Geodynamic Processes at Rifting and Subducting Margins

GeoPRISMS

Implementation Plan

3. Rift Initiation and Evolution

3.1. Introduction and Overview

(Revised May 15, 2013)

3.1.1. Scientific Objectives

Continental rifts and their end products, passive margins, define the majority of the Earth's coastlines, and are the expression of fundamental processes that continually shape planetary surfaces. They encompass much of the world's population and hydrocarbon resources, and are also vulnerable to irreversible changes induced by long-term climate change and sea-level rise. The overarching objective of the Rift Initiation and Evolution (RIE) Initiative is to identify the key processes that drive continental rifting and margin evolution and to determine the parameters and physical properties that control these processes. Rifts are locations where the continental lithosphere is modified by tectonic, magmatic and sedimentary processes, where magmas, and fluids are generated and transferred, where climatic and surface processes govern mass transfer and tectonic activity, and where volcanic activity and exposure and alteration of mantle rocks result in poorly understood volatile exchange. Continental margins of all ages reflect an active interplay of mantle, crustal, and surface processes that demand the system-level, amphibious research approach of the GeoPRISMS program. Specifically, the RIE Initiative seeks to develop predictive models for the spatial and temporal evolution of rifts and rifted continental margins with a focus on four key questions identified with the GeoPRISMS draft science plan (DSP):

- *Where and why do continental rifts initiate?*
- *How do fundamental rifting processes, and the feedbacks between them, evolve in time and space?*
- *What controls the architecture of rifted continental margins during and after breakup?*
- *What are the mechanisms and consequences of fluid and volatile exchange between the Earth, oceans, and atmosphere at rifted continental margins?*

Several of these questions can only be addressed in areas of active rifting, where rift initiation and the early and intermediate stages of rift evolution can be directly observed and measured. Such investigations are well complemented by studies of passive margins, where rifting has gone to completion, and the cumulative history of tectonic, magmatic, isostatic, and surficial processes, is preserved. Considering the temporal and spatial range under consideration, RIE studies will emphasize several problems that span the system, including the influence of magmatism and volatile flux on rift evolution, documenting feedbacks between surface processes, tectonics, and lithospheric and asthenospheric processes, predicting passive margin evolution from initial rifting processes and conditions, and understanding active processes and associated hazards throughout the entire evolution of rifts.

Rifted margins are very diverse in their structure, magma content, sedimentation rate, and subsidence and thermal histories. This diversity is the result of many factors, and their relative importance may change throughout their evolution. Initiation of a rift is a rare event, but passive margins are ubiquitous. An amphibious approach whereby the onset of rifting and early rift evolution as well as continental breakup and post-breakup evolution of the mature margin are being studied is thus required. The ambitious goal of this program is to understand the entire lifetime of rifted margins, from their initiation through break-up, formation of an oceanic basin, and evolution of the resulting passive margin. To do so effectively requires a new approach to carrying out amphibious studies, where a mostly offshore site is paired with a mostly onshore site, to enable broadly integrated comparisons of the earliest and latest stages of rifting. This exciting concept offers many possibilities, including stronger interactions between marine and terrestrial researchers interested in all aspects of rift initiation and evolution.

3.1.2. Selection of RIE Primary Sites

The community selected two primary sites that represent complementary end-member stages of largely orthogonal rifting process: The youthful, active *East African Rift System* (EARS) and the fully developed *Eastern North American Margin* (ENAM). The EARS exhibits the entire history of continental rupture, from the initiation of border faulting in the south to seafloor spreading in the Afar, while the ENAM captures an extensive post-rift evolution of the passive margin sedimentary prism as well as the cooling and further evolution of the mantle lithosphere below. Both the EARS and ENAM capture a diversity of magmatic and mantle influences on the rifting process. The ENAM system in particular encompasses archetypes of fully magmatic rifting adjacent to the southeastern US, as well as magma-limited continental break-up offshore Nova Scotia and Newfoundland. Both systems also span a north-south climatic gradient with resulting diversity in sediment flux and potential tectonic-climate interactions. There are further compelling logistical benefits to each site: ENAM leverages considerable US infrastructure, including EarthScope and the USGS Law of the Sea survey activities, while the intermingling of on-land and lacustrine rift settings in the EARS present exciting opportunities to intimately connect across the onshore-offshore divide that motivates the scope of GeoPRISMS science.

Although the shared diversity of processes encompassed by the EARS and ENAM will motivate important comparative efforts and synthesis, there are also important contrasts between the two systems. For example, although both rifts are strongly influenced by pre-existing fabrics developed during continental collision, the EARS is further affected by 500 Myr of cooling and strengthening of the lithosphere prior to the onset of rifting. Conversely, the ENAM initiated immediately following the culmination of Appalachian orogenesis. Such differences help to motivate comparative studies between these sites, and also provide opportunities for thematic studies that contrast attributes such as rift obliquity and strain rate that are not fully captured by the primary sites.

3.1.3. Thematic Studies

Despite the wide range of processes recorded within the GeoPRISMS primary sites, they cannot encompass the full temporal evolution nor the entire parameter space deemed relevant to understanding rift initiation and evolution. In particular, the range of compositional and structural heterogeneity in the lithosphere and asthenosphere of rifting regions, temporal and spatial variations in strain rate at a variety of scale lengths, and the ranges in volumes and distribution of sediment input cannot all be captured within the primary sites or over the decadal time scale of GeoPRISMS. Our evolving understanding of primary sites, however, is contingent upon developing greater insight into these very questions. By complementing focused research at primary sites with a variety of smaller-scale thematic approaches that utilize diverse comparative, experimental, numerical modeling, and petrological and geochemical techniques and take advantage of existing datasets, we can advance farther towards a comprehensive understanding of rifting processes. Thematic studies can also build upon the framework developed through investigations of past MARGINS focus sites, and through direct comparisons with observations made at the new GeoPRISMS primary sites. The five themes identified following the RIE Implementation Workshop include:

- *Theme 1: Rift obliquity*
- *Theme 2: Rift processes as functions of strain rate*
- *Theme 3: Volatiles in rift zone processes*
- *Theme 4: Sediment production, routing and transport during and after rifting*
- *Theme 5: Discrete events at rifted margins*

RIE thematic studies are intended to be subsidiary to research that can be carried out at the selected primary sites, but should also complement and complete such investigations. Proposals to carry out thematic research should clearly explain their relationships to past or future work done at the primary sites and/or former MARGINS focus sites, and outline a clear plan for integrating such research within the GeoPRISMS RIE framework.

3.1.4. Planning Workshops and Start-Up Activities

Both the EARS and ENAM primary sites, as defined, are vast primary sites spanning 1000s of kilometers along-strike. Both sites also encompass a long and rich history of prior research upon which to build a focused, community driven GeoPRISMS RIE program. To initiate research at these primary sites, early planning workshops are required, to obtain community input, synthesize existing data sets in these locales, and coordinate initial data acquisition efforts. These workshops are necessary determine where in these expansive sites to concentrate GeoPRISMS investments to best advantage, most likely along a few corridors well-populated with preliminary geophysical, geodetic, structural, stratigraphic, and geochemical observations. Two joint EarthScope-GeoPRISMS workshops took place in 2011, to jump-start new experiments and fully leverage time-limited opportunities such as the deployment of EarthScope's USArray along the eastern portion of the US. A planning workshop for EARS took place in Fall 2012, detailing ongoing efforts in East Africa and a wide range of international activities. Both workshops were well attended and representative of the GeoPRISMS community, international collaborators, and new contributors.

Opportunities also exist for preparatory GeoPRISMS research at both primary sites, as well as for the thematic studies listed above. Initial primary site research should focus on data synthesis efforts, utilization of existing data products, and reconnaissance studies to set the stage for subsequent community experiments. Ramp down activities at the existing MARGINS focus sites are also justified, particularly in the context of comparative thematic studies.

3.1.5. Synthesis and Integration

The selection of two primary sites representing temporal end-members of continental rifting, and encompassing such a wide range of tectonic and magmatic processes, necessitates strong integration within GeoPRISMS to fully address the objectives of RIE. The two primary sites are distinct yet complementary, with the potential to inform each other in meaningful ways. For example, both regions exhibit substantial along-strike variations in key features, such as magmatism, pre-rift fabric lithospheric and asthenospheric conditions. Unlike the EARS, where rifting involves cold cratonic lithosphere without the involvement of subducting slabs, rifting along much of the ENAM involved extension of a young, hot orogen. A complete stratigraphic sequence records the evolution of rifted systems in the ENAM, which is not possible at an active rift zone. In Africa, active magmatism and the deformational response to this magmatism can be observed in near real time. Although this is not possible along the Atlantic margin, ENAM and its conjugate preserve the full volume and ultimate distribution of rift-magmatic additions, which in principle, can be observed. Similarly, a true assessment of the apparent lack of crustal-level magma during amagmatic rifting can only be made at a passive site such as the North Atlantic rift system. Numerous other complementary contrasting observables exist between these sites.

Further integration within the RIE initiative will be enabled by thematic studies, and by numerical modeling and laboratory experiments, all of which will expand the temporal and spatial range beyond those documented at either site. Over the 10-year time frame of GeoPRISMS, the compatible approaches of data gathering and analysis, combined with laboratory and theoretical modeling efforts, will facilitate continued refinement and improvement of the resulting models. In addition, the synthesis of initial field and modeling studies will guide subsequent data gathering efforts. Major synthesis activities will be fostered through regular workshops spanning RIE research, e.g., Theoretical and Experimental Institutes, as well as enhancing data sharing and collaboration, reviewing ongoing studies, developing comprehensive models for rift evolution, and building the GeoPRISMS community.

3.2. East African Rift System - Primary Site

(Replaced May 15, 2013; revised December 23, 2013)

3.2.1. Overview of the East African Rift System

The EARS exhibits a wide variety of rift processes and characteristics, making it an ideal target for GeoPRISMS goals. Aspects of all of the four key rift initiation and evolution (RIE) questions defined in the GeoPRISMS draft science plan (DSP) can be addressed in part or entirely in this primary site, given the great variety of rift processes and characteristics expressed in this setting.

The northern end of the EARS, in Ethiopia and the Afar region, is highly extended and appears to be strongly influenced by the Afar Plume. This northern region experienced voluminous volcanism during the initiation of rifting in the Red Sea and Gulf of Aden as Arabia separated from Africa at ~30 Ma. The timing of onset of volcanism varies, but within Afar, Ethiopia, and the Eastern rift, bimodal volcanism has been and remains an active process. These voluminous extrusive volcanic rocks have blanketed the earth's surface, and dramatically altered drainage basins and landscapes. Ongoing volcanic activity is manifest at about 100 centers active in the Holocene in the EARS through ground deformation, earthquakes, gas emissions and effusive and explosive volcanic eruptions. In contrast, the Western and Southwestern rift segments show little surface expression of magmatism and appear to be less extended. Instead, this part of the rift zone is characterized by deep, narrow rift basins bound by ~100-km-long border faults and by deep earthquakes (> 30 km).

At deeper levels, the entire EARS overlies an asthenosphere with the largest mantle low-velocity zone on Earth, the African Superplume. The pre-rift lithosphere includes deeply-rooted Archean cratons ringed by Proterozoic to Pan-African orogenic belts (Figure 3.1). Initial rift stage fault systems commonly lie along lithospheric-scale structures such as the boundaries of deeply rooted cratons and Proterozoic-Pan-African suture zones. Earthquakes, monitored teleseismically or by temporally and or spatially sparse local arrays, may occur throughout the crust and possibly the upper mantle, including moderate-sized earthquakes (e.g., the 2006 M_w 7.0 event in Mozambique), or in the upper 10 km in areas of incipient plate rupture. Present-day rift opening velocities along the length of the rift system are poorly constrained except in the Afar rift where extensional velocities are 20 mm/yr and the Main Ethiopian rift with velocities of 6 ± 3 mm/yr; outside this zone, rigid-plate models predict velocities of < 3 mm/yr.

A fundamental property of the EARS is the along-axis segmentation of both magmatic and tectonic systems. In the youthful SW, Western, and southern parts of the Eastern rift arms, pronounced tectonic segmentation at the surface is defined by ~100 km long border faults linked via obliquely-oriented accommodation zones. In these early-stage zones, fault reconstructions indicate that most of the extension appears to occur along the border faults, with intrabasinal faults accommodating hanging wall collapse. As extension progresses, strain along border faults may migrate to magma intrusion zones within the central basin. In highly evolved rift zones, fault-controlled segmentation is replaced by ~50 km-scale tectono-magmatic segmentation.

Along-axis segmentation patterns, superimposed on broad plateau uplifts, exert strong controls on drainage and deposition patterns. Short-wavelength footwall uplifts associated with discrete border faults influence regional drainage evolution and intra-basinal sediment pathways. Fault-bounded basins along the length of the rift contain an extensive and, in some regions, continuous sedimentary record of deformation and East African climate change at all stages of rift evolution. Feedbacks between faulting, flank uplift, sedimentation, and subsequent deformation are recorded. Widespread tephra deposits, and their vertical succession, provide valuable controls for constraining rifting and climate histories on a variety of temporal scales. Sedimentary basins spanning 30° latitude preserve high-resolution histories of climate belt fluctuations from the mid-Miocene through the late-Quaternary, and document the high-frequency and high-amplitude hydrologic variability of the region, driven by the evolving East African monsoon system.

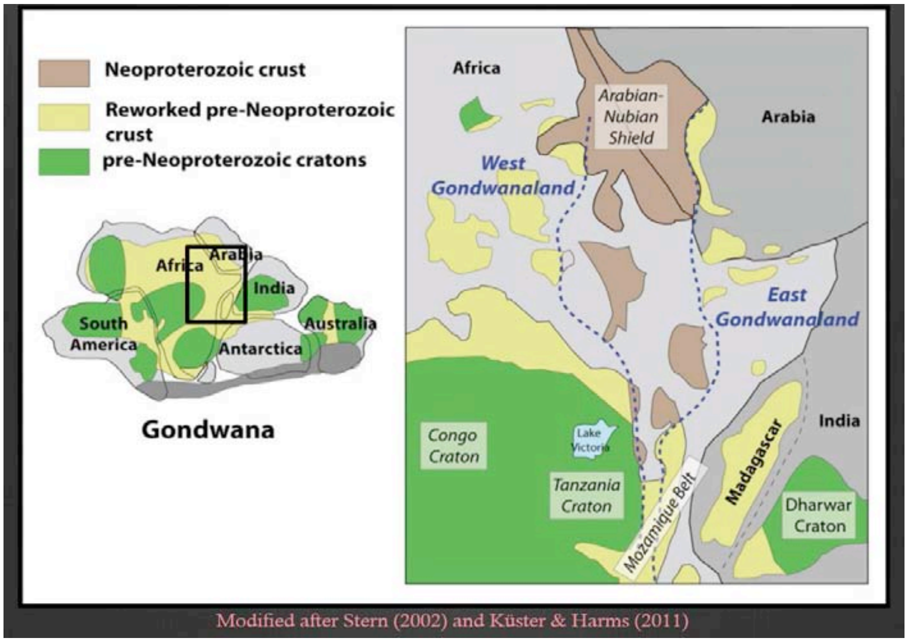


Figure 3.1. Construction of the regional lithosphere during the Pan-African Orogeny, modified after Stern (2002) and Küster and Harms (2011). Courtesy of Wendy Nelson.

The EARS provides a rare, yet accessible window into actively occurring rift events. These events present significant natural hazards to local communities and to regional infrastructure and commerce. GeoPRISMS research in East Africa will focus on the following set of research questions, specific to the EARS site:

- *How does the presence or absence of an upper-mantle plume influence extension?*
- *How does the mechanical heterogeneity of continental lithosphere influence rift initiation, morphology, and evolution?*
- *How is strain accommodated and partitioned throughout the lithosphere, and what are the controls on strain localization and migration?*
- *What factors control the distribution and ponding of magmas and volatiles, and how are they related to extensional fault systems bounding the rift?*
- *How does rift topography, on either the continental- or basin-scale, influence regional climate, and what are the associated feedback processes?*.

Sections of the rift system were identified that could best address the five overarching science questions and that would also maximize the potential for success within the timeframe of the program (Figure 3.2). Additional considerations taken into account when picking focus areas included: safe and relatively easy access (some sections of the rift present logistical and geopolitical difficulties to fieldwork); leveraging and collaborative opportunities, ongoing or planned efforts at various sections along the rift; and support of budding research groups in those regions. With this in mind, one section of the rift was identified to be the primary target of new GeoPRISMS efforts. Two other areas, for which there are substantial leveraging and collaborative opportunities, were also identified, and highlighted as such below. Finally, there are opportunities presented by identifying and filling system-wide data gaps to improve our ability to constrain key processes common to the system as a whole (e.g., the role of plume dynamics on shaping the rift evolution). The chosen sites and their attributes are summarized below. Updated information on current and planned projects in the region also will be made available through the GeoPRISMS website (http://www.geoprisms.org/) so that prospective PIs can use this information to structure their own efforts and to foster collaborations.

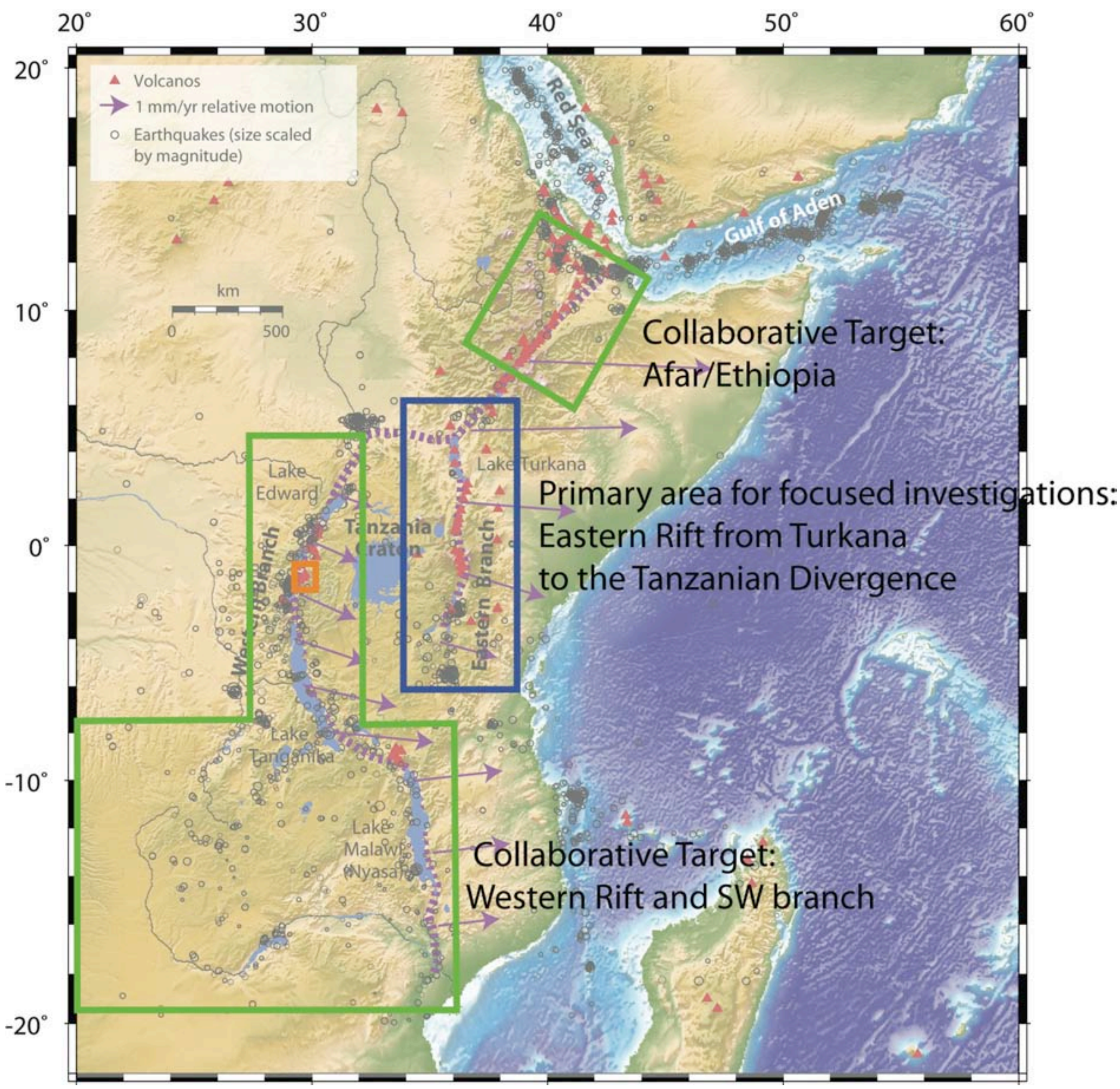


Figure 3.2. Map of the East African Rift System (EARS) highlighting the primary focus area and the collaborative targets of opportunity discussed in the text.

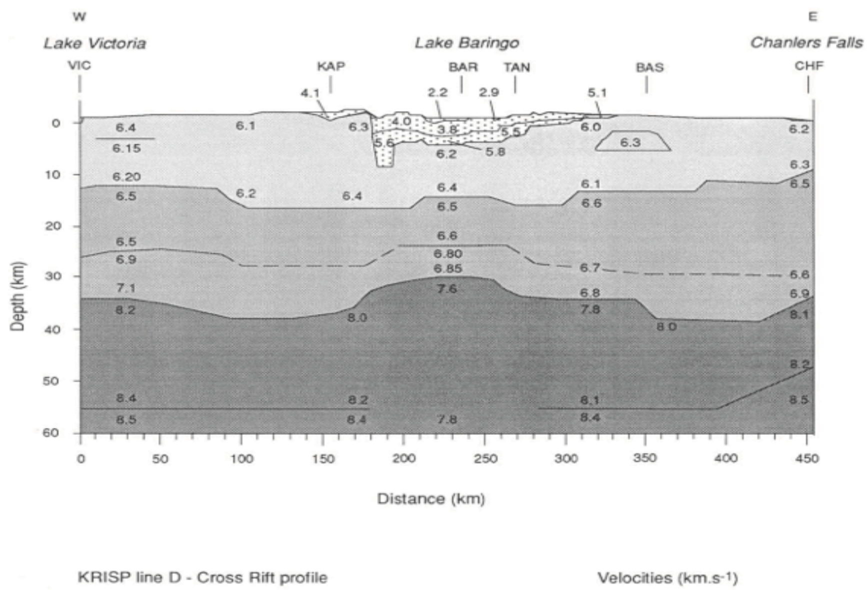


Figure 3.3. P-wave velocity cross-section from the KRISP experiment across the Kenya Rift (modified after Maguire, 1994).

3.2.2. Primary Focus Area: The Eastern Rift

The Eastern Branch of the EARS (Figure 3.2) was identified as a location where a focused interdisciplinary effort could substantially impact our understanding of rift processes and effectively address the majority of the science questions that form the core of the science plan. This region would encompass the rift from the Tanzanian divergence in the south to Lake Turkana and southern Ethiopia to the north. Particular opportunities highlighted by discussion include (but are not limited to) the role/origin of a plume in this part of this rift; the interaction of the rift and plume with major lithospheric structures; an active magmatic system; along-strike variations in the amount of cumulative extension and lithospheric thickness (thin in the north; thick in the south); the preservation of a record of the interplay of climate and tectonics. Existing studies in this region (e.g., Figure 3.3) provide a rich framework upon which GeoPRISMS science can build.

- *How does the presence or absence of an upper-mantle plume influence extension?*

  This site offers the possibility of testing the hypothesis that two upper mantle plumes, rather than one whole mantle plume influence rifting. Questions remain as to the distribution of plume material in the upper mantle in this region, the potential distinctive composition of plume material, and the extent of the plume when compared to that inferred for Afar/Ethiopia. Additional observations are needed to resolve the plume contribution to magmatism in the focus area and understanding how, where and why melts are generated in this region remains a key unknown. additional geochemistry (isotopic studies, volatile characterization, experimental melting), and geophysics (upper mantle and lithospheric structure) will constrain the absence or presence of plume material in the regional upper mantle and conditions of melt generation.

- *How does the mechanical heterogeneity of continental lithosphere influence rift initiation, morphology, and evolution?*

  The presence of the Tanzania Divergence within the study area, and the intersection of the rift with the Tanzania Craton (Figure 3.1), allows for the study of mechanical lithospheric heterogeneity on the rifting process. Specifically, comparisons can be made between rifting that occurs within mobile belts and that which may impinge on a deeply-rooted craton. Within the study region, the rift appears to be taking advantage of pre-existing structures, but questions remain as to how this strain and magmatic localization has evolved in terms of fault kinematics and the influence of magma. Existing observations, that there is variation in earthquake depth from north to south, raise further questions as to along-axis variability in structures and processes. To address the questions related to existing mechanical heterogeneity, needed studies include: xenoliths and basement exposures, fault kinematics, geophysical imaging of the lithospheric density contrasts (e.g., at the Moho), geodetic surveys, geochemical studies of lithosphere-derived magmas, structural mapping of the relationships between rifts, magma and pre-existing structures, and borehole stress or other stress measurements.

- *How is strain accommodated and partitioned throughout the lithosphere, and what are the controls on strain localization and migration?*

  This more weakly extended, but magmatic rift, provides a comparison in terms of strain with the more highly extended Afar/Ethiopian segment. The upper crustal diking event in thick continental lithosphere associated with the July-August 2007 seismo-volcanic sequence in the weakly extended Natron rift and Oldoinyo Lengai volcano, seems surprising and so understanding how faulting and magma intrusion contribute to strain accommodation within a youthful continental rift could facilitate the development of coupled thermo-mechanical models of extension in rheologically-layered continental lithosphere.

- *What factors control the distribution and ponding of magmas and volatiles, and how are they related to extensional fault systems bounding the rift?*

  Satellite Interferometric Synthetic Aperture Radar (InSAR, Figure 3.4) and other studies provide evidence of active inflation and deflation of volcanoes along the length of the Eastern rift (e.g., Paka, Menengai, Longonot, Suswa, Oldoinyo Lengai). Understanding the generation, migration and storage of magmas and the magmatic plumbing through time using, for example, geochemical and geochronological studies, experimental studies, fault length-displacement studies adjacent to and distant from volcanoes, and the imaging of magma bodies would be compelling.

- *How does rift topography, on either the continental- or basin-scale, influence regional climate, and what are the associated feedback processes?*

  The development of significant topographic relief associated with the EARS evolution has been suggested as a significant influence on regional air mass interactions and climate over the African continent. There may also be feedback mechanisms whereby changing climate influences local rift margin tectonics and exhumation rates. The Eastern rift is also an area of great interest for understanding Earth surface/tectonic interactions in the EARS because of its important paleoanthropological record, which may have been impacted by these Earth history events. Topographic changes allow testing models of how local and regional topography feeds back into climate and to test how much tectonic change is needed to have a climatic influence. Specific opportunities for looking at climate/tectonics interactions could come from some focused studies of erosion/accumulation rates in the context of paleoclimate records from targeted sites with good continuous stratigraphic records. Probably the most continuous for the Kenya rift is in the Tugen Hills section, but other long records could come from the Turkana Basin. Both of those sites, as well as sites in the Chew Bahir Basin, Magadi Basin and Koora Graben have or will be drilled in the context of the Hominin Sites and Paleolakes Drilling Project (*http://www.icdp-online.org/front_content.php?idcat=1225*).

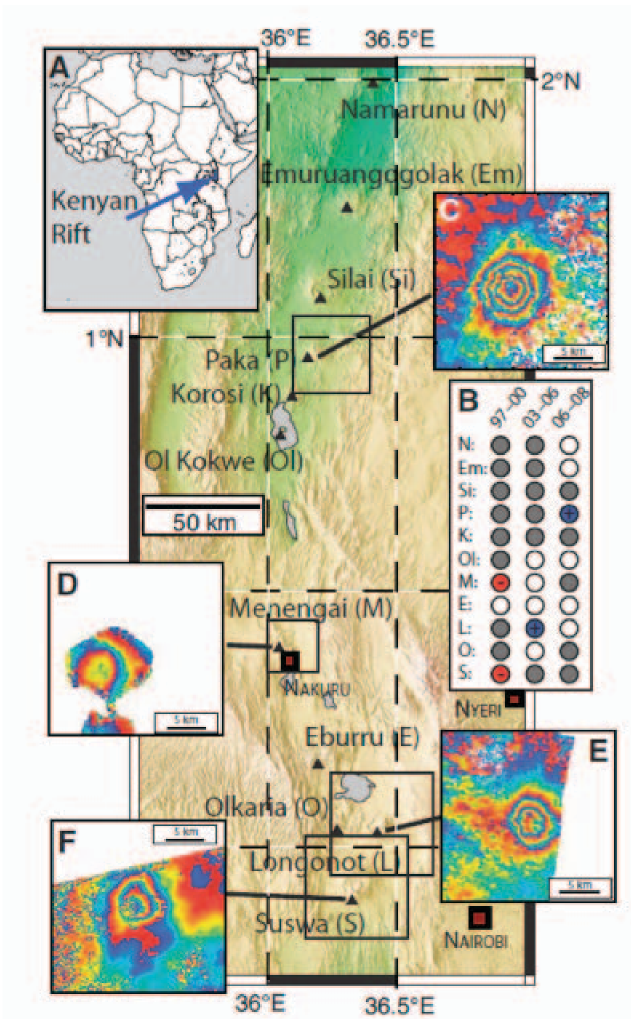


Figure 3.4. Interferograms of active volcanoes in Kenya showing geodetic activity (Biggs et al., 2009).

3.2.3 Collaborative Targets of Opportunity: The Afar and Main Ethiopian Rift

This part of the rift system is the focus of intense recent and ongoing international and US efforts. Further GeoPRISMS studies that could enhance our understanding of rifting processes include (but are not limited to) efforts that examine strain localization and studies probing the origin and role of a plume in rifting. The recent rifting and multiple volcanic eruptions in this region allow studies of active processes. Despite the large amount of geodetic and geophysical work done by the Afar Rift Consortium (*http://www.see.leeds.ac.uk/afar/*), there is still a need for further geophysical, geochemical and geological observations in the Afar region.

- *How does the presence or absence of an upper-mantle plume influence extension?*

  This site features geophysical images of the plume through a variety of seismic methods, and so the plume and its interaction with the lithosphere are well characterized. However a central question remains as to how melts are created and the relationship of these melt generation processes to ongoing extension. Such questions can be addressed by utilizing the long magmatic record present in this area, allowing for the analysis of the temporal and chemical evolution of the plume magmatism and the identification of the contribution of such magmatism to the evolving rift system.

- *How does the mechanical heterogeneity of continental lithosphere influence rift initiation, morphology and evolution?*

  The region contains the boundary between the Nubian and the Ethiopian plates in addition to a triple junction. Magmatic underplating identified beneath the western Ethiopian plateau, and other compositional heterogeneities in the lithospheric mantle may equally influence the heterogeneity and structure of the lithospheric plates. This region thus encompasses a variety of lithospheric structures through which the rift has cut and provides a rich template to examine the possible impact of lithospheric heterogeneity on rift development.

- *How is strain accommodated and partitioned throughout the lithosphere and what are the controls on strain localization and migration?*

  Archived and ongoing seismic monitoring throughout the study region provide perhaps the longest records of seismicity north of S. Africa. For example, Ethiopia has 8 broadband seismic stations in the national network. The high extension rates throughout this region make it an ideal environment to study seismic and aseismic strain partitioning through combined seismic and geodetic monitoring. Sparse GPS data have been collected throughout the region, although there could be benefit in re-occupying critical sites and creating new sites to fill gaps. There is extensive documented diking and faulting through the region.

- *What factors control the distribution and ponding of magmas and volatiles and how are they related to extensional fault systems bounding the rift?*

  This region is highly magmatic with well-documented and -imaged volcanic centers. Seismic studies reveal multiple active eruptive centers localized near the centers of rift segments, but with other magma chambers in off-axis and inter-segment zones. Combined geochemical and geophysical studies have successfully created a framework for understanding the crustal distribution of magmatism and its relationship to strain within in the Ethiopian Rift and Afar. However, little information exists as to the volatile flux and the potential linkage of such volatiles with the activation of faults and volatile concentration in the zone of active magma intrusion, or in areas with the highest fault density. Magneto-telluric studies when combined with seismic and geochemical evidence have been successful in delineating the geometry of magma bodies in the crust and mantle lithosphere.

- *How does rift topography on either continental- or basin-scale influence regional climate and what are the associated feedback processes?*

  This site offers an extensive stratigraphic and sedimentary record interpreted within a thermo-chronological framework. These existing data make it possible to undertake much needed paleo-landscape reconstructions. The paleo-anthropological record along the Awash River is well studied, but further delineation of its paleo-environmental and tectonic context is need. The triple junction offers the possibility to understand the influence of this major tectonic feature on climate.

3.2.4. Collaborative Targets of Opportunity: The Western Rift and SW branch

These sites provide the opportunity to examine the role of magmatism in rifting by comparing this comparatively less magmatic system with the highly magmatic Eastern Rift. The Southwestern rift zone contains the most weakly extended and youngest portions of the rift and thus can be used to tackle questions concerning incipient rifting. Finally, deep lakes along the Western Rift contain the longest continuous record of climate/tectonic/geomorphic interactions available for the EARS. There is an obvious opportunity to contrast this young rift with the more established fault and magmatic systems in the Afar and Eastern rift sectors, as well as offering a comparison to ultra-slow spreading ridge systems.

- *How does the presence or absence of an upper-mantle plume influence extension?*

  The possible influence of a mantle plume on the Western Rift is unknown, though some recent geophysical and geochemical studies suggest that there is a plume influence (e.g., from Helium isotopes) even though the surface expression of magmatism is limited. Further studies characterizing the distinctive composition of the plume as well as lithosphere in this region, the extent and nature of their interactions will be necessary to address these questions. This area offers the chance to examine how far south a plume may be participating in rifting and how it relates to other plumes proposed in this rift system.

- *How does the mechanical heterogeneity of continental lithosphere influence rift initiation, morphology and evolution?*

  There is some broad-scale geophysical evidence of heterogeneity in lithospheric structure through this region, particularly between Proterozoic-Precambrian orogenic belts and Archean cratons. The incipient nature of rifting in the Southwestern rift allows testing of models of how pre-existing lithospheric structure guides rift initiation. These early stage processes include strain localization and onset of magmatism, influenced by preexisting lithospheric features, e.g., zones of weakness and lithosphere-asthenosphere topography.

- *How is strain accommodated and partitioned throughout the lithosphere and what are the controls on strain localization and migration?*

  Incipient segments of the rift provide the opportunity to examine how strain is distributed at the early stages of breakup. Studies will also enable an examination of processes throughout the lithosphere during the initiation of rifting, including the formation and growth of fault systems, the importance of lithospheric thinning versus magmatic assistance, and the possible role of small-scale mantle convection.

- *What factors control the distribution and ponding of magmas and volatiles and how are they related to extensional fault systems bounding the rift?*

  Volcanism along this part of the rift system is limited to a few small provinces, which exhibit diverse geochemistry and indicate metasomatism, or introduction of significant volumes of volatiles, to the mantle lithosphere. Almost all of them are located within transfer zones between rift segments, but the distribution of magmatism at depth (and its relationship to border faults and accommodation zones) is poorly known. The Western Rift offers the opportunity to examine magmatic plumbing systems in a weakly extended region thought to have relatively thick, cold, strong lithosphere with those in the highly magmatic eastern rifts and Afar.

- *How does rift topography on either continental or basin scale influence regional climate and what are the associated feedback processes?*

  Lakes along the Western Rift contain a rich record of tectonic and climatic events. Studies in this region should permit integrating landscape studies of erosion, exhumation and uplift rates with stratigraphic records. There is an existing drill core from Lake Malawi (Nyasa), which covers the last ~1.25Ma and strong paleoclimate community backing for obtaining a similar but much longer record from Lake Tanganyika. The region offers the possibility of examining the influence of rifting on hydrology and climate.

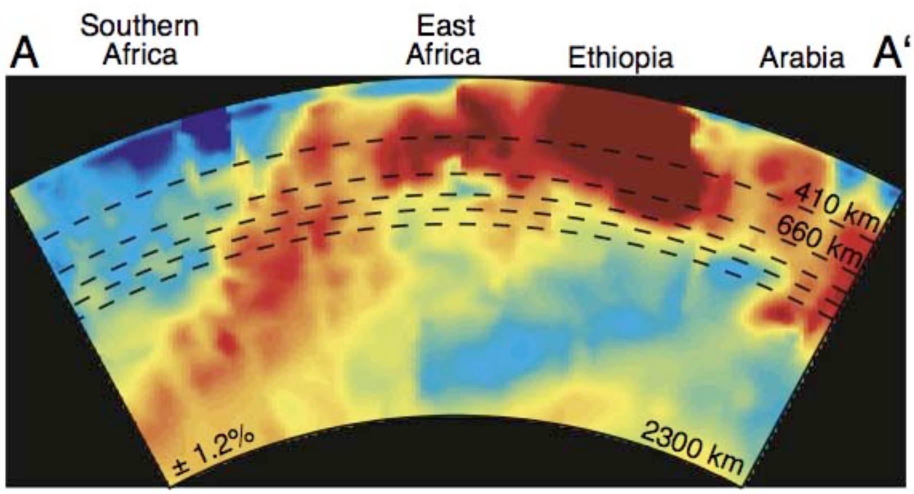


Figure 3.5. Cross sectional P-wave velocity model through the African and Arabian mantle. Dashed lines mark the 410 and 660 km discontinuities as well as depths of 800, 900 and 1000 km (Hansen et al., 2012).

3.2.5. Collaborative Targets of Opportunity: Synoptic Investigations Along the Entire Rift

There are also questions in the science plan that are best addressed by examining the rift as a whole. These concern rift-wide variations in the origin, composition, and timing of volcanism, the rate and distribution of strain along and across the rift systems and large scale pre-rift structure and dynamics underpinning the rift system (Figure 3.5). Thus, components of EARS science could include broad and open data assimilation efforts, strategic infilling of climatic, geochemical, and geophysical observations, and modeling and experimental work, which would provide a framework for the focused investigations along the rift.

One of the driving factors behind this target is the wealth of data that already exist across the rift system but with the knowledge that there are spatial (and in some cases temporal) gaps in coverage. This effort is expected to consist of the accumulation, integration, and quality assessment of existing data, re-processing of data where feasible and necessary, and the identification of data gaps with the intent of filling in these gaps through targeted field campaigns. It was specifically noted that reoccupying critical geodetic sites can have a big payoff by extending existing time series, whereas new sites require a long duration and so may need to begin as soon as possible.

The kinds of geophysical data sets that exist already with varying degrees of coverage include seismic (for example, through Africa Array, EAGLE, Afar Rift Consortium), magnetotelluric, geodetic, and very limited and relatively old heat flow stations. There is also an extensive geochemical data set including analyses of lavas, helium, and volatiles. sedimentary data sets from long cores could also be augmented through strategic coring under this effort.

Climate studies under this target might include running the NOAA Geophysical Fluid Dynamics Laboratory's (GFDL) Earth Systems Model (http://www.gfdl.noaa.gov/earth-system-model) (correctly parameterized for early and later rifting topography) which would offer a good way to see more accurately the dynamical effects of elevation on climate and climate/tectonic feedbacks.

3.2.6. Numerical and Experimental Studies

The development of a theory of continental rifting also depends on numerical investigations of loss of thickness and mechanical competence under extensional boundary conditions as well as surface processes. However, in comparison to regions of continental collision such as Tibet, the range and specificity of numerical investigations remains much more limited, and much progress in the description of rift related processes can be anticipated from numerical studies.

Focus of the modeling studies may range from surface processes (erosion, sedimentation) to crustal scale deformation- and upper mantle scale convection. Conceptual approaches may include plate-asthenosphere flow interactions, 2D and 3D dynamical models of crust and lithosphere deformation, magma generation and migration models, and regional-scale convection models. Fully coupled regional atmospheric flow, surface process, and lithospheric dynamics models can be applied to explore the development of drainage networks, mass flux across the landscape and into depositional systems, and any feedbacks between erosion and mechanical responses (which are seen in collisional systems and are expected to be modest but evident in extension). Some of this work has been done, but could be much expanded.

Simulations that overlap in time with the various data-campaigns will provide support for interpretations and may direct ongoing acquisition of field data. Recently developed 3D models suggest that the time and length scales of surface deformation during rifting are related to lithosphere rheology and layering, and efforts have started to understand earthquake patterns and other observables by comparing them with numerical model predictions.

Abundant evidence for lateral variations in EARS lithospheric competence exists, especially the loss of the mantle lithosphere northward toward the Afar triple junction. Numerical simulations of fully 3D mechanics are rare for any setting, with just a few results from compressional regimes such as Tibet and even fewer for rift settings. Such models require data for initial and boundary conditions that may not yet have been collected or documented. A longer-term goal of GeoPRISMS will be the development of such an integration of new data and new simulations

Experimental studies can help us to understand the effect of volatiles on the evolution of magmas erupting along the rift, constrain source lithologies, and examine the impact of volatile elements in melt production. These approaches are of utility in examining the evolution of magmas as they relate to plume-induced and decompression-induced magmatism (Figure 3.6). In particular experimental studies can have great utility in placing constraints on the possible volatile contents of magmas, in the absence of melt inclusion bearing tephras.

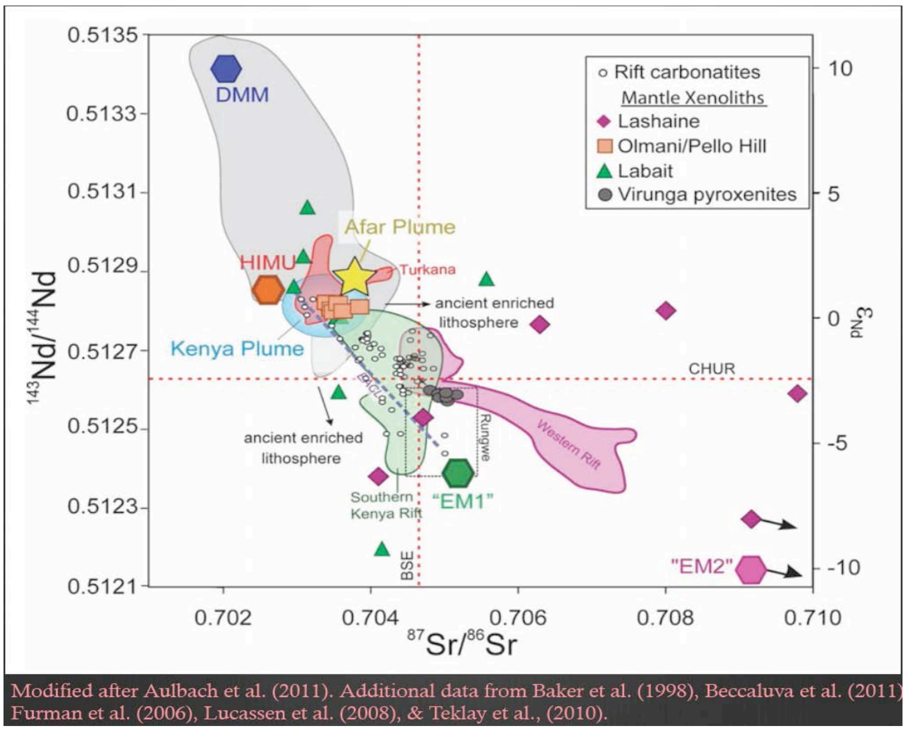


Figure 3.6. Isotopic variation of selected lavas and xenoliths from the East African Rift System, modified after Aulbach et al., 2011 with data from Baker et al. (1998), Beccaluva et al. (2011), Furman et al. (2006), Lucassen et al. (2008), and Teklay et al. (2010). Courtesy of Wendy Nelson.

3.2.7. Research Strategies and Partnerships

Given the limited program resources, leverage and collaboration with international partners is expected to play a key role in successful GeoPRISMS proposals to work on the EARS. There are also additional sources of potential funding, both within NSF and also at other US and foreign agencies. Below are a few of these possibilities. This list is likely incomplete and readers should refer to the GeoPRISMS website for an updated list.

NSF Science, Engineering, and Education for Sustainability (SEES): The goal of this program is to advance understanding of fundamental processes associated with specific natural hazards and technological hazards linked to natural phenomena, and their interactions. Proposals should be multi-disciplinary with the goal of improving capabilities for forecasting or predicting hazards, mitigating their effects, and enhancing capacity to respond to and recover from resultant disasters. The very nature of the EARS with its associated rift related earthquakes, volcanic eruptions and volatile emissions provides a natural laboratory for the GeoPRISMS-EARS community to take advantage of this funding opportunity.

NSF Integrated Earth Systems (IES): This new program in the Division of Earth Sciences (EAR) focuses specifically on the continental, terrestrial and deep Earth subsystems of the whole Earth system. Overall, the goals of IES are to: (a) provide opportunity for collaborative, multidisciplinary research into the operation, dynamics and complexity of Earth systems at a budgetary scale between that of a typical project in the EAR Division's disciplinary programs and larger scale initiatives at the Directorate or Foundation level; (b) support study of Earth systems that builds on process-oriented knowledge gained from EAR programmatic research and enables systems-level hypothesis testing and analysis of coupled processes; and (c) provide a "bridge" among the EAR disciplinary programs in order to foster the exchange of questions, ideas, and knowledge between disciplinary discovery and system-level investigations.

NASA has several programs relevant to EARS science. In addition to these potential sources of funding, there are upcoming missions that, subject to budgets, could potentially provide important data sets including deformation, atmospheric volatile concentrations and altimetry.

ROSES program (http://nspires.nasaprs.com/external/) supports projects that use data from NASA satellite or airborne platforms to study a variety of earth processes relevant to the EARS program. For example, the Earth Surface and Interior program (http://solidearth.jpl.nasa.gov/) funds projects that asess, mitigate and forecast the natural hazards that affect society, including earthquakes, landslides, coastal and interior erosion, floods and volcanic eruptions.

SERVIR program (https://www.servirglobal.net/EastAfrica.aspx) aims to integrate satellite observations, ground-based data and forecast models to monitor and forecast environmental changes and to improve response to natural disasters.

Africa Array (http://www.africaarray.psu.edu) was started in 2004 as a vehicle to create new geoscientific research and training programs and rebuild existing ones in Africa. While the long-term vision for *AfricaArray* is to support training in many geoscience fields, initial efforts have focused on geophysics. Specific undertakings have included the development of new geophysical training programs and also the expanded support of existing ones; promotion of geophysical research; and design and establishment of a network of geophysical stations. The program has been particularly responsible for installing and maintaining a seismic network which, among other goals, has assisted in imaging the African superplume. It has also collected GPS and weather data.

Hominin sites and the Paleolakes Drilling Project (http://www.icdp-online.org/front_content.php?idcat=1225): Five drilling areas spanning late Tertiary/Quaternary lakes and paleoanthropology questions. Cores will provide high-resolution archives of environmental history (including local tectonics, erosion and exhumation history) with the potential to test hypotheses of the relationship of human evolution, extinction events and demography to environmental history. Projects established as a result of this effort have synergies with GeoPRISMS goals including studies of: basin tectonics, watershed reconstruction and paleogeomorphology-cosmogenic Isotopes and low temperature detrital thermochronology; seismite records/earthquake recurrence; landscape modeling; global and nested regional climate modeling; climate-tectonic-surface process feedbacks.

Lake drilling projects: There are a series of drill cores either collected or planned in East African Rift Lakes. Long cores are aimed at addressing the dynamics of the last ~7Myrs of African climate and assessing the sensitivity of east African hydrology and temperature to orbital scale climate forcings. The long cores also plan to address issues related to fault kinematics, earthquake recurrence intervals and the volcanic history of EAR volcanoes such as Rungwe.

International efforts: Below is brief information on international efforts, where readers can seek information on completed or ongoing projects or find potential partners for collaborative efforts. Again, this list is not complete, and we encourage viewing the GeoPRSISMS website for updated information:

Afar Rift Consortium (ARC) (http://www.see.leeds.ac.uk/afar/) is a project funded by the UK Natural Environment Research Council (NERC). It is made up of scientists from the Universities of Leeds, Bristol, Oxford, Edinburgh, and Cambridge, and Project Partners at the British Geological Survey, Universities of Addis Ababa, Auckland, Brittany, Rochester, Purdue, and Columbia (LDEO). The linked NSF-funded SEARIFT project supports the US partners (http://www.ees.rochester.edu/ebinger/SEARIFT). These projects, nearing completion, aimed to capture in 4D the partitioning of magmatic and tectonic strain, and the geodynamic conditions for the onset of along-axis segmentation at plate rupture. The ARC has conducted geophysical experiments in Afar using seismology, geodesy, gravity, and magnetotellurics; it has used geology and petrology to map and understand the magmatic history of the Dabbahu rift segment; it has used high-resolution LiDAR topography to understand the history of faulting; and it has used numerical models to understand the evolution of the region and the response to the diking episode.

The French government has funded, through Agence Nationale pour la Recherche (ANR), a large number of projects focused on or around the EARS. L'Institut National des Sciences de l'Univers (INSU) has also funded a seismic experiment in the Eastern Afar, and a project looking at volcanism and structure during extension.

The GEOBSNET program of the Royal Central African Museum of Belgium targets scientific efforts for assessing geo- and environmental hazards *(http://www.africamuseum.be/GEORISCA)*

The Global Earthquake Model (http://www.globalquakemodel.org/) aims to construct a global framework of data that permits enhanced risk assessment at the local scales and which fosters international collaboration.

ICTP (http://africa.ictp.it/) has a long tradition of scientific capacity building in Africa by facilitating exchange visits for African scientists. The science fields cover a broad range of physics, mathematics, geophysics and climatology.

Riftlink (http://www.riftlink.de/) is a research program studying rift dynamics uplift and change in Africa, through a consortium of German and African institutions

African collaborations: Collaborations with local scientists are essential to the success of any project launched within Africa. This collaboration is typically facilitated with the signing of a memorandum of understanding (MoU). Collaboration should be a two way street. For the European and American scientists, the importance of local knowledge, language and logistical assistance cannot be overstated. The monetary value of logistical assistance can be substantial – reliable vehicles are often hard to come by, for example. The type of institution available for collaboration is dependent on the country: in some cases, the pertinent geological survey is the first point of contact, in others a university is. Strong collaborations with local scientists can also serve to enhance the educational experience of GeoPRISMS students especially those looking for study abroad opportunities as well as short-term exchange visits. For the local scientists, sustainable relationships with their US and European peers can help with capacity building in several areas: through training of staff, particularly early-career faculty; providing scientific input into the long-term strategic planning for sustainable resources management and hazards evaluation/mitigation for the countries transected by the rift; the development of geophysical and geochemical skills that are valuable for mineral and water resources exploration; and for future scientific investigations in the host countries.

Industry collaborations: There are numerous examples of where industry has partnered with academia to facilitate the collection of data in Africa. For example, the SAMTEX consortium collected a large number of MT stations that were, in part, funded with a partnership with several mining companies (DeBeers, BHP and RTZ). World Bank and African Development bank loans support geothermal research throughout the proposed study regions, and many have been trained through alternative energy programs. Gold and other economic mineral exploration companies continue to support geophysical, geochemical, and geological research in East Africa. The petroleum industry has interests and active exploration programs in Afar, and the Eastern and Western rift, many of which could be leveraged through science/industry partnerships.

3.2.8. Broader Impacts

3.2.8.1 Capacity building, education and outreach in Africa

Working in Africa creates potential for capacity building through collaboration with local scientists. Collaborations are essential to the success of any project. NSF offers some avenues to facilitating capacity building. For example, the African partners of funded NSF projects can seek funding via the PEER program is an NSF partnership with USAID (http://sites.nationalacademies.org/PGA/dsc/PEERscience/index.htm). Some capacity building can be included as part of normal NSF awards, depending on the program. Africa Array has been carrying out capacity building and its website (http://www.africaarray.psu.edu) offers concrete examples of capacity building exercises, including workshops and summer schools, visiting scientist programs and student exchanges.

Capacity building through individual projects can be a challenge, and successful approaches will depend on the science being completed. African colleagues at the Morristown meeting emphasized the importance of engaging the local community in the science. They also highlighted the need to have an awareness of the different expectations of the local stakeholders involved in the effort. Governments have community development interests to consider, whereas the local community itself might want to understand how a project will address daily problems they encounter. Universities will look for educational and research opportunities, within the scope of their limited faculty staff and students. Individual scientists might look for training experiences that can advance their careers and that provide them with knowledge they can in turn pass onto their colleagues and students. Examples of approaches to successful capacity building that have been used successfully include:

- Sandwich programs that enable African students to get degrees at their home institutions but spend a significant amount of time abroad being co-supervised by someone at a foreign institution. This is much cheaper than bringing the student to the foreign institution for a degree, and helps the student keep connections back home, which in turn helps to address the brain drain problem.

- Technical training in country, formally and informally, on equipment operation and maintenance, data archiving, and data processing. Support for these activities can be built into budgets and are relatively inexpensive.

- Long term (post-project) commitment to helping scientists keep research equipment operating. This is really more a time commitment issue on the part of the PI rather than a financial commitment. Often, local scientists simply need advice on what to do when things break down.

- Providing ownership of a component of the project to local scientists. This can be done by providing opportunities for reduced-cost equipment purchase, support and training in secure data archiving, opportunities for data sharing across political boundaries, and support of existing networks, such as the SADCC seismic network operators training courses, and access to regional training workshops (e.g., Potsdam seismic training, ICTP geophysics courses, IAVCEI workshops). It can also involve training the scientists to collect their own data set and assisting with the data reduction, analysis and interpretation. The survey design and goals can be up to the local scientists and can be tailored to meet the larger aims of their institution (governmental or academic). Exchange programs wherein the scientists visit US institutions to carry out part or all of the analysis can accelerate the training process.

GeoPRISMS projects in Africa also offer tremendous educational opportunities for American students and young scientists. The active EARS is particularly well suited to interdisciplinary studies, providing young scientists with exceptional opportunities to interact with other American and African scientists doing complementary work. Besides the obvious scientific learning that comes through close international collaboration, working closely with African scientists and in the field in Africa is an invaluable cultural experience for students. Internationalization of young American scientists will serve them well in whatever field they chose.

Executing GeoPRISMS science in the EARS also enables an international outreach effort. Field programs in Africa offer the chance for abundant interaction and outreach to people living within and near the rift system on the fundamental earth processes at work and the associated geohazards. Outreach opportunities that combine field work and outreach could include deploying instruments near schools, and giving presentations in local communities during field work.

3.2.8.2. Hazards

The EARS can produce damaging earthquakes (Mw > 7), fatal landslides with frequency increasing with land denudation, potential anoxic lake overturns and seiche/lake tsunamis, and also presents volcanic hazards (eruptions with Volcano Explosivity Index > 4 along with lahars, lava flows, landslides, etc.) to the growing population of the region. In some places, these hazards are not fully appreciated by the government or the local scientists lack funding, local instrument networks or training to better document them. Comparatively small natural disasters can have substantial long-term societal effects in these developing economies, and the growing body of knowledge indicates that volcanic hazards are grossly underestimated in many rift sectors.. Thus, there are many opportunities for broader impacts by better understanding the hazards through collaborating with local geological surveys or NGOs for risk assessment, community education, or multi-disciplinary collaborations through programs such as NSFs Hazards SEES or NASA's SERVIR program (see above).

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.

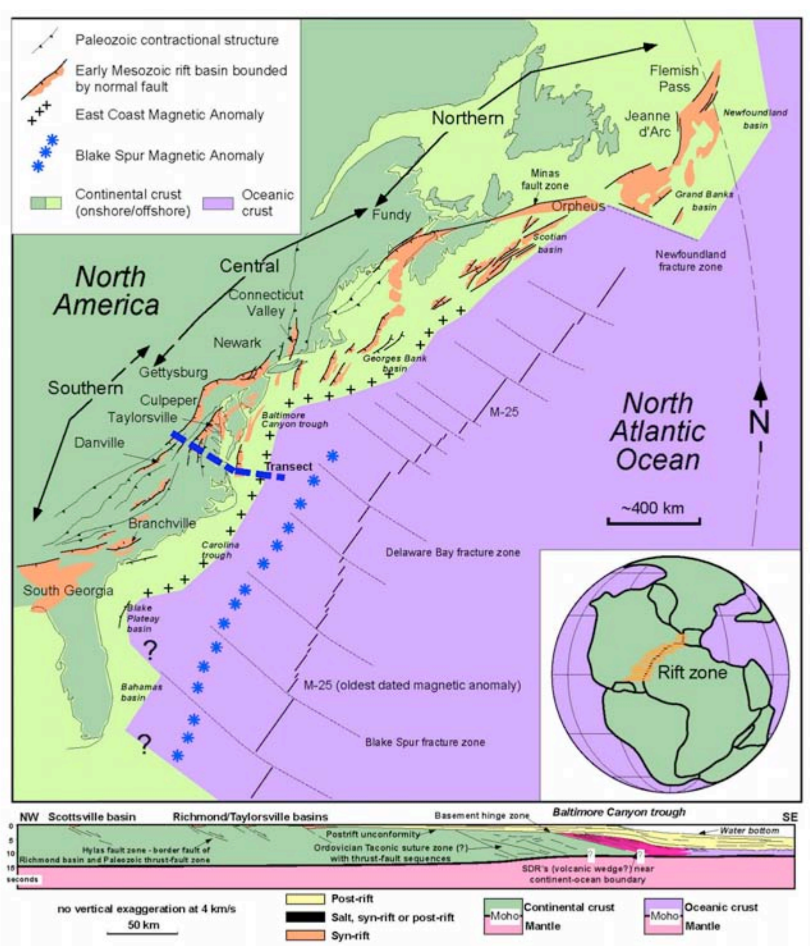
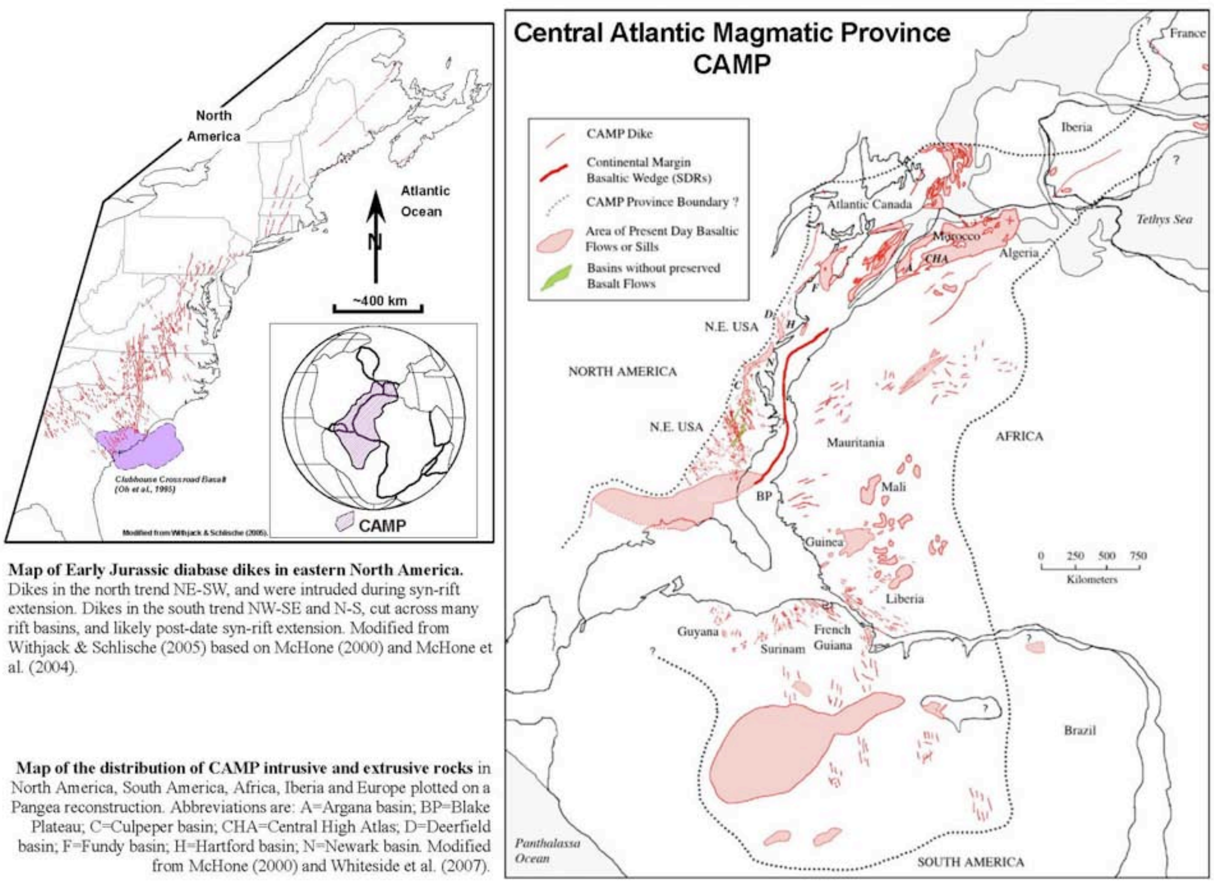


Figure 3.7. ENAM and the major tectonic elements. The East Coast Magnetic Anomaly approximates the extent of seaward dipping reflectors in the continent-ocean boundary (red reflectors in the cross-section. M-25 is the oldest dated magnetic anomaly. Inset shows the configuration of Pangea during the late 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.

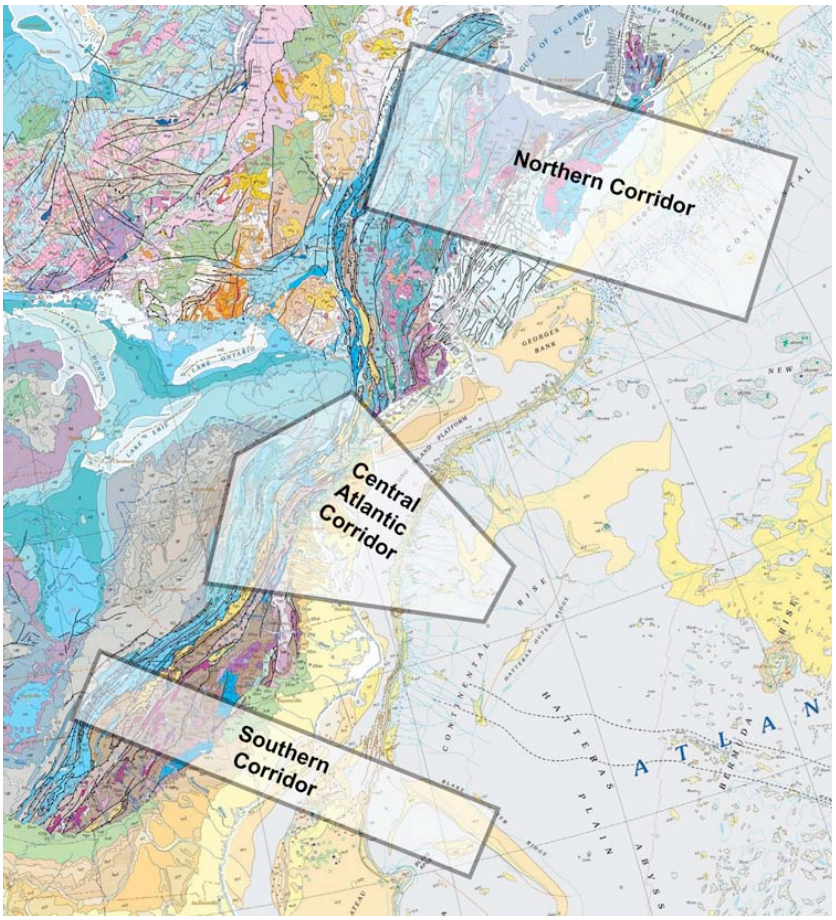


Figure 3.9. DNAG (Decade of North American Geology) geologic map of eastern North America showing the focus areas defined for GeoPRISMS research in ENAM. Modified from http://esp.cr.usgs.gov/info/gmna/)

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*

<u>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.</u> 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

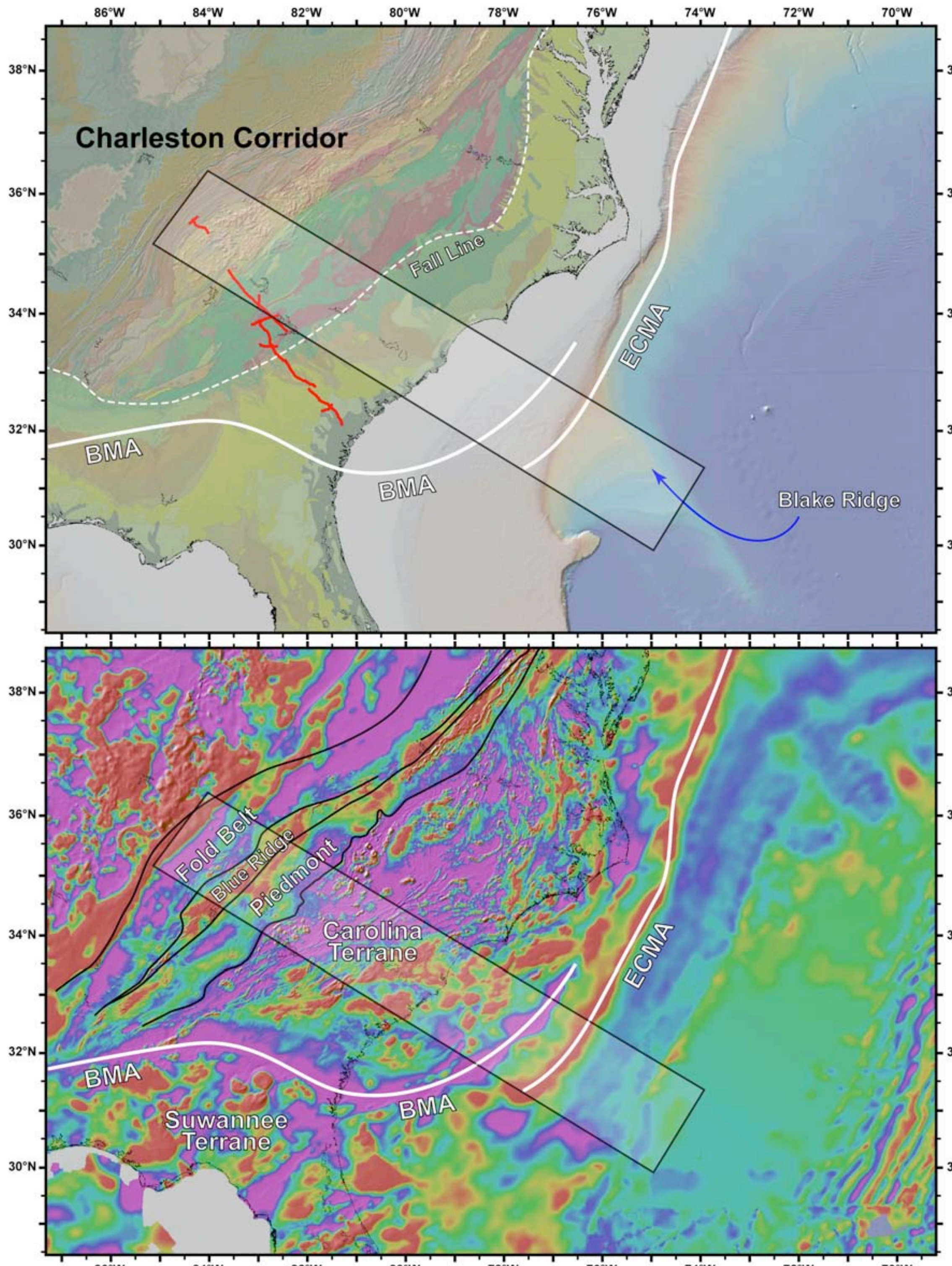


Figure 3.10. Top: Topography and onshore geology of southern ENAM. Box indicates the Charleston Corridor. BMA, Brunswick magnetic anomaly, thought to mark the Alleghanian suture. ECMA, East Coast magnetic anomaly, effectively marks the continent/ocean transition and the seaward-dipping reflector sequence. 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.

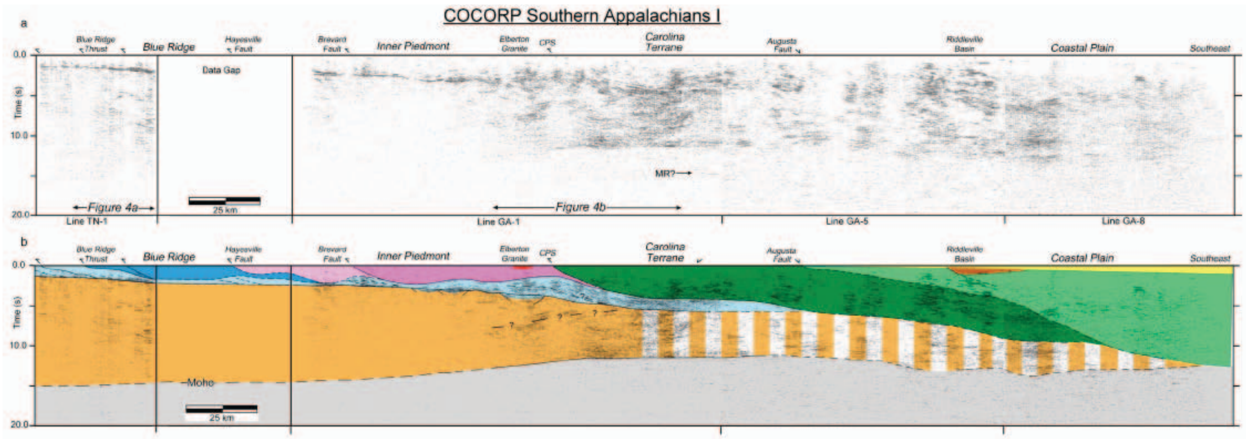


Figure 3.11. (a) Migrated, coherency filtered, and uninterrupted data from COCORP lines TN-1, GA-1, GA-5, and GA-8 subparallel to the Charleston focus area. A portion of the west end on the line GA-5 has been removed due to overlap with line GA-1. (b) Interpretation of (a) modified from Cook et al. (1979,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

<u>Geochronology, Geochemistry:</u> 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.

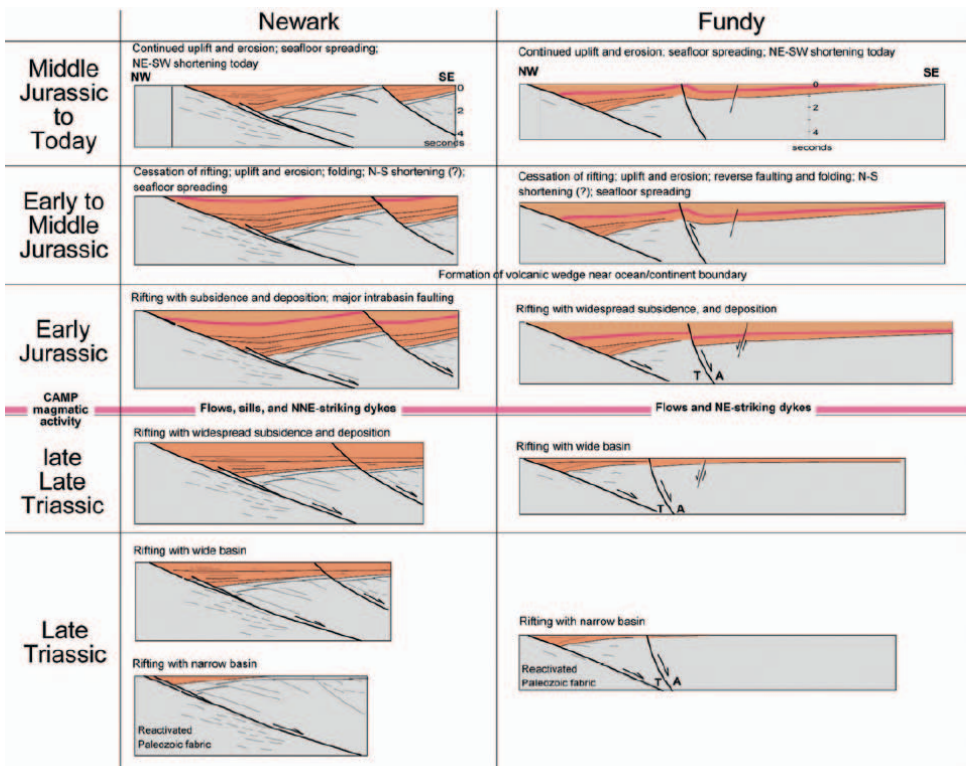


Figure 3.12. Evolution of representative rift basins from the Central focus area (Newark Basin) and the Northern focus area (Fundy Basin). Both basins show evidence for post-rift inversion, uplift and rotation. Extensional faults within the Fundy Basin show reactivation as reverse faults, contributing 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.

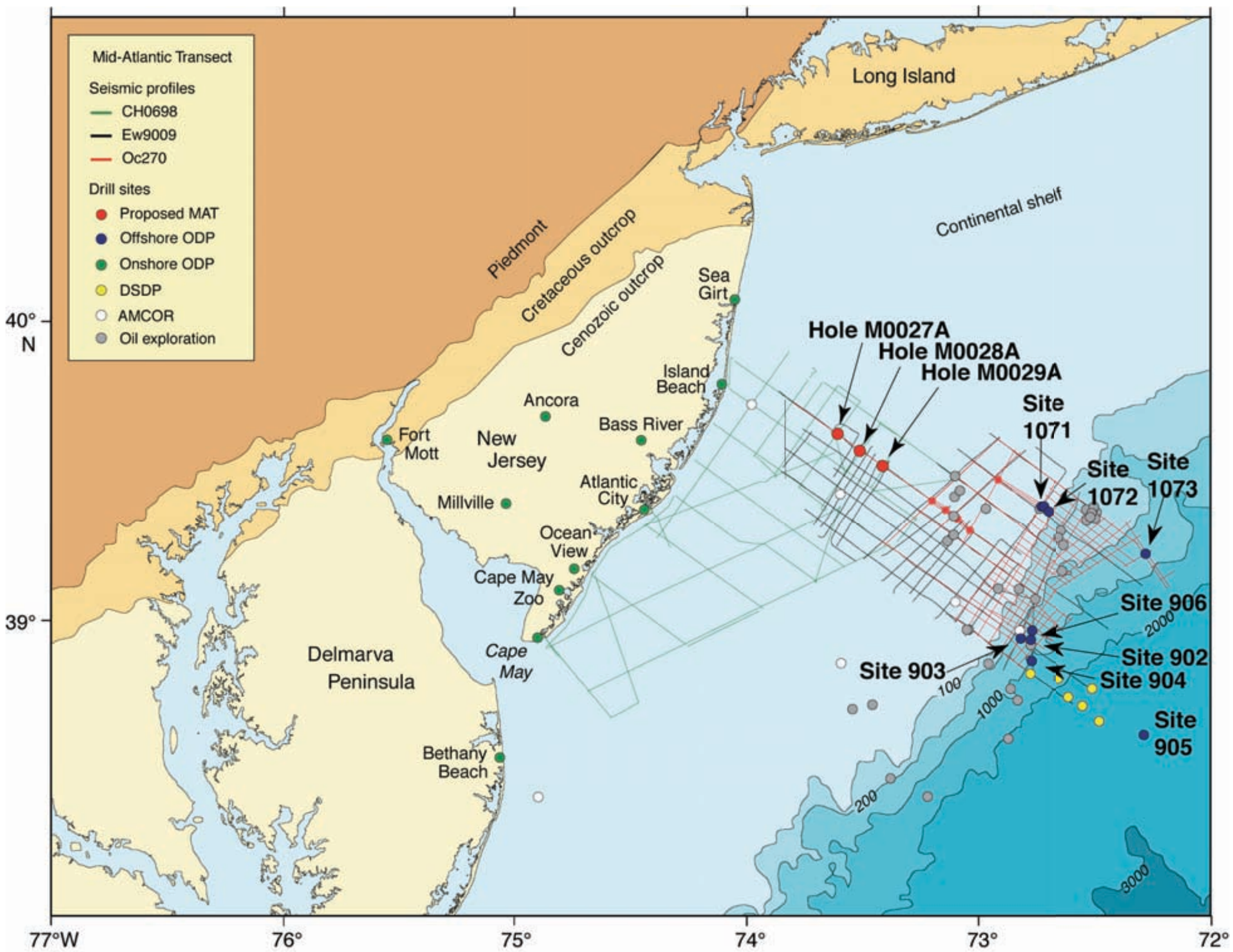


Figure 3.13. The New Jersey continental margin showing Expedition Holes M0027A, M0028A, and M0029A along with other completed boreholes both onshore and offshore. Tracks of reconnaissance seismic lines are also shown. (Expedition 313 Scientists, 2010).

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

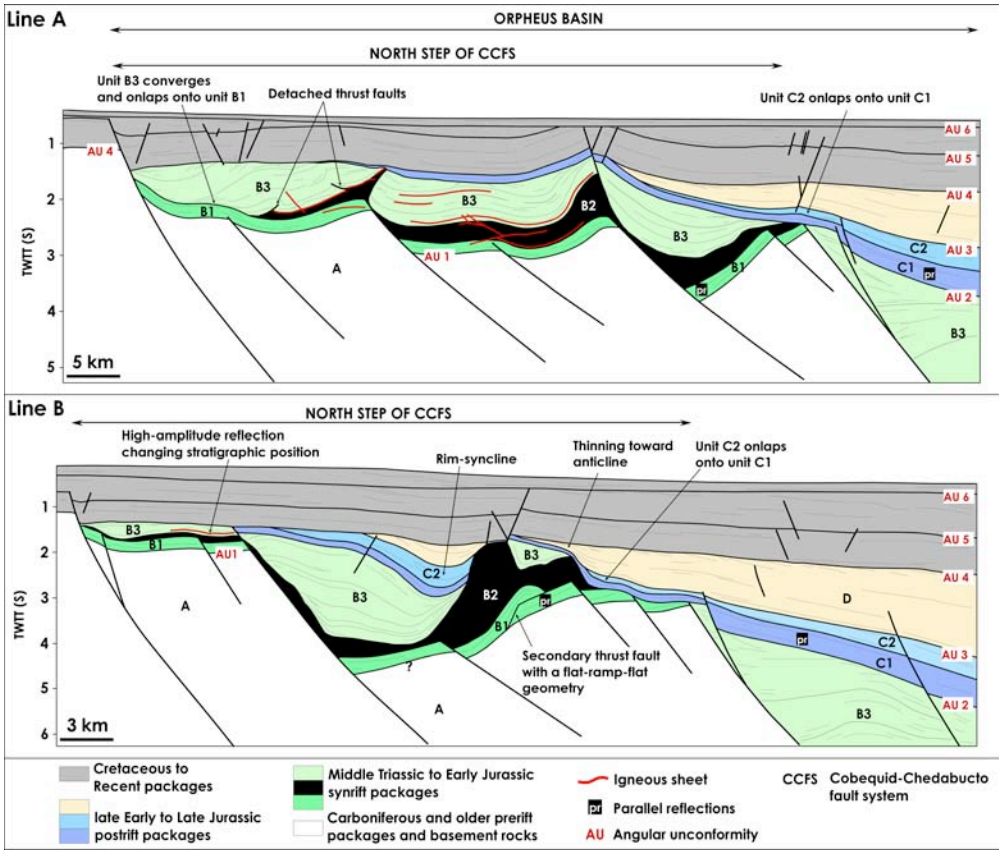


Figure 3.14. Interpreted line drawings of seismic lines A and B across the Orpheus Basin, offshore Nova Scotia, showing unconformity-bounded packages within the Paleozoic-Mesozoic-Cenozoic section of the Orpheus basin (From Syamsir et al., 2010).

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.

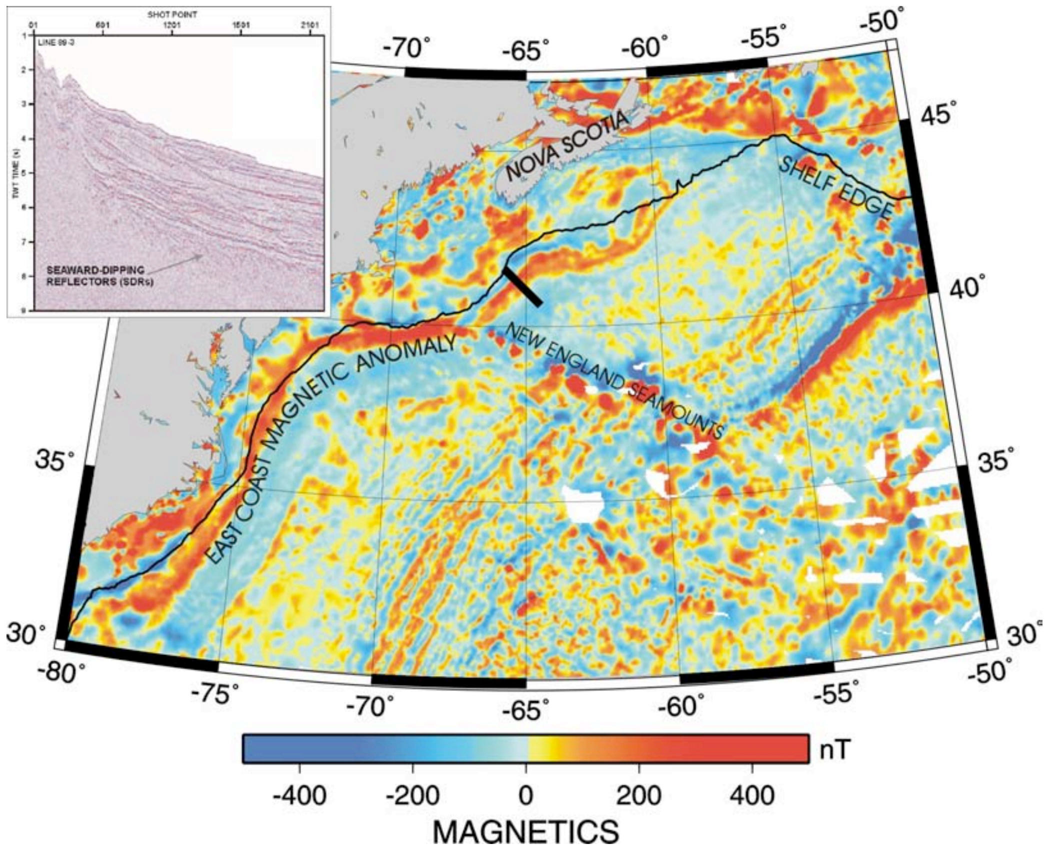


Figure 3.15. The distinct East Coast Magnetic Anomaly (ECMA), which shows up clearly along southern ENAM, dies out to the north, near the western edge of the Laurentian Channel. The reduction in ECMA amplitude off Nova Scotia may be due to a decrease in the volume of extrusive volcanic layers. Inset 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.

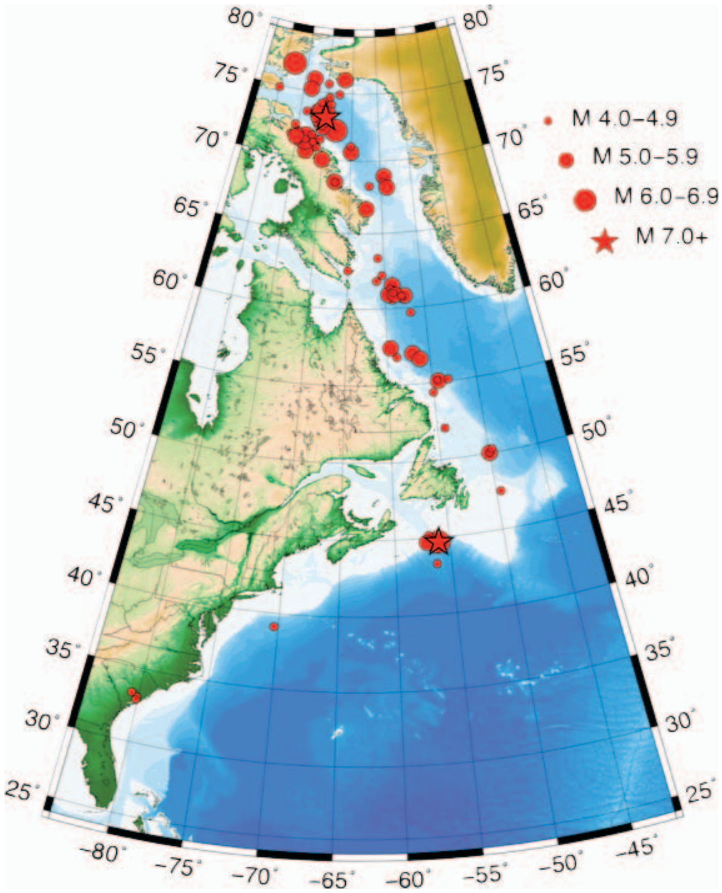


Figure 3.16: Magnitude of historic earthquakes along the Eastern North American margin. (Source: http://www.earth.northwestern.edu/people/seth/Lectures/index.html, Events from Schulte & Mooney, 2005), ANSS, and Earthquakes Canada; figure prepared by S. Stein).

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.

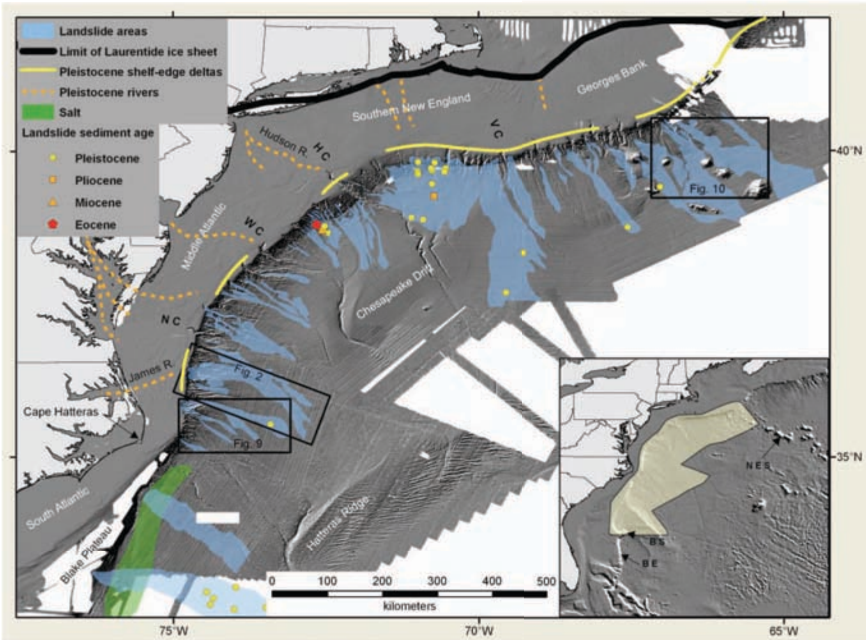


Figure 3.17. Distributions of mapped submarine landslides and debris fields along the Eastern North American Margin. From Twichell et al. (2009).

<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 $3.5x10^5$ 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.

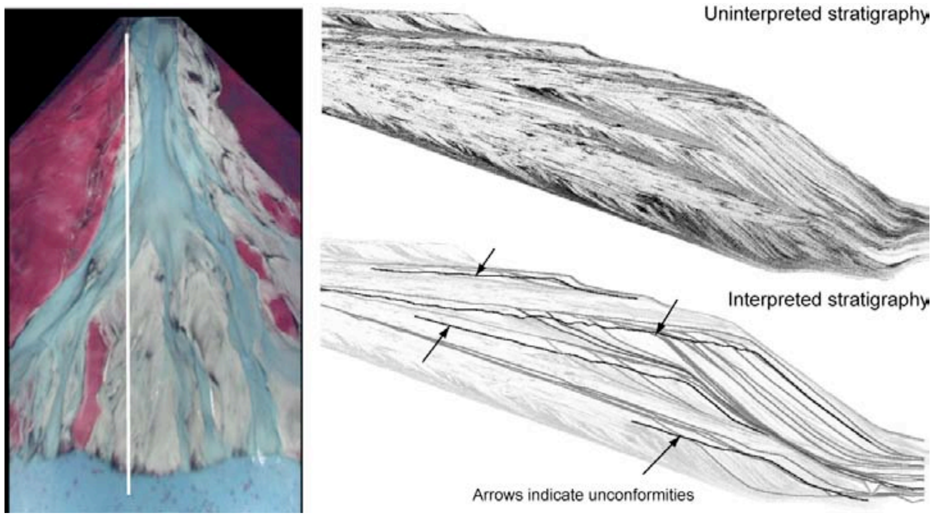


Figure 3.18. Stratigraphic evolution as seen through the depositional filter via experiment, with scans of surface topography (gray) compared against mapped unconformities and sequence boundaries (black). A significant challenge in linking process to form is the connection between instantaneous surface 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.

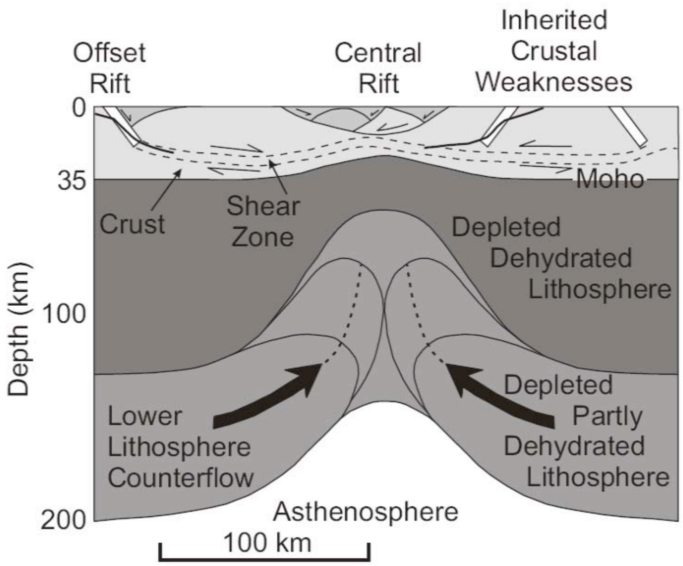


Figure 3.19. Concepts of lower lithosphere counterflow and reactivation of inherited crustal weak zones as offset rift basins in the context of lithospheric extension and rifting (from Beaumont and Ings, in press).

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.

<u>*Physical Analogue Models:*</u> 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.

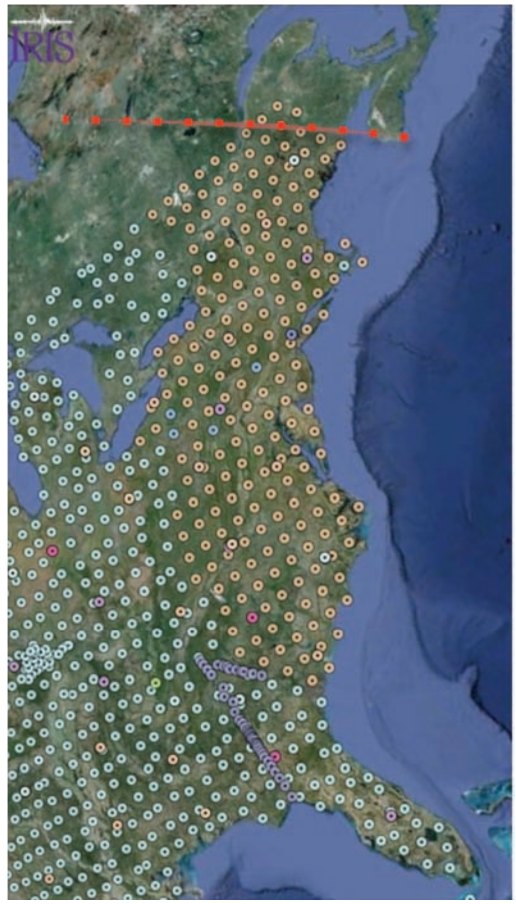


Figure 3.20. Map of EarthScope Trasportable Array (blue – deployed, tan – planned for 2013-2015), Flexible array experiments (dense clusters of symbols) and various other permanently operating seismic observatories. A passive seismic experiment in Nova Scotia, Maine and Quebec (red line) will deploy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

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.

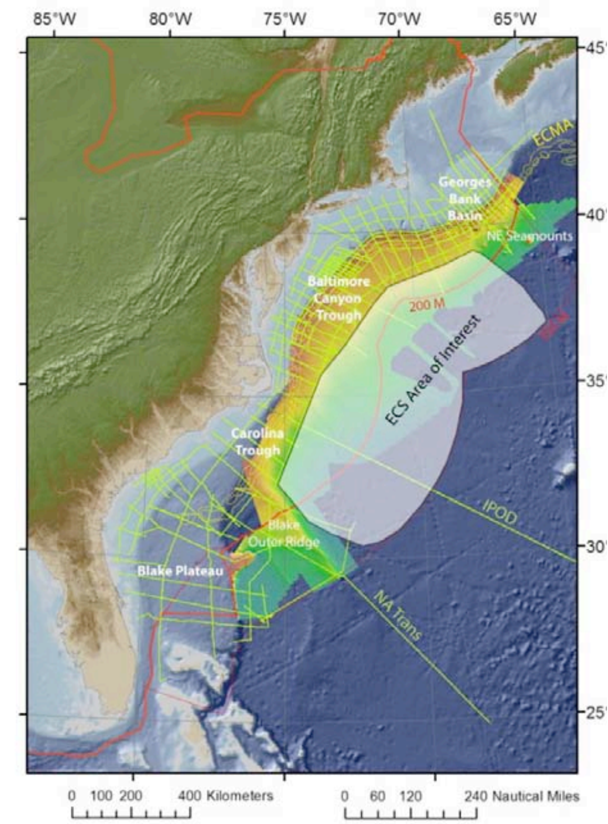


Figure 3.21. Map of existing 2D MCS lines across the eastern US continental margin, and area of interest for proposed USGS survey to map the ECS. (Courtesy of D. Hutchinson)

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.

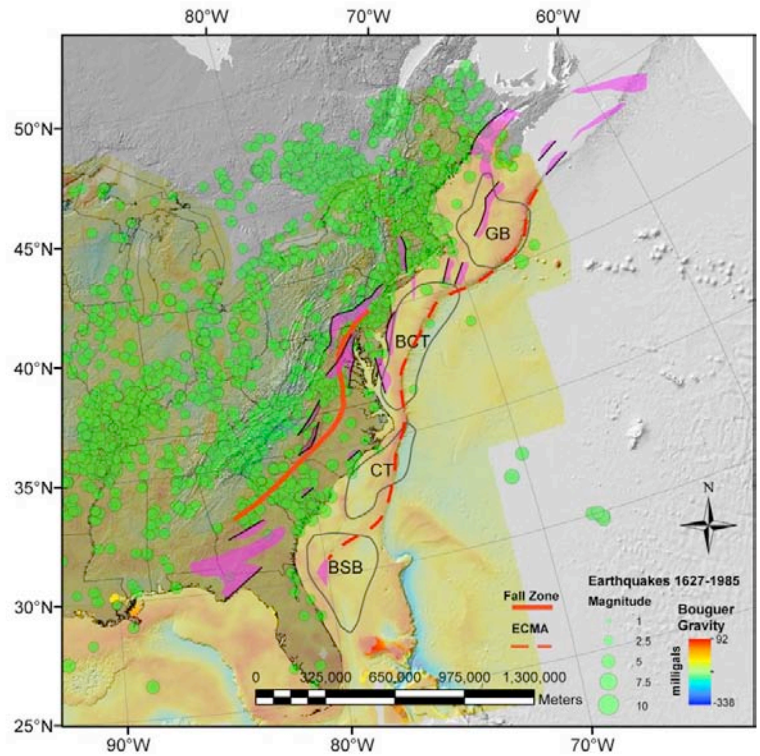


Figure 3.22. Map of ENAM showing the Bouguer gravity anomaly draped on Appalachian topo-graphy and Atlantic Ocean bathymetry. Green circles are earthquake locations. Purple poly-gons are syn-rift basins with border faults in black. Black-outlined polygons are approximate boundaries of shelf-slope basins; 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.

3.4. Comparative and Thematic Studies

Theme 1: Rift obliquity

Far-field extensional forces may be oriented at oblique angles to pre-existing structural and compositional heterogeneities in the lithosphere, such that extension is accommodated by the development of an oblique rift. Oblique extension will impact the evolution of tectonic and magmatic segmentation, as well as extensional style throughout the lithosphere, although it remains unclear to what degree the mismatch between pre-existing lithospheric fabrics and extensional stress control the development of such features. It also remains unclear how the orientation of faults and magmatic intrusions evolve over the life of the rift to produce orthogonal structures at the eventual mid-ocean ridge. This theme focuses on probing lithospheric structure, and in particular magmatic and tectonic features, in a variety of environments where oblique extension of varying magnitudes may be active. Oblique extension, for example, may result in the development of segmented en-echelon rift border faults and/or magmatic belts on the rift floor.

The selected GeoPRISMS primary sites, the East African Rift System (EARS) and Eastern North American Margin (ENAM) incorporate a significant range in extensional morphologies including oblique segments, but these rifts constitute dominantly orthogonal rift systems, and thus provide end-members to address the fundamental concept of strain localization and how it may be impacted by obliquity in terms of extension. Comparative, targeted studies of rifts incorporating a range of obliquity and magmatic activity are required to investigate variations in processes with obliquity (e.g., Gulf of California-Walker Lane). Magmatic and tectonic features preserved within variably oblique rifts may provide evidence of how shifting stress fields may manifest within primary sites and their impact on strain localization. Such studies should take advantage of existing datasets from the MARGINS program as well as other US and international programs by synthesizing previously acquired data, providing key missing datasets (e.g., structural observations, reinterpretations of lithospheric structure from existing seismic studies, geochemical investigations of magmatic plumbing system dynamics) in otherwise well-studied oblique rifts, and through numerical modeling and analogue experiments.

Theme 2: Rift processes as functions of strain rate

Numerical models indicate that strain rate is a key parameter controlling the style and magnitude of extension, efficiency of conductive cooling, and the production of magma. However, spatial and temporal patterns in strain rate are very poorly known for many extensional systems, and consequently, so are their links to deformation and magmatism. Constraints on geologically averaged strain rate during rifting at passive margins are derived from dated sediments and volcanic rocks and from magnetic anomalies associated with early seafloor spreading. GPS and InSAR data are beginning to provide the first constraints on the spatial and temporal patterns in present day strain rates in rifts. This theme focuses on integrating constraints on the temporal development of rifts with spatial patterns in deformation and magmatism, at a range of time scales, to elucidate the response of rifts to strain rate. Rifts opening at slow strain rates have been shown to accommodate deformation in unusual ways, such as through exhumation of serpentinized mantle, which could also lend important, general insights into strain accommodation in the lithosphere.

When compared with oceanic rift systems, the active EARS primary site constitutes a slow-end member, with opening rates of 1-6.5 mm/yr. Likewise, time-averaged strain-rates for the ENAM primary site have relatively slow half spreading rates of ~7 mm/yr. Focusing solely upon these relatively slowly extending systems, scaling rifting processes with strain rate is impossible. Themed studies should therefore emphasize comparisons between the GeoPRISMS primary sites, and other active and passive settings with higher strain rates, particularly those that have existing constraints on magmatism and deformation (e.g., Woodlark basin, Gulf of California-Walker Lane system, Gulf of Corinth). These studies will be directed towards illuminating linkages between strain rate and other rifting processes.

Theme 3: Volatiles in rift zone processes

Recent work highlights the critically important role that volatiles can play in the initiation and evolution of magmatism, strain localization and other key aspects of the rifting process. The origin and abundance of volatiles likely varies significantly from plume- to slab-dominated environments and between regions with different lithospheric compositional structure. This theme will focus on complementing the datasets central to characterizing the primary sites, through studies of rifts where the volatile species or pathways may be substantially different. Evolution of rifting will depend strongly on the control volatiles exert over lithospheric rheology, and in particular the key processes controlling changes in this rheology: e.g., partial melting, sill and dike intrusion, and hydrothermal systems. Likewise, volatile exchanges with the ocean and atmosphere vary tremendously with the amounts and compositions of magmatism, interactions of magmas with sediments, and serpenitization, with implications for environmental change.

The chosen RIE primary sites, EARS and ENAM, are ideally suited to examine the role of rift maturity in controlling rift volatile reservoirs and pathways. A second constraint that is necessary to understand the volatile budget within a rift system, however, is to characterize external inputs to the rifting system. Specifically, mantle plumes and subducted slabs may provide significant concentration of volatiles but also impact/buffer the volatile species present within a rift system. While the EARS focus site provides an example of a plume-influenced rifting environment, thematic studies should seek to expand upon possible volatile sources that impact upon but are external to the rift system (e.g. subducted slab). Such studies should focus on determining the volatile characteristics (volatile species, concentration, spatial or temporal heterogeneity) in rifts where significant external control on volatile systematics has been previously demonstrated (e.g. Gulf of California), but also in rifts where unique volatile pathways or interactions have a recognized impact on rift evolution. Likewise, thematic studies should also focus on volatile exchange with the oceans and atmosphere in a variety of settings.

Theme 4. Sediment production, routing and transport during and after rifting

The volume, distribution and composition of sediments can have a dramatic impact on syn- and post-rift evolution of basins and margins at all levels of the lithosphere. In active rifts, thick sediments may enhance strain localization via thermal blanketing and reducing buoyancy contrasts and inhibit strain localization through distributed deformation. Even relatively thin sediment cover may enhance the amount and style of magmatism, while overwhelming sedimentation may inhibit magmatism or otherwise mask its contribution. On passive margins, sediment flux is likely to control the frequency of landsliding and the rates and style of deformation of the sedimentary prism. This theme focuses on integrating observations and modeling of rifting and rifted margin processes interacting over the full range of potential sediment fluxes, including overfilled conditions that are not well captured by the GeoPRISMS primary sites.

Both of the GeoPRISMS RIE primary sites exhibit low to moderate sediment flux conditions. For example, EARS basins are typically underfilled, lacustrine-dominated systems, even where these manage to capture a significant river system such as the Okavango. Although portions of the ENAM recently have been subjected to high sediment flux due to continental glaciation, overall this site is relatively starved of sediment input from large river systems. Comparative investigations should thus focus on sites subject to extremely high sediment flux during their evolution, such as where a continental-scale river crosses the rifted margin. Such studies should be limited to providing synthesis and key data sets in otherwise well-studied systems, such as how sediment from the Colorado River affects the development of northern Gulf of California MARGINS focus site or of how the Mississippi river delta influences active processes on the Gulf of Mexico passive margin. These objectives should be strongly coupled to modeling studies in order to tease out observations that can discriminate sometimes conflicting conclusions of the role of sediment flux in RIE.

Theme 5. Discrete events at rifted margins

Observations across time scales and various stages of seismic or magmatic cycles are needed to fully understand how distributed, dominantly elastic deformation is resolved as fault slip or genesis of new magmatic crust. This theme focuses on discrete events, such as dike injection and earthquakes, which can provide unique information on the shortest time-scale, episodic deformation and magmatic processes. Fundamental questions to be addressed with such comparative studies include what controls the sizes of rift-related earthquakes and magmatic events, and how do these relate to the development of border faults and rift segmentation. This theme also includes discrete events at passive margins, addressing questions such as what triggers large landslides and rare earthquakes in these settings. Although both GeoPRISMS primary sites are well suited to capture such events, their inherently unpredictable nature warrants a complimentary thematic approach. Comparative studies under this theme should be geared towards rapid, nimble, and focused amphibious scientific response to rare rift and rift-margin events, no matter where these may occur but with preference for the primary sites when possible. Additional comparative studies could include modeling and synthesis of observations from well-studied examples of rift earthquakes and landslides that lie outside of the primary sites.