3.3. Eastern North American Margin – Primary Site

(Replaced May 29, 2012; revised December 23, 2013)

3.3.1. Background and Motivations: Relationships to RIE Questions

Rifted "passive" margins play an important role in our understanding of the rifting process because they contain a record of the entire geologic history, from rift onset to continental breakup to the initiation of seafloor spreading and the maturation of the margin. The goals of the RIE initiative, as outlined in the GeoPRISMS Draft Science Plan (DSP), are to understand how rifts initiate, how the processes that drive rifting interact and evolve, how these processes lead to particular rift architectures, and what the elemental fluxes are between earth, oceans and atmospheres during both rifting and post-rift margin evolution. The Eastern North American Margin (ENAM, Figure 3.7) and its conjugate form an ideal system for making substantial progress on RIE goals. ENAM encompasses large variations in fundamental rift parameters, including the volume of magmatism during breakup, the pre-existing lithospheric template, and the duration of rifting. ENAM continues to evolve today, millions of years after the cessation of rifting. A thick wedge of sediments and sedimentary rocks, with maximum thicknesses of 10 km or more, has been deposited along the Atlantic margins and hosts a record of syn- and post-rift processes, sea-level change, and paleoclimate. ENAM also hosts numerous types of hazards, including offshore landslides and intraplate earthquakes, such as the recent M5.8 Mineral Virginia quake.

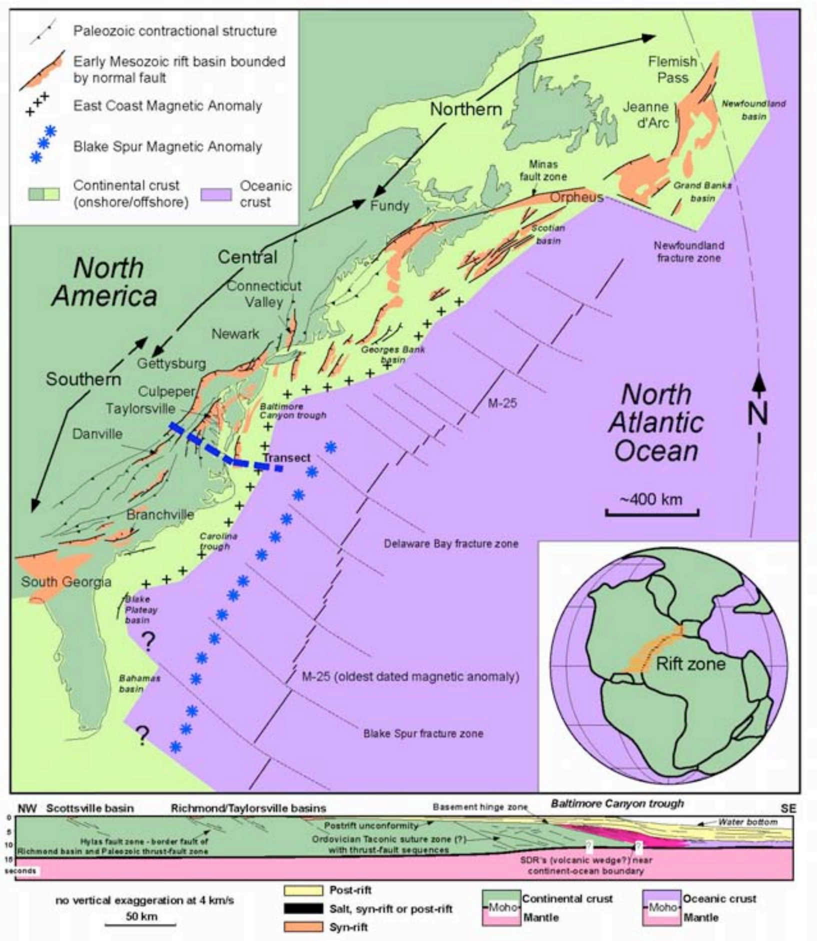
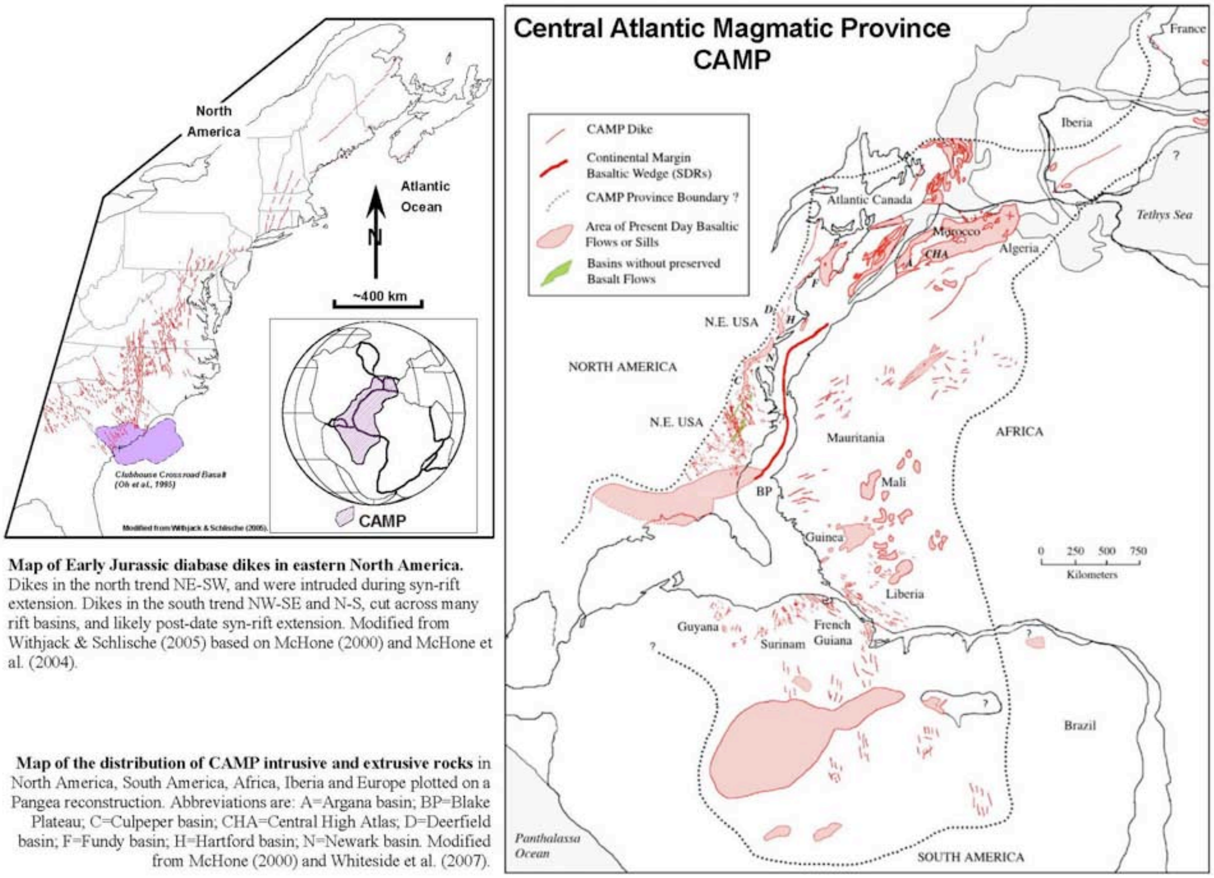


Figure 3.7. ENAM and the major tectonic elements. The East Coast Magnetic Anomaly approximates the extent of seaward dipping reflectors in the continent-ocean boundary (red reflectors in the cross-section. M-25 is the oldest dated magnetic anomaly. Inset shows the configuration of Pangea during the late Triassic (Olsen, 1997) and highlights the rift zone between ENAM and NW Africa and Iberia. Modified from Withjack and Schlische (2005).

3.3.1.1. Background and Science Questions

ENAM formed during Mesozoic rifting that led to the breakup of the Pangean supercontinent. Rifting was broadly distributed, commonly reactivating earlier structures, including sutures of Paleozoic accreted terranes. During breakup, extension became more focused, causing the lithosphere to rupture near the edge of the modern continental shelf and leaving behind numerous abandoned rift basins. Most aspects of this breakup, including the role of sutures, however, remain unclear. In the southern U.S., breakup was roughly coincident with one of the most voluminous but short-lived magmatic events in Earth's history, the Central Atlantic Magmatic Province (CAMP), and breakup along the margin was correspondingly magmatic (Figure 3.8). In contrast, breakup of the northernmost portion of this margin (offshore Newfoundland) occurred much later and is distinctly magma-poor. Here, breakup left behind wide tracks of highly thinned continental crust and exposed, serpentinized mantle along the margin. In addition to end-member variations in rift-related magmatism on the scale of the entire margin, variations in magmatism and deformation are also seen on smaller scales between adjacent segments. Segmentation is apparent throughout the margin, from abandoned rift basins onshore to oceanic crust offshore, but many questions remain about the development and evolution of segmentation through time. This margin and its conjugate are particularly well preserved and relatively uncomplicated by subsequent tectonic events, making it an excellent setting in which to examine the deformation, magmatism and segmentation that led to continental breakup.



Map of Early Jurassic diabase dikes in eastern North America. Dikes in the north trend NE-SW, and were intruded during syn-rift extension. Dikes in the south trend NW-SE and N-S, cut across many rift basins, and likely post-date syn-rift extension. Modified from Withjack & Schlische (2005) based on McHone (2000) and McHone et al. (2004).

Map of the distribution of CAMP intrusive and extrusive rocks in North America, South America, Africa, Iberia and Europe plotted on a Pangea reconstruction. Abbreviations are: A=Argana basin; BP=Blake Plateau; C=Culpeper basin; CHA=Central High Atlas; D=Deerfield basin; F=Fundy basin; H=Hartford basin; N=Newark basin. Modified from McHone (2000) and Whiteside et al. (2007).

Figure 3.8. Extent of CAMP magmatism in ENAM, modified from Withjack and Schlische (2005), McHone (2000), and Whiteside et al. (2007).

The thick wedge of sediments along the margin stores a rich record of dynamic margin forcing mechanisms, such as lithospheric flexure and subsidence, lower crustal flow, deep mantle flow, and responses to paleoclimate and eustatic sea level changes. Patterns of erosion, transport and deposition evolve through time in response to these and other processes, recording this response in sedimentary sequences. In many places throughout ENAM, the margin's response to post-rift tectonic and geodynamic processes is recorded as post-rift deformation within sedimentary sequences. At the shelf edge, gravity-driven sediment transport (e.g., landslides and turbidity flows) destabilize the slope and carry sediment to the deep sea where it may be redistributed by oceanographic processes. The sedimentary section can also be altered chemically via diagenesis, methanogenesis and other processes that are associated with venting of carbon-rich fluids and gasses. Several aspects of the sedimentary wedge make ENAM ideally suited for rifted margin studies. First, because ENAM is 'salt-free' along much of its length, many of the processes recorded in the sedimentary wedge can be imaged without limitations posed by diapiric evaporite bodies common to many other rifted margins. Second, sedimentation was nearly continuous and rates were relatively high along the margin for much of its history, providing a robust record of sedimentary environments ranging from glacial-dominated to carbonate.

The four broad questions that define the goals of the RIE initiative motivated the selection of the two primary RIE sites, ENAM and East Africa. The GeoPRISMS community then met at an implementation planning workshop in Lehigh, PA, and developed a plan to address the RIE science goals within ENAM by focusing on the following set of research targets:

- *The role of tectonic and magmatic inheritance in rifting and rift evolution*
- *The role of magmatism in rifting, breakup, and post-rift lithospheric evolution*
- *The relationships between breakup, rift-related magmatism, and CAMP*
- *The along-strike transition from magma-rich to magma-poor extension at breakup*
- *The evolution of segmentation from initial rifting to mature seafloor spreading*
- *Mass and elemental fluxes into and out of the sedimentary wedge*
- *Factors that control offshore landslides and their distribution*
- *Post-rift margin evolution, drivers and responses: subsidence, epeirogeny, dynamic topography, landscape evolution, erosion, deposition*
- *Relationships between rift structures and seismic hazard within ENAM*
- *Understanding the passive-margin sedimentary record: comparative studies of exposed and buried margin sedimentary sequences*

The ENAM implementation planning workshop in Lehigh was held jointly with GeoPRISMS and EarthScope. There is a great potential for synergy between the research efforts of these two groups within ENAM, and a unanimous sentiment at this meeting was that it is important to make special efforts to maximize this potential. The science targets listed above are specific to GeoPRISMS, but they are informed by the entirety of the joint workshop outcomes and, in some cases, presuppose some level of EarthScope collaboration. There was also a stated awareness at the workshop that the coincidence of the arrival of EarthScope and the beginning of GeoPRISMS focus on the U.S. eastern margin presents a special opportunity for the Earth science community as a whole to engage the public in new and significant ways. It is thus hoped that maximizing scientific synergies will lead naturally to maximizing outreach opportunities.

Moreover, there is an increasing awareness that ENAM hosts a range of active processes that can have a substantial impact on the densely populated regions along the east coast. Submarine landslides pose a tsunamigenic risk to coastal communities and can damage offshore infrastructure such as cables and pipelines. Landslides have been documented along the entire eastern margin. Additionally, intraplate earthquakes regularly occur along rifted margins worldwide, and along the eastern North American margin in particular, as exemplified by the M5.8 Virginia earthquake in 2011. Seismic-wave propagation is more efficient in the cold, old crust of the eastern U.S. (compared with the western U.S.), such that the effects of smaller quakes can be more widespread. Such issues demonstrate the high societal relevance of carrying out focused scientific investigations of eastern North America, to better understand the controls on and the dynamics of such active processes along this rifted margin.

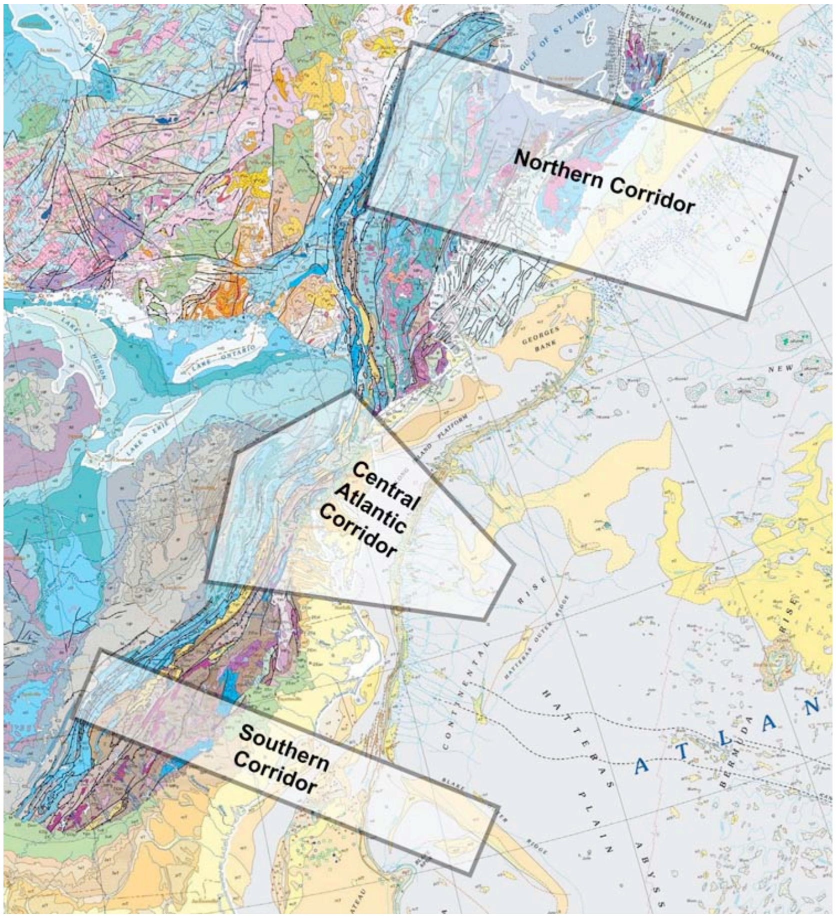


Figure 3.9. DNAG (Decade of North American Geology) geologic map of eastern North America showing the focus areas defined for GeoPRISMS research in ENAM. Modified from http://esp.cr.usgs.gov/info/gmna/)

3.3.1.2. Geographical Focus Areas

During the ENAM implementation workshop, the community identified a series of corridors or focus areas within which GeoPRISMS research is to be focused (Figure 3.9). Each of these corridors contains key features that are required to address the science targets above, targets that address interconnected processes operating over hundreds of millions of years. Taken together, the corridors span the large-scale along-strike changes in inherited orogenic structures, style of rifting, rift-related magmatism, and post-rift evolution that make ENAM a desirable focus for the RIE initiative. The corridors are each intended to be wide enough to capture smaller-scale along-strike variability and to provide flexibility for effective science. The precise borders should not be taken too literally but instead to delineate the general areas selected by the community for focused research efforts.

What follows is a summary of each of the ENAM research corridors. Each summary provides an overview of the corridor, highlights the particular ENAM science targets that may be best addressed within the corridor, provides an overview of existing data, and describes possible new GeoPRISMS activities. The corridor summaries are followed by a description of possible synoptic studies within ENAM, important partnerships, and the broader impacts of GeoPRISMS research within ENAM.

3.3.2. Southern Focus Area (Charleston)

RIE Key Topics

- ***The role of tectonic and magmatic inheritance in rifting and rift evolution***
- ***The role of magmatism in rifting, breakup, and post-rift lithospheric evolution***
- ***The relationships between breakup, rift-related magmatism, and CAMP***
- *Mass and elemental fluxes into and out of the sedimentary wedge*
- *Factors that control offshore landslides and their distribution*
- ***Relationships between rift structures and seismic hazard within ENAM***
- *Understanding the passive-margin sedimentary record: comparative studies of exposed and buried margin sedimentary sequences*

The primary GeoPRISMS focus in the Southern Focus Area is on understanding: i) the role of inheritance in the evolution of the margin; ii) the source, timing, volume and residua of voluminous rift-related magmatism and its relationship to CAMP; and iii) the mass and geochemical fluxes into and out of the thick passive-margin sedimentary wedge. Synergies between offshore geophysical surveys (e.g. to image Paleozoic sutures, the distribution of magmatic additions during breakup, and relationships to the continent/ocean boundary) and ongoing EarthScope and DOE projects onshore provide opportunities to study the southern ENAM in the context of inheritance through a full Wilson cycle.

The Southern ENAM focus area was conceived at the ENAM implementation workshop as a corridor extending across the heart of the southern Appalachians eastward onto Atlantic oceanic crust (Figure 3.10). From west to east, the corridor crosses the highest topography of the Appalachian Mountains, the allocthonous Blue Ridge and Piedmont terranes, the massive Carolina terrane - bound by the Taconic suture in the west and the Alleghanian suture in the east, the large onshore South Georgia Basin rift system mostly within the Carolina terrane, a voluminously magmatic continent/ocean transition, and the exceptionally deep Carolina Trough prism of rifted margin sediments and sedimentary rocks before reaching “normal” oceanic crust. This corridor also includes two zones of known seismicity (Charleston and Eastern Tennessee), the extensive Blake Ridge contourite gas hydrate province, and large landslides preserved on the slope north of Blake Ridge. This particularly rich record of the tectonic and geologic evolution of ENAM provides opportunities to address a very broad spectrum of Earth science questions.

Where and why continental rifts initiate is deeply connected to structural inheritance. Many rifts localize along terrane boundaries and sutures inherited from accretionary and collisional tectonic events. These boundaries may represent weak zones, or they may be strong boundaries that localize extension by preserving inherited rheological contrasts; they may be pathways for rift

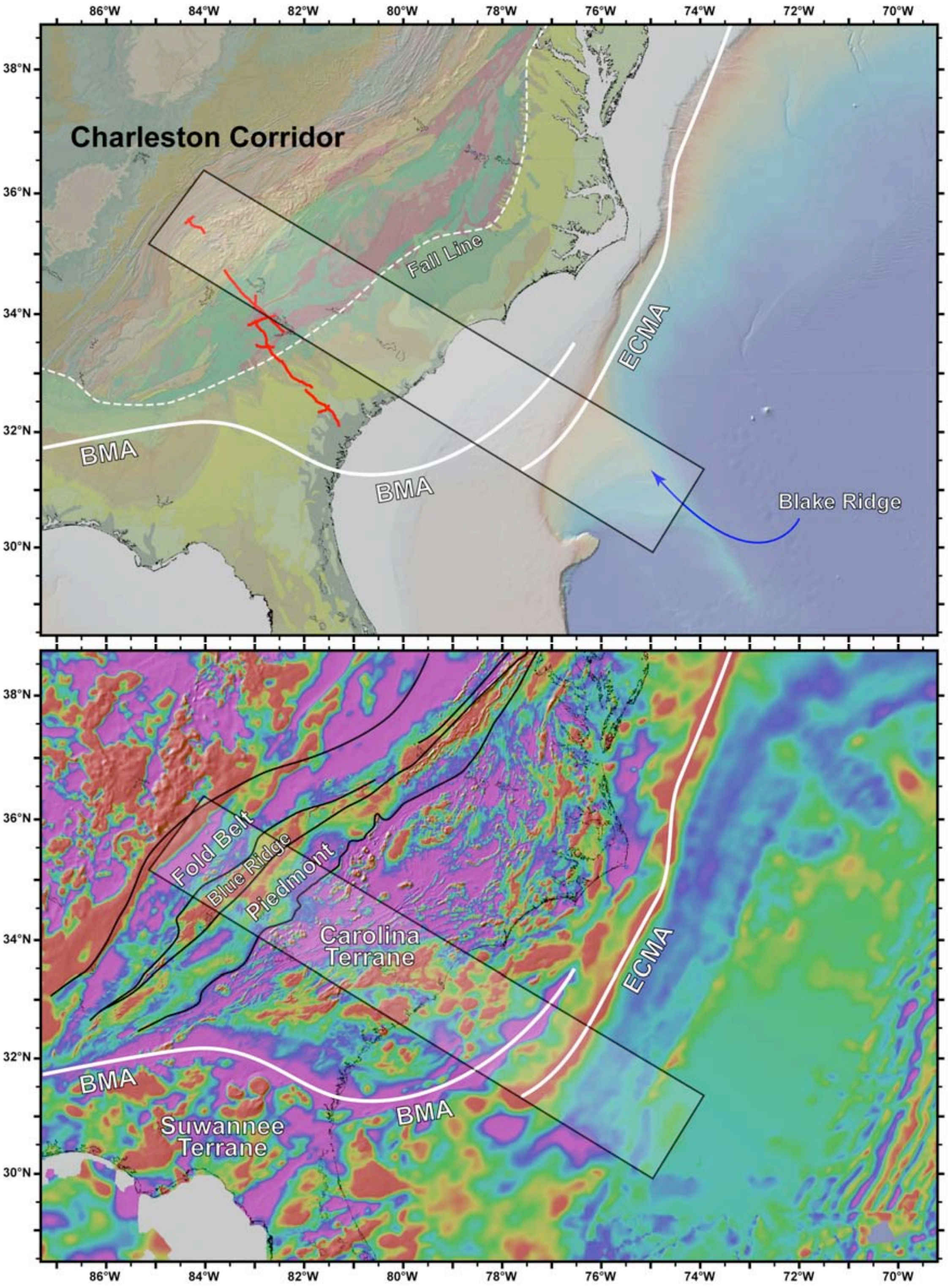


Figure 3.10. Top: Topography and onshore geology of southern ENAM. Box indicates the Charleston Corridor. BMA, Brunswick magnetic anomaly, thought to mark the Alleghanian suture. ECMA, East Coast magnetic anomaly, effectively marks the continent/ocean transition and the seaward-dipping reflector sequence. Red are COCORP lines shown in Figure 3.11. Bottom: Magnetic anomaly map indicating the same features and the extension of the corridor onto normal oceanic crust.

presenting thermal edges in the asthenosphere that drive small-scale convection; they can be several of these things at once and other things as well. The Southern ENAM focus area is very well suited for developing a mechanistic understanding of rift evolution in the presence of inherited fabric. Advantages of this location include: i) well delineated Paleozoic terrane boundaries that had varying responses to Mesozoic rifting and magmatism, ii) a solid observational framework, including geologic data, core samples from beneath the coastal plain sediments, and several deep-penetrating seismic profiles targeting these terrane boundaries, and iii) ongoing field efforts funded through EarthScope that address the relationship between sutures and rifting onshore in area. A possible role for GeoPRISMs is to complement EarthScope efforts with new observations of the sutures offshore, targeting their role in contributing to rupture.

The Southern focus area provides several opportunities for advancing our understanding of the source, timing, volume, feedback and residua of voluminous rift and breakup magmatism. The expression of magmatism throughout the region is dramatic, including the widely distributed dikes, sills and flows from the apparently brief (~1 Ma) CAMP event and the voluminous new igneous crust emplaced at the continent/ocean transition beginning at or near the time of CAMP activity and continuing for some time after breakup. Lithospheric rupture and CAMP magmatism are closely linked in both time and space. It is unclear, however, if this linkage is causal, and perhaps common to magma-rich rupture, or simply coincidence. This relationship is central to the ongoing debate about the geodynamic origin of both CAMP and volcanic margins generally. The U.S. east coast margin has played an important role in this debate as an example of a voluminously volcanic continent/ocean transition with considerable along-strike extent that is difficult to explain with the type of plume explanation that works so well for the North Atlantic. Detailed knowledge of the timing, volume, distribution and mechanics of emplacement of CAMP and rift-related magmatism would advance our understanding of processes related to voluminous magmatism at continental breakup and how the residue of these processes affect the long-term stability of the margin. As with targets related to inheritance, ongoing EarthScope and DOE projects within the Southern focus site are targeting questions related to Mesozoic magmatism, providing opportunities for coordinating complementary GeoPRISMS activities.

Studies of the relationship between rift structures and seismic hazard would be an obvious extension of any basin- or crustal-scale studies near the coast within the Charleston corridor. The Charleston earthquake of 1886 is estimated to have had a magnitude of M_L ~7, and the region remains seismically active today. The USGS conducted a number of geological and geophysical studies in the Charleston area in the 1970s and 80s, both onshore and offshore, in an effort to better understand the structural controls on seismicity. That work indicated a relationship between seismicity and faults and boundaries of the South Georgia Basin rift system. Seismic data collected offshore show inverted Triassic basins, with large reverse separation on reactivated basin-bounding faults. More modern data recently collected onshore, through the DOE project described below, has dramatically improved the delineation of portions of the South Georgia Basin, and it is likely that new data acquired offshore would be similarly transformative.

Employing new approaches for understanding the passive-margin sedimentary record was a key theme of the MARGINS decadal review. This theme was echoed during the implementation meeting at Lehigh, noting that joint *EarthScope/GeoPRISMS* efforts to compare seismic images of the offshore margin section with nearly complete Appalachian exposures of similar Laurentian passive margin sedimentary wedges would represent a novel approach that capitalized on the common science interests of these programs. The Carolina trough, with sediment thicknesses locally up to 12 km or more, provides an extensive record of passive-margin subsidence and sediment accumulation and could serve as the offshore reference section for such a study. The Carolina trough section is also interesting in that the slope sediments merge into the large Blake Ridge contourite deposit, which is a well studied methane gas hydrate reservoir. The Blake Ridge is similar to other large sediment accumulations along the ENAM continental rise, whose distribution and deposition are controlled to a great degree by contour currents. The Blake Spur fracture zone seems to exert considerable control on the morphology of the Blake Ridge, and similar rift segmentation may exert control on the rise sediment accumulations elsewhere throughout ENAM. The nature of such segmentation, however, remains poorly defined, and detailed study along this corridor may resolve many unknowns. The Blake Ridge is also an obvious location to study the flux of carbon out of passive-margin sediments, with considerable work already having been done here. The offshore sediments of the Charleston corridor are also well suited to a more comprehensive study of the geochemical fluxes, including carbon and nutrients, out of the seafloor of the entire passive-margin sedimentary sequence. Many of the advances within this emerging field of study have been made based on observations from within the South Atlantic Bight, and so both an observational framework and a community of scientists already exists for this region. Similarly, landslides are common along the slope of the South Atlantic Bight, with the Cape Fear landslide being one of the largest and best studied within ENAM. While the GeoPRISMS approach to landslide studies is likely to be synoptic, landslide studies within the Charleston corridor will benefit from or could piggyback on geophysical cruises focusing on other aspects of GeoPRISMS study in this area.

3.3.2.1. Existing Datasets and Studies in the Area and Data Gaps

A number of seismic, geologic and geochemical datasets exist both onshore and offshore within the Southern focus area. Onshore, nearly all of the rift structures within the focus area are buried beneath coastal plain sediments. Subsurface geology is known from numerous borehole core samples, many of which have published geochemical analyses. The COCORP southern Appalachians lines provide the primary crustal-scale multi-channel seismic (MCS) data onshore (Figure 3.11). Those data provide images of the Taconic and Alleghanian sutures, broad-stroke delineation of the South Georgia Basin, and some indication of the extent of CAMP basalt flows beneath the coastal plain. The only controlled-source, crustal-scale refraction data are those acquired by recording quarry blasts. However, EarthScope has funded a project to acquire two long refraction lines across the South Georgia Basin and Alleghanian suture in southern Georgia. EarthScope has also funded the SESAME project, now underway, which is aimed at defining the deep structure of relic Pangean sutures. In addition, DOE has funded a project for basin-scale MCS data acquisition and drilling within the South Georgia Basin. The goals of that project are to assess the utility of buried CAMP basalt flows for carbon sequestration. Offshore, the USGS collected a number of crustal-scale, margin-crossing MCS transects in the 1970's all along ENAM. One of these lines was instrumented with ocean-bottom seismometers (OBSs) and provided the first indication that a high-velocity magmatic body (coincident with the East Coast Magnetic Anomaly, ECMA) underlies the continent/ocean transition. The USGS also acquired a focused grid of crustal-scale and high-resolution MCS lines on the shelf just offshore Charleston. In the late 1980's, NSF funded a large academic seismic experiment that acquired six margin-crossing, crustal-scale seismic transects within the Charleston corridor with the aim of testing the hypothesis that the Brunswick Magnetic Anomaly marks the Alleghanian suture offshore. Two of those lines were instrumented with short-period OBSs, though the spacing was sparse by today's standards. The result of that experiment was the discovery of seaward-dipping reflector sequences along the margin and the realization that the margin was massively volcanic. In addition to these publicly funded datasets, a number of 1970's industry datasets are also available via the USGS-hosted data portal. Those datasets consist of several dense grids of speculative MCS data over particular target features.

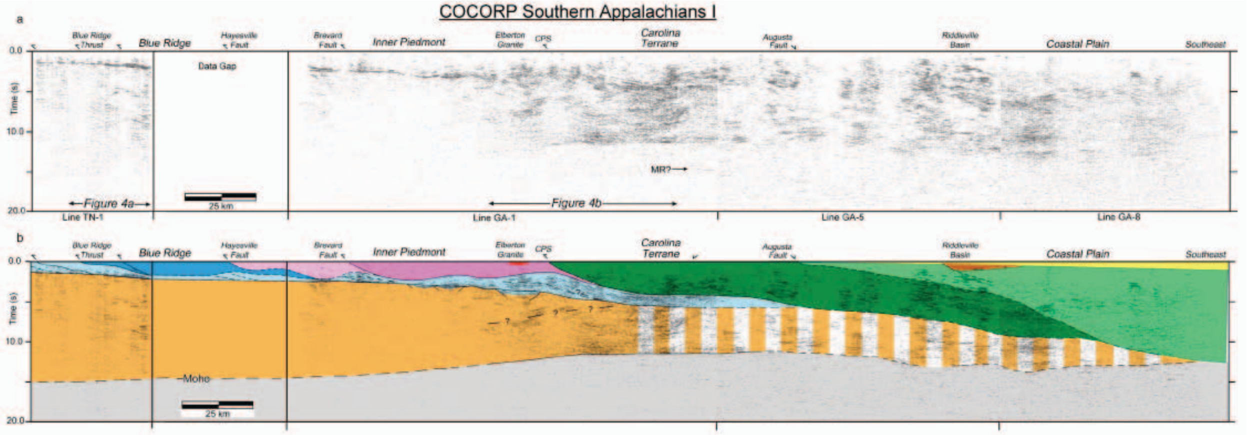


Figure 3.11. (a) Migrated, coherency filtered, and uninterrupted data from COCORP lines TN-1, GA-1, GA-5, and GA-8 subparallel to the Charleston focus area. A portion of the west end on the line GA-5 has been removed due to overlap with line GA-1. (b) Interpretation of (a) modified from Cook et al. (1979, 1981). See Figure 3.10 for line of section.

3.3.2.2. Examples of GeoPRISMS Studies

Geophysical Imaging: Addressing RIE questions within southern ENAM, such as the roles of inheritance and magmatism in rifting and breakup, will require crustal and upper mantle imaging that targets a range of particular features throughout the corridor. During the Lehigh ENAM implementation workshop, it was noted that a bold approach to imaging key features would be via a "grand" transect through the entire corridor, from the East Tennessee Seismic Zone eastward across the Appalachian mountains, the piedmont, the coastal plain, the Charleston earthquake zone, and continuing offshore across the ocean/continent transition onto normal oceanic crust. Whether targeted or grand, complementary margin-parallel surveys, both onshore and offshore, are needed to constrain along-strike variability in order to clarify the relationships between onshore basin development, segmentation and oceanic fracture zones. Studies imaging key features onshore are already funded through EarthScope. The arrival of the USArray on the east coast provides new opportunities for coordinating with GeoPRISMS, including deep geophysical imaging of the lithosphere offshore, which is needed to constrain the lithospheric manifestation of sutures and extension, to detect the residue of voluminous mantle melting, and to capture the ocean continent boundary and the transition to mature oceanic lithosphere.

In addition to imaging surveys (which might involve both seismic and magneto-tellurics), high-resolution magnetic and gravity surveys would further resolve terrane boundaries, basins, and rift-related igneous bodies. Offshore, deep-towed magnetic surveys may provide new insights into the nature of the BMA and its role in rifting as well as the detailed magnetization of the volcanic wedge. Onshore, the integration of 3D potential field data with subsurface samples will continue to provide our most comprehensive means of inferring rift structure and magmatic emplacement buried beneath the coastal plain.

Geochronology, Geochemistry: A large number of existing samples of exposed and sub-crop CAMP dikes, sills and flows have been analyzed for age dating and for bulk- and trace-element geochemistry. The utility of these samples is not close to exhaustion, however, and it is likely that results from GeoPRISM and EarthScope work in the southern focus area will motivate new and novel analyses of various existing sample suites. In addition, new samples are being acquired as part of the DOE project, and the community holds out hope for a deep drill hole into the seaward dipping reflection sequence. Geochemical studies need not be limited solely to Mesozoic igneous rocks. Studies of the geochemical flux out of the seafloor on passive margins rely on shallow borehole installations across the shelf to record temporal records of flux as driven by various oceanographic phenomena. One could envision such studies being undertaken in concert with stratigraphic studies of shelf deposition and geotechnical studies of shelf sediment mechanical properties.

3.3.3. Central Focus Area (Richmond - Philadelphia)

RIE Key Topics

- ***The role of tectonic and magmatic inheritance in rifting and rift evolution***
- ***The relationships between breakup, rift-related magmatism, and CAMP***
- *The evolution of segmentation from initial rifting to mature seafloor spreading*
- *Mass and elemental fluxes into and out of the sedimentary wedge*
- *Factors that control offshore landslides and their distribution*
- ***Post-rift margin evolution, drivers and responses: subsidence, epeirogeny, dynamic topography, landscape evolution, erosion, deposition***
- *Relationships between rift structures and seismic hazard within ENAM*

> *The primary GeoPRISMS focus within the central region is on constraining the relative contributions of lithospheric composition, isostasy, erosion, and mantle dynamics contributing to the evolution and present-day morphology of the margin. The central portion of the ENAM encompasses the area north of the Carolinas to southern New England. A number of the Mesozoic rift basins were inverted and deformed shortly after rifting took place, and there are strong indications that neotectonic processes are actively uplifting portions of this region, but there are few constraints on the mechanisms contributing to past and present deformation. This region also provides the opportunity to study the comparative roles of preexisting weaknesses in the lithosphere and magmatism on rifting processes. This region is characterized by strong transitions in the structure of the Appalachian orogen, the age and structural style of Mesozoic rifts, and degree and style of magmatism during rifting and breakup, and is therefore an ideal location to investigate the contributions of preexisting structure and magmatism to variations in rift structure. Because these along-strike variations in this region are present over a large region onshore, EarthScope will likely have a greater role in addressing these questions in this region.*

The central region of the ENAM has undergone substantial changes in morphology since continental breakup in the early Jurassic. Significant post-rift contraction and uplift occurred within this region shortly after breakup, and there are indications in the geomorphic and sedimentary record that the region experienced uplift during the Miocene and Quaternary. Evidence for post-rift contraction includes basement-involved reverse faulting, significant erosion and arching in some (but not all) onshore rift basins (e.g., 5+ km removed from the Newark Basin), onshore and offshore unconformities, large Cretaceous sediment fluxes, and folding within the rift basin sediments (Figure 3.12). While basin inversion is a well-known and documented phenomena, it is unclear how the inversion in the ENAM was related causally and temporally to CAMP magmatism, emplacement of the SDRs, and a hydrothermal event in the Middle Jurassic. The origin of the basin inversion is also unclear, though asthenospheric upwelling, ridge-push forces, and continental resistance to plate motion have been suggested as causes. Additional questions remain regarding the overall magnitude of basin inversion and how the inversion is spatially controlled, whether upper crustal strength or deeper dynamic processes exert mechanical control over the inversion.

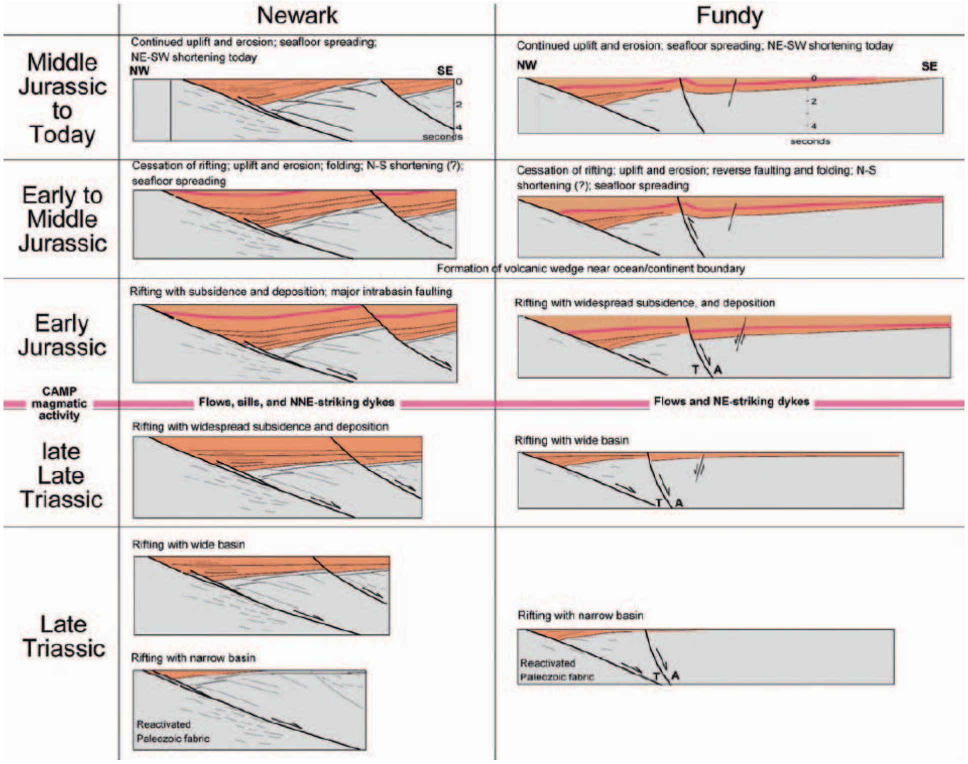


Figure 3.12. Evolution of representative rift basins from the Central focus area (Newark Basin) and the Northern focus area (Fundy Basin). Both basins show evidence for post-rift inversion, uplift and rotation. Extensional faults within the Fundy Basin show reactivation as reverse faults, contributing to excellent surface exposures today. Modified from Withjack et al. (2012)

Evidence for Cenozoic uplift and neotectonic activity in the region includes recent intra-plate seismicity, knickpoint migration along stream profiles, and increased sediment flux during the Miocene. Furthermore, Eocene volcanism emplaced ~150 Myr after CAMP in the southern Mid-Atlantic suggests that there have been active processes in the mantle that have recently impacted the lithosphere. Recent geodynamic models, tomographic images, and shear wave splitting measurements of the mantle beneath this region suggest that there may be vertical mantle flow related to the foundering Farallon slab that could contribute to neotectonic signals at the surface. It is necessary to characterize the relative contributions of lithospheric composition, isostasy, erosion, and mantle dynamics to the present day topography of the region. Characterizing the interaction of these processes on land is key to understanding what controls the preset-day form of the continental slope and how sediments are presently moving across the system.

The central ENAM region also provides opportunities to study the comparative roles of inherited structures and magmatism on rifting processes. This region is characterized by strong transitions in the structure of the Appalachian orogen, the age and structural style of Mesozoic rifts, and degree and style of magmatism during rifting and breakup. This area represents the transition zone between the northern and southern Appalachians, and there are differences related to terrane accretion and a number of identified Paleozoic contractional structures. These variations likely played a role in the segmentation and structural style of Mesozoic rifts within the region.

Mesozoic magmatism also varied from south to north within this region (Figure 3.8). The orientation of dikes rotates from NNW to NE from the southern to the northern portion of this area and slightly younger dikes overprint the NNW dikes in the southern area, suggesting that there was a transition in the state of stress across this region during emplacement. Furthermore, it appears that distributed rifting had already ceased during CAMP emplacement in the southern portion of the area, whereas it may have persisted longer in the northern portion of the region.

This region also contains the northern terminus of the Blake Spur Magnetic Anomaly (BSMA), and therefore contains the transition between early and later ridge segment development. Because there are strong variations in inherited structures along the margin, as well as variations in magmatic timing and style, this is the ideal location to investigate their relative effects on rifting and breakup. As there is not a clear African counterpart to the BSMA, it has been suggested that it represents a sliver of margin crust that that was originally conjugate to the U.S. margin. After the incipient mid-ocean ridge jumped to the east, perhaps after 25 Myr, it left the BSMA near the US margin. This scenario would explain the asymmetry between US and northwest African rifted margins. Alternatively, seafloor spreading may have been asymmetric during early opening of the Atlantic Ocean.

3.3.3.1. Existing Datasets and Studies in the Area and Data Gaps

A variety of onshore seismic data sets exist in this area, derived from both passive broadband and short period stations, as well as various controlled source experiments. Several permanent broadband seismic stations operate in the region (i.e., by Lamont Doherty Earth Observatory, Penn State University, USGS). The TEENA (Test Experiment for Eastern North America) array operated in Virginia and West Virginia for one year, and consisted of 9 broadband seismic stations oriented across the strike of the Appalachian mountains; the 18 month-long MOMA (Missouri to Massachusetts) experiment crossed the northern portion of the region. A handful of new passive seismic stations have come on-line following the 2011 Virginia earthquake. Controlled source experiments in this region include the I-64 Virginia Tech line, as well as other proprietary lines, such as the PR-3 in Virginia. Several older COCORP lines sampled the northernmost portion of the region in NY State, and seismic-reflection data have been acquired by industry in the Taylorsville and Newark basins.

Offshore data in this region include two wide-aperture controlled-source experiments of the offshore region, the LASE (offshore New Jersey) and EDGE (offshore Virginia) experiments in the early 1990s. Extensive seismic reflection profiles were acquired across the continental shelf by industry and the USGS, imaging the submarine sediment wedge, and COST wells and numerous ODP Sites have been drilled in the area (Figure 3.13), as well as some industry wells.

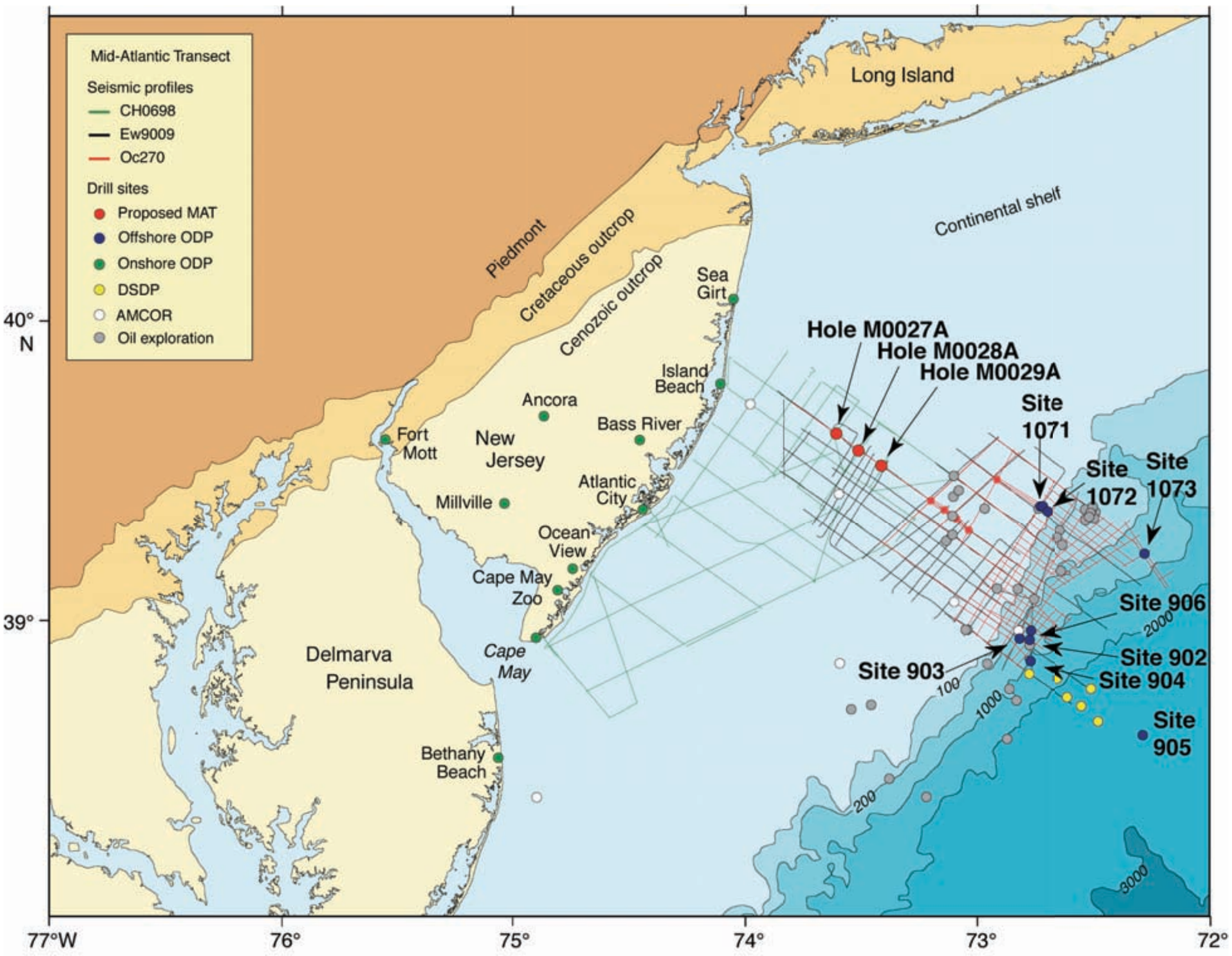


Figure 3.13. The New Jersey continental margin showing Expedition Holes M0027A, M0028A, and M0029A along with other completed boreholes both onshore and offshore. Tracks of reconnaissance seismic lines are also shown. (Expedition 313 Scientists, 2010).

Building on deep-penetration seismic profiling of the Baltimore Canyon Trough by the USGS in the 1970s (Outer Continental Shelf initiative) and academia in the 1980s and 1990s (LASE, EDGE), the mid-Atlantic region has been a natural laboratory for the study of Cretaceous-Recent eustatic change for more than 20 years. With support from the Office of Naval Research, NSF and the New Jersey State Geological Survey, "nested" 2D seismic profiles at a variety of depth and resolution scales have imaged the drift section, and then been complemented by suites of drillholes both on the Coastal Plain and the continental shelf and slope (Figure 3.13). Nowhere else in the world has a passive margin received this level of attention from the academic community.

3.3.3.2. Examples of GeoPRISMS Studies

Geophysical Imaging: The Central region of ENAM is ideally suited for an along-strike, on-land passive seismic experiment to examine (a) the transition between the northern and southern Appalachians, and (b) the nature of segmentation and progression in age and structural style of the Mesozoic rift basins. Dense across-strike seismic profiles will be necessary to investigate small-scale variations in crustal thickness, mantle anisotropy, and signals related to layering and suturing in the lithosphere (these signals would be aliased by the 75 km Transportable Array station spacing). Additional controlled source experiments would constrain mid- and lower-crustal structure across the region. Additional geomorphic data from the Appalachian highlands would be required to constrain the nature and location of transient erosional features.

Offshore, additional deep velocity control, perhaps best achieved with dense OBS deployments along a finite number of deep-penetration MCS profiles across the mid-Atlantic continental shelf and slope, will augment envisioned USGS UNCLOS profiling farther seaward. After decades of geophysical experiments: (a) the structural nature of the transition from continental to oceanic crust in this region remains unclear, although we now know that that transition is in part marked by a seaward-dipping reflector succession, (b) the spatial and temporal relationships of suspected along-strike variations in CAMP volume/spatial dimensions have not been linked to known Appalachian/Newark Series segmentation, and (c) the stratigraphic relationships of rift/earliest drift sediments within the crustal transition at the North American continent's seaward edge remain unknown, because the predominant effort to date has been on detailed examination of the "Greenhouse" and "Icehouse" sediment sections of this margin in service to sea-level studies.

Geochronology, Geochemistry: The Central region of the ENAM contains exposed intrusive and extrusive igneous rocks from the Paleozoic, Mesozoic, and Cenozoic. Constraining the timing and composition of these rocks will shed light on the composition of the mantle prior to rifting, the contribution of magmatism to rifting and breakup, and the evolution of the mantle following the rupture of the lithosphere.

Of particular interest is constraining the mantle response following rifting and breakup, and how the bottom of the lithosphere was altered (depleted, dehydrated, crustal underplating, etc) by rifting. Some of these questions can be addressed by characterizing the composition and cause of Eocene volcanism in Virginia and in the Carolinas long after breakup. Questions also remain regarding the timing of Cretaceous "Stone Dome" and its relationship to other magmatic activity along the continental margin that occurred after breakup. In the central study area, the SDRs are not the same age as CAMP. In this area, the CAMP extrusives and intrusives were emplaced during the rifting phase preceding breakup (~200 Ma). If the SDRs were emplaced at the time of breakup, then they must be younger than CAMP. Depending on the age of breakup (~195-185 Ma), the SDR's could be 5-15 million years younger than CAMP.

Sedimentary Processes: Central ENAM is a natural focal point for studies of epeirogeny within ENAM. The New Jersey continental margin is already a natural laboratory for both eustatic and relative sea-level change. The considerable observational and intellectual infrastructure that make up this laboratory include detailed seismic images of shelf sedimentary sequences, geologic control on seismic stratigraphy, particularly through the Cenozoic, from an array of borehole observations, and an extensive literature documenting analyses of these data. As noted below in Section 5, testing hypotheses for the geodynamic origin of margin uplift will likely require synoptic efforts that span a significant length of the margin. The initial steps in these efforts, however, require formulating tests for the various existing hypotheses and applying these tests to existing observations, and these initial steps are almost certainly best taken within the offshore laboratory of central ENAM. A focus on the sedimentary record of vertical motions would of necessity lead to studies of more general questions of sediment deposition on rifted margins, such as what controls the preset-day form of the continental slope and how sediments are presently moving across this system.

3.3.4. Northern Focus Area (Nova Scotia)

RIE Key Topics

- *The role of tectonic and magmatic inheritance in rifting and rift evolution*
- ***The role of magmatism in rifting, breakup, and post-rift lithospheric evolution***
- ***The along-strike transition from magma-rich to magma-poor extension at breakup***
- ***The evolution of segmentation from initial rifting to mature seafloor spreading***
- *Post-rift margin evolution, drivers and responses: subsidence, epeirogeny, dynamic topography, landscape evolution, erosion, deposition*

> *The primary GeoPRISMS focus in the northern area is the transition from magmatic breakup in the south to magma-poor breakup in the north. This transition is evidenced by the northward weakening and eventual disappearance of the East Coast Magmatic anomaly (ECMA), and also by the changes in the structure of igneous crust within the continent-mantle transition zone. Whether the along-strike variation in magmatism had its origin in deep mantle compositional or temperature anomalies or whether it was an expression of the style of lithospheric extension is not yet known.*

Southeastern Canada is a quintessential Atlantic continental margin with Paleozoic orogenic belts, Mesozoic rift basins, CAMP-related magmatic activity, post-rift basin inversion, and thick offshore post-rift sedimentary packages. Thus, the Northern Focus Area presents a good target for studies of continental rifting, breakup, and basin inversion in ancient mountain belts. The issue of tectonic inheritance is especially apt here. As elsewhere in eastern North America, continental rifting in southeastern Canada reactivated structures of the Appalachian orogen, which resulted in rift basins that largely parallel the older structures. These Appalachian structures, in turn, largely reflect pre-existing geometry of the Laurentian margin rifted during the opening of the early-Paleozoic Iapetus Ocean.

Numerous rift basins developed throughout southeastern Canada (e.g., the Fundy and Orpheus basins, Figure 3.14) during Late Triassic to earliest Jurassic time. In the Early Jurassic, continental breakup occurred, followed by seafloor spreading. Existing active-source seismic data and magnetic anomalies for offshore Nova Scotia show that the style of breakup varied along strike from magma-rich in the south to magma-poor in the north, correlated with the northward disappearance in the ECMA (Figure 3.15). The origin of this transition may be linked to tectonic inheritance from past rifting and orogenic episodes, or else it may be completely independent of them, and instead represent an evolution of the process in time (i.e., magmatic and amagmatic stages of breakup could be diachronous). It is notable that this along strike variation in magmatic activity observed offshore contrasts with an apparent continuity of tectonic

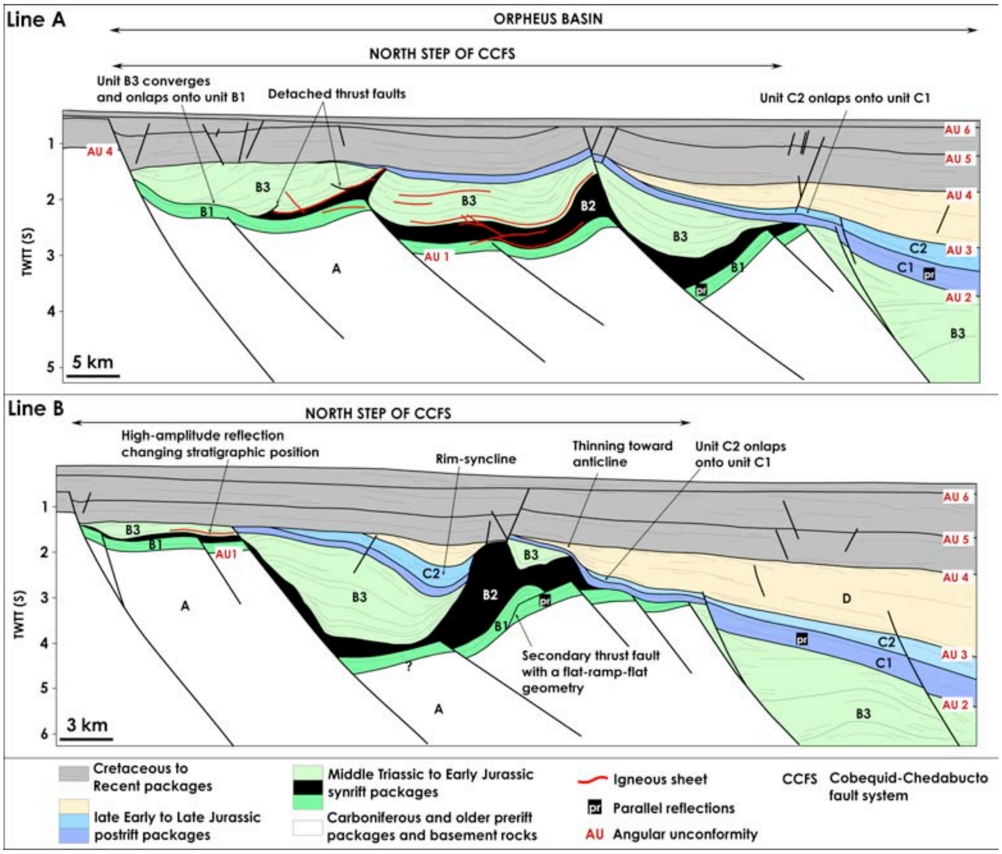


Figure 3.14. Interpreted line drawings of seismic lines A and B across the Orpheus Basin, offshore Nova Scotia, showing unconformity-bounded packages within the Paleozoic-Mesozoic-Cenozoic section of the Orpheus basin (From Syamsir et al., 2010).

fabric and magmatic activity onshore. Major terranes of the Appalachian orogeny continue along the entire length of Nova Scotia, and syn-rift magmatic activity associated with CAMP is found throughout southeastern Canada.

The Northern Focus Area contains the best sedimentary record of basin inversion within ENAM (Figures 3.12 and 3.14). Basin inversion is a term that broadly encompasses compressional deformation of a sedimentary sequence. Such deformation often occurs soon after lithospheric rupture, as it did in northern ENAM. In other locations, such as in southern ENAM, post rift compressional deformation can be inferred from regionally distributed post-rift unconformities. Despite the common observation of basin inversion and post-rift uplift and erosion, the processes that cause these phenomena and the factors that control them, such as pre-existing structure, remain very poorly understood. Basin inversion is not only dramatically expressed within the basins of northern ENAM, it is also imaged by scores of industry-quality seismic data within the North Focus Area, making this site particularly well suited for studying deformation processes that commonly follow soon after continental rupture.

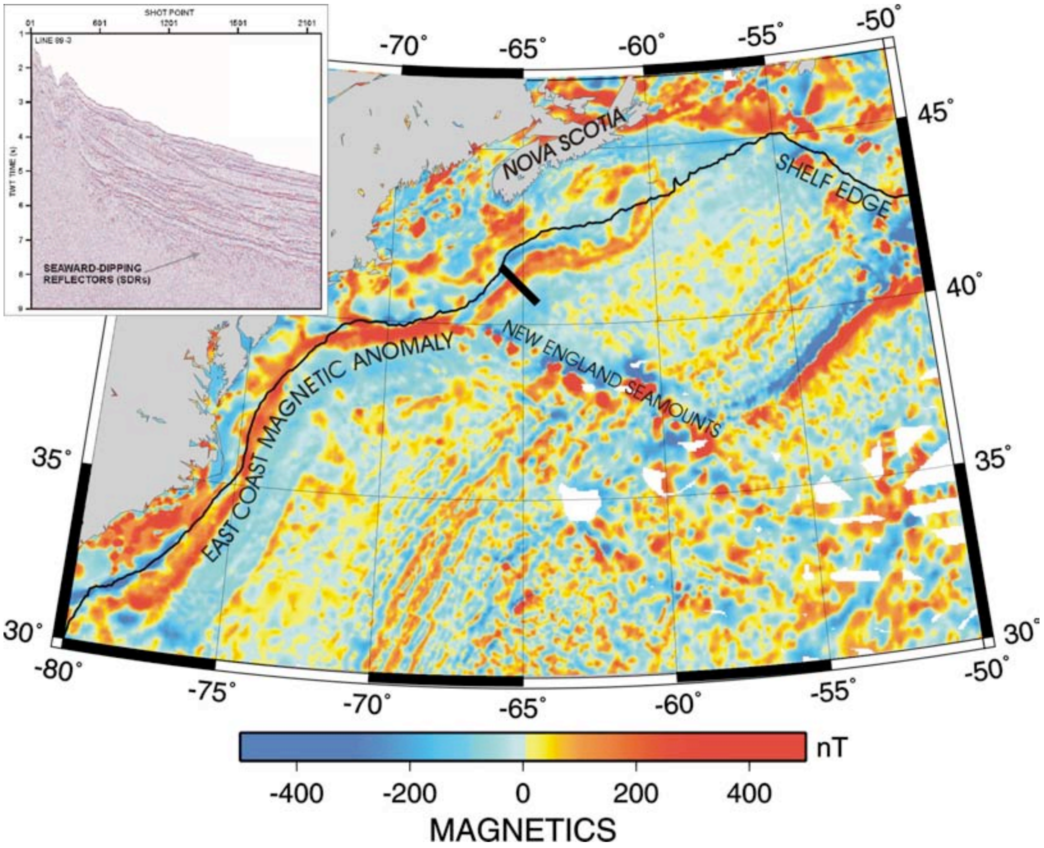


Figure 3.15. The distinct East Coast Magnetic Anomaly (ECMA), which shows up clearly along southern ENAM, dies out to the north, near the western edge of the Laurentian Channel. The reduction in ECMA amplitude off Nova Scotia may be due to a decrease in the volume of extrusive volcanic layers. Inset shows seismic character of seaward dipping reflectors (SDRs) from profile across pronounced ECMA (black bar on map). (Adapted from http://www.nrcan.gc.ca/earth-sciences/energy-mineral/geology/marine-geoscience/geology-of-scotian-margin/9295).

GeoPRISMS studies in the Northern focus area will help to expose the crustal and lithospheric structural elements associated with multiple Wilson cycles in this area, and unravel the detailed geologic history leading ultimately to rifting of the North Atlantic. This work relates directly to two key questions of the GeoPRISMS RIE initiative: (1) What is the temporal and spatial evolution of rifting processes? And (2) What controls the rifted margin architecture, both during and after the breakup? Answers to these two questions most likely reside within (or even below) the lithosphere, and may involve a complex interplay of inheritance (relating to lithospheric thickness and strength variations), magmatic forcing (due to an impinging plume), and margin evolution (driven, at least in part, by global plate motions). New data will be needed to image the large-scale structure of the lithosphere, both offshore and onshore.

3.3.4.1. Existing Datasets, Studies and Data Gaps.

The present-day structure of the Nova Scotia margin is known reasonably well on the basis of seismic studies and drilling. It represents a record of the past rifting and basin inversion processes. Across the southern and central Nova Scotia margin, the Lahave Platform occupies the outer shelf and continental slope area, with the Shelburne Basin located on the continental slope. In contrast, across the northern margin segment, the Sable Basin with syn-rift basins unconformably overlain by a thick wedge of post-rift sedimentary rocks is situated beneath the outer shelf. The oldest syn-rift deposits in the Sable Basin are non-marine Triassic redbeds. These are overlain by shallow marine sedimentary rocks of Late Triassic–Early Jurassic age, including salt of the Argo Formation, which produces extensive allochthonous structures in the Slope Diapiric Province.

The marine seismic reflection and refraction data acquired offshore Nova Scotia provide some of the best constraints on deep crustal structure of the entire ENAM focus site. The 2001 SMART seismic refraction study showed the basic differences in crustal structure of the southern and northern Nova Scotia margin. The 2010 OCTOPUS seismic refraction experiment and recent results from industry MCS profiles (Ion/GX Technology NovaSPAN 5100) along and across the margin show variations in thickness of igneous crust that suggest a narrow magma-dominant to a wide magma-poor along-strike transition between the southern and the central Nova Scotia margin. In the southern Nova Scotia margin, 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. 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, suggesting a higher degree of volcanism and a thinner layer of serpentinized mantle to the southwest.

The most significant data “gap” in the Northern focus area is the paucity of passive seismic data, especially offshore, but also onshore. As a consequence, the large-scale architecture of the margin is known only in places where seismic refraction studies were undertaken (SMART, OCTOPUS). As the processes shaping the margin were likely three dimensional, it will be desirable to acquire coverage that can resolve 3D variations in large-scale structure, spanning both onshore and offshore regions.

Some capacity for passive seismic studies exist in the region, in the form of permanent seismic observatories operated by the Geological Survey of Canada. The Earthscope Transportable Array deployment will extend to the southwest of Nova Scotia, and at least one EarthScope-supported study (a Quebec – Maine – Nova Scotia line) will place passive seismic observatories in Nova Scotia synchronously with the TA. These resources, available in the next 3 years, may be built upon, both on-land and offshore.

3.3.4.2. Examples of GeoPRISMS Studies

Key targets in the Northern focus area include obtaining constraints on the nature of lithospheric structure, both onshore and offshore, in order to address what controlled the transition from magma-rich to magma-poor continental breakup in this location, and the role of tectonic inheritance on this transition. Additional questions relate to the source of the magma and its variations along strike and through time. Spatial and temporal variations in magmatism may have influenced the observed structures, and records of these changes may still be detectable in variations in lithospheric mantle compositions.

It is also unclear how important magmatism was in facilitating continental breakup. Comparisons of existing OBS lines offshore Nova Scotia suggest that sea-floor spreading began more abruptly and more robustly (i.e., greater crustal thickness) to the south, relative to central and northern Nova Scotia, where the oceanic crust thins and layer 3 has a lower velocity on the seaward end of the profiles. However, the distance between existing marine seismic refraction lines is too great to determine if there is a direct along-strike correlation.

Additional questions relate to the relationships between CAMP-related magmatism, more evident to the south, and the transition from magma-rich to magma-poor breakup observed offshore Nova Scotia. And finally, what is the tectonic history of the Northern Appalachians from their formation to eventual continental breakup. This work would benefit from comparative studies of (or results from) the conjugate margin in Morocco.

Synthetic Studies Utilizing Existing Data Sets: The availability of an excellent archive of publicly accessible seismic reflection data collected offshore Canada, the results of past refraction studies, the drill core archives and detailed geological maps on land make this region well suited for synthesis studies. Such studies could mine existing data, with a focus on addressing issues of long-term tectonic evolution, the details of the rifting process in the Mesozoic, and evolution of the margin after breakup. Results of such synthetic studies would be very important for guiding future data collection efforts to fill in identified gaps, and for the development of models of the rifting process.

Geophysical Imaging: The existing geophysical data (seismic reflection and refraction data, detailed magnetic surveys) from the Nova Scotia margin provide a framework for future geological and geophysical studies under the GeoPRISMS RIE initiative. As a lot of the data are open (Enachescu, 2007), or available through cooperative agreements with Canadian researchers, excellent opportunities exist for studies that would integrate, synthesize and re-interpret these data, and formulate the goals of more targeted data collection .

On a broader scale, lithospheric structure could be targeted by shoreline-crossing seismic imaging efforts that would lead to the development of a truly 3D model of the margin on lateral scales of 10s to 100s of km. To obtain meaningful constraints, an area centered on the ECMA weakening at ~43°N/64°W and ~ 200-km wide in a N-S direction would need to be imaged. The eastern (seaward) boundary of the corridor needs to be at least 400 km offshore to include true oceanic lithosphere. The western (landward) extent of the proposed corridor has to extend onshore, ideally including the Appalachian front (i.e., area west of the St. Lawrence River). A deployment of a regular grid of OBS instruments would be useful to achieve this objective, using both passive and active sources. An extension of the regularly spaced passive seismic array on land would be essential to trace the large-scale structures across the shoreline. This land observing array may also act as a receiver for onshore-offshore active-source studies, both in the Atlantic and the Bay of Fundy. The Amphibious Array Facility currently deployed in Cascadia has the combination of technical elements necessary to study the Northern Focus Area.

3.3.5. Synoptic Studies

RIE Key Topics

- The role of tectonic and magmatic inheritance in rifting and rift evolution
- The role of magmatism in rifting, breakup, and post-rift lithospheric evolution
- The relationships between breakup, magmatism, and CAMP
- The evolution of segmentation from initial rifting to mature seafloor spreading
- **Mass (fluid and solid) and elemental fluxes into and out of the sedimentary wedge**
- **Factors that control offshore landslides and their distribution**
- **Post-rift margin evolution, drivers and responses: subsidence, epeirogeny, dynamic topography, landscape evolution, erosion, deposition, and deformation**
- **Relationships between rift structures and seismic hazard within ENAM**

> *The primary opportunities provided by synoptic studies along ENAM are comparative studies to understand along- and across-strike variations in tectonic, magmatic, and surface processes between the focus areas and along similar margins, as well as distributed processes that encompass the entire margin, such as geomorphic and geodynamic evolution. In addition, certain phenomena, such as landslides and earthquakes, must be studied where and when they occur, to gain a clearer understanding of their role along the entire margin.*

Addressing the scientific questions outlined in Section 1.1 requires, in some cases, synoptic studies on ENAM and beyond. We envision synoptic studies under two broad categories: Tectonic Evolution and Active Processes. These efforts will complement the more targeted studies envisioned by GeoPRISMS and may not, in general, require systematic and expensive new data collection. In many cases, they will rely on a synthesis of existing data, reanalysis of existing samples, exploitation of data collected by the EarthScope facilities, or data collected by community experiments or community expeditions. Areas where significant data gaps exist may be targeted for new data collection. In some cases, the number of high quality locations (e.g. magma evolution) for carrying out studies will be limited and may spread over the length of the margin.

3.3.5.1. Tectonic Evolution

Segmentation: The causes and consequences of margin segmentation may be most effectively addressed in larger, margin-scale studies where the transition between multiple segments can be observed. These studies can illuminate whether we can correlate segment boundaries with mappable onshore features, how these segment boundaries control the formation of new features on oceanic crust, whether major boundaries extend to the mantle lithosphere, and whether segment boundaries are reactivated during subsequent contractional and extensional events.

Tectonic and Magmatic Inheritance: The multi-stage history of rifting and orogenic events recorded at ENAM has ensured a rich magmatic and tectonic structure upon which multiple Wilson cycles have been imposed. The presence of inherited structures such as a magmatic underplating, diking, metamorphic fabric, and translated accreted terranes can significantly influence later rifting events. A better understanding of inheritance may illuminate the mechanisms for repeated rifting and orogenic events. A subset of such inherited structures lie within the various research corridors that have been defined. However, variations in these inherited structures may extend over areas larger than the proposed research corridors, and thus require studies that extend along-strike over significant portions of the margin.

Magmatic Evolution: Extensional and compressional magmatic systems play a role in the formation of ENAM, and the superposition of these and other tectonic events controls the modern ENAM lithospheric structure. Studies of magmatic processes along ENAM are fundamentally limited by exposure and access to suitable rock types. Exposures showcasing key rifting processes such as plume-lithosphere interaction, melting of lithospheric metasomes, and post-rifting volcanism are limited and may span multiple corridors. Where it can be demonstrated that study of rift-critical magmatic processes cannot be adequately addressed within the research corridors, studies of these processes should be pursued.

Conjugate Margin Studies: Our understanding of pre- and syn-rift processes will be furthered if we study the conjugate margin pair. Continental rifting and breakup typically takes place over about 10 my to 50 my. During this phase, continental crust and lithosphere thinning, and volcanism vary temporally and laterally in complex ways. The resulting rifted margins are never completely symmetric, nor are they asymmetric in a simple fashion. Therefore, observing rifting process at the conjugate rifted margin can illuminate rift processes beyond what can be learned from only one side of the rift. To better understand margin evolution, the conjugate rifted margin segment to each ENAM transect should be characterized. These data might include a good plate reconstruction with error estimates in the dip and strike directions, maps of geological and geophysical observations on- and off-shore of the conjugate margin, and the current understanding of the geology of the conjugate margin.

3.3.5.2. Active Processes

ENAM is a laboratory for the study of active processes including landscape evolution, sediment transport and deposition across the margin, slope failure processes, and late-stage crustal deformation and epeirogeny.

Crustal Deformation and Epeirogeny: ENAM is an outstanding laboratory to investigate the interplay between tectonic processes nucleating on relict pre- and syn-rift faults and dynamic rock uplift supported by sub-lithospheric mantle flow. Active seismicity and long-wavelength crustal warping are both present. The long-wavelengths of this behavior require analysis beyond specific corridors. These studies may inform our understanding of geohazards. For example, hazard maps are often biased toward areas that have had past earthquakes (Figure 3.16). However, this may represent a stochastic sampling of geologic behavior, and other areas may represent areas of equal or greater geohazard. A broader, more regional understanding of crustal stresses, neotectonic forcing and behavior may provide more accurate forecasts of such geohazards.

Landscape Evolution and Dynamic Topography: An emerging view is that a significant component of late Cenozoic landscape evolution at long length-scales (>100 km) may reflect changes in dynamic topography due to an evolving mantle flow field, driven in part by the subducted Farallon slab. Given the scale of the mantle features responsible for dynamic topography along ENAM, the resolution of geodynamical models and seismic tomography, and the long wavelength of likely geologic evidence for dynamic topographic, research efforts must incorporate a significant length of the margin (3° latitude or more). Tests of geodynamic models may have the greatest chance of success in the mid-Atlantic region centered over northern Virginia, but will have to extend from at least New Jersey to the Carolinas or Georgia, effectively combining the areas of two entire discovery corridors.

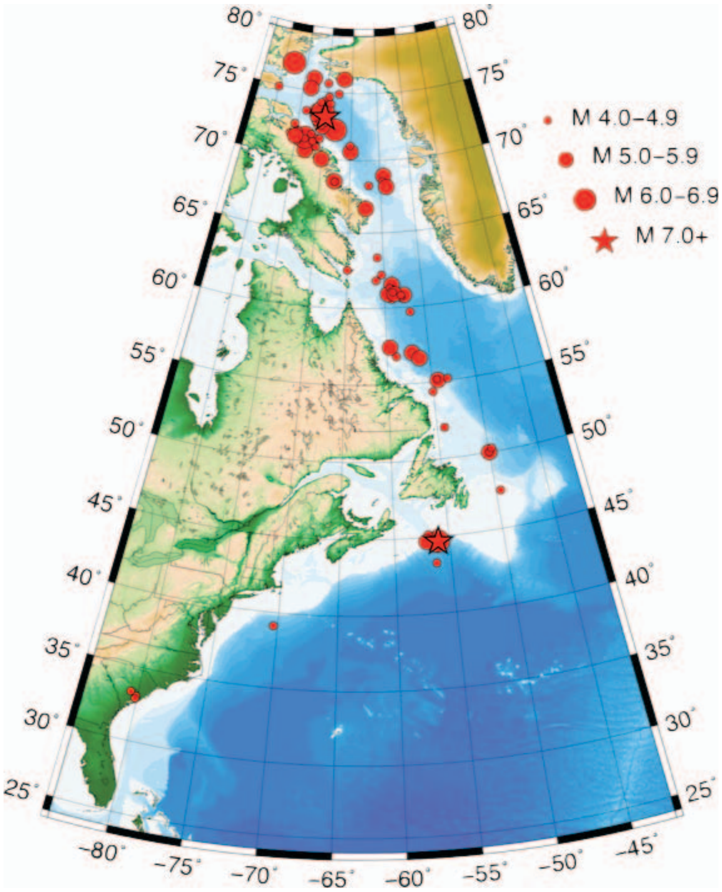


Figure 3.16: Magnitude of historic earthquakes along the Eastern North American margin. (Source: http://www.earth.northwestern.edu/people/seth/Lectures/index.html, Events from Schulte & Mooney, 2005), ANSS, and Earthquakes Canada; figure prepared by S. Stein).

Slope Stability: Large submarine landslides have been mapped along the length of ENAM (Figure 3.17) Some large submarine landslides and associated tsunamis are generated by earthquakes and others may be driven by depositional processes, or hydrate dissociation. To unravel the relative role of these drivers, it will be necessary to look at specific locations where slope instability is present and the driving mechanisms are known to be different. These synoptic studies may span ENAM. For example, earthquakes are a clear driver for submarine landslides along the northern ENAM where the crust is still responding to glacial unloading. In contrast, in southern ENAM stratigraphic history alone may control the generation and style of submarine landslides. With the large number of documented failures along the ENAM, targeted research studies can look at slides of multiple sizes, slides linked to different sediment distribution systems, and slides associated with various potential triggers (e.g., earthquakes as in Grand Banks, gas hydrate at Blake Ridge). Establishing the process controls on the size, rates, and recurrence of failures will also help constrain the tsunamigenic potential of slides and thus geohazard risk for the Atlantic margin.

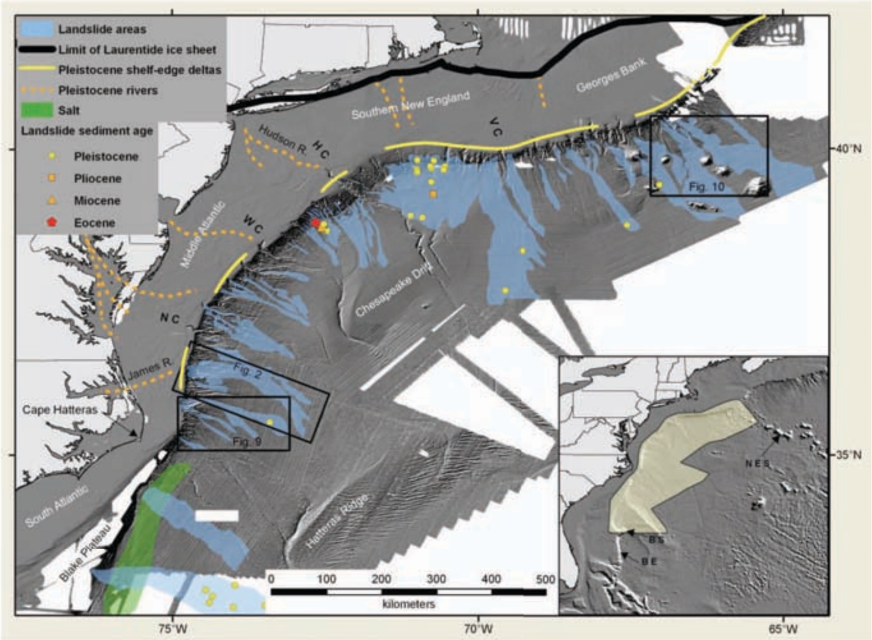


Figure 3.17. Distributions of mapped submarine landslides and debris fields along the Eastern North American Margin. From Twichell et al. (2009).

<u>*Fluid Exchange on Passive Margins:*</u> Fluid and element exchange at passive margin systems has arisen as a central issue as we look at problems as broad as methane venting in the arctic and hydrocarbon seepage in the Gulf of Mexico. An understanding of the mechanisms and fluxes of these mass exchanges will help us understand the carbon cycle, support of ecosystems, and the impact on global change. Some studies can be addressed at specific locations at ENAM, or are suited to a synoptic approach.

Groundwater hydrology of continental shelves is a new frontier in the hydrological sciences that has important links to continental shelf geochemistry, the deep biosphere, global biogeochemical cycles and environmental and climate change. Large volumes of freshwater within the continental shelf environment appear to be a global phenomenon. Estimates of offshore fresh water resources vary widely, with models suggesting as much as 1300 km^3 of fresh water trapped off the New England shore and 3.5×10^5 km^3 within passive continental margins globally. For reference, the city of New York consumes roughly 1.5 km^3 per year [http://www.nyc.gov]. These studies are backed up by documented submarine discharge of fresh and saline groundwater along the entire US East Coast margin, up to nearly 100 km offshore, and by recent IODP drilling in the central corridor region off New Jersey. The low salinity of submarine groundwater presents an electrically resistive target that is suitable for geophysical imaging using controlled source electromagnetic (CSEM) technology developed for offshore hydrocarbon exploration.

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, in order to gain an accurate assessment of groundwater volumes, 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

3.3.6. Numerical and Experimental Studies

Numerical models and laboratory experiments are a critical element for ENAM studies, playing a particular role in addressing RIE thematic studies outlined in the GeoPRISMS Implementation Plan. They also provide tractable means to test process-based models and hypotheses relating to the formation and formation of ENAM, informed by field studies. Many field studies only provide snapshots of the margin today, whereas models and experiments can explore a range of conditions, and the full evolution of the system. These non-field based studies expand the toolbox available to GeoPRISMS researchers to understand active processes, ranging from lithospheric deformation to sediment transport and fluid flow, and the linkages between then. Laboratory experiments can also isolate distinct phenomena to obtain a more complete understanding of the controlling factors.

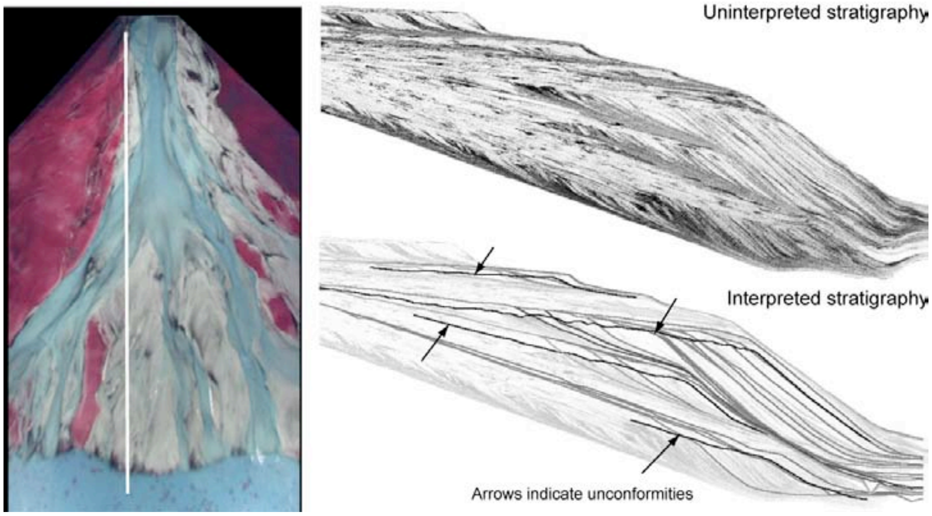


Figure 3.18. Stratigraphic evolution as seen through the depositional filter via experiment, with scans of surface topography (gray) compared against mapped unconformities and sequence boundaries (black). A significant challenge in linking process to form is the connection between instantaneous surface topography (left image) and preserved stratigraphy. Stratigraphic evolution is driven by external forcings dominated by climate and tectonics and internal (autocyclic) adjustments in local sediment flux controlled by process transitions and material property variation (Strong & Paola, 2008; Martin et al., 2009).

3.3.6.1. Experimental Studies

<u>*Sediment Transport/Flume Experiments:*</u> The topography of the Appalachian mountains and the stratigraphy of the Eastern Atlantic continental shelf and slope are linked through dynamic topography and sediment transport. For example, there is growing recognition that autogenic processes (e.g., floodplain deposition, channel avulsion, delta lobe progradation) play major roles in generating sedimentary deposits. However, it is not well understood how the time and length scales of autogenic behavior vary with rates and style of “allogenic” processes, such as lithospheric deformation and sea-level change, or how short-term variations in sediment flux and routing combine to produce the long- term stratigraphic record. The complex interplay of allogenic and autogenic processes complicates attempts to accurately reconstruct sea-level elevations and shoreline positions from preserved marginal stratigraphy. This is a challenging yet fundamentally important question because the timescales of fluctuations in tectonic forcing (e.g.,

fault network evolution, earthquake clustering), global sea level, and regional climate are known to overlap in some settings. In addition, linking the offshore dynamics with onshore forcing needs more investigation. Laboratory experiments on sediment transport can help delineate the key controls on mass transfer from the hinterland to the basin as influenced by the topographic evolution of the mountains and long-term sea-level change. Flume-type experiments (Figure 3.18) provide a laboratory to isolate different driving forces and observe the system dynamics linking sediment source, transport, deposition, and stratigraphic preservation. Well-designed experiments can provide insights into basic processes, which then can be linked through numerical modeling. Such experiments and models will help us translate observations of margin stratigraphy into an improved understanding of geodynamic and sediment-transport processes that have acted on ENAM.

Geotechnical Experiments: Numerous examples of small-to-large slope failures along the continental slope transport sediments to the deep ocean, and have implications for coastal geohazards. Laboratory experiments are the only means to observe complete slope failures and to potentially link failure deposits to failure process. Geotechnical and geomechanical experiments on intact sediment samples therefore are required to define the interplay of deformation, sediment strength, and fluid flow. Depending on initial conditions and failure rate, submarine slides can be slow, fast, large, or small. To date, however, basic poromechanical models on strength and failure have not been calibrated or tested rigorously in terms of submarine slope failures. Controlled laboratory experiments can provide basic information on the deformation, flow and strength properties of shallow marine sediment necessary to develop forward models of slope failure and to back-calculate conditions of previous failures along the margin. Shallow piston coring can help sample the shallow section of pre- and post-failed sediments. Deeper coring operations provide access to past failures. Experiments on shallow and deep pre- and post-failure sediments can be used to delineate initial conditions, near-post-failure conditions, and post-failure evolution of sediment properties. Sampling of various environments coupled with experimental analysis provide a first step in up-scaling observed laboratory failure mechanisms to the field-scale phenomena. In situ measurements of pore pressure and strength provide another means for measuring sediment properties, better linking measurement between laboratory and regional observations.

3.3.6.2. Numerical and Physical Analogue Studies of Rifting Processes

Geodynamic models: Continental rifting and margin evolution are influenced by a wide range of controlling factors, many detailed above. The relative importance of these factors in system evolution can be explored through integrated geodynamic modeling. The development of geodynamic models has advanced to a stage where the complex interaction of several factors can be assessed (Figure 3.19). Specialized models address the large variety and scale of problems that require specific modeling tools, illustrating the many opportunities that lie within geodynamic modeling studies. Several of the major RIE questions (e.g., related to tectonic inheritance and syn-rift differential deformation for example) can be addressed by current models; further model development is needed to study problems such as those related to magmatic processes, margin segmentation, and syn- and post-rift topography.

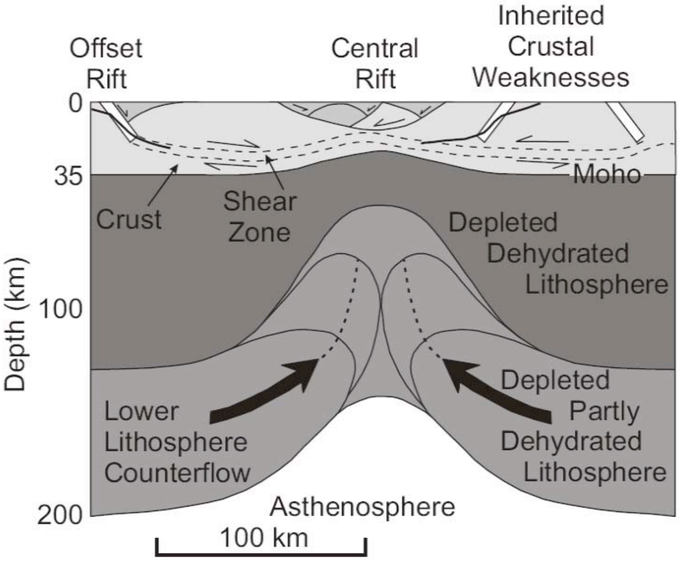


Figure 3.19. Concepts of lower lithosphere counterflow and reactivation of inherited crustal weak zones as offset rift basins in the context of lithospheric extension and rifting (from Beaumont and Ings, in press).

Two-dimensional models have focused on lithosphere-scale structural deformation of rifts and rifted margins, magmatic intrusions, tectonic inheritance, lithosphere-asthenosphere boundary processes and mantle shear zones, and (dynamic) topography. An important outcome of these studies is the recognition that rheology, heat flow, and lithosphere layering are dominant factors for the structure of margins and the fate of rifting. Relatively minor variations in these parameters seem to result in dramatically different margin structures. Existing models focused on the mantle lithosphere and asthenosphere indicate that processes at the lithosphere-asthenosphere boundary, including metasomatism and development of downwellings or detachments, may affect magmatism and surface uplift during rupture and post-rift topography of the margin. The relative importance of different parameters is as yet unclear, emphasizing that more research is needed for results and insights to converge.

All rifted margins are segmented, and may vary in structure, magmatism and topographic evolution, sometimes abruptly, along-strike of the margin. This segmentation originates in the earliest continental rift stage, and three-dimensional models have, thus far, focused on studying the early phase of segmentation formation that is confined to the crust. These first three-dimensional crustal models point toward an important role of magmatic intrusions and brittle crust behavior. More model development is needed to address along-strike variations in magmatic processes, lithosphere structure, and topography. Geodynamic model development by both CIG (Computational Infrastructure for Geodynamics) and individual groups is currently underway. Syn-rift and post-breakup topography evolution of rifts and rifted margins requires further model development to include surface processes. Magma generation and migration are generally not incorporated yet in geodynamic models, and are addressed by the CIG magma focus group.

Similarly, simulations of coupled sediment transport and deposition (e.g., SYSDMS) are now able to make the linkages between field observations and experimental studies. The field programs record the sedimentary processes, experimental studies provide a scaled model of the transport processes, and numerical models test hypotheses on the physical processes that control the processes active in the laboratory and along the ENAM. Extensive modeling efforts can then be used to assess which active processes are dominant along different portions of the margin, and how they are linked to the uplift and erosion, climate, and sea-level variations. A second contribution of numerical models is the description of controls on slope failure and sediment delivery beyond the slope. Geophysical data provide spatial constraints on these processes, but numerical models are the only way to understand what primes the slope for failure, what initiates the failure, and what determines if a failure will trigger a hazardous landslide.

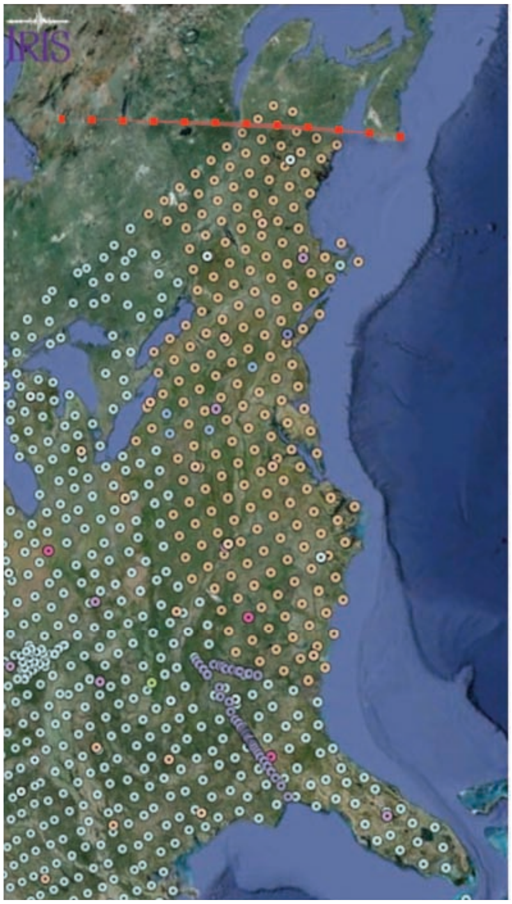


Figure 3.20. Map of EarthScope Trasportable Array (blue – deployed, tan – planned for 2013-2015), Flexible array experiments (dense clusters of symbols) and various other permanently operating seismic observatories. A passive seismic experiment in Nova Scotia, Maine and Quebec (red line) will deploy a line of instruments from 2012 through 2015. Station locations from: http://www.iris.edu/earthscope/usarray

Physical Analogue Models: Physical models are complementary to numerical studies. These models specifically have an advantage over numerical models in three-dimensional setups. Analogue modeling techniques have advanced in the last decade to include techniques to model processes such as magma intrusions in addition to illustrating temporal and spatial evolution of crustal structures in three-dimensions.

3.3.7. Research Strategies and Partnerships

3.3.7.1. EarthScope Collaborations

The arrival of the *EarthScope* Transportable Array (TA) stations to the US east coast in 2012, several FlexArray (FA) experiments, and the coincident beginning of the GeoPRISMS focus on the ENAM present the community with a unique opportunity to take advantage of the synergy between the two research efforts (Figure 3.20). EarthScope's facility of transportable and flexible arrays of seismometers allows for the imaging of the lithospheric and sub-lithospheric architecture of the continental margin, directly responding to some of the prominent research questions regarding structure and evolution of the ENAM. In particular, the uniform deployment of the EarthScope transportable array (TA) will help address some of the broad questions spanning the whole margin, such as the long debated north to south transition in Appalachian structure, the west to east transition from craton to continental crust, and the along strike segmentation of the margin. As the last TA instruments leave ENAM in 2015 to be redeployed in Alaska, IRIS is considering the possibility of leaving one in four TA stations deployed along the ENAM margin, prolonging the EarthScope focus in the area and ENAM science coordination with GeoPRISMS. Opportunities are also available to take advantage of the FA, which allows for focused observation and study of key geophysical locales through the NSF proposal process. These instruments can be used to augment the permanent instruments, extend investigations into

Canada and Mexico, and respond to volcanic and/or tectonic opportunities. FA instruments can be spaced more tightly than, and in complement with, the TA in order to image the crust, Moho, and higher-detail features in the mantle lithosphere. There are obvious advantages to planning FA deployments to spatially and temporally correspond to the TA. In addition, FA projects can leverage deployments of instruments offshore through GeoPRISMS, addressing processes that cross the shoreline.

In addition to the TA and FA, there are opportunities to take advantage of other EarthScope-aligned facilities and initiatives, such as PBO GPS receivers and borehole strain meters, LiDAR, and InSAR in the next five years of EarthScope operations and maintenance. These instruments might be used in novel ways to study GeoPRISMS research targets in ENAM, including active seismicity, subsidence and rebound, induced surface displacements, and surface processes.

3.3.7.2. USGS Collaborations

Opportunities exist to coordinate the timing and location of onshore and offshore geophysical (active and passive source seismic data) acquisition along ENAM with the planned USGS-NOAA effort to define the US Continental Shelf maritime zone (US Extended Continental Shelf, ECS, Project - http://continentalshelf.gov) as part of the Law of the Sea. The Atlantic margin is one of the highest priorities for ECS acquisition of seismic reflection and refraction data, generally focused in the region between 200-350 nmi from the coast. The USGS plans to acquire 2-D seismic reflection data on east-west profiles spaced at 60 km along portions of the US Atlantic margin with the *R/V Langseth* in 2013-2014 (Figure 3.21). Where practical, coincident gravity data will be acquired concurrent with the seismic data acquisition.

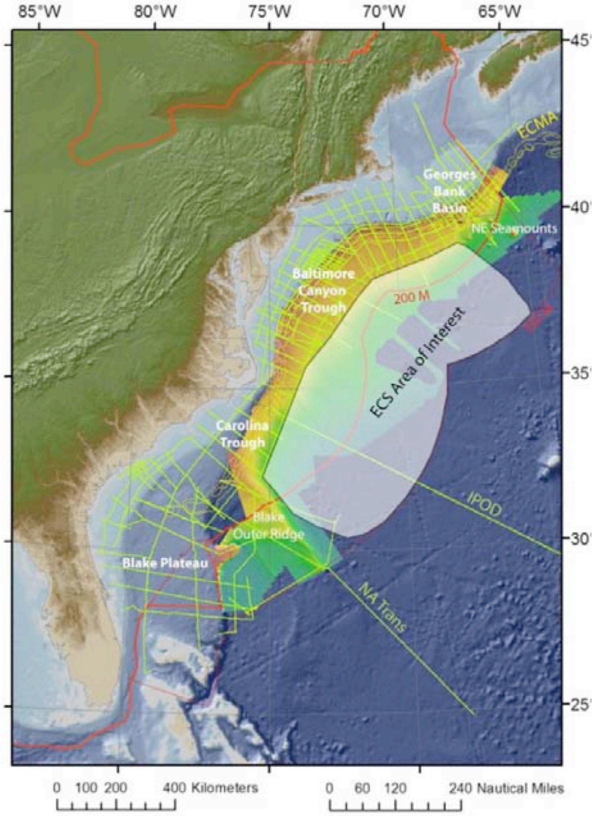


Figure 3.21. Map of existing 2D MCS lines across the eastern US continental margin, and area of interest for proposed USGS survey to map the ECS. (Courtesy of D. Hutchinson)

Science of opportunity also may be possible concurrent with the planned cruises, if this can be done without interfering with the main objectives of the ECS surveys. In addition, the University of New Hampshire CCOM is acquiring full-coverage multibeam bathymetry over the deep-water portion of the Atlantic margin for the ECS project. The focus area for these data is from the shelf break seaward. Three major acquisition programs are already complete and data are freely available (http://www.ccom.unh.edu/). A fourth is planned for 2012. In general, all ECS-derived data will be publically available soon after data acquisition. These data have the potential to provide a critical synoptic perspective from seafloor to the deep crust in the distal parts of the continental margin, augmenting these planned experiments with refraction and reflection seismic studies along selected lines across the continental slope and shelf and onto land.

3.3.7.3. Industry Collaborations

This is also an opportune time to cooperate with industry to pursue regional reflection and refraction seismic lines across the continental shelf. The petroleum industry has substantial interest in ongoing studies of continental breakup and the formation of new oceans. Although GeoPRISMS research objectives differ somewhat from those of the petroleum industry, there are clear overlaps in interests that justify data sharing and collaboration for mutual benefit. We are in a unique window where there has been little modern seismic data collected across ENAM in U.S. waters, yet it is an area attracting increasing interest for the industry. There is opportunity to look for industry contributions to the geophysical study of ENAM, particularly within the scope of a community project. There is also increasing interest among industry and academic groups in examining sediments and basalt flows in rift basins along the ENAM, as possible targets for carbon sequestration, providing another avenue for collaboration and to expand the societal impacts of GeoPRISMS.

3.3.7.4. Community Experiments

Large onshore-offshore geophysical datasets provide critical observations needed to address the core science questions at the ENAM primary site, specific to the geographical focus areas as well as synoptic studies. The GeoPRISMS community, particularly in collaboration with the EarthScope community, have embraced the concept of acquiring some large geophysical datasets as community efforts when possible and sensible for a given project. Here we define community experiments as large field efforts planned and executed by the community rather than a small group of PI's; data acquired from these programs would be made publically available immediately. This approach would enable a much larger group of people to benefit quickly from the data, and the use of the data by a broader community will maximize their scientific impact. It would also facilitate the involvement and training of junior scientists and students. The GeoPRISMS community has expressed enthusiasm for designing and carrying out community experiments in ENAM where possible. A collaborative geophysical survey of the US continental margin and shelf with USGS ECS efforts (see Section 7.2) is one example.

3.3.7.5. Amphibious Array Facility

The community-based Amphibious Array Facility (AAF) was funded by NSF in 2009 through the ARRA (American Recovery and Reinvestment Act) primarily for the purpose of understanding hazards in the Pacific Northwest. Composed of 60 broad-band ocean bottom seismographs and 27 broad-band land seismographs similar to the elements of the Transportable Array of the Earthscope program, AAF is currently deployed as part of the Cascadia Initiative (CI). The CI has a finite duration of 4 years (scheduled through 2014), with the expectation that the onshore and offshore components of the AAF will likely move together to other locations following its completion. In the context of the ongoing EarthScope and GeoPRISMS programs, high priority locations are ENAM and Alaska. A community workshop in early 2014 has been proposed as a venue to decide on the future use of equipment presently constituting the AAF.

The passive margin focus site in the ENAM presents a natural target for the future use of the AAF. Lack of offshore broadband observations is a significant "gap" in the knowledge about the ENAM. True to the intent of its funding for hazards mitigation, an AAF deployment in the ENAM focus site would serve the needs of a very large fraction of the US population concentrated in this "low hazard high risk" region. Notably, the "low" seismic hazard may be higher then expected given the recent Virginia earthquake.

The residence of the EarthScope TA within the ENAM focus site during 2013-2015 makes a compelling case for the deployment of the AAF offshore elements here upon the completion of the CI. Various strategies for retaining parts of the TA infrastructure within the ENAM site past 2015 are under discussion, and the addition of the on-land component of the AAF to the resources available for ENAM data collection would be highly advantageous. A resulting data set will be the first ever shoreline-crossing sample of the stable continental margin, in the same way that CI is assembling a unique data set covering the entire width of a convergent margin.

To take full advantage of other EarthScope and GeoPRISMS elements (TA, active source community experiment, funded flexible arrays), the AAF would be best used in the region spanning the southern and central focus sites. The northern focus site is also an excellent target for at least a subset of the AAF resources, however the timing of its deployment there is less critical, as the TA does not reach into Nova Scotia.

3.3.7.6. International Collaborations

GeoPRISMS studies in ENAM will also benefit from collaborations with international investigators. In particular, research along the Nova Scotia corridor would serve as an excellent opportunity for US-Canadian cooperation, at both academic and government agency levels. Investigators from Europe, most prominently, the UK, Germany, France, Spain, and Portugal, have strong interests in comparative studies between conjugate margins, and have acquired most of the geophysical and other data on several conjugate margins on the European (and African) side of the Atlantic. There may also be opportunities for joint funding of future US geophysical acquisition on both margins.

3.3.7.7. Scientific Ocean Drilling

Continuing opportunities exist and new opportunities are tangible for effective collaborations between GeoPRISMS and Scientific Ocean Drilling (DSDP, ODP, IODP, and its successor, International Ocean Discovery Program). The 2013-2023 Science Plan for the International Ocean Discovery Program (http://www.iodp.org/Science-Plan-for-2013-2023/) identifies four science themes (Climate and Ocean Change; Biosphere Frontiers; Earth Connections; Earth in Motion). Each of these themes has linkages to the GeoPRISMS research plan for the ENAM. For example, onshore-offshore geophysical transects along any of the GeoPRISMS corridors would provide regional site survey data to help optimize drilling locations and target depths. Similarly, sedimentological and age data from scientific drilling would provide ground-truth observations and age constraints for GeoPRISMS studies. Numerical models or physical experiments as part of GeoPRISMS research would benefit from inputs derived from drilling (e.g., physical, mechanical, and compositional constraints). Geological and geophysical data acquired by GeoPRISMS can both take advantage of existing well control from academic drilling and can be used to guide plans for future drilling. One example of such a collaboration is the ongoing investigation of a portion of the New Jersey continental shelf (Figure 3.13), integrating industry drilling, IODP drilling, academic and industry seismic reflection surveys, and now a proposed 3D survey to better understand sediment supply and deposition along the ENAM and its relation sea-level variations. Clearly, leveraging research funding and interests between IODP and GeoPRISMS will strengthen both programs, expanding the scientific community and research opportunities. Future GeoPRISMS investigations can benefit from coordinating with international drilling efforts, and proposing future drilling activities along ENAM.

Continuing opportunities exist for effective collaborations between GeoPRISMS and Scientific Ocean Drilling (DSDP, ODP, IODP, and its successor, International Ocean Discovery Program). Geological and geophysical data acquired by GeoPRISMS can both take advantage of existing well control from academic drilling and can be used to guide plans for future drilling. In many cases, IODP expeditions provide the only means for obtaining ground-truth for seismic observations and interpretations and stratigraphic age control, as well as physical, mechanical, and compositional constraints. Future GeoPRISMS investigations can benefit from coordinating with international drilling efforts, and proposing future drilling activities along ENAM.

3.3.8. Broader Impacts

GeoPRISMS research along the ENAM offers important opportunities to address a range of societal issues that can impact the most densely populated part of the nation. In recorded history, there have been very large, damaging earthquakes, and there is emerging, if controversial evidence for tsunamis. Other, related hazards include submarine landslides, potentially catastrophic clathrate degassing, fluid venting, sedimentation and erosion, flooding, and sea level rise. Infrastructure built along the North Atlantic margin range from wind power to telecommunications, and would be affected by such catastrophic events, as well as long-term sea level change. ENAM research also will contribute to the geotechnical considerations of siting the next generation of nuclear power plants, a dozen of which are operating, under construction, or ordered as of 2009-11. The Atlantic margin is a prime target for hydrocarbon exploration, motivating an improved understanding of past and present processes of the ENAM. Onshore and offshore basins and basalt flows are being evaluated as targets for carbon sequestration. Research in ENAM is poised to take advantage of these opportunities because of another obvious practical advantage– this primary site is close to home. The proximity to a large portion of the UNOLS fleet will expand the opportunity for research cruises of many sizes and scopes, as well as opportunities for undergraduate and non-scientist participation in expeditions. Finally, focusing efforts on the North Atlantic margins, particularly in eastern North America, opens the door for extensive education and outreach to US schools and universities.

3.3.8.1. Active Tectonics

Inspired by destructive historic seismicity and the 26 August, 2011, M 5.8 earthquake in Louisa County, active tectonic research with an emphasis on ENAM seismicity (Figure 3.22) has been identified as key broader impact. Examples of active tectonic research were identified in all three focus areas and as synoptic topic for the entire margin. The Southern focus area includes ongoing seismic activity from the Tennessee Seismic zone to the great Charleston earthquake to the offshore earthquakes along the Helena Banks fault and elsewhere. Within the last decade there was a >4.0 earthquake offshore of South Carolina, probably along the Helena Banks fault, however, very little is known about the cause of these earthquakes, their frequency, or possible magnitude. Study would inform the community about the offshore active structures, the probable cause of the offshore earthquakes, and look at the possibility of them triggering offshore landslides.

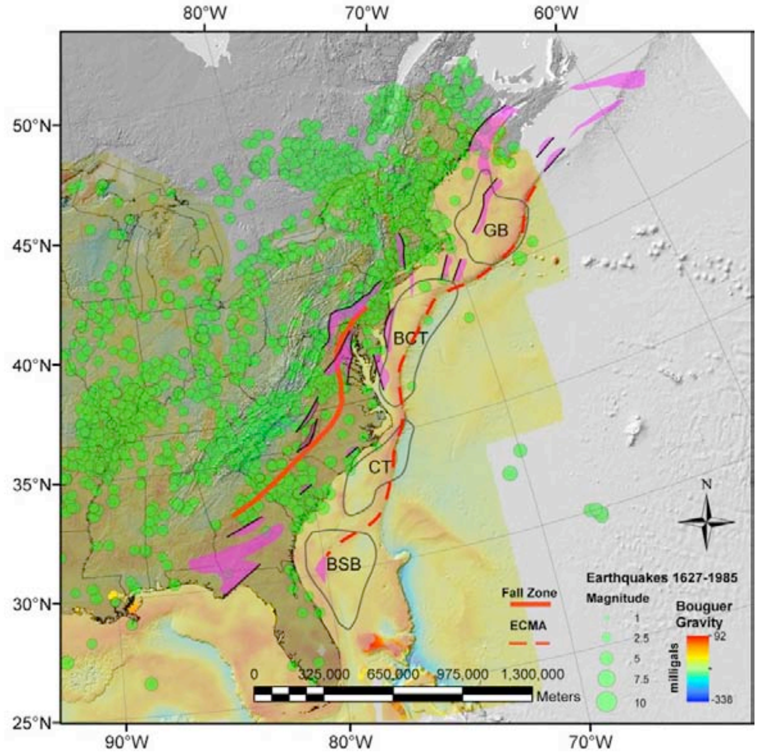


Figure 3.22. Map of ENAM showing the Bouguer gravity anomaly draped on Appalachian topo-graphy and Atlantic Ocean bathymetry. Green circles are earthquake locations. Purple poly-gons are syn-rift basins with border faults in black. Black-outlined polygons are approximate boundaries of shelf-slope basins; GB = Georges Bank basin, BCT = Baltimore Canyon trough, CT = Carolina Trough, BSB = Blake Spur Basin. Topographic, bathy-metric, and geophysical data are all from online USGS GIS data repositories. (Courtesy of F. Pazzaglia)

The faults that caused the 1886 Charleston earthquake continue to be active with a number of small earthquakes each year, however, why these faults are a locus of activity is unclear. Similarly, the central and northern focus areas encompass well-known seismic zones and some of the most densely populated regions in ENAM, which provides an opportunity to showcase active tectonic research to decision makers. Research on the nature of seismicity along ENAM would not only create a broader understanding of the direct causes behind these earthquakes, but would also help to inform the community about east coast earthquakes in general and what areas are most likely to be at risk.

3.3.8.2. Shelf Processes, Sea Level Rise, and Biogeochemical Cycles

ENAM offers excellent opportunities for study of geologic hazards related to sea level rise, eustasy, flooding, and biogeochemical cycling. Gravity-driven sediment transport (e.g., landslides and turbidity flows) destabilizes the slope and carries sediment to the deep sea (Figure 3.3.11) where it may be redistributed by oceanographic processes. Swath bathymetric coverage along the ENAM reveals that the margin is covered with submarine landslide deposits and excavations over a range of sizes. However, relatively few landslides are well dated and even fewer have accurate volume estimates. Such information is essential to determine landslide recurrence rates, their link to triggers including earthquakes, and their potential to generate hazardous tsunamis.

3.3.8.3. Education and Outreach

Finally, focusing efforts on the North Atlantic margins, particularly in eastern North America, opens the door for extensive education and outreach to US schools and universities active in Earth Science research. The large number of 2- and 4-year colleges in ENAM the region also would enable the scientific community to involve associated faculty and students in local research, while educating them about the geologic setting, outstanding questions, and societal hazards. The proximity to large population centers along ENAM also enhances the value and relevance of GeoPRISMS research, and ensures excellent visibility.