played a key role in the formation of the east coast margin.

The eastern North American margin was formed by a series of accretion and rifting events throughout the Paleozoic and Mesozoic, leaving behind distinct terranes separated by sutures, each with different lithologies and patterns of faulting and magmatism (e.g., Sheridan et al., 1993). Understanding the role this fabric played during periods of accretion, extension, and magmatism along the east coast margin can address at least two critical questions: 1) What is the role of preexisting structures in the evolution of continental margins in general? 2) How does the lithospheric architecture observed along the eastern North American margin influence lithospheric stability?

The lack of resolution in offshore magnetic data, as well as the paucity of near-bottom data, prevents us from better understanding how sutures and other inherited structures influenced localization of the Atlantic rift margin and the associated continent/ocean transition (COT). Two example locations of where better magnetic data would be especially illuminating are offshore of Georgia and New Jersey. In Georgia, the Alleghanian Suture separates the Carolina and Brunswick Terranes from African crust and appears to mark the axis of a major abandoned rift basin, the South Georgia Rift (Hatcher, 1989). Offshore, existing magnetic data appears to show that the Alleghanian Suture turns north at the westward extension of the Blake Fracture Zone, eventually merging with the East Coast Magnetic Anomaly (ECMA), a feature spatially correlated with the voluminous, rift-related magmas of the East Coast Margin Igneous Province and the Atlantic COT (e.g., Holbrook and Kelemen, 1993). Further north and offshore of New Jersey, the ECMA/COT turns abruptly to the east-northeast at what appears to be the boundary between the Carolina and Avalon Terranes. The relative geometry of these sutures and the ECMA/COT suggests that Paleozoic sutures may have exerted control over the localization of rifting of the Atlantic (e.g., Rankin, 1994). In both offshore regions, the exact geometry of the sutures is difficult to determine on existing, low-resolution magnetic data. Near-bottom/near-source, magnetic observations made at sea would enable high-resolution mapping of these sutures and other magnetic features, informing our understanding of east coast margin evolution.

A variety of near-bottom magnetic platforms exist, and they can be operated from a range of vessels, making the collection of high-resolution magnetic data a feasible and valuable addition to larger marine expeditions. For example, magnetometers mounted on a deep-towed sled (e.g., the Woods Hole Oceanographic Institution's TowCam) could be used to rapidly (tow-speed of ~10 kts) collect high-resolution, three-component vector magnetic anomaly data before or after seismic operations on the R/V *Langseth*. If Autonomous Underwater Vehicles (AUV) (e.g., AUV Sentry of the National Deep Submergence Facility) are being used to explore a region in detail, vector magnetometers can be mounted alongside side-scan and/or chirp-sonars. Such a configuration makes it possible to simultaneously obtain high-resolution bathymetric data, revealing the morphology of seafloor features such as fault scarps, slumps, pockmarks, and submarine channels, and near-source, three-component magnetic anomaly data, both with accurate navigation. Furthermore, high-resolution, multi-channel seismic data could be collected during periods of AUV battery charging using a portable MCS system (e.g., the Scripps portable seismic system). The variety and portability of these magnetic platforms make it possible to efficiently obtain high-resolution magnetic data along with other geophysical observations, providing a comprehensive, detailed picture of the potential offshore extension of sutures, the ECMA, and other yet-unresolved structural features.

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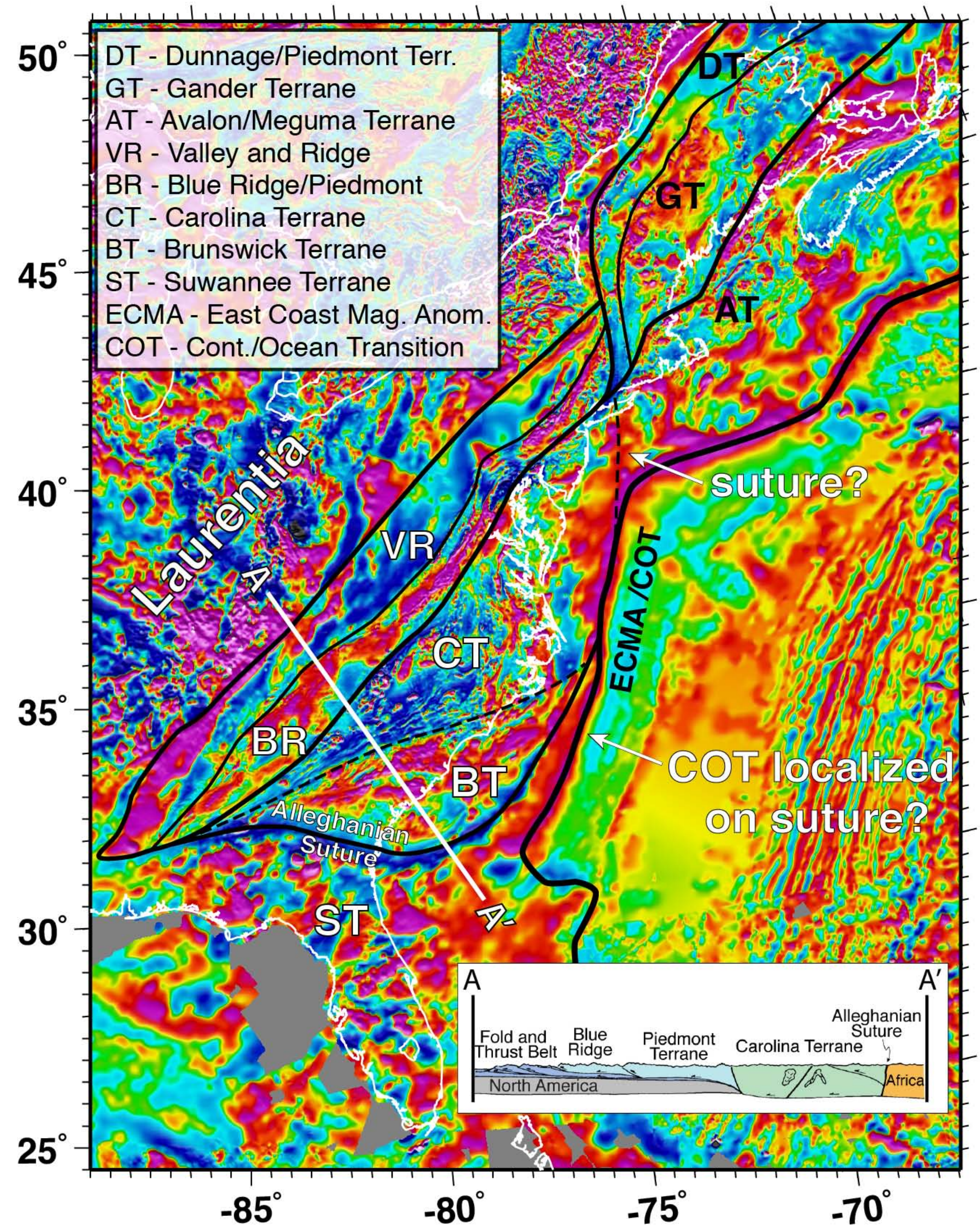

Figure 1. Magnetic anomaly data from airborne surveys over the eastern North American margin. Onshore, the series of accreted terranes (black lines) are precisely delineated by the magnetic data. Offshore, poor data resolution, a result of attenuation by deep water and thick sediments, makes mapping structures difficult. Inset cross-section is from Hatcher (1989).

TITLE: Transition from magma dominant to magma poor rifting along the Nova Scotia Continental Margin

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White Paper: Passive margins have been characterized as magma-dominant (volcanic) or magma-poor (non-volcanic). However, the conditions under which margins might switch states are not well understood as they typically have been studied as end member examples in isolation to each other. The Nova Scotia (NS) continental margin, however, offers an opportunity to study the nature of such a transition between the magma-dominant US East Coast margin to the south and the magma-poor Newfoundland margin to the north within a single rift segment. This transition is evidenced by a clear along-strike reduction in features characteristic of syn-rift volcanism from south-to-north along the NS margin, such as the weakening of the East Coast Magnetic Anomaly (ECMA) and the coincident disappearance of seaward dipping reflector sequences (SDRS) on multichannel seismic (MCS) reflection profiles.

Results from recent industry MCS profiles along and across the margin (Figure 1) suggest a potentially narrow magma-dominant to magma-poor along-strike transition between the southern and the central NS margin. Such a transition is broadly consistent with results of several widely-spaced, across-strike ocean bottom seismometer (OBS) wide-angle profiles (Figure 1). In the southern region, the crustal structure exhibits a narrow (~120-km wide) ocean-continent transition (OCT) with a high velocity (7.2 km/s) lower crust, interpreted as a gabbro-rich underplated melt, beneath the SDRS and the ECMA, similar to crustal models across the US East Coast. In contrast, profiles across the central and northern margin contain a much wider OCT (150-200-km wide) underlain by a low velocity mantle layer (7.3-7.9 km/s), interpreted as partially serpentinized continental mantle, which is similar to the magma-poor Newfoundland margin to the north. However, the central-to-northern OBS profiles also exhibit significant variations within the OCT and the along-strike continuity of these OCT structures is not yet clear. Preliminary analysis of 2010 wide-angle seismic data from the 240 km-long 20 OBS OCTOPUS margin parallel profile, which extends from the central to the northern margin segments along an existing industry MCS profile (Ion/GX Technology NovaSPAN 5100), indicates that the cross-strike structures are continuous within the OCT. However, a substantial anisotropy in velocity (~8% lower parallel to the margin) is observed within the OCT. This result is consistent with an interpretation of partially serpentinized mantle that flowed perpendicular to the margin during its extension. In addition, along strike variations are also observed along the profile, which suggest a higher degree of volcanism and a thinner layer of serpentinized mantle to the southwest.

The results already generated at the Nova Scotia margin provide a framework for future studies to, for example, investigate questions such as:

1. What are the characteristics and causes of a single-rift-segment transition from a magma-poor to a magma-dominant margin regime? Can variations in magma underplating within the magma-rich to magma-poor transition be related to along-strike differences in mantle temperature?

2. What is the nature of along-strike variability in magmatism between magma-dominant rift segments?
3. Is there a correlation between variations in magmatic addition to the crust and mantle structure?
4. Did magmatism facilitate continental breakup? Comparison of the OBS lines suggests that sea-floor spreading began more abruptly and more robustly (i.e., greater crustal thickness) offshore southern Nova Scotia, relative to offshore central and northern Nova Scotia, where the oceanic crust thins and layer 3 has a lower velocity on the seaward end of the profiles. But the gap between lines in the south is too great to know if there is a direct correlation.
5. Can changes in the transition and characteristics of post-breakup sea-floor spreading be related to variations in magmatism along the margin?

The existence of high quality 2D crustal profiles opens the door for a more 3D approach to examining crustal structure and a framework for looking deeper into the mantle.

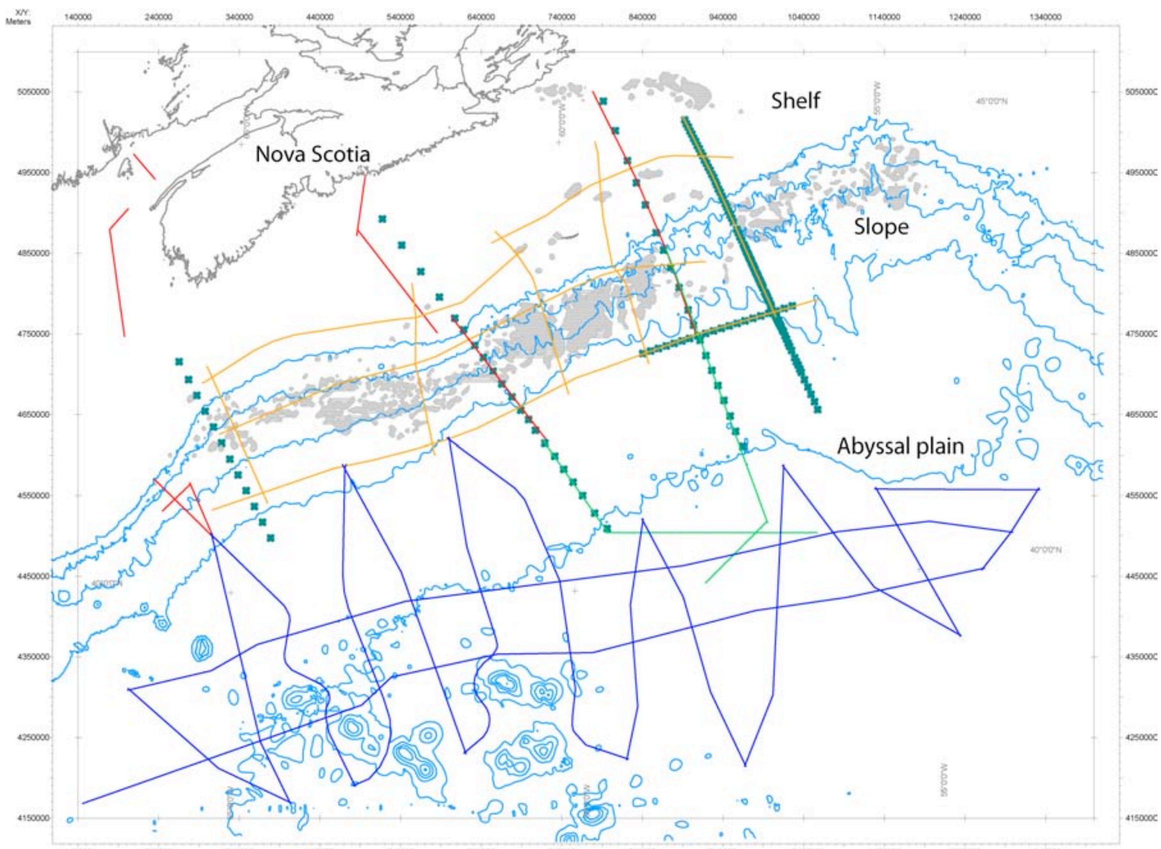

Figure 1. Offshore Nova Scotia region. Earlier MCS profiles available as raw data and processed images: Lithoprobe lines (red, 3-4 km-long streamer); BGR lines (green, 3-4 km -long streamer). Modern MCS profiles available as raw data and processed images: NovaSpan 2003 lines (orange, 9 km-long streamer); UNCLOS 2007 lines (blue, 4-km-long streamer). Green crosses mark OBS locations: Three long margin-normal profiles are from SMART project, one 100 OBS profile is the 2009 OETR profile, and the one margin-parallel profile is from the 2010 OCTOPUS project. Gray areas are salt dominated regions of the slope. Blue lines are bathymetry at 1000, 2000, 3000, 4000 and 5000 m depth. Coast is outlined in gray.

Accretion of terranes and growth of continental crust along the southern margin of Laurentia during assembly of Pangaea [and modifications by opening of the Gulf of Mexico]

Thomas, Dumond, Harrelson, Harry, Horton, Keller, Langston, Magnani, Mickus, Mueller, Powell, Russo

Two significant accreted continental terranes within the late Paleozoic southern Appalachian-Ouachita orogen document growth of continental crust of southern ENAM (Fig. 1). Around the Ouachita embayment of the rifted margin, the late Paleozoic Ouachita orogen includes a forearc complex and accretionary prism associated with southward subduction of Laurentia beneath the Sabine continental terrane (affinity unknown) and continental-margin arc. On the corner of the Alabama promontory, the Suwannee-Wiggins suture truncates Laurentian continental crust, reflecting continent-continent collision of Laurentia with the Suwannee (Africa) terrane. The Suwannee-Wiggins suture trends westward toward the Sabine terrane; however, the possible relationships between the Sabine and Suwannee terranes are unknown. Are these terranes components of a single larger terrane, or are they distinct separate continental blocks? Does accretion of these terranes reflect a unified event or separate events of plate convergence? Regardless, terrane accretion contributed significantly to late Paleozoic growth of Laurentian/North American continental crust. Mesozoic rifting, leading to opening of the Gulf of Mexico, somewhat extended parts of the accreted terranes, and established a new continental margin on the south. Did the fabric of late Paleozoic accretion significantly constrain Mesozoic extension? Critical information to be gained from Transportable Array and Flexible Array densification includes thickness and nature of the crust from continental Laurentia across the terrane boundaries, terranes, and Mesozoic extensional faults. Resolution of subducted slabs and sutures is necessary to discriminate the Sabine accretionary prism from the Suwannee-Wiggins suture. The area, where the two terranes are traced to a near intersection, will be critical in comparing and contrasting the crustal structure of the terranes, as well as the nature of the accretionary fabrics. How did the accreted terranes affect Mesozoic extension? And how has the accreted continental crust been modified by Mesozoic extension?

Sedimentary deposits in the Ouachita embayment record rift initiation and evolution, as well as subduction-related processes. The Ouachita embayment, bounded by the orthogonal northeast-striking Ouachita rift and northwest-striking Alabama-Oklahoma transform, was formed in Cambrian time by the rifting of the Argentine Precordillera away from Laurentia (Thomas and Astini, 1996). Sedimentary deposits record the new continental margin and evolving oceanic crust, including a Cambrian-Mississippian carbonate facies on the passive-margin shelf and a temporally equivalent, mud-dominated continental-slope-and-rise prism and abyssal plain on oceanic crust, parts of which are now incorporated in the Ouachita thrust belt (summary in Thomas, 2011). An abrupt increase in sedimentation rate in the Middle Mississippian indicates the change from passive-margin deposition to early synorogenic deposition, indicating the initial approach of the Sabine terrane. Subsequent Upper Mississippian–Middle Pennsylvanian forearc-basin deposits and an accretionary prism are associated with a continental-margin arc on the leading edge of the Sabine terrane. A Middle Pennsylvanian synorogenic clastic wedge in the Ouachita foreland records rapid foreland crustal subsidence as a result of tectonic loading on the southern margin of Laurentian continental crust. Deformed synorogenic deposits are overlain by an undeformed Upper Pennsylvanian–Middle Permian shallow-marine fill of a successor basin, indicating the termination of orogenic contraction and terrane accretion within the Ouachita embayment at ~309 Ma (Nicholas and Waddell, 1989).

The orthogonal intersection of the northwest-striking Alabama-Oklahoma transform fault with the northeast-striking southern segment of the Blue Ridge rift outline the Alabama promontory of Laurentian crust (Fig. 1). Late Paleozoic continent-continent collision with the Suwannee terrane truncated and obliterated part of the corner of the Alabama promontory (Fig. 1); therefore, the rift and post-rift history of the margin must be reconstructed from projections from other areas. Northeast along strike, synrift sedimentary and volcanic accumulations indicate the time of opening of Iapetus and continental rifting to be latest Precambrian (543 Ma) (summary in Thomas, 1991). Repeated episodes of Appalachian orogenesis have obliterated any possible off-shelf continental slope-and-rise deposits; however, a robust Cambrian-Ordovician passive-margin carbonate-shelf facies documents the early post-rift history of the Alabama promontory. Palinspastic restoration of the passive-margin carbonates now in the Appalachian thrust belt shows that the original extent of the shelf was somewhat greater than the presently preserved extent of shallow Laurentian crust, thereby documenting truncation of Laurentian crust during continent-continent collision with the Suwannee terrane (Thomas, 2011). Diachronous elements of foreland synorogenic clastic wedges indicate episodic orogenesis at different places around the margin of the Alabama promontory. Although foreland subsidence and clastic-wedge progradation began earlier to both the west (Ouachita) and northeast (Appalachian), foreland subsidence and clastic-wedge progradation did not begin on the corner of the Alabama promontory until middle Early Pennsylvanian (315 Ma), signifying initiation of continent-continent collision with the Suwannee terrane. A wide band of metamorphic lithons, interlaced with mylonites, marks the suture between Laurentian continental crust and the African crust and cover of the Suwannee terrane (summary in Thomas, 2010); metamorphism along the Suwannee-Wiggins suture is as young as ~300 Ma (Steltenpohl et al., 2008), indicating later convergence than along the leading edge of the Sabine terrane.

The Mesozoic Bahamas fracture zone of the Atlantic mid-ocean ridge projects into southern North America diagonally across the area of the uncertain relationship between the Sabine and Suwannee terranes. Orientation of gravity anomalies suggests that the western part of the Suwannee-Wiggins suture may have been rotated counter-clockwise by Bahamas transform motion. This region offers an excellent opportunity to understand the growth of continental crust by accretion of terranes, as well as modification of crust by later supercontinent breakup.

Both the Sabine and Suwannee terranes are adequately documented by data from deep wells, seismic reflection profiles, and potential-field and seismic-velocity models; however, the characterization of these terranes, especially the lower crust and lithosphere remains inadequate. Currently active and proposed EarthScope projects will address the boundaries between Laurentian crust and the accreted Sabine and Suwannee terranes. The relationship between the two terranes, however, remains a first-order tectonic question and is a prime target for EarthScope and GeoPRISMS research in the unknown area between the documented terranes.

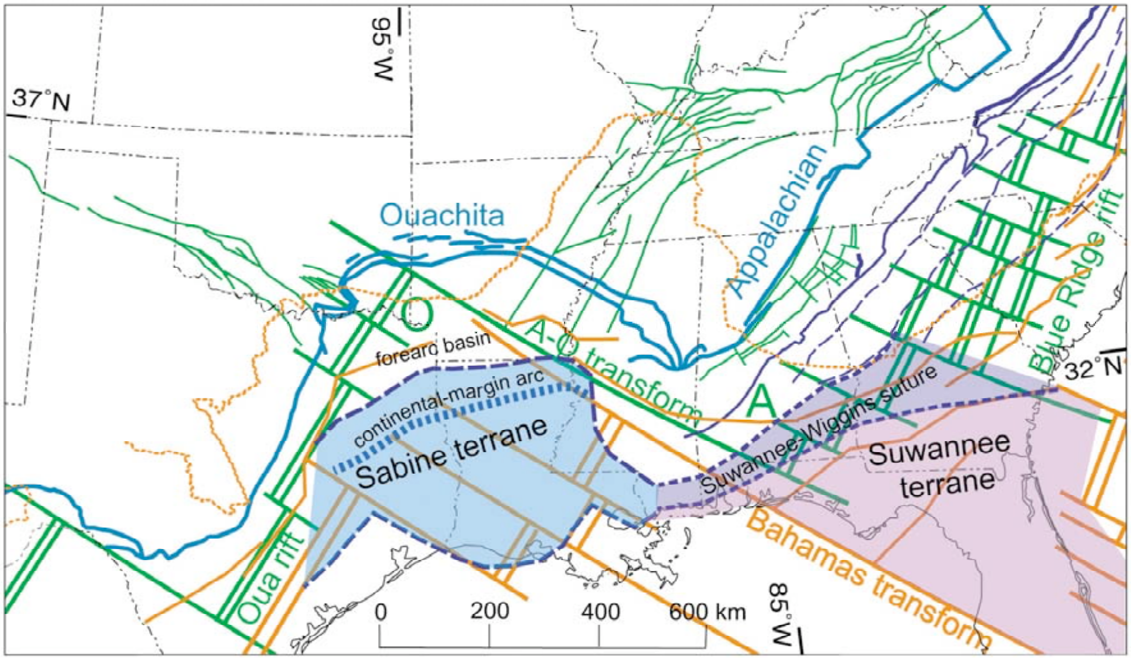

Figure 1. Map of Iapetan rifted margin of Laurentia (green lines), trace of Appalachian-Ouachita thrust front (blue lines), accreted Sabine and Suwannee terranes and related structures, and Atlantic-Gulf rifted margin of North America (orange lines). Abbreviations: O—Ouachita embayment, A—Alabama promontory, A-O transform—Alabama-Oklahoma transform, Oua rift—Ouachita rift.

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Evolution of continental crust through two Wilson cycles in ENAM

Thomas, Anastasio, Bailey, Blackmer, Crespi, Gates, Karabinos, Klepeis, McQuarrie, Sak, Williams, Wise

The continental crust of eastern North America, the birthplace of the concept of the Wilson cycle (Wilson, 1966), has undergone two cycles of supercontinent assembly and breakup since the Mesoproterozoic. EarthScope research presents opportunities to improve understanding of tectonic inheritance from the Grenville orogen (assembly of Rodinia), though Neoproterozoic supercontinent breakup and opening of Iapetus, to Paleozoic Appalachian orogenesis and assembly of Pangaea, and subsequent Mesozoic breakup of Pangaea and opening of the Atlantic. The results of these large-scale events are and have for >2 centuries been the focus of studies of outcrop and shallow subsurface geology; now EarthScope can investigate fabrics and heterogeneities of these events in the deeper crust and mantle lithosphere. Although the problems to be addressed are regional in scope, focused studies, using Transportable Array (TA), Flexible Array (FA), and GeoPRISMS research in selected transects and areas, are needed to illuminate the geometry and spatial distribution of lateral and vertical variations in thickness and strength of continental crust and lithosphere, and overprints of successive events.

Discovery of the lithospheric geometry of the successive major constituents of eastern North America will form the basis for understanding fundamental processes. This margin offers opportunities to test two fundamental hypotheses: (1) during continental rifting, brittle faulting of the upper crust is linked to ductile extension of the continental lower crust and mantle lithosphere; (2) transform motion is expressed in brittle faults in the upper crust and by linked ductile transform-parallel fabrics in the mantle lithosphere. First characterizing the lithospheric structure of the Iapetan rift margin, the Appalachian orogenic belt, and the Mesozoic rift margin will support testing of other hypotheses: for examples, (1) rift-stage structures significantly influence subsequent orogenic structures and foreland-basin evolution; and (2) continental fabrics of earlier events of extension and contraction exert controls on Mesozoic rift structures.

Reconstructing the geometry of the Neoproterozoic Iapetan rifted margin of Laurentia is fundamental to understanding the role of tectonic inheritance in Appalachian contraction and Mesozoic extension. Basement-rooted Appalachian structures shortened and translated various components of the older rifted margin. Balanced restorable cross sections have supported palinspastic restoration of the geometry of the Iapetan rifted margin (Fig. 1) from the Marathon embayment to the Virginia promontory (Thomas, 1991, 1993, 2011), and from the Quebec embayment through the Newfoundland embayment (Allen et al., 2009, 2010). In the region between—around the Pennsylvania embayment and New York promontory, basement massifs reflect complex Appalachian deformation (Fig. 1); however, the present (displaced) distribution of Neoproterozoic synrift and Cambrian-Ordovician passive-margin rocks document rift initiation and evolution along the Neoproterozoic rifted continental margin. Structural complexity and uncertain magnitude of translation frustrate efforts to use conventional techniques of structural geology in building an accurate palinspastic reconstruction of the margin, indicating the need for nonconventional approaches. The lithospheric expressions of rift segments and transform faults can be characterized where the rifted margin has been palinspastically restored, and then that expression can be used as guide to the location of the rift where it cannot be restored by conventional methods. Along-strike variations in rift expression between lower-plate and upper-plate configurations of basement faults are partitioned by transform faults, some of which offset the trace of the rift. Facies and thickness of synrift and passive-margin stratigraphy vary along strike in patterns that indicate differences in lithospheric subsidence history between upper-plate and lower-plate rifts and along transform faults (summary in Thomas, 2006).

The tectonic load placed on the Iapetan continental margin by Appalachian deformation is reflected in foreland-basin subsidence. Magnitudes of tectonic thickening of the crust and foreland subsidence require lithospheric adjustments, and resolution of lithospheric structures is essential to understanding evolution of continental crust during contractional events that lead to supercontinent assembly. Variations in subsidence along the orogenic foreland correspond to large-scale transform faults of the Iapetan rift margin (Thomas, 2006), suggesting a focus for investigation of along-strike variations in lithospheric thickness and strength. Appalachian foreland structures and crustal subsidence change dramatically along strike between the Pennsylvania embayment and New York promontory (contrasts between the central and northern Appalachians).

Inboard from the Iapetan rift (and from the contractional effects of Appalachian orogenesis), basement fault systems have rift-parallel and transform-parallel orientations (Fig. 1), and are temporally and kinematically linked to Iapetan rifting (Thomas, 2006, 2010, 2011). Distal to Appalachian synorogenic foreland basins, high-amplitude, long-wavelength cratonic domes/arches and basins characterize the North American craton. Expressions of these structures in the lower crust and mantle and linkages to Iapetan rifting and/or Appalachian contraction are yet to be determined; however, they have important implications for understanding the structure and stability or instability of continental cratons, as well as intraplate seismicity and seismic hazards. In this context, crust-lithosphere studies along the eastern margin can be linked to EarthScope projects in the Midcontinent.

Mesozoic continental breakup and opening of the Atlantic Ocean overprinted the extensional phase of another Wilson cycle upon the Iapetan extensional and Appalachian-Pangaean contractional crustal structures (Thomas, 2006). The fill of Triassic grabens and seaward thickening Jurassic and younger deposits of the Atlantic Coastal Plain record rift initiation and evolution to passive-margin subsidence. Some components of Atlantic opening directly overprint older Iapetan extensional structures and/or Appalachian-Pangaean contractional structures, whereas some elements of the Atlantic rift margin cut across the older structures (Thomas, 2006). One challenge here will be to differentiate the effects of Iapetan and Atlantic extension at the scale of crust and lithosphere.

The TA and densification with the FA will be necessary to resolve the shallow crustal structures. New seismic data must be integrated with the outcrop geology to give the best possible resolution of the Appalachian contractional structures. Available relatively high-resolution geologic mapping will guide locating of FA transects, some of which should incorporate active-source reflection surveys, as well as passive-source experiments. Studies of lithospheric structure along the eastern Laurentian margin will enable unique interpretations of (1) the growth and modification of continental lithosphere and sedimentary cover through two Wilson cycles of continental accretion and rift initiation and evolution, (2) along-margin variations in structure and evolution of the lithosphere, and (3) tectonic inheritance through two Wilson cycles.

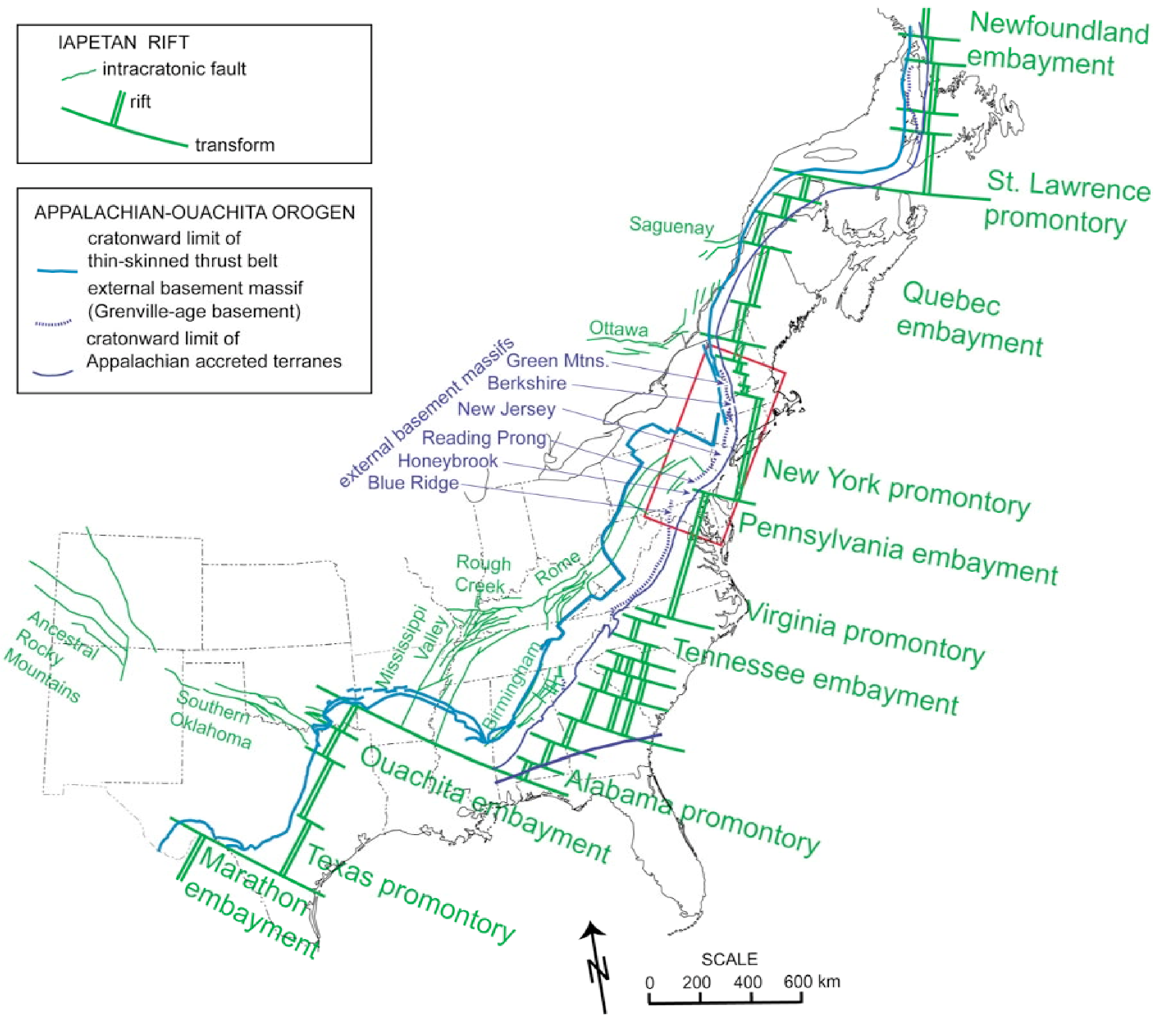

Figure 1. Map of Iapetan rifted margin of eastern Laurentia (green lines) and Appalachian-Ouachita orogenic belt (blue lines). Red rectangle shows focus area.

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Accretion of terranes and growth of continental crust along the southern margin of Laurentia during assembly of Pangaea [and modifications by opening of the Gulf of Mexico]

Thomas, Dumond, Harrelson, Harry, Horton, Keller, Langston, Magnani, Mickus, Mueller, Powell, Russo

Two significant accreted continental terranes within the late Paleozoic southern Appalachian-Ouachita orogen document growth of continental crust of southern ENAM (Fig. 1). Around the Ouachita embayment of the rifted margin, the late Paleozoic Ouachita orogen includes a forearc complex and accretionary prism associated with southward subduction of Laurentia beneath the Sabine continental terrane (affinity unknown) and continental-margin arc. On the corner of the Alabama promontory, the Suwannee-Wiggins suture truncates Laurentian continental crust, reflecting continent-continent collision of Laurentia with the Suwannee (Africa) terrane. The Suwannee-Wiggins suture trends westward toward the Sabine terrane; however, the possible relationships between the Sabine and Suwannee terranes are unknown. Are these terranes components of a single larger terrane, or are they distinct separate continental blocks? Does accretion of these terranes reflect a unified event or separate events of plate convergence? Regardless, terrane accretion contributed significantly to late Paleozoic growth of Laurentian/North American continental crust. Mesozoic rifting, leading to opening of the Gulf of Mexico, somewhat extended parts of the accreted terranes, and established a new continental margin on the south. Did the fabric of late Paleozoic accretion significantly constrain Mesozoic extension? Critical information to be gained from Transportable Array and Flexible Array densification includes thickness and nature of the crust from continental Laurentia across the terrane boundaries, terranes, and Mesozoic extensional faults. Resolution of subducted slabs and sutures is necessary to discriminate the Sabine accretionary prism from the Suwannee-Wiggins suture. The area, where the two terranes are traced to a near intersection, will be critical in comparing and contrasting the crustal structure of the terranes, as well as the nature of the accretionary fabrics. How did the accreted terranes affect Mesozoic extension? And how has the accreted continental crust been modified by Mesozoic extension?

Sedimentary deposits in the Ouachita embayment record rift initiation and evolution, as well as subduction-related processes. The Ouachita embayment, bounded by the orthogonal northeast-striking Ouachita rift and northwest-striking Alabama-Oklahoma transform, was formed in Cambrian time by the rifting of the Argentine Precordillera away from Laurentia (Thomas and Astini, 1996). Sedimentary deposits record the new continental margin and evolving oceanic crust, including a Cambrian-Mississippian carbonate facies on the passive-margin shelf and a temporally equivalent, mud-dominated continental-slope-and-rise prism and abyssal plain on oceanic crust, parts of which are now incorporated in the Ouachita thrust belt (summary in Thomas, 2011). An abrupt increase in sedimentation rate in the Middle Mississippian indicates the change from passive-margin deposition to early synorogenic deposition, indicating the initial approach of the Sabine terrane. Subsequent Upper Mississippian–Middle Pennsylvanian forearc-basin deposits and an accretionary prism are associated with a continental-margin arc on the leading edge of the Sabine terrane. A Middle Pennsylvanian synorogenic clastic wedge in the Ouachita foreland records rapid foreland crustal subsidence as a result of tectonic loading on the southern margin of Laurentian continental crust. Deformed synorogenic deposits are overlain by an undeformed Upper Pennsylvanian–Middle Permian shallow-marine fill of a successor basin, indicating the termination of orogenic contraction and terrane accretion within the Ouachita embayment at ~309 Ma (Nicholas and Waddell, 1989).

The orthogonal intersection of the northwest-striking Alabama-Oklahoma transform fault with the northeast-striking southern segment of the Blue Ridge rift outline the Alabama promontory of Laurentian crust (Fig. 1). Late Paleozoic continent-continent collision with the Suwannee terrane truncated and obliterated part of the corner of the Alabama promontory (Fig. 1); therefore, the rift and post-rift history of the margin must be reconstructed from projections from other areas. Northeast along strike, synrift sedimentary and volcanic accumulations indicate the time of opening of Iapetus and continental rifting to be latest Precambrian (543 Ma) (summary in Thomas, 1991). Repeated episodes of Appalachian orogenesis have obliterated any possible off-shelf continental slope-and-rise deposits; however, a robust Cambrian-Ordovician passive-margin carbonate-shelf facies documents the early post-rift history of the Alabama promontory. Palinspastic restoration of the passive-margin carbonates now in the Appalachian thrust belt shows that the original extent of the shelf was somewhat greater than the presently preserved extent of shallow Laurentian crust, thereby documenting truncation of Laurentian crust during continent-continent collision with the Suwannee terrane (Thomas, 2011). Diachronous elements of foreland synorogenic clastic wedges indicate episodic orogenesis at different places around the margin of the Alabama promontory. Although foreland subsidence and clastic-wedge progradation began earlier to both the west (Ouachita) and northeast (Appalachian), foreland subsidence and clastic-wedge progradation did not begin on the corner of the Alabama promontory until middle Early Pennsylvanian (315 Ma), signifying initiation of continent-continent collision with the Suwannee terrane. A wide band of metamorphic lithons, interlaced with mylonites, marks the suture between Laurentian continental crust and the African crust and cover of the Suwannee terrane (summary in Thomas, 2010); metamorphism along the Suwannee-Wiggins suture is as young as ~300 Ma (Steltenpohl et al., 2008), indicating later convergence than along the leading edge of the Sabine terrane.

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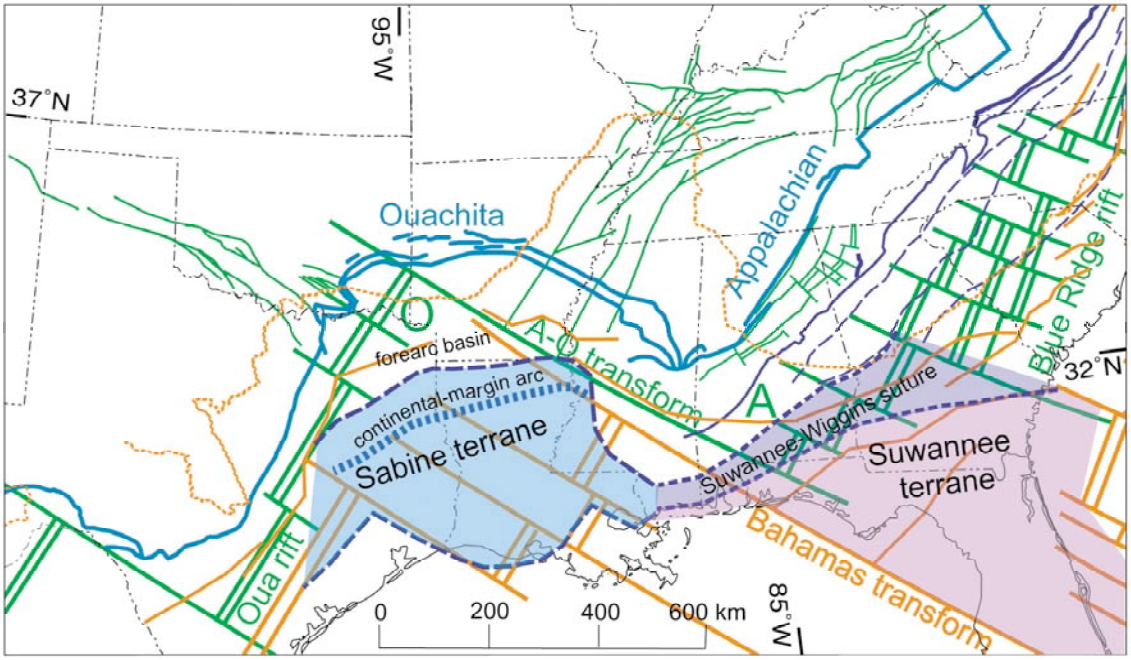

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White Paper

Early Post-Rift Deformation on the Rifted Margin of Eastern North America: Relationship to Breakup and the Early Stages of Seafloor Spreading

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Introduction

A massive rift zone developed within the Pangean supercontinent during early Mesozoic time (Fig. 1, inset). The part of the rift zone now preserved on the margin of eastern North America (ENAM) consists of a series of exposed and buried rift basins extending from the southeastern U.S. to the Grand Banks of Canada (Fig. 1). Rifting along the entire zone was underway by early Late Triassic time. The end of rifting (and presumably the onset of seafloor spreading) was diachronous, occurring first in the southeastern U.S. (latest Triassic), then in the northeastern U.S. and southeastern Canada (Early Jurassic), and finally in the Grand Banks (Early Cretaceous) (Withjack & Schlische, 2005; Schettino & Turco, 2009).

Deep-seated, compressional post-rift deformation occurs on most rifted continental margins; however, its cause remains controversial (e.g., The Nature and Origin of Compression in Passive Margins, Geological Society of London, Johnson et al., 2008). Here, we propose to study the deep-seated, post-rift deformation of the ENAM margin that is broadly coeval with the early stages of seafloor spreading. The ENAM margin is particularly well suited for this study because its post-rift deformation has not been overprinted/obscured by subsequent plate collision (e.g., Alpine deformation) or, for the U.S. part of the margin, by later salt tectonics.

Early post-rift deformation

The ENAM rift system consists of a series of asymmetric rift basins (half grabens) that developed within Paleozoic and older orogenic belts. The border-fault zones (BFZs) of the rift basins are mostly reactivated, pre-existing structures that dip either seaward or landward with gentle to moderate dips (e.g., Lindholm, 1978; Ratcliffe et al., 1986; Withjack et al., 1995) (Fig. 1). Most BFZs strike NE-SW (parallel to the pre-existing fabric and faults) and underwent mostly normal displacement during rifting (e.g., Schlische, 1993, 2003).

Structural restorations indicate that the geometry of the ENAM rift basins today differs significantly from their geometry during the final stages of rifting. Much of their current geometry reflects deformation that apparently occurred soon after rifting (Figs. 2, 3a), including: 1) reactivation of BFZs and intrabasin faults with reverse and/or strike-slip components of displacement (e.g., Venkatakrishnan & Lutz, 1988; deBoer & Clifton, 1988; Withjack et al., 2010); 2) fault-parallel folding near BFZs and intrabasin faults (i.e., buttress folds associated with basin inversion) (Withjack et al., 1995, 2010; LeTourneau, 2003); 3) fault-perpendicular folding near BFZs and intrabasin faults (Lucas et al., 1988, Withjack et al., 2010); and 4) very broad arching that produced regional tilting and uplift, leading to locally > 5 km of erosion (Withjack et al., 2011). This post-rift erosion considerably reduced the size (depth and width) of the ENAM rift basins (e.g., Steckler et al., 1993; Malinconico, 2003; Withjack et al., 2011). The timing of the ENAM post-rift deformation is poorly constrained, but a growing body of evidence suggests that much occurred during breakup and/or the early stages of seafloor spreading. In the southeastern U.S., post-rift deformation occurred during the development of the Central Atlantic Magmatic Province (CAMP) in latest Triassic/earliest Jurassic time (Withjack et al., 1998; Schlische et al., 2003). In the Orpheus rift basin of SE Canada (Fig. 1), most post-rift deformation occurred in Early Jurassic time (e.g., Syamsir et al., 2010). Similar post-rift arches are present on other rifted continental margins, including those on the rifted margins of the North Atlantic (e.g., Lundin & Dore, 2011) (Fig. 3b), some of which are temporally associated with the North Atlantic Igneous Province.

Research questions:

Our proposed research addresses several fundamental science questions related to the crustal and lithospheric properties and processes of rifted continental margins.

- When did post-rift deformation occur? Were there multiple episodes as on other rifted continental margins? Is deformation related to the development of the CAMP and/or to the formation of seaward-dipping reflectors?
- What is the relationship between the early post-rift deformation and the pre-existing structures? Are the pre-existing zones of weakness produced during Paleozoic orogenic activity (e.g., thrust ramps, strike-slip faults) more commonly reactivated than those produced during Mesozoic rifting (e.g., normal faults)? Why do many post-rift arches overlie the Appalachian Gravity Gradient?
- What is the deep expression of the post-rift deformation? Is the Moho elevated beneath the post-rift arches (e.g., the elevated Moho beneath the Long Island platform; Hutchinson et al., 1986)?
- What are the rheological properties of the crust and upper mantle beneath the post-rift arches? Does anomalous mantle underlie the post-rift arches of ENAM as hypothesized for the North Atlantic (Lunden & Dore, 2011)?
- What is the temporal and spatial relationship between the landward and seaward deformation associated with breakup and the early stages of seafloor spreading? For example, was the more-landward post-rift deformation coeval with the more-seaward focused extension associated with breakup? What variability exists along the margin? How much is related to pre-existing Paleozoic structures? How much is related to the northeastward transition from volcanic to non-volcanic passive margin?
- What were the stress and strain states associated with the post-rift deformation? Did they vary spatially and temporally? Is there a relationship with the current state of stress?
- What causes the post-rift deformation? Folding, reverse faulting, uplift, and erosion are not classic passive-margin processes (e.g., fault-controlled subsidence during rifting followed by thermal subsidence), and later orogeny cannot have caused post-rift deformation in ENAM.

Answers to these questions will provide insight into fundamental rifting and breakup processes. Specifically, the information would allow us: 1) to better reconstruct rift geometries and define crustal and mantle behavior during the final stages of rifting, 2) to better understand the spatial variability of deformation during breakup and the early stages of seafloor spreading by comparing landward and seaward deformation, and 3) to provide an improved framework for understanding ENAM seismicity.

Approach and possible discovery corridors:

The proposed research requires a multi-faceted approach: 1) acquisition of regional 2D seismic-reflection profiles that link the onshore and offshore crustal structures associated with breakup and the early stages of seafloor spreading; 2) deployment of coincident focused (~ 5-km spacing) passive seismic sensors to determine the deep expression of these deformational features (e.g., “frozen” rock fabric in the crust and uppermost mantle related to the last deformational activity); and 3) detailed field studies of exposed rift basins and their BFSs to better define the relationship between the early post-rift deformation and pre-existing structures, the timing and magnitude of early post-rift deformation, and the stress/strain states associated with early post-rift deformation. Existing field, core, well, and seismic-reflection data obtained by academia, government, and industry will augment the newly acquired geophysical and geological data. Four potential discovery corridors are from north to south (Fig. 1):

1: NW-SE regional transect across onshore and offshore New England (Georges Bank basin)
2: NW-SE regional transect across PA, NJ, and offshore NJ (northern Baltimore Canyon trough
3: NW-SE regional transect across onshore and offshore VA (southern Baltimore Canyon trough)
4: NW-SE regional transect across onshore and offshore North Carolina (Carolina trough)

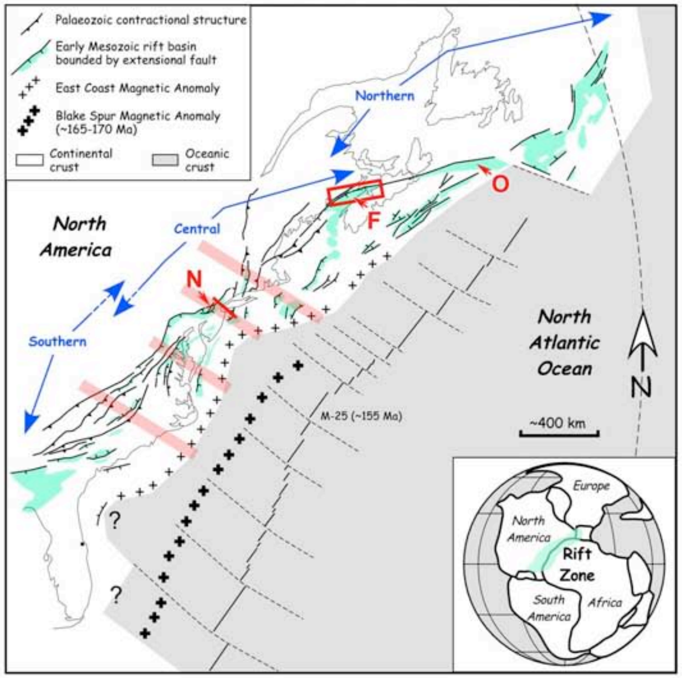


Fig. 1. Map of eastern North American margin (ENAM) showing key tectonic elements (for references, see Withjack et al., 1998). Transparent red rectangles are potential discovery corridors; F, N, and O are Fundy, Newark, and Orpheus rift basins; red box shows location of Fig. 2a; red line is location of regional cross section in Fig. 3a.

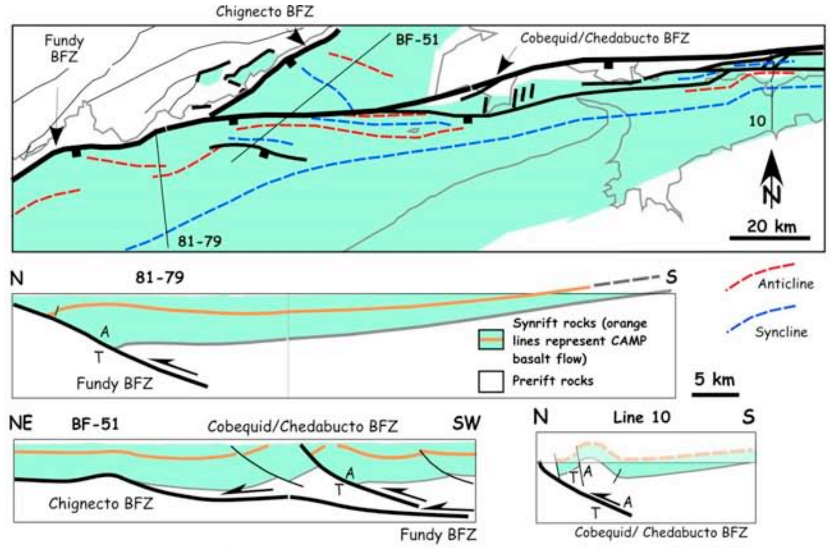
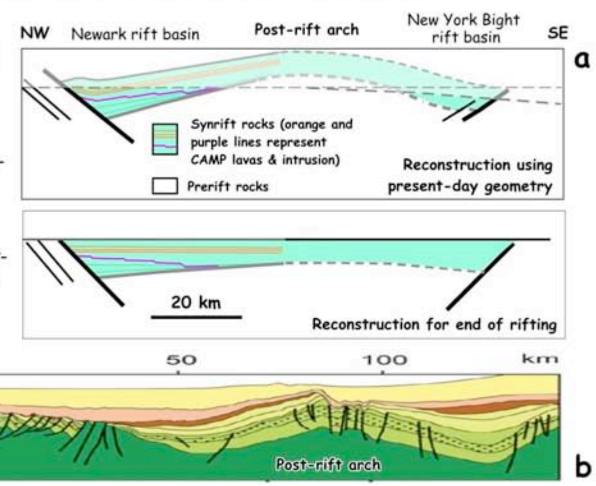


Fig. 2. Map of northern Fundy rift basin (top) showing border-fault zones (BFZs) and post-rift folds. Representative cross sections through basin based on seismic-reflection profiles (bottom). A is motion away from viewer; T is motion toward viewer. After Withjack et al. (2010).

Fig. 3. a) Regional cross section across Newark and New York Bight rift basins from Withjack et al. (2011) and Hutchinson et al. (1986). b) Interpretation of regional seismic line from Voring basin showing broad-wavelength arch (from Lundin & Dore, 2011). Displayed with 2/1 vertical exaggeration assuming a velocity of 4 km/s.



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