Project Summary

Intellectual Merit: Some of the most important unresolved questions in plate tectonics concern the formation and rupture of continents. How does the accretion of terranes contribute to the construction of continental lithosphere? What processes enable continental lithosphere to rupture? Repeated accretion and rifting events through the Paleozoic and Mesozoic fundamentally modified eastern North America. Hundreds of kilometers of exotic terranes were added to North American during the most recent orogeny (Alleghenian orogeny, ~290 Ma), notably the large Carolina terrane in the SE US. Wide-spread extension followed beginning at ~230 Ma, which lead to the formation of a series of large rift basins along eastern North America. But rupture did not occur until 30-40 m.y. later, coincident with the arrival of the Central Atlantic Magmatic Province (CAMP), one of the largest known igneous events in Earth history.

Here we seek to understand the interaction of extension, sutures and magmatism in the development of rift systems in general and in the tectonic evolution in the eastern US in particular. We propose an active-source seismic refraction study of the South Georgia Basin. This is the largest of the Triassic rift systems that formed during the early stages of the breakup of Pangea; it spans the Suwannee suture (the only well delineated Alleghenian suture), and was at the center of CAMP. The shallow structure of this basin is known from existing COCORP seismic reflection profiles, and the age and geochemistry of flows and sills and the stratigraphy of syn- and post-rift sediments are known from numerous wells drilled throughout the basin. The arrival of the Transportable Array and the Earthscope-funded Flexible Array project (K. Fischer et al) will target the lithospheric-scale structure of the Suwannee suture and the South Georgia basin. The key missing dataset is crustal-scale seismic refraction data. Surprisingly, such data have never been acquired across this basin or any of the other Triassic basins along the eastern US. The refraction data we propose to acquire will enable us to determine the basic parameters of this rift system and it's relationship to the Alleghenian suture, including the spatial extent of the rift, the magnitude and pattern of crustal thinning, the volume and distribution of rift-related and CAMP magmatism, crustal thickness and seismic-velocity contrasts across the suture, and the seismic properties of the suture itself.

Our proposed experiment consists of two 275-km-long profiles across the basin and a densely instrumented 100x100 km box. Our lines are nearly coincident with COCORP reflection data and the dense 2D passive arrays (Fischer et al) funded by EARTHSCOPE. New refraction data will enable us to understand the interplay of extension, magmatism and pre-existing structures in a rift system that occupied a central location during the breakup of Pangea and the emplacement of CAMP, two of the most recent and fundamental tectonic events to shape the east coast of North America.

Broader Impacts: Large magmatic events are often linked with dramatic environmental changes, which cause biotic crises in the oceans by warming, ocean acidification and growth of algae and onshore by soil acidification. The CAMP event was marked by extinctions at the Triassic-Jurassic boundary. Our study will delineate the volume and distribution of magmatism and clarify the geodynamic conditions that brought about those changes. Additionally, our 3D box will better quantify the amount of magma that intruded sediments and potentially caused degassing of CO_2 and SO_2. Flood basalts are also potential reservoirs for carbon sequestration. Basalt flows associated with CAMP constitute one of the largest volcanic rock reservoirs on the east coast of the US; we will better constrain the volume and distribution of basalt stored in the South Georgia basin.

Our project will also involve a large, multi-faceted education and outreach effort. The acquisition, analysis and interpretation of seismic refraction data acquired during this study will be the focus of PhD dissertations for two graduate students. Sixty additional graduate and undergraduate students from schools in Georgia will participate in the field program and gain first-hand experience in acquiring active-source seismic data and learn more about the tectonic past of Georgia. Shillington, Lizarralde and Harder will give guest lectures in undergraduate classes at schools and universities in Georgia and public lectures in nearby towns during their scouting visits. These lectures will inform students and the community as a whole about the tectonics of their state and the implications for past climate changes. Taken together, our proposed educational and outreach activities will introduce a wide spectrum of students and the general public to geophysical investigations of the earth and their importance for understanding the linked evolution of the solid earth and climate systems.

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Summary of scientific motivation

The South Georgia Basin has been shaped by the most significant geologic events involved in building the eastern North American continent. It is the largest of a series of failed Mesozoic rift basins that formed during the breakup of Pangea. It straddles the Suwannee suture, the only well-defined remnant of the Alleghenian suture that joined North America and Gondwana, forming Pangea. The extensional structures of this rift basin thus reflect the contrasting rheologies of these juxtaposed lithospheric terranes and the suture that joined them. The South Georgia Basin also lies at the center of the Central Atlantic Magmatic Province (CAMP), one of the largest igneous provinces in the world, and thus holds an as yet unmeasured volume of this magmatic event as sills within the basin's sediments and intrusions within the crust. However, the South Georgia basin is buried beneath the Coastal Plain of the southeastern U.S., and very little is known about the crustal or lithospheric structure of this or any of the other rift basins that flank the U.S. Atlantic passive margin. Defining the crustal architecture of the South Georgia Basin is a scientifically rich goal, as this basin records the construction of the North American continent by amalgamation of exotic terranes, the initiation of extension that ultimately led to the breakup of Pangea, the involvement of sutures and other pre-existing structures in extension, and the distribution of CAMP magmatism and the interaction of shallow intrusions with basin sediments.

We propose an active-source seismic refraction study of the South Georgia Basin (Fig. 1) to image the crustal structure of this rift system, characterize the crustal expression of the Alleghenian Suwannee suture, understand the roles of sutures and other pre-existing structures on localizing deformation and magmatism during post-orogenic extension, and quantify the regional distribution and volumes of CAMP magmatism. This experiment is complementary to a recently funded EarthScope passive-source seismic experiment (see letter of support from Fischer) to study related problems on a lithospheric scale. Our study also includes a multi-faceted educational and outreach effort, which will engage undergraduate students from universities throughout Georgia.

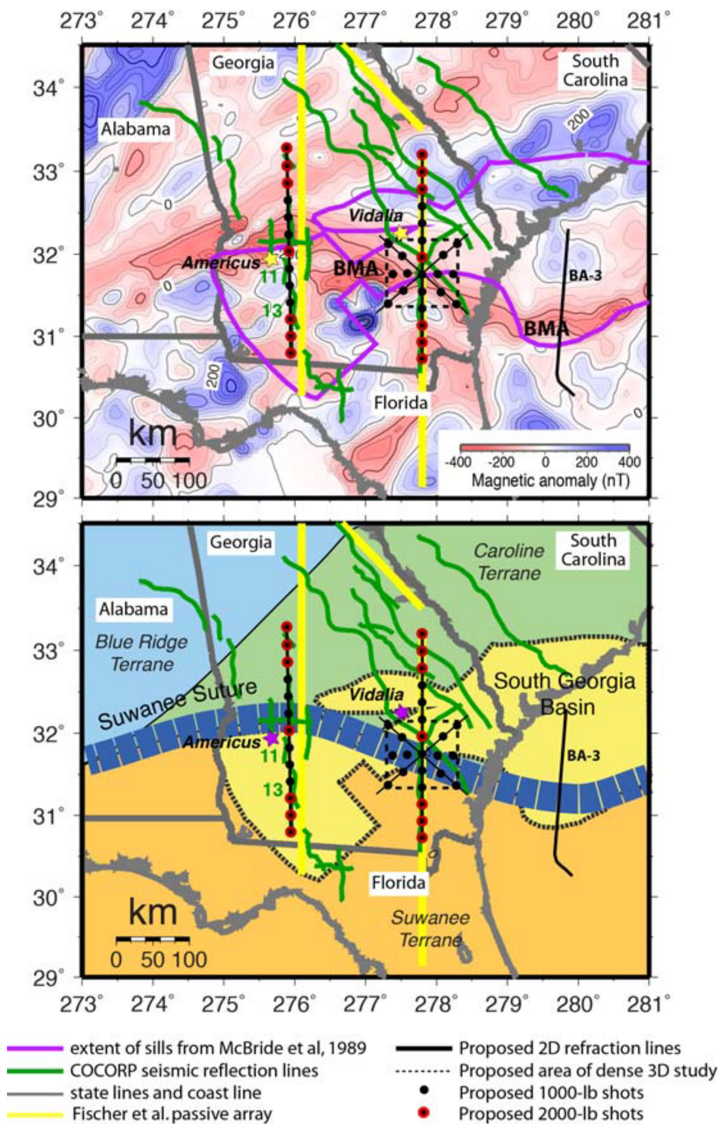


Fig. 1: *Existing and proposed datasets overlain on magnetic anomaly map (above) and a simplified representation of major tectonic elements based on potential-field and subcrop data (below). Purple line (above) and yellow region (below) delineate the inferred extent of South Georgia Basin [McBride et al., 1989]. Green lines show COCORP seismic reflection lines. Yellow lines are locations of a funded passive seismic array by Fischer et al. Black lines are proposed instrument locations. Black dots and black/red dots are proposed 1000-lb and 2000-lb shot locations, respectively. Dashed box shows dense 3D instrument deployment. BMA-Brunswick Magnetic Anomaly.*

History of this proposal

We submitted previous versions of this proposal to Earthscope in 2009 and 2010. The reviews and panel comments from both submissions were very positive, and their constructive comments helped us to improve the experiment design and refine the science. The primary differences between this submission and the previous one concern the budget and timing of the experiment. We have reduced the overall cost by proposing to do auger drilling for the shots (a relatively new approach) and redistributing costs between institutions. Additionally, we propose to conduct the experiment in two parts in Years 1 and 2 for logistical ease and to divide the project costs more evenly between years.

Introduction

Some of the most important unresolved questions in plate tectonics concern the formation and rupture of continents. How does the accretion of terranes contribute to the construction of continental lithosphere? What processes allow continental lithosphere to rupture? Both end-members of the plate tectonic cycle have fundamentally modified eastern North America, which was shaped by the closure and formation of a series of ocean basins throughout the Paleozoic and Mesozoic. These events created the Appalachian mountains, led to the emplacement of other accreted terranes that constitute eastern North America (Fig. 2), and resulted in the formation of a series of deep rift basins and the present-day rifted margin.

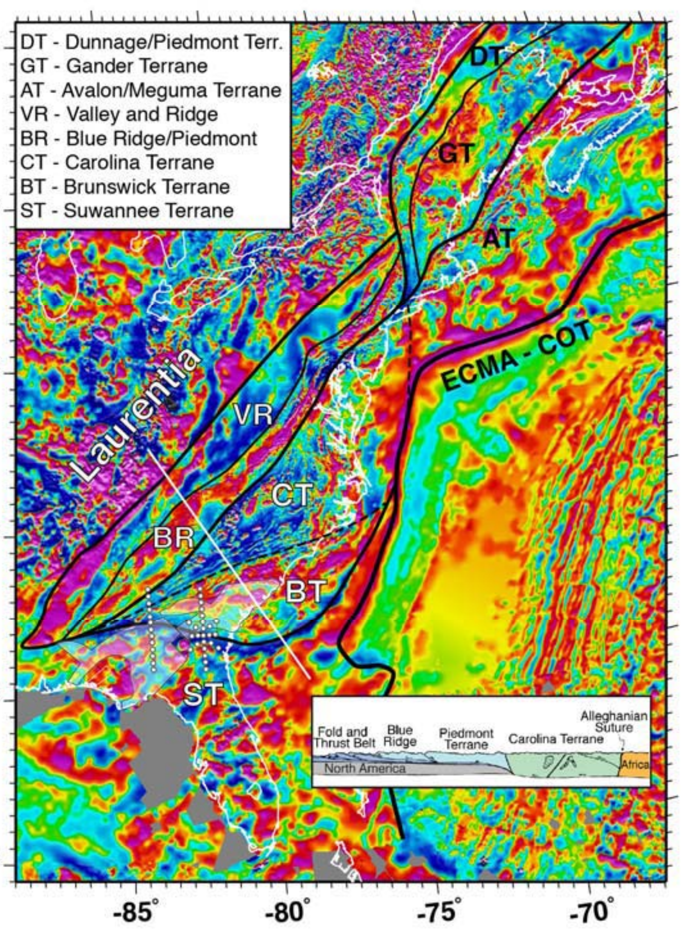


Figure 2*: Magnetic anomaly of eastern US. Note the series of terranes (black lines and text) that form the outer ~800 km of North America. ECMA: East Coast Magnetic Anomaly. BMA: Brunswick Magnetic Anomaly. Lightly shaded area shows South Georgia Basin, and white lines and dots are proposed experiment. Inset shows cross section from Hatcher [1989].*

Continental amalgamation and rupture are closely related to one another. Buck [2004] estimates that a force of ~30 TeraN may be required to rupture strong, cold, continental lithosphere, but only ~3-5 TeraN are available from plate tectonics [Bott, 1991]. Two mechanisms commonly proposed to overcome this apparent paradox are pre-existing structures and magmatism. Tectonic events leave behind faults in the upper crust and mechanical anisotropy in the mantle lithosphere [e.g., Tommasi and Vauchez, 2001]; less force may be required for rupture along these pre-existing structures. In addition, thick orogenic crust can be substantially weaker than adjacent areas [Dunbar and Sawyer, 1989]. Magmatism can lessen the force required for rupture by weakening the lithosphere and through magmatic diking, which requires less force than forming new faults [Buck, 2004]. Numerical modeling implies that if moderate amounts of magma are involved in early-stage extension, rifting can proceed during the later stages at tectonic forces similar to those from plate tectonics without further magmatism [Bialas *et al.*, 2010]. Although many rifts and passive margins formed by continental extension do appear to be accompanied by magmatism and/or occur along pre-existing weaknesses, the relative importance of these and other factors remain controversial. Magma-assisted rifting is clearly documented in active rifts such as Afar (East African Rift) [Kendall *et al.*, 2005;

Wright *et al.*, 2006] and Lake Baikal [Thybo and Nielsen, 2009]. However, other authors propose that early rifting in Afar was influenced more by pre-existing structures than magmatism [Keranen and Klemperer, 2008]. Rift basins next to rifted margins are useful places to assess the relative importance of these factors because they were not successful even though conditions necessary for rupture existed, as evidenced by extension proceeding to lithospheric rupture nearby.

Failed rift basins associated with lithospheric sutures are also useful places to study crustal formation. One of the primary means of building new continental lithosphere is the amalgamation of accreted terranes [e.g., Taylor, 1967], but many questions remain about the style of accretion, the modification of the accreted terranes during emplacement, and their preservation afterwards. How are terranes and the sutures between them manifested at depth in the crust and lithosphere? Are collisional zones "thick-skinned" or "thin-skinned"? Although the lateral extent of accreted terranes in the upper crust can often be estimated using a combination of potential fields data and field mapping, their geometry at depth remains almost completely unknown. How is shortening in the upper crust related to deformation in the mantle lithosphere? Are they coupled [Royden, 1996]? Crustal and lithospheric thickening during collision has also been postulated to cause delamination in many orogens [Sacks and Secor, 1990; Nelson, 1992]. Finally, how do accreted terranes respond to and exert an influence on subsequent tectonic events? In some orogens, features in seismic reflection profiles appear to be truncated at the base of the crust and are not associated with Moho topography, possibly implying modification in later tectonic events [e.g., Nelson *et al.*, 1985a]. Subsequent magmatism and deformation might be focused along the suture [McBride and Nelson, 1988; Sheridan *et al.*, 1993]. When extension follows collision, the effectiveness (or lack thereof) of sutures in localizing subsequent deformation is critical to determining where rifting occurs and thus how terranes are distributed between continental masses.

We propose to investigate the relationships between extension, sutures and magmatism with a seismic refraction experiment across the South Georgia Basin, a failed rift system that formed during late Triassic / early Jurassic extension prior to the breakup of Pangea and opening of the Atlantic Ocean.

Overview of tectonic and magmatic history

Eastern North America was built by a series of Paleozoic orogenies that were separated by rifting events. While the Appalachian mountains (allocthons obducted onto the Laurentian margin) are perhaps the most dramatic Paleozoic additions to North America, the Carolina and Avalon terranes are by far the largest additions. These exotic arc-affinity terranes were accreted during the Alleghenian orogeny as Laurentia collided with Gondwana at ~290 Ma, forming Pangea. The Carolina terrane appears to span hundreds of kilometers at a shallow level based on magnetic data (Fig. 2), but the size and distribution of this and other accreted terranes along eastern North America at depth in the crust and mantle lithosphere is very poorly known. Additionally, the nature of the contacts between terranes remains a subject of considerable debate. These orogenies may have juxtaposed terranes with highly variable rheologies. The architecture of sutures and rheological differences between juxtaposed terranes are important not only for the style of accretion, but these factors also likely exert a large influence on subsequent rifting events.

The latest (Alleghenian) orogeny was followed by widespread Mesozoic extension beginning at ~230 Ma [Traverse, 1987], which culminated in the breakup of Pangea and the opening of the Atlantic Ocean at least 30 m.y. later. The earliest phase of extension left behind deep abandoned rift basins along eastern North America, northwest Africa and northeast South America, inboard of the successfully rifted margin. The South Georgia Basin is the largest of these abandoned rifts (Figs. 1-3). Very little is known about the evolution of Mesozoic rifting that led to the abandonment of the inboard basins. It is not known, for example, how much extension these basins experienced, the style of that extension, or if all basins were active simultaneously with the eventually successful rift or if rifting jumped. The volume of magmatism and the roles of inherited structure and magma in basin formation are also not known, though both undoubtedly influenced rifting.

In contrast, a great deal is known about the structure of the U.S. rifted margin [e.g., Tréhu *et al.*, 1989; Holbrook and Kelemen, 1993]. Two well-studied transects offshore South Carolina and Chesapeake Bay

[Holbrook *et al.*, 1994a; Holbrook *et al.*, 1994b] suggest that both magmatism and crustal sutures played important roles in continental breakup. The continent/ocean transition in both of these locations is abrupt – juxtaposing extended and intruded continental crust with exceptionally thick new igneous crust of this volcanic passive margin [Tréhu *et al.*, 1989], and it is marked by the East Coast magnetic anomaly (ECMA) [Holbrook and Kelemen, 1993] (Fig. 2). The age of the ECMA is most likely the same as CAMP, based on a presumed correlation between the youngest sub-areal basalt flow imaged seismically at the margin [Oh *et al.*, 1991] and dated drilling samples of these basalts onshore [Lanphere, 1983; Hames *et al.*, 2000], and by the short duration of their emplacement at the margin [Lizarralde and Holbrook, 1997]. Thus, rupture was probably complete by ~200 Ma. The temporal coincidence between continental breakup and the very brief CAMP episode [Hames *et al.*, 2000] suggests a genetic link between them, but the geodynamic nature of this linkage is unclear.

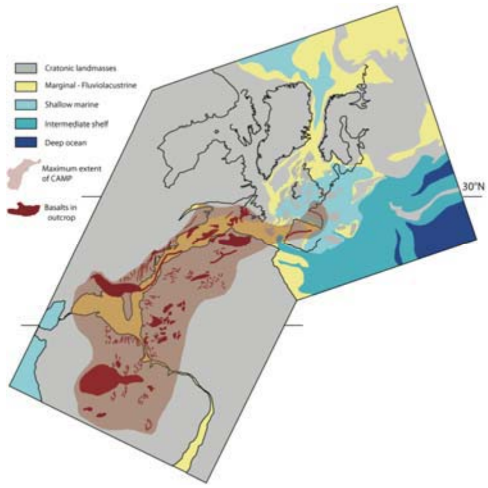


Fig 3. *Map showing reconstruction of North America, South America and Africa at ~200 Ma and the estimated distribution of shallow CAMP magmatism (van de Schootbrugge et al., 2009).*

The entire Mesozoic rifting event, not solely breakup, seems to have been influenced by structures formed during earlier orogenic events. At the large scale, the trend of onshore Triassic basins and the shape of the present-day margin suggest that early rifting was partially controlled by the ancient Iapetus rifted margin [Williams, 1984; Thomas, 2006] and by sutures from previous orogenies [Tommasi and Vauchez, 2001]. An influence of sutures on breakup is suggested by interpretations that a remnant of the Alleghenian suture in the mid Atlantic lies very near the continent/ocean boundary [Lefort and Max, 1991; Rankin, 1994] and the plausibility that the modern continent/ocean boundary could track the entire former Alleghenian suture between Avalonia and Gondwana, with the suture now masked by extensional deformation and voluminous breakup magmatism. At a smaller scale, shallow-dipping border faults that bound many Mesozoic basins are reactivated Paleozoic thrusts [Schlische, 1993], which first formed by 'thin-skinned' shortening [Cook and Vasudevan, 2006]. The manner in which pre-existing structures influenced later extensional features partly depends on the orientation of extension with respect to these older structures [Schlische, 1993]. The effectiveness of sutures in facilitating continental extension and rupture is likely to place strong controls on the location of final breakup and the distribution of terranes between continents after rifting. Over 800 km of accreted terranes were emplaced in the southeastern North American continent by a series of orogenies. Had Triassic rifting along the inboard basins been successful, the bulk of North American Paleozoic additions might have been lost, and a large portion of what later became the early American colonies (and Florida) would now be part of Africa.

<u>CAMP.</u> The Central Atlantic Magmatic Province, one of the largest igneous provinces in the world, records an apparently brief (~1 Ma) but voluminous episode of diking and volcanism at ~200 Ma across North America, Africa and South America [Hames *et al.*, 2000] (Fig. 3). As noted above, this magmatic event postdated the onset of extension by ~30 m.y., with seismic reflection profiles from the eastern U.S. clearly showing sills emplaced within and above thick, late Triassic – early Jurassic synrift sediments in many basins [Nelson *et al.*, 1985b; McBride *et al.*, 1989] (Figs. 4 and 5); and it appears to have been roughly coincident with continental breakup.

The source of the CAMP magmatism remains an open debate. Magmatism due to extensionally driven decompression melting is expected during rifting [McKenzie and Bickle, 1988], but the extent of CAMP magmatism is extraordinary and seems inconsistent with apparent amounts of stretching. Moreover, the thicknesses and seismic velocities of magmatic underplates beneath the eastern U.S. margin [Holbrook *et al.*, 1994a; Holbrook *et al.*, 1994b] likely require some form of compositional or thermal anomaly in the mantle using the criteria of Holbrook *et al.* [2001] and Korenaga *et al.* [2002]. A number of geodynamic mechanisms have been proposed to explain CAMP. The simplest of these is a mantle thermal anomaly due to a hot plume [White and McKenzie, 1989], but several lines of reasoning argue against a plume: 1) there is no clear track from a known hotspot; 2) variations in crustal thickness and dike orientations do not exhibit a radial pattern [Holbrook and Kelemen, 1993; McHone, 2000; Beutel, 2009]; 3) temporal patterns in magmatism cannot be explained by a plume [Oh *et al.*, 1995]; and 4) basalts from CAMP can be grouped into several compositionally distinct subsets, which would not be expected for a plume [McHone, 2000]. Alternative explanations include the thermal insulation effects of the Pangea supercontinent [Coltice *et al.*, 2007] and combinations of the effects of orogenic collapse, thermal insulation and edge-driven convection [Hames *et al.*, 2000; Anderson, 2005]. Our current knowledge of the crustal distribution of CAMP magmatic additions and their relationship to largely unknown basin crustal structure is insufficient to distinguish between these competing hypotheses.

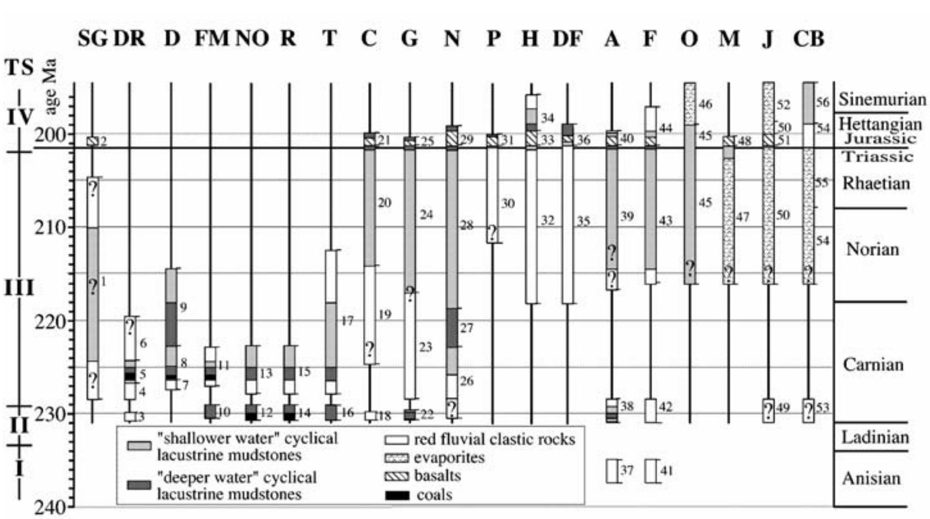


***Fig. 4**: Ages, facies, and formations in eastern North America basins from south (left) to north (right) [Olsen, 1997]. SG: South Georgia, DR: Deep River, D: Danville, FM: Framville, NO: Norfolk, R: Richmond, T: Taylorsville, C: Culpeper, G: Gettysburg, N: Newark, P: Pomperaug, H: Hartford, DF: Deerfield, A: Argana, F: Fundy, O: Orpheus, M: Mohican, J: Jeanne d'Arc, CB: Carson. Note: Basalts overlie late Triassic synrift sediments.*

***Rifting, magmatism, CO2, climate and extinctions**.* The CAMP magmatic event appears to have occurred very close to or at the Triassic-Jurassic boundary, which was associated with one of the largest known biotic crises in Earth's history [Raup and Sepkoski, 1982]. There was a turnover of approximately 80% of marine invertebrate taxa as well as a major ecosystem collapse onshore at this boundary [van de Schootbrugge *et al.*, 2009]. Coordinated dating of basalts and bio- and magneto-stratigraphy of sedimentary sections from this interval in Morocco indicates that CAMP straddles the Triassic/Jurassic boundary and thus might be the cause of extinctions [e.g., Marzoli *et al.*, 2004]. Turnover of marine biota appears to be caused by carbon-cycle perturbations, warming, and green algal blooms, while turnover in plant species might additionally be caused by soil acidification, warming and atmospheric change [van de Schootbrugge *et al.*, 2009]. The emplacement of large igneous provinces can influence climate in a couple of ways: CO_2 and SO_2 degassing from sediments and crust intruded by magmas can result in warming [e.g., Svensen *et al.*, 2004; Svensen *et al.*, 2009], or an increase in particles introduced to the atmosphere by volcanic eruptions can cause cooling [e.g., Briffa *et al.*, 1998]. The link between CAMP and climatic and biotic changes at the Triassic/Jurassic boundary remains controversial; other authors argue that CAMP postdated the T-J boundary by ~600 kyr [Whiteside *et al.*, 2007].

South Georgia Basin. The South Georgia basin comprises a number of sub-basins buried beneath the Coastal Plain that, together, represent one of the largest rift basins to form during Mesozoic extension before breakup. This system was located atop a major suture, near the triple junction between North and South America and Africa and near the center of CAMP (Fig. 3). The sub-basins of the rift are bound by border faults that span southern Georgia and eastern Alabama; they have depths of up to 7 km and widths of 100 km [McBride, 1991]. Many of the border faults are reactivated Paleozoic thrusts [Schlische, 1993].

The South Georgia basin is closely associated with what is believed to be a major Alleghenian suture, the Suwannee suture (Fig. 2), that joined North American lithosphere (the Carolina terrane) with a Proterozoic Gondwanan terrane of pan-African affinity (the Suwannee terrane) left behind during the breakup of Pangea based on the geochemistry and ages of sub-crop basement samples [Smith, 1982; Opdyke *et al.*, 1987]. This suture is marked (or very nearly marked) by the prominent E-W trending negative Brunswick magnetic anomaly (BMA), though ideas differ on exactly how the suture is manifest in the anomaly [e.g., Nelson *et al.*, 1985b] (Figs. 1 and 2).

The Suwannee suture appears to bound the northern edge of the South Georgia basin to the west and the southern edge of the basin to the east (Fig. 1), but it is unclear what this might mean. The formation of the basin involved reactivated Paleozoic thrusts along its northwestern edge, but it is unknown how lithospheric extension and magmatism might have been affected by the Suwannee suture, which is believed to be a deeply rooted [McBride and Nelson, 1988]. There also appears to be a close spatial association between the extent of extrusive magmatism related to CAMP and the South Georgia basin at a shallow level. Drilling and seismic reflection data indicate that CAMP sills overlie part of the Triassic-Jurassic synrift section within the basin (Figs. 4 and 5), and the overall estimated lateral extent of sills is similar to that of the basin itself. A relationship with CAMP is also suggested by magnetic anomalies. The South Georgia basin north of the BMA lies exclusively within the southern portion of the Carolina terrane that is often referred to as the Brunswick terrane due to its a distinct magmatic anomaly pattern; the large positive magnetic anomalies within this geophysically defined sub-terrane are believed (and in many cases have been shown) to be due to Mesozoic mafic intrusions. However, despite these various suggestive correlations, the genetic relationships between Mesozoic extension, magmatism, and the Alleghenian suture remain almost completely unknown.

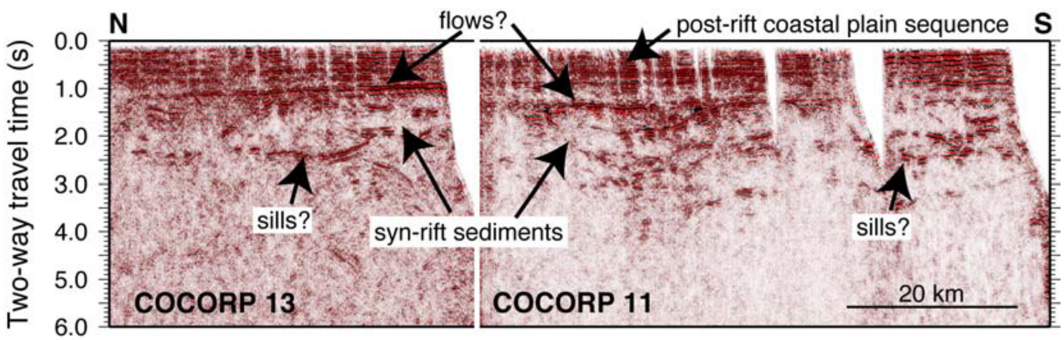


***Fig 5**. Seismic reflection data from COCORP [Nelson et al., 1985b; McBride et al., 1989]. Note the thick synrift section below a bright horizon that likely represents a flow and the numerous cusp-shaped reflections within the synrift section that appear to be sills.*

The relationship between extension, magmatism and sutures in South Georgia remains poorly understood in part due to uncertainties in the interpretation of key geological and geophysical features and uncertainties in the configuration of the basin itself. The extent of the basin is constrained by cores [Chowns and Williams, 1983], COCORP seismic reflection profiles and potential field data [e.g., McBride and Nelson, 1988]. Drill holes provide detailed point information, but are too sparsely spaced to fully delineate the basin. Moreover, the top of basement is often poorly imaged on COCORP lines, possibly due to poor signal penetration beneath lava flows and sills (Fig. 5). Thus, though many datasets exist to help pose and address outstanding questions regarding rifting and magmatic processes that shaped the eastern U.S., key datasets remain missing. They key missing dataset needed to resolve relationships between the Suwannee suture and Mesozoic rifting and magmatism is crustal-scale seismic refraction data. Crustal-scale refraction data have never been acquired across the South Georgia basin or, surprisingly, from anywhere within the accreted Carolina and Avalon terranes, with the exception of quarry-blast recordings to offsets of ~140 km from near the edge of the Coastal Plain in Georgia [Hawman, 1996]. Crustal-scale refraction data are required to determine the basic parameters of this rift system and it's relationship to the Alleghenian suture, including the spatial extent of the rift, the magnitude and pattern of crustal thinning, the volume and distribution of rift-related and CAMP magmatism, crustal thickness and seismic-velocity contrasts across the suture, and the seismic properties of the suture itself, including it's wide-angle reflectivity and dip. With these new data, along with observations from the Transportable Array and the passive-seismic deployment (SESAME) led by K. Fischer (Fig. 1, see supporting letter), which targets the lithospheric-scale expression of these processes, we believe substantial progress can be made in understanding the continental evolution of the eastern U.S.

Scientific questions and intellectual merit

The proposed work targets poorly understood processes and events that have built and shaped the eastern North American continent. Eastern North America comprises a series of exotic accreted terranes, the most recent of which was added in the Alleghenian orogeny at ~290 Ma, completing the Paleozoic construction of Pangea. Extension began around ~230 Ma, leading to the formation of a series of basins along the present-day margins of the Atlantic ocean, but rifting was not successful in rupturing Pangea until some 30-40 m.y. later in the Jurassic, with breakup apparently occurring along the Alleghenian Gondwana/Avalonia suture and, also apparently, aided by the voluminous CAMP magmatism.

The question at the core of this proposal is**:** *Why did Triassic rifting fail and Jurassic rifting succeed?*

This question echoes what remains the overriding question of rifting studies, generally, namely what conditions are required to successfully rupture continental lithosphere. This question, and rift-related questions generally, are intertwined with continent-building processes, not only because post-orogenic rifting controls what orogenic additions remain in place, but also because collisional tectonics place controls on rifting via the juxtaposition of terranes of contrasting rheologies, the emplacement of presumably weak suture zones, and delamination events that may trigger extension and magmatism. Untangling these processes to address specific questions is difficult, but we believe that the proposed location provides an excellent opportunity to make substantial progress.

We propose to acquire a crustal-scale seismic refraction dataset across the South Georgia basin and the Suwannee suture to address basic questions about the crustal structure of the basin, its formation, and its role in the breakup of Pangea and the emplacement of CAMP. Our proposed work addresses the specific questions of how a major lithospheric suture, the Suwannee suture, and magmatism, including the voluminous CAMP event, influenced the evolution of this failed rift system. Below we outline these questions, distinguishing the roles of the suture and magmatism while realizing that the effects of these factors are probably interconnected. A summary of possible end-member crustal configurations beneath our proposed transects is shown in Fig. 6, and we refer to these conceptual models in the questions outlined below. In addition, we describe related questions concerning the origin of CAMP and the potential for CAMP magmatism to have influenced atmospheric greenhouse-gas concentrations.

What is the role of crustal sutures in controlling extension and magmatic emplacement?

The Alleghenian suture between the accreted Avalonia terranes and Gondwana may have had everything or nothing to do with controlling the locus of Pangean breakup. Existing observations across the modern margin indicate that, north of Florida, both extension and magmatism were highly localized near the current continent/ocean transition, now marked by the ECMA (Fig. 2). It is plausible that this localization occurred along and was due to an Alleghenian suture that followed the trace of the ECMA, but it would be very difficult to test this notion or to assess the role that the suture may have played in localizing extension and magmatism because the voluminous breakup magmatism obscures most other crustal signals. Fortunately, the well defined presence of the Alleghenian Suwannee suture in southern Georgia, and the fact that this suture is bisected by the large Triassic South Georgia Basin, provides an ideal situation for assessing the influence that this and similar sutures can have on rift evolution.

<u>We hypothesize</u> that a deeply rooted lithospheric suture affects rift evolution by enhancing structural and magmatic localization, both of which promote advective heating (via mantle upwelling and melt transport) and so a positive feedback leading to lithospheric rupture. There are several means by which the Suwannee suture might have promoted localization. The suture may have represented a weak zone that acted as a dislocation surface. In this case, we would expect asymmetric basin structure about the suture, with the locus of extension rooted in the suture itself and modest extensional deformation and

crustal thinning in the upper plate, which would be the Suwannee terrane if the suture is south dipping, as suggested by COCORP profiles [McBride and Nelson, 1988]. Alternatively, the suture may primarily represent a boundary between rheologically distinct terranes. It is plausible that the young, hot arc components of the Carolina terrane would be weaker than the older, colder material of the juxtaposed Suwanee terrane. In this case, we would expect distinct styles of extensional deformation in the two terranes, with deformation in the Carolina terrane tending more towards distributed, wide-mode rifting. Localization would be accomplished in a similar fashion to that in the Walker Lane/Owens Valley region of the western U.S., where Basin and Range style extension terminates again the resistant Sierras. Finally, localization may occur solely due to focusing of melt along the suture, and we would expect substantial magmatic additions along and around the suture and consequent weak-fault behavior as described above. All of these cases would predict crustal structure similar to Models I and II (Fig. 6), with a close association between patterns of extension and the suture as well as some degree of asymmetric extensional deformation across the suture.

<u>*Alternatively,*</u> the Suwannee suture may have had little to no influence in localizing either extension or magmatic emplacement. This null hypothesis predicts no discernable relationship between either extensional deformation or the distribution of Mesozoic magmatic additions and the suture, and we would expect crustal structure similar to Models III or IV.

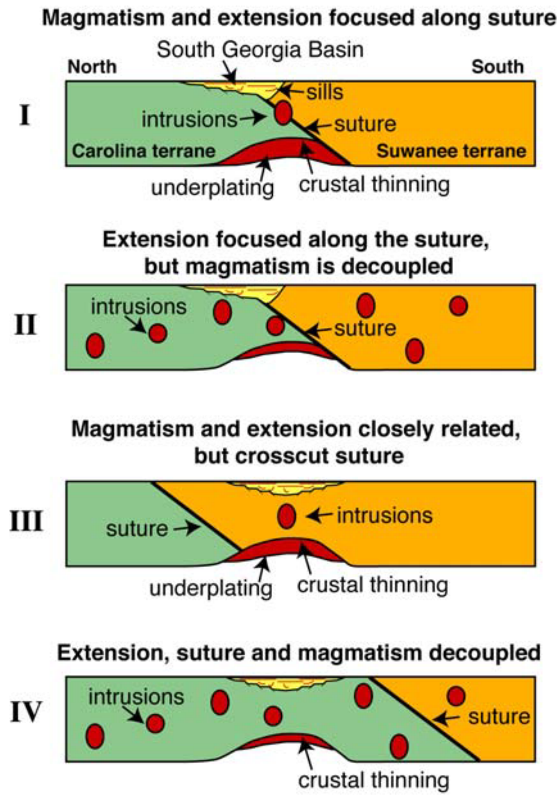


Fig. 6*. Cartoon illustrating end-member relationships between extension, magmatism, the suture, and contrasts in rheology associated with the suture.*

The proposed seismic refraction experiment provides the means to distinguish between our hypothesis and the alternative null hypothesis and to distinguish between the various suggested mechanisms of localization in the case that the suture does play a role in localizing extension. The crustal-scale seismic velocity structure resulting from the experiment will reveal detailed basin structure, crustal thinning profiles, and estimates of bulk mafic magmatic additions, enabling comparisons of crustal thinning, basin and crustal asymmetry, and magmatism to the location of the suture with depth in the crust. Variations in crustal thinning can be estimated from variations in crustal thickness, and mafic intrusions can be identified by their relatively high seismic velocity [e.g., Kelemen and Holbrook, 1995; Korenaga et al., 2002; Keranen et al., 2004](Fig. 7). We expect that the suture will be manifest by lateral changes in velocity structure, and it may also have distinct wide-angle reflectivity. We will also use existing coincident COCORP profiles to refine our identification of magmatic intrusions and their relationship to the suture. Previous studies indicate that these juxtaposed terranes have distinct crustal reflectivity patterns [Peavy et al., 2004], and bright mid-crustal reflections have been interpreted to represent magmatic intrusions [Barnes and Reston, 1992]. The spatial relationships between extension, magmatism and the suture may prove indicative of, for example, vertical magmatic emplacement above thin, extended crust versus subvertical transport of melt along a suture.

How did magmatism respond to and influence continental rifting in the South Georgia Basin?

Outcrops, drilling and existing seismic data indicate that numerous sills were emplaced over a relatively short period of time (1 m.y.) in the South Georgia Basin and other rift basins in the eastern U.S. at ~200 Ma as part of CAMP [Hames et al., 2000]. These sills appear to have been emplaced above and within the synrift sequence, implying that this magmatism postdated much of the extension that formed the

South Georgia Basin [McBride et al., 1989] (Fig. 4). Such a long period of time (30 m.y.) between the onset of extension and this final magmatic episode raises a number of questions. Was there substantial extension-driven magmatism during Triassic rifting? If yes, did it influence basin evolution and was CAMP a culmination of this rift-related magmatism; if no, did the lack of syn-rift magmatism inhibit successful lithospheric rupture? While it will be difficult to fully answer these questions with the proposed experiment, we can provide strong tests to the following hypotheses based on the association of crustal thinning and estimated magmatic additions:

1) Magmatism was at least partially a consequence of extension. Distributed extension beginning in the Triassic resulted in crustal thinning and decompression melting, possibly enhanced by edge-driven convection [e.g., Mutter et al., 1988; Holbrook and Kelemen, 1993] and incubation of the mantle beneath a supercontinent [e.g., Gurnis, 1988; Coltice et al., 2007]. Wide-mode rifting within the Carolina terrane, as suggested above, might lead to lithospheric thinning localized only at the edges of the weak terrane. Substantial syn-rift magmatism would thus be delayed until sufficient thinning had occurred, and the greater volume of this magmatism would be localized along terrane boundaries. The CAMP event might represent, in some sense, the culmination of prolonged extension and magmatism. This hypothesis would predict crustal structure similar to Model I, with underplating and intrusion focused primarily at the suture, which represents a rheologic contrast between the juxtaposed terranes.

2) Magmatism accompanied and facilitated Triassic rifting, but total extension was insufficient for continental rupture. This hypothesis predicts crustal structure similar to Model III, with a distinct relationship between crustal thinning and magmatic intrusion and underplating. This signal would be overprinted by distributed CAMP intrusions, with the CAMP event not related to lithospheric thinning.

3) Magmatism and rifting were decoupled. Magmatism postdated the majority of extension in the South Georgia rift and thus had little impact on its formation. This hypothesis predicts structure similar to Models II and IV, which show no relationship between the distribution of magmatic additions and crustal thinning. As with (2), CAMP is caused by a separate event, such as the arrival of a plume or slab/lithospheric delamination that is not directly related to the rifting process.

An association between inferred magmatic additions and crustal thinning (hypotheses 1 and 2) would indicate that Triassic rifting was accompanied by syn-rift magmatism. Such an association would suggest that crustal thinning accompanied by an "imageable" volume of magmatism (certain to be larger than a small number of through-crustal dikes) is insufficient to result in successful lithospheric rupture. Alternatively, crustal thinning without substantial associated magmatism (hypothesis 3) would be consistent with the notion that significant syn-rift magmatism is required for successful lithospheric rupture and would point to either insufficient extension or anomalously magma-poor extension as explanations for unsuccessful Triassic rifting.

Tests of these hypotheses will be based on crustal thinning estimates, estimates of expected syn-rift melting for measured amounts of crustal thinning, and estimates of the volume and distribution of magmatic intrusion beneath the basin and in the surrounding crust based on the seismic velocity models along each of the profiles. The expected relationship between lithospheric extension, as inferred from measured crustal thinning, and the predicted volume and composition of syn-rift, decompression melts can be estimated from existing models [e.g., Bown and White, 1995; Armitage et al., 2008] under varying assumptions for mantle potential temperatures and rift durations. The delineation of crustal intrusions is more difficult than measuring crustal thickness, but the Hawman [1996] quarry-blast results from the Carolina terrane and borehole samples from the Suwannee terrane suggest that the upper crust of both of these terranes is tonalitic. Pervasive to massive gabbroic intrusion into the upper crust over spatial scales of 10 km, and perhaps less, should be easily identifiable given our ~20-km shot spacing. Imaging lower crustal intrusions may be more problematic, as limited seismic measurements suggest gabbroic seismic velocities within the lower crust of the Carolina terrane (6.8-6.9 km/s) [Hawman, 1996] and the Suwannee terrane offshore from near the shelf edge (6.7-6.8 km/s) [Lizarralde et al., 1994] (Fig 2). However, melts generated during either the earliest stages of extension or from anomalously hot mantle are both more mafic than gabbro due to higher average pressures of melting [White and McKenzie, 1995].

The seismic velocities of intrusions from these melts are expected to range from 7.0 km/s to as much as 7.5 km/s, and so sufficiently large lower crustal intrusions or underplates would be discernable.

What conditions and processes led to the emplacement of CAMP?

The origin of CAMP has been debated for the last 20 years and remains controversial. Understanding the origin of CAMP is important for a number of reasons. It is important to the science questions of this proposal because CAMP appears to be nearly synchronous with continental breakup, and it contributed voluminous magmatic additions to the continental margin and perhaps the surrounding accreted terranes. CAMP may have facilitated or substantially driven continental rupture while at the same time stabilizing the margin via a deep, low-density depleted residue of melting. If CAMP and similar large igneous provinces (LIPs) at continental margins are genetically linked to rifting processes, then our understanding of rifting will not be complete until the geodynamic origin of these LIPs is understood. Additionally, the formation of LIPS are dramatic events that have been hypothesized to affect global temperature and atmospheric chemistry and thus implicated in mass extinctions [e.g. Coffin and Elholm, 1994; Lo et al., 2002; Saunders, 2005], and yet LIP formation remains the sole major volcanic and crust-forming process for which we lack a generally accepted, systematic geodynamic model. For the origin of CAMP in particular, a number of models have been proposed, including a plume [e.g., May, 1971; White and McKenzie, 1989], incubation beneath a supercontinent [e.g., Gurnis, 1988; Coltice et al., 2007], edge-driven convection arising from rifting [e.g., Mutter et al., 1988; Holbrook and Kelemen, 1993], possibly enhanced by changes in the orientation in stress field [Beutel, 2009], and lithospheric delamination with subsequent melting of crustal components [Anderson, 2005]. While our proposed work is unlikely to end the debate on the origin of LIP formation, our new observations from near the center of CAMP will help distinguish between competing hypotheses for the formation of this particular LIP.

The volume, distribution and velocity structure of magmatic additions to the crust, can be used to make strong inferences about the dynamics of mantle melting responsible for CAMP. The volume and seismic velocity of melt generated by passive, extension-driven mantle upwelling can be predicted from the amount of crustal thinning for a given mantle potential temperature and rift duration. If the measured volume and seismic velocity of magmatic additions are greater than predicted for passive upwelling given the measured crustal thinning, than some other mechanism, such as anomalous temperature or active upwelling (e.g., edge-driven convection) would be implicated. These mechanisms can similarly be distinguished based on volume/velocity relationships. Excess crust produced by increased mantle temperature will have a higher seismic velocity than that produced by active upwelling because the former would have higher average pressures of melting. These relationships have been used to estimate the influence of mantle temperature on the formation of the North Atlantic volcanic margins [Holbrook *et al.*, 2001; Korenaga *et al.*, 2002; White *et al.*, 2008], which has been influenced by the Iceland hotspot.

The distribution of crustal magmatic additions in combination with volume/velocity relationships can be very diagnostic. Magmatic additions localized beneath thinned crust, with volumes consistent with normal-mantle potential temperature and gabbroic seismic velocity (6.8-7.2 km/s) would suggest passive, extension-driven melting. If these localized additions or magmatism localized near terrane boundaries were thicker than predicted from passive upwelling but yet had gabbroic seismic velocities, then edge-driven convection would be implicated. Broadly distributed magmatism with ultra-mafic seismic velocities (>7.2 km/s) would implicate a hot-mantle (e.g., plume or incubation) source for melting, while broadly distributed magmatism with gabbroic or slower seismic velocity would suggest delamination as the mechanism driving magmatism. These diagnostic seismic signatures of the geodynamic origin of melting from near the center of CAMP can be combined with similar observations from across the margin [e.g., Holbrook and Kelemen, 1993; Lizarralde et al., 1994] and other observations, including dike orientations and compositions [McHone, 2000; Beutel, 2009], to provide tests of the various hypotheses for the geodynamic origins of CAMP and so move our understanding of this important event forward.

What is the volume and distribution of intrusions and flows in the sediments of the South Georgia Basin, and what was the resulting potential for degassing?

The degassing of sediments intruded by magmas can release CO_2 and SO_2 into the oceans and atmosphere and cause significant environmental change. Biotic crises at the Paleocene-Eocene Thermal Maximum (PETM), the Triassic-Jurassic boundary and the Permian-Triassic boundary have been attributed to climate change caused by this mechanism [Svensen *et al.*, 2004; Svensen *et al.*, 2009]. A secondary objective of this proposal is to provide information that can be used to assess the magnitude of degassing that may have occurred due to intrusion of magmas into basin sediments during rifting and/or CAMP. Our study will quantify the volume of magma intruded into sediments of the South Georgia Basin, the largest of the abandoned rift basins flanking the eastern North American margin. We hypothesize that the volume of mafic intrusions into this basin, primarily as sills, is most likely substantial given the location of the basin with respect to CAMP, the identification of very large (~20 km across) shallow sill complexes in magnetic anomaly maps verified by drilling [Daniels *et al.*, 1983], and the abundant bright reflections in COCORP profiles that are likely to represent sills and flows (Fig. 5).

Our work will not provide definitive constraints on degassing, but it constitutes the requisite first step towards evaluating the possible importance of this mechanism in climate dynamics due to CAMP and will provide a point of comparison to other magmatic events being studied for their climate impacts [Svensen *et al.*, 2004; Svensen *et al.*, 2009]. By combining constraints on the overall amount and distribution of magmatic material intruded into basin sediments using the 3D box along the eastern line (Fig. 1) with published constraints on sediment lithologies and contact aureoles from cores [Chowns and Williams, 1983], it is possible to begin to assess the volume of sediment that might have undergone heating and degassing as a result of magmatic intrusion and thus make first-order estimates on the amount of CO_2 and SO_2 that may have been released.

Proposed data acquisition

Experiment description and rationale

To address the questions posed above, we propose to acquire wide-angle seismic refraction data along two ~275-km-long profiles oriented roughly N-S and crossing the South Georgia basin, the Suwannee suture and the mapped region of sills [Chowns and Williams, 1983; McBride *et al.*, 1989](Fig. 1). These lines will delineate variations in crustal thickness and velocity structure within the basin and to the north and south, magmatic underplating and intrusion along the lines and the subsurface expression of the Suwannee suture. We plan to use a combination of 2000 lb and 1000 lb shots along each of these profiles as the sources. Shots will be spaced at ~20 km. The outer 3 shots and the center shot on each line will be 2000 lb, while the rest will be 1000 lb (Fig. 1). We propose to densely instrument each line with single-channel RekTek 125A seismometers ("Texans") spaced at 275 m, yielding a total of 1000 seismometers along each profile. Larger shots are required at the ends of the lines to ensure deep penetration and recordings to large offsets, while smaller shots (1000 lbs) are sufficient near the centers of the lines. The large source-receiver offsets on these profiles will provide reversed ray coverage of the Moho and upper mantle, which will enable us to produce well constrained models of the entire crust.

The third component of our study is a 100x100km 3D box centered on the basin along the eastern profile. The purpose of the box is to constrain the 3D distribution of magmatic intrusions in the basin and upper crust in this area. 3D ray coverage will be achieved in this box with a grid of 1000-lb shots spaced at ~30-40 km and by deploying Texans along the diagonals of the box at a spacing of 500 m and along the edges of the box at a spacing of 1 km, yielding a total of 1000 Texans in the box. We plan to acquire data in the box and along the eastern profile simultaneously to maximize the distribution of azimuths and offsets within the 3D box (i.e., all Texans will be deployed during all shots on the eastern profile and box). A 3D experiment layout with sparser instrument and shot spacing and a larger box in Ethiopia yielded excellent constraints on the distribution of intrusions in an active rift system [Keranen *et al.*, 2004](Fig. 7).

Both proposed 2D lines are coincident with COCORP profiles, which provide constraints on the geometry of the sedimentary basin and other shallow structures. The west profile coincides with COCORP lines 12, 11, 13, 21, and the east profile coincides with COCORP lines 16 and 18. Likewise, the diagonals of the box coincide with COCORP lines 9 and 17. SEG-Y files for processed profiles and raw shot gathers are available online. Like the coincident COCORP lines, our proposed profiles lie close to roads, allowing for efficient deployment of seismometers and convenient access to shot sites for drilling and shooting.

Experiment logistics

The experiment layout described above will involve the deployment of 1000 Texans on the western profile and 2000 Texans on the eastern profile and box. It includes 13 shots along each line and an additional 12 shots within the box on the eastern profile, for a total of 38 shots. The scale of the experiment will require a series of scouting visits to the area during the first six months of the project (Table 1). We propose to divide the experiment into two parts to make the logistics more manageable and to distribute the project costs more evenly between years. We will drill and shoot the western profile during Year 1 and the eastern profile and box in Year 2.

<u>Scouting visits</u>: We propose three trips to the area between 1 July 2012 and 1 December 2012 to (1) scout shot locations and obtain permission from landowners, (2) inspect shot sites with explosives companies and drilling companies, and (3) meet with county and state government officials to discuss the experiment, obtain permits and identify field centers in Americus and Vidalia, GA. Shillington, Lizarralde and Harder will give lectures in classes at the University of Georgia, Georgia Southwestern State University and other Georgia colleges during and prior to the experiment (see supporting letters from R. Hawman and S. Peavy).

Table 1: *Timeline of proposed data acquisition.*

			Days
Year 1	**Scouting** July - Dec 2012	Scout shot locations, obtain permissions	14
		Inspect sites with drillers/explosive reps	7
		Permitting for experiment with gov't	7
	West profile Jan - Feb 2012	Drilling, two months	
		Oversight: PI visits and local bird-dog	6
	Experiment-West profile Mar. 2012	PI's arrive and mobilze in Americus	1
		Students contact land owners, PASSCAL prepare instruments	6
		Deploy 1000 Texans	2
		Detonate shots	2
		Recover Texans	2
		Demobilization	1
		total	**14**
Year 2	**East profile & box** July - Aug. 2012	Drilling, two months	
		Oversight: PI visits and local bird-dog	8
	Experiment-East profile & box Sept. 2012	PI's arrive and moblize in Vidalia	1
		Students contact land owners, PASSCAL prepare instruments	9
		Deploy 2000 Texans	2
		Detonate shots	3
		Contingency day	1
		Recover Texans	2
		Demobilization	2
		total	**19**

<u>Drilling and acquisition</u>: In January - February 2013, drilling companies will auger drill holes at each of the shot sites on the western profile. We estimate that it will take ~6-8 hours to drill each of these holes. We propose to acquire data along the Western profile in March 2013. We will coordinate the timing of our acquisition with spring break so that undergraduate students are available to participate in the field party. The western profile is simpler since it involves only 13 shots and 1000 Texans as well as a smaller field party, and it thus make sense to shoot this profile first. We will set up a field station that will serve as the staging area for instrument deployments and recoveries in Americus, which is close to the western profile (Fig. 1). We will rent vacant retail space or a hotel conference center for this purpose.

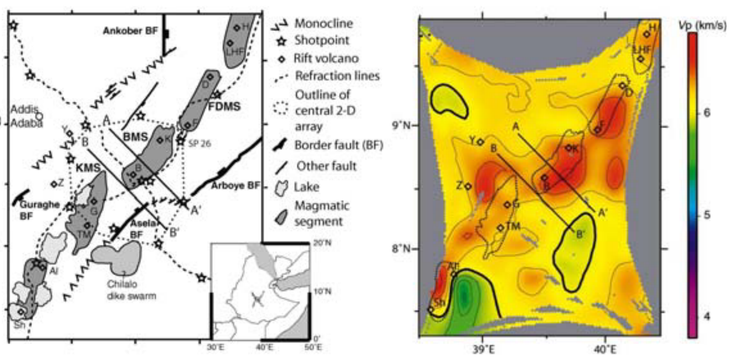
For the eastern profile and box, drilling will take place in July – August 2013, and we will acquire data in late August – early September 2013. We will plan this acquisition to occur before the end of the summer recess so that students can participate. The staging area for the eastern profile will be in Vidalia (Fig. 1).

Before acquisition on both profiles, a subset of the field party will go in teams to visit landowners of property where we plan to deploy seismometers to seek permission (Table 1). We estimate that this will take 6 days on the western profile and 9 days on the eastern profile/box. During this time, PASSCAL engineers will prepare Texans for deployment. Next, the field party will deploy seismometers along the profile in teams of two, each equipped with a truck, GPS, and other necessary equipment. We estimate that each team can deploy 4-5 Texans an hour, and thus 80 seismometers total in two days. Based on these numbers, ~15 teams are needed to deploy 1000 Texans on the western profile, and ~30 teams are needed to deploy 2000 Texans on the eastern profile/box. Next, explosives companies will load pre-drilled holes with explosives and detonate shots, primarily at night. This will minimize cultural noise in the data, disturb the fewest people, and enable us to clean up the sites before the next day. Finally, the field party will recover the Texans, which will require two days.

To assemble the large field party needed for this experiment, we plan to draw on graduate and undergraduate students from schools in Georgia as well as a few students from LDEO, WHOI and UTEP. Rob Hawman at the University of Georgia and Sam Peavy at Georgia Southwestern State University will help the proponents identify interested students at their schools (see supporting letters). Guest lectures in classes at various Georgia schools will also alert students of the opportunity for a field experience and enhance the educational component. Both Shillington and Lizarralde have extensive contacts in Georgia that can be used to find interested students. Shillington grew up in Atlanta and completed her undergraduate work at the University of Georgia, and Lizarralde was a faculty member at Georgia Tech for 5 years. We have budgeted for travel and subsistence costs for the entire field party.

Proposed data analysis

The acquisition described above will result in a substantial volume of seismic refraction data. LDEO and WHOI will share the majority of the analysis, with help from UTEP. The primary objectives of data processing are two-fold: 1) imaging of 2D variations in overall crustal thickness and velocity structure along both profiles and 3D variations in the box, and 2) imaging of velocity structure within the basin sediments and underlying upper crust. The former will be used to test hypotheses regarding the relationship between extension, magmatism and the suture. The latter will be used to quantify the volume of basalts intruded into the basin both for understanding the distribution of intrusions with respect to extension and the suture, and for evaluations the potential for CO_2 and SO_2 degassing as a secondary target. Below we describe the processing and modeling strategies we plan to employ to meet these complementary objectives.



Keranen et al., *Geology*, 2004

Figure 7: *Example of 3D seismic refraction experiment from Ethiopia [Keranen et al., 2004]. Left: experiment map. Right: Horizontal slice at 10-km depth through the P-wave model. The size of our proposed 3D box is smaller and contains denser shot and receiver spacing.*

Prior to modeling, we will process the data to facilitate phase identification. Time-variant frequency filtering, deconvolution, trace normalization and time and offset varying gains will be applied to all shot gathers. Static corrections with first arrivals may also be applied to assist in identifying secondary phases.

To obtain the first images of crustal structure, we will apply first-arrival tomography to both of the profiles and the 3D box [Zelt and Barton, 1998]. We will first invert for a 1D velocity model that best fits both profiles and the box, which will serve as the starting model for first-arrival tomography. We will then invert for 2D velocity structure along the profiles and 3D velocity structure within the box. Although we will invert for 2D structure along the profiles, 3D ray-tracing will be essential since instruments and shots will not form a perfect line. The tomographic code, FAST, will be used for this phase of velocity modeling [Zelt and Barton, 1998]. It is capable of 3D ray-tracing and 2D and 3D inversion, making it ideal for our purposes.

To image the shallow structure associated with the basin and the upper crust, we will apply reflection-refraction tomography using travel-time picks from our newly acquired refraction survey together with picks on select shotgathers from the COCORP data (e.g., Fig. 8). Magmatic material will be associated with higher velocities than the surrounding sedimentary rocks, allowing us to use velocity models to constrain the distribution of basalts in the sediments. Reflection studies indicate that sills here have velocities of ~6.3 km/s [McBride *et al.*, 1989]. Shallow refractions and reflections from with the basin and upper crust are apparent on COCORP shotgathers [Barnes and Reston, 1992](Fig. 8). These gathers

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can provide denser constraints on shallow structure that will complement our sparse, longer-offset information. COCORP pre-stack data are online. We will then invert for deeper 2D (along profiles) and 3D structure (in the box) in the crust and upper mantle whilst leaving the shallow velocity structure fixed. We will use either JIVE3D [Hobro *et al.*, 2003] or a revised version of Harm Van Avendonk's code [Van Avendonk *et al.*, 2001; Van Avendonk *et al.*, 2004]. Both allow 3D raytracing and regularized tomographic inversion for 2D or 3D structure for a model with multiple layers. Shillington and Lizarralde have extensive experience with forward modeling and tomographic inversion for sedimentary and crustal velocity structure [e.g., Lizarralde *et al.*, 2007; Shillington *et al.*, 2009b].

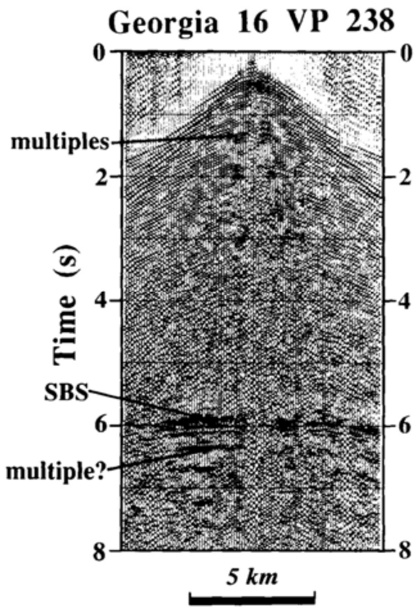

Fig. 8*: Shotgather from COCORP Line 16 [Barnes and Reston, 1992], which coincides with the proposed eastern profile (Fig. 1). Note the shallow refractions and mid-crustal reflections. We plan to interpret such phases in COCORP prestack data and include them in an inversion for shallow structure together with proposed refraction data.*

We also propose to do potential field modeling based on the velocity modeling results. We will compare the gravity signature predicted by our velocity models with observed gravity structure as an independent check on results. Density structure can be estimated from velocity structure using a standard relationship (e.g., Nafe-Drake curve) and used to calculate a predicted gravity anomaly. We will also do magnetic modeling to assess the affect of the inferred distribution of intrusions on the magnetic signature.

Broader Impacts

As described above, the emplacement of large igneous provinces is often linked with dramatic environmental change. CAMP was associated large numbers of extinctions and first arrivals at the Triassic-Jurassic boundary [Marzoli *et al.*, 2004]. Our study will better elucidate the volume of magma, and the causal mantle conditions that brought about those changes.

Secondly, flood basalts make attractive sites for carbon sequestration because CO_2 reacts with Ca, Mg and Fe cations to form solid carbonates via *in situ* mineralization under the right conditions, thereby resulting in permanent storage with no chance for escape [e.g., McGrail *et al.*, 2006]. This stands in contrast to more common use of sedimentary units as sequestration reservoirs, where CO_2 is stored as a supercritical fluid and can more readily leak. Basalt flows associated with CAMP constitute one of the largest volcanic rock reservoirs on the east coast of the US. The South Georgia basin is close to a concentrated region of CO_2 emissions from power plants [McGrail *et al.*, 2006]. Our study will better constrain the volume and continuity of basalt stored in the South Georgia basin, which will assist joint industry/academic efforts that are currently underway to assess the viability of mafic intrusions within the South Georgia basin as sites of CO_2 sequestration [A. Wilson, pers. comm.; D. Goldberg, pers. comm.]

Destructive seismicity has occurred along the edge of this rift system near Charleston, S.C. This basin provides a site complementary to the Reelfoot rift and New Madrid seismicity. While our program does not target the structures and stresses directly responsible for regional seismicity, obtaining basic knowledge of crustal structure and heterogeneity is a necessary first step towards understanding the seismicity of this high seismic hazard region.

Finally, this project involves a large multi-faceted education and outreach effort. The acquisition, analysis and interpretation of seismic refraction data acquired during this study will be the focus of PhD dissertations for two graduate students. Sixty additional graduate and undergraduate students from schools in Georgia and from LDEO, WHOI and UTEP will participate in the field program and gain first-hand experience in acquiring active-source seismic data and learn about the tectonic past of Georgia. Shillington, Lizarralde and Harder will give guest lectures in undergraduate classes at the University of

Georgia, Georgia Southwestern State University and other Georgia schools during their scouting visits, which will mostly take place during the school year (see supporting letters). These lectures will cover general scientific background on continental extension and rupture, the tectonics of the SE US and methods for constraining those tectonics, including active source seismology. The PI's will also arrange to give public lectures in nearby towns. Taken together, our proposed educational and outreach activities will introduce a wide spectrum of students and the general public to geophysical investigations of the earth, the geologic evolution of North America, and the linked evolution of the solid earth and climate.

Prior Support

D.J. Shillington (with M.S.Steckler, J.B.Diebold, L.Seeber, C.Sorlien) OCE-09-28447, $300,000 9/1/09-08/31/11 *Collaborative Research: The North Anatolian Fault in the Marmara Sea, Turkey: The Growth of Continental Transform Basins*. This project supports the analysis of high-resolution reflection data acquired in July 2008 and June 2010 and their integration with other existing geophysical and geological data from Marmara to understand the recent history of strike-slip tectonics and basin growth. We have used stacked lowstand deltas in Imrali basin to develop the first age framework for the Marmara Sea, which indicate steady state tectonics in this active basin rather than a tectonic regime change at 200 kyrs [Sorlien et al., submitted]. We also identify large areas of downslope creep on nearly all sedimented slopes of Marmara and develop a generic model for the formation and evolution of these features [Shillington et al., in review]. Ongoing work is quantifying the distribution of gas and its relationship to slumps and faults [e.g., Shillington et al., 2009a], and the formation and growth of basins associated with transform faults with bends [e.g., Seeber et al., 2009]. This project has also facilitated strong international partnerships with institutes in Turkey and numerous student exchanges between the two countries.

D. Lizarralde (with G.Axen, A.Harding, W.Holbrook, G.Kent, & P.Umhoefer) OCE-011198, $504,921 4/01-3/03 *Collaborative Research: Seismic and Geologic Study of Gulf of California Rifting and Magmatism.* This project aimed to define the crustal-scale style of extension across multiple rift segments in the Gulf of California, assessing variations in extension style along the gulf, and interpreting these variations in terms of parameters such as temperature, pre-rift crustal structure, extension rate, etc. MCS and OBS seismic data acquired across three segments in the southern GoC revealed surprisingly large variation in rifting style and magmatism between segments, from wide rifting with minor syn-rift magmatism to narrow rifting in magmatically robust segments. These differences encompass much of the variation observed across most other non-end-member continental margins. We relate this variation to inferred variation in mantle depletion/fertility linked to pre-rift magmatism. Fertility may vary over small distances in regions that have transitioned from convergence to extension, as in the GoC and many other rifts. [Lizarralde *et al.*, 2007; Páramo *et al.*, 2008; Sutherland *et al.*, submitted]

S. Harder (with G.R. Keller) EAR-0506972, $784,135, 9/05-9/10 *Collaborative Research: Intraplate Magmatic Growth and Tectonic Modification of a Continent: A Case Study from the Pacific Northwest.* The HLP project seeks to establish a better understanding of why the Pacific Northwest, specifically eastern Oregon's High Lava Plains, is so volcanically active. This region was chosen for study because of its accessibility, its high volcanic flux (this the most volcanically active area of the continental United States), and its relatively young age. None of the accepted paradigms about crustal formation and magmatism fit eastern Oregon. A range of techniques, including geochemistry, seismic imaging, and geodynamic modeling will be used to examine new data that constrain the roles of lithosphere structure, tectonics, flat-slab subduction, slab roll-back, and plumes as instigators of aerially extensive magmatism continuing from plate margins into continental interiors. The active-source seismic component of this project took place in September 2008 and involved the largest number of instrument deployments of any study of its kind. Harder was one of the primary scientists involved in the acquisition of this dataset.

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