GeoPRISMS

Implementation Plan

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Implementation Plan

1. Executive Summary

1. Executive Summary

GeoPRISMS (Geodynamic Processes at RIfting and Subducting MarginS), successor to MARGINS, will guide a decade of community-driven, interdisciplinary research on the origin, evolution, and active processes at continental margins. Building upon a decade of community-driven continental margin science guided by the MARGINS Program, GeoPRISMS will develop a fundamental understanding of these shoreline-crossing systems and their importance in global Earth processes, resource distribution, and geohazards. Over the next decade, GeoPRISMS will support a wide range of broadly integrated research approaches, including marine and terrestrial field campaigns, along with experimental and modeling studies, and projects both large and small. GeoPRISMS research will utilize major NSF and related infrastructural investments, and leverage strong international collaborations, while continuing to build and educate a broad research community that will elevate continental margin studies to a new level.

The scientific reach of GeoPRISMS is outlined in the Draft Science Plan (DSP), submitted to NSF in April 2010 (http://geoprisms.org/science-plan.html). The document enclosed here (also found on that site) is an addendum to the DSP, and outlines the specific implementation plans for the GeoPRISMS initiatives. These plans arose from two community workshops, held in Santa Fe, NM (Nov 4-6, 2010) and Bastrop, TX (Jan 5-7, 2011). At these workshops, each attended by more than 120 participants, the community prioritized the scientific goals of the program, selected primary sites at which major research efforts will be concentrated, identified immediate and long-term research needs and strategies for these sites, and outlined thematic studies to complement and integrate GeoPRISMS primary site and MARGINS focus site investigations. The overarching aspects of GeoPRISMS science, partnerships and collaborations, education and outreach, and data management, are summarized in the DSP and not repeated here.

The *Subduction Cycles and Deformation (SCD) Initiative* will focus holistically on long-term margin evolution and material transfer, as well as short-term plate boundary deformation. The initiative will enable studies of strain build-up and release along the plate boundary, the role of volatiles, and the growth and evolution of volcanic arcs and continents. But more importantly, SCD research will explore the interplay of processes across the system, for example: How does the transport and release of fluids regulate the occurrence of great earthquakes? How efficiently are volatiles returned to the Earth's surface over geologic time? What are the linkages among surficial processes, fault-slip behavior, volatile release, and magmatism? Addressing these questions requires an interdisciplinary approach, and the integration of observations from many settings representing the range of subduction zone conditions and stages.

Three primary sites were selected for SCD, listed in order of priority: *Alaska* (including the southern mainland and extension into the Aleutian Islands), *Cascadia*, and *New Zealand*. These three sites offer tremendous potential to address major questions about subduction earthquake and fault slip processes in societally critical settings, and to carry out comparative studies of deep-seated interactions that drive volatile release and magmatic processes to build the continents. The three sites provide immediate and long-term opportunities to leverage recent and upcoming investments in infrastructure, through EarthScope and the Cascadia Initiative at the US sites, and through collaborations with international researchers, in particular in New Zealand.

Five process-based themes were identified within SCD that require broader research approaches than can be achieved at the primary sites. Such thematic studies are fundamental to constraining and contextualizing observations made at the primary sites, and will enable complementary global geochronological, petrological, structural, and geochemical studies, as well as laboratory experiments and computational modeling efforts. The five themes include:

- *Theme 1: Identifying controls on fault slip behavior and deformation history*
- *Theme 2: Understanding mantle wedge dynamics*
- *Theme 3: Fore-arc to back-arc volatile fluxes*
- *Theme 4: Metamorphic and igneous conditions and processes at depth*
- *Theme 5: Subduction initiation*

Focused primary site planning workshops must be carried out in the near-term for all three primary sites, with particular urgency for Cascadia to decide how to take scientific advantage of the new infrastructure provided through the Cascadia Initiative, and for Alaska to ensure coordination between future EarthScope and GeoPRISMS activities, e.g., planning the USArray deployment across the state and integrating the maturing observations of deformation by Plate Boundary Observatory. Both workshops should take place within the year. An international planning workshop should precede any major GeoPRISMS investments in New Zealand, to establish the status of activities in the area, and to prioritize targets to build most effectively upon existing and future infrastructure. This workshop should take place in 2012 or 2013.

The *Rift Initiation and Evolution (RIE) Initiative* will focus on identifying the key processes that drive continental rifting and margin evolution, from rift initiation to the formation and modification of passive margins, and defining the active interplay of mantle, crustal, and surface processes throughout margin development. Examples of overarching questions include: What are the feedbacks between sedimentation and magmatism, and how does this influence the final form of rifted margins? Are rifted margins net sinks or sources for volatiles, and how does this balance change throughout rift evolution? Continental margins of all ages reflect an active interplay of mantle, crustal, and surface processes that demand the interdisciplinary system-level, amphibious research approach of the GeoPRISMS program. Several of the key RIE questions can only be addressed where active rifting is occurring today, whereas others merit studies of passive margins where rifting has gone to completion and the full history of tectonic, magmatic, isostatic, and surficial processes is preserved.

Two primary sites were selected for RIE investigations: the active *East African Rift System* (EARS), which exhibits the entire history of continental rupture, and the fully developed *Eastern North American Margin* (ENAM), which preserves an extensive post-rift evolution. Both systems also exhibit variations in the degree of magmatic activity along strike, and span a north-south climatic gradient with resulting diversity in sediment flux and tectonic-climate interactions. The ENAM site leverages considerable US infrastructure, including EarthScope and the Extended Continental Shelf surveys being carried out by the USGS. The selection of these two sites introduces a new approach for carrying out amphibious studies, where a mostly offshore system is paired with a mostly onshore system, to enable broadly integrated comparisons of the earliest and latest stages of rifting. This exciting approach should lead to strong interactions between marine and terrestrial researchers interested in rift initiation and evolution.

Five thematic studies were identified within RIE to address the influence of parameters poorly represented at the two primary sites. These investigations, intended to be complementary but subsidiary to primary site studies, enable diverse comparative field, experimental, and numerical investigations, also building upon results of past MARGINS studies. The five themes 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*

Open community-wide planning workshops are needed for both primary sites before major GeoPRISMS experiments are initiated, to determine where in these expansive primary sites to concentrate GeoPRISMS investments, and to obtain community input and assess existing data. Early planning for the ENAM site is necessary to leverage time-limited opportunities, such as the deployment of EarthScope's USArray along the eastern US and complementary geodetic studies of subsidence and inundation of coastal areas. This workshop should take place within the year. An international planning workshop for the EARS site should take place in 2012 or 2013.

Immediate Opportunities. Both initiatives offer opportunities for immediate GeoPRISMS research. Early research for both RIE and SCD primary sites should focus on data synthesis efforts, utilization of existing and forthcoming data products, and reconnaissance studies that set the stage for subsequent planning and community experiments. The subsidiary thematic studies can also initiate early, particularly those that help to integrate GeoPRISMS primary site and MARGINS focus site results. Ramp-down activities at the previous MARGINS focus sites are also justified, particularly if they contribute to the scientific objectives of the thematic studies.

Integration, Broader Impacts, and Outreach. Proposed research within GeoPRISMS will yield pronounced broader impacts, including improved understanding of geohazards and enhanced education and outreach, international partnerships, training, and data sharing. SCD studies emphasize understanding the causes and distributions of large megathrust earthquakes, capable of generating devastating tsunami. Volcanic eruptions in subduction and rifting environments can be disruptive and damaging. Continental rifts and passive margins encompass much of the world's population and hydrocarbon resources, and are vulnerable to changes induced by climate change and sea-level rise. Strong international collaborations will arise from GeoPRISMS research, with opportunities to work closely with colleagues in many host countries (e.g., African nations, New Zealand), and to enhance regional training and development. The GeoPRISMS Office will facilitate these transfers of knowledge within the scientific community and more broadly, by running regular workshops, maintaining open channels of communication (e.g., the website, newsletter, publications), and providing direct access to the GeoPRISMS data portal.

Funding Strategies and Priorities. The ambitious scientific objectives of GeoPRISMS require multiple strategies to support them, including leveraging NSF core programs, special programs such as FESD and CD, and international collaborations. Most importantly, GeoPRISMS must make it a priority to engage a broad cross-section of investigators, from experienced PIs to early-career scientists, and do so by maintaining a mix of funding levels and mechanisms, soliciting and supporting both large and small projects, from community experiments to PI-driven proposals. This will ensure that GeoPRISMS continues to foster the strongest, most innovative, interdisciplinary continental margin science.

GeoPRISMS

Geodynamic Processes at Rifting and Subducting Margins

GeoPRISMS Implementation Plan

2. Subduction Cycles and Deformation

2.1. Introduction and Overview

(Updated December 23, 2013)

2.1.1. Scientific objectives

Many fundamental Earth processes occur along subduction margins, from the formation and growth of volcanic arcs, their modification into continental crust, the fluxing of fluids and volatiles from the surface into the mantle, and back through arc volcanoes. Furthermore, subduction is thought to play a major, and perhaps the dominant, role in driving plate tectonics. The occurrence and magnitude of the largest earthquakes on Earth are strongly influenced by material properties on subduction zone megathrust faults, metamorphic and geodynamic processes, and the rheology of the crust and upper mantle. Many of these processes occur in cycles (for example, the seismic cycle, or the cycling of volatile mass through the subduction system). The research directions of the Subduction Cycles and Deformation (SCD) Initiative are inspired by a set of key questions, outlined below, which demonstrate the interconnectedness of geodynamic, geochemical, hydrologic, biologic, and seismologic processes in subduction zones, which span from outboard of the trench to the volcanic arc and from the surface to depths of magma genesis.

The SCD Initiative will focus holistically on margin evolution and material transfer over the long term, as well as short-term plate boundary deformation. In particular, the initiative will encourage studies of the properties, mechanisms, and manifestations of strain build-up and release along the plate boundary, the transport and release of volatiles such as H_2O and CO_2 through the megathrust zone, the fore-arc, and sub-arc mantle, linkages among surficial processes, fault-slip behavior, and magmatism, and the many ways in which their interconnections affect the long-term growth and evolution of volcanic arcs, back-arcs, and continents. In so doing, SCD will improve fundamental scientific understanding of some of the most destructive natural hazards on the planet. The key questions to be addressed through GeoPRISMS SCD research, updated following the SCD implementation workshop, include:

- *What governs the size, location and frequency of great subduction zone earthquakes and how is this related to the spatial and temporal variation of slip behaviors observed along subduction faults?*
- *How does deformation across the subduction plate boundary evolve in space and time, through the seismic cycle and beyond?*
- *How do volatile release and transfer affect the rheology and dynamics of the plate interface, from the incoming plate and trench through to the arc and backarc?*
- *How are volatiles, fluids, and melts stored, transferred, and released through the subduction system?*
- *What are the geochemical products of subduction zones and how do these influence the formation of new continental crust?*
- *What are the physical and chemical conditions that control the initiation and development of subduction zones, including subduction initiation and the evolution of mature arc systems?*
- *What are the feedbacks between surface processes and subduction zone mechanics and dynamics?*

Organized under these headings are a series of more specific scientific questions, all of which were prioritized and refined during the SCD Implementation Workshop, held in Bastrop, TX, January 5-7, 2011. Community progress toward answering these questions will require strong interdisciplinary research teams, and integrated approaches that merge field data collection, careful laboratory experimentation, and computational modeling. Those teams, moreover, must examine the entire subduction system from outboard of the trench to the sub-arc, arc, and back-arc regions. High resolution geodynamic models will need to incorporate complex rheologic and thermodynamic data to test data-driven hypotheses, leading to an integrated understanding of the long-term mechanical, thermal, and chemical evolution of the Earth. In turn, these models will both be informed by, and guide, field, and laboratory experimental data collection.

This iterative and collaborative approach builds on the SEIZE and SubFac initiatives of MARGINS, as envisioned by the Decadal Review Committee, but the SCD strategy also drives the science in new directions in response to discoveries over the last decade. Research carried out at the former MARGINS focus sites, and throughout the MARGINS Program, provide a strong basis for future GeoPRISMS investigations, although the latter will be concentrated at new primary sites. Thus in general, MARGINS-related work will ramp-down as GeoPRISMS studies ramp-up, although several key programs in certain focus sites are still on-going (e.g., NanTroSEIZE, CRISP, IBM seismic surveys). Ultimately, GeoPRISMS thematic studies will provide a means to integrate both MARGINS and GeoPRISMS data sets.

2.1.2. Selection of SCD primary sites

The SCD Implementation Workshop devoted substantial discussion to prospective primary sites during break-outs and plenary sessions. This discussion led to a decisive vote in favor of three primary sites, listed here in order of priority: *Alaska* (including the southern mainland and extension into the Aleutian Islands), *Cascadia*, and *New Zealand*.

Alaska/Aleutians was given the highest priority because it offers real opportunities to address a wide variety of questions outlined within the SCD science plan. Among its many attributes are the fundamental along-strike variations in both fault-slip behavior and magmatism. It was also recognized, however, that GeoPRISMS investigations in that part of the world will require significant ramp-up time and face difficult logistics. There is strong potential for integration with EarthScope deployments; while USArray efforts are still in the early stages of planning, PBO time series are now maturing. GeoPRISMS investigators will participate in such planning discussions to ensure the coordination of critical onshore and offshore activities.

Cascadia offers GeoPRISMS some outstanding immediate-term opportunities to build upon the existing EarthScope infrastructure, e.g., ongoing deployment of the joint EarthScope-MARGINS amphibious array and high-rate geodesy as part of the Cascadia Initiative. Work in that region will engage a broad range of US, Canadian, and international scientists, and leverage a rich trove of geologic and geophysical data accumulated both onshore and offshore over recent decades.

New Zealand generated significant excitement among the workshop participants, due in part to major new investments by their national government in both onshore and offshore scientific infrastructure. The New Zealand margin exhibits a wide range of fault slip and volcanic phenomena with significant along-strike variations in a compact setting. There is also a zone of active subduction initiation, as well as excellent exhumed exposures of arc crust and youthful accretionary prism. Growing international collaborations in New Zealand include an IODP proposal in the pipeline and a number of collaborations with scientists in Japan, Europe, and the United States. In addition, GeoPRISMS investigators will be able to leverage MARGINS research accomplishments from Source-to-Sink investigations carried out along the northern Hikurangi margin.

2.1.3. Thematic studies

Some key questions of the SCD science plan require thematic research that cannot be accomplished solely at primary sites. In particular, processes taking place at depth within subduction zones, processes not presently taking place in modern subduction zones, or processes that can only be resolved through comparative study, cannot be directly sampled or observed within the primary sites or over the decadal time scale of GeoPRISMS. Yet these processes are fundamental to constraining and contextualizing observations made at the primary sites. The deeper levels, temporal dimensions, and global variations of subduction megathrust boundaries and arc systems, however, are made accessible through thematic approaches, including geochronological, petrological, structural, and geochemical studies of small-scale features within exhumed systems, simulation of conditions at depth through laboratory experiments, sophisticated computational modeling, and comparative analyses that build upon the framework of past MARGINS focus sites and observations at the new GeoPRISMS primary sites. The five process-based themes identified following the SCD Implementation Workshop include:

- *Theme 1: Identifying Controls on Fault Slip Behavior and Deformation History*
- *Theme 2: Understanding Mantle Wedge Dynamics*
- *Theme 3: Fore-arc to Back-arc Volatile Fluxes*
- *Theme 4: Conditions and Reactions in Subduction Zones at Depth*
- *Theme 5: Subduction Initiation*

SCD thematic studies are intended to be subsidiary to research that can be carried out at the selected primary sites, but they 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 SCD framework.

2.1.4. Planning workshops and start-up activities

Given the geographic breadth represented within and among the three chosen primary sites, early planning workshops for each locale will be critical. Research efforts at the three primary sites are at different stages of maturity, defining different degrees of urgency. Cascadia and Alaska represent the highest priorities for immediate planning, with New Zealand following closely behind.

Cascadia: *(Updated June 20, 2012)* Significant advance planning that has already taken place for Cascadia operations, in particular within the scope of the Cascadia Initiative (CI); the onshore CI deployments are in place, the first year OBS deployments are complete and data recovered. A series of 2-D marine seismic lines also will be collected over the Cascadia accretionary prism and shelf in 2012. Thus, components of GeoPRISMS work in Cascadia can start immediately. Also, a science and planning workshop, joint between GeoPRISMS and EarthScope, took place April 5-6, 2012, to further clarify how to take scientific advantage of the new infrastructure provided through the Cascadia Initiative, and to decide what ancillary projects require immediate attention and community input.

<u>Alaska:</u> *(Updated March 24, 2012)* GeoPRISMS investigations in Alaska required further community deliberation, in collaboration with EarthScope researchers. Two workshops took place in 2011: one before the EarthScope National Meeting (May 2011) to define the USArray deployment plan in Alaska, and the second, a joint GeoPRISMS-EarthScope planning workshop, took place in Portland, OR on September 22-24, 2011. The primary goals of the latter workshop were to clarify common research objectives with both USArray and PBO, to select appropriate "Discovery Corridors" for future study, and to outline detailed implementation plans and timelines considering available resources and infrastructure. A key outcome of the September 2011 workshop was a detailed implementation plan for the Alaska primary site, which can be found in Section 2.2. Additional reconnaissance studies, data inventories, and synthesis efforts will provide important input over the next year as planning for future Alaska studies continues.

<u>New Zealand:</u> *(Updated December 23, 2013)* An international planning workshop took place in Wellington, NZ, April 15-17, 2013, with the objectives of establishing the status of New Zealand and international activities in the area, and prioritizing targets to build most effectively upon existing and future infrastructure. This planning workshop enabled initial coordination of efforts in both onshore and offshore settings, and solidifed important international collaborations. A detailed implementation plan for GeoPRISMS and collaborative research in New Zealand is found in Section 2.4.

Opportunities also exist for GeoPRISMS-related research at all three primary sites, and within the secondary thematic studies listed above. Early primary site research should focus on data synthesis efforts, utilization of existing and forthcoming data products (e.g., from the Cascadia Initiative), and reconnaissance studies that will set the stage for subsequent planning and community experiments. Ramp down activities at the previous MARGINS focus sites may also be supported, particularly if they contribute to the scientific objectives of thematic studies.

2.1.5. Integration within SCD

The combination of three new primary sites and five thematic topics will build upon rich datasets acquired from the three SEIZE and SubFac MARGINS focus sites, to address the key SCD questions. The strong GeoPRISMS community offers the means to integrate the breadth of observations and interpretations acquired in all of these settings. For example, investigations of seismogenic processes along the Hikurangi margin of New Zealand will benefit from comparable 3-D seismic surveys and IODP drilling ventures along the Nankai and Costa Rican margin, and similarly, can inform interpretations of slow slip processes in those settings as well as Cascadia. Contrasting arc settings in the new primary sites, and MARGINS SubFac focus sites, will expand the parameters that can be studied as controls on magma compositions and volatile content around the world. Investigations of exhumed forearcs and arc volcanoes will provide critical insights into deeper structures and processes that govern subduction zone behavior, which can then be compared with in-situ studies at the primary and focus sites. Theoretical and Experimental Institutes will provide important mechanisms for such intra-initiative exchanges, as well as opportunities to design and plan future thematic activities.

The integration of observations within the SCD initiative also will be enabled by numerical modeling and laboratory experiments, which expand the temporal and spatial range beyond those documented at the primary sites. The synthesis of initial field and modeling studies can then guide subsequent data gathering efforts. Major synthesis activities will be fostered through regular workshops spanning SCD research, enhancing data sharing and collaboration, reviewing ongoing studies, developing comprehensive models for subduction processes, and further building the GeoPRISMS community. The GeoPRISMS Office will facilitate these exchanges, enabling the broad dissemination of results, maintaining open channels of communication (e.g., website, newsletter, publications), and providing direct access to the GeoPRISMS data portal for data sharing.

2.2. Alaska/Aleutian Margin – Primary Site

(Replaced March 24, 2012)

2.2.1. Background and Motivation: Relationships to SCD questions

The Aleutian-Alaska subduction zone (AASZ) and associated volcanic arcs define the most tectonically active region in North America (Figure 2.1). It is an ideal location to study arc magmatism, structure and the contributions of arc volcanism to the development of continental crust. The AASZ is also ideal for study of earthquake processes and the seismic cycle. The margin is seismically active at a range of temporal and spatial scales, with segments in various stages of the earthquake cycle and showing different modes of slip. Examples include megathrust events (e.g., M_W 9.2 1964 Prince William Sound earthquake), freely slipping zones (e.g., Shumagin Gap), and apparently locked sections (Figure 2.2). Important factors potentially controlling both seismogenesis and volcanism vary systematically along strike and properties of both the seismogenic zone (Figure 2.2) and arc volcanism (Figure 2.3) vary as well, so that along-arc studies and/or comparisons of different segments of the arc have the potential to reveal the causes for the observed variations in behavior.

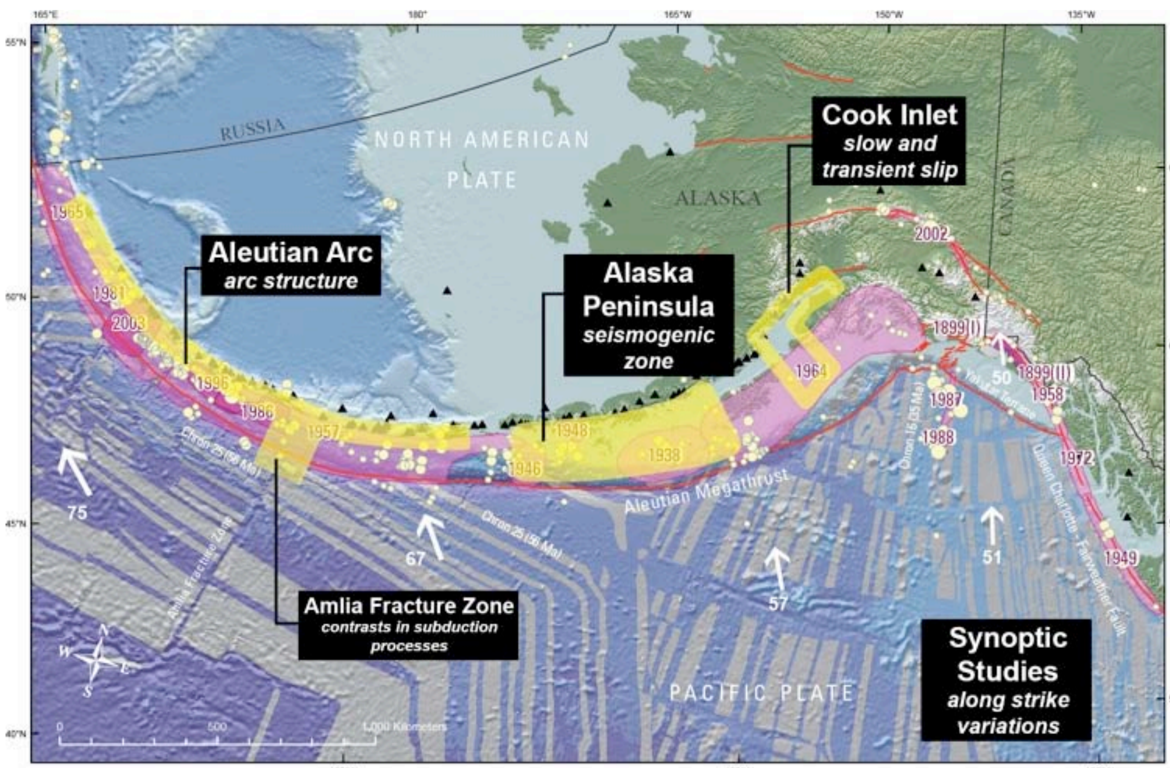

Figure 2.1. Tectonics of Alaska and proposed Geographic Focus Areas. The three regions shown in yellow are the Aleutian Island Arc, the Alaskan Peninsula, and Cook Inlet. Subduction along the Alaska-Aleutian subduction zone (AASZ) transitions into strike-slip motion along the Queen Charlotte-Fairweather fault. Holocene volcanoes (black triangles) extend along the entire subduction plate boundary. Red lines are major active faults. Significant earthquakes (white circles, scaled to size) since 1980 and large to great megathrust earthquake aftershock areas (pink) are shown and marked by year. White arrows indicate the Pacific-North America (using HS3-Nuvel1A model) and Yakutat Terrane-North America relative motions (Elliott et al., 2010.); associated numbers indicate relative velocities in mm/yr. Magnetic anomalies of the incoming Pacific plate from the map of Atwater and Severinghaus (1989).

2.2.1.1. Background and Science Questions

Subduction has been active beneath the Alaskan margin since Triassic time, but the Aleutian arc formed relatively recently, ~50 Myr ago. It exhibits no backarc extension and the lack of intra-arc rifting enables the time-integrated magma flux and the bulk composition of the arc to be measured directly by seismic methods. The age of the subducting oceanic lithosphere changes moderately along the arc, but obliquity and associated rates of subduction, crustal thickness in the hanging wall, sediment flux to the trench, forearc, and arc, width of the accretionary complex (arc-trench gap), the composition of volcanic rocks, and occurrence of subducting topography, all change markedly along the arc.

The characteristics of the volcanic arc change systematically along strike. Although eastern Aleutian arc lavas are tholeiitic on average, western Aleutian volcanic rocks – and intermediate to felsic plutons throughout the oceanic arc – are the most compositionally similar to bulk continental crust of any intra-oceanic arc. However, western Aleutian volcanic rocks also have the smallest contribution of recycled components derived from subducting continental sediments (Figure 2.3); they represent the isotopically depleted end-member for arc lavas worldwide. This provides an unmatched opportunity to address how continental crust is created from volcanic arcs, enabling a definitive hypothesis test of the "andesite paradox."

The general along-arc (east to west) decrease in the size of Aleutian volcanoes suggests that volcanic production rates are linked to trench-normal subduction rates, resulting in large and predominantly basaltic volcanoes in the eastern Aleutians, shifting to smaller and more calc-alkaline volcanoes with greater abundances of andesite and dacite in the west. A slightly different pattern is seen along the continental part of the arc, where smaller calc-alkaline systems are found at a variety of locations, but the large basaltic systems are confined to the eastern part of the oceanic arc and the western part of the continental arc. Along-arc changes in isotopic compositions of Aleutian lavas indicate that significant recycling of sediment/continental materials occurs in the eastern part of the arc, but not in the west. Where large fracture zones are being subducted (Amlia Fracture Zone), the compositions of basalt may reflect an increased role of serpentine dehydration into the mantle wedge, further linking subduction inputs and arc processes.

Megathrust slip behavior may be influenced by sediment influx or by changes in other subduction parameters, such as plate age, convergence rate, slab dip, and obliquity. The largest known megathrust event in the AASZ, the 1964 M_W 9.2 Prince William Sound earthquake, occurred in the sediment-rich eastern-half of the subduction zone, where Neogene glacial erosion led to an elevated flux of sediment to forearc basins and the trench. This part of the subduction zone also features the shallowest slab dip within the seismogenic zone. However, the second and third largest historic events (M_W 8.7 1965 Rat Islands and M_W 8.6 1957 Central Aleutians) occurred in the oceanic part of the arc. Great earthquakes ($M_W > 8.0$) occur every 13-14 years on average, and have been observed or inferred on almost all segments of the AASZ. In the east, along the Alaska Peninsula, convergence is nearly orthogonal to the trench with a rate of ~6 cm/year. Moving to the west, subduction becomes increasingly oblique, reaching nearly 90º, and a slightly faster convergence rate of 7 cm/year. The dip angle of the slab at depths < 50 km varies significantly along strike, as does the dip angle and length of the deep slab. Other evidence suggests that geometric features within the subduction zone (e.g., fracture zones, upper plate segmentation, etc.) strongly influence the rupture areas of great earthquakes, although dramatic along-strike changes in seismogenic properties have been observed that have not yet been correlated with such features. Significant along-strike changes make the AASZ an ideal laboratory for studying what controls the slip behavior and segmentation of the seismogenic zone.

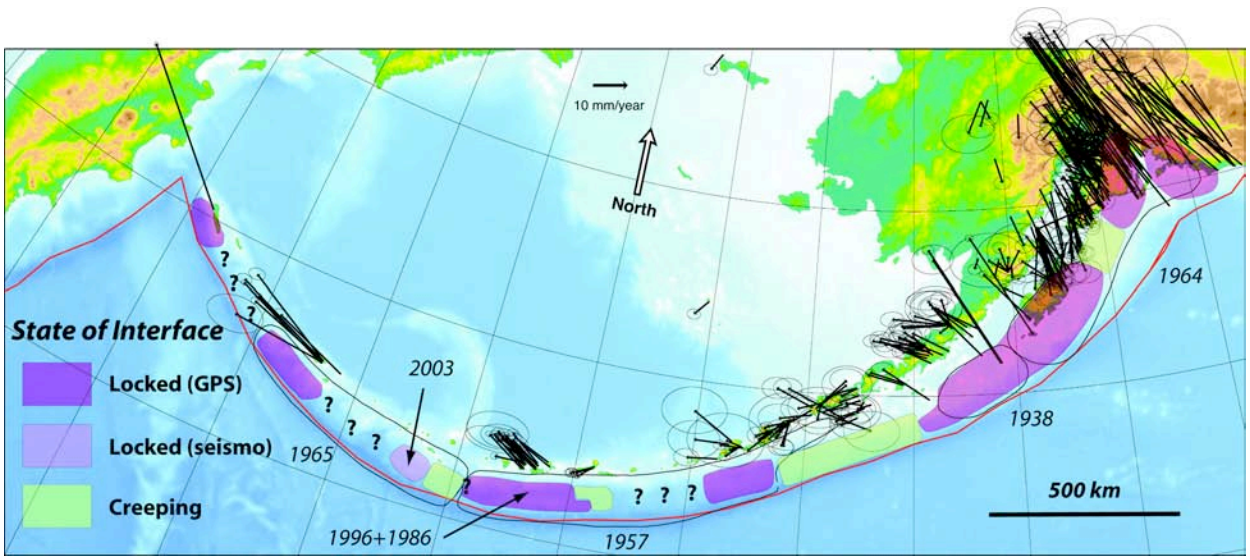

Figure 2.2. Plate coupling variations along the arc. Colored regions indicated the state of the plate interface, with dark areas indicating locked regions (significant slip deficit). Darker shading indicates the locked region is based on GPS data, while lighter shading indicates an assessment based on seismic ruptures alone. Regions shaded in yellow are inferred to creep, while areas shown with question marks do not have enough data to determine the state of the plate interface.

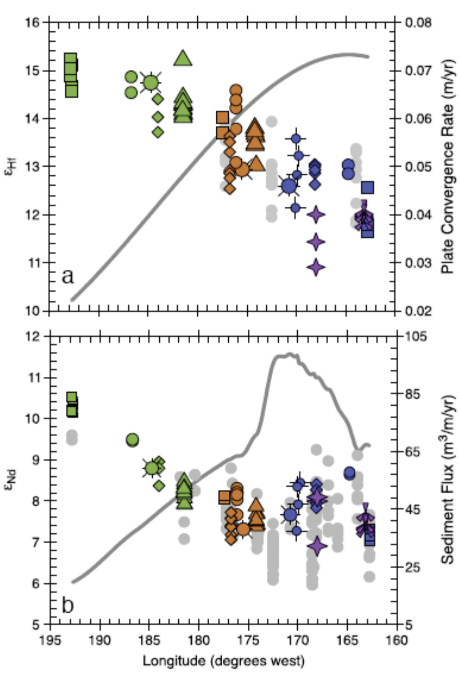

Figure 2.3. Along-arc changes in Aleutian lavas for Hf and Nd isotopes plotted with convergence rate and sediment flux. The eastern end of the graph is located at the western tip of the Alaska Peninsula. The western end is in the far western Aleutian Komandorsky area (see also Figure 2.1). Along-arc changes are inferred to reflect decreasing rates of sediment subduction from east-to-west along the arc. From Yogodzinski et al. (2010 – Figure 3).

The GeoPRISMS community, through a series of planning workshops, identified the AASZ as the highest priority setting in which all of the SCD science topics can be addressed. Research targets for these topics may include:

- *Along-strike variations in earthquake cycle style and magnitude:* Overall contrast in earthquake cycle (i.e., creeping, locked) and earthquake magnitudes from east to west related to changes in upper plate composition (continental – oceanic), changes in obliquity of convergence (normal – extremely oblique), incoming plate features (sediment thickness and composition, seamounts, ridges, etc).

- *Spectrum of fault behavior:* Determine the relation of tremor and slow-slip with the seismogenic zone and within the earthquake cycles, and evaluate changes in locking depth through time. Study along-strike variations in the seismogenic zone, and the causes for the abrupt along-strike changes between dominantly locked and dominantly creeping segments.

- *History of multiple earthquake cycles:* Determine the paleoseismic history along the subduction zone to evaluate their relationship to historical ruptures and to other kinds of fault slip, such as areas of slow slip.

- *Relationship between long-term deformation and earthquake cycle:* Establish how upper plate and accretionary prism structures (thrust sheets; forearc basins and highs; marine terraces) behave during the seismic cycle and their influence on rupture behavior and the overall strain budget.

- *Storage, transfer & release of volatiles, melts & fluids:* Establish how along-strike variability in sediment thickness, crustal age, hydration, and deformation of subducting slab relate to magmatic end-members (mafic vs. intermediate/felsic) and magma flux/activity.

- *Geochemical products of subduction and creation of continental crust:* Use along-arc geophysical surveys and associated geochemical analyses to determine crustal structure and composition, fractionation processes in oceanic portion of subduction zone

- *Shallow/crustal controls on volcanism:* Document how a volcano is constructed through intensive geophysical and geological mapping at a few key volcanoes.

- *Mass fluxes (sediment, ice) and the control on evolution and architecture of the subduction margin and effects on subduction dynamics:* Investigate the role that differences in sediment character along-strike have in megathrust behavior (e.g. Surveyor and Zodiac fans and sediment-starved western Aleutians) and geochemical fluxes and volcanism (e.g. roles of clay, opal). Explore the response of the geometry and seismicity of the forearc wedge responded as the sediment mass balance and ice cover fluctuated throughout the Plio-Pleistocene.

- *Subduction initiation beneath the Alaska Peninsula and the Aleutian Arc*: Determine timing of subduction zone initiation and relationship to Pacific-wide tectonic processes versus more local tectonic processes.

GeoPRISMS studies in the AASZ have high societal relevance, primarily due to the impact of earthquakes, tsunamis and volcanic eruptions. The largest U.S. subduction earthquake on record, the M_W 9.2 1964 Prince William Sound event, ruptured the eastern portion of the subduction megathrust, an area that continues to pose significant seismic hazard for the growing populations in Anchorage and along the Kenai Peninsula. Subduction zone earthquakes are highly tsunamigenic, and large events along the AASZ pose a grave risk to the entire Pacific basin, in particular to Hawaii and the US west coast. Moreover, the Aleutian arc is among the most active volcanic regions on the planet, with the potential to disrupt a critical air transport pathway between Asia, North America, and Europe. This is not a hypothetical hazard: for example, in 1989 a KLM passenger jet was forced to make an emergency landing in Anchorage after volcanic ash disabled all four engines. In addition to earthquake and volcanic hazards, the oceanic Aleutian arc is the site of massive undersea landslides, some with extents of more than ~400 km^2, with km-sized individual blocks. The largest of these slides were certainly tsunamigenic. In addition to delineating seafloor landslide debris, an important focus of future studies will be to identify and quantify the hazard utilizing tsunami deposits that likely ring the Bering Sea and Gulf of Alaska. The high potential impact of AASZ geohazards opens the door for educational and outreach opportunities, both nationally and locally.

Logistically, the AASZ can be a challenging environment to work because of its large size, severe climate, and small, dispersed population centers. However, several key features allow GeoPRISMS to move forward in this region. There has been substantial on-land mapping and sample collection that can be analyzed for geochemistry and geochronology. There are legacy and recent marine surveys (e.g., seismic, bathymetry, dredging) that can help identify geographic areas for study. Scientific oceanic drilling, both past and future, provides coarse constraints on subduction inputs. There are numerous potential statewide, national, and international partners, providing an opportunity for leveraging of resources. These include the Alaska Volcano Observatory (AVO), a joint program of the United States Geological Survey (USGS), the Geophysical Institute of the University of Alaska Fairbanks (UAFGI), and the State of Alaska Division of Geological and Geophysical Surveys (ADGGS), and the Alaska Earthquake Information Center (AEIC). Other programs within the USGS are potential partners. International partners active in the westernmost Aleutians include Japan, Russia, and Germany, and Canada is actively exploring the consequences of subduction in the easternmost part of the region. EarthScope is currently active in the region through the 139 Plate Boundary Observatory (PBO) continuous GPS stations that have been operating in Alaska since 2008, and the USArray Transportable Array will be deployed across Alaska beginning in 2014 onward. Redeployment of the Amphibious Array (OBS, GPS) is possible after conclusion of its initial program in Cascadia. Although, there are logistical challenges for new research, workshop participants highlighted that these can be overcome through proper planning, communication, coordination, and cooperation among government agencies and academic scientists, and community efforts and experiments can maximize science returns.

2.2.1.2. Geographic Focus Areas

The community has identified key geographic regions within the AASZ in which individual SCD questions can best be addressed (Figure 2.1); this leads naturally to particular kinds of research studies being focused on these key regions. The community concluded that a strict focus on a few small focus sites would miss the key opportunities afforded by the along-strike variability of the AASZ. Instead, the community supported an approach in which three broader geographic regions were chosen, with each having a focused science questions and a limited scope of investigations. Detailed plans for proposed investigations should identify opportunities for synergy across the entire SCD program. In addition, the community concluded that some questions are best addressed through synoptic-scale studies that compare processes along the entire subduction zone. These are studies that ought to be carried out wherever possible to capture the along-strike variations in inputs or outputs of the subduction system, although they do not necessarily require new data collection. To avoid repetition, topics best suited for synoptic studies are combined together in a separate section. The next sections of this plan are organized geographically, and highlight the scientific rationale and possible studies in each region in turn, followed by the synoptic studies. Timing, staging and partnership opportunities are described in later sections.

In the following sections, bulleted lists indicate the primary SCD key topics that can be addressed in each region, with those in ***bold*** being the main priorities for that region.

2.2.2. Aleutian Island Arc

SCD Key Topics

- ***Geochemical products of subduction and creation of continental crust***
- ***Subduction zone initiation and arc system formation***
- *Storage, transfer, and release of volatiles through subduction systems*
- *Controls on size, frequency and slip behavior of subduction plate boundaries*

The primary GeoPRISMS focus in the Aleutians is on the structure, history and composition of the arc crust through the study of Miocene-and-older volcanic and plutonic rocks, combined with geophysical imaging of the arc lithosphere. Studies of lavas from the modern volcanoes are important for the storage, transfer, and release of volatiles through subduction systems, and will be discussed in the section on synoptic studies. Study of along-strike segmentation of the seismogenic zone across the Amlia fracture zone would address important questions in that key topic, and would be complementary to geophysical studies of the arc crust and structure.

Crustal genesis is a central theme for GeoPRISMS research in the oceanic part of the Alaska-Aleutian subduction system. This theme unites several SCD key topics, especially those related to subduction zone initiation and the geochemical products of subduction and their role in the creation of continental crust. Seismic and geochemical observations indicate that the composition of continental crust is similar in most respects to subduction-related andesite. These observations present a significant challenge to our understanding of crustal genesis, because mantle-derived magmas in subduction zones are generally interpreted to be basaltic – not andesitic. The central question then becomes, how can the genesis of continental crust that is andesitic be understood in the context of magmatism in island arcs that is largely basaltic? A particular advantage for crustal genesis studies in the Aleutians stems from the fact that the arc was never rifted, so the products of ~50 million years of subduction-related crustal growth are intact and available for study. The physical character of Aleutian crust, which may be inferred from its seismic properties, is therefore the product of magmatic and tectonic processes over the lifetime of the arc, combined with the oceanic foundation upon which the arc was constructed.

The mid-crust of some arcs is seismically slow, and has been inferred to be tonalitic and therefore to have a composition consistent with that of primitive continental crust (Figure 2.4). Calc-alkaline plutons (those with Mg#>0.50 at intermediate SiO_2 contents) are particularly important because they are relatively felsic (Figure 2.5) and therefore buoyant and because they are emplaced as massive bodies at depth, and so are more likely to be preserved during collision and amalgamation of larger crustal masses than are volcanic rocks of similar age. The Aleutians are likely the best active island arc on earth for investigating the relationships between the plutonic rocks of the arc (magmas that did not erupt) and their coeval volcanic rocks (magmas that did erupt). Volcanic and plutonic masses produced in the early and intermediate stages of Aleutian arc growth, which are accessible on islands and by dredging of the seafloor, provide key opportunities to quantify magmatic production rates, and to investigate the timing and nature of subduction initiation in the Aleutians. A better understanding of pluton genesis, in particular a better understanding of the high-SiO_2 end-members in Aleutian plutons, is also key to understanding the nature and evolution of the deep crust, which can be observed geophysically, but is difficult to sample for geochemical studies.

Volcanoes of the western-most Aleutians produce lavas that have major and trace element characteristics of continental crust, even though their isotopic compositions indicate that they contain virtually no recycled continental material. This means that the western Aleutians (Adak area and west) provide an opportunity to investigate the idea that andesitic crust, with major and trace element characteristics of continental crust, may be produced largely out of mantle and subducted oceanic lithosphere, with only a minor role for recycled continental material. If large blocks of western Aleutian crust were produced by primitive andesitic magmatism, they will be readily distinguished from the seismically fast and apparently mafic compositions that dominate crust that underlies the eastern parts of the arc (Figure 2.4a). Anticipated high water contents of primitive andesitic magmas indicate that subduction-related volatile cycling and pre-eruptive volatile contents of arc magmas may also be important in models for arc crust formation.

The oceanic arc displays along-strike variations in the behavior of the seismogenic zone, and the intersection with the Amlia Fracture Zone (AFZ) is of particular interest. There is an abrupt change in the pattern of seismicity at the intersection of the arc and the AFZ, and the 1986 Andreanof Islands earthquake terminated at or near there. GPS data and modeling suggest that this represents a transition from a locked region to the west and a freely slipping region to the east. Although the 1957 earthquake ruptured across this segment, a lack of aftershocks in the zone immediately east of the AFZ suggest that the rupture may have jumped the segment with little strain release. Multi-channel seismic reflection data from USGS studies (1980 and 1981) crossed the trench and fore-arc, and an Ewing cruise in 1994 crossed the central Aleutian trench, fore-arc, and volcanic arc. These reflection data, combined with satellite gravity and magnetic data, indicate a distinct and systematic difference in slab, slab dip, mantle wedge, and upper-plate structure/properties between the segments of the margin that display varying seismogenic behavior. Terrigenous sediment input to the trench stops at the AFZ due to a bathymetric barrier to westward sediment flow (Figure 2.3b). Deformation within forearc sediments transitions from compressional in the western segment to extensional on the eastern side, and the spacing between adjacent volcanoes is disrupted as is the trench-volcano distance at the AFZ.

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

Geophysical constraints on the crustal structure of the Aleutian arc come primarily from an onshore/offshore seismic reflection/refraction study in 1994 that acquired an along-arc profile and two cross-arc profiles. The along-arc profile covered the eastern part of the oceanic arc from Atka Island to the oceanic-continental transition at Unimak Island. The refraction dataset is sparse, with only 15 instruments deployed onshore and offshore along this 800-km-long section of the arc. No geophysical data are currently available on arc crustal structure west of Atka Island. Bathymetric data for most of the oceanic arc is limited to 1980s GLORIA data. Seismic and geodetic data comes mainly from dense networks on currently active volcanoes, augmented by stations in the villages and logistical hubs (Dutch Harbor, Nikolski, Atka, Adak, Amchitka, and Attu).

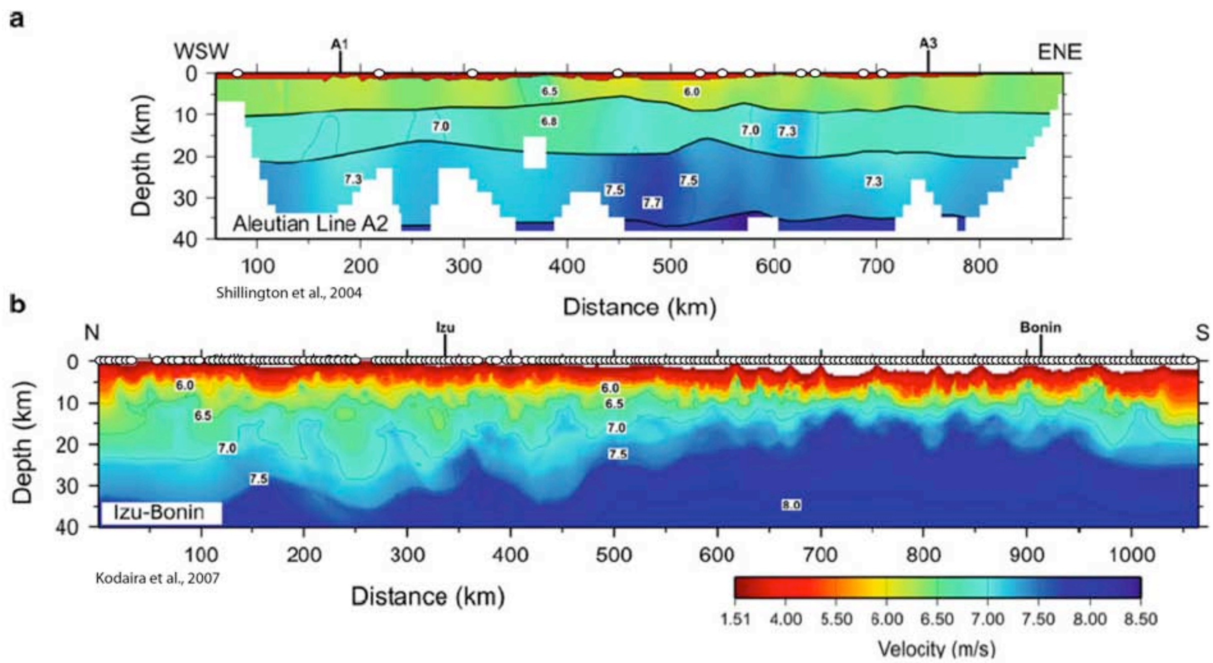

Figure 2.4 Comparison of crustal P-wave velocity structure along (a) the central Aleutian island arc (Shillington et al., 2004) and (b) the IBM arc (Kodaira et al., 2007) from wide-angle seismic reflection/refraction data (figure modified from Calvert et al., 2011). White dots indicate approximate locations of seismometers along each line. Note the sparse spacing of instruments along the Aleutians compared with recent datasets along the IBM (spaced at ~5 km). Dense data in IBM reveal changes in crustal thickness and velocity structure that can be correlated with volcanoes at the surface. Minimal data in the Aleutians hint at possible along-strike changes in velocity structure, but are too sparse to constrain variations at ~20-50 km scale.

Studies based on the existing profiles (Figure 2.4a) showed that the crust in the oceanic arc crust near Seguam island is 30 km thick, with relatively high P-wave velocities in the middle to lower crust (~6.9-7.2 km/s), indicating an average basaltic composition. Importantly, these data do not provide evidence for significant volumes of andesitic material observed in other island arcs (e.g., the Izu-Bonin arc). A ~7-km-thick layer in the middle crust with velocities of 6.8 km/s is interpreted as the Kula plate, upon which the arc was built. The transition from oceanic to continental arc has a more complicated structure, interpreted to arise from deformation of the Kula plate. P-wave velocities of 7+ km/s in the fore-arc lower crust/upper mantle are interpreted to represent serpentinization of the mantle wedge. The along-arc profile displays a relatively thick (32-35 km) and mafic crust from the vicinity of Atka Island in the west to Unimak Pass in the east. Although the dataset is sparse, significant along-strike variations in velocity structure are observed, particularly in the lower crust, and hint at a correlation with along-strike variations in the composition of volcanism at the surface. But these data are far too sparse to determine if along-strike changes in crustal velocity structure and thickness comparable to those observed in the IBM arc are present (Figure 2.4). Recent reprocessing of seismic reflection data along the arc also reveals considerable variability in the reflective structure of the deep crust.

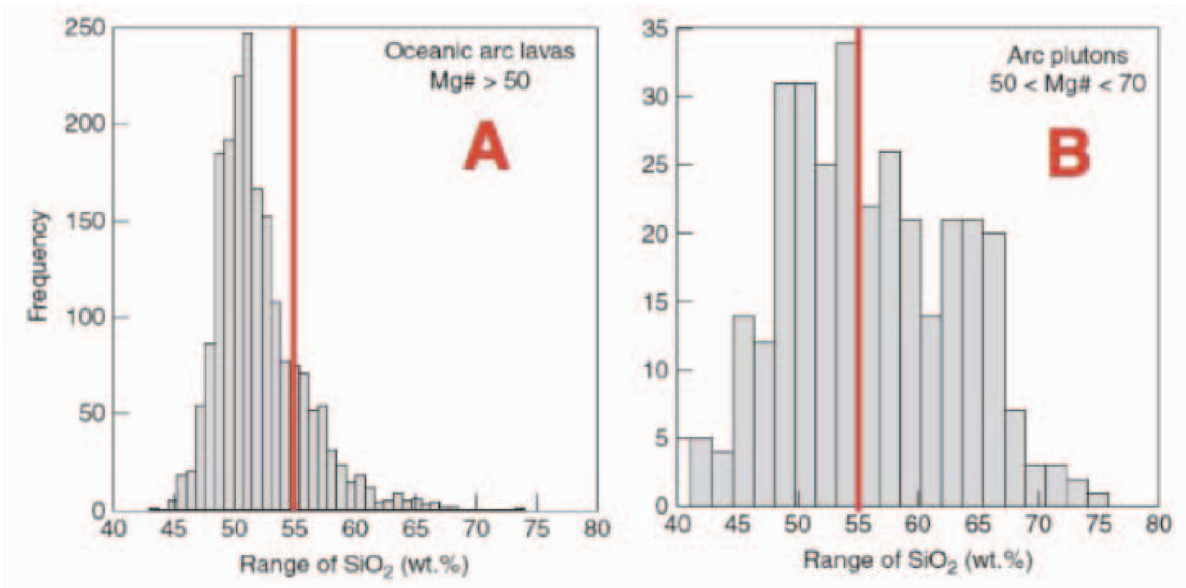

Figure 2.5 Comparison of whole-rock compositions showing systematically higher SiO_2 contents for arc plutons compared to island arc lavas. Data from arc lavas are compiled from locations worldwide. Arc plutons data are mainly from the Aleutians, Talkeetna, Kohistan, Ladakh, Mt. Stuart, Peninsular Ranges and Tanzawa. Compilation and figure from Kelemen et al., Treatise on Geochemistry (2003 – Figure 5).

Geochemical studies of the modern volcanoes provide a starting point for constraining the nature of Aleutian crustal genesis. What is missing is a thorough characterization and understanding of the Miocene-and-older parts of the arc – both volcanic and plutonic – which are critical to establishing a chronology of crustal growth and evolution, and which provide the basis for calculation of rates and for understanding key topics such as subduction initiation and lower crust formation and evolution. Subsequent to reconnaissance work by the USGS in the years following World War II, geochemical and geochronological studies of Miocene-and-older rocks in the Aleutians have focused primarily on a few easily accessible islands, especially Adak, Unalaska, Amlia and Attu. In general, the Miocene-and-older volcanic and plutonic rocks are geochemically similar to the Quaternary lavas, although many appear to be somewhat less enriched in the most incompatible elements (higher Ba, Th, U relative to La). The highly depleted and primitive boninites and island arc tholeiites that are observed in the early histories of some western Pacific arcs have not been observed among Miocene-and-older Aleutian lavas collected either on land or among the small number of submarine samples – are such rocks a characteristic feature of the earliest phases of arc magmatism? Isotopic data on Miocene-and-older volcanic and plutonic rocks are only sparsely available and whole-rock trace element measurements by modern ICPMS methods are nearly non-existent. Available data indicate that the average Aleutian plutonic rock from the eastern part of the arc (Adak area and east) is granodioritic, with 60-66% SiO_2 and 1-3% K_2O. This is significantly more felsic and more potassic than the average of Quaternary lavas from the same part of the arc (average SiO_2 <54%, K_2O<1%). These differences in major element abundances mean that Aleutian plutons may have geophysical characteristics that more closely resemble continental crust than those of the average volcanic rock.

2.2.2.3. Potential GeoPRISMS Studies

New constraints from along-strike geophysical imaging of the Aleutian lithosphere combined with geochronological and geochemical studies of Miocene-and-older volcanic and plutonic rocks are needed to better understand the role of island arcs in the formation of continental crust. Geochemical and geochronological studies of this type also provide an opportunity to determine the timing and nature of subduction initiation in the Aleutians, and its relation to subduction initiation in other Pacific island arcs. Focused studies in each of the western and eastern parts of the arc would complement work to characterize the arc along-strike. Cross-arc geophysical imaging in key locations with existing geochemistry and geochronology can further illuminate arc crustal genesis and evolution, and can image properties related to the seismogenic zone and inputs to the subduction system (sediments). The community identified the Amlia fracture zone and immediate surroundings as a high-priority corridor for such cross-arc studies. Examples of potential research approaches to address AASZ SCD research topics in this geographic focus area could include, but are not limited to:

<u>Geophysical Imaging:</u> The backbone of this effort could include geophysical imaging of along-strike variations in arc crustal structure at length scales of ~20 km that would provide comparable constraints on crustal structure to the active-source seismic imaging along the IBM arc (Figure 2.4). Cross-arc imaging will also be needed in key locations in the eastern and western arc to understand variations in structure across the arc platform, which could arise from changes in temperature and composition; these cross-arc lines may enable studies of other SCD key topics at those locations. Examples of data sets that could address these goals include: 1) dense active-source refraction data to constrain along- and across arc patterns in crustal structure; 2) seismic reflection imaging of crustal and upper mantle reflectivity in combination with Moho and slab topography beneath the arc along and across strike; 3) passive seismic studies or other geophysical imaging along the arc that will provide pointwise estimates of the thickness and velocity structure of the arc crust as well as information on variations in mantle conditions beneath the arc, including the possible presence of ultra-mafic cumulates below the Moho and the temperature structure and distribution of melt beneath the arc.

Electromagnetic methods offer a complementary view to seismic approaches. The electrical conductivity is very sensitive to the presence of fluids (aqueous or melt) and has been used increasingly in subduction zone settings to identify fluids entering the system, fluids released from the downgoing slab and the generation and transport of melt to the arc. Resistivity images of the incoming plate could address issues of hydration, particularly as plate bending opens pathways through the crust and into the upper-mantle. Variations in the degree of upper-mantle hydration as a function of subduction obliquity could be tested in Alaska where there is a strong gradient in subduction orientation along the length of the arc. The interaction of the Amlia fracture zone and the trench, and how fluids are introduced into the system through this collision, would be a possible target. Variations in along strike fluid input, related to variations in orientation of faults with the trench could also be a target. Imaging variations across the arc would require a combination of marine CSEM and MT experiments, with the potential to place some land stations on islands along the Aleutian chain.

Geochronological and Geochemical Investigations: Geophysical imaging of the arc could be coupled to geochronological and geochemical investigations into the nature and timing of Miocene-and-older magmatism that constructed the Aleutian crust. High-priority targets for campaigns of rock sample collection could include locations along the arc where prior studies indicate that Miocene-and-older volcanic and plutonic basement rocks are well exposed (e.g., Unalaska, Amlia, Atka, Adak, Amchitka and Kiska islands). Offshore sampling of basement outcrops by dredging and ROV could complement onshore efforts and might include submerged areas of the Aleutian fore-arc, which may be particularly fruitful from the Adak area west, where the arc massif has been broken into crustal blocks and displaced by clockwise rotation to produce steep-sided submarine canyons and fault-bounded summit basins at several locations along the arc. Offshore sampling could be aided through international collaborations with the German-Russian KALMAR project. Additional discussion of this topic is presented below in section 2.2.7.6.

Geochronological (40Ar/39Ar, U-Pb) and geochemical studies of new and existing samples could provide a basis for quantifying the geochemical evolution of the arc crust and its rate of growth. Detailed characterization of arc basement age and composition at several locations along the east-west extent of the arc would make it possible to link along-arc changes in arc basement geochemistry and geochronology to changes in the geophysical character of the arc, which will be observed in along-arc and cross-arc lines. Studies of this type also provide a basis for evaluating the timing and nature of subduction initiation. Coupling geochemical and geochronological data to geophysical observations of the lithospheric-scale structure of the arc would make it possible to produce a fully quantitative accounting of the crustal growth over the entire ~50 Ma history of subduction.

Geodetic Studies and Passive-source Seismology: Properties of the seismogenic zone could be assessed from estimates of plate coupling based on geodetic data, and from seismicity and structural variations, measured by passive-source seismology. Potential changes in these properties across the Amlia Fracture Zone are a particular priority within the oceanic arc, especially if integrated with structural and mapping investigations. More general studies of this type within the oceanic arc fall into the category of synoptic studies, and potential scientific objectives and methods are discussed in Section 2.2.5.

Heat Flow Studies: Quantifying variations in the thermal state of in the Pacific plate prior to subduction, along the subduction thrust and across the arc is important to understanding subduction zone processes. Along strike variations in heat flow unrelated to variations in crustal age can provide essential constraints for understanding thermally mediated hydration and dehydration processes along the subduction thrust and deeper subduction zone. Heat flow transects across the arc can delineate mantle wedge flow patterns. These data are complementary to seismic, geodetic, and electromagnetic data that link surface observations with processes at depth. Heatflow data would be particularly interesting in the oceanic part of the arc, but could also be fruitfully undertaken along the Alaska Peninsula and Cook Inlet area of southern Alaska.

2.2.3. Alaska Peninsula

SCD Key Topics

- ***Controls on size, frequency and slip behavior of subduction plate boundaries***
- ***Spatial-temporal deformation patterns during seismic cycle***
- ***Feedbacks between surface processes and subduction dynamics***
- *Storage, transfer, and release of volatiles through subduction systems*

The Alaska Peninsula focus region extends from approximately Kodiak Island to Unimak Island, the first of the Aleutian islands (but separated from the mainland by a narrow and shallow channel). The primary GeoPRISMS focus within the Alaska Peninsula region is to determine the processes controlling the spatial and temporal patterns of megathrust earthquakes and the extent of megathrust earthquake ruptures. The Alaska Peninsula region should be the focal point for studies of the feedbacks between surface processes and subduction dynamics, in particular how surface processes are affecting the forearc and seismogenic zone, and vice versa. The general question of the role of sediment flux into the subduction zone impacts the entire arc, and falls under synoptic studies.

The Alaska Peninsula region includes multiple historical megathrust earthquake ruptures. Large or great earthquakes occurred in 1938, 1957 and 1964, and smaller earthquakes occurred in 1946 and 1948 (Figures 2.1, 2.2). A large or great megathrust event occurred in 1788, although the details of the event are poorly known. The Alaska Peninsula segment encompasses a complete range in locking and slip behavior. The observed range in slip behavior, from completely locked in some areas to freely slipping in others, begs to be explained. Geodesy, seismology, paleoseismology, and crustal imaging all can contribute to a better understanding of megathrust slip behavior. The region includes the most volcanically productive part of the continental arc, as well as a transition from calc-alkaline to tholeiitic volcanism. Although studies of magma processes from slab to surface are discussed under Synoptic Studies, this is the best place in the continental arc for such studies. There are significant variations in sediment input and structure along the subduction zone (Surveyor Fan, Zodiac Fan, Shelikof Strait, Aja Fracture Zone, Patton Murray Seamounts, Figure 2.6), which likely affect a broad range of subduction zone and magmatic behavior. The region was a depocenter for massive glaciers emanating from the Shelikof Strait - Cook Inlet region (Figure 2.7), and an examination of these inputs can address the impact of glaciers and climate cycles on subduction dynamics.

Due to the geometry of the margin, tsunamis generated by great earthquakes in the Alaska Peninsula pose an extra hazard to Hawaii and the west coast of the U.S. The April 1, 1946 earthquake (Figure 2.1) and tsunami was one of the most puzzling and controversial events anywhere. The earthquake had a conventional magnitude (M_S) of only 7.4, but modern reinterpretations put the moment magnitude (M_W) at 8.6. The earthquake apparently had exceptionally slow rupture and exceptionally large shallow slip. It produced a tsunami with local run-up of 42 m at Scotch Cap on Unimak Island that crossed the Pacific and killed 159 people in Hawaii. This earthquake occurred within a section of the subduction zone that shows very little coupling according to GPS results, and it is the only significant case of a mismatch between geodetic and seismic estimates of segmentation. These puzzles of the 1946 event might be explained if it resulted from extreme slip at very shallow depth near the trench, such as was observed in the March 2011 Tohoku-oki earthquake. The consequences of a similarly tsunamigenic earthquake with a much longer rupture length, comparable to those of historic great earthquakes, could be devastating. A record of prehistoric tsunamis from the region needs to be developed to assess their frequency, and how they relate to the megathrust earthquake record.

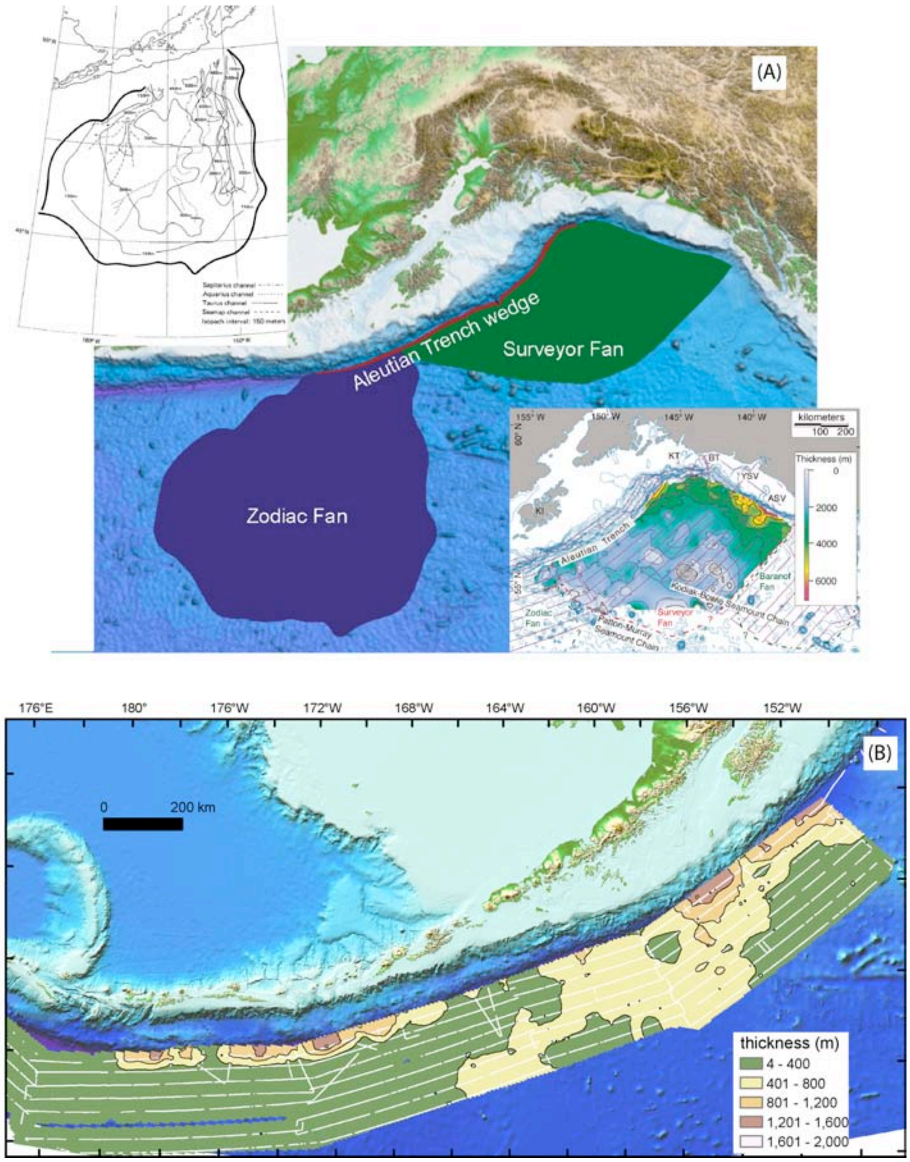

Figure 2.6. Thickness of sediment on the subducting Pacific plate based on MCS and single-channel reflection profiles. Thicknesses are in meters assuming a sediment velocity of 2 km/s (A) Sediment bodies and isopachs in the Gulf of Alaska. The spatial extent and thickness of the Zodiac Fan is after Stevenson et al. (1983) and the Surveyor Fan from Reece et al (2011). Background image courtesy of Robert Reece. (B) Thickness of sediment west of Kodiak Island, including the trench and incoming plate from Ryan et al. (in review). Note different isopach color scale between A and B.

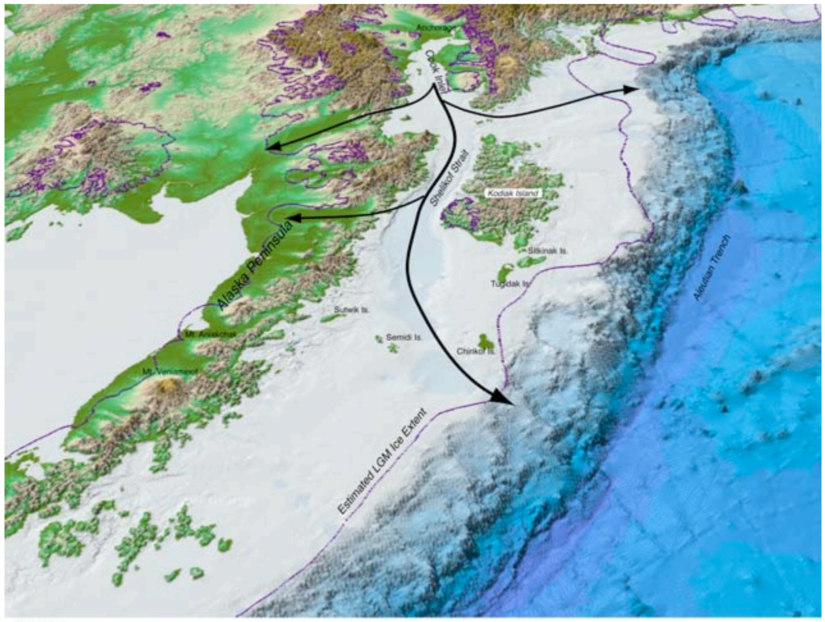

Figure 2.7. Bathymetry and topography of Alaskan Peninsula annotated with Late Wisconsin (Last Glacial Maximum) glacial coverage shown in purple. A large lobe of the Alaskan Cordilleran Ice sheet flowed from Cook Inlet through Shelikof Strait over the Alaskan Peninsula and adjacent Pacific continental shelf (hypothetical flow paths shown by arrows). Topography from GLOBE dataset and Alaska Region Bathymetric DEM from Danielson et al. (2008). Glacial extent from Manley and Kaufman (2002). Horizontal scale varies with distance; vertical exaggeration is 6x.

Because of the dominance of Pleistocene glacial coverage in the region, there is no better location to study how mass fluxes (sediment, ice) control the evolution and architecture of a subduction margin. Kinematic models and observations from the eastern Gulf of Alaska margin document how step increases in sediment flux to an orogenic wedge can lead to a broad temporal and spatial transition of deformation within the wedge. A large ice tongue sourced in the Alaska Range and Upper Cook Inlet likely led to a massive transfer of sediment from the arc to forearc and trench in Plio-Pleistocene time (Figure 2.7). Thus, it is the ideal location in Alaska to explore if the geometry and seismicity of the forearc wedge has responded as the sediment mass balance and ice cover fluctuated throughout the Plio-Pleistocene. Glacial erosion and changes in glacial loads can affect tectonic strain localization, seismicity, and potentially volcanic productivity, making glaciers a potentially critical feedback between surface processes and subduction zone mechanics and dynamics. Thus, the evolution of ice cover over time and quantitative estimates of erosion are needed to understand and model this feedback.

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

Pre-existing data and an existing framework of geological and geophysical studies provide a strong foundation for focused studies. Islands between the peninsula and the trench allow on-land geologic investigations and the opportunity to provide ground-truth for observations made offshore through geophysical studies. Shore-based seismic and geodetic studies also can be carried out at substantially lower cost than marine studies. Much of the area has been mapped geologically, with accompanying stratigraphic and geochronology studies; intensive geological studies of the accretionary prism have been carried out; new and legacy seismic reflection data have been collected on both sides of the arc (Figure 2.8); geodetic and seismic monitoring networks exist across the region, including on several volcanoes. Moreover, there have been intensive studies of the bedrock of the accretionary prism on Kodiak and some of the adjacent islands. A substantial data gap exists for the paleoseismic and paleotsunami record for the region, for which there is no published information.

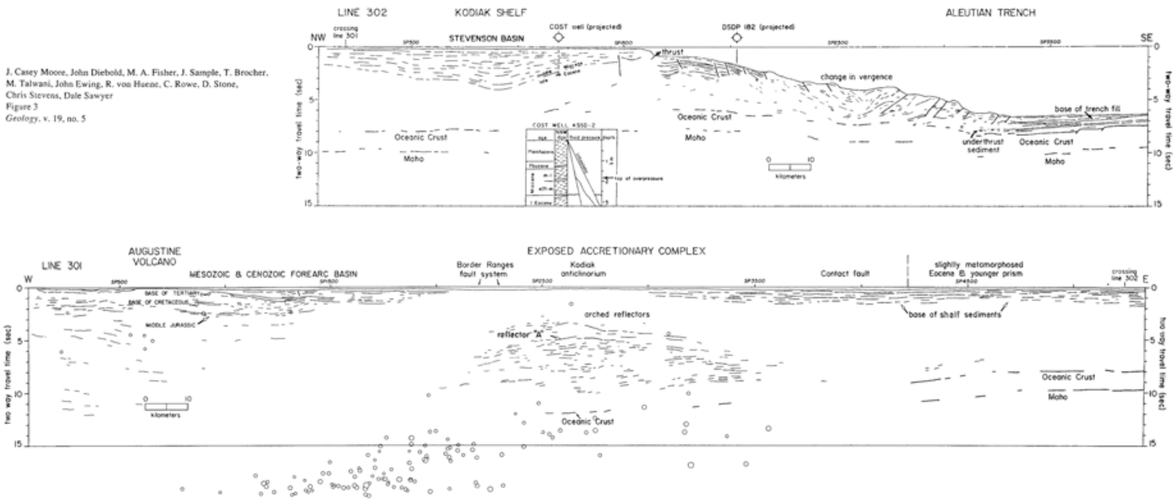

Figure 2.8. Line drawing of migrated EDGE seismic line showing projected earthquakes and COST and DSDP wells. From Moore et al. (1991).

Marine seismic reflection data exist on both sides of the arc, but recent multi-channel data are limited to the 2011 ALEUT project. Lower quality legacy USGS and oil industry data exist, along with exploration boreholes on the north side of the Alaska Peninsula. The incoming trench and slope were drilled during DSDP Leg 18 north of this region, but no boreholes or long cores exist for the region. A significant data gap is in bathymetry data; high-resolution mulitbeam data are available in a few places along the slope and trench near Kodiak (collected by Geomar) and along the ALEUT shiptrack; however, there is very little detailed bathymetry away from the shorelines south of Kodiak.

Both campaign GPS sites and PBO continuous GPS sites span the entire region, with a concentration on the islands south of the Alaska Peninsula and on the volcanoes of Unimak Island. PBO provides a sparse but complete backbone network across the region (station spacing generally ~60-150 km), with a dense cluster of sites around Westdahl and Shishaldin volcanoes on Unimak Island. The permanent seismic network consists of a sparse backbone and several volcano networks, with a few key sites on islands near the trench. The EarthScope USArray transportable array (TA), to be deployed starting in 2014 will provide a significant, if temporary, enhancement to the network.

There is also a shortfall of potential fields data. Regional, low frequency gravity data exist from satellite altimetry, however, land and marine data are lacking. Moreover, there are almost no aeromagnetic data, which would be useful for deciphering crustal structure and interpreting regional geotherms.

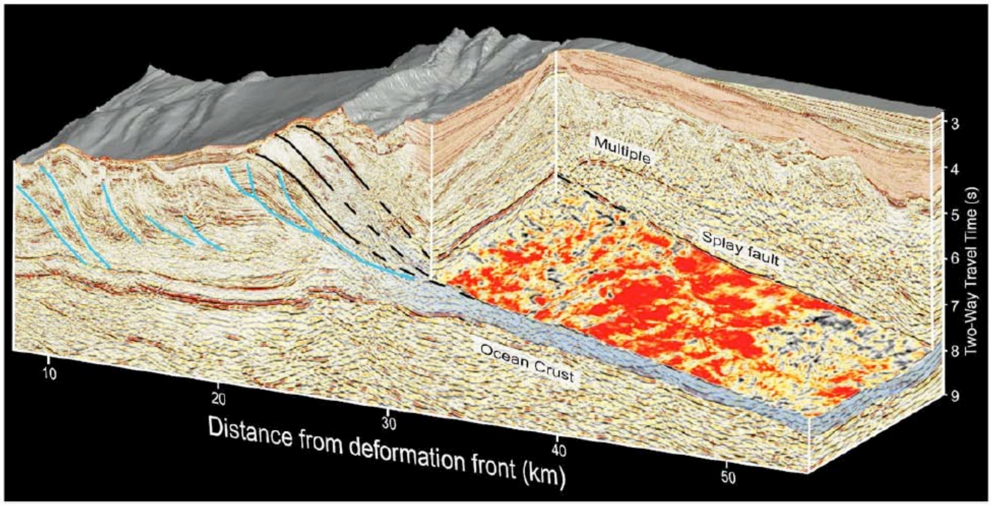

Figure 2.9. Example of 3-D seismic reflection volume that could be collected within Alaskan Peninsula geographic focus area. Image is a perspective view from Bangs et al. (2009) of the Nankai 3-D seismic volume with cut-out to show high-amplitude, reversed-polarity seismic reflection from the deep splay fault (red areas). Cube is 12 km wide by 50 km long..

2.2.3.3. Potential GeoPRISMS Studies

Examples of potential research approaches to address AASZ SCD research topics in this geographic focus area could include, but are not limited to:

Geophysical imaging of the megathrust – Legacy 2D USGS seismic reflection data and the recent (2011) ALEUT project deep active-source reflection and refraction data provide crucial crustal-scale framework data, however data coverage is limited. In order to make fundamental observations of changes in megathrust character along and across strike, additional seismic experiments will be needed. High priority targets for imaging include transitions in locking at the plate boundary, such as the transition from the locked 1938 rupture area to the narrow locked zone in the Shumagin Islands and the apparently creeping segment to the west at the end of the Alaska Peninsula. This latter segment includes the presumed 1946 rupture area, and study of this region offshore may reveal insights into the puzzling earthquake and tsunami generation there. High-resolution geophysical imaging (e.g., Figure 2.9) could identify the location and nature of surface deformation associated with that event, including possible landslides, the presence of active splay faults, and how deformation is manifest offshore. Forearc deformation may also be influenced by patterns of sediment deposition, e.g., derived from ice streams originating from Shelikof Straight, and depositing southwest of Kodiak (Figure 2.7). Examples of geophysical datasets that could address these goals include bathymetric mapping and seismic reflection imaging. Deep imaging (e.g., passive seismic studies) can provide complementary information to the active-source studies. e.g., better constraining the deep configuration of the slab, overriding plate and mantle wedge beneath the Alaska Peninsula. Given the high rate of seismicity, tomography could improve understanding of processes from slab to surface. The map pattern of seismicity in the forearc is similar to the Tohoku region of Japan, where onshore/offshore passive seismic networks have enabled successful tomographic inversions that have imaged the slab, interface and overriding plate. Moreover, shear-wave splitting studies would help to reveal the character and role of mantle flow across the entire width of the subduction zone.

The deployment of dense networks in conjunction with the USArray TA is an obvious opportunity for synergy with EarthScope. The redeployment of the Cascadia Initiative Amphibious Array (AA), after its demobilization in the Pacific Northwest, represents a great opportunity to better understand crustal structure and seismic processes in this area. The timing of such a deployment also would influence the ideal sequencing of studies. Optimally, the AA deployment would coincide with the USArray deployment, along with other broadband seismometers.

Active deformation – Geodetic studies are needed to assess variations in locking and slip behavior along the length of the megathrust, as well as deformation associated with arc volcanoes. The campaign GPS sites in the area have not been surveyed for more than a decade, and most have not been visited for more than 15 years. A repeat survey would dramatically improve the number of sites with usable data and provide a high-precision data set for modeling. Additional sites could be focused on the along-strike transition zones between wide locked zones and creeping zones. Higher spatial resolution is needed for interseismic models in these areas, and continuous GPS sites could show whether these boundaries remain stable with time or if slip transients are responsible for some of the along-strike variation. Ideally, such GPS sites should be established early during GeoPRISMS studies in the area to recognize temporal changes over a meaningful period of time. Sections of the megathrust that are dominated by creep are particularly promising targets for seafloor geodesy. These measurements are the only way to determine if creep extends to the trench, or if the near-trench region is locked and potentially seismogenic. Seismicity studies would help to define earthquake activity, tremor patches, and loci of deformation. More careful studies of historical seismicity (for example, relocations using updated 3D velocity models) may better define rupture areas for the historical events, cumulative moment release, and invite a comparison to geodetic inversions. As described above, the deployment of dense networks in conjunction with the USArray TA is an obvious opportunity for synergy with EarthScope, and Alaska would be an excellent target for the Amphibious Array.

Paleoseismology and paleotsunamis – One high priority in this region is to define the paleoearthquake and paleotsunami history of the region, to evaluate if the historical rupture boundaries repeat or change through time. Moreover, it is vital to establish how often megathrust ruptures generate significant tsunamis. Submarine paleoseismic records should also be developed, and methodologies will need to be honed for this task. Some of the offshore islands, such as Chirikof Island (Figure 2.7), show a wealth of useful geomorphic features and have sites that are promising for further paleoseismic and paleotsunami research.

Mass flux studies – Comprehensive thermochronology studies would establish the history and rates of rock exhumation, and allow linkages between tectonic, collisional, or climatic events. Moreover, structural mechanisms of exhumation could be examined through bedrock structural or seismic reflection studies. The transfer and accumulation of sediment derived from erosion must be determined across the forearc and trench. Geophysical imaging studies may define high-priority coring and drilling targets. After collection and interpretation of seismic reflection data, a sequence of scientific boreholes can be proposed to characterize the physical characteristics of the incoming sediment, structural development of the toe of the accretionary prism, fluid escape from deforming sediments, and the timing and evolution of slope basins. A drilling transect of the toe of the prism (e.g., ODP Leg 171; NanTroSEIZE) may be desired.

2.2.4. Cook Inlet

SCD Key Topics

- ***Controls on size, frequency and slip behavior of subduction plate boundaries***
- ***Spatial-temporal deformation patterns during seismic cycle***
- *Volatile storage, transfer, and release in subduction systems*
- *Feedbacks between surface processes and subduction dynamics*

The Cook Inlet focus region extends from Prince William Sound approximately to Kodiak Island, and includes the rupture zone of the great 1964 M_W 9.2 earthquake. The primary GeoPRISMS focus within the Cook Inlet region is on slip behavior of the megathrust, and in particular transient slip. This region provides the opportunity to study large and small slow slip events and their associated tremor, transient postseismic deformation following the 1964 earthquake, and a dramatic along-strike boundary in the slip behavior of the plate interface that appears to correlate with the edge of the subducted Yakutat terrane. This region is also the source of most of the trench sediment for the entire AASZ, and for the sediment deposited in the forearc in the adjacent Alaska Peninsula. The greater land area in this focus region, also means that EarthScope will have a greater presence here. Given the complementary science goals, The Cook Inlet focus region is an excellent target for joint GeoPRISMS-EarthScope projects. and for leveraging EarthScope data.

The Cook Inlet region experienced a watershed seismic event in 1964, triggering long-lived postseismic deformation transients that provide an opportunity to study the mechanics of the lithosphere and asthenosphere and improve models of the seismic cycle. Measurements of surface deformation and improved 3D models of structure and anisotropy are needed to determine the stress distribution and rheology of the fault zone, and of the lithosphere and asthenosphere. Multiple slow-slip transients have now been observed in this region, including a very large (M > 7) slow slip event, transient variations in the width of the locked zone, and what appear to be small and short-lived events perhaps similar to Cascadia ETS events. More detailed observations and models are needed to understand the stress evolution and slip mechanisms controlling these events.

The Yakutat terrane is subducting under and colliding with southern Alaska at the eastern end of the AASZ, with the transition from subduction to collision occurring east of the eastern end of the 1964 earthquake rupture (Figure 2.10). The Yakutat terrane crust is thick and buoyant, and is probably composed of continental sediments deposited on top of an oceanic plateau. Subduction of this buoyant crust has affected the margin strongly for at least the last 6 million years and possibly as long as 20-30 million years. It results in a very shallow slab dip (essentially a flat slab), enhanced deformation of the overriding plate, and a gap in the volcanic arc. The subducted Yakutat slab extends to the northwest under the Cook Inlet region, and the SW edge of the subducted Yakutat crust correlates roughly with the edge of the Prince William Sound asperity of the 1964 rupture, and a transition from a very wide seismogenic locked zone to a segment dominated by creep (Figure 2.2). The Yakutat slab edge offers a chance to study the effects of a dramatic change in properties of the subducted crust on the seismogenic zone and arc volcanism.

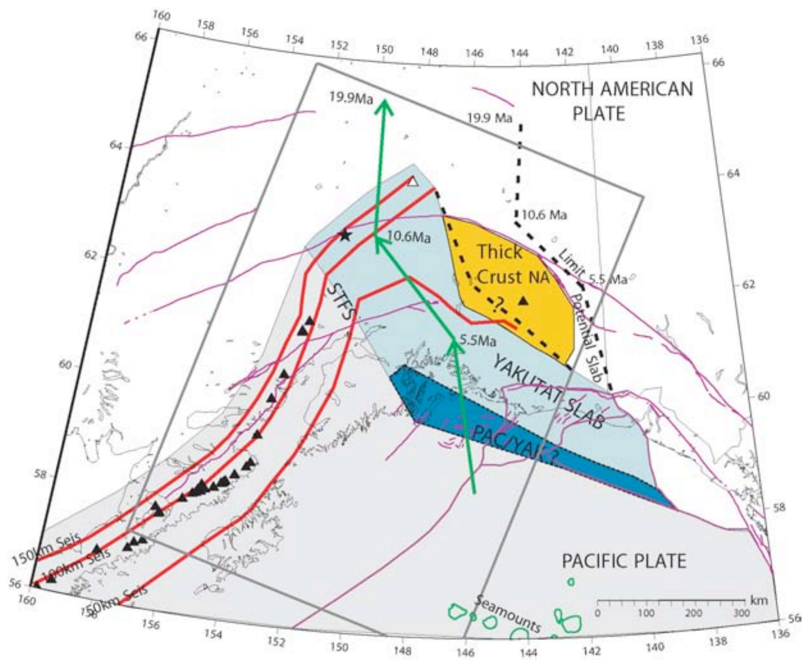

Figure 2.10 Subducting plate as inferred by Eberhart-Phillips et al. (2006), gray = Pacific, light blue = Yakutat, dark blue = schematic region of Pacific underthrust Yakutat (actual amount not certain). Thick crust east of the slab is in the overlying plate. Red lines show slab depth as defined by seismicity. Seamounts from bathymetry. Green arrows show cumulative plate motions for the last 20 Ma for a spot on the Pacific plate. For the hypothetical case of zero Pacific-Yakutat displacement and a dipping slab, the dashed line shows cumulative motion for a point at the surficial edge of the oceanic Yakutat terrane, and thus limits the potential 'missing' slab. The plate motions are from Stock and Molnar (1988), and the 19.9 Ma vector is approximate.

The very high seismicity rate of the region provides sources that can be used in tomographic and other imaging, if seismometers are installed to record them. The effectiveness of seismic imaging depends on the number of intermediate magnitude earthquakes that are large enough to be recorded well over a large area, but small enough to have very simple sources. The slab beneath Cook Inlet and southern Alaska is a particularly rich seismic source, generating hundreds of earthquakes per year that would be broadly recorded in the overlying region. Frequent seismicity also allows for studying the physical properties that control and/or are diagnostic of the slip behavior of the interface. Slow slip phenomena (geodetic transients, tremor, etc.) could be useful for examining these coupling questions (Figure 2.11).

The Cook Inlet region is the continental end-member for the AASZ, providing a strong contrast to SCD processes active along the oceanic Aleutian Arc. This part of the subduction zone has the largest distance globally from a trench to an arc, with magma generation through relatively thick continental crust. Neotectonic exhumation and Quaternary glaciation in southern Alaska results in large terrigenous sediment fluxes across the region and into the subduction zone. The volatile-rich eruptions from volcanoes in Cook Inlet may be driven by the combination of these conditions. The prevalence of Pleistocene ice cover in Cook Inlet results in strong surface process signals, and this region has the potential for the strongest climatic/glacial influence on volcanism and seismogenesis in Alaska.

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

A tangible benefit of the Cook Inlet region is the greater amount of existing data relative to the Alaska-Aleutian subduction system to the west. In addition, EarthScope plans include deployment of a large number of USArray TA stations across the region (Figure 2.11). The greater accessibility of the Cook Inlet region has allowed for longer-term volcanic and geophysical monitoring through the AVO and PBO. The denser spatial coverage of existing geodetic measurements and vertical motion data in this region allows modeling of megathrust slip events, although data on the recurrence of megathrust events remains limited. Geophysical data are available at moderately dense spatial coverage that resolve deep-to-shallow structures and 'slow' slip phenomena (geodetic transients, tremor, etc.).

Deep seismic reflection data exists in Cook Inlet and Prince William Sound from 1980s and 1990s projects, including EDGE and TACT. Cook Inlet is home to Alaska's oldest producing oil and gas basin, and both industry and public domain map, core, seismic reflection and well log data exist for potential interpretation of neotectonic deformation and the Neogene sedimentation (Figure 2.10). Additional deep seismic reflection lines in Cook Inlet are unlikely due to permitting restrictions, and future work of that type is most likely limited to the area offshore the Pacific coast. Past OBS deployments were very limited, which means there are great opportunities for acquiring fundamental new data given the high seismicity rate and limits to past information.

Pre-existing campaign GPS networks cover most of the region, especially along the road system, with sparser coverage on the NW side of Cook Inlet and other more remote regions. PBO operates continuous GPS sites across the region, with a typical station spacing of ~80 km. For comparison, this is similar to the station coverage in the northern part of Cascadia prior to PBO (current Cascadia PBO station spacing is ~40 km). Greater densification in targeted areas would be justified. Data from a few additional sites, mostly located on the road system, are available from the University of Alaska Fairbanks and various other station operators.

AVO plays a key role on the study of Cook Inlet volcanoes. It has a program of real-time seismic monitoring at the four active Cook Inlet volcanoes — Spurr, Redoubt, Iliamna, and Augustine — plus the recently active Fourpeaked Mountain at the NE end of the Alaska Peninsula. AVO has 4-station GPS networks on Redoubt and Spurr. For some volcanoes, AVO has remote, real-time video capability and obtains intermittent airborne sulfur dioxide and carbon dioxide measurements. AVO also oversees a regional tephra laboratory to systematically measure and catalog tephra-producing eruptions, establish radiocarbon-controlled tephrostratigraphic frameworks, and to evaluate the magnitude and frequency of tephra-producing eruptions. This tephra catalog has the potential to enable long-distance correlation of tephras, provide greater detail on the chronology of eruptions, and establish a longer-term context for tephra hazards.

Quaternary sedimentation is likely dominated by glacial processes interacting with active deformation in the forearc and volcanic arc, but quantification of mass flux is still in early stages; uplift and exhumation are relatively well understood, but how this translates to mass transfer and timing of sediment delivery to forearc and trench is still poorly known. A significant amount of sediment from this region exited through Shelikof Strait, contributing sediment to the trench in adjacent segments of the subduction zone. This region also has been examined using three-dimensional numerical geodynamic models of both crustal and mantle processes to investigate the mechanical evolution of the southern Alaskan plate corner where the Yakutat and the Pacific plates converge on the North American plate. These models allow for hypothesis testing linking geodynamic and surface processes.

2.2.4.3. Potential GeoPRISMS Studies

Many GeoPRISMS science targets within the Cook Inlet region could be addressed by exploiting existing and planned on-land infrastructure, augmented by targeted offshore data. GeoPRISMS and EarthScope have common scientific goals that can be met collaboratively and synergistically in this region. For example, densification of the EarthScope USArray TA and PBO facilities with focused FlexArray and GPS deployments would provide data that could be used to resolve the plate interface and mantle flow, deep-to-shallow structures, slow-slip events, and volcanic activity. Such efforts could be supported by a combination of GeoPRISMS and EarthScope funding. The key scientific targets within the region are to record data needed to develop models of deformation throughout the seismic cycle, focusing on slow and transient slip the effects of the 1964 event, and the subducted Yakutat slab and its impacts. The largest known slow slip event in Cook Inlet (Figure 2.11) was studied primarily through campaign GPS surveys, which was possible only because of the event's enormous size. Analysis of existing continuous GPS data is needed to identify and determine the slip history of smaller events, and additional continuous GPS sites would provide further data for study of these events, and their spatial relationship. Ideally, these studies would benefit from complementary geodynamic modeling over geologic and earthquake cycle timescales and exhumation rate measurements to better relate short-term geodetic and seismological measurements to longer-term Quaternary deformation and mass fluxes.

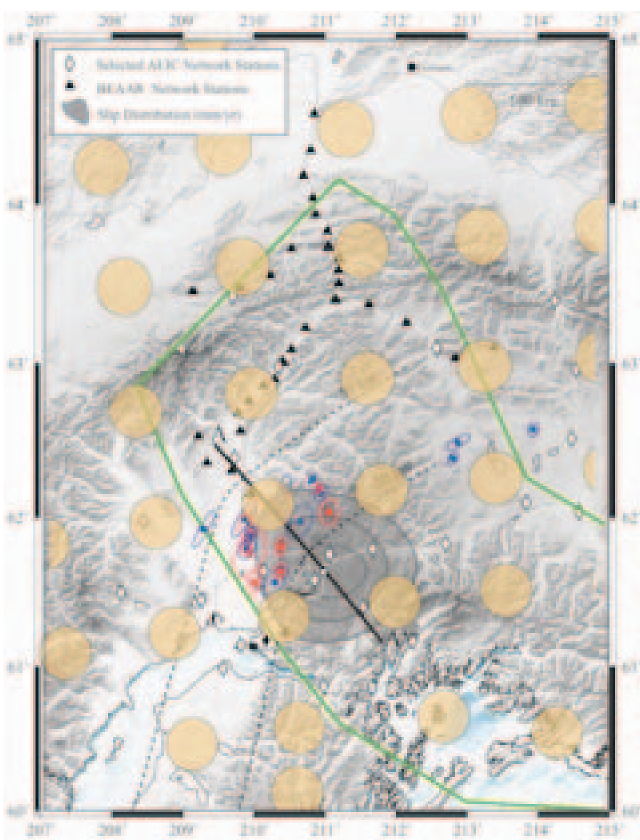

Figure 2.11. Locations of nonvolcanic tremor from Peterson and Christensen (2009). Summer of 1999 (red circles) and summer of 2000 (blue circles). Note that all but three events are located in the region of the slow slip event. BEAAR stations are mapped as black triangles; selected AEIC stations are mapped as white diamonds. Orange circles delineate 20-km footprint of potential EarthScope Transportable Array deployment. Slip distribution [Ohta et al., 2006] from the 1998–2001 slow slip event is shown by dark gray solid lines with rates in mm/a and one GPS station, ATW2, used in the Ohta et al. [2006] model is shown by the white circle in the center of the slip region. The green outline shows the subducted Yakutat terrane as modeled by Eberhart-Phillips et al. [2006]. The 30 km and 50 km contours of the subducting Pacific plate are shown by the dashed lines.

Determining the extent and geometry of subducting Pacific Plate, especially near the western edge of the subducted Yakutat terrane, is a priority for this focus area because of the profound changes in interseismic deformation and arc volcanism observed. The details of the subducted Yakutat slab are broadly known from tomographic inversion and at shallower levels, a prominent magnetic anomaly. It's impact on mantle wedge properties are not known, although there is a clear gap in eruptive arc volcanism above the Yakutat slab, and shear-wave splitting directions are parallel to the strike of the slab in the mangle wedge. Better characterization of the seismic, electrical, and thermal properties of the mantle wedge are needed, as are models of mantle flow. A combination of land-based and OBS seismic deployments could provide the data needed for such images. Densified GPS deployments could improve the resolution of geodetic models.

2.2.5. Synoptic Studies

SCD Key Topics

- ***Controls on size, frequency and slip behavior of subduction plate boundaries***
- ***Spatial-temporal deformation patterns during seismic cycle***
- ***Volatile storage, transfer, and release in subduction systems***
- ***Feedbacks between surface processes and subduction dynamics***

The dramatic change along strike of many basic subduction parameters is one of the most important features of the AASZ. Synoptic studies that encompass the entire arc are needed to capture the effects of variations in these parameters. Synoptic studies provide essential data sets or analyses needed to understand variations in the inputs or outputs of subduction cycles and deformation. Knowledge of along-strike trends, variation or segmentation in the quantities measured by these studies will allow more robust conclusions to be drawn from the more focused investigations that will be done at a much smaller number of sites along the arc.

Five categories of synoptic studies are needed to complement the more targeted studies envisioned by GeoPRISMS: geology and geochemistry; geodesy; paleoseismology and paleotsunami; sediment flux; and broadband seismology. Such synoptic studies may not, in general, require systematic and expensive new data collection along the entire arc. 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 (defined in Section 2.2.7). Specific areas where significant data gaps exist may be targeted for new data. In the case of paleoseismic and paleotsunami studies, the number of high quality sites for carrying out studies will be limited, but spread out over the length of the arc.

2.2.5.1. Geology and Geochemistry

The AASZ provides a prime opportunity to understand how the magmatic output of a subduction system responds to along-strike variations in the physical parameters of subduction. The primary targets of synoptic studies in this disciplinary area are to determine the causes of along-arc variations in magma chemistry including pre-eruptive volatile contents.

The existing rock sample collection is extensive and provides the opportunity to develop a fully synoptic geochemical view of volcanic output for the AASZ. Large collections of Quaternary-age Aleutian lavas exist at several universities (e.g., Columbia, Cornell, Johns Hopkins, South Carolina, Wisconsin, Wyoming). Geochemical data from more than 2000 of these samples have been published or compiled in reviews and are publically available. The Alaska Volcano Observatory (AVO) holds a larger, more geographically extensive sample set, covering the whole arc with greatest focus on the Alaska Peninsula and Cook Inlet. The AVO collection includes approximately 3600 fully modern XRF and ICPMS whole-rock analyses from a single laboratory.

Despite the widespread availability of samples and decades of study, there remains a great opportunity to exploit the existing samples and gain new insights, especially for new isotopic studies. Available Pb, Sr, Nd and Hf isotopic data provide a clear view of geochemical changes to lavas along the Aleutian part of the AASZ. Further east, for volcanoes on the Alaska Peninsula and in southern Alaska, the availability of isotopic data is poor and insufficient to provide anything beyond the most basic conclusions about geochemical variability in the continental part of the AASZ. New isotopic studies of existing samples will therefore provide a basis for making detailed comparisons between the continental and oceanic parts of the arc, and for assessing the impacts of varying subduction inputs, convergence rate, slab geometry and overriding plate thickness. It is very likely that acquisition of a large quantity of high-quality isotopic data over the whole arc (for Pb, Sr, Nd and Hf), combined with existing major and trace element data, will reveal systematic differences from the Alaskan part of the arc that will be interpretable in the context of key questions about subduction magma genesis.

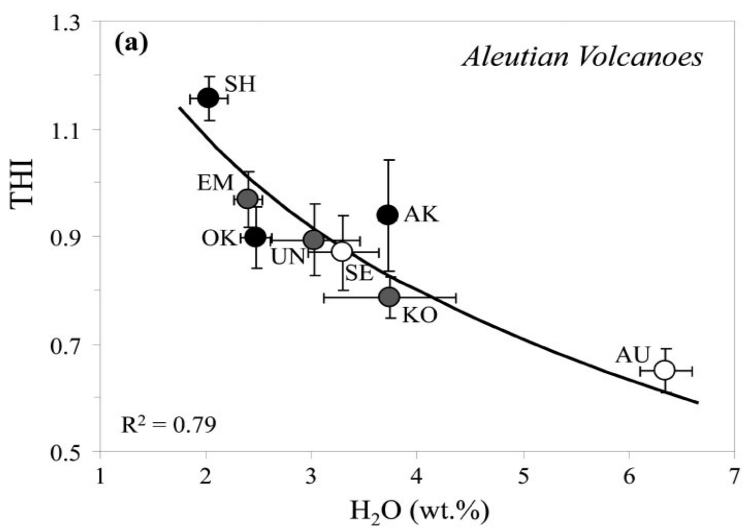

Figure 2.12. Graph of tholeiitic index (THI) versus pre-eruptive water contents from Aleutian melt inclusion samples. The inverse relationship indicates that water contents control whole-rock FeO/MgO variability (THI) and igneous series types (tholeiitic vs. calc-alkaline) expressed at Aleutian volcanoes. Sample locations are Shishaldin (SH), Mt. Emmons (EM), Okmok (OK), Unalaska Island (UN), Seguam (SE), Akutan (AK), Korovin (KO) and Augustine (AU). From Zimmer et al. (2011 – Figure 7a).

Storage, transfer, and release of volatiles through subduction systems were among the key topics motivating GeoPRISMS research in AASZ. Measurement of pre-eruptive volatile contents is therefore an area of disciplinary focus that should be pursued throughout the AASZ, wherever modern measurements have not been made and appropriate samples can be obtained. Volatile contents have long been known to play a central role in the control of subduction magma genesis (Figure 2.12). There has been a significant growth in recent years in the number of direct measurements of pre-eruptive volatile contents in melt inclusion and submarine glass samples from arc and back-arc locations. These results provide a much-improved basis for evaluating the role of water in controlling magmatic production rates and geochemical fluxes of volatile and related soluble metals which are abundant in arc lavas, and which play a central role in our understanding of how arc magmas are produced. Volatiles are one area where the existing sample collection (described above) probably does not represent a sufficient potential source of high quality data. This is because direct measurements of volatiles require well-quenched, melt-inclusion or submarine glass samples that retain their pre-eruptive volatile contents. Additional sampling of volcanic systems may therefore be justified, with the goal of producing a synoptic view of water and related volatile and elemental contents that can be linked to more widely available geochemical parameters which are already known to change systematically along-strike for large segments of the AASZ (Figure 2.12).

2.2.5.2. Geodesy

The primary focus of geodetic synoptic studies is on along-strike variations in the slip behavior of the seismogenic zone. The gross pattern of interseismic slip deficit and stress/strain accumulation is known for many segments of the arc, but data from the central Aleutians are almost completely missing. This leaves the major part of the rupture zone of the great 1957 earthquake unstudied. There are other data gaps in the eastern Aleutians and to a lesser extent along parts of the Alaska Peninsula segment. A more complete assessment of the interseismic strain pattern is needed to test whether or not the along-strike segmentation of present-day slip deficit matches the pattern of high and low slip in the last great earthquakes. The hypothesis that asperities and creeping sections of the interface are persistent features predicts that the interseismic slip deficit and coseismic slip will match each other. Mapping out the development of slip partitioning of oblique subduction in the central and western Aleutians is a secondary goal, a likely side benefit of additional data but not a top community priority by itself.

Individual studies, community experiments, or community expeditions to fill in the data gaps along the arc are needed, in addition to the studies discussed earlier that focus on already-known segmentation boundaries. Except where dense networks can be deployed, the likely spatial resolution for inverse models of variations in the seismogenic zone will be a few tens of km, so the top priority is for along strike sampling at approximately that spacing. Where the distribution of land allows it, it would be highly desirable to have sites at different distances from the trench. Even small trench-normal differences of ~10 km or so allow a measurement of strain that provides new information for models. GPS data already exist for the Bering Sea islands and back-arc areas of the mainland, so new data are needed only along the arc.

Earthquake cycle models are needed to relate surface site velocities to the slip history on the megathrust. The simplest models are elastic, and in that case the site velocity is proportional to the slip deficit distribution on the interface – that is, the strain on the surface is caused by the parts of the plate interface that are locked and building up stress for future earthquakes. To apply these models, the motion of the overriding plate must be known in addition to the relative plate motion. For the entire AASZ, the arc and forearc of the overriding plate move relative to North America, so motion of the arc relative to North America (or relative to the proposed Bering plate) needs to be estimated or accounted for. Data from adjacent segments can aid with this. In addition, the trench-parallel motion of the arc or a forearc sliver due to slip partitioning of oblique subduction needs to be accounted for. Potential effects of postseismic deformation will need to be considered for segments that have ruptured recently, although outside of the 1964 rupture zone there is no clear-cut evidence for ongoing postseismic effects today from any subduction event in Alaska.

Seafloor geodesy provides a complementary and potentially critical measurement to add to GPS observations on land. The limitation of land-based geodesy is that the ability to resolve whether the near-trench part of the interface is locked or creeping is nearly zero due to the shallow depth there and distance from the source to the sites. Seafloor measurements in the outer forearc would resolve this question. The enormous slip near the trench in the March 2011 Tohoku event raises a serious concern that the seismic potential of the near-trench region may have been dramatically underestimated. While the highest priority for seafloor geodetic studies would be in the Alaska Peninsula region, where the 1946 tsunami earthquake already provides evidence for a locked zone near the trench, such studies at any place along the arc would have considerable value and they should be considered at any location where opportunity permits.

2.2.5.3. Paleoseismology and Paleotsunami Studies

The primary focus of synoptic studies of paleoseismology and paleotsunami is to extend the temporal record of great earthquakes over several millennia. The instrumental record lasts only slightly more than 100 years, and the historical record no more than 250 years, and this record is not long enough to capture even a single full earthquake cycle for a great earthquake rupture. Information about past events will tell us if earthquake segment boundaries are persistent, and provide key information on the recurrence intervals. The prehistoric earthquake and tsunami record is needed to tell us whether the earthquakes of the last century are typical, are extreme events, or if much larger earthquakes can happen. This information is critical for accurate geohazards risk assessment, and thus brings with it strong broader impacts. It is likely that the number of potential paleoseismological or paleotsunami sites along the arc is limited, but they should be pursued wherever possible.

Paleoseismology in a subduction zone setting involves finding depositional evidence for abrupt changes in relative sea level caused by great earthquakes. Coastal marshes are generally required for preservation of deposits, and earthquakes smaller than the magnitude 8 range are probably invisible because they do not produce enough vertical coseismic displacement. Most of the Alaska-Aleutian subduction zone lacks paleoseismological data, with the Cook Inlet region being the exception. Paleoseismological data are scarce or absent along the Aleutian arc west of Kodiak Island. Paleoseismology research on the Alaska Peninsula and in the Aleutian Islands has great potential to test the temporal fidelity of spatial correlations between areas of high moment release, or asperities, during large earthquakes and forearc structure, or other competing hypotheses for the cause of asperities. Making precise measurements of the amount of vertical deformation over multiple earthquake cycles is the objective of a relatively new sub-discipline of paleoseismology called paleogeodesy. Along the temperate coast of western North America studies of the change in fossil diatom and foraminiferal assemblages associated with stratigraphic evidence of great earthquakes employ statistical transfer functions that estimate the precise (0.1-0.3 m resolution) amount of coseismic subsidence. This technique has been used for the AD 1700 Cascadia earthquake and the 1964 Alaska earthquake, but not for any part of Alaska outside of Cook Inlet.

Existing paleoseismological data in the Cook Inlet region chronicle nine megathrust earthquakes in the past ~5,000 years in the area of the Prince William Sound asperity of the 1964 earthquake.

At Girdwood and the Copper River Delta, geologic evidence for sudden land-level change and ^{14}C age data indicate a median recurrence interval for great earthquakes of ~560 years with a range of 333–875 years. However, regional correlations of paleoseismological records from Kodiak to Icy Cape reveal that variable recurrence intervals and heterogeneous rupture extents best characterize the history of the Alaska megathrust. For example, evidence from the Kodiak Islands suggests that this segment ruptured alone about 500 years ago. Yet, the penultimate earthquake considered similar in size to the 1964 event occurred 860–900 years ago and may have been larger if it also involved rupture of the Yakutat microplate. Still earlier predecessors, one about ~1480 and another in 2130 years ago, are also considered similar to the 1964 event because evidence of coseismic displacement overlies the Kodiak and PWS segments of the megathrust. The spatial extent of older earthquakes is less certain because of incomplete paleoseismic records in most of the region.

Paleotsunami investigations along shorelines of the Aleutian Islands and the Alaska Peninsula may yield important information on the frequency of large tsunamis, their spatial extent and contribute empirical data that can be used to estimate the hydrodynamic properties of the waves, including flow depth and flow speed. Paleotsunami data can also be used to validate and improve tsunami hydrodynamic models used for hazard mitigation. Paleotsunami investigations along the Alaska-Aleutian arc can provide crucial data to estimate tsunami recurrence intervals, characterize the source mechanisms and assess inundation hazards for vulnerable communities in Alaska and around the Pacific Ocean. The recurrence interval of such outsized tsunamis such as the 1946 event at Unimak Island in the Aleutians is unknown. The 1964 M_w 9.2 Prince William Sound earthquake caused $430 million in damage and killed 106 people in Alaska, 5 in Oregon and 13 in California. Yet despite these risks, predecessors to these tsunamis are poorly known. In the remainder of the Aleutians, there are no paleostunami data at all, although shoreline sampling by Gary Carver showed evidence for sand beds interpreted as deposition from repeated large tsunamis. This anecdotal evidence suggests that the record of paleotsunamis may be present and a critical first step is to carry out reconnaissance assessments of potential sites, perhaps as part of a community expedition. The most promising sites could then be targeted for focused studies.

2.2.5.4. Sediment Flux

The primary focus of synoptic studies of sediment flux is to characterize the lithological input into the AASZ (Figure 2.6). This is an essential parameter that affects both the physical properties of the subducting slab and the volatile budget of the system. The input of hydrous phases and thermal state constrain the dehydration reactions and subsequent metamorphic reactions. Subduction of a thick section of trench-floor sediment may create a sediment-packed subduction channel that mechanically smooths the subducted sea-floor relief, favoring lengthy trench-parallel rupture during a megathrust earthquake. For all of the above, the incoming sediments must be fully characterized along-strike at representative sites that reflect the main variations in sedimentology-lithology (both composition and thickness) and thermal regimes. However, incoming sediment composition is poorly known because there are only three existing DSDP drill sites. Sediment thickness in the trench is known from crustal-scale seismic data at only a few locations. Seismic reflection profiling and swath bathymetry with targeted coring and drilling are the only methods to constrain these parameters. GeoPRISMS geophysical investigations along the arc should include complementary sampling of sediments wherever possible. Targeted studies of sediment properties would ensure a more complete coverage.

Along-arc variability in incoming sediment flux is a dominant characteristic of the AASZ (Figure 2.6). A dominant terrigenous source exists in the northern Gulf of Alaska, whereas hemipelagic and more diatomaceous material accumulates on the Pacific plate towards the western Aleutians. Three major sediment bodies lie atop the subducting Pacific Plate: the Surveyor Fan, the terrigenous outwash body that comprises the majority of the Alaska Abyssal Plain; the Kodiak-Bowie Seamount Chain and the inactive Zodiac Fan; and an axially-deposited wedge of Aleutian Trench fill that lies atop the subducting Surveyor and Zodiac Fans. The along-strike variation of sediment thickness arriving at the Aleutian Trench has clearly affected the size and shape of the accretionary prism and forearc; the width and thickness of the prism decreases substantially towards the distal Aleutians. Any increase in sedimentation to these systems could extend the transition from accretionary to non-accretionary/erosional subduction system. A five-fold increase in sediment delivery to the Aleutian Trench during the Pleistocene may have altered subduction zone dynamics through significant along-strike and temporal variations in the incoming sedimentary section, and sediment loading within forearc basins. Lastly, the AASZ is unique in its incoming lithology, as diatoms comprise a significant portion of the subducting sediments. Whereas the subduction of clays results in a limited number of dehydration steps, diatom dehydration occurs over a range of temperatures that results in more complex patterns of volatile release. Diatoms, if at high concentration, also strongly affect the physical properties of sediments, in particular, the permeability and the porosity reductions with burial depth.

2.2.5.5. Passive Seismology

Synoptic studies involving passive seismology would be aimed at (1) improving information about the distribution of earthquake and tremor sources, (2) mapping the crustal thickness, (3) crust, slab, and mantle wedge velocity and attenuation structure, (4) and shear-wave anisotropy below the arc. By integrating new high-precision earthquake locations for "background" seismicity (and any large earthquakes that do occur) with existing long-term regional and global catalogs, a clear picture of the seismogenic megathrust will emerge. When coupled with tremor and geodetic observations, a more complete picture of the spatial patterns of megathrust behavior will emerge. The seismic velocity structure and thickness of the crust provides critical information for understanding crustal growth. Similarly, down-going slab and mantle wedge structure (velocities and Q) provide insight into initial slab hydration, dehydration processes, and melt generation and migration paths. Shear-wave splitting data are a unique and critical source of information regarding mantle flow patterns.

The standard toolbox of passive seismic imaging will be applied, including body-wave and surface-wave tomography (including ambient noise techniques), attenuation tomography, receiver function imaging/migration, and shear-wave splitting analyses. The application of these passive techniques to explore the structure of the crust and mantle beneath the AASZ is an important complement to active source imaging. For the continental part of the arc, temporary arrays deployed within the backbone of USArray, coordinated with OBS deployments and marine seismic profiling, will extend the length, width, and penetration depth of such profiles. Dense array studies of active volcanoes are also a high priority. Offshore islands, in particular Kodiak, provide excellent opportunities for carrying out large array studies in the forearc. For the marine portion of the arc, the strategies would be similar, but much more emphasis would necessarily be placed on OBS deployments. This is strong motivation for bringing the Amphibious Array to Alaska.

2.2.5.6. Magnetotellurics

Magnetotellurics (MT) is widely recognized as an important component of lithosphere and especially volcano imaging efforts, given that the conductivity of melt is significantly higher than that of the surrounding crust. Melt conductivity is also a function of temperature and composition. Dense networks of 3D broadband MT stations can be used as part of integrated experiments to image the structure inside volcanoes as has been done in other locations. There is a growing pool of instrumentation for land MT operated as a national facility through Oregon State University that would be available for GeoPRISMS field projects.

2.2.6. Numerical and Experimental Studies

Numerical and experimental studies will prove important for the AASZ, as they provide a means to integrate interdisciplinary field observations, test fundamental hypotheses, and constrain critical parameters that govern observed phenomena. Geodynamic modeling can serve as a synthesis activity, bringing together a variety of geological, geophysical, and geochemical data and interpretations into a broader framework that can be used to constrain ideas and make testable predictions.

2.2.6.1. Experimental Studies

Experimental studies are an important means to better constrain material properties and to test hypotheses developed from field observations. Representative studies include laboratory measurements of rock and fault gouge frictional behavior, in order to evaluate the role of rock composition and physical properties, as well as state variables (pressure, fluid chemistry, and temperature) on fault sliding stability, and the origin of specific slip behaviors, including episodic tremor and slow slip. Laboratory experiments can also provide insights into the linkages between surface processes, sediment transport, and accommodation, linked to both field and theoretical studies. Similarly, laboratory experiments provide a direct approach to quantify the effects of hydrous fluids and melts on mantle rheology relevant to the origin of arc volcanoes and volatile fluxes. Experimental studies are also essential for establishing the physical conditions of subduction zone fluid and melt formation and evolution. Without experimental constraints, the significance of volcanic and plutonic rock compositions and their variability through time and space at the earth's surface cannot be unambiguously understood. A holistic approach involving an experimental component will be particularly important. Fluid and melt formation and migration through subduction zones constitutes a complex problem of reactive transport and heterogeneous equilibria that can only be understood by coupling detailed laboratory constraints (experimental mineralogy, petrology, geochemistry) with observations of bulk physical properties on a lithospheric scale (geophysical data) and with a detailed knowledge of the petrology and geochemistry of volcanic and plutonic rocks, which constitute the end products of subduction crustal genesis. All of the resulting data can be incorporated into geodynamic models that test specific hypotheses for the AASZ, including the dynamics controlling slab dip, anisotropy and flow in the mantle wedge, and the slip behavior of the slab/mantle interface.

2.2.6.2. Numerical Modeling

Regional 3D geodynamic models can be used to investigate several SCD thematic questions, for example:

Plate-mantle decoupling in subduction zones: Away from subduction zones, the surface motion of oceanic plates is well correlated with mantle flow direction, as inferred from seismic anisotropy. However, this correlation breaks down in subduction zones where shear wave splitting studies suggest the mantle flow direction, both in the mantle wedge and beneath the slab, is spatially variable and commonly non-parallel to plate motions. This implies local decoupling of the lithosphere from the mantle, yet the magnitude of this decoupling is poorly constrained. Regional 3D numerical models, constrained by subduction zone geometry and observations of seismic anisotropy, can be used to further explore this decoupling of mantle flow from surface plate motion, in terms of both direction and magnitude.

Evolution of deformation in space and time: Possible modeling targets include the rheological characteristics of the megathrust, thermal evolution of the down going slab and overriding plate, long-term evolution (>10 Ma) of the plate boundary and developing embedded models with higher resolution geological, geophysical and topographic inputs to explore components of the system.

Feedbacks between tectonic and surface processes: Sophisticated models are available for both crustal and surface processes; however, a complete description of an active landscape requires characterization of the interation between these processes. At present, available evidence of such coupling is rudimentary at best. Consideration of temporal and spatial variability in material erodibility is currently lacking in most surface process models. Application of strain-softening material to lithosphere-scale models of the central Southern Alps of New Zealand and Namche Barwa in the Eastern Syntaxis of the Himalayan collision illustrate the time dependent variability of material strength fields within actively deforming regions. The addition of similar type strain-softening materials coupled to glacially driven erosion should be a next step in geodynamic/geomorphological models of the Alaskan margin, facilitated by the Community Surface Dynamics Modelling System (CSDMS) Group. Mesoscale atmospheric models now can be used to condition the surface boundary.

Short term vs long term strain: Identification of long-period great earthquakes is problematic as on many margins the last event occurred prior to reliable historic records. Although some structures are clearly evident through transitional paleoseismic studies, the signals of many structures reside in the permanent strain fields over the past 10 kyr. It is necessary to add to our tools that aid identification of characteristic geological/topographic signals in the landscape that can be used to identify locations of great earthquakes that have occurred outside the historic record. Linking kinematics of the permanent strain field to high-frequency topography using the evolving geomorphic theory of tectonic:surface coupling can provide constraints on timing and location of low-frequency, great earthquakes.

2.2.7. Research Strategies and Partnerships

2.2.7.1. Shared Logistical Support for Remote Field Studies - "Community Expeditions"

The costs in time and dollars of moving people and equipment to and from remote locations in the AASZ are substantial, and in many cases place significant limitations on the research goals that can be achieved. One step toward maximizing efficiency and lowering field support costs would be to operate projects in tandem that have similar field support needs, and can therefore be supported from a common, and perhaps mobile, logistical base. One can imagine for example, a helicopter operating from the deck of a ship, moving east-to-west along the arc, supporting a variety of scientific groups at different locations throughout the 3-month Alaska field season. Such an effort might be proposed as a "community expedition", a direct analogue of the community experiments envisioned for the collection of large offshore geophysical imaging data sets. On a smaller scale, centers of logistical support could be established at remote airstrips and in other places where fuel and supplies can be safely cached, and where a common base of field operations could be established and used by diverse groups. This approach to logistical support would require diverse groups, which may or may not have common scientific goals, to collaborate and coordinate their field operations in a detailed way. The potential payoff in terms of cost savings and expanded scientific opportunities would be potentially great.

In order to manage such logistical complications associated with conducting field work in the AASZ, upcoming field activities and community planning events could be announced on a website, facilitating partnerships among investigators. Ideally, the website or wiki page could be hosted by GeoPRISMS and mentioned in any program solicitations from NSF.

2.2.7.2. Community Experiments

Large onshore-offshore geophysical datasets are among the critical observations needed to address the core science questions in some of the geographical focus areas. The GeoPRISMS community and the broader earth science community have embraced the concept of acquiring some large geophysical datasets as community efforts when it's possible and makes sense 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 expressed enthusiasm for community experiments in Alaska where possible.

2.2.7.3. Amphibious Array Facility (AAF) in Alaska

There is great scientific potential if the Amphibious Array Facility (AAF) were to move to Alaska. This $10M facility, funded by NSF in 2009 through ARRA (American Recovery and Reinvestment Act) for understanding hazards in the Pacific Northwest, is currently deployed in Cascadia as part of the Cascadia Initiative (CI). The funds, channeled through UNAVCO, IRIS, and OBSIP, were used to improve real-time GPS capabilities, densification of the onshore seismic networks, and to construct ocean-bottom seismometers (OBS) to better record offshore earthquakes in the region. The CI has a finite duration of 4 years, with the expectation that the onshore and offshore components of the AAF will likely move together to other locations following the completion of the CI. In the context of the ongoing EarthScope and GeoPRISMS programs, high priority locations include Alaska and the East Coast of North America. A community workshop in 2014 has been proposed as a venue to decide on the next deployment of the AAF.

There are compelling reasons to redeploy the AAF in Alaska. Alaska is the clear choice in terms of adhering to the earthquake hazards issue that was central to the initial funding of the AAF. There are ~5 times the number of earthquakes within Alaska each year as in all of the lower 48 states combined, and there is significant potential for hazardous high magnitude subduction earthquakes and tsunamis. Alaska was also the top choice of the GeoPRISMS community for subduction zone research. In 2014, USArray is expected to begin deployment in Alaska, subject to funding. Therefore by 2015, USArray should be well established in southern Alaska to provide synergy for AAF deployments. PBO has been fully deployed in Alaska since 2008 and time series are now mature, although there certainly could be opportunities for station upgrades, high-rate, low-latency GPS observations, and targeted station densification. A key aspect of GeoPRISMS efforts in Alaska will be the need for coordinated research efforts with shared logistics, given the short field season and relatively high field costs. This defines a unique opportunity to deploy the AAF in Alaska to take full advantage of the synergy with GeoPRISMS and EarthScope.

2.2.7.4. EarthScope Program

In addition to the collaborative CI Amphibious Array Facility, a variety of current and future EarthScope activities in the AASZ are apparent above, demonstrating the common scientific objectives with GeoPRISMS. Ongoing cooperation between the two programs is anticipated, particularly given the complementary nature of the GeoPRISMS and EarthScope research strategies. The pending deployment of EarthScope's Transportable Array (TA) to Alaska will provide an important framework for more focused onshore-offshore studies, particularly in the Cook Inlet area (Figure 2.11). Geophysical imaging along the Aleutian Arc will augment lithospheric scale studies in continental Alaska. The current recommendation to IRIS is that a single trans-Alaska long-period magnetotelluric profile utilizing the existing road network be carried out as part of Earthscope TA array data collection. This profile would largely follow the TACT line but could include some additional stations closer to the trench, such as on Kodiak Island. EarthScope's PBO facility is already gathering critical geodetic observations relevant to focused studies of megathrust processes, as well as proposed GeoPRISMS synoptic studies. Continued coordination between GeoPRISMS and EarthScope investigators is encouraged and expected to lead to strong synergistic collaborations.

2.2.7.5. USGS and NOAA Cooperation

Addressing GeoPRISMS science objectives in the AASZ can benefit by coordination with other state and national agencies and entities active in southern Alaska.

There are opportunities for partnerships with the USGS. The USGS part of the AVO conducts an extensive volcano monitoring and research program throughout the Alaska-Aleutian arc. AVO welcomes GeoPRISMS research on these volcanoes and related volcanic and tectonic processes. USGS scientists will endeavor to participate in, and facilitate, GeoPRISMS research. Interested researchers should contact AVO staff to discuss collaboration. The USGS also conducts paleoseismology and paleotsunami research along the Alaskan margin. There may be opportunities for collaborative work with this group of researchers as well, because their goals for the Alaska Peninsula region are similar to those in this Implementation Plan. Lastly, the Earthquake Hazards Program of the USGS is encouraging researchers to submit proposals to its external grants program that complement existing or planned GeoPRISMS proposals. There is plenty of overlap in the objectives of GeoPRISMS and this grants program, so this potential source of funding may be useful for some researchers, and collaborative proposals with the USGS may also be developed.

NOAA also has considerable interests along the southern margin of Alaska, in particular for improving tsunami impact forecasts. Any information that leads to better assessment of tsunami generation along the southern Alaska margin is valuable to the tsunami warning centers. In particular, present tsunami inundation models and evacuation plans could be inadequate if giant tsunamis like that generated by the Tohoku event occured in Alaska; paleotsunami studies will be critical for revealing whether or not this is the case. NOAA collects the definitive bathymetric datasets for all US waters, and through the Alaska Interagency Hydrography Working Group, they encourage collection of higher quality bathymetry that may be incorporated into NOAA bathymetry maps, which are then available for all to use. NOAA has volunteered to help with multibeam data acquisition plans, and may be able to provide tide gauges during data collection. Lastly, fisheries researchers within NOAA also collect bathymetry data, and there may be opportunities for collaborating with them for shallow water (<200 m) data acquisition.

2.2.7.6. International Collaborations

Aleutian crustal genesis and subduction-initiation studies described in Section 2 of this document will be closely coordinated with complementary studies that are ongoing under the German-Russian KALMAR Project (http://kalmar.ifm-geomar.de/?Home). All offshore work funded under GeoPRISMS for the sampling of Aleutian basement outcrops should be coordinated with work of the *R/V Sonne* done under KALMAR. The KALMAR work will focus on dredging of the fore-arc in the Adak area and locations further west, where strike-slip faulting and block rotation has produced steep slopes and abundant basement outcrops in the Aleutian fore-arc. Dredging targets for the KALMAR cruises will include Adak Canyon and Murray Canyon – the two major submarine canyons of the Aleutian fore-arc, which have been so far explored only in reconnaissance by prior cruises. Areas of extensive basement outcrop in the fore-arc located by dredging on KALMAR cruises should be investigated in detail by ROV-supported geologic mapping and sampling in follow-up cruises funded under GeoPRISMS. The KALMAR cruises will also focus on dredging of basement outcrops on the incoming Pacific Plate. This work will extend as far east as the Amlia Fracture Zone, but will be focused primarily from the Adak area west. Geochemical studies of rocks from the Pacific side of the trench will provide control over the nature of subduction inputs, which are poorly known but are vital to interpretation of the geochemical evolution of the arc crust.

2.2.7.7. International Ocean Discovery Program Opportunities

The International Ocean Discovery Program (IODP) is proposed as a 10-year program beginning in 2013, with a focus on four main research themes, two of which have strong synergy with the goals of GeoPRISMs and SCD science in particular: Earth in Motion and in Earth Connections.

Several SCD research targets in the AASZ, such seismogenic zone segmentation, mass fluxes, and the fate of volatiles can be addressed through scientific drilling. Earth in Motion addresses dynamic processes that occur on human time scales, including those leading to and resulting from earthquakes, landslides, and tsunami. Scientific ocean drilling can resolve the frequency, magnitude, mechanisms, and impacts of these events. Documenting the controls on the timing, size, nature, and effects of megathrust earthquakes is important for characterizing associated hazards and for understanding the underlying mechanisms that may control the nature of slip, and determine why there is such a variability in seismic behavior along the AASZ. Given the high rate of seismicity in the AASZ, scientific ocean drilling is well positioned to elucidate earthquake and faulting processes possibly through continuous, real-time monitoring from subseafloor observatories installed in boreholes. Scientific ocean drilling at key input locations along the AASZ can also explore fluid flow in seafloor sediments and volcanic crust determine how much CO_2 and water are fed into subduction zones, where their return to the surface may dictate the along-strike variability in Aleutian arc magmatism. Proposed drilling expeditions in the AASZ region can be organized through workshops that identify potential scientific objectives and research opportunities in the region. The dissemination of existing site survey data and plans for acquisition of new data would be a key component of these workshops.

2.2.7.8. Rapid Response

The frequent seismic and volcanic activity in the AASZ illustrates the potential for large magnitude events that would require a rapid response to document post-event processes. Examples of recent events that NSF has supported with Rapid Response Research (RAPID) grants are the 2010 earthquakes in Chile and Haiti, the 2011 earthquakes in Japan and New Zealand. Examples in Chile of such a response is the collection of an open community dataset using portable seismograph deployments supported by the IRIS Consortium to record aftershocks for approximately six months post-event and the marine geophysical characterization of structural changes in the seafloor that resulted from movement along faults and submarine landslides (SIOSEARCH). A rapid response program for an event in the AASZ should leverage existing infrastructure and logistical knowledge of the AVO and USGS.

2.2.9. Broader Impacts

2.2.9.1. Geohazards

Fundamental contributions to understanding earthquake and tsunami hazards can be made through GeoPRISMS. Studies of the Alaska Peninsula and the Amlia fracture zone can help us understand the geologic controls on megathrust ruptures, variations in locking behavior along the megathrust, and tsunami generation. In the aftermath of the devastating tsunami that resulted from the 2011 M9.0 Tohoku Japan earthquake, concerns are heightened as to whether a similar tsunami could be generated along the Alaskan-Aleutian subduction zone. A Tohoku-like tsunami triggered by an earthquake along the Alaskan margin would cross the Pacific Ocean and cause extensive damage along the highly populated U.S west coast and Hawaiian shores, with ports being particularly vulnerable. As a case in point, a tsunami caused by a near-trench earthquake in 1946 off Unimak Pass caused significant damage along the U.S. west coast, took 150 lives in Hawaii, and inundated shorelines of south Pacific islands and Antarctica. Currently, assessments of the seismic and tsunami potential of the Alaska margin lag far behind assessments of the

Cascadia margin, despite the fact that 4 of the twelve instrumentally recorded giant earthquakes ($M_w \geq 8.5$) that have occurred worldwide were from the Alaska margin.

The chief hazard presented by volcanoes of the North Pacific region is from airborne clouds of volcanic ash, which can severely damage and disable jet engines of aircraft that inadvertently fly through them. Accurate forecasting of eruptions and close monitoring of ongoing eruptions by AVO and other groups provide the most direct approach to alleviating volcanic hazards to air traffic over the North Pacific. At a basic research level, the GeoPRISMS focus on the storage, transfer and release of volatile components in magmas, provides an opportunity to better understand the interrelationships of volatile contents, magma chemistry and eruption dynamics that underlie the processes by which volcanic ash is formed. Direct measurement of volatile species and related elemental abundances (H_2O, CO_2, F, Cl, S) in melt inclusions in tephra from a large variety of AASZ magma types will create linkages between key volatile components (especially H_2O), and other more widely known geochemical parameters. Linking these geochemical measurements to textural features in volcanic ash, which record the physical characteristics of eruptions, will greatly expand the database of observations in natural samples from which the dynamics of explosive eruptions may be inferred and modeled. For some volcanoes, geophysical data collected by GeoPRISMS will complement these volatile studies, allowing for more complete hazard assessments or improved monitoring. AVO and GeoPRISMS scientists can work closely on this problem; AVO will actively use any seismic and geodetic data supported by GeoPRISMS that are available for enhanced volcano monitoring capability.

2.2.9.2. Student and Teacher Involvement

Established pathways exist through GeoPRISMS and EarthScope to convey important GeoPRISMS research results in Alaska into college classrooms around the country, including through the development of GeoPRISMS mini-lessons and the GeoPRISMS Distinguished Lectureship Program. Both resources can also be adapted to younger or informal science audiences, enhancing broader impacts on local communities in Alaska. Involving nearby schools and communities in instrument deployment and data collection has also proven effective in engaging residents in scientific activities in their area. Efforts to develop a GeoPRISMS REU program would also enable new training opportunities for future scientists interested in Alaskan studies. Cooperation with existing state-wide programs will further these activities as research ramps up in the Alaska Primary Site.

2.2.9.3. Engaging Local Communities

Small, relatively isolated towns are sprinkled across the Aleutian Islands, Alaska Peninsula, and Cook Inlet. Larger communities and Alaska's main city (Anchorage) are located within the Cook Inlet region. Residents in these areas are routinely exposed to the hazards associated with the subduction zone. But because many communities are accessible only by boat or plane, outreach poses particular challenges. GeoPRISMS activities in Alaska offer an excellent opportunity to connect with people who live next to this active plate tectonic boundary. Scientists can take the opportunity to visit schools and give community presentations while visiting remote communities. Deploying instruments near schools is another means to engage young people and educate them on their surroundings. Education and outreach efforts should also involve follow-up with local communities on the results of scientific investigations in the area (not just visits during field campaigns) either in person or remotely (e.g., via video conference).

2.3. Cascadia Margin – Primary Site

(Replaced June 20, 2012)

2.3.1. Background and Motivations: Relationships to SCD

The Cascadia subduction zone, extending from Northern California through southwestern Canada (Figure 2.13), juxtaposes a tectonically and volcanically active region with large population centers in western North America. A unique opportunity exists in the Cascadia region to gain an unprecedented view of the spectrum of active processes that influence the behavior of subduction zones, because the region is highly accessible for fieldwork and a wealth of co-located research efforts offers the rare prospect of integrating and building upon multiple community experiments and infrastructure. In the geologic record, this margin reveals a history of terrane accretion, arc evolution, large megathrust earthquakes and frequent volcanic eruptions. The structure of the Cascadia arc appears segmented in a variety of geological and geophysical parameters, including volcanic distri-bution, seismic properties of the mantle, and incoming plate structure and sedimentation. The subducting plate at Cascadia is the youngest and hottest on Earth, making this system a global end-member.

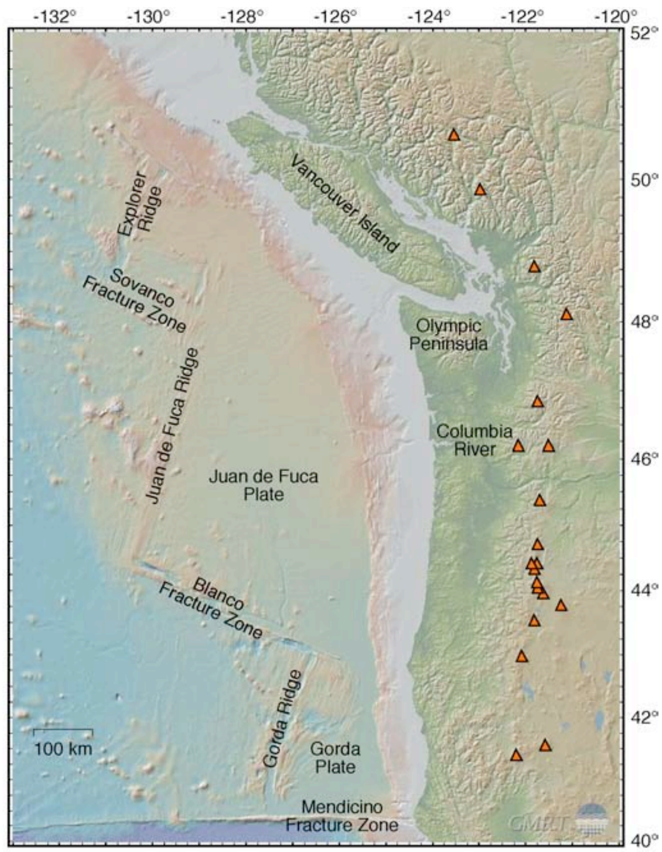

Figure 2.13. Bathymetry & topography of the Cascadia margin and associated tectonic elements. Significant arc volcanoes indicated by orange triangles. Map generated using GeoMapApp.

The GeoPRISMS community, through a series of planning workshops, designated the Cascadia subduction zone as a Primary Site at which all of the Subduction Cycles and Deformation Initiative key topics may be addressed.

• *Controls on size, frequency and slip behavior of subduction plate boundaries*

Paleoseismic evidence, gathered through both onshore and offshore studies, suggest recurrence intervals for large Cascadian earthquakes on the order of 300-500 years, with shorter recurrence intervals in the southern part of the margin. The most recent M9 earthquake occurred in 1700, and the Cascadia margin may be due for a large earthquake. Downdip of the seismogenic zone, the Cascadia plate interface also accommodates relative plate motion by slipping purely aseismically and in a transitional mode that includes transient seismic and aseismic slip. Focused geophysical studies continue to advance understanding of the temporal and spatial distribution and processes underlying these slip modes.

• Spatial-temporal deformation patterns during the seismic cycle

The response to the current state of stress and deformation in Cascadia exhibits a range of seismic behaviors, from relatively active beneath Puget Sound, to relatively quiet throughout western Oregon and the Olympic Peninsula. Geologic studies reveal a variety of long-term responses to plate boundary deformation throughout Cascadia. Along-strike segmentation in tremor and slow slip occurrence, the locations of offshore sedimentary basins, and other geophysical characteristics suggest linkages between processes acting from the near-surface to the plate interface. The dimensions and simplicity of Cascadia relative to other subduction zones, and its accessibility, make it ideal for thoroughly characterizing and understanding subduction zone deformation at many scales.

• Volatiles and the rheology/dynamics of the plate boundary interface

The release of volatiles from the subducting plate may play an important role in controlling the rheology of the plate boundary interface and the depth at which the subducting plate becomes coupled with the overlying mantle. Yet, geophysical observations suggest that the coupling depth may be universal for all arcs, at ~70-80 km. Differing devolatilization regimes for slabs with contrasting thermal states may thus not exert the primary control on this key variable. Testing hypotheses in Cascadia, where the slab is a hot global end-member, is needed to advance our understanding of the interface between the subducting and overriding plates, and mantle wedge.

• Storage, transfer, and release of volatiles through subduction systems

Models and observations of the metamorphic petrology of the subducted slab, key mineral phases, and devolatilization reactions at Cascadia will provide end-member constraints on the transport and distribution of volatiles throughout a region with a hot subducting plate. The identities, properties, and migration pathways of volatiles may closely relate to the slab petrology and the P-T-fO_2 conditions of the slab and mantle wedge. Relating these variables with observations of the compositions and patterns of volatile release at the surface, through volcanism and hydrothermal activity, are central to understanding the driving forces of magmatism at Cascadia and global arcs.

• Geochemical products of subduction and creation of continental crust

The Cascades arc is characterized by large, relatively silicic stratovolcanoes, with isolated, small mafic volcanism interspersed between the major edifices. Constraints on the net magmatic composition and magmatic flux of the Cascades arc are needed to assess the role that this arc may play in creating continental crust. The Cascades arc has migrated eastwards with time, leaving behind an exposed plutonic record in the west, ideal for accessing temporal changes in magmatic composition and distribution, and the inter-crustal magmatic systems that often are not erupted at volcanoes, and may link closely to the overall crustal evolution of the Cascades and arcs in general.

• Subduction zone initiation and arc system formation

Understanding the formation of the Cascadia subduction zone requires understanding the origin of the Siletz and Crescent terranes, thick accumulations of tholeiitic basalt forming the basement of the Oregon and Washington Coast Ranges. Siletz terrane basalts predate the earliest magmatic rocks of the Cascade arc by ~15 Ma and are thrust beneath the margin, suggesting an allochthonous origin. Was it an accreted oceanic plateau that collided with N. America, forcing the subduction zone to jump to the west? Or is Siletzia related to ridge-trench interactions, or perhaps the result of subduction initiation, similar to that suggested for the Izu-Bonin-Mariana arc system? Understanding the origin of the Siletzia terrane could be an important part of integrated study of the Cascadia convergent margin, clarifying how the Cascadia margin evolved and behaves today. Constraining the timing and geometry of the pre-subduction system, and the specific role of Siletzia in the initiation of subduction, is central to refining models of how subduction initiates on Earth in general.

• *Feedbacks between surface processes and subduction zone dynamics*

Cascadia is an exceptional natural laboratory to investigate feedbacks between surface processes and subduction zone dynamics. Recurring megathrust ruptures along the subduction zone impart immediate and long-term impacts to sediment production, dispersal, and deposition along the margin. Coseismic vertical displacements near the coast alter stream base level, which influences rates and patterns of estuary sedimentation. The impulsive coseismic shaking may also generate prodigious landslides, possibly resulting in channel aggradation and landslide-dam lakes that modulate sediment dispersal to coastal environments. Natural disturbances, such as storms and fire, have been shown to drive pulses of sediment yield along the margin, but the relative contribution of earthquake-driven fluxes remains unknown. As a result, substantial work is required to document the suite of mechanisms that drive terrestrial sediment fluxes to the continental shelf and eventually to the subducting plate. Over millenial and longer timescales, the accretionary flux into the subduction zone has been quantified for portions of the margin, although the balance of sediment accretion and erosion is poorly constrained across most of Cascadia. Sediments on the down-going slab have been implicated in slow-slip events, as well as other subduction zone processes, which emphasizes the importance of documenting sedimentary processes and records.

2.3.2. Cascadia Margin

> *The Cascadia Margin offers opportunities to address all of the SCD topics, but is particularly well-suited to exploring the nature and origin of the well-expressed episodic tremor and slip (ETS) and its relationships to great megathrust earthquakes. The young age of the subducting slab at Cascadia defines a thermal end-member for global subduction zones, enabling unique studies to understand the conditions and processes by which slabs dehydrates and arc magmas are generated. Along-strike changes in many different processes and properties enables fundamental questions about the origin of arc segmentation to be studied in a compact setting.*

The active Cascadia subduction system became established by the middle Eocene and produced voluminous magmas in the Oligocene through the Miocene; subsequently, arc igneous activity diminished. The system is notable worldwide for the youth, and therefore high temperature, of the subducting Juan de Fuca plate. The arc is also strongly segmented, and this is evident in a number of diverse data sets (geophysics, seismicity, volcano age and distribution, geochemistry, geodesy and paleogeodesy, etc.), although the ultimate causes remain unclear. In part this likely reflects the changes in tectonic setting of the arc, which varies from south to north, with impingement of the Basin and Range extensional province onto the eastern margin of the arc in northern California and southern Oregon, a weak graben along the arc axis from central Oregon to the Columbia River, and widespread basement uplift from central Washington northward into British Columbia. GPS measurements show weak cross-arc extension and right lateral displacement in the south, passing to arc-normal convergence across the strongly uplifted North Cascades. Paleomagnetic studies concur with Tertiary rocks in the southern and central parts of the arc having rotated clockwise and translated westward and northward as the Basin and Range opened to the northwest. Volcanic style correlates with neotectonic and geomorphic differences, with widespread basaltic volcanism and interspersed andesitic stratovolcanoes in northern California through central Oregon, passing to isolated andesitic and dacitic stratovolcanoes from southwest Washington into British Columbia. Diminution, isolation, and increased evolution of volcanic centers with increased basement uplift and arc-normal convergence are evidence for an important role for the crust and lithosphere in modulating magmatism.

This roughly 1000 km long region spans the subduction of the Juan de Fuca (JdF) and Gorda plates beneath North America from Vancouver Island in the north to Cape Mendocino in the south, with convergence rates of ~3-4 cm/yr (Figure 2.13). The subduction of the JdF plate has produced many great earthquakes, most recently in 1700 AD, with recurrence intervals on the order of ~500-600 years based on paleoseismic studies. Recent studies of the processes on this megathrust have focused on slow slip events and non- volcanic tremor, especially down-dip of the inferred interseismically locked region. Evidence suggests that the characteristics of these Episodic Tremor and Slip (ETS) events vary along the entire Cascadia seismogenic zone, with along-strike segmentation possibly related to changes in the upper plate geologic structure and past rupture boundaries for the great earthquakes.

The Cascadia subduction zone is the only region of the lower 48 states likely to produce a Mw 9 earthquake and has the greatest potential for volcanic eruptions. There is a significant body of work documenting great earthquakes extending back 10,000 years; the size, composition, and timing of Quaternary volcanic eruptions; and a wide range of fault slip behaviors, including slow and "normal" earthquakes, and non-volcanic tremor. A trove of new geological, geodynamic, and geophysical data has recently been collected and more will be forthcoming in the next four years thanks to NSF investments in EarthScope and the onshore/offshore ARRA-funded Cascadia Initiative. GeoPRISMS has the opportunity to facilitate the maximum scientific payoff from this investment through its interdisciplinary research community. Because of these investments, Cascadia-related GeoPRISMS research is able to begin immediately, with valuable outcomes emerging in the coming few years.

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

NSF has enabled an ongoing community collection of onshore and offshore data by way of the EarthScope program and the ARRA-funded Cascadia Initiative. The Cascadia Initiative provides dense OBS coverage in several regions of interest to the GeoPRISMS community, as well as a real time 1 Hz GPS network and densified seismic coverage onshore expanding that provided by the Pacific Northwest Seismic Network and Berkeley Digital Seismic Network. These data are complemented by a significant investment by the Canadian government in the NEPTUNE-Canada observatory to instrument the northernmost portion of the margin both on and offshore and planned installation of an observatory offshore the central Cascadia segment as part of the NSF Ocean Observing Initiative.

There is a wealth of other existing datasets including, but not limited to:

- Well-documented ETS catalogs, delineating multiple cycles and segments.
- Continuous and campaign GPS and other land-based geodetic measurements that densely cover the entire margin to allow the study of the locking state of the megathrust and the deformation of the upper plate.
- A comprehensive paleoseismic record for subduction zone earthquakes.
- Substantial ocean drilling results, including Legs 139, 146, 169, 173 and 204, and Expedition 311, spanning from southern Vancouver Island through Oregon and northern California.
- A series of 20th century 2-dimensional multichannel seismic and 2 and 3-D active-source, large-aperture onshore/offshore surveys collected by US and international investigators, which are available to guide planning for modern 3D studies.
- Baseline onshore 3D seismic tomographic images derived using core US-Array and investigator-driven higher resolution seismic arrays combined with data from regional and teleseismic earthquake sources.
- Onland geologic mapping of forearc and backarc structure and volcanic features.
- Geochronologic and geochemical studies of Quaternary volcanic edifices. Much of these data and results from geologic mapping exist in less accessible "grey" literature (theses, field guides and other non-peer reviewed sources) and one positive outcome from GeoPRISMS will be to mine this data and move it to more accessible sources (on line databases, published papers etc.).
- High-resolution topographic/bathymetric, gravity and magnetic surveys onshore and offshore (although some gaps remain to be filled)
- Seismic data extending back to the 1970s, from over 200 seismometers operated by the Pacific Geoscience Center (Vancouver Island/British Columbia), the PNSN (Washington/Oregon) and the Northern California Seismic Network (California).
- Real-time high sample-rate GPS data with dense coverage of the active plate boundary.

Outstanding gaps in available data include detailed seismic imaging of critical regions of the plate boundary megathrust, the subducting slab, mantle wedge, and overlying volcanic arc. This gap will be diminished in the near future as new projects come on-line, including offshore 2D multichannel seismic surveys, onshore volcanic imaging studies, and analysis of new OBS and geodetic data, although holes will still remain, in particular, offshore geodesy. Expanded catalogs of seismicity, tremor and GPS displacements are needed to clarify the temporal and spatial distribution of deformation processes along the margin, and their relationships to megathrust properties. New high-precision geochemical analyses of arc rocks are needed to assess magmatic processes and sources, and volatile fluxes. A comprehensive knowledge of sediment flux through time, both onshore and off, is needed to assess the interplay of sedimentary processes and tectonics along the margin.

2.3.3. Potential Topics for GeoPRISMS Studies

Community discussions identified a set of future research directions for Cascadia, guided by new observations, growing infrastructure and data sets, and the ability to carry out integrated studies of the Cascadia subduction system. Key targets and topics include, but are not limited to:

2.3.3.1. Great earthquakes, interseismic locking, and ETS.

Cascadia is thought to be at a late stage of its great megathrust earthquake cycle and is exceedingly rich in ETS (Figure 2.14). Such slow-slip phenomena likely tell us something about the seismogenic potential of the Cascadia plate interface. Strain release associated with slow aseismic slip events may be nearly equal to that accumulated between major earthquakes, and if verified, it implies little if any strain exists to sustain seismic rupture into the slow slip zone. However, an unexplained gap of several 10s of km appears to exist between source locations for tremor and slow slip and areas of inferred significant plate locking. Does the extremely low interplate seismicity at present indicate a fully locked megathrust? The inference of the locking state at Cascadia is limited by the poor offshore resolution of land-based geodetic measurements and depends on how much of the observed geodetic deformation is attributed to permanent upper plate deformation. A clear definition requires near-source observations such as seafloor geodesy. What is the physical mechanism of ETS? What is the relationship between the seismogenic zone and the ETS zone? Is there really a gap between them? Answering these questions requires improved observations at Cascadia, as well as comparative studies with subduction zones at different stages of their earthquake cycles, including in other settings with ETS-type phenomena. In particular, little information exists about slow slip phenomena above the plate interface offshore, although based on studies elsewhere (mostly Japan), they are likely to occur there. GeoPRISMS promises to provide needed offshore observations, in such a way that a complete picture, extending from the trench to the back-arc, of Cascadia plate-interface slip may be developed.

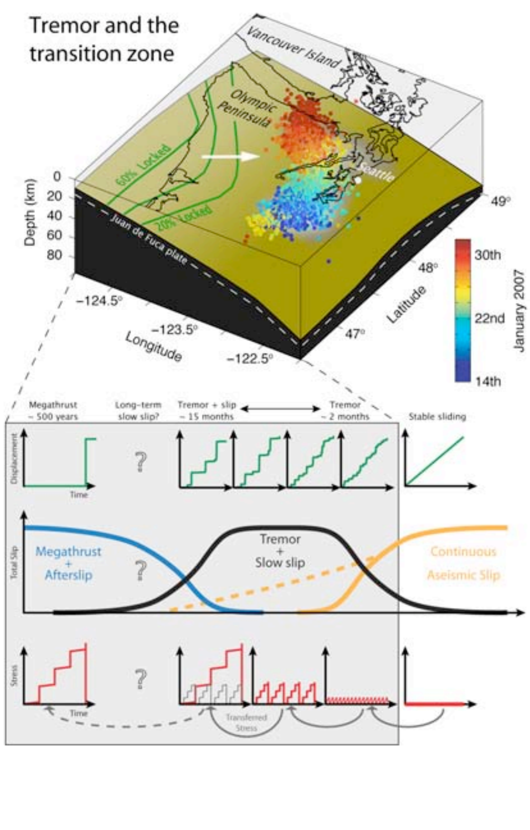

Figure 2.14. Top (from Forsyth et al., 2009): The Juan de Fuca plate subducts beneath the North America plate with convergence direction shown by the white arrow. The plates are locked along part of their interface (khaki-colored surface) by varying degrees; the locking model here shows the fraction of relative plate motion that isn't occurring, increasing downdip from 60% to 20% (green contours) (from McCaffrey et al., 2007). Inland of the locked zone, tremor epicenters projected onto the plate interface (circles) overlie the area that experienced slow slip (gray area on plate interface) during January 2007. Color shading of tremor epicenters shows its temporal migration. Bottom (from Wech et al., 2011): Top panel shows a profile of displacement timelines from the locked zone to stable sliding. Middle panel shows a schematic profile of how the different regions accommodate plate convergence. Lower panels shows a schematic profile of stress timelines, illustrating a stress transfer model in which stable sliding loads the downdip weakly coupled tremor region, which slips easily and transfers stress updip to stronger portions of the fault.

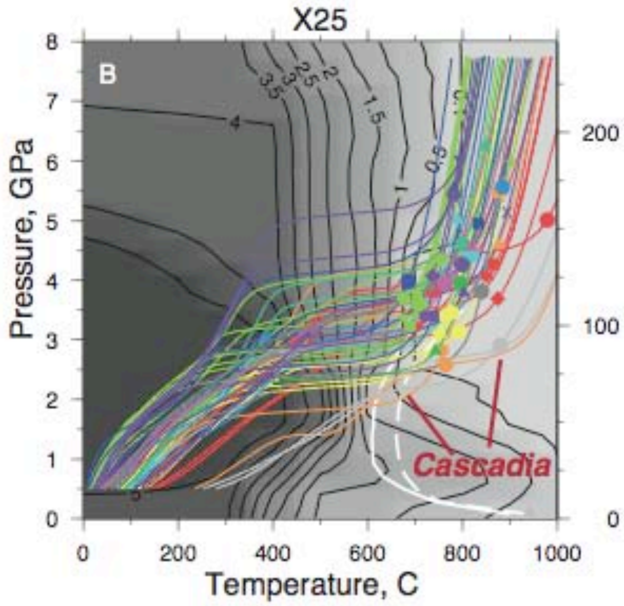

Figure 2.15. Calculated slab surface temperature-pressure paths (colored) for worldwide subduction zones, superimposed on plot of structurally bound H_2O retained in metabasalt (grayscale). Note that Cascadia slab models define the high-T at low-P endmember of subduction systems, and that the basaltic slab would be expected to be nearly anhydrous by ~3 GPa, typical of slab depths beneath active arcs (modified from Syracuse et al., 2010).

2.3.3.2. The hot and dry slab paradox

The young subducting slab at Cascadia is calculated to be one of the hottest worldwide (Figure 2.15). Such high slab temperatures predict early devolatilization, i.e., beneath the forearc rather than the arc. Furthermore, geodynamic modeling predicts only modest hydration of the subducting lithosphere prior to entering the trench, limiting the overall availability of H_2O beneath the Cascade arc. These characteristics suggest that fluid-flux melting processes beneath the Cascades should be minimal, requiring alternative mechanisms and/or sources for creating arc magmas. Paradoxically, however, Cascades magma compositions are broadly similar to those of other arcs, and existing measurements of pre-eruptive water contents in Cascadia basalts also seem within the range of other arcs. These pieces of evidence suggest a disconnect between geophysical and geodynamic predictions and the magmatic record. To resolve this, geochemical and petrological estimates of volatile fluxes in Cascadia need to be reconciled with thermal models that predict a hot and dry subduction system. Questions to address include: What are the relative contributions of fluid-flux and decompression melting to Cascadian magmas? How hydrated is the young oceanic plate prior to subduction? What are the pathways and processes by which volatiles are transported by the downgoing slab and released into the mantle wedge beneath the magma generation zone? The relationship between timing and extent of slab dehydration, and the role of volatile fluxes in magmatism remains unclear. Integrated geochemical and geophysical studies of the Cascade arc, combined with experiments and modeling, are needed to resolve this enigma.

2.3.3.3. Role of volatiles in megathrust coupling / decoupling

Substantial aqueous fluids are thought to be carried into the Cascadia megathrust fault zone with the subducting plate, in the pore space of the thick sediment pile, fractures in oceanic crust, or hydrous minerals. The very young and hot subducting slab should cause most of the hydrous minerals to dehydrate at shallower depths, where high pore-pressures can most affect the strength of the plate interface, the slip behavior of the megathrust, and the long-term coupling of the slab with the overlying mantle wedge. The slip behavior of the megathrust, including seismic rupture and locking, aseismic creep, sub-convergence creep ("partial locking"), and episodic slip and tremor, is thought to be linked to fluid processes, and in particular, high pore fluid pressures in the fault zone. Corresponding evidence for a weak interface is given by low margin-normal compression inferred from earthquake focal mechanisms and other stress indicators, and minimal frictional heating on the megathrust inferred from heat flow measurements. A range of questions arise in efforts to explain the interplay of fluids and fault processes: How can high fluid pressures be maintained in this environment? What is the balance between fluid production and permeability? Under what conditions does elevated pore fluid pressure make the fault more seismic or aseismic? Laboratory experiments are needed to simulate in situ conditions to constrain how various hydrous minerals in the fault zone affect fault slip.

2.3.3.4. Imaging physical properties deep within the crust and upper mantle.

Certain phenomena, including the transition from stick-slip to stable sliding along the megathrust and the migration of magma through the crust, are difficult to image geophysically, but provide critical insights into processes occurring deep within the subduction system. For example, preliminary geophysical imaging of the subducting slab and overlying crust and mantle wedge reveal strong correlations between locked zones, tremor regions, and zones of seismic reflectivity and anomalous Vp/Vs ratios, suggesting a petrologic or metamorphic control on these transitions in slip behavior. These observations potentially relate to dehydration reactions and fluid release along or below the plate boundary, capable of producing near lithostatic pore fluid pressures. The association of ETS with very high pore fluid pressure is consistent with preliminary theoretical modeling demonstrating that slow slip events can arise spontaneously under extremely low effective normal stress. However, the geophysical conditions for, and physical mechanisms of, ETS occurrence are largely unknown. A key contribution from GeoPRISMS studies could be the improvement of traditional techniques for imaging subsurface seismic velocity and electrical conductivity to better image these processes, and the integration of these images with other geophysical and geochemical observations.

2.3.3.5. Along-strike compositional diversity of lavas and tephras and distribution of volcanism

The Cascades represents a key location to investigate the causes of variation in the style, distribution and composition of volcanic output along the arc, and for study of the interplay between lithospheric and crustal conditions, heterogeneity within the downgoing slab, and fluxes of magma produced within the mantle wedge. Although stratovolcanoes occur along the arc, there are significant variations in both the range of compositions and in the rates of volcanic output. There are also differences in the style of volcanism, with the isolated stratovolcanoes occurring in northern Washington and British Columbia contrasting with a relative abundance of dispersed mafic magmatism occurring in Oregon and California. Compositional and productivity variations are not systematic along strike (Figure 2.16), as might be expected if the gradual decrease in age of the Juan de Fuca plate exerted overriding control. Instead these variations appear to reflect more localized interactions within the crust, lithosphere or downgoing plate. Thus, the ultimate controls on the distribution of volcanism in Cascadia remain uncertain. Specifically, what parameters influence the formation of large central volcanoes that occur along the arc versus more dispersed monogenetic volcanism that characterizes the regions between the larger volcanoes? Is this distribution linked to properties or geometry of the slab, structures in the mantle wedge, or structures in the upper plate? How do the relatively localized back-arc volcanic complexes (Simcoe, Newberry, Medicine Lake) relate to the arc system? What are the roles of mantle fluxes, solid/fluid flow vectors, and crustal magma processing? A combination of geochemical, petrological, geophysical, and modeling studies are needed to place constraints on the production of various types of magma and how they interact with their surroundings, from the point of generation in the mantle wedge to their ultimate emplacement in the crust or at the surface.

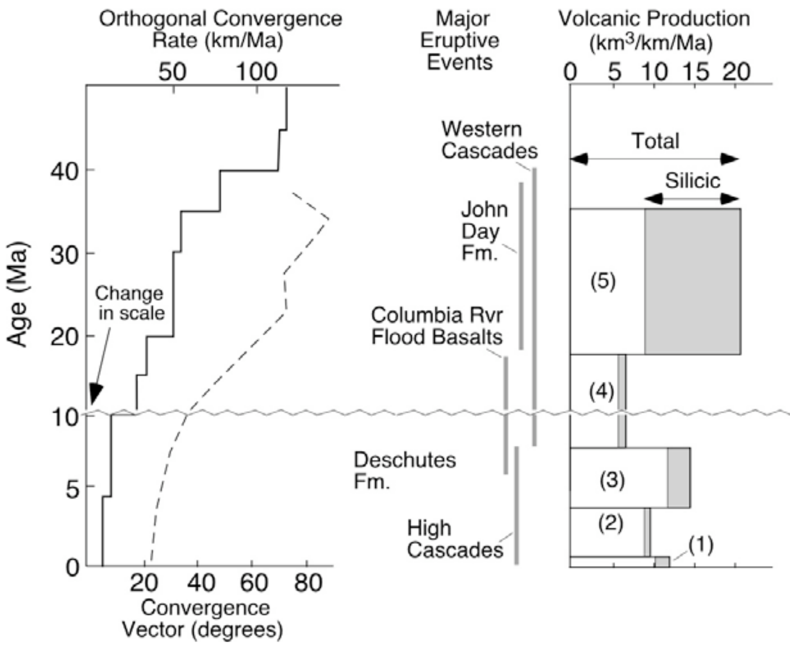

Figure 2.16. Comparison of orthogonal convergence rate and convergence vector with magma production rates for the Central Oregon Cascades over the previous 40 million years. Figure modified from Priest (1990), convergence rates (solid line) and vector (dashed line) are from Verplank and Duncan (1987). The intervals representing major eruptive episodes on the arc and nearby are shown. Numbers 1-5 show the eruptive episodes defined by Priest (1990) and represent: (1) 0.730-0 Ma; (2) 0.731-3.9 Ma; (3) 4.0 - 7.4 Ma; (4) 7.5-16.9 Ma and (5) 17.5-43.2 Ma.

2.3.3.6. The nature of segmentation along the subduction zone.

A number of diverse data sets (geophysics, seismicity and paleo-seismicity, volcano age and distribution, geochemistry, geodesy and paleo-geodesy, etc.) reveal that the Cascadia subduction zone is segmented along strike. Key uncertainties remain. Are the scales of segmentation the same for different data sets? What are the ultimate controls of segmentation evident in different data? What is the influence of the incoming plate on segmentation? What is the influence of the inherited crustal structure and composition of the upper plate? Do the same factors control segmentation along the plate boundary at depths of 30-50 km (the ETS domain) and at depths of a few to ~20 km (the nominally locked zone)?

2.3.3.7. Subduction initiation beneath Cascadia and the origin of the Siletzia terrane

Arc volcanism began in Cascadia by 35-45 Ma, indicating that the Cascadia subduction zone formed sometime before this. Why and how did it form, well to the west of the pre-existing Andean-type margin in Idaho (Challis Arc; Idaho Batholith)? The formation of the Cascadia subduction zone is linked to emplacement of the Siletzia terrane, a mafic LIP (~2.6 million km^3) that is exposed in the Cascadia forearc, the Coast Ranges of Oregon and Washington. Siletzia lavas mostly erupted underwater, comprising basal tholeiites overlain by alkalic lavas. Volcanism began in the south (56-53 Ma) and migrated north (54-50 Ma). There have been many explanations for voluminous Siletzia volcanism, including 1) an accreted oceanic plateau, 2) beginning of the Yellowstone mantle plume, 3) a tear in the subducted plate, and 4) continental-margin rifting due to interaction with a trench-ridge-trench triple junction. Based on studies of the Izu-Bonin-Mariana arc system and ophiolites, it is increasingly clear that many forearcs form as a result of voluminous yet ephemeral igneous activity accompanying subduction initiation, suggesting the alternate possibility that Siletzia formed in response to formation of the new Cascadia subduction zone.

Because it is so accessible and so controversial, Siletzia provides a remarkable opportunity for testing and refining models of subduction initiation. It is exposed above sea level for ~200 km width, and because Cascadia is a young, accretionary margin, negligible crust has been removed by tectonic erosion. The complete record is preserved, allowing igneous forearc crust to be studied in greater detail than anywhere else in the world, allowing an unparalleled opportunity to test and refine subduction initiation models. This understanding is central to the success of the larger GeoPRISMS effort to understand the Cascadia convergent margin. The composition of Siletzian lavas reveal ambient mantle compositions, unaffected by subduction-related metasomatism, critical information needed for solving how modern Cascade arc magmas form. It is also important to understand Siletzia forearc lithosphere because its mode of formation is manifested compositionally, exerting important controls on upper plate rheology and thus upper plate deformation and seismogenesis, which can be studied in unparalleled detail because the subducted slab interface is as little as 15 km below land. It is thus clear that understanding the role of Siletzia in the initiation of the Cascadia convergent margin is central to understanding the modern Cascadia geosystem as well as for refining models of how subduction initiates on Earth.

2.3.3.8. Short-term and long-term effects of sediment genesis, transport on accretion and erosion

The transport of sediment from the subaerial forearc to offshore is both a response to tectonic processes and also a generator of sediment records of past tectonic events. In addition, these sediments play a significant role in defining the forearc structure, the mechanics of earthquake rupture, and partitioning of sediments through accretion and subduction. The Coast Ranges, the Salish/Puget/Willmette forearc basin and the Cascade Range to the east, collectively form an active orogenic belt, most of the mass of which is ultimately redistributed by erosion. In the time frame of megathrust earthquakes (hundreds of years) and for the spatial scale of the Coast Ranges, subduction zone earthquakes affect the genesis, transport and storage of sediment through the Coast Ranges to the estuaries and offshore. In the longer term (millions of years) and over the whole upper plate from the arc to offshore, the accretionary flux from mass accreted or erupted onto the upper plate must be balanced by the erosional flux. Is such a balance in steady state, as proposed for the Olympic Mountains (the only subsystem studied to date)? What is the role of subduction zone earthquakes in initiating landslides, in creating readily mobilized sediment sources and in modulating estuaries as sediment storage compartments or as conduits for sediment delivery to the offshore? Can records from lakes, especially landslide-dammed lakes, be valuable archives of erosion history in the Coast Ranges? How effective are carbon and other biomarkers in tracing sediment through watersheds to the offshore and can these methods, along with sediment transport data, be applied to determine sediment mass balances for Coast Range watersheds located at different latitudes along the Cascadia margin? How are these sediments distributed in the offshore environment and reworked during deformation? Improved inventories of sediment yield data, sediment accretion rates, uplift rates, and a modeling framework specifically adapted to different portions of the margin will help address these questions. Offshore studies will be advanced by state-of-the-art 3-D active source seismic imaging techniques integrated with sediment transport and geodynamic modeling.

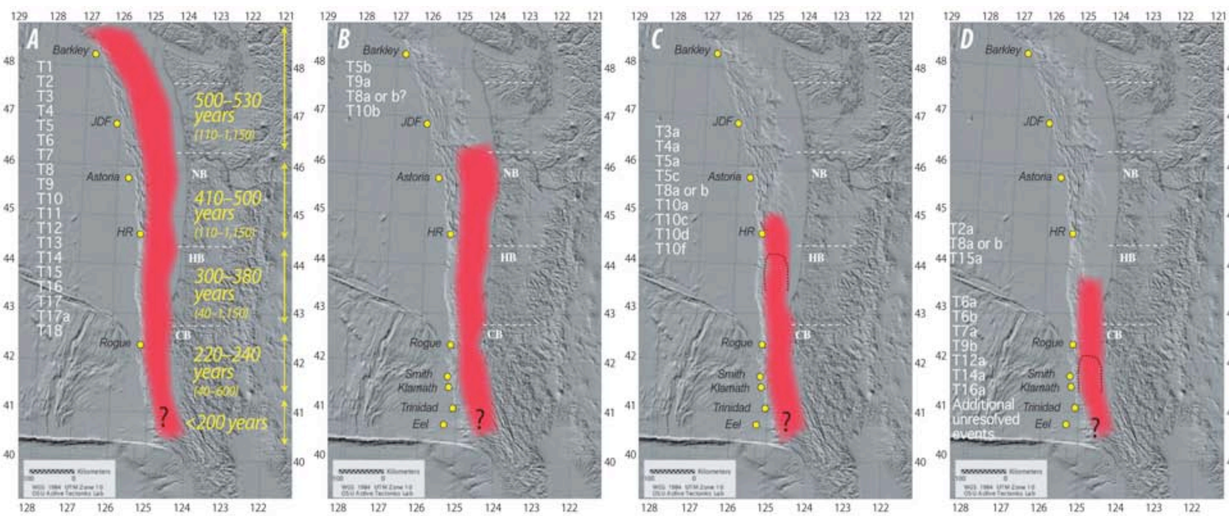

Figure 2.17. Holocene rupture lengths of Cascadia great earthquakes based on marine and onshore paleoseismology. Four images showing rupture modes inferred from turbidite stratigraphic/14C correlation, supported by onshore radiocarbon data. Marine core sites controlling rupture-length estimates are shown as yellow dots. A, Full or nearly full rupture, represented at most sites by 19 events. B, Mid-southern rupture, represented by 3–4 events. C, Southern rupture from central Oregon southward represented by 10–12 events. D, Southern Oregon/northern California events, represented by a minimum of 7–8 events. Recurrence intervals for each segment are shown in A. Rupture terminations are located approximately between three forearc structural uplifts, Nehalem Bank (NB), Heceta Bank (HB) and Coquille Bank (CB). Paleoseismic segmentation shown also is compatible with latitudinal boundaries of episodic tremor and slip (ETS) events proposed for the downdip subduction interface (Brudzinski and Allen, 2007) and shown by white dashed lines. A northern segment proposed from ETS data at approximately lat 48° N. does not show a paleoseismic equivalent. (Figure from Goldfinger et al., 2012; see for details).

2.3.3.9. Earthquakes and the turbidite record.

Inferences have been drawn from turbidite records that earthquakes rupturing only part of the plate boundary (M>~8 events) have regularly occurred in southern Cascadia, whereas the northern portion ruptures only in entire-boundary, M9 earthquakes (Figure 2.17). The boundaries between rupture regions may also correlate with observed geophysical segmentation noted above. These suggestions warrant further study as they have important impacts on hazard estimates and our basic understanding of the earthquake cycle along the plate boundary. A promising 'amphibious' approach (working in both marine and onshore environments) to test these inferences involves correlating offshore turbidite records with those from onshore studies in lakes, also presumed to record seismogenic ground-shaking. Studies of the overall linkages between earthquakes and turbidite generation and distribution are also warranted, to confirm that the latter can be used as a proxy for paleo-earthquakes.

2.3.3.10. Paleogeodesy applied to Cascadia

Paleogeodetic information provides critical data on relief generation in the past at different temporal and spatial scales. Generation of relief ultimately drives wedge mechanics in the long term and can be used to model crustal strain build up and release in the short term. Investigations into the generation and evolution of topography at the Cascadia convergent margin is a nascent field. On short-term time scales, co-seismic and interseismic land level changes at coasts are potentially recorded in microfossil assemblages that are preserved as relative sea level change in response to plate convergence. Over longer time scales, the ability to determine uplift rates in rocks within the Cascade Range through techniques such as (U-Th)/He and fission track age dating has potential to provide constraints for wedge dynamic modeling within the Cascadia forearc wedge.

2.3.3.11. Role of surrounding regions

Cascadia did not develop in isolation, and important questions remain regarding the evolution of Cascadia in relation to surrounding geologic provinces. These include the Yakima fold and thrust belt, the Basin and Range, The High Lava Plains, Klamath/Sierra block, the Mendocino triple junction, the Yellowstone hot spot trail and the Juan de Fuca ridge. How have the interactions between the subduction zone and these geologic provinces changed through time to influence the formation and evolution of the North American continent?

2.3.4. Potential GeoPRISMS Studies

Future GeoPRISMS studies in Cascadia can leverage many significant existing and newly acquired datasets. Some additional studies, however, will also be useful.

<u>Geophysical studies:</u> A necessary complement for the available and planned datasets will be imaging from active source seismology to better characterize the structure and composition of the onshore and offshore regions in targeted areas. Example studies fundamental to GeoPRISMS objectives include 3-D marine seismic surveys to better resolve the megathrust interface, structural architecture of the subducting and overriding plates, and seismic properties of the margin. High-resolution active source seismology experiments onshore, embedded in a dense passive seismic network, coupled with Magneto-telluric (MT) data, could elucidate melt pathways and zones of magma storage within target arc volcanoes, providing independent constraints to better interpret existing geochemical and petrological models of volcanic processes. Such studies could test existing models for magma transfer, and improve our understanding of magma differentiation, crustal evolution, and volcanic hazards. Marine MT studies are needed to extend the onshore grid of MT stations, included as part of the EarthScope USArray program. Marine data would provide constraints on the incoming plate structure, and provide connections between the downgoing slab and the conductive mantle wedge. Long-period seafloor MT instruments deployed with the Cascadia amphibious array would provide the opportunity to jointly interpret velocity and conductivity of the plate boundary. Additional heat flow measurements are needed across the entire margin: the incoming plate, across the accretionary complex, and within the volcanic arc. Creative new approaches are needed to correct conventional measurements for the effects of ocean water temperature changes offshore and shallow meteoric water onshore.

<u>Seafloor Geodesy:</u> A potentially transformative new observation that GeoPRISMS could enable is quantification of seafloor motion throughout the earthquake cycle (a.k.a., seafloor geodesy). NSF's Cascadia Initiative will provide a seamless onshore-offshore seismic network that spans a subduction zone thrust interface. The onshore geodetic (GPS) component of the initiative, however, stops at the shoreline, severely limiting our ability to fully constrain the likely slip distribution in the next great Cascadia earthquake. The duration of the GeoPRISMS Program (5-10 years) and its shore-line crossing approach, could enable a suite of offshore geodetic

benchmarks, optimally, deep-moored GPS buoys linked to submarine cabled observatories (e.g, NEPTUNE), to obtain periodic or continuous measurements over a long time span. This would be a unique and revolutionary dataset for understanding a great M9 earthquake before it happens.

High-precision isotopic, petrologic, and experimental studies of Cascade magmas: As the worldwide hot-slab end-member, the Cascades provide opportunities to evaluate how the transport and supply of volatiles, and potentially slab melts, influence the compositions, productivity, and spatial configuration of arc magmatic systems. Due to long-term geologic mapping, sampling, and dating studies by the USGS, the magma types, proportions, and ages of Cascade volcanic products are as well or better characterized than in other arcs, but comprehensive petrogenetic studies utilizing modern high-precision isotopic measurements of Sr, Nd, Pb, Hf, Os, and O, measurements of trace element and dissolved volatile concentrations, constraints on magmatic redox states, and experimental studies, have not kept pace. High-precision analytical approaches are required for understanding the origins of Cascade magmas because much of the pre-arc crust is unevolved, so crustal interactions need not produce large isotopic and chemical effects, and can be difficult to distinguish from signals produced at slab and mantle-wedge depths. With notable exceptions (Medicine Lake, Shasta), experimental studies on Cascade magmas have focused on upper crustal magma storage and syn-eruptive ascent (Mt. St. Helens), as opposed to deep crustal, mantle, and slab depths that might be sites of magma generation and differentiation.

Field studies of subduction-related metamorphic and igneous processes: A variety of exposed terranes in the Cascadia region provide unique windows into the deeper slab, crustal, and temporal processes that have converged to assemble the modern Cascadia subduction zone. The Juan de Fuca plate, currently subducting under North America, is a remnant of the larger Farallon plate that started subducting in the Mesozoic. Exhumed remnants of the Farallon plate and the interface between the subducting and overlying plates are exposed in the Cascadia region in the form of high-pressure/low-temperature metamorphic rocks, including the Shuksan Metamorphic Suite in the Northern Cascades, as well as the Catalina Schist and the Franciscan Complex to the south and west of the Cascadia primary site. Investigations of these exposed high-pressure terrains provide direct links to the subducting plate presently beneath the active Cascadia arc, and may provide representative analogs for the metamorphic reactions associated with warm-slab subduction. Field, laboratory, and geodynamic modeling studies of the Siletzia terrane and its relationship to the Cascadia forearc can provide important temporal constraints on the initiation and construction of the early Cascadia arc. In particular, studies will determine whether Siletzia is an exotic terrane that collided with N. America or if it formed in place. Specific mapping studies should focus on constraining the timing of collision and the sequence of events leading to the formation of a new subduction zone to the west, and the relationship between Siletzia and onset of subduction-related magmatism. Additionally, the crystalline core of the North Cascades provides unique opportunities to study the architecture of arc mid- and lower crust. The Skagit Gneiss, Swakane Gneiss and Chiwaukum Schist, for example, may be metasedimentary rocks. The processes by which these sediments were emplaced remains largely unknown, but these felsic materials may play a key role in arc crustal growth and continental crust genesis. Petrological, geochemical, and geochronological studies of these various exposed crustal rocks will provide essential input to the interpretation of isotopic and chemical signals in modern arc volcanic rocks in Cascadia, and to the interpretation of geophysical mapping of the plate interface, mantle wedge, and crustal structure at this primary site.

2.3.5. Research Strategies, Resources and Partnerships

GeoPRISMS can play an important role in facilitating community use of existing infrastructure and new community activities already underway to enable multidisciplinary science along the Cascadia margin. This is possible within a 3 to 5 year timescale. Clear opportunities exist to leverage EarthScope facilities and intellectual resources, along with new OOI and Neptune-Canada offshore deployments. Strong cooperation already exists, and will be enhanced, with USGS researchers at Cascades Volcano Observatory and elsewhere, who maintain and monitor seismic and volcanic activity. Additional collaborations exist with many international researchers, in particular in Canada (Geological Survey of Canada) as well as in Japan and Europe. GeoPRISMS research in Cascadia will engage a broad range of US, Canadian, and international scientists, and leverage a rich trove of geologic and geophysical data accumulated both onshore and offshore over recent decades.

Cooperation within the GeoPRISMS community will be guided by topical working groups to plan and coordinate Cascadia research focusing on, for example, (1) integration of multiple datasets to develop the best constrained model of the plate interface (location and physical characteristics); (2) synthesis of observations of surface deformation to create an onshore-offshore lithospheric map of deformation; (3) design and implementation of a multidisci-plinary experiment to illuminate the structures of magma pathways and reservoirs beneath active volcanoes that cannot be resolved with existing datasets.

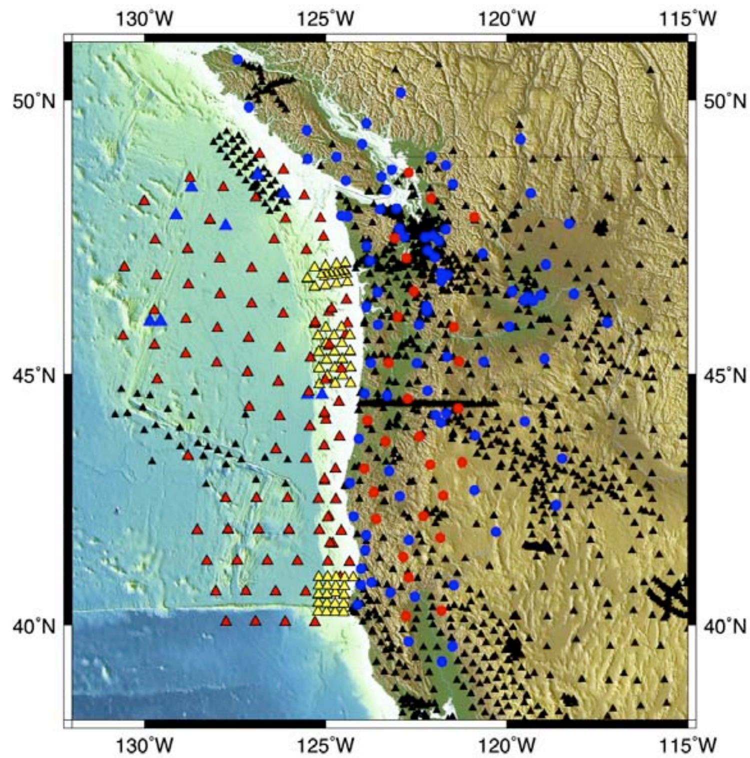

Figure 2.18. Stations that will have publicly available seismic data as of 2015. Offshore triangles show data to be collected over the 4 years of the Cascadia initiative. Circles on land show locations of USArray stations that will be deployed until 2013 as part of the Cascadia Initative. Black triangles on land show data from past PASSCAL and Earthscope Flexible Array deployments. More than 200 high-rate GPS stations that are part of the Cascadia initiative (not shown) will be available through 2018.

2.3.5.1. Cascadia Initiative

The Cascadia Initiative (Figure 2.18) was funded by the ARRA. It includes reoccupation of selected EarthScope US-Array sites and upgrading of PBO GPS sites to high-sample rate, real-time recording as well as construction of 60 broadband ocean bottom seismometers (managed as the Amphibious Array Facility) that are being deployed for 4 consecutive year-long deployments starting in summer 2011 (see http://cascadia.uoregon.edu/CIET for maps of the current and planned deployments). This facility is being operated as a Community Experiment (see 2.3.5.2).

2.3.5.2. Community Experiments

In addition to the Cascadia Initiative, an open-data access experiment to acquire a series of 2D multichannel seismic reflection lines across the Cascadia accretionary complex offshore Washington is planned for July 2012 on the R/V Langseth, an example of a "community experiment," in which projects are planned and vetted by and for the community. The data acquisition phase is being run as a "teaching cruise," with ~16 young investigators and graduate students participating in the cruise. These were selected from an applicant pool of 55 and were chosen in part based on their potential for writing future proposals to use the R/V Langseth. Initial data processing will be performed rapidly by a commercial company and will be available to the community very soon after the cruise. Funding for further data processing and interpretation for this and other Community Experiments will be through PI-initiated proposals to the NSF Marine Geology and Geophysics program.

2.3.5.3. EarthScope Program

EarthScope aims to explore the structure and evolution of the North American continent mainly through its three major observatories: the USArray seismological and magnetotelluric facility, the Plate Boundary geodetic Observatory, and the San Andreas Fault Observatory at Depth. Cascadia figures prominently in the research targets for EarthScope and is highlighted in the EarthScope Science plan (http://www.earthscope.org/ESSP). The GeoPRISMS and EarthScope science questions/targets are complementary and have been discussed at joint planning workshops. The onshore component of the Cascadia Initiative is managed by EarthScope Facilities (IRIS for seismology and UNAVCO for geodesy; 2.3.5.1). In addition, sustained and synoptic onshore observations from EarthScope (Figure 2.18), as well as an active science community (with a dedicated NSF program and portable instrumentation for investigator-driven proposals), and a vigorous broader impacts apparatus provide an important implementation partnership for GeoPRISMS. The EarthScope and GeoPRISMS science programs at NSF are well coordinated for joint proposal review and leveraged support.

2.3.5.4. Cooperation with US Government Agencies

In addition to the aforementioned NSF-sponsored programs that complement GeoPRISMS, other NSF programs may offer collaborative opportunities for Cascadia studies (e.g., the Network for Earthquake Engineering Simulation with facilities for doing active seismic source studies). US Geological Survey programs focused on earthquake, volcano, and landslide hazard reduction increasingly rely on partnerships. Not only does the USGS partner directly with GeoPRISMS community members, but it may serve as a link between GeoPRISMS and state and local institutions with whom USGS regularly partners and who can provide valuable data, knowledge, and field access. Opportunities to collaborate exist with other US agencies, such as the National Oceanic and Atmospheric Administration that oversees tsunami research, and the US Office of Naval Research.

2.3.5.5. International Collaborations (Canada, Japan)

The Geological Survey of Canada (GSC), with GPS and seismic networks covering much of the northern Cascadia margin, has a strong Cascadia research program and has developed collaborative relationships with many U.S. Earth Science institutions. NEPTUNE Canada, a cabled seafloor monitoring system, is already contributing to the OBS operations of the Cascadia Initiative and the design of seafloor monitoring networks in the U.S. The Japanese subduction zone research community has a sustained, keen interest in studying the Cascadia subduction zone, because Cascadia and Nankai (SW Japan) are both end-member warm-slab subduction zones and share many striking similarities and because Cascadia and the Japan Trench (NE Japan) are opposite end-member warm-slab and cold-slab subduction zones. The GSC, JAMSTEC (Japan Marine-Earth Science and Technology Center) of Japan, University of Victoria, and Woods Hole Oceanographic Institution have an ongoing joint project, SeaJade, to monitor seismic activity in northern Canadia, in coordination with the CI. The first SeaJade deployment of OBSs was made in 2010. The second deployment will take place in 2013.

2.3.5.6. International Ocean Discovery Program and Ocean Observing Initiative Opportunities

GeoPRISMS has a number of Cascadia-related science objectives in common with the International Ocean Discovery Program (IODP) and the Regional Cabled Observatory (RCO) of the Ocean Observing Initiative (OOI). IODP and OOI are currently collaborating on installing borehole instrumentation on the Canadian Neptune cabled observatory on the accretionary prism offshore Vancouver Island (see http://www.neptunecanada.ca/about-neptune-canada/neptune-canada-101/ and section 2.3.5.5), and proposals are in the development and evaluation stage for borehole observatories on Hydrate Ridge on the continental margin off Oregon (http://www.interactiveoceans.washington.edu/story/OOI+Regional+Cabled+Network%3A+The+Cabled+Component+of+the+NSF+Ocean+Observatories+Initiative).

The IODP and its predecessors have carried out several drilling legs off the west coast of North America. Their margin projects have focused on gas hydrate and fluid processes, and their mid-plate and ridge-flank projects have focused mainly on hydrothermal processes in the young oceanic crust. The IODP and its predecessors have supported a series of cruises to the flank of the Juan de Fuca ridge to study the hydrology of oceanic crust (ODP Legs 139 and 168; IODP Expeditions 301 and 327). These expeditions, and continuing work at this site, provide important background constraints on the temperature and water content of the lithosphere subducted in Cascadia. IODP focus sites at other subduction zones around the world, including the ongoing SEIZE initiative in the Nankai trough, the J-FAST project in the Japan trench, Project IBM in the Izu-Bonin arc, and the CRISP project off Costa Rica are also very relevant. Many U.S. scientists are participating in deep drilling projects to sample and monitor the updip portions of the seismogenic faults at Nankai, Costa Rica, and Japan Trench, to recover in situ sections of arc crust at different evolutionary stages in the Izu-Bonin arc, and are involved in developing IODP proposals to study slow slip at the Hikurangi margin, New Zealand, and other IODP subduction zone studies. There is potential to explore further IODP drilling and monitoring along the Cascadia margin.

The NEPTUNE cabled observatory and the OOI-RCO also include broadband seismometers and other seafloor sensors on the accretionary complex that provide data to address GeoPRISMS Cascadia science objectives. NEPTUNE has been recording seismic data since 2011. The RCO includes plans for several arrays in which a broadband seismometer is embedded in focused arrays of short period seismometers; these arrays will be installed in 2013.

2.3.5.7. Rapid Response.

Earthquakes, tsunamis, volcanic events, landslides and other geologic events provide learning opportunities that should not be missed. Most of these events come with little or no warning. GeoPRISMS must be poised to capitalize on these opportunities when they arise. This may require developing official response plans and/or collaborating with agencies (e.g., USGS, FEMA) that already have plans and facilities ready. At a minimum, flexibility should be built into GeoPRISMS plans such that facilities may be reconfigured and redeployed nearly immediately. Researchers seeking to conduct scientific research as part of a rapid-response effort to a geologic event are directed to the NSF guidelines for submitting RAPID proposals (http://www.nsf.gov/pubs/policydocs/pappguide/nsf10_1/gpg_2.jsp#IID1), and are encouraged to contact NSF program officers directly for guidance on the submission of such proposals.

2.3.6. Broader Impacts

2.3.6.1. Geohazards

Fundamental contributions to understanding processes that underlie the hazards posed by earthquakes, volcanoes, tsunamis and landslides will be made through GeoPRISMS and EarthScope. The offshore component of GeoPRISMS permits observation of seismic and aseismic deformation in areas where presently few exist, and the amphibious nature of the Cascadia Initiative promises a more complete view of the subduction zone processes that drive the geologic hazards. Products of GeoPRISMS and EarthScope research will have direct impact on the certainty and resolution of monitoring and long-term hazard assessments, particularly hazard maps. For example, higher resolution images of plate interface coupling should lead to better forecasts of the rupture limits of future great earthquakes, as well as their potential to generate tsunamis. New understanding of accretionary wedge deformation and splay faulting also will improve models of Cascadia tsunami potential and impacts, needed for new probabilistic tsunami hazard maps. Volcano hazard assessments rely heavily on models of the magmatic systems that govern the unique behaviors of each of Cascadia's volcanoes, and thus will benefit from focused volcanic GeoPRISMS and EarthScope studies. The enhancements to infrastructure and technologies for measurement of geologic phenomena, data analysis methodologies, and deeper understanding of geologic processes made through GeoPRISMS and EarthScope directly impact time-dependent and even real-time hazard assessments and response. In addition to expanding and improving continuous geodetic and seismic monitoring networks, the development of earthquake early warning system for Cascadia would not be possible without GeoPRISMS and EarthScope.

2.3.6.2. Student and Teacher Involvement

Both the GeoPRISMS and EarthScope programs have well established outreach pathways that can provide support to students and teachers from the K-12 classroom through and beyond the postdoctoral level. The GeoPRISMS program, in cooperation with the Science Education Resource Center (SERC), has put together a collection of mini-lessons that capture many of the key scientific advances of the last decade. Though primarily aimed at an undergraduate audience, this resource can be adapted to younger or informal science audiences. The GeoPRISMS Distinguished Lectureship Program (and the EarthScope Speakers series) provides a pool of experts that can offer talks aimed at both specialized and more general audiences. Additional efforts to encourage a new generation of undergraduates to take part in Cascadia science include an ongoing effort to develop a formal or informal GeoPRISMS REU program that would be based on the very successful model pioneered by IRIS. The EarthScope program has a mature outreach program, many parts of which are based around the USArray program that is so important to the Cascadia region. In addition to the numerous resources provided for students and teachers on the EarthScope web page and in the Active Earth Monitor, the Teachers on the Leading Edge program provides a source of professional development for Pacific Northwest teachers of Earth Science. Further opportunities for students in the Cascadia region include participation in the OBS deployment and retrieval cruises and the Cascadia open-access 2D seismic reflection cruise.

2.3.6.3. Engaging Local Communities

Residents throughout the Cascadia region are routinely exposed to the hazards associated with subduction zone seismicity and the many active volcanoes that are proximal to major population centers. In many cases, outreach by the USGS, universities, and other organizations has familiarized a significant segment of the population with the inherent hazards of living in the area, as well as the role of geologic processes in the development of the spectacular natural resources of the region. GeoPRISMS and EarthScope activities in the Cascadia region offer an excellent opportunity to connect with people who live along this active plate tectonic boundary. Scientists can take the opportunity to visit schools and give community presentations while working in the area. The deployment of instruments near schools is a means to engage young people and educate them on their surroundings. Education and outreach efforts should also involve follow-up with local communities on the results of scientific investigations in the area (not just visits during field campaigns).

2.4. New Zealand – Primary Site

(Replaced December 23, 2013)

2.4.1. Background and Motivation: Relationships to SCD questions

New Zealand offers a wealth of opportunities as a primary site for GeoPRISMS subduction zone research. Aspects of all of the SCD key questions can be effectively addressed at specific locations within the New Zealand primary site. The New Zealand primary site can be broken down into six geographic regions (Figure 2.19), which offer unique combinations of GeoPRISMS research targets. From south to north, these locations include: the Puysegur Trench (subduction initiation), Fiordland (exhumed Mesozoic arc crust), Hikurangi Margin (seismogenic zone processes; feedbacks between sedimentation, climate and forearc deformation), the Taupo Volcanic Zone (TVZ; arc volcanism and intra-arc and back-arc rifting), the southern Kermadec Arc (arc volcanism), and the Havre Trough (back-arc rifting) (Figure 2.19).

The New Zealand primary site also offers plentiful opportunities for international collaborations and associated leveraging of resources, including major ongoing and planned efforts within the New Zealand-based geoscience community and by Japanese and European groups. Although the science priorities identified for the New Zealand Primary Site are many and varied, we expect many can be realistically accomplished over the next ten years due to the additional resources of the broader, international community that can be brought to bear on these topics.

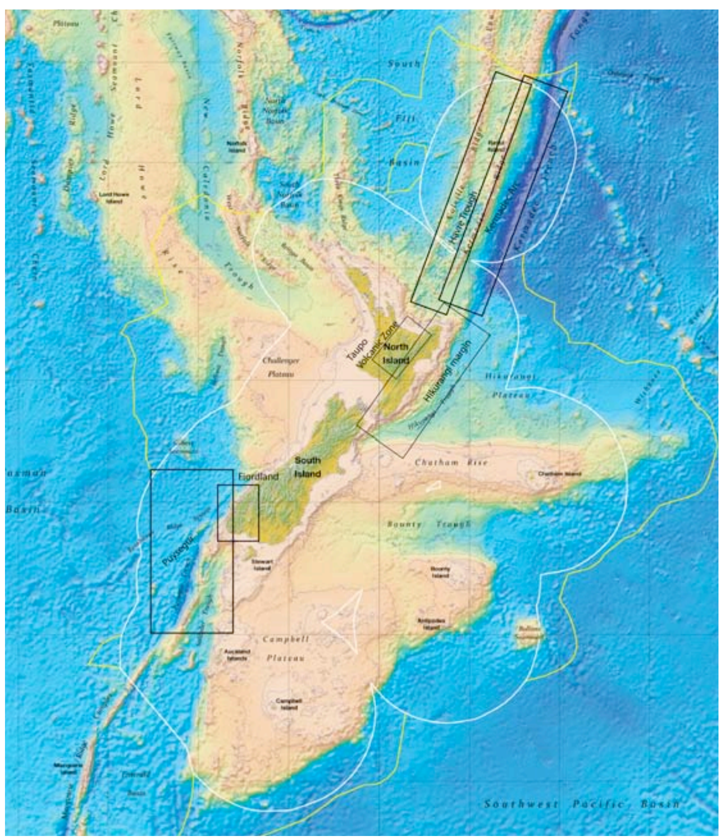

Figure 2.19. Bathymetry and Topography of the New Zealand region, with major tectonic and geographic features labeled, as well as boxes labeled for the main regions of SCD GeoPRISMS interest discussed here. Data from GNS Science.

2.4.1.1. Key science questions to address at the New Zealand primary site

New Zealand's rock record reflects various phases of subduction since Cambrian times through to the present day, and is currently the site of two oppositely dipping subduction zones: the Hikurangi/Kermadec system in the north, and the Puysegur Trench in the south. From the Puysegur trench offshore the South Island, to the Hikurangi and Kermadec subduction systems in the North, there is a rich record of active and ancient subduction margin processes, from subduction initiation through to fully developed, mature subduction systems.

For simplicity, the seven SCD key questions (Section 2.1) can be organized into four over-arching questions to be addressed at the New Zealand primary site. The four questions, discussed in more detail below, are:

- *What are the geological, geochemical and geophysical responses to subduction initiation and early arc evolution, and how do they affect subduction zone development?*
- *What are the pathways and sources of magmas and volatiles emerging in the arc and forearc, and how do these processes interact with upper plate extension?*
- *What controls subduction thrust fault slip behavior and its spatial variability?*
- *What are the feedbacks between climate, sedimentation, and forearc deformation?*

New Zealand is the site of two of only a few well-preserved examples of subduction initiation worldwide, including the newly initiating Puysegur Trench to the south of New Zealand, and an outstanding record of Eocene subduction initiation at the Tonga-Kermadec-Hikurangi Trench in the north. Unique opportunities exist to decipher the structural, stratigraphic and volcanic record of subduction initiation within the context of an active system and a well-established plate motion history. Exhumation of Fiordand's Paleozoic to Mesozoic crystalline basement began in the Late Miocene in response to subduction initiation at the Puysegur Trench. Likewise, at the Hikurangi and Kermadec margins, arc rocks, sedimentary basins, and allochthons preserve a potentially rich record of Cenozoic subduction initiation that appears analogous to that recently described from the earlier MARGINS focus site in the Izu-Bonin-Mariana (IBM) system. Questions to be addressed at the New Zealand focus site include: How does the new slab first enter the mantle? What is the fluid expression and thermal structure of subduction initiation? What is the relationship between initiation and the onset of magmatism? Focused geophysical surveys can tackle fundamental questions about the onset of convergence and associated vertical motions, offshore thermal and crustal structure, newly developing arc volcanism, and the geometry of subduction initiation.

The Kermadec Arc and Taupo volcanic zone (TVZ) offer prime settings to understand magmatic and volatile fluxes at a well-developed volcanic arc from the forearc through to the backarc. The full spectrum of Early Miocene to Recent arc-related volcanism is uniquely accessible along strike in New Zealand, from discrete arc-front volcanoes and a developed back-arc spreading center to nascent back-arc rifting of an existing, mature upper plate, to the complete shutdown of subduction volcanism south of Mount Ruapehu in the central North Island. These dynamic surface expressions of underlying processes provide an important test of the relationship between slab and mantle wedge conditions and processes (dehydration, melting, and the vectors of solid and fluid flow) and the emergence of their products at the surface. Moreover, there is outstanding accessibility to fluids emerging in the onshore forearc in seeps and springs, that enable a look at volatile pathways and sources above the shallow portion of the subduction thrust (e.g., <50 km depth). Finally, in Fiordland, South Island, the only pristine Cretaceous arc section in the Circum-Pacific offers a prime locale to investigate the root zones of an ancient arc, at outcrop scale.

Some of the major questions to be addressed include: How does the mafic flux from the mantle translate to voluminous rhyolitic magma production? What is the nature of interaction between volcanism and upper plate extension? Comparison of the Kermadec Arc corridors with the TVZ affords an opportunity to assess the influence of the continental/oceanic crust transition in the overlying plate and the nature of the subducting plate on arc development. The New Zealand-Kermadec margin also provides an ideal location to distinguish tracers of contributions of magmatic assimilation to the upper plate and the addition of subducted sediment to the magma source region, as the upper plate composition changes from continental to oceanic along strike.

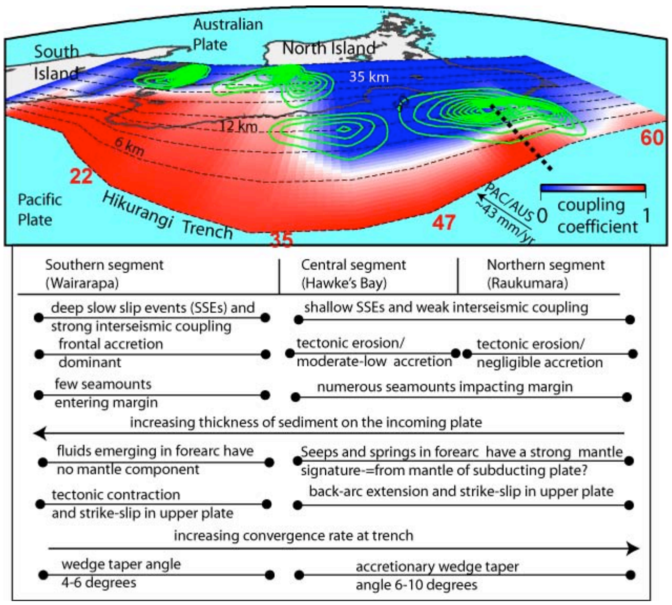

Figure 2.20. Perspective view of the Hikurangi margin illustrating the portions of the subduction interface that undergo stick-slip (red) vs. aseismic slip (blue), in the context of other along-strike variations in subduction margin characteristics. Green contours show areas of slip in slow slip events since 2002. Convergence rates at the trench are labeled as red numbers (mm/yr). Pacific/Australia convergence shown by black arrow. Black dashed line shows location of proposed IODP drilling transect. Courtesy of Laura Wallace.

Systematic along-strike variations in interface locking behaviour and slow slip events (SSEs) provide an unparalleled setting to test hypothesized physical controls on megathrust locking and SSE behavior (Figure 2.20). These major changes in megathrust behavior also correlate with changes in sediment thickness and accretion, convergence rate, seafloor roughness on the incoming plate, and upper plate stress state. Together, these changes likely play an important role in the subduction thrust behavior. Integrated geophysical, geological, and geochemical studies of the onshore and offshore forearc and incoming plate are expected to reveal the major controls on variations in subduction interface behavior. Key questions related to this topic are: How do topography and material of the incoming plate control fault zone structure and slip behavior? What is the slip behavior and rheology of the near-trench portion of subduction fault and what controls it? What is the role of fluids in controlling megathrust behavior and slow slip events? Has the subduction thrust produced great earthquakes in the past, and how does the distribution of these relate to its modern behavior?

The east coast of the North Island preserves thick sedimentary successions in subsiding shelf and slope basins. The storage of riverine sediment in shelf basins and bypassing to the slope are complex functions of margin deformation rates relative to sediment supply, and rapidly varying eustasy in the Quaternary. The accommodation space developed on the shelf allows for the development of thick sequences and an extremely high-resolution record (relative to passive margins) of climate change (e.g., ENSO) and mass fluxes for areas sensitive to both terrestrial and marine influences. Major questions relating to this topic can be raised: What are the pathways and timescales of sediment input? What is the role of large subduction megathrust earthquakes in landscape evolution? What are the feedbacks between the sedimentary inputs (both from the land, and the incoming plate) and accretionary wedge development? How does elemental cycling vary across the forearc? How does seamount and Hikurangi Plateau subduction influence uplift, erosion, and deformation of the onshore margin, and the evolution of the accretionary wedge?

2.4.1.2. Geographic focus areas

The scientific topics outlined above correlate well with distinct geographic focus areas in and around New Zealand (Figure 2.19). The characteristics and opportunities for GeoPRISMS and collaborative research for each of these areas, as framed by community discussions, are detailed in the sections below. In addition, the community determined that certain topics are best addressed through the study of exhumed terranes, which preserve archives of deeper processes that cannot be studied in-situ. Potential research efforts of this type might effectively make use of existing data and observations, which can be viewed through a GeoPRISMS lens to address certain thematic questions that cannot be resolved in any one location. The next sections of this plan are organized geographically, from south to north, and highlight the scientific rationale and possible studies in each region in turn, followed by the studies of exhumed terranes. Timing, staging and partnership opportunities are described in later sections. In the following sections, bulleted lists indicate the primary SCD key topics that can be addressed in each region, with those in ***bold*** being the main priorities.

2.4.2. Puysegur Trench

SCD Key Topics

- ***Subduction zone initiation and arc system formation***
- ***Volatile storage, transfer, and release in subduction systems***
- ***Geochemical products of subduction and creation of continental crust***
- *Effects of volatile release and transfer on the plate-boundary interface*
- *Feedbacks between surface processes and subduction dynamics*

The Puysegur Trench region provides unique opportunities to identify and investigate the key physical parameters involved in the geodynamics of subduction initiation, as it is a juvenile subduction zone "caught in the act" of initiation. In addition, vertical motions associated with this process have led to deep exhumation of the only pristine Cretaceous arc section in the Circum-Pacific, found in Fiordland in the South Island, which offers a prime locale to investigate the root zones of an ancient arc at outcrop scale.

The Puysegur Trench region (Figure 2.21) bears the hallmarks of nascent subduction and arc magmatism, and provides extraordinary opportunities to address the SCD science questions (some uniquely so). The Puysegur subduction zone initiated about 12 million years ago and was associated with profound vertical motions across the shoreline (for example driving the uplift that ultimately led to the spectacular Fiordland landscape). The youth of the geological structure, the lack of subsequent over-printing, the clearly identifiable nature of the earlier tectonic state, and the well-constrained plate tectonic motions make this incipient boundary globally unique and a natural laboratory to study the initiation of subduction.

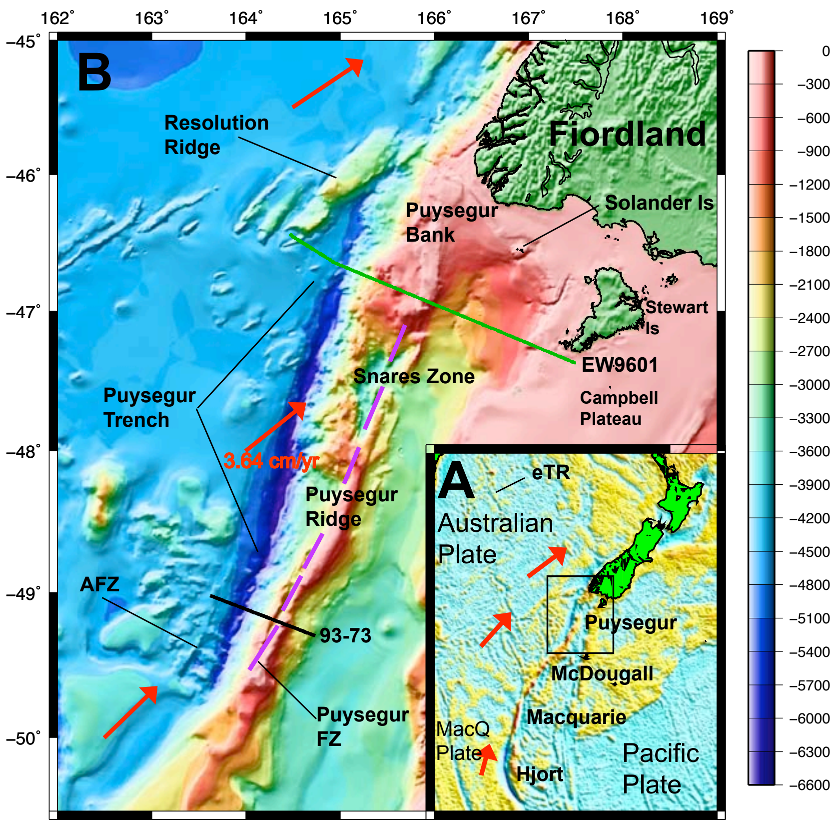

Figure 2.21. A. Location of the Puysegur focus area (black rectangle). Puysegur is one of four sectors of the Macquarie Ridge Complex (MRC). Base map is free-air gravity inferred from satellite altimetry. B. Bathymetry (depth in meters) of the Puysegur Ridge and Trench region just to the south of the South Island of New Zealand. The sector denoted Puysegur Trench has experienced active subduction. AFZ is l'Atalante Fracture Zone. The Puysegur Fault Zone is shown as dashed purple line. Bathymetry assembled by NIWA. Red arrows denote relative motion of AUS or MACQ with respect to fixed PAC from MORVEL present day plate model (DeMets et al., 2010).

Key questions relating to subduction initiation, which could be addressed in the Puysegur subduction zone, are how does the balance of forces acting on the plates change at the onset of subduction, and what are the spatial and temporal effects of these changes. During the early phase in the initiation of many subduction zones, the external forces lead to compression, formation of a new seismogenic thrust interface localizing the occurrence of great earthquakes, and the descent of a slab tip into the mantle. Eventually, the balance reaches a tipping point when the negative buoyancy of the slab (local slab pull) starts to drive the system. At this time, we do not understand this process or associated sequence of events very well, and studies of Puysegur will allow us to address this question empirically. Important questions to be addressed include: What is the dip of the new plate interface in juvenile and evolved settings? What is the difference in the force balance associated with these different settings? How does the crust compress and thicken as subduction initiation unfolds? How is the topography controlled by the thickness of the crust and slab pull? What is the three-dimensional shape of the slab and how does it correlate with the space-time evolution of vertical motions and volcanism?

The converging plate in a subduction zone also causes enormous cumulative deformations in the over-riding plate, such that after millions of years of convergence the earliest stages of that evolution are erased away. This influences how deformation across the subduction zone evolves in space and time, and in particular, how deformation is distributed between the upper plate and slip along the plate boundary. The Puysegur boundary allows us to study this earliest phase of deformation and how the partitioning of deformation has changed over time.

Another question that can be addressed in this setting is at what stage of subduction development do volatiles start to be released from the downgoing plate. Furthermore, what role do these volatiles play in defining mantle rheology? The volatile content and release budget of mature arc settings has been extensively modeled for many systems worldwide. However, recent geophysical studies of the Marlborough region show that fluids are exsolving continuously along the plate interface and rising into the crust well before the circulating mantle wedge is established. The along-strike sequential growth of the Puysegur subduction zone serves as a proxy for time snapshots at different stages of development. Volatiles are only now being injected into upper mantle, thus defining a unique opportunity to better understand how volatiles affect mantle rheology. Volatiles profoundly influence the viscosity of the mantle wedge, which in turn governs the dip of the slab in the upper mantle. Here we have an opportunity to study a slab that has now just started to perturb the upper mantle and to examine how conditions vary along strike at increasingly younger states of initiation.

The volcanic products of the incipient arc are quite limited, however, the study of those that occur provides us with a unique opportunity to study volcanic sequences unperturbed by subsequent over-printing or tectonic loss. Through the time-transgressive nature of the Puysegur system, we have a chance to image melt accumulation in the deep crust prior to magma ascent and arc volcanism. In this way, we can examine the geochemical products during the earliest stages of subduction, to understand how these influence the formation and modification of new continental crust.

The Puysegur area has enormous advantages as a natural laboratory for the study of subduction initiation and associated processes: the initial tectonic state of the system has been reconstructed; the convergence between the Australian and Pacific plates is well constrained during the entire phase of subduction initiation; and study of existing topography and gravity suggests that Puysegur is currently in the midst of a critical transition from forced to self-sustaining subduction. No other incipient subduction zones shares these advantages.

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

The remote location of Puysegur, extending from the southern extreme of New Zealand into the Southern Ocean (Figure 2.21), has limited its prior characterization, leaving several open avenues for GeoPRISMS research. What is known comes from several geophysical, geodynamic and petrologic studies. The regional plate kinematic history since 45 Ma as deduced from magnetic lineation and fracture zones constrains the timing of convergence initiation to 12-15

Ma. Previous work in the Fiordland segment has documented the seismicity and tomography below Fiordland, as well as the Miocene rock uplift history (see Figure 2.22). Only the emergent "tip" of the nascent magmatic arc, Solander Island volcano, has been mapped and geochemically analyzed. There are gravity and bathymetry data with some swath coverage, as well as reflection seismic that provide a stratigraphic framework on and across the Puysegur Bank into the Solander Basin. A particularly notable survey was the GEODYNZ project with the French R/V L'Atalante which shot 11 active source seismic lines over the Puysegur ridge during the early 1990's; unfortunately this survey imaged no structures below about 3 s two-way travel time (TWTT). Most of the MCS lines have been shot close to the shore on the continental shelf. Seismic interpretation of these lines has benefited from lithostratigraphic information from two deep petroleum wells and some offshore surface cores.

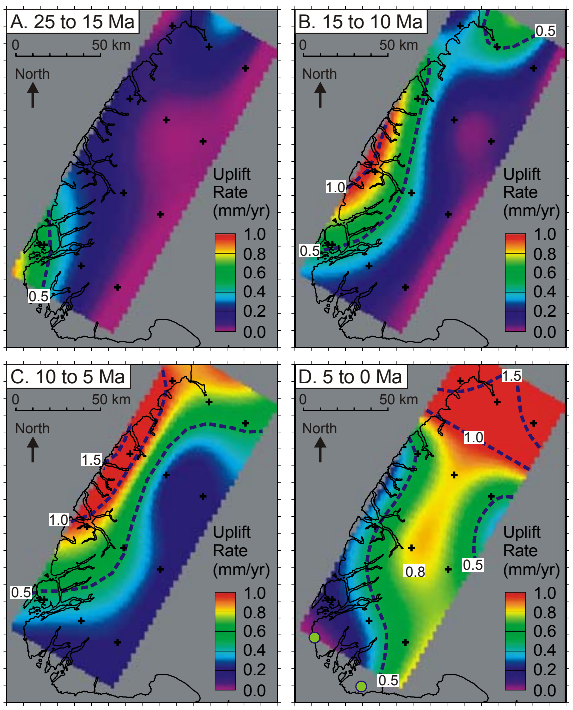

Figure 2.22. Evolution of rock uplift in Fiordland from a 3D (2 in space and one in time) inversion using 410 apatite and zircon fission track and (U-Th)/He ages, The data set is amongst the most comprehensive anywhere for such a compact region. The inversion showed the onset of rapid exhumation at 25–15 Ma in southwest Fiordland, immediately following a time of significant change in regional plate motions. During the period 15–5 Ma, the locus of rapid exhumation broadened and migrated toward the northeast at ~30% of the plate motion rate. This signal has been interpreted as being driven by the earliest phase of subduction initiation. From Sutherland et al. (2009).

A number of knowledge and data gaps remain in the Puysegur region pertaining to dynamics, rheology, magmatism and element transfer. These include uncertainties in the overall offshore crustal structure, the geometries of the new slab and associated subduction interface, as well as lack of knowledge about the seismic and electrical structure of the mantle wedge and deep crust, and the thermal structure of and heat flow across the nascent plate boundary. The limited offshore field studies have incompletely defined the nature of the incoming plate, and composition and structure of the new trench. New field studies could help to constrain the age of vertical motions along the Puysegur Ridge.

2.4.2.2. Potential GeoPRISMS Studies and Contributions

A range of GeoPRISMS studies are feasible in the Puysegur area, and can contribute to several fundamental questions relating to subduction initiation. Two key questions guide these efforts: (1) What is the geodynamic evolution during subduction initiation? (2) How do volatiles first emerge from a new subduction zone?

Active source geophysical surveys: Active source seismic surveys, combining multi-channel seismic (MCS) and OBS wide-angle surveys, are needed to resolve the structure of the crust and lithosphere. Ideally, at least two transects would cross the Puysegur Trench and Ridge: in a more juvenile setting to the south where the Ridge is presently uplifting, and in a more evolved setting that has started to subside. Seismic studies can help constrain gravity models to test dynamic models for force coupling between the nascent slab and Puysegur Ridge. In addition, geophysical constraints are necessary to determine the dip and character of the new thrust interface. MCS lines will also be necessary for siting future IODP drill sites on the margins of the Puysegur Bank, where offshore seismic reflection data indicate compression, uplift and erosion of the nearshore stratigraphic section. Controlled-source electromagnetic and magnetotelluric (CSEM/MT) transects are needed to constrain variations in the hydration state of the incoming crust and uppermost mantle prior to subduction, and to detect fluids released along the thrust interface and escaping into the overlying forearc mantle and crust.

Onshore-offshore MT, heat flow, and passive seismic surveys: Geophysical properties would help to constrain the presence and distribution of volatiles in the lower crust and upper mantle. Heat flow data would better constrain the thermal models of the downgoing slab and thus the nature of volatiles or melts imaged geophysically. The integration of the present day structure of the slab with the convergence history will provide the boundary conditions needed to track the motion of the slab and volatiles into the mantle, and their role in early melting and lithospheric deformation. An offshore/onshore passive source seismic experiment would constrain the distribution of inferred seismicity that might define the incipient Benioff Zone along strike. Onshore seismometers within Fiordland could reveal tremor activity, often attributed to movement of volatiles away from the seismogenic interface. Both MT and passive seismic data can assess if subducted oceanic crustal eclogitization is underway even at this early stage, as has been imaged for more mature systems elsewhere.

Offshore dredging, swath mapping, and coring: Marine mapping and samples are needed to document the nature of the incoming plate from south to north, including the sediment cover, composition and properties of the trench fill, and degree of alteration of the subducting crust. These studies will better define aspects of the upper plate, including the nature of the sediment cover on Puysegur Ridge, and the extent and nature of the submarine volcanic record associated with subduction.

Ocean drilling: IODP drilling will be essential to test existing structural and stratigraphic interpretations, and to more fully constrain the space-time evolution of evolving topography associated with subduction initiation, in particular, associated vertical motions (e.g., Figure 2.22), and the timing and geochemical nature of the development of the nascent magmatic arc.

2.4.3. Hikurangi Margin

SCD Key Topics

- ***Controls on size, frequency and slip behavior of subduction plate boundaries***
- ***Spatial-temporal deformation patterns at subduction zones***
- ***Effects of volatile release and transfer on the plate-boundary interface***
- ***Feedbacks between surface processes and subduction dynamics***
- *Volatile storage, transfer, and release in subduction systems*

The Hikurangi margin is well suited to studying the causes and consequences of the spectrum of slip behavior along subduction megathrusts, given geophysical and geological evidence for pronounced along-strike changes in margin tectonics and subduction interface behavior. Also a complete late Neogene record of strain, and tectonic and eustatic controls on sedimentation in the Hikurangi subduction wedge are preserved along the east coast of the North Island and in adjacent submarine basins. The well-preserved sedimentary record makes it an ideal location to address the feedbacks between climate, sedimentation and forearc deformation.

Dramatic and systematic along-strike changes in megathrust slip behavior along the Hikurangi Margin, including variations in both interseismic locking and the character of slow slip events, coincide with variations in other fundamental margin characteristics, such as subduction erosion vs. accretion, and roughness of the incoming plate. This makes the Hikurangi Margin (Figures 2.20 and 2.23) an ideal natural laboratory to investigate hypotheses for the processes that govern the occurrence of megathrust earthquakes, as well as spatial and temporal variations of slip

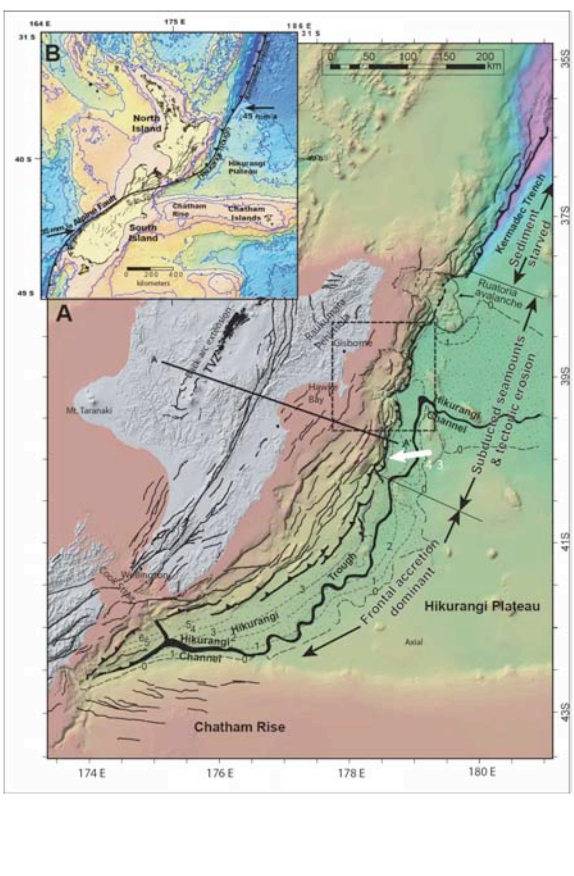

Figure 2.23. Detailed bathymetry and fault distributions of the onshore and offshore Hikurangi margin (after Barnes et al., 2010). Black dashed contours east of the Trench show sediment thicknesses on the incoming plate (in km). Black dashed box shows shallow slow slip area that is the focus of IODP proposals.

behavior. The correlation of along-strike variations in fault slip behavior with changes in the character and roughness of the subducting crust, the extent of frontal accretion, upper plate stress state (and potentially permeability), taper angle, and fluid seep geochemistry all suggest potential links between fluid release, pore pressure, and fault strength and slip behavior.

The Hikurangi subduction margin is especially well suited as a focus area to study dewatering and fluid fluxes in the forearc. Previous studies documented deeply sourced and chemically distinct fluids emanating from an extensive network of seeps and mud volcanoes onshore, and although less well studied, fluid seepage likely extends offshore as at other subduction zones. Notably, variations in the deeply sourced component of seep fluids may also correspond to along-strike changes in the extent of sediment accretion, taper angle, and interseismic locking.

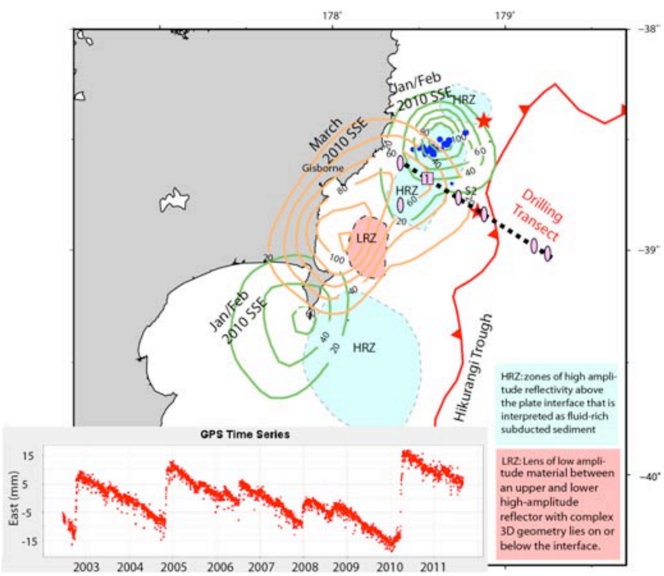

Figure 2.24. Location of slip on the northern Hikurangi interface in the January/February (green contours) and the March/April (orange contours) 2010 SSEs (Wallace and Beavan, 2010) and the reflective properties of the subduction interface (Bell et al., 2010; see key for explanation). Black dashed line shows the location of the proposed IODP drilling transect line, pink square shows the proposed riser drill hole to intersect the SSE source, and pink ellipses are the riserless sites. Blue dots are locations of triggered seismicity during the January/February 2010 SSE. Red stars are the location of two tsunamigenic subduction interface earthquakes (Mw 6.9-7.1) in March and May of 1947. Inset figure in lower left shows the east component of the position timeseries for a cGPS site near Gisborne to demonstrate the repeatability of SSEs since they were first observed in 2002.

Large slow slip events (SSE) occur here with periodicities ranging from 1-5 years (e.g., Figure 2.24). The short interval between the SSE's provides the opportunity for observations through multiple complete slow slip event cycles, with the possibility of identifying important pre-slip and post-slip processes. There are also important opportunities to conduct research to refine the record of prehistoric subduction megathrust ruptures, and to assess the spatial and temporal relationships between earthquakes that occur on the megathrust and within the upper plate.

Owing to its relatively compact scale, the Hikurangi margin may be the most tractable location in the world to demonstrate how along-strike variations in subduction inputs affect long-term rates of accretionary-prism growth, subduction erosion, and fault-slip behavior. The influence of basement structure and topography on stratigraphy on the subducting plate is particularly important in this context. At the same time, sediment provenance and transport paths from continental sources to abyssal sinks (including submarine canyons, trench-floor channels, and large-scale mass-transport deposits) are known to evolve in response to both climate-eustasy and subduction dynamics. In the case of Hikurangi, the opportunity now exists to build beyond the foundation of MARGINS Source-to-Sink, which focused mostly on the Holocene Waipaoa River watershed and adjacent continental shelf.

Key questions that can be addressed along the Hikurangi margin include: What controls the spectrum of fault slip behavior on the shallow subduction thrust? What determines along-strike variations in seismogenic zone geometry of the megathrust? What is the relationship between megathrust earthquakes and upper plate deformation? What role do the subducting plate and incoming sedimentary section play in subduction margin dynamics, fault behavior, accretionary wedge development, and uplift and exhumation of the margin, and what are the feedbacks among these processes? How do volatile and fluid release, cycling, and the hydrological setting of the Hikurangi margin impact megathrust processes and subduction margin development?

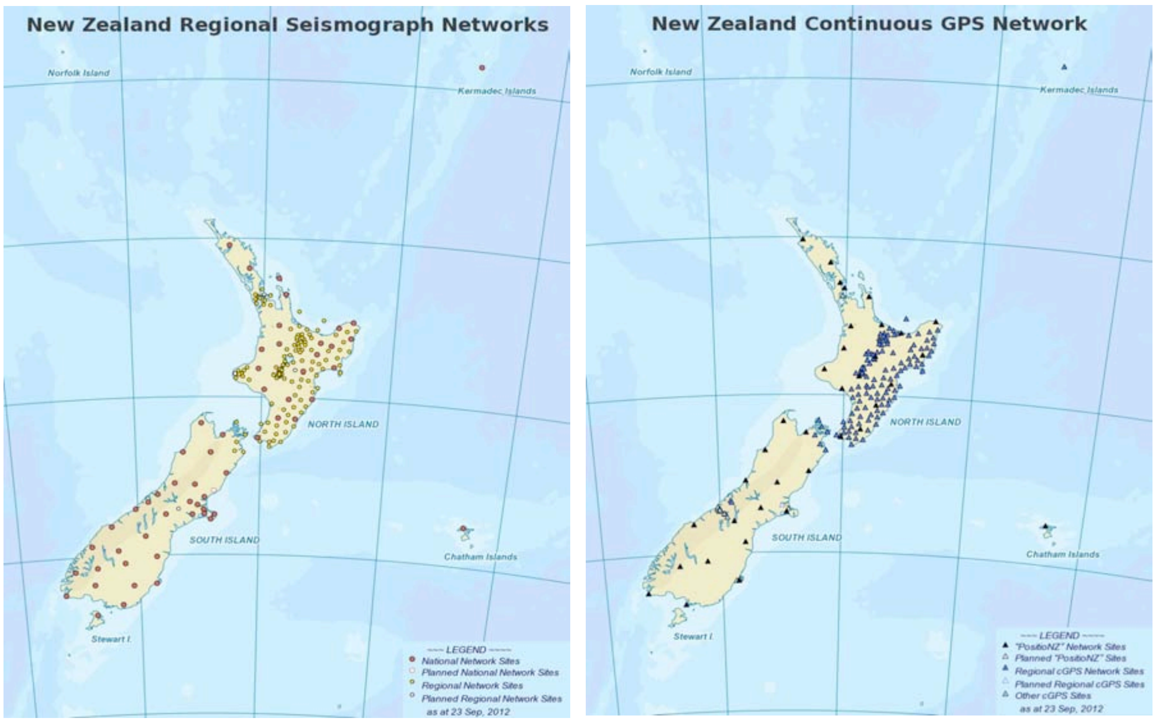

Figure 2.25. Left: GeoNet seismograph network. Right: GeoNet Continuous GPS (cGPS) network. Note the high density of cGPS and seismographs along the Hikurangi margin relative to other parts of the country. The data from these networks are available at www.geonet.org.nz.

2.4.3.1. Existing Datasets in the Area and Data Gaps

New Zealand has made a large investment over the last decade in land-based seismic and geodetic monitoring (Figure 2.25; from www.geonet.org.nz), as well as a range of other geophysical studies. The establishment of permanent geophysical monitoring networks, along with numerous studies using temporary instrument deployments, have permitted the development of regional-scale models of 3D seismic velocity and attenuation structure and crustal deformation along the margin. Continuous GPS (cGPS) and seismological data from the GeoNet network are publicly available; a comprehensive catalog of earthquakes is also maintained by GeoNet; cGPS data have been used to identify slow slip events on the Hikurangi subduction thrust from 2002 to the present, and an extensive campaign GPS network provides a regional picture of crustal deformation over a longer period of time (e.g., last 15-20 years).

The New Zealand government and New Zealand and international researchers have been expanding the database of onshore and offshore 2D active-source seismic data. Surveys conducted by the Ministry of Economic Development between 2005-2009 resulted in ~8000 line kilometers of industry-quality 2D seismic data over the offshore Hikurangi margin. In 2007, wide-angle seismic data were acquired across the Hikurangi Plateau and the eastern part of the Raukumara forearc basin as part of the MANGO project. GNS Science, Tokyo University, and the University of Southern California recently conducted an onshore/offshore seismic transect (the SAHKE transect) to image the strongly locked portion of the southern Hikurangi margin. The 2001 North Island GeopHysical Transect (NIGHT) project collected onshore-offshore reflection and refraction data across the central North Island, including 300 km of multichannel seismic data (MCS) data. In addition, the petroleum industry has gathered vast datasets offshore New Zealand (note, all industry seismic data collected in New Zealand become open file within five years after acquisition). Onshore, there is also substantial MT data in volcanic areas, and the collection of MT data in the onshore Hikurangi forearc is currently ramping up. More detailed imaging (e.g., 3D seismic) at the northern Hikurangi margin could, for the first time, reveal the detailed properties of a plate interface undergoing slow slip and aseismic creep. Similarly, an onshore and offshore active and passive seismic experiment at north Hikurangi could reveal broader scale processes within the upper plate and interface. An onshore passive seismic and continuous MT experiment is already underway by GNS Science to investigate temporal variations in seismicity and conductivity related to slow slip events at north Hikurangi.

From 1993-2010, the New Zealand government funded the production of new, high-quality geologic maps of New Zealand at 1:250000 scale, including the onshore Hikurangi margin. The maps are underpinned by all available existing geological data, and additional fieldwork was undertaken in areas where data were lacking. New Zealand researchers have developed a long-term stratigraphic history of the Hikurangi margin. Regional rock-exhumation and million year timescale vertical motion data for the margin are available from geological markers and sparse thermochronometric ages. The Waipaoa catchment at the northern Hikurangi margin also was a MARGINS Source to Sink (S2S) focus area, so substantial onshore and offshore datasets exist for that area. Additional geological samples and cores are still needed, together with thermochronology to further constrain feedbacks between climate, sedimentation and tectonics.

Substantial paleoseismological and active fault research has been conducted on many of the onshore Hikurangi margin faults. There is a publicly available, comprehensive dataset of all known onshore active faults and their slip rates, and a good understanding of the past earthquake history of many of the most active faults. Hikurangi has some of the most extensive marine terraces of any subduction margin, providing a record of coastal uplift in relation to subduction margin processes. These aspects make it well suited to addressing questions about the relationship between upper plate deformation and processes on the subduction thrust. However, the record of prehistoric subduction interface earthquakes is relatively poor, and additional paleoseismic work, both onshore and offshore (e.g., turbidites) is needed to address this.

High volumes of fluids emerge at springs and seeps in the forearc at Hikurangi, making it an ideal place to examine volatile release from the shallow forearc portion of the subduction zone (e.g., <30 km depth). Fluid geochemistry has been documented by New Zealand researchers in many locations, and additional data collection is underway. To date, however, little work has been done on the geochemistry of fluids emerging at the offshore forearc, which is needed to assess volatile release along the shallowest portion of the plate interface (e.g., <12 km depth).

2.4.3.2. Potential GeoPRISMS Studies

Although many high-quality datasets exist for the Hikurangi margin, additional data are necessary to address GeoPRISMS SCD questions. Examples of such studies are detailed below.

Geophysical Studies: Heat flow data will constrain the thermal structure of the SSE source region, and help to determine the role that temperature might play (if any) in along-strike variation of seismogenic zone geometry at Hikurangi. Ocean Bottom Seismometer (OBS) deployments will serve to characterize seismicity, tremor and crustal structure in the shallow slow slip regions, of particular importance during a slow slip event cycle. Seafloor and sub-seafloor geodetic studies are needed to investigate the slip behavior of the shallow Hikurangi subduction thrust. Additional onshore geodetic instrumentation, such as strain meters and tilt meters, and densification of the existing cGPS network (current spacing is ~30 km) would reveal more subtle SSE characteristics and smaller deformation events. A targeted 3D seismic survey at north Hikurangi would help to constrain the physical properties of the slow slip portion of the shallow subduction thrust. Offshore MT and controlled-source electromagnetic (CSEM) profiles could map along strike variations in the fluid content of the crust and mantle to constrain volatile transfer and release along the megathrust, complementing existing onshore MT efforts. Integrated interpretation (e.g., by numerical modeling) of geophysical observables between north and south Hikurangi can help to discern which parameters are responsible for the bimodal SSE behavior and variations in coupling that are observed along the margin.

Paleoseismology Studies: An improved paleoseismic record of the Hikurangi Margin will help in establishing a paleoseismic record and evidence for large subduction zone events. This would involve investigations of new sites onshore along the Hikurangi Margin together with acquiring correlative offshore archives from marine turbidites. Defining the extent of paleoearthquakes and quantifying the vertical land-level motion throughout multiple earthquake cycles will to clarify the relationship between upper plate fault movement and movement on the subduction thrust, yield more precise measurements of coseismic and interseismic deformation over timescales of decades to centuries, provide more extensive measurements of post-earthquake vertical deformation for prehistoric earthquakes.

Fluid and Rock Sampling and Observatories: Direct sampling of the materials and fluids that compose the margin is also critical. A comprehensive characterization of subduction inputs (e.g., through IODP drilling and coring) will provide key knowledge about the incoming sediments, rocks, and pore fluids that ultimately control the lithologic and hydrological properties of the subduction interface, and the geochemical contributions to the volcanic arc. Coordinated onshore sampling of outcrops will allow along-strike assessment of sediment composition going back into the Pliocene, which can be integrated with offshore observations and interpretations to obtain a more comprehensive understanding of margin evolution. Hydrological and fluid geochemical processes and pathways can be constrained through combined onshore measurements and offshore observatories at proposed IODP holes at north Hikurangi. Measurements spanning multiple slow slip event cycles will reveal the role that the margin hydrogeology and fluid release play in SSE occurrence. Integration of these observations with passive and active seismic surveys of the Hikurangi Margin will help to assess how these materials and properties change down dip, and how they influence megathrust behavior. Numerical modeling studies can help to test interpretations of these datasets, and to further refine sampling and data acquisition strategies.

<u>*Sediment Feedbacks and Structural Evolution:*</u> Finally, a holistic characterization of the trench wedge will be necessary if we hope to tease apart the episodic and/or cyclic influences of canyon incision, climate change, eustatic sea level fluctuations, submarine mass wasting, and uplift/unroofing of sediment sources, and their role in controlling margin behavior. The interplay between subduction accretion and erosion, as well as the structural architecture of the frontal prism, are acutely sensitive to incoming sediment thickness, mineralogy, and texture, so it is likewise important to document how those linkages have varied and responded along strike over time scales that extend back into the Pliocene. High-resolution active source seismic imaging, geological sampling both onshore and offshore, as well as proposed IODP drilling at Hikurangi are needed to address these issues.

2.4.4. Taupo Volcanic Zone

SCD Key Topics

- ***Geochemical products of subduction and creation of continental crust***
- ***Volatile storage, transfer, and release in subduction systems***
- *Effects of volatile release and transfer on the plate-boundary interface*
- *Spatial-temporal deformation patterns at subduction zones*

The Taupo Volcanic Zone is well known to be the most productive rhyolitic system on Earth. The region also coincides with substantial extensional faulting. Some of the major topics to be addressed in this region include: How does the mafic flux from the mantle translate to voluminous rhyolitic magma production? What is the nature of interaction between volcanism and upper plate extension? How does arc front volcanism relate to voluminous rhyolite production? How do the magmatic and hydrothermal systems in the volcanic arc respond to events in the adjacent seismogenic zone?

The Taupo Volcanic Zone (TVZ) is recognized as one of the prime regions of the world for studying subduction-related rifting and associated silicic volcanism and hydrothermal circulation (Figure 2.26). Thus the TVZ offers important opportunities for GeoPRISMS-related science and for collaboration between GeoPRISMS scientists and international partners. Ongoing research into the volcanic, tectonic and other features of the region for many decades has resulted in a number of large data sets and mature studies that can be incorporated into GeoPRISMS studies. In addition, the presence of geothermal resources within the region means that there has been considerable public and private investment in defining and understanding the geology and geologic resources of the region, providing a number of large relevant geophysical data sets. There are also key questions that can be addressed relating to the links between the TVZ and the structure and composition of the overriding and subducting plates, and also to the transition from continental rifting to oceanic subduction and rifting in the Kermadec system.

The TVZ offers opportunities to investigate questions related to the widespread crustal extensional faulting, active throughout the TVZ. The significant Pleistocene-Holocene cover from ongoing volcanism also provides opportunities for dating fault movement and rates of slip. The rapid ongoing extension within the region is also a major influence on volcanism and thus the TVZ offers excellent opportunities for understanding the relationship and interplay between magmatism and deformation. As the only GeoPRISMS SCD site with a considerable component

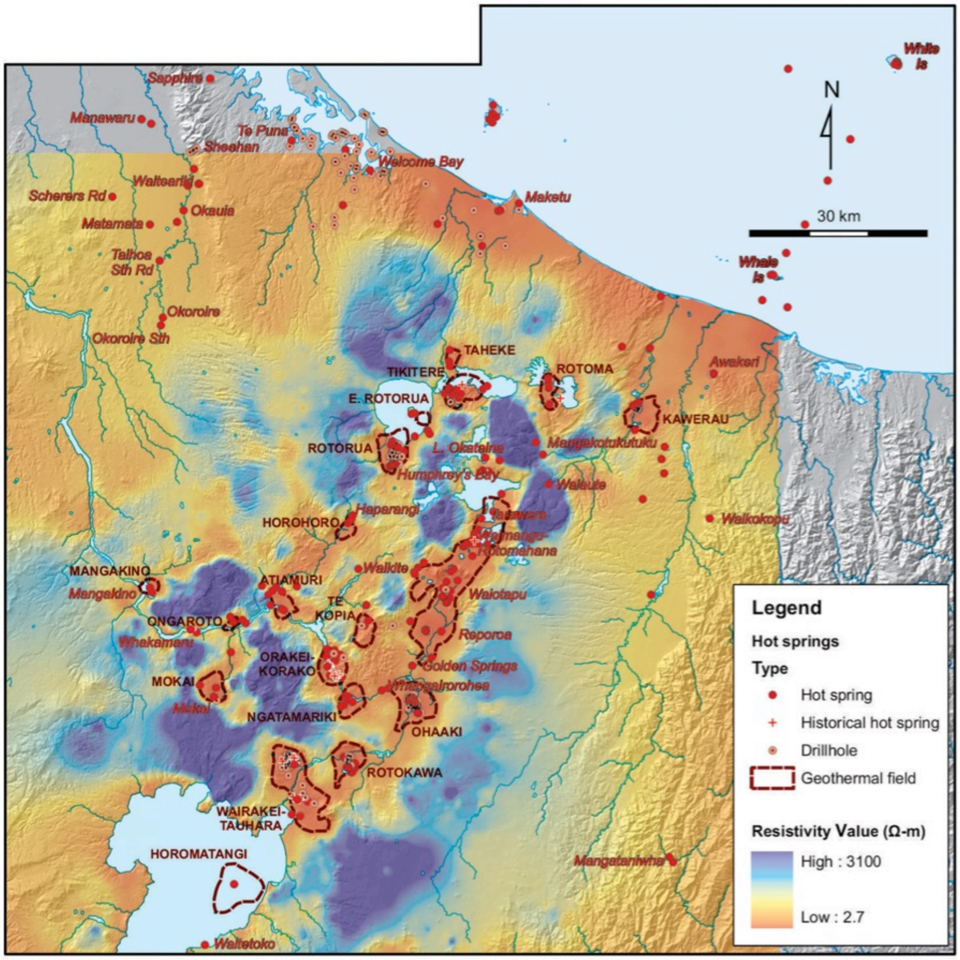

Figure 2.26. Resistivity map of the central TVZ and locations of hot springs and drill holes. Some active fault scarps are also visible in the topographic relief model. From Leonard et al., 2010.

of back arc rifting and with a recent history of voluminous rhyolitic eruptions, the TVZ provides insight into the relationships and interplay between faulting and magmatism, the role of the crust as a "filter" for mantle derived magmas, and the relationship between extensive crustal melts in rifts and more conventional intermediate magmatism along the arc front.

Also of interest in the TVZ is the study of crustal volatile fluxes and their effects on intermediate and rhyolitic crustal magmatism in crust of variable thickness that is currently experiencing differing degrees of extension. In addition, although basaltic rocks are relatively uncommon in this area, the tremendous spatial and temporal coverage of silicic volcanism provides opportunities for looking at equivalent spatial and temporal variability in volatile fluxes associated with volcanism. There also may be definable relationships between volatile fluxes and the voluminous crustal melting zones that feed rhyolitic centers, and the mantle and magmatic contributions to volatile fluxes expressed as geothermal systems. Because of the paucity of primitive or near primitive volcanic rocks in the TVZ and adjacent volcanic arc, the opportunities to address issues of mantle wedge composition and magma generation are relatively limited. However, the TVZ offers unsurpassed opportunities to investigate the role of the crust in filtering and modifying mantle-derived magma and associated volatile fluxes.

Changes in the composition and structure of the subducting Hikurangi Plateau also should be reflected in variations in volatile fluxes, and potentially, in magmatism and crustal structure.

In addition to the research themes outlined for the SCD initiative, it is worth noting that studies within the TVZ also have the potential to address important themes within the GeoPRISMS Rift Evolution and Initiation (RIE) initiative. These include: How do fundamental rifting processes (such as tectonics, magmatism, and erosion, transport, and sedimentation), and the feedbacks between them, evolve in time and space? What are the mechanisms and consequences of fluid and volatile exchange between the Earth, oceans, and atmosphere at rifted continental margins?

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

A large number of existing studies have addressed magmatism, physical volcanology, structure, geothermal, heat flow and other aspects of the TVZ. The TVZ is predominantly terrestrial, and geological and volcano maps are available at a range of scales. Swath bathymetry and high-resolution seismic profiles have been collected in some of the lakes and in the northern, submarine TVZ. Active faults are well expressed and their kinematics and seismic histories have been characterized using tephra stratigraphy and chronology, all of which are publicly available (http://data.gns.cri.nz/af/). There are also extensive tephra, rock and geochemistry datasets (http://pet.gns.cri.nz/) and logs available for numerous boreholes (Figure 2.26), primarily drilled for geothermal resource exploration and evaluation. Various geophysical datasets exist at a regional scale, including gravity, MT, and resistivity (Figure 2.26), and localized geophysical datasets exist at selected volcanic centers and active faults, for example, gravity, GPR seismic reflection and 3D MT. Extensive seismograph, strong motion, and cGPS networks span the onshore TVZ, as well as visual, gas, and chemistry volcano monitoring. All datasets are publicly available (www.geonet.org.nz).

In addition, several large geophysical experiments have been completed. These include the 2001 North Island GeopHysical Transect (NIGHT) active source experiment, which collected seismic reflection and refraction data across the central TVZ and the Hikurangi margin. The simultaneous Central North Island Passive Seismic Experiment (CNIPSE) collected seismic data from a dense network across the central North Island. Identified data gaps include high resolution bathymetry and MT data for Lake Taupo, better controls on structure in the upper 20 km, and the location and nature of magma reservoirs, and other data on the physical properties of rocks and partial melts that can be related to existing and future geophysical measurements.

2.4.4.2. Potential GeoPRISMS Studies

Although no single major geophysical experiment was identified by the community to address topics of interest in the TVZ, it was widely recognized that there are abundant opportunities for focused studies that can identify and address key data gaps or refine data sets or models of subduction and extensional processes within the Taupo zone. Examples include:

<u>Geophysical imaging and associated studies</u>: Seismic imaging of magmatic bodies and vents, sampling of fluids and rocks, and focused MT studies are all necessary to improve identification and resolution of magmatic features and crustal structure in the TVZ. High-resolution datasets from such efforts could be used to constrain new or existing numerical models.

Magma genesis and evolution: Further studies of magma genesis, particularly those providing data on magma production and volatile transfer rates, and the thermal history of magma storage zones, would contribute to better understanding of crustal generation and geochemical cycling.

Structural evolution and magmatism: The relationship between magmatism and the structural evolution of the TVZ was also recognized as an important area for future research opportunities. This might include integration of high-resolution geophysical, structural and geochronological studies to further constrain the timing and nature of extensional faulting and the relationship between extension and ongoing magmatism.

The relationship between TVZ and Hikurangi Margin: Coupled investigations of the TVZ and adjacent Hikurangi Margin could also form the basis for future studies. These might include definition of corridors or transects that image the top of the subducting Hikurangi Plateau from the trench to beneath the back arc in the TVZ, with associated fluid and rock sampling, and geophysical studies. Along-strike changes could be addressed in corridors or transects along the TVZ, or from the TVZ to the Kermadec Arc.

Data compilation and synthesis: One unique feature of the TVZ is the large amount of previous work that has been done through academic studies, governmental research organization and private sources. For this reason, a useful investment via GeoPRISMS may be a more detailed evaluation and compilation of existing resources and more detailed gap analysis (perhaps within separate disciplines) for guidance regarding placement of GeoPRISMS resources.

2.4.5. Kermadec Arc

SCD Key Topics

- ***Volatile storage, transfer, and release in oceanic subduction systems***
- ***Geochemical products of subduction and creation of continental crust***
- ***Subduction zone initiation and arc system formation***

The Kermadec-Havre Trough region includes a well-preserved example of Eocene subduction initiation, providing unique opportunities to examine the structural, stratigraphic and volcanic record associated with subduction initiation and subsequent arc evolution. This area is also ideally suited to the study of volatile fluxes from the fore-arc to the back-arc, and to determine the effects of along-strike changes in composition and sediment inputs of the incoming plate. The presence of rhyolitic magma also provides opportunities for study of silicic magma formation in oceanic arc systems.

The Kermadec Arc – Havre Trough (KAHT) and Tonga arc systems extend over 3000 km from latitude 15° to 40°S, forming the southwestern quadrant of the circum-Pacific subduction system. In the KAHT, older Pacific plate lithosphere (> 80 Ma) subducts westwards beneath the Australian plate at the Kermadec Trench. Convergence rates at 31°S are 80–85 mm/year, representing a Pacific plate vector of about 65 mm/year, together with trenchward migration of the Kermadec Ridge of 15–20 mm/year. The KAHT consists of an arc–backarc basin–remnant arc triplet, with the three sectors of the Kermadec portion of the KAHT, i.e., the Kermadec Ridge, the Havre Trough and the Colville Ridge (Figure 2.27). The KAHT, together with the

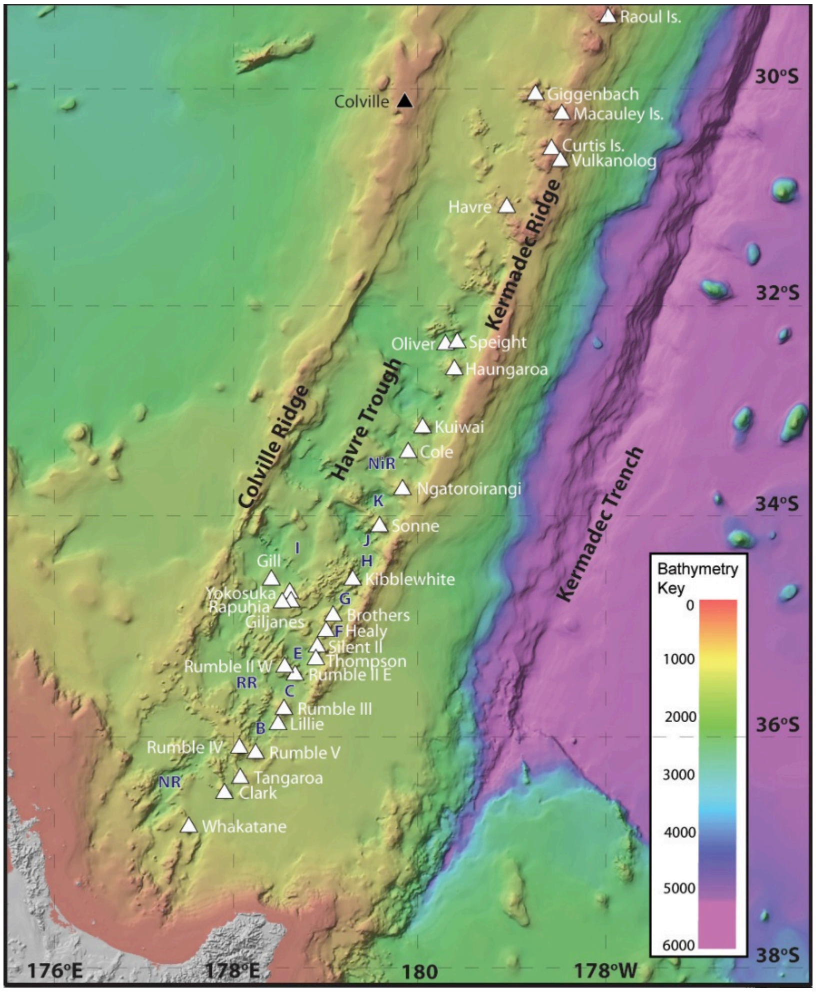

Figure 2.27. Bathymetry of the KAHT system. Triangles represent the locations of individual volcanoes.

Tonga-Lau system to the north collectively define a classic intraoceanic arc – back-arc pair. The KAHT extends north from the Taupo Volcanic Zone of New Zealand, to the Tonga-Lau subduction system. The subduction of the Louisville Seamount chain at ~25°S represents the boundary between the KAHT and Tonga-Lau systems, although the two can be considered coeval. With a well-defined arc front, an ancient proto-arc (the Colville and Kermadec Ridges) and a back-arc > 100 km wide, the KAHT - Tonga-Lau system is a prime setting for investigating a range of arc processes, including arc initiation, tectonic and mass transfer processes, magma genesis and volatile fluxes.

Some of the specific questions that can be addressed though detailed studies of the KAHT and adjacent arc systems include:

- *Is there an observable signature of Hikurangi Plateau subduction along or across-strike?*
- *What are the volatile fluxes in the TVZ/Kermadec/Tonga system and how do they relate to along and across strike variations?*
- *What is the relationship between tectonism, magmatism, and fluid fluxes during the rifting stage of backarc development?*

- *What systematic variation is there in subducted components and what is the partitioning of magmatism and fluxes in the forearc, volcanic front, and back-arc?*
- *How do arcs initiate – what are the timing, mechanisms, rock types etc.? How does the record of arc initiation in the KAHT relate to the well-documented record in the Izu-Bonin-Mariana forearc?*

The broad KAHT system, extending north to Tonga-Lau and west to the Lord Howe Rise, is unique in many respects. The presence of a number of arcs of different age but related to the same system provides an opportunity for understanding the temporal evolution of arcs from their initiation. The presence of the Hikurangi Plateau allows a unique opportunity to investigate the effects of plateau subduction or collision. Hydrothermal venting enables detailed study of active hydrothermal systems and their resource potential. Large silicic calderas provide time scales of rhyolitic volcanism and impacts on society. Finally, the change from continental to oceanic crust, decreasing trench sediment northwards, and the presence of the Hikurangi Plateau to the south, allow examination of changes in volatile fluxes with changing subduction input.

The KAHT system is specifically well suited to the investigation of two SCD Themes: (1) fore-arc to back-arc volatile fluxes and (2) subduction initiation. The Colville and Kermadec ridges preserve material related to Oligocene-Eocene initiation of the KAHT, and studies here will complement advances in understanding subduction initiation in circum-Pacific subduction systems from recent work in the Izu-Bonin Mariana (IBM) system. Moreover, a recently proposed transect of IODP boreholes along and across strike between New Zealand and New Caledonia will quantify the timing and magnitude of vertical motions, compression, and volcanism related to the subduction inception process at the Tonga/Kermadec/Hikurangi trench.. In concert with the TVZ, the KAHT provides the opportunity to examine volatile fluxes, magma genesis and other processes in the transition from oceanic to continental convergence regimes, and from volcanic front to extensional back arc environments. Numerous volcanoes (Figure 2.27) also provide opportunities for studying magma and volatile fluxes along and across the arc. The presence of abundant silicic magma also provides opportunities for study of silicic magma formation in oceanic arc systems.

Previous work in the Izu-Bonin-Mariana (IBM) forearc provides insights into subduction initiation that can be tested in the KAHT. Recent IBM studies illustrated that most or all of its length consists of an ophiolitic geology with depleted peridotite overlain successively by gabbro, diabase, MORB-like basalts, and boninites. Several studies have postulated that this sequence was associated with subduction initiation at 52 Ma and the first 7-8 million years of early arc development. Similar rocks with similar ages have been dredged from the southern Tonga forearc, suggesting that the Early Eocene Pacific subduction initiation could have extended this far south, although complexities in the forearc crust compositions and ages stretching from the Cretaceous to Pliocene allow for alternative geological interpretations. The age of subduction initiation in the IBM system corresponds with a significant reorganization of global plate motions, as well as a hot-house climate (the Early Eocene Climate Optimum), illustrating this could have been a globally significant tectonic event and a contributor to climate change. Proposed IODP drilling to investigate subduction inception at the Tonga-Kermadecs will enable tests of predictions from alternate classes of geodynamic models for subduction initiation developed in the context of global plate kinematics.

The KAHT is less well studied than its northern extension in Tonga-Lau but enough work has been done in the last decade, and has been proposed recently by collaborating countries, that GeoPRISMS projects are well-timed. As the only GeoPRISMS focus site to include backarc spreading processes, the KAHT also blurs the boundary between SCD and RIE scientific objectives by extending study of the Taupo Volcanic Zone rift into the oceanic realm. From a magmatic point of view, this also creates opportunities to explore how mantle deformation and melting processes evolve from the fluid-rich corner-flow flux melting of island arcs into the drier mid-ocean ridge-like decompression melting of mature backarc spreading centers such as the Central Lau Spreading Center to the north. Transects extending from the subducting Pacific Plate, across the KAHT, and into the older South Fiji backarc basin to the west can capture this range of scientific objectives.

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

Since initial studies of the KAHT in the 1960's, many of which were seminal in developing models for arc and back-arc subduction processes, our understanding of this subduction system has increased substantially. As the KAHT system is nearly completely submarine, with the exception of a few small islands that are the emergent tips of submarine volcanoes, studies have depended on a number of research cruises, predominantly by New Zealand but also US, German, Japanese and in the early years of exploration, Russian research voyages. Initial bathymetry and tectonic models were based on satellite data and airborne geophysical surveys. The recent advent of higher resolution (12 kHz and now 30 kHz) swath mapping systems bathymetry has led to a significant increase of data, leading to the discovery of most of the volcanoes and compilation of detailed maps. Even so, only the southern KAHT (south of 35.2°S) has been mapped in any detail. North of this, only the volcanoes of the arc front have been mapped, with the back-arc and fore-arc almost completely unknown.

Despite the fact that arc front volcanoes make up < 5% of the areal extent of the KAHT, they have received almost all of the scientific attention. This is in part historic, as the southern seamounts were known to the fishing industry and as some were seismically active (e.g., the "Rumble" volcanoes), they became the first scientific targets. The discovery of hydrothermal venting on the volcanoes, and associated economic deposits, intensified interest in the edifices. Most of the arc-front volcanoes have now been swath mapped and sampled by dredge, and explored for hydrothermal activity, with only a few edifices explored in any detail by ROV, most notably Brothers Caldera.

Due to the costs of ship time and need for expensive equipment to explore the KAHT, a number of significant gaps persist in our knowledge of the system. Only the region south of 32°S has been surveyed in any detail through swath mapping, and even here much of the data is low quality due to old instrumentation or poor weather conditions. North of this, the arc front volcanoes have been mapped, but the Havre Trough and Colville and Kermadec Ridges remain poorly explored. The forearc in particular has received little attention anywhere in the KAHT.

Even in areas that have been swath mapped, there is a paucity of geophysical data, in particular, geopotential data, including magnetic, gravity data, electromagnetic and heat flow data. High quality backscatter data are also lacking, and seismic data are limited. Several single channel seismic lines and two recent multi-channel seismic lines that cross the KAHT perpendicular to the trench have been acquired. Multi-channel seismic lines have also been acquired over several arc front volcanoes, but the coverage is still quite sparse.

In addition, there are only limited areas with detailed sampling and surveying. The majority of sampling has been through rock dredging with very little coring. Most of this work has been carried out on the arc front volcanoes with very little investigation in the back-arc region or on the ridges. ROV, AUV and manned submersible surveys have been few and concentrated on only a few volcanic edifices, notably ones that are hydrothermally active, as well as one basin (Ngatoroirangi Rift) in the Havre Trough. Even camera observations for the rest of the system are sparse.

2.4.5.2. Potential GeoPRISMS Studies

The consensus opinion of the community at the New Zealand focus site workshop was that the most efficient approach to address the key scientific questions in the KAHT, given the large surface area of the system, was to concentrate efforts on geographical 'corridors' rather than individual disparate regions for each study. This would involve focused multidisciplinary research on one or more corridors ~100 km wide extending from the Pacific Plate, across the trench and to the western side of the Colville Ridge. Individual research voyages would ideally follow a nested approach, building on and adding to previously acquired datasets, along one or more of the corridors. Only with detailed knowledge of focused areas, obtained through interdisciplinary, multinational studies, can the key scientific questions be adequately addressed. The number of or locations of potential corridors remain to be decided, and workshops to address these key decisions are essential. A need to compile a database and to compare it with Izu-Bonin, Central America, Chile, Aleutians, Cascadia is also encouraged.

The KAHT system also offers potential locations to investigate the length scale and timing of subduction initiation at the southern end of the western Pacific arc and back-arc systems. The bathymetry of the Kermadec forearc is like that of the southern Tonga forearc, but the area is presently unsampled. The escarpments on either side of the Havre trough also offer potential outcrops of early arc crust, but likewise have been poorly studied. Dredging and detailed bathymetric investigations of these areas are clearly needed, perhaps followed by diving and drilling if warranted. The Lord Howe Rise region offers important opportunities to quantify the timing and magnitude of vertical motions, compression, and volcanism related to subduction initation, including dramatic deepening of the New Caledonia Trough during subduction inception.

A number of overlapping studies are seen as important to adequately survey and sample the corridors. In order to achieve the key objectives, detailed coordination of field campaigns (ship schedules, proposal writing/deadlines) will be helpful; this could be facilitated by the GeoPRISMS Office and website. Plans for focused data acquisition and prioritization of data sets will be determined at future community planning workshops. Example studies include:

Swath mapping, gravity and magnetics: Swath mapping, which has been carried out locally over certain features, could be completed for the selected corridor(s) at a suitable resolution (30 kHz), along with complementary geopotential studies, including gravity and magnetics.

Hydrothermal studies: Fluid sampling and mapping of the water column could be carried out over suitable areas. These measurements would provide background data, helping to identify key submarine features, and would provide key information for tectonic models.

Physical sampling by rock dredge, ROV, and IODP drilling: Key targets include the incoming Pacific Plate and Hikurangi Plateau material, primitive arc and back-arc samples, well-exposed early-arc igneous sequences, old arc (Colville) material, rhyolitic sequences, and hydrothermal fluids and deposits. There are two existing IODP proposals to (a) investigate the stratigraphic record of Tonga-Kermadec-Hikurangi subduction inception, and (b) to investigate the hydrothermal system at Brothers Volcano in the Kermadec Arc.

Deep tow and AUV studies: These surveys would be focused on selected targets, particularly hydrothermal systems, which have been identified through other means.

Regional geophysical surveys: Active and passive OBS surveys, electromagnetic studies, and heat flow measurements would help to assess crustal porosity and permeability, and the distribution and role of fluid pathways in the crust and mantle wedge.

2.4.6. Exhumed & Remnant Terranes – The Fiordland Example

SCD Key Topics

- ***Geochemical products of subduction and creation of continental crust***
- ***Volatile storage, transfer, and release in subduction systems***
- ***Subduction zone initiation and arc system formation***
- *Feedbacks between surface processes and subduction dynamics*

Exhumed terranes across New Zealand offer excellent opportunities to address several SCD thematic studies, and also provide unique views into deep arc roots that bear on understanding active subduction zones around the world. For the example highlighted here, exposures of lower arc crust in Fiordland allow examination of fluid and magma transfer processes, geochemical modification and diversification of arc magmas, and thermal and material transfer processes from the mantle wedge to the lower crust during arc construction and collapse.

The New Zealand primary site includes the exhumed Early Cretaceous deep crust of Fiordland (Figure 2.28), which is of particular significance as a well-preserved example of a deep arc root. The eclogite-granulite transition is observed here, representing dioritic crust that equilibrated as deep as ~65 km prior to extensional exhumation in the mid-Late Cretaceous, and transpressional uplift from the Miocene to present. For comparison, mid to shallow levels of the same arc are also present adjacent to Fiordland along the strike of the arc in Westland (Figure 2.28). Coeval volcanics are rare, but equivalents may exist in a possible continuation of the same arc in Queensland, eastern Australia. Together with adjacent forearc, accretionary wedge, fossil "trench" and jammed Hikurangi Plateau, the exhumed Triassic-Early Cretaceous subduction zone is apparently the only well-preserved exhumed Cretaceous subduction margin in the western Pacific region. Thus it provides unique opportunities to look deep inside a continental arc to tackle SCD questions that cannot be addressed in active settings.

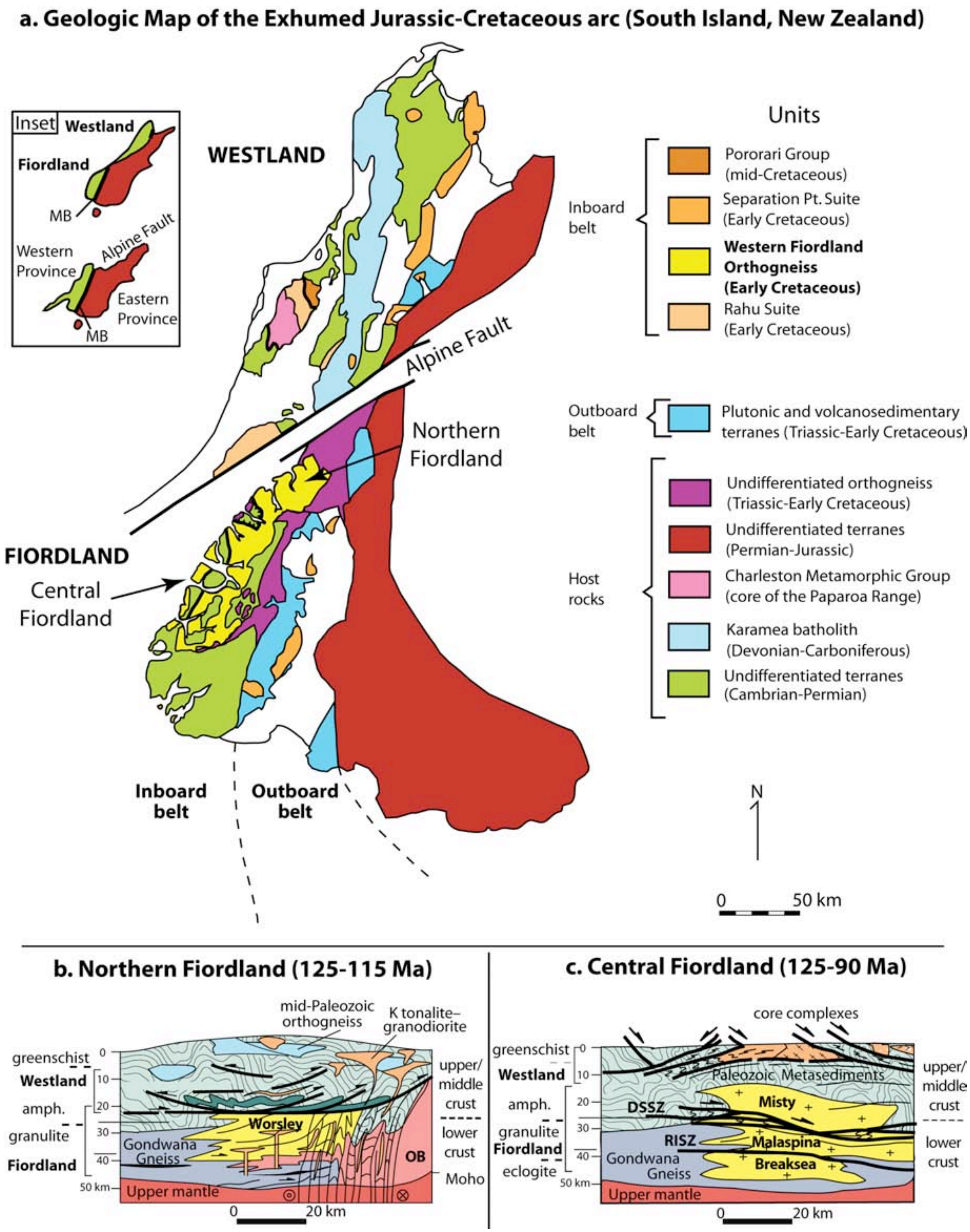

Figure 2.28. (a) Simplified geologic map of the western part of the South Island, New Zealand (after Klepeis et al. 2004; Miller and Snoke, 2009). Inset shows present configuration (top) and Cretaceous arc after removing slip along the Alpine fault. Schematic lithospheric profiles of (b) Northern Fiordland, showing syn-magmatic contraction, and (c) Southern Fiordland, illustrating post-magmatic extension (both after Klepeis et al., 2003). OB = outboard belt; RISZ = Resolution Island Shear Zone; DSSZ = Doubtful Sound Shear Zone; amph = amphibolite.

The Jurassic to Cretaceous New Zealand arc may also be the best global example of Phanerozoic tonalite-trondhjemite-granodiorite suite (TTG)-like magmatism, which is common in Archean rocks worldwide. TTG rocks in Fiordland are characterized by high Sr/Y values indicating magma equilibration with a garnet-rich, plagioclase poor residue. The broad geochemical diversity of TTG rocks in Fiordland, and their relatively large proportion (c. 50%) among the local plutonic rocks, may be unique and provides the opportunity to understand the genesis and evolution of these magmas in the roots of a continental arc. Strong similarities of these plutons with the Peninsular Ranges Batholith of North America suggest that the distinctive characteristics of the Median Batholith magmas are not unique, and therefore have global significance to understanding arc processes.

Studies of exhumed terranes, such as those exposed in Fiordland, are complementary to studies of active subduction in the SCD primary sites, defining a thematic component of GeoPRISMS research. The following key SCD questions can be well addressed in the exhumed deep crustal exposures in Fiordland (and shallower equivalents):

What are the geochemical products of subduction zones and how do these influence the formation of new continental crust? The Triassic-Early Cretaceous continental margin arc (i.e., Median Batholith) is composed of two margin parallel plutonic belts (Figure 2.28). The outboard belt has typical subduction-related chemistry, whereas the inboard belt is dominated by plutons of TTG-like/adakitic/high Sr/Y (HiSY) compositions. The especially strong HiSY signature of these rocks, related to the stability of garnet in the source region, makes them prime candidates for studies into the origin of such rocks and the production of dense garnet-rich cumulates at the base of the arc.

What are the rates and processes of arc crust growth and differentiation, and how is arc crust transformed to continental crust? The TTG-like magmas appear to have been formed in high-flux events at overall rates 4-10 times faster than the earlier "normal" arc magmas. The rapid change to TTG-like magmatism during the last 25 Ma of arc magmatism likely holds important clues to the formation and differentiation of arc crust, and to the growth of continental crust in general. Preliminary data suggest a two stage development of crust is likely, involving (a) 235-130 Ma typical mantle wedge-derived magmatism causing basaltic underplating, during which derivatives from the zone of Melting Assimilation Storage and Hybridization (MASH) were emplaced into the upper crust, followed by (b) 130-105 Ma TTG-like magmas produced by partial melting of the earlier underplated material. The unique exposures in Fiordland and Westland thus enable the study of the transformation from arc to continental crust, including the metamorphism and partial melting of earlier igneous and metasedimentary rocks. For example, rocks from the exposed lower crust preserve thermal and barometric evidence that suggest arc contraction and deep burial and loading, followed by delamination of dense lower crustal residues and uplift and exhumation. However, there is still uncertainty in the magnitude and extent of this loading, which must be resolved to evaluate mass transfer and its relationship with magma emplacement.

What processes drive thermal and vertical changes to arc crust during magmatic construction? Three large plutons (1000-2000 km^2) of the Cretaceous Western Fiordland Orthogneiss dominate Fiordland. They were emplaced within a brief 10 Ma period into the crust and then buried to lower crustal conditions. Strong garnet signatures in the compositions of these plutons suggest that Fiordland magmas equilibrated with significant volumes of high density eclogitic residues. Current work supports the notion that magmatism operated in concert with granulite- and eclogite-facies metamorphism. Subsequent retrograde metamorphism preserves near isobaric and spatially heterogeneous cooling and reheating. Metastability is common, suggesting that loading and rebound was transient and that average geothermal gradients may have been lower than expected.

What are the physical and chemical conditions that control the evolution of subduction zones and subduction zone magmas, including the evolution of mature arc systems? Fiordland offers insight into the evolution of mature arc systems. Long-lived 'normal' basalt-andesite-dacite-rhyolite (BADR) arc magmatism in New Zealand operated for nearly 100 Ma, and was followed by a relatively brief period of high-flux TTG magmatism for 25 Ma. The physical conditions of the arc during this transition remain to be resolved, including why magmatism suddenly ceased at 105 Ma. Furthermore, it would useful to understand the possible links between subduction cessation and geochemical changes in arc magmas from BADR to TTG-like compositions. In addition, what role does the Hikurangi Plateau play in the cessation of subduction?

What are the critical feedbacks between surface processes and subduction zone mechanics and dynamics? The possible delamination of high density residues may have enabled significant surface uplift by isostatic rebound, and development of a prominent mountain range above the arc. Removal of a high-density lithospheric root may also have been associated with a shift from contraction to extension across the arc, and also basin formation. Focused isotopic, thermobarometric, and thermochonological studies are needed to test these hypotheses and better understand their relationships to arc evolution.

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

Although difficult terrain and weather limits easy access to much of Fiordland, GNS Science recently completed a new 1:250,000 geological map of New Zealand (Q-Map Series), which includes a new map of Fiordland completed in 2010 (Figure 2.28). This map and associated text summarizes the current state of knowledge in the region. GNS Science also operates a comprehensive sample collection and analytical database (http://pet.gns.cri.nz/). Data for Fiordland include 12,358 records, 1,539 geochemical analyses, 5,262 magnetic susceptibility analyses, and 325 geo-thermochronological analyses. For example, the GNS Science mapping program has distinguished several major intrusive bodies that comprise the Western Fiordland Orthogniess, and established the presence of eclogites of likely cumulate origin defining the deepest parts of the arc exposed in the Breaksea Sound region. In addition, zircon geochronology has confirmed the rapid emplacement of plutons, apparently overlapping with arc contraction and thickening. Substantial whole rock XRF chemistry exists for the region, however, rare earth element and isotopic data are underrepresented in existing data sets.

Thus, there are a number of gaps in the datasets in Fiordland related to arc magmatism, metamorphism and deformation. In particular, geochemical characterization of deep-crustal arc plutons is lacking, and thus, geochemical and isotopic changes associated with arc magmatism are poorly understood. Timescales of arc construction are lacking for parts of Fiordland, and no systematic geochronology studies have been undertaken. High-temperature thermochronology studies are also limited, resulting in apparently contradictory data from the same region. New

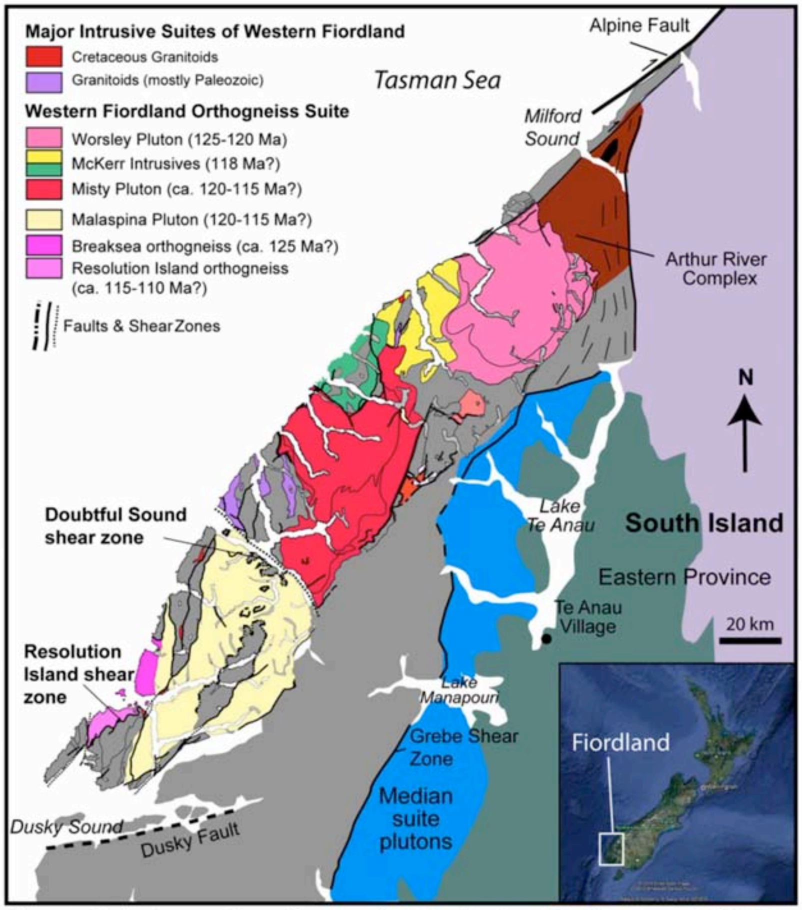

Figure 2.28. Geologic map of central and northern Fiordland resulting from 6-year GNS mapping program (after Allibone et al., 2009; Stowell, personal communication).

field-based studies, coupled with geochemical and isotopic analyses and integration of existing data, would help to establish the relationships between arc magmatism, vertical motions, and thermal changes, and associated lower crustal flow processes.

Some geophysical constraints on arc structure exist from previous and ongoing efforts, but new opportunities exist to augment these datasets. Passive seismic studies completed in Fiordland, resulted in 3D velocity and attenuation models and surface wave models. Earthquake data (continuous broadband since 2005; short-period triggered events prior to that) are available from GeoNet (http://www.geonet.org.nz/), and could be used to update models or to apply additional techniques, although permanent stations are sparse. Gravity data that could be used to improve crustal models are available across New Zealand (http://www.nzpam.govt.nz/cms/pdf-library/petroleum-conferences-1/2013/presentations/Advantage_2013_Davy.pdf).

2.4.6.2. Potential GeoPRISMS Studies

GeoPRISMS provides the impetus for coordinated, interdisciplinary approaches integrating structural geology, metamorphic petrology, geochemistry, geochronology, and geophysical studies with field, analytical, modeling and experimental approach with a primary goal of understanding transport and redistribution processes occurring at high pressure and temperature within the dynamic subduction zone environment. Planned work should include cooperative transport and sampling for multidisciplinary studies on single sample sets that could be lodged in PETLAB. Specific questions that can be addressed include:

Geochemical Sampling and Analyses: Sparse samples exist and limited analyses have been conducted to address some of the basic questions relating to the evolution of this ancient arc. More complete sampling, particularly of plutonic rocks that may record processes associated with lithospheric delamination, basaltic underplating, and intra-arc extension, will provide direct opportunities to analyze the geodynamic interpretations posed above. A focus on rocks that record the sudden and complete switch to HiSY TTG-like plutonism at c. 135 Ma would be key to understanding this episode. In addition, rare earth element and isotopic studies remain to be carried out in the area.

Thermochronology: Characterization of the processes that drove deep burial to 10-20 km, and subsequent exhumation of the arc roots now exposed in Fiordland, require systematic high-temperature thermochronology studies that could resolve timescales and rates of loading and exhumation, and the spatial distribution of regional flow paths in the crust. These data can be integrated with thermobarometry estimates and constraints on lithospheric velocity structure to assess arc composition and associated vertical motions responsible for the present structure. The timing of the cessation of subduction may also be resolved by study of the relict accretionary wedge. Similarly, the timing of the onset of rifting and the nature of the rifting processes can be examined.

Geologic Mapping: The recently completed more detailed geological mapping of Fiordland conducted by GNS Science provides a strong base to build on for additional geological mapping, in particular, to identify and date key deformation zones and structures, both brittle and ductile, and to document patterns and signatures of crustal melting, magma mixing, and flow, indicative of deep crustal flow that accommodates lateral and vertical motions.

2.4.7. Numerical and Experimental Studies

The New Zealand plate boundary is an excellent natural laboratory for understanding physical processes that control subduction, rifting, and volcanic arcs. Many high-quality geophysical and geological datasets already exist to constrain models, and to link with experimental datasets. Several IODP drilling campaigns are proposed and/or awaiting possible scheduling, and will provide opportunities to obtain samples for experimental studies, as well as key datasets to better constrain models. Critical gaps that could be addressed by modeling and experimental studies include: (1) the effect of along-strike flow and transport along the New Zealand plate boundary on dynamics of subduction, magmatism and rifting; (2) links between fluid-flow, heat-flow and mechanics at a range of timescales from millions of years to seconds; and (3) the laboratory study of rock properties from the New Zealand plate boundary. Below, we describe the potential role such studies could play for key SCD topics.

2.4.7.1. Numerical and Analog Modeling

Current generation numerical models of New Zealand tectonics have focused on diverse topics, such as the dynamics of accretion and subduction; the interaction of magma and rift tectonics; coupled tectonic-climate feedbacks; and the effect of subduction initiation on mantle flow and deformation of the overriding plate. Improved 3D numerical and analogue modeling techniques make this an ideal time to advance such modeling efforts via GeoPRISMS-related science and partnerships.

For example, numerical models of subduction initiation suggest a change from forced to self-sustaining subduction as the incipient lower plate is pushed downwards. The Puysegur-Fiordland region may currently be transitioning to a self-sustaining system. This is the only subduction zone presently in this critical state, and enhanced 2D and 3D numerical models of this transition, combined with new geophysical datasets, offer an unprecedented opportunity to understand subduction initiation processes and the forces operating on young subduction systems. Dynamic models that track the evolution of transform and normal faults making up the initial Australian-Pacific plate boundary into the present convergent setting will be essential. How the evolution of and geometry of the shear zone is reflected in the growth of topography on and offshore will be essential to exploit the current (such as the rock uplift in Fiordland) and expected (seismic structure) constraints. Further north, the Tonga-Kermadec system has well-preserved sedimentation and geochemical signatures of subduction initiation that place strong constraints on the timing of the onset of convergence and associated vertical motions relative to regional tectonic events, offshore thermal and crustal structure, newly developing arc volcanism, and the geometry of subduction initiation. These constraints can be used to test numerical models of subduction zone initiation.

Numerical models can also test the hypothesis that changes in subduction angle and subducted material along-strike in the Tonga-Kermadec arc have strongly influenced the geochemical signature of volatiles and magma. Similarly, detailed "subduction factory" calculations for the combined subduction/rift system onshore North Island can explore questions about the nature of magmatic products, particularly the change from andesite to rhyolite dominated magmatic systems in the TVZ, and help to understand the extremely high heat-flow and volatile flux component emerging through this rift. Preliminary tectonic modeling of this rift suggests a feedback between rifting and volcanism, but further coupled numerical models including fluid and volatile fluxes are needed to understand this process. Improved modeling of melt generation would help address magma-tectonic interactions.

The Hikurangi subduction margin offshore of the North Island, New Zealand is prime territory for numerical models to explain the contrasting slip behavior along its length. The cause of the abrupt change in subduction zone locking depth and distribution and the frequency of slow-slip events along-strike is not well-understood. The Hikurangi margin is an ideal test-case for modeling studies to explore whether fluid pressure variations, changes in incoming subducting sediment and/or lower plate, changes in stress in the over-riding plate, or other effects are responsible for subduction thrust fault slip behavior and its spatial variability. Numerical models coupling a variety of timescales, from millions of years to decadal timescales (plate geometry; effect of subducting an ocean plateau on mantle dynamics, upper plate stress, fluid production and pressure, and their influence on stress accumulation and release during the seismic cycle) are needed. Improved thermal models are also required, incorporating fluid flow, upper mantle viscosity changes associated with partial melt, and informed by new and existing heat-flow measurements and more detailed information on subduction inputs. Rate-and-state and earthquake simulator models specifically adapted to include upper plate structure and the geometry of the subduction interface could be constructed, in order to explore interactions between the subduction thrust and the overlying plate and forearc. Dynamic models of slow-slip events propagating along-strike can be used to inform the effect of these events on hazards.

Sediments are generated in response to tectonic and magmatic forcing, and commonly contain a record of these events – for example seismic shaking, uplift, erosion and volcanism. Sediments play a significant role in defining forearc structure, and the mechanical properties of the subducting slab – e.g., roughness, sediment composition, and sediment thickness on and below the subduction thrust. Sophisticated 3D models are available for both lithospheric and surface processes; however, a complete description of an active landscape requires characterization of the interaction between these processes, as well as inclusion of atmospheric driving. At present, available coupling is rudimentary at best. To better understand the linkages between sedimentation and deformation, next generation models coupling both sets of processes must be used. These developments are being facilitated by the Community Surface Dynamics Modeling System (CSDMS) and their Geodynamics Focus Research Group (co-sponsored by GeoPRISMS). Some projects are already underway applying these numerical modeling tools to the New Zealand plate boundary, including projects partly sponsored by the precursor to GeoPRISMS (the MARGINS Source-to-Sink project).

With increasingly high resolution data to constrain models, and identification of short-duration events in the sediment record (e.g., tsunami deposits and turbidite records of past earthquakes), we can expand on current modeling to address targets such as the rheological characteristics of the plate interface, links between upper and lower plate deformation and uplift along the Hikurangi subduction zone, the interplay between rifting and magmatism in the TVZ, and overall influence of sediment budget and its relationship to fluids and magmatism in the subduction/rift system. Such advances require embedded models with higher resolution geological, geophysical and topographic inputs to explore components of the system.

Finally, earthquakes, surface uplift, storms, fires and volcanic eruptions all potentially drive pulses of terrestrial sediment fluxes to the continental shelf and eventually to the subducting plate. The relative contribution of earthquake-driven fluxes is largely unknown at present and is an obvious area that GeoPRISMS-related researchers could explore. Numerical models may help elucidate the role of subduction zone earthquakes in initiating landslides, creating readily mobilized sediment sources, predictions that can be tested against the sediment record.

2.4.7.2. Experimental Studies

Like numerical studies, laboratory experiments conducted under controlled conditions are an essential component of the GeoPRISMS SCD initiative. Experimental programs allow testing of hypotheses related to deformation and rheology in the seismogenic zone and in the upper mantle, fault slip behaviors, metamorphic reaction rates, melting behavior, solubility, and transport of fluids and magmas. Experiments also allow linkage of field observations (e.g., geodetic locking along subduction thrusts; water content in magmas) with underlying physical and chemical processes, and provide key constraints to inform numerical modeling studies. In this context, experimental studies are tightly allied both with thematic studies relevant to *all* primary sites, and with testing of hypotheses specific to individual primary sites.

In conjunction with numerical modeling studies described above, experimental data defining rock properties are a key ingredient in testing hypotheses about both fault and upper plate rheology, hydrogeology, and deformation. For example, laboratory measurements of rock and fault gouge frictional behavior, permeability, and elastic properties are central to understanding the role of frictional properties and stress boundary conditions on the mode of subduction fault slip. The Hikurangi margin of the New Zealand focus site offers an outstanding opportunity to investigate the controls on along-strike variability in locking and the nature of slip on the subduction megathrust. Experimental studies are a key component of testing hypotheses to explain the occurrence of slow slip events at Northern Hikurangi: are the SSE related to a specific fault zone composition with frictional properties that facilitate slow slip? Are they related to elevated pore fluid pressure? Similarly, the role of seamounts as asperities and/or as barriers to slip, and in driving heterogeneous pore fluid pressure and stress distribution along the plate interface, require tight linkage of numerical models (described above) and laboratory data that parameterize models (e.g., permeability, elastic moduli). Detailed measurements of acoustic and electrical properties for relevant subduction zone rocks provides key data to link between *in situ* conditions and properties, and geophysical datasets that remotely sense rock attributes over large regions (e.g., seismic reflectivity, low P-wave speed). Ultimately, these experimental data will provide a basis for quantitative extrapolation of rock properties and *in situ* stress and pore fluid pressure conditions away from boreholes in the shallow subduction zone, and allow rigorous testing of hypothesized causes for anomalous low-velocity and high reflectivity over depths ranging from the trench to the downdip reaches of the seismogenic zone. The plan to drill into a slow-slip zone in the northern Hikurangi margin, if successful, will provide a unique opportunity to access relevant materials for these studies.

The well-studied fluid seeps along the Hikurangi margin provide an exquisitely detailed geochemical record of devolatilization beneath the forearc. Experimental studies that provide detailed constraints on the P-T conditions associated with liberation of specific chemical species during prograde diagenesis and metamorphism (e.g., hydrocarbon generation, thermally driven desorption and release of structurally bound fluid-mobile elements including B and Li, clay dehydration) will yield insights into the source regions for these volatiles observed at the land surface, thereby providing powerful new constraints on the budgets and transport of these volatiles through forearc and subarc.

The rheology of rocks containing partial melt, fluids, and effects of fluid-alteration (e.g., serpentinization) is also critical to understand pathways, fluxes, and sources of volatiles, their relationship to deformation, and to constrain models of these processes – for example, beneath the North Island and offshore in the Tonga-Kermadec arc system. Detailed experimental rock studies that address how tomographic and electrical conductivity signatures relate to these properties (e.g., hydration state, serpentinization) are also needed. Questions include: how do signatures change below the brittle-ductile transition, and as a function of strain? Such studies could also help inform codes that compute changes in density, rheology, melt and fluid content as a function of pressure and temperature changes, particularly if they were based on protolith material representative for New Zealand (e.g., greywacke; anomalous oceanic plateau material; and mantle). For a better understanding of how fluid circulation in the TVZ crust interacts with tectonics and magmatism, we also need improved understanding of how permeability changes with deformation, pressure and temperature.

2.4.8. Research Strategies and Partnerships

The New Zealand primary site is already the focus of significant research efforts within the international community. This affords a wide range of opportunities for linking GeoPRISMS studies with a vast body of previous work on subduction systems in NZ, leveraging existing infrastructure, and collaboration in numerous ongoing and planned investigations. These ongoing endeavors include significant investments from the NZ government and efforts within the NZ geosciences community, as well as active research programs led by Japanese and European-based investigator groups. Any GeoPRISMS studies at the NZ primary site should build on these substantial existing and ongoing studies; there are significant opportunities to leverage GeoPRISMS research investments through collaborations with international partners.

2.4.8.1. New Zealand Resources, Infrastructure & Databases

A large New Zealand-based community of geoscientists has been undertaking a wide range of marine and shore-based investigations at New Zealand's subduction zones for many decades. These investigations include government-funded research focusing on subduction processes conducted by Crown Research Institutes (GNS Science, NIWA), and at several universities. There is relatively strong NZ government support for subduction–related research, due to their relevance for understanding both geohazards and resources. New Zealand maintains a marine geophysical data acquisition and research capability in part via its research vessels, which are owned and operated by NIWA, and in part through oceanographic surveys organized through international collaborations. The largest and most capable New Zealand vessel is the 70 m long RV *Tangaroa*. *Tangaroa* is equipped with a Dynamic Positioning DP2 and a 30 kHz multibeam echo-sounder with full water column capability. NIWA's multichannel seismic reflection acquisition system can easily be deployed from *Tangaroa*. It is also equipped to conduct seafloor sampling (dredging, shallow coring, multicorers, CTD, etc.), and is suitable for the deployment of a range of geological and geophysical equipment such as ROV and AUV.

The GeoNet network discussed previously (Figure 2.25) constitutes a major scientific infrastructure investment dedicated to earthquake, tsunami, volcano and landslide monitoring. GeoNet includes a comprehensive seismograph network that includes 52 broadband national network stations, 126 regional stations, and more than 240 strong ground motion stations. There are 180 continuous GPS sites in New Zealand, with the vast majority of these deployed along the Hikurangi forearc and within the volcanic region of the central North Island. In addition to seismic and cGPS, the volcanic regions also undergo routine water and gas chemistry monitoring. All of the raw data gathered by GeoNet is publicly available on their website: www.geonet.org.nz. Processed time series of the cGPS sites are also openly available. GeoNet routinely locates all detectable earthquakes in New Zealand, and maintains a comprehensive earthquake catalog.

Many of the results and samples from extensive previous geological studies in New Zealand have been integrated into national databases. From 1993-2010, the New Zealand government funded the QMAP project to produce new, high-quality geologic maps of all of New Zealand at 1:250000 scale (see data.gns.cri.nz/geology). The maps are underpinned by all available existing geological data, but extensive fieldwork was also undertaken in areas where such data were lacking. A database of over 177,000 rock and mineral samples gathered from throughout onshore and offshore New Zealand and Antarctica are catalogued in PETLAB (pet.gns.cri.nz). The Fossil

Record Electronic Database (FRED; fred.org.nz) contains information on nearly 100,000 fossil localities in New Zealand and Antarctica. A comprehensive database of New Zealand's active faults is maintained by GNS Science, and is publicly accessible at www.data.gns.cri.nz/af. This database contains detailed information, including fault geometry, kinematics, paleoearthquakes, photographs, and references to published studies on each fault.

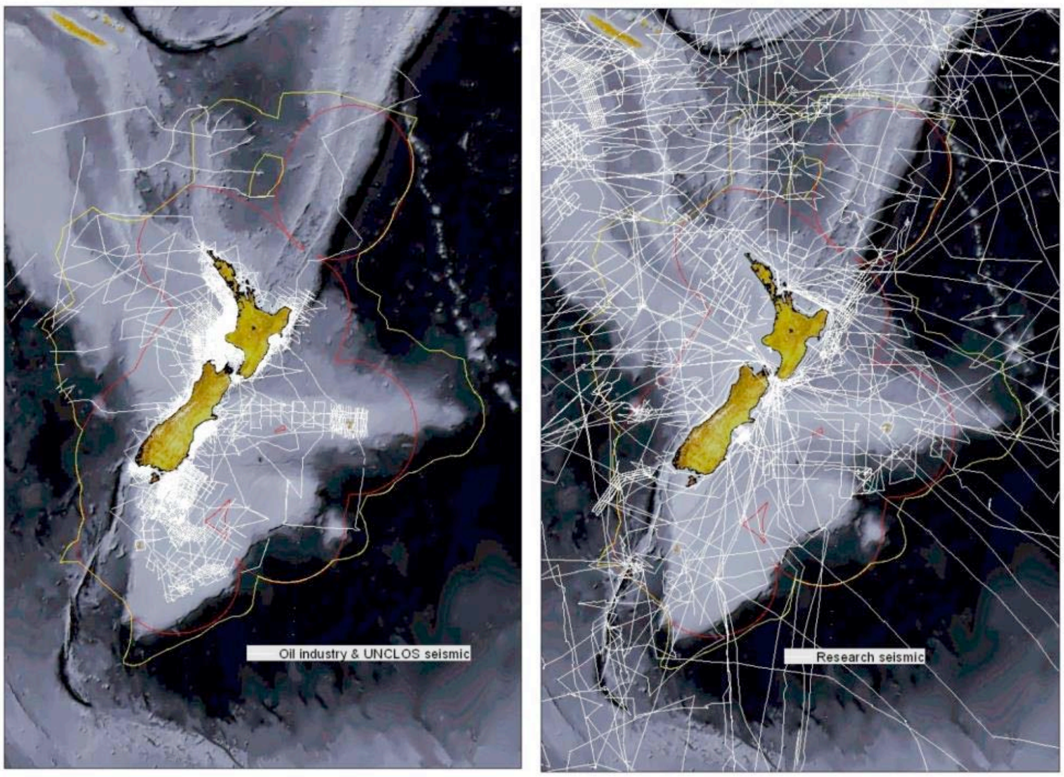

Figure 2.29. Locations where active source seismic data have been acquired. Map on left shows data acquired by industry, or for the purposes of the United Nations Law of the Sea (UNCLOS) project. The figure on the right shows seismic data acquired for research purposes. Source: GNS Science.

A large body of data has also been gathered in New Zealand's offshore environment through both New Zealand-based and international scientists (Figure 2.29). The petroleum industry has also gathered vast datasets in New Zealand waters, and these datasets are required by law to become open file (publicly available) within five years after the data acquisition. Active source seismic data are available through New Zealand Petroleum and Minerals (www.nzpam.govt.nz), a department of the Ministry of Business, Innovation and Employment, or via GNS Science's data portal (http://data.gns.cri.nz/dataportal/). A comprehensive database of bathymetry data offshore New Zealand compiled by the National Institute for Water and Atmospheric Research (NIWA) can be found at: www.bathymetry.co.nz. Rock samples gathered offshore via dredging, seafloor grabs, and shallow coring methods are catalogued in the PETLAB database (pet.gns.cri.nz).

2.4.8.2. International Collaborations

In addition to the research activities being undertaken by the New Zealand-based geoscientific community, there is substantial interest from the global scientific community in subduction-related research in the New Zealand region. Researchers from Germany, Japan, France, the United Kingdom, Australia, and several other countries already have ongoing projects related to subduction in New Zealand. Collaborative international efforts and future international community experiments at the New Zealand primary site offer outstanding opportunities that will greatly amplify the outcomes of any NSF/GeoPRISMS investments there.

Strong tectonic similarities between NZ and Japan, and common interests in seismic and tsunami hazard, has led to mounting interest from Japanese researchers in conducting projects on New Zealand's subduction setting. The University of Tokyo's Earthquake Research Institute (ERI) is heavily involved in the SAHKE project to image the locked part of the Hikurangi subduction interface. ERI and Tohoku University (in collaboration with GNS Science) are conducting pilot deployments of OBS and absolute pressure gauges to investigate slow slip offshore North Hikurangi. Later in 2013, the Japanese submersible Shinkai 6500 is slated to dive at a series of locations along the Kermadec Arc and Kermadec Trench. Japanese researchers are developing plans and proposals to conduct additional future studies in New Zealand, including: OBS and seafloor geodetic studies of slow slip, active source surveys of the subducting Hikurangi Plateau, and offshore magnetotelluric studies of the Hikurangi margin. Moreover, research activities related to the series of IODP proposals for drilling the Hikurangi margin have major Japanese involvement. In the coming years, there is excellent potential for Japanese research vessels to conduct studies in New Zealand waters (such as seismic surveys, OBS deployments, and ROV deployments) that will complement any GeoPRISMS funded studies.

Researchers from Germany have a long-standing interest in New Zealand subduction science, and have conducted a number of studies in the New Zealand region, including the MANGO project (wide-angle seismic data across the Hikurangi and Kermadec margins), and several research cruises to investigate gas hydrates and fluid flow at the offshore Hikurangi margin, explore seafloor hydrothermal systems related to submarine arc volcanoes, and to map and sample the Hikurangi Plateau. Some projects are scheduled to be undertaken using the German research vessel Sonne in 2014/2015, while others are being proposed. One scheduled project is to use MeBo (a seafloor based drilling rig) to core submarine landslides in the region of the proposed IODP drilling transect at North Hikurangi, while another will have a specific focus on hydrothermal systems and their capacity to form mineral deposits and host extreme microorganisms. There is interest among German researchers in conducting geochemical sampling and hydrological monitoring at offshore seeps to investigate the role of hydrogeology in the seismic behavior of the Hikurangi subduction thrust. A proposal is also in development to investigate the evolution of the Vitiaz-Kermadec Arc from arc initiation to arc splitting through formation of the Havre Trough through extensive sampling and detailed mapping (multibeam, gravity, magnetics) along the southern part of the Kermadec and Colville Ridges and Havre Trough. All of these studies will contribute greatly to the major SCD questions outlined for the New Zealand primary site, and will underpin future GeoPRISMS funded studies.

The UK has a long history of research collaboration with New Zealand, particularly in the area of tectonics. Currently, UK researchers are actively collaborating on arc volcanism, mineralization and fault processes within the Kermadec-Tonga Arc, and extensional fault networks within the Taupo backarc. Specifically related to subduction, UK researchers from Universities of Oxford and Durham have conducted active seismic experiments across the Tonga-Kermadec arc, studying the impact of seamount subduction and arc volcano eruptive and collapse processes. Tectono-magmatic interactions and the economic resources of arc volcanic systems within the Kermadec arc have involved both UK-led projects and UK-NZ collaborations primarily between University of Southampton, GNS Science and NIWA, including the newly submitted Brothers volcano IODP proposal. The University of Leeds has collaborated with New Zealand researchers in an active seismic experiment to analyze the large-scale structure of the Hikurangi subduction zone. A number of potential future collaborative experiments, prompted by the IODP proposal for the northern Hikurangi margin, are in the planning or proposal stages. These include support for a 3D seismic proposal within the targeted drilling area (to be submitted to NSF), and an Imperial College, London proposal to conduct a 3D full waveform inversion complementing other seismic studies in the area. In addition, UK partners (primarily Southampton and Imperial) are investigating potential OBS seismic experiments and/or EM-MT to further illuminate structure, physical properties and fluid processes within the subduction forearc, plate boundary and downgoing plate.

A number of researchers from the France, Australia, and Canada also have ongoing interests and involvement in New Zealand subduction research across the entire range of SCD topics, offering additional important partnership opportunities at the New Zealand primary site. In addition to substantial scientific expertise in subduction-related topics, these countries have marine geophysical and laboratory/analytical capabilities that could be brought to bear on a variety of SCD topics. Two proposed French cruises to use the RV L'Atalante to investigate Tonga-Kermadec-Hikurangi subduction initiation have been ranked very highly, and await scheduling.

8.3. International Ocean Discovery Program Opportunities

Historically, the MARGINS and IODP communities have had strong linkages because of IODP subduction drilling efforts at MARGINS focus sites at Nankai, Costa Rica, and the Izu-Bonin-Mariana system. The New Zealand primary site offers an excellent opportunity to continue this relationship between GeoPRISMS and IODP; proposals for three subduction-related projects in New Zealand waters have been submitted to IODP over the last 3 years. The proposals are: (1) Hikurangi margin slow slip event drilling (IODP Proposals 781-MDP; 781A-Full; and 781B-Full); (2) Drilling at the Lord Howe Rise to investigate the Eocene record of Tonga/Kermadec/Hikurangi subduction initiation (IODP Proposal 832-Full); and (3) Drilling at Brother's volcano (Kermadec arc) to investigate the subseafloor hydrology of an arc hydrothermal system, the transfer of metals from magma to seafloor, a range of arc volcanic processes, and the deep biosphere (IODP Proposal 818-Pre). The aims of all three of these proposed projects are strongly allied with GeoPRISMS SCD science questions, and if they are scheduled for drilling, we expect that they will yield significant opportunities for leveraged studies and integration with GeoPRISMS investigations. It is also anticipated that the IODP projects will help motivate and focus future GeoPRISMS studies in New Zealand.

2.4.9. Broader Impacts

2.4.9.1. Geohazards

Given its position astride the boundary zone between the Pacific and Australian Plates, New Zealand is exposed to significant geohazards. The sequence of devastating earthquakes in Christchurch in 2010 and 2011 highlights this, with insured economic losses on the order of 20-30 billion dollars, making it the third costliest earthquake in history. A large proportion of the geohazards that New Zealand faces are related to the Hikurangi/Kermadec and Puysegur subduction plate boundaries. The outcomes of GeoPRISMS SCD efforts in New Zealand will provide important new insights into the seismic, tsunami, and volcanic hazards posed by the subduction zones there.

Subduction margins produce the largest and most destructive earthquakes and tsunamis on Earth. In particular, there is very little knowledge about the past seismic behavior of the Hikurangi subduction, which poses what is arguably the largest "unknown" seismic and tsunami hazard to New Zealand. Can the Hikurangi subduction margin produce giant (Mw ~9.0) earthquakes similar to that observed in Tohoku in 2011? Further paleoseismic studies are needed to address this. New insights gained from GeoPRISMS SCD studies into the cause of the transition from interseismic coupling (southern Hikurangi) to aseismic creep (northern Hikurangi) will have global significance for our knowledge of why some subduction thrusts lock up and produce large earthquakes, while others tend to accommodate plate motion largely aseismically. Knowledge of the mechanics of fault slip behavior on subduction thrust interfaces are necessary to understand and mitigate the hazards posed by these major plate boundary features. Another important outstanding question involves the relationship of slow slip events to major megathrust earthquakes. Can slow slip events trigger major, damaging earthquakes? Due to the strong association between SSEs and microseismicity, New Zealand is an ideal location to evaluate this important, societally relevant question.

New Zealand has been the site of major explosive volcanic eruptions, including supervolcano eruptions at Taupo Caldera, such as the Oruanui eruption 26,500 years ago that produced ~1200 km^3 of eruptive material. Since European settlement, a few smaller-scale eruptions and unrest events have occurred, with the largest being the eruption of Mount Tarawera (~2 km^3 of eruptive material) in 1886. Secondary effects of eruptions have also proven hazardous, such as a lahar in 1953 that took out a railway bridge, killing 151 people, and ash from a 1966 eruption of Ruapehu volcano that disrupted services at several airports. Imaging magma supply at depth via MT or seismic surveys will enable better understanding of the location of potential future eruptions. GeoPRISMS research on volatile cycling and the magmatic plumbing system will enable better understanding of the feedbacks between volatile content, magma chemistry and eruptive style.

2.4.9.2. Economic Resources

The offshore New Zealand region contains petroleum and minerals resources, although the extent of these resources is not fully understood. Studies of the offshore Kermadec arc may yield new insights into the formation of metals at submarine volcanoes. For example, some of the most acidic, high-temperature and metal-rich fluids ever seen occur at the vent sites of Brothers Volcano. Moreover, the hydrothermal system at Brothers contains the ex-solution of gases from the active magmatic system below, thus the transportation of metals to the seafloor and eruption processes can also be studied. Extensive petroleum resources are currently being exploited in the Taranaki Basin, a retroarc foreland basin, which also holds a signature of vertical motions during subduction inception at the Hikurangi margin. Similar basins further north also contain a record of subduction initiation, and any seismic surveys from these areas (and other areas in New Zealand) will contribute to regional characterization of resource potential in these areas. Abundant gas hydrates exist at the offshore Hikurangi margin; seismic, heat flow, and fluid geochemical studies offshore Hikurangi may yield new insights into gas hydrate formation.

2.4.9.3. Engaging Local Communities

The significant geohazard potential of the New Zealand region elicits great public concern and interest in learning about the seismic, tsunami, and volcanic hazards that they are exposed to. It will be important to coordinate public outreach on GeoPRISMS projects at the New Zealand primary site in collaboration with colleagues at New Zealand universities, at GNS Science, and at NIWA. These activities would include media coverage (radio and television interviews, newspaper articles), and directly interfacing with the public through lectures and ship tours. We anticipate that such exchanges will help inspire the next generation of New Zealand geoscientists (including underrepresented groups such as Maori), as well as inform the local population and foster good will. There was substantial local media coverage of the recent GeoPRISMS Implementation Plan workshop for the New Zealand primary site held in Wellington, New Zealand in April 2013. This included several radio interviews on New Zealand National Radio, and high-profile articles in the major newspapers, such as the Dominion Post and New Zealand Herald. In part due to recent disasters such as the Christchurch earthquakes in 2010-2011, the New Zealand public and media have a large appetite for learning about geohazards in New Zealand. This will certainly broaden the impact of any GeoPRISMS funded studies in New Zealand.

2.5. Comparative and Thematic Studies

Theme 1: Identifying controls on fault slip behavior and deformation history

Studies at the GeoPRISMS primary sites will advance our understanding of physical processes and material properties that control fault slip behavior and deformation along subduction plate boundaries. Current hypotheses suggesting strong feedbacks between surface processes and subduction zone dynamics can be tested. GeoPRISMS has the potential to contribute significantly through data acquisition at the three primary sites, all of which produced great earthquakes in the past and/or exhibit significant variations in fault slip behavior and deformation history. The primary sites, however, are not sufficient to answer these questions on a global basis because of their limited diversity of slip behavior, site characteristics, and deformation history. The field of "comparative subductology" was founded on the observation more than 30 years ago that some subduction zones produce great earthquakes (Mw > 8, called "Chilean style") while others do not ("Mariana style"). Although comparative subductology has identified several potential controls on slip behavior, it has shown that most subduction zones do not fall into the end-member groups. To extrapolate results from GeoPRISMS primary sites globally, a comparative subductology approach across multiple disciplines is necessary. Additionally, experimental and theoretical studies are essential toward understanding the controls on fault slip behavior, yet by definition these efforts are not tied to a single focus-site.

Therefore, in order to complement and extend insights gained from observations at primary sites, and to test hypotheses that arise from new data, laboratory and theoretical studies, comparative field studies, global comparisons, and targeted observations at non-primary subduction zones will be essential. Studies envisioned to meet this theme must be comparative (involving multiple active subduction zones, exhumed systems, or global) and interdisciplinary (including, where possible, thermo-mechanical and geochemical datasets). Ancient analogs, focused comparisons among the GeoPRISMS primary sites, and integration of results from the MARGINS focus sites (Nankai Trough, Izu-Bonin-Mariana, and Costa Rica) will allow more thorough hypothesis testing across disciplines. Detailed mapping, sampling, and laboratory analyses of exhumed fault zones will help correlate ancient subduction zone structure across a range of scales with specific slip processes, such as large earthquakes, ETS, or creep. Studies that exploit the recent surge of great earthquakes will provide new data on slip and deformation behavior over the co-seismic and post-seismic periods. Global comparisons of site characteristics (climate, convergence rate, crustal thickness, relief, volcanism, sediment types, supply and dispersal), particularly if such characteristics are not well represented within the primary sites, will be important for showing how sediment composition, exhumation, and erosion rates affect subduction margins. Laboratory studies should target the full spectrum of frictional, mechanical and diagenetic behavior of subduction zone materials. Other specific activities and datasets include: seismic and geodetic characterizations of slip events; 3-D mapping of stratigraphic positions of plate interfaces; high resolution bathymetry to identify variations in oceanic plate and forearc structures; surface deformation observations at subduction zones at different stages of the seismic cycle; gravity and magnetic data; heat flow and thermal history; mineral assemblages and recorded fluid and deformation processes along exhumed subduction faults and mantle wedges; low- and high-temperature deformation experiments on the effect of volatiles on slip behavior; laboratory measurements and deformation experiments on serpentine and other hydrated minerals; and modeling of the evolution of surface deformation and fault slip behavior over the seismic cycle.

Theme 2: Understanding mantle wedge dynamics

The rheology and dynamics of the mantle wedge link the shallow subduction processes contributing to megathrust earthquakes to arc and back-arc processes. Devolatilization, deformation, and fluid/melt transport must fundamentally affect the dynamics of the mantle wedge, but broad-scale questions remain on the relative contribution of each. This theme focuses on integrating comparative field observations, thermal and numerical modeling, and laboratory observations to better constrain the maximum depth of plate interface decoupling (MDD), effect of serpentine or other hydrated minerals on wedge and interface strength, and flow geometry within the mantle wedge. The MDD, for example, dictates the trench-ward extent of mantle wedge flow, which in turn controls the thermal and petrologic structures of subduction zones. Flow geometry, if measured by seismic anisotropy, depends on water content, temperature and other parameters, even in an olivine-dominated lithology.

The GeoPRISMS primary sites provide excellent opportunities to gather the interdisciplinary datasets needed to characterize system-wide changes in thermal structure, volatile distribution, seismic observations of mantle flow, and hydration state of the wedge. These will aid in obtaining more accurate modeling of wedge dynamics along these margins. Of the GeoPRISMS primary sites, New Zealand has the oldest slab (~100 Ma), but it is primarily an oceanic plateau with an atypical crustal thickness (~15 km). Comparative, targeted geophysical observations of older, colder, and dryer subduction zones will also be necessary. Such studies should be limited to providing key missing datasets (surface heat flow, thermal modeling, velocity and attenuation images, anisotropy studies) in otherwise well-studied margins. Additional laboratory studies and numerical modeling are required to characterize mantle wedge dynamics and are themselves strongly linked. We do not yet understand how to distinguish between free fluid and hydrous minerals in seismic imaging, but these boundary conditions are fundamentally important in numerical simulations of the mantle wedge. Additional laboratory studies that provide data on the effect of water and volatiles on seismic properties, such as velocity or anisotropy, on typical mantle wedge assemblages are needed. Deformation experiments on materials along the slab-mantle interface could provide important constraints on numerical models exploring mechanisms that control the strength contrast between the plate interface and overriding mantle. Serpentinization of the mantle wedge and incoming oceanic plate is frequently invoked to explain strength changes along the subduction plate interface, but laboratory measurements and deformation experiments on serpentine minerals and other hydrated minerals are necessary to significantly advance our understanding of serpentinization and subduction dynamics in general, and mantle wedge dynamics in particular.

Theme 3: Fore-arc to back-arc volatile fluxes

Volatile elements play a uniquely central role in the functioning of subduction zone processes at all levels. Although the identities of some key volatile-bearing phases (e.g., clays, serpentine, chlorite) are reasonably well-constrained, others are not (e.g., supercritical fluids or melts). Furthermore, critical constraints on the specific carriers, fluxes, and transport pathways of volatiles from their release at the slab, through the forearc and/or mantle wedge and upper plate lithosphere are largely missing. At their core, these questions cannot be addressed at any one focus site because the controlling factors are likely to be globally heterogeneous and may not be fully encompassed at the selected primary sites. For example, the variables that control serpentinization of the subducting lithosphere, and the extent to which serpentinization may control volatile fluxes into subduction zones, are as yet unknown. Thematic study of volatile fluxes will seek to identify a geochemical "smoking gun" for the contribution of such hydrous minerals to slab fluid composition and/or magma genesis, and allow the linkage of such tracers to geophysical and geochemical observations at the primary sites. In addition, geochemical and geochronological study of high-pressure metamorphic rocks can yield information regarding the rates and extents of loss (or retention) of volatiles to subarc depths and the isotopic compositions of volatiles entering the subarc mantle wedge and deeper parts of the mantle.

Thematic studies of volatile fluxes will incorporate ongoing surveys in the Marianas, and the recent results from Central America, which are examples of data from the MARGINS ramp-down that will be available for comparative study with the new GeoPRISMS primary sites. Accurate measurement of volatile output fluxes generated by subduction processes requires more accurate surveys of cross-arc transects, particularly including both the fore-arc and back-arc regions. Moreover, to determine global volatile fluxes, or to resolve the underlying controls on variations in volatile output among the primary sites or at global arcs, it is clearly important to synthesize surveys from as many different subduction settings as possible, which will involve broader international collaborations. In the laboratory, anticipated studies will test models against mineral phase equilibria experiments conducted over an extended range of pressures, constrain timescales of volatile uptake, release, and transport processes by examining the rates and kinetics of reactions and transport processes, and explore the physical mechanisms of volatile migration (e.g., in the form of fluids or melts) through a combination of of field metamorphic studies, modeling, experimental investigation, and integration with 3-D geophysical imaging of subduction systems.

Theme 4: Metamorphic and igneous conditions and processes in subduction zones at depth

The metamorphic and igneous processes taking place at depth within subducted slabs, the mantle wedge, and the arc crust represent key aspects of active subduction that cannot be directly observed *in situ*. To address the nature and composition of residues that subduction returns to the Earth's mantle, the mechanisms by which the subducted plate releases fluids or melts, the rates and processes of arc and continental crustal growth, and the overall role of subduction in global geochemical cycling, requires direct access to the deeper levels of subduction zones. Processes such as these, taking place at depth, within the arc crust, mantle wedge, and the slab itself, are inaccessible in active systems and require an alternate, thematic approach that complements studies ongoing at active primary sites. Specifically, geophysical imaging of primary sites will be accompanied by geological studies of exhumed slabs, mantle wedges, and arc crust that exemplify conditions expected within the primary sites. Such studies will require individual field campaigns in several different localities, with a coordinated and centralized sample management system, to obtain a reasonable picture of the range of at-depth conditions encompassed by the primary sites. Thematic studies will allow for coordinated, interdisciplinary approaches in which metamorphic petrology, geochemistry, geochronology, and geophysical studies will integrate with field, analytical, modeling and experimental approaches, and work together to understand transport and redistribution processes occurring at high P and T within the dynamic subduction zone environment.

A. Metamorphism of the subducted slab

The fluids and melts released by metamorphism are the fundamental drivers of arc magmatism, and many of the great subduction zone earthquakes occur in metamorphic rocks. Investigation of exposed high-pressure metamorphic terrains will allow us to disentangle processes of mixing and material transport occurring within subducting slabs and at the slab-mantle interface. In addition to H_2O, metamorphic studies will provide constraints on other volatile and non-volatile elements released by the subducting slab, rates and length scales of devolatilization, and the fluid flow paths (fractures, channels, porous flow) through the slab and deep mantle wedge. A broader range of laboratory experiments is required to quantify initial and boundary conditions for dynamic models, calibrate petrological models, and guide the interpretation of geophysical images. High pressure devolatilization studies are needed to address mineral stability and breakdown rates to higher pressures at depths >120 km (e.g., up to 410 km), constrain reaction kinetics to assess equilibrium vs. non-equilibrium conditions, assess the rheological effects of volatile/fluid species on constraining rates, and evaluate the mechanisms of volatile/fluid/melt transport under variable P-T conditions. Geodynamical models will complement this work by incorporating rheologic, kinetic, and petrologic information arising from laboratory experiments and field studies to ensure continued evaluation and testing of model results as well as to improve interpretations of large geophysical experiments.

B. Metamorphism, melting, and fluid/melt migration in the mantle wedge

The mantle wedge is the primary origin of arc magmas. As P-T conditions within the wedge cross the conditions of the hydrated peridotite solidus, metamorphism becomes melting, and these two processes may be difficult to segregate. Accessing the loci of key metamorphic and melting reactions within the mantle wedge, and determining the mechanisms and pathways by which fluids and melts are transported within the wedge, requires thematic study that combines field studies of exhumed mantle wedge terranes with petrological experiments and geodynamical modeling. For example, probing the deep roots of arc volcanoes to determine what physical features, if any, may “tether” them to the slab or mantle wedge will require intense geophysical and geochemical study of one or more arc volcanoes at a primary site, to be paired with geodynamic models of melt migration within the mantle wedge and arc crust that are constrained and refined by field studies of melt distribution in exposed wedge-analog peridotites. Petrological experiments will explore the P-T conditions of the mantle wedge, approaching the peridotite solidus to expose interrelationships between melting and metamorphic reactions, and examining phase equilibria at P-T conditions that may be encountered by ascending melt.

C. Arc crustal architecture and evolution

The rates and processes of arc and continental crustal growth cannot be directly observed in active subduction systems and require access to deep levels of arc crust. For example, information about the controls on, and relative contributions of, volcanic vs. plutonic components of arc crust is currently heavily biased towards accessible, erupted volcanics in active systems, but the material that doesn’t erupt is of equal (or greater) importance to the architecture of arc crust, and direct sampling of lower arc crust is important in order to understand the role of lower crustal foundering in differentiation. Thematic studies of exhumed arc upper, middle, and lower crust, through a combination of geochemical, petrological, geochronological, and geodynamical approaches, will be designed to complement the crustal imaging obtained through large geophysical experiments planned for the primary sites and those already executed at MARGINS sites. Field studies of exhumed arc crust, in combination with laboratory experiments at crustal P-T conditions, will combine analysis of petrology/ geochemistry/ geochronology/ petrofabrics with a detailed look at the geometry of melt and fluid-filled fractures and use new analytical tools to obtain very high precision chronologies and detailed maps of element distribution. Detailed and refined geodynamical modeling of arc crustal evolution is needed to constrain thermal development of arc crust, determine the key controls on crustal differentiation, test the importance of foundering on crustal development, and merge thematic observations with those from the active primary sites. Also important are structural studies of exposed volatile/fluid/melt migration paths to better constrain the physical conditions under which mass transport occurs through the lithosphere.

Theme 5: Subduction initiation

All three GeoPRISMS primary sites will provide essential observations to develop a fuller understanding of subduction initiation and the evolution of arc systems. However, subduction initiation is a transient phenomenon and is arguably only unfolding at one location today, the Puysegur subduction zone in New Zealand, a selected primary site. Subduction initiation may occur either spontaneously or be induced by far-field plate dynamics, unfold in different tectonic environments and occur over several to about ten million years when the dynamic, kinematic, and magmatic conditions of the margin dramatically change. The products of ancient subduction initiation events are partially to completely overprinted structurally and magmatically and buried beneath sediments; such complications increase with age. Similarly, uncertainties in the plate tectonic context of different subduction initiation sites become larger for older systems. Studies of the Puyseguer subduction zone, combined with investigations of subduction initiation in Alaska and Cascadia, will provide valuable insights, but by themselves, cannot resolve how 1000-km scale convergent margins become established. Consequently, it will be essential to complement existing knowledge and new understandings of the primary sites with comparative studies of other locales within the context of auxiliary studies.

In addition to studies that are specific to the focus sites, a much broader effort is needed if we are to develop a general theory of subduction initiation. Comparative field studies, global comparisons, and targeted observations at non-primary site subduction zones within the context of new computational studies will be essential to distinguish between prevailing hypotheses on the driving mechanisms of subduction initiation. Specific examples of observational studies include those that target the inner trench wall of mature subduction zones, field and geochemical analysis of ophiolites, and deep sea drilling. Combined structural, stratigraphic, petrologic and geochemical studies of the products and remnants of infant and early stage subduction provide fundamental constraints on the sequence of kinematic, vertical motion, crustal thinning/thickening, thermal state, and volcanic and volatile outputs in time and space which are particularly powerful if they can be placed in the context of plate tectonic reconstructions. Studies of both the inner trench wall (especially in naked, i.e. sediment-free, fore-arcs) and back-arcs become more valuable if the history of both back-arc and fore-arc can be synthesized for the same subduction initiation example. Dredging, submersible sampling, and drilling of fore-arc and back-arc settings can be particularly important to decipher early evolution of volcanic output in arcs and pin down the timing and magnitude of deformation identified from MCS surveys. Enormous information on subduction initiation can be gleaned from onshore study of ophiolites, with the caveat that not all ophiolites form during subduction initiation. Ophiolites should also be selected with the intention of drilling and coring, to better compare their extrusive and mantle rocks with those recovered by fore-arc drilling.

Analyzing existing and future numerical models of subduction initiation can guide the selection of sites in fore-arcs where crucial information on initiation is likely to be present, analyze existing passive/transform plate boundaries worldwide to determine their stability and suitability for observing early stages of initiation, and to construct refined 2-D and 3-D numerical models of initiation applicable to observational sites. Computational studies are needed to provide broader context for these observations, including how the asthenosphere flows and melts, how fluids penetrate into the overriding asthenosphere, how the slab dip evolves, how hot fore-arc mantle cools and becomes lithosphere, and how subduction initiation is a cause or a consequence of global plate motions.

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.

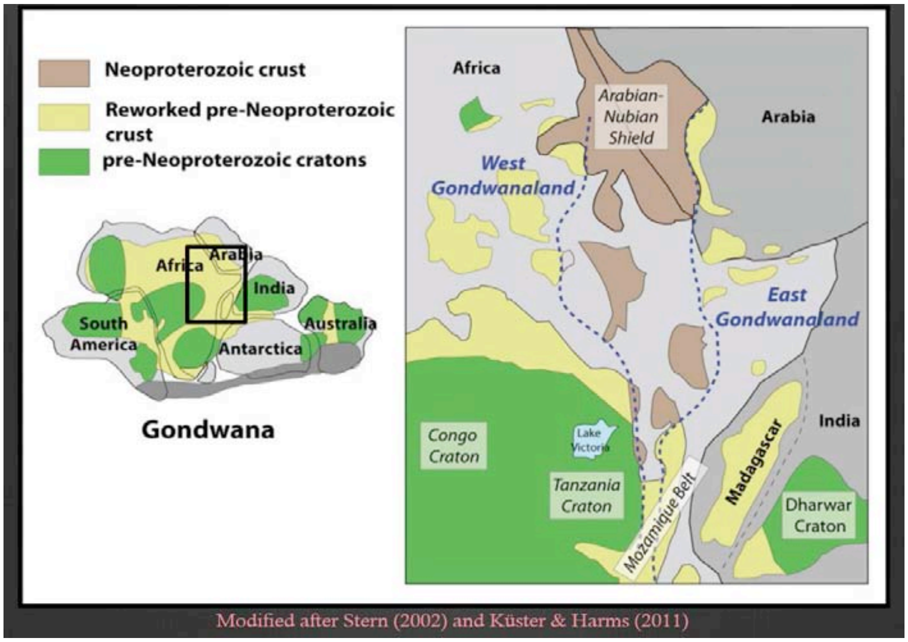

Figure 3.1. Construction of the regional lithosphere during the Pan-African Orogeny, modified after Stern (2002) and Küster and Harms (2011). Courtesy of Wendy Nelson.

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.

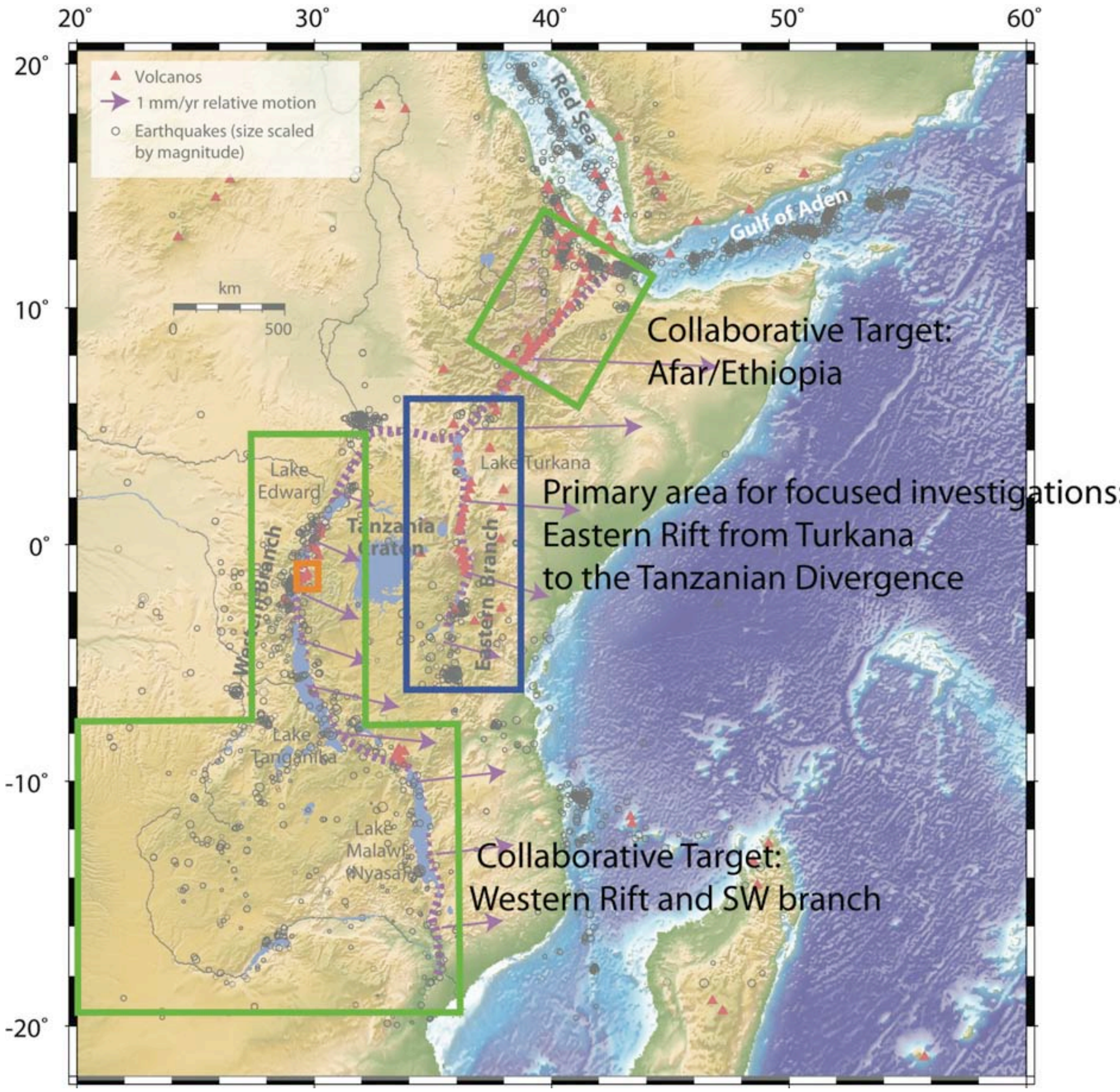

Figure 3.2. Map of the East African Rift System (EARS) highlighting the primary focus area and the collaborative targets of opportunity discussed in the text.

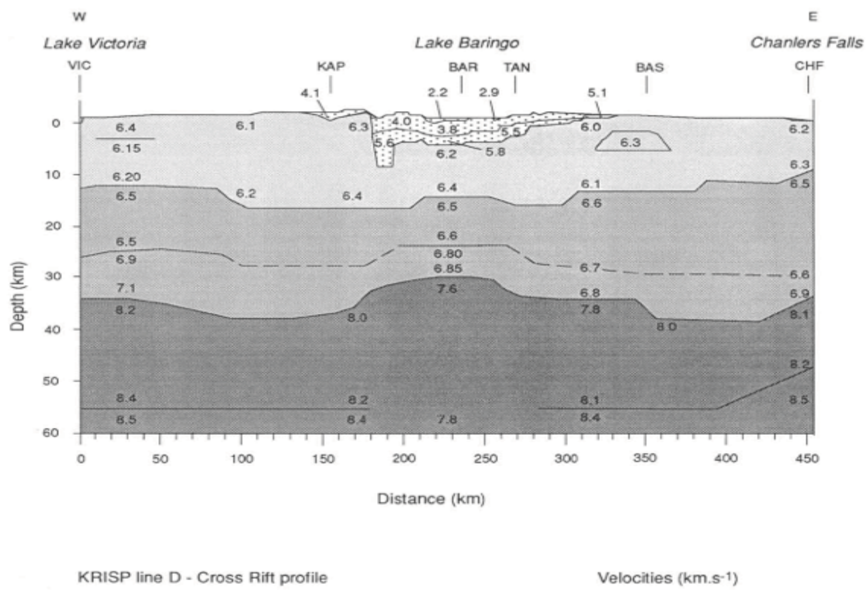

Figure 3.3. P-wave velocity cross-section from the KRISP experiment across the Kenya Rift (modified after Maguire, 1994).

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*).

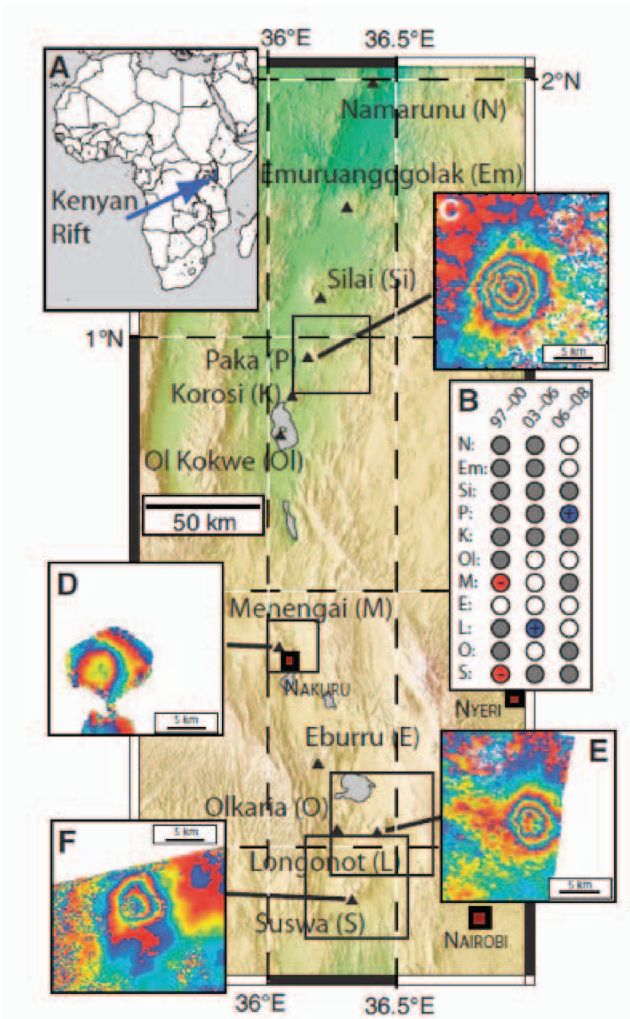

Figure 3.4. Interferograms of active volcanoes in Kenya showing geodetic activity (Biggs et al., 2009).

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.

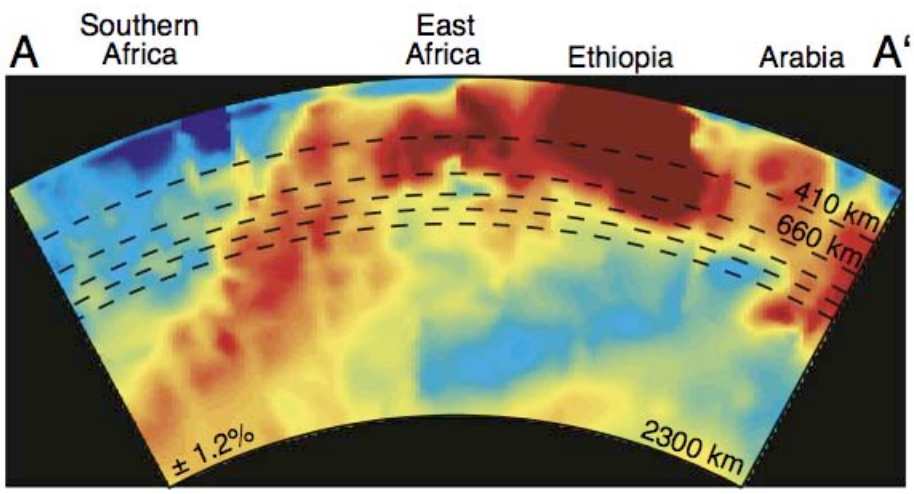

Figure 3.5. Cross sectional P-wave velocity model through the African and Arabian mantle. Dashed lines mark the 410 and 660 km discontinuities as well as depths of 800, 900 and 1000 km (Hansen et al., 2012).

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.

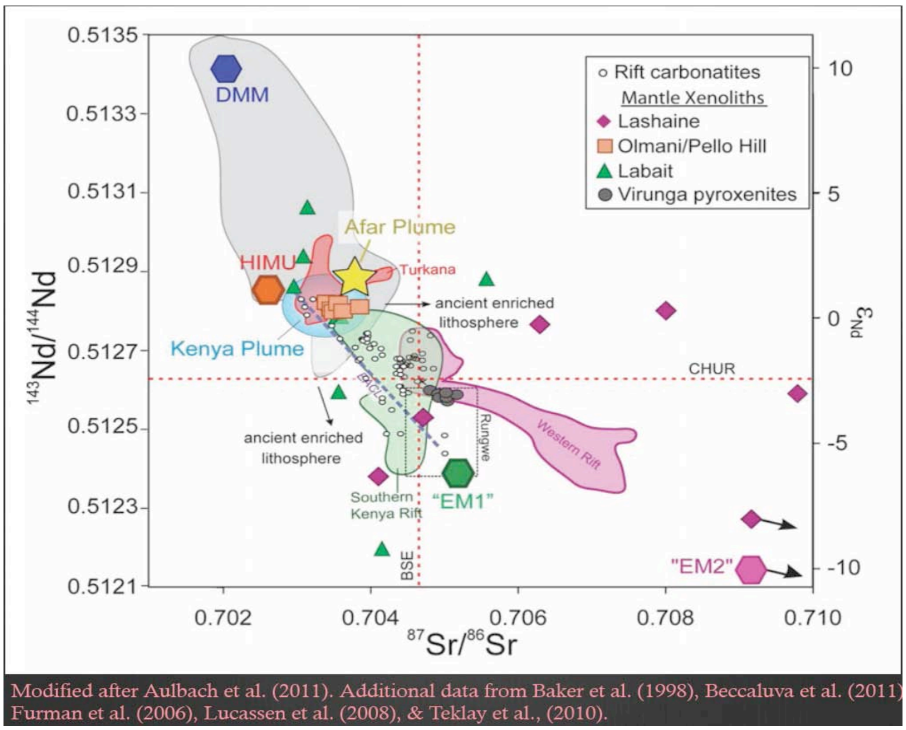

Figure 3.6. Isotopic variation of selected lavas and xenoliths from the East African Rift System, modified after Aulbach et al., 2011 with data from Baker et al. (1998), Beccaluva et al. (2011), Furman et al. (2006), Lucassen et al. (2008), and Teklay et al. (2010). Courtesy of Wendy Nelson.

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.

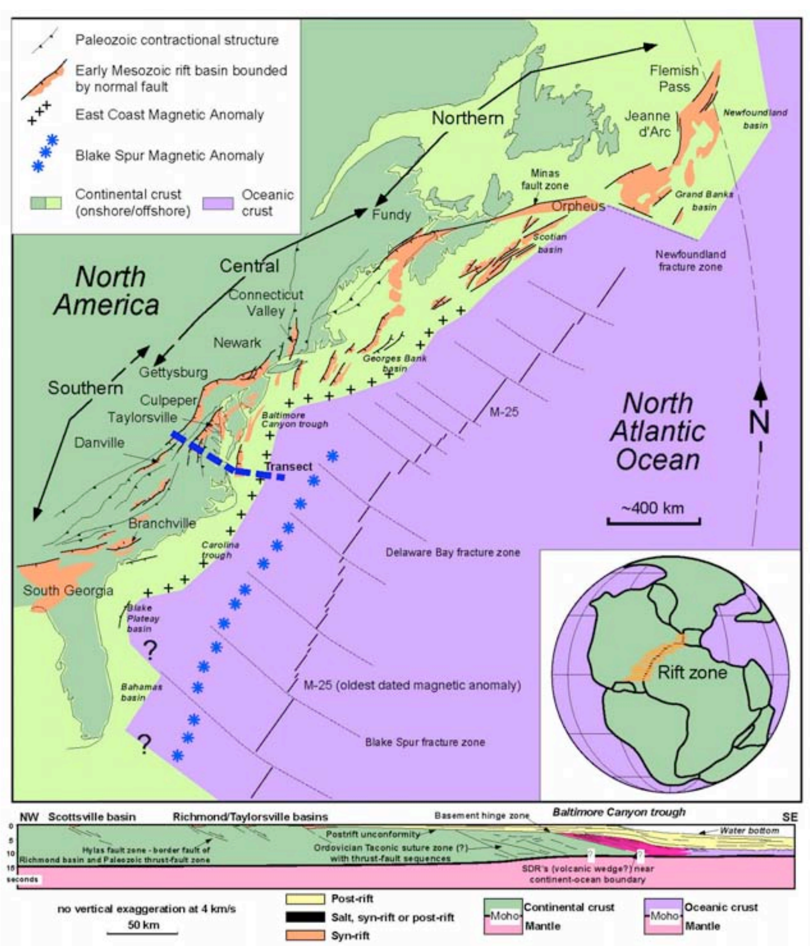

Figure 3.7. ENAM and the major tectonic elements. The East Coast Magnetic Anomaly approximates the extent of seaward dipping reflectors in the continent-ocean boundary (red reflectors in the cross-section. M-25 is the oldest dated magnetic anomaly. Inset shows the configuration of Pangea during the late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

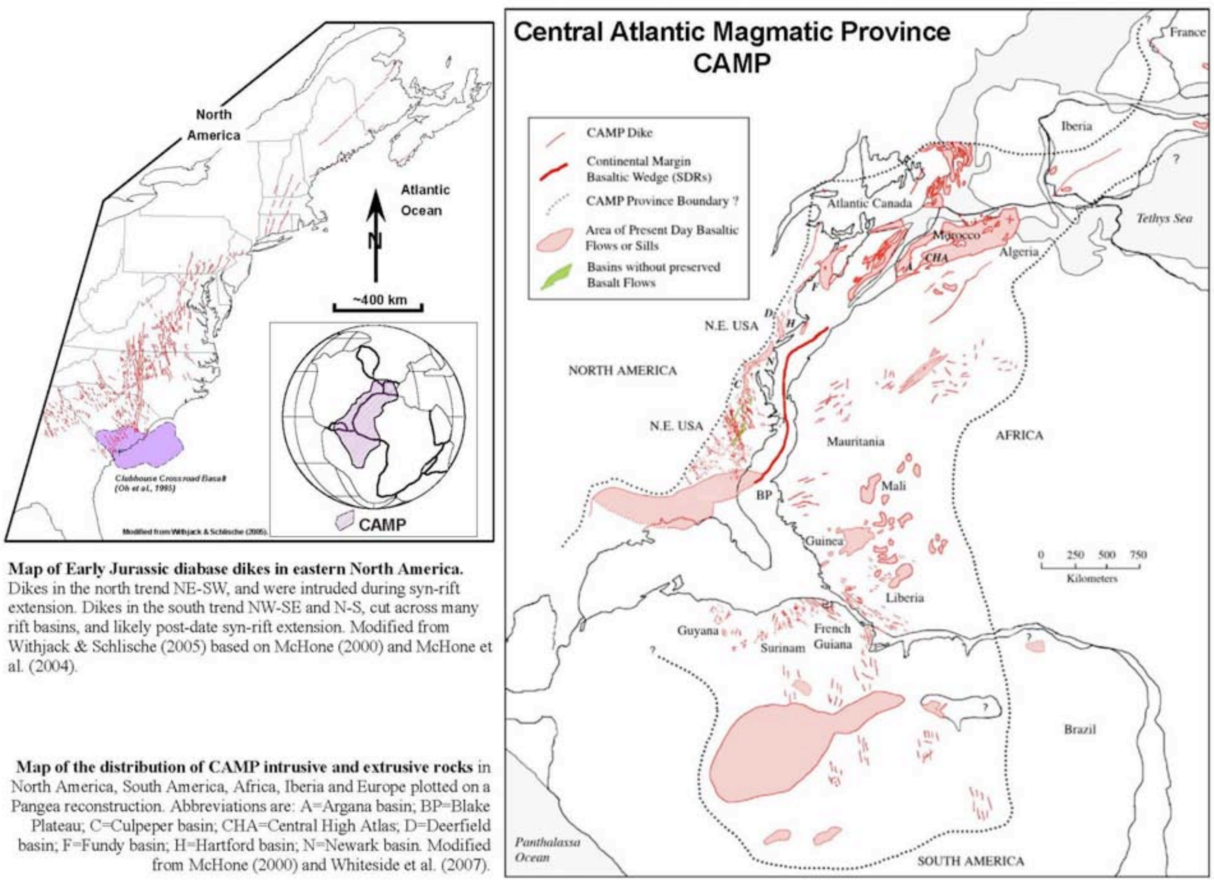

Figure 3.8. Extent of CAMP magmatism in ENAM, modified from Withjack and Schlische (2005), McHone (2000), and Whiteside et al. (2007).

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

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

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

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

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

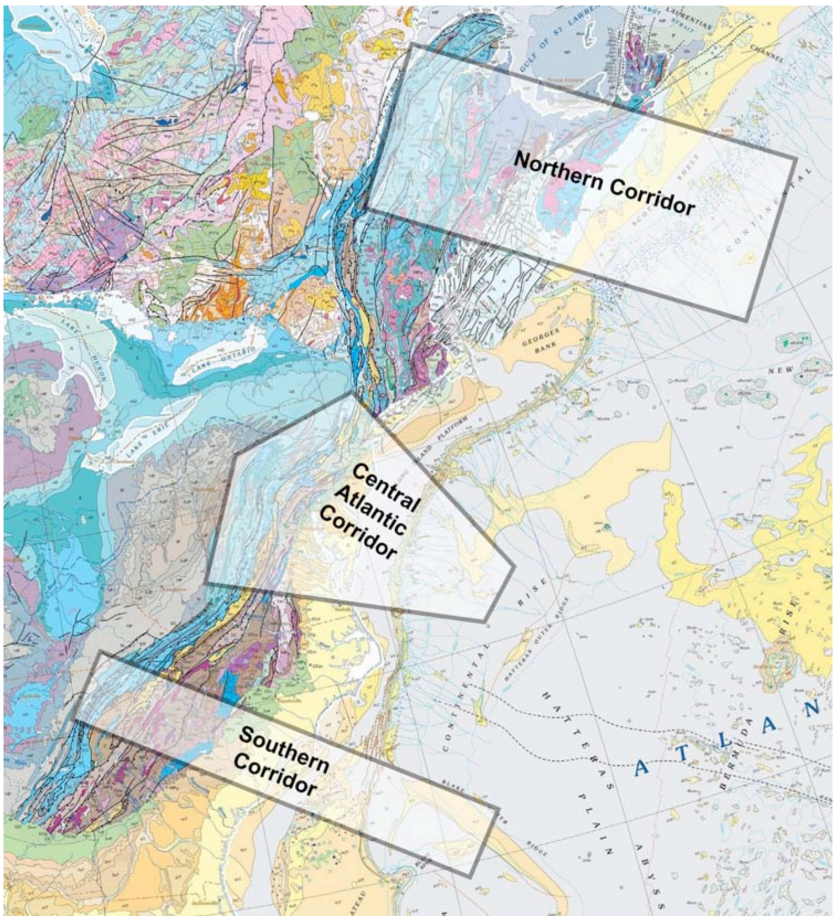

Figure 3.9. DNAG (Decade of North American Geology) geologic map of eastern North America showing the focus areas defined for GeoPRISMS research in ENAM. Modified from http://esp.cr.usgs.gov/info/gmna/)

3.3.1.2. Geographical Focus Areas

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

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

3.3.2. Southern Focus Area (Charleston)

RIE Key Topics

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

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

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

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

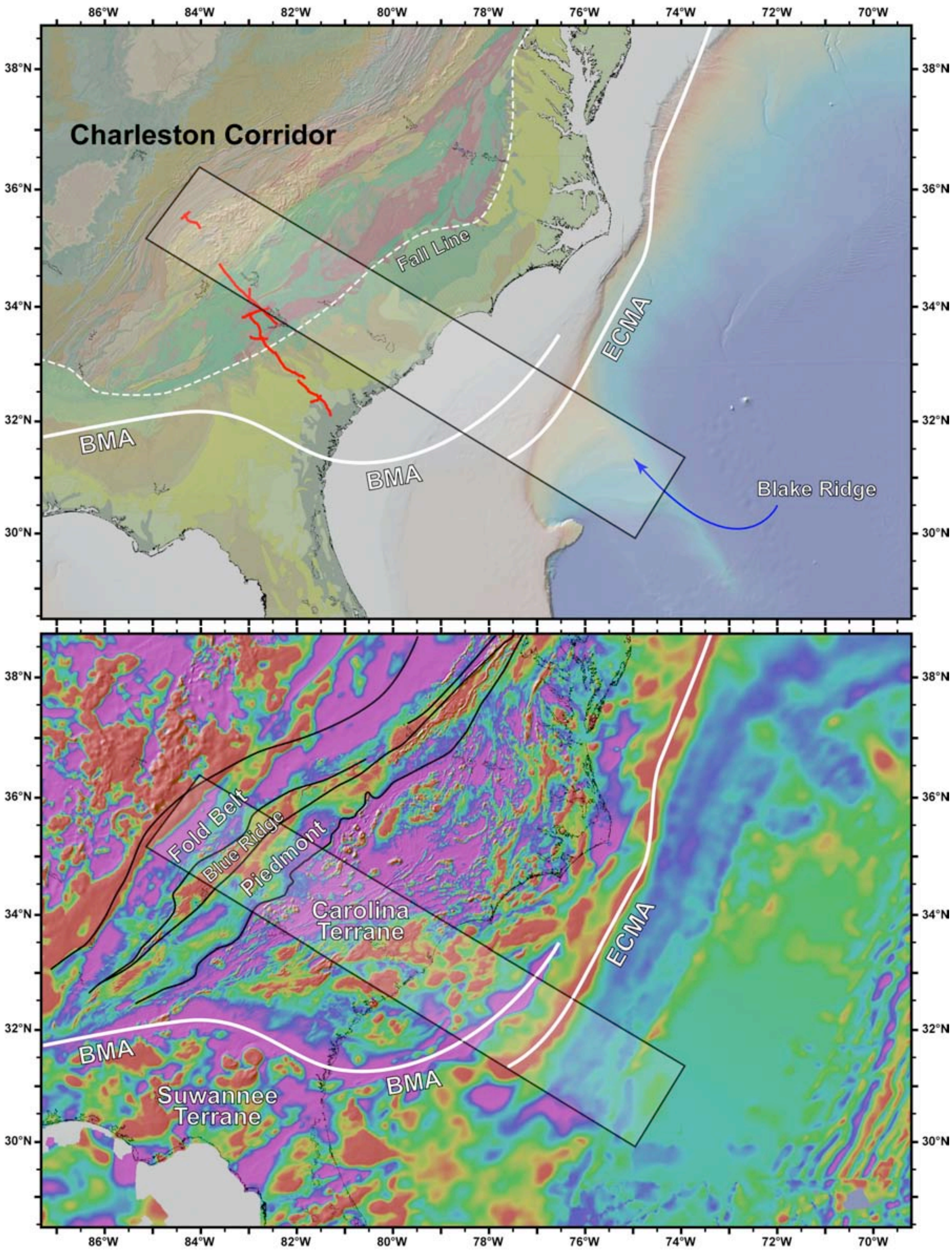

Figure 3.10. Top: Topography and onshore geology of southern ENAM. Box indicates the Charleston Corridor. BMA, Brunswick magnetic anomaly, thought to mark the Alleghanian suture. ECMA, East Coast magnetic anomaly, effectively marks the continent/ocean transition and the seaward-dipping reflector sequence.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

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

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

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

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

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

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

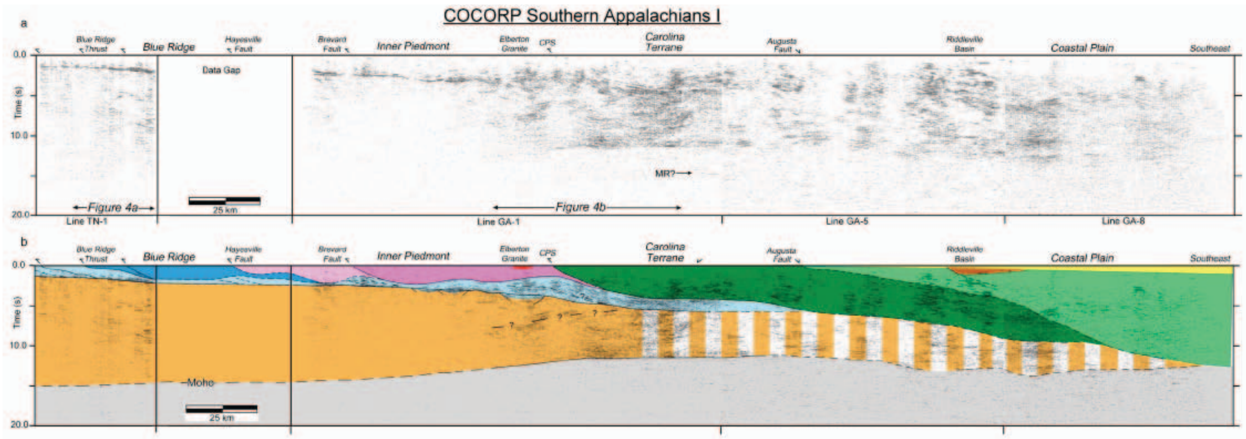

Figure 3.11. (a) Migrated, coherency filtered, and uninterrupted data from COCORP lines TN-1, GA-1, GA-5, and GA-8 subparallel to the Charleston focus area. A portion of the west end on the line GA-5 has been removed due to overlap with line GA-1. (b) Interpretation of (a) modified from Cook et al. (1979,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

3.3.2.2. Examples of GeoPRISMS Studies

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

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

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

3.3.3. Central Focus Area (Richmond - Philadelphia)

RIE Key Topics

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

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

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

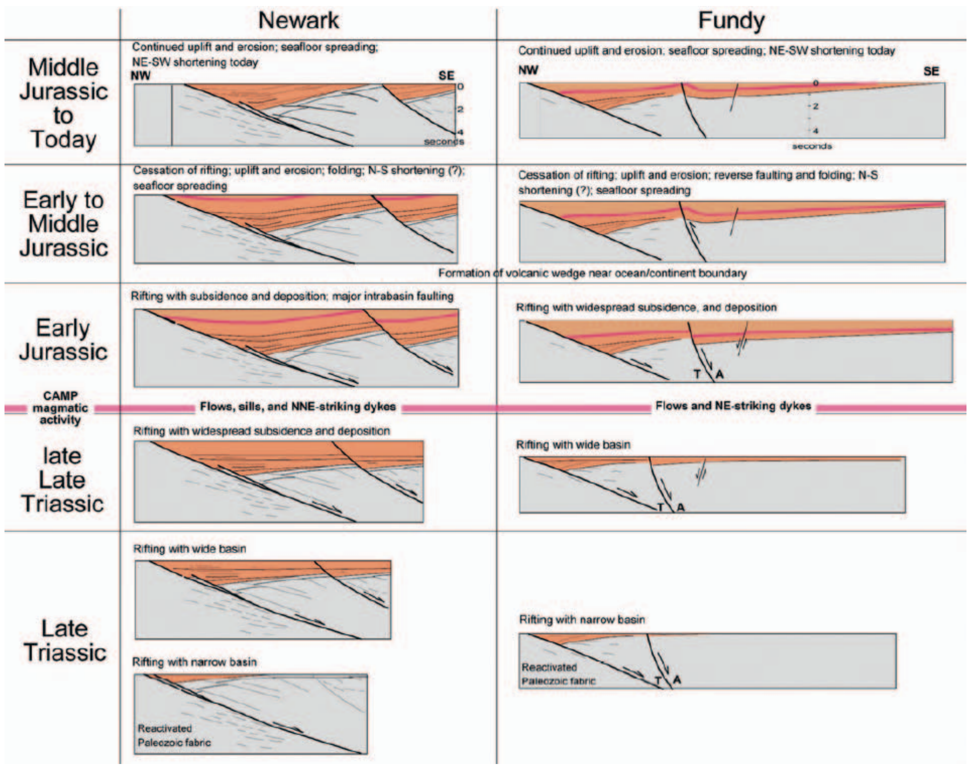

Figure 3.12. Evolution of representative rift basins from the Central focus area (Newark Basin) and the Northern focus area (Fundy Basin). Both basins show evidence for post-rift inversion, uplift and rotation. Extensional faults within the Fundy Basin show reactivation as reverse faults, contributing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

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

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

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

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

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

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

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

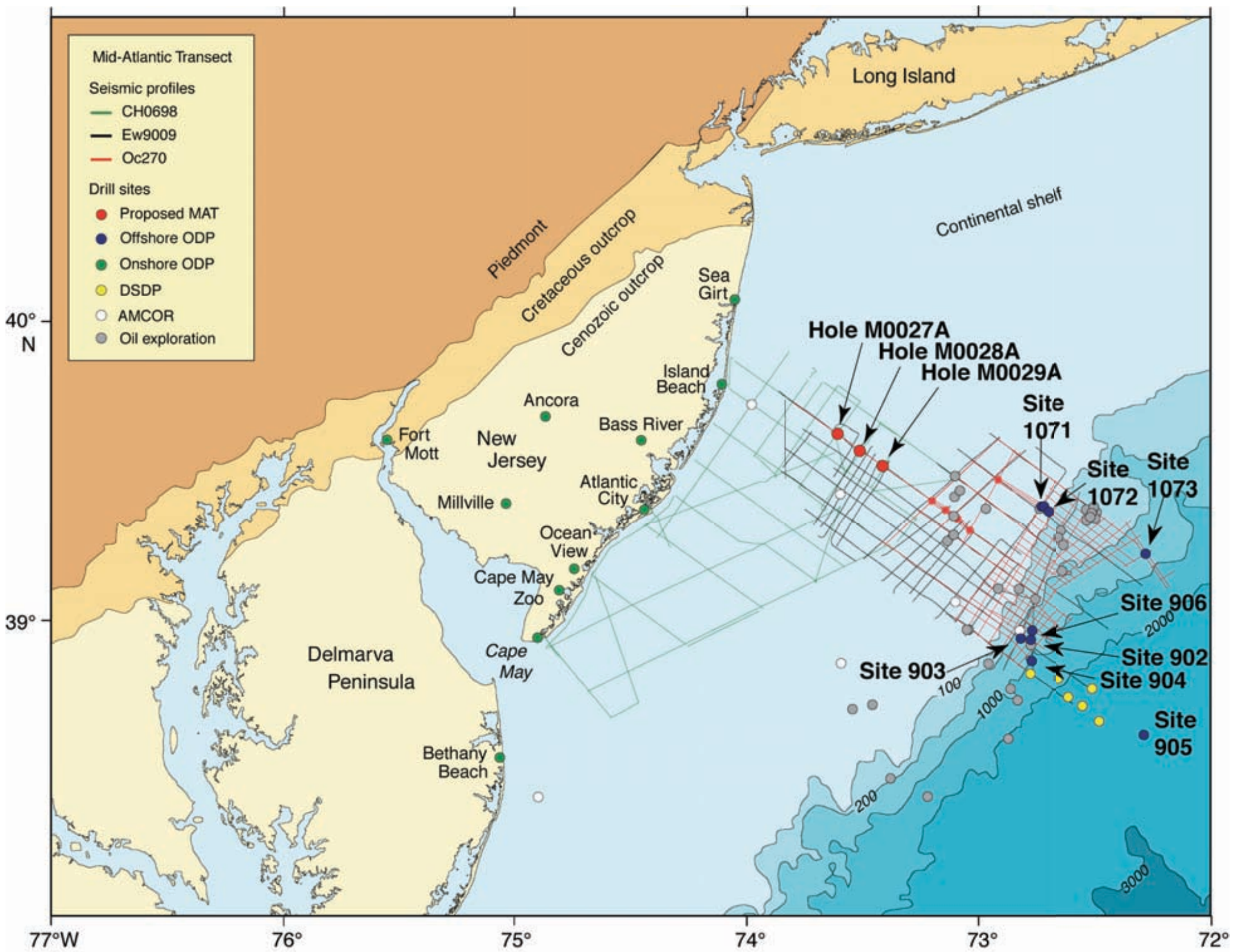

Figure 3.13. The New Jersey continental margin showing Expedition Holes M0027A, M0028A, and M0029A along with other completed boreholes both onshore and offshore. Tracks of reconnaissance seismic lines are also shown. (Expedition 313 Scientists, 2010).

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

3.3.3.2. Examples of GeoPRISMS Studies

<u>Geophysical Imaging:</u> 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.

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

<u>Sedimentary Processes</u>: 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

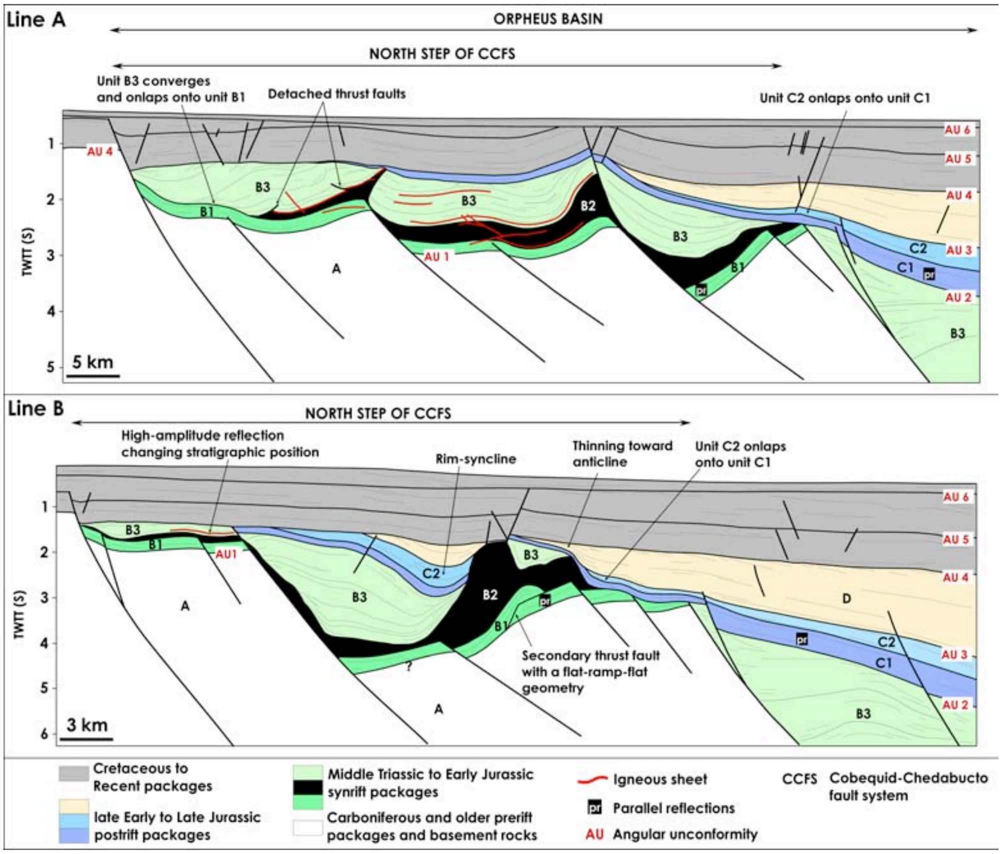

Figure 3.14. Interpreted line drawings of seismic lines A and B across the Orpheus Basin, offshore Nova Scotia, showing unconformity-bounded packages within the Paleozoic-Mesozoic-Cenozoic section of the Orpheus basin (From Syamsir et al., 2010).

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.

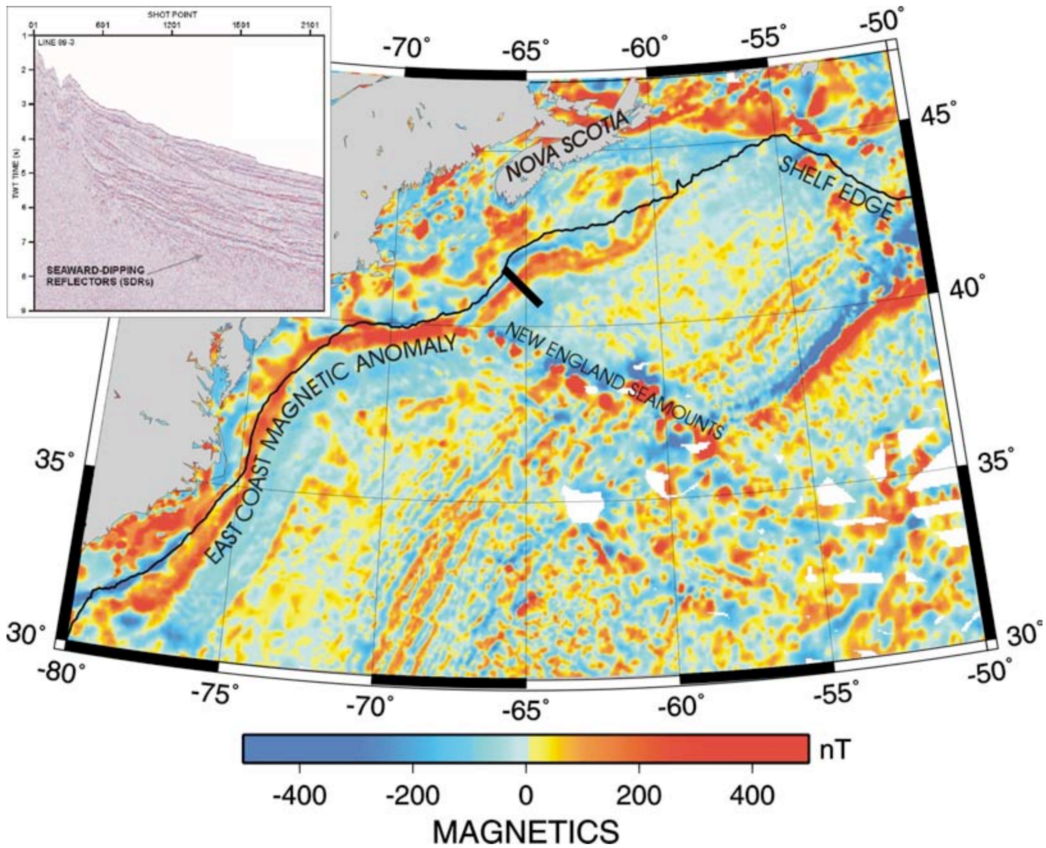

Figure 3.15. The distinct East Coast Magnetic Anomaly (ECMA), which shows up clearly along southern ENAM, dies out to the north, near the western edge of the Laurentian Channel. The reduction in ECMA amplitude off Nova Scotia may be due to a decrease in the volume of extrusive volcanic layers. Inset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

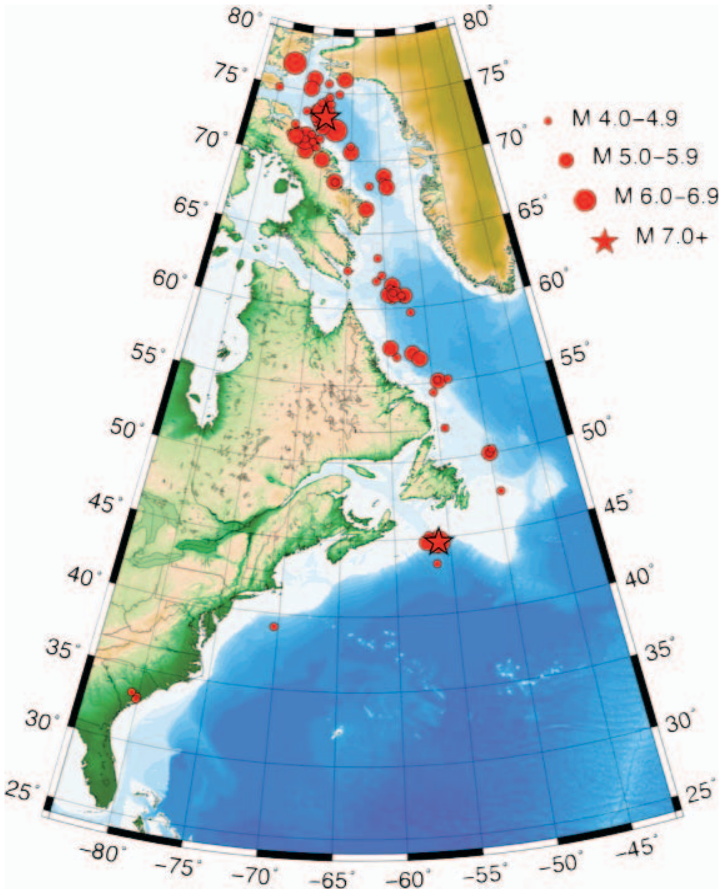

Figure 3.16: Magnitude of historic earthquakes along the Eastern North American margin. (Source: http://www.earth.northwestern.edu/people/seth/Lectures/index.html, Events from Schulte & Mooney, 2005), ANSS, and Earthquakes Canada; figure prepared by S. Stein).

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.

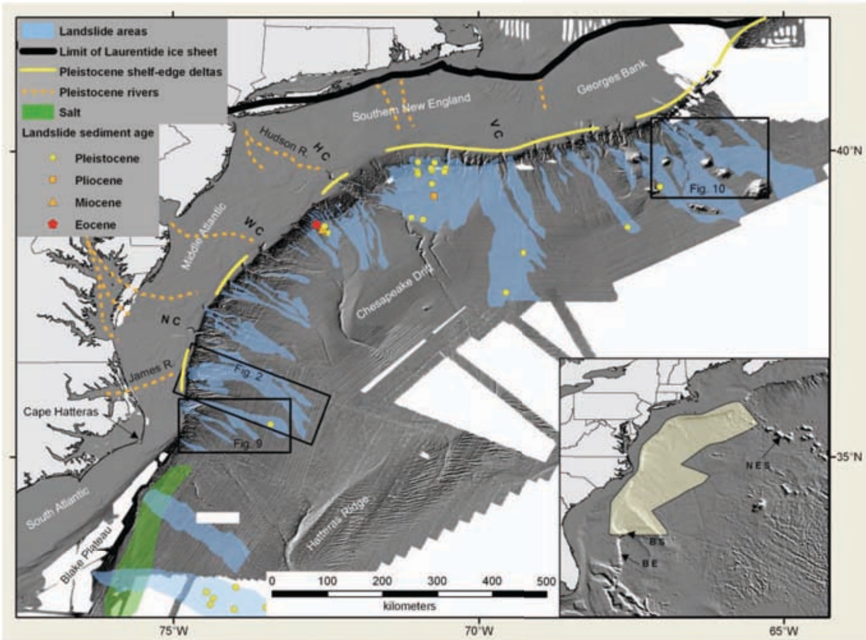

Figure 3.17. Distributions of mapped submarine landslides and debris fields along the Eastern North American Margin. From Twichell et al. (2009).

Fluid Exchange on Passive Margins: 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.

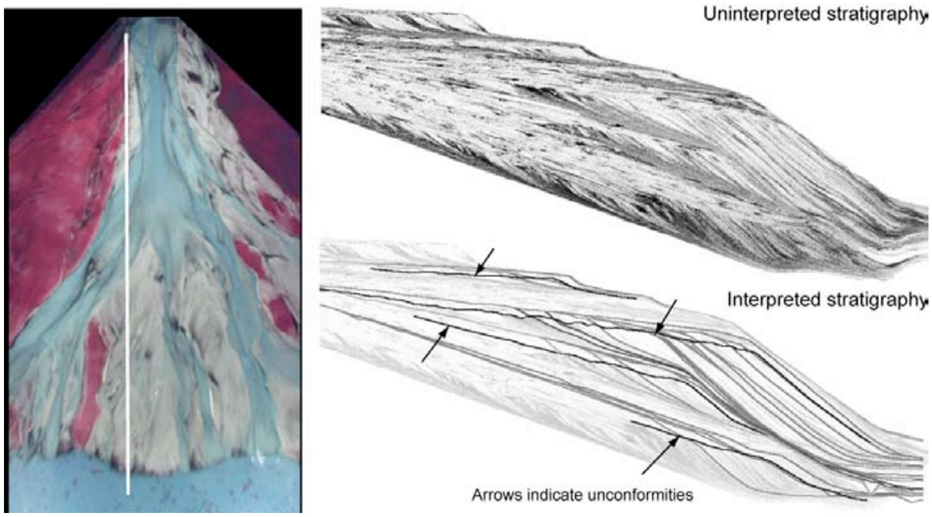

Figure 3.18. Stratigraphic evolution as seen through the depositional filter via experiment, with scans of surface topography (gray) compared against mapped unconformities and sequence boundaries (black). A significant challenge in linking process to form is the connection between instantaneous surface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

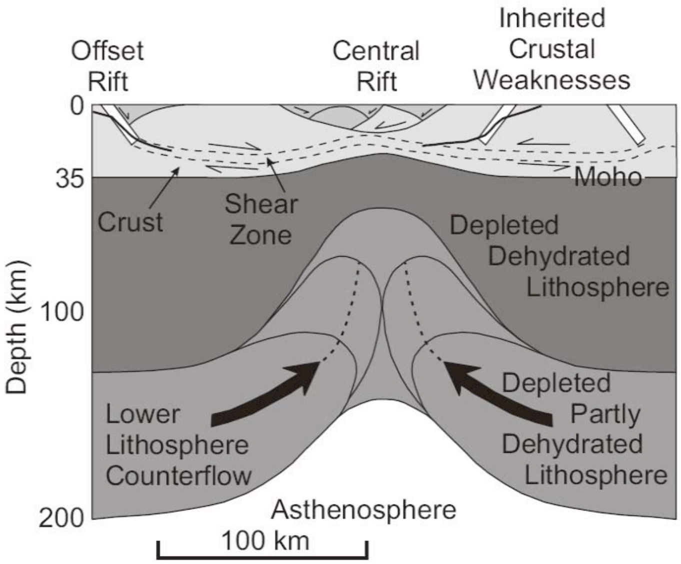

Figure 3.19. Concepts of lower lithosphere counterflow and reactivation of inherited crustal weak zones as offset rift basins in the context of lithospheric extension and rifting (from Beaumont and Ings, in press).

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.

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

3.3.7. Research Strategies and Partnerships

3.3.7.1. EarthScope Collaborations

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

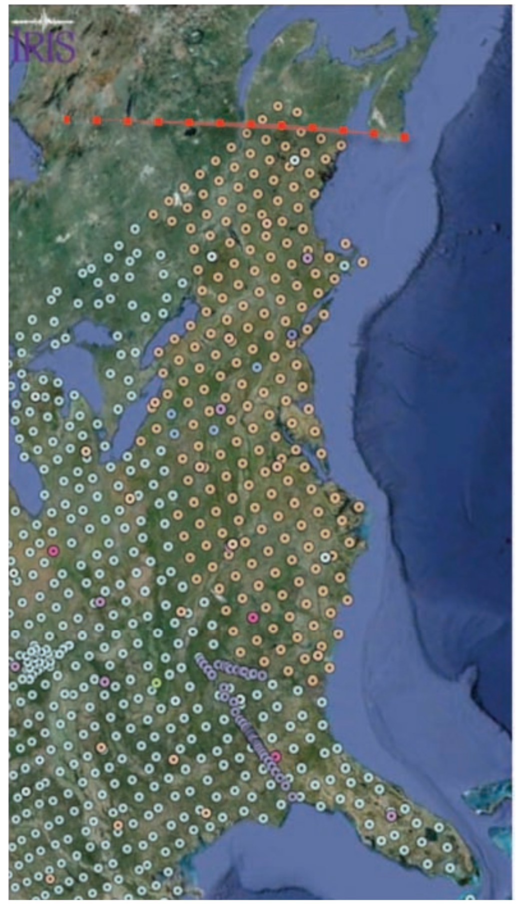

Figure 3.20. Map of EarthScope Trasportable Array (blue – deployed, tan – planned for 2013-2015), Flexible array experiments (dense clusters of symbols) and various other permanently operating seismic observatories. A passive seismic experiment in Nova Scotia, Maine and Quebec (red line) will deploy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

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.

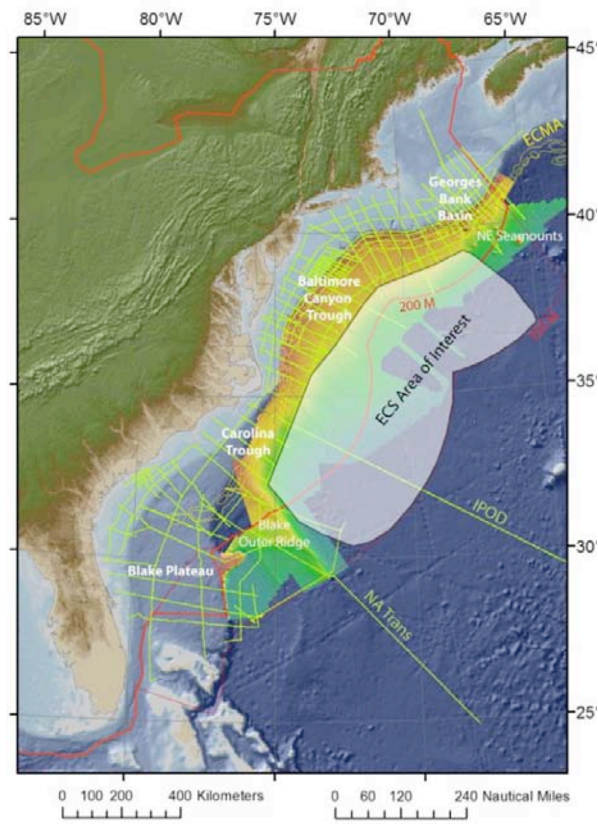

Figure 3.21. Map of existing 2D MCS lines across the eastern US continental margin, and area of interest for proposed USGS survey to map the ECS. (Courtesy of D. Hutchinson)

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.

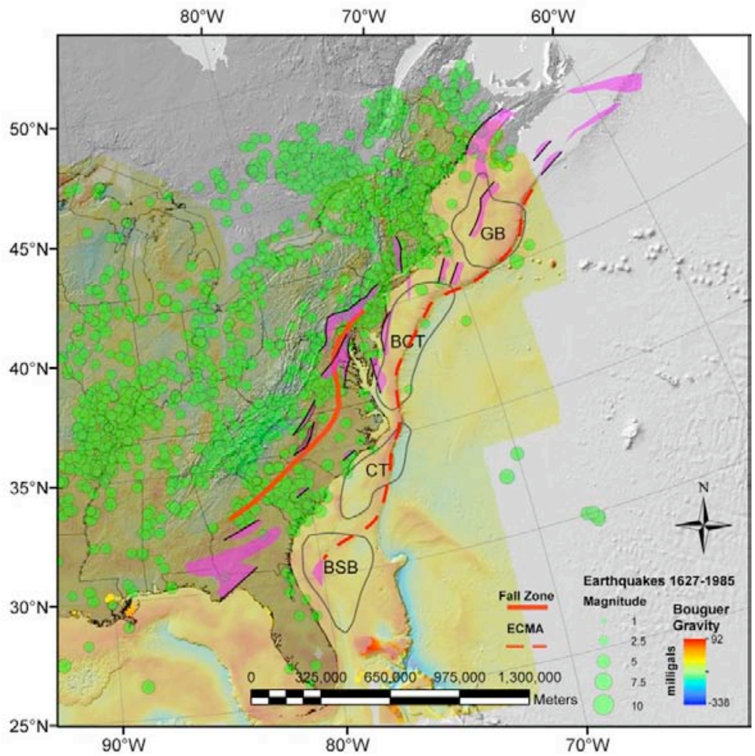

Figure 3.22. Map of ENAM showing the Bouguer gravity anomaly draped on Appalachian topo-graphy and Atlantic Ocean bathymetry. Green circles are earthquake locations. Purple poly-gons are syn-rift basins with border faults in black. Black-outlined polygons are approximate boundaries of shelf-slope basins;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

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4. Funding Strategies and Priorities

4. GeoPRISMS Funding Strategies and Priorities

The ambitious scientific goals of GeoPRISMS require an equally ambitious strategy for attracting research funds to meet our objectives. Funds allocated for the GeoPRISMS Program will provide a strong base for such efforts, but these funds will have to be augmented through additional sources. Promising avenues for co-funding include NSF divisional core funds, but also larger special programs such as Continental Dynamics (CD) and the new biennial Frontiers of Earth System Dynamics (FESD), both of which encourage the strongly collaborative and interdisciplinary research approach that is the hallmark of GeoPRISMS.

International collaborations and leveraged funding also played a significant role in carrying out MARGINS research around the world. We anticipate similar opportunities within GeoPRISMS, particularly in Africa and New Zealand, but we also hope to engage international collaborators to US-based primary site investigations. Several GeoPRISMS targets also overlap with the interests of industry (in particular, the petroleum industry along the Eastern North American Margin, but also the minerals industry), opening up possibilities for collaborations and data sharing. The USGS charge to survey the US Extended Continental Shelf presents unique near-term opportunities to share survey data, and potentially, to support low-cost piggy-back studies in areas of mutual interest (e.g., Eastern US margin, Alaska); similar opportunities exist with NOAA along all of the US margins. Funds for proposed enhancements to the GeoPRISMS education and outreach programs will be sought from external sources, including relevant NSF education and outreach programs.

By necessity, new GeoPRISMS activities at each of the five primary sites will ramp-up on a unique schedule, as will the thematic studies, based on immediate and long-term opportunities. Research funds also will be phased in over time. Research and funding priorities are highest for Alaska, Cascadia, and Eastern North American Margin, given the immediate need to leverage EarthScope activities and the Cascadia Amphibious Array, and the high US societal relevance of all three settings. Major funding for GeoPRISMS investigations in New Zealand and the East African Rift System should await the outcomes of international planning workshops, and thus will be phased in more slowly than for the other three primary sites. This approach will also provide time to develop strong international collaborations and co-funding arrangements for these two sites, enhancing the impact of GeoPRISMS studies.

Most importantly, GeoPRISMS must make it a priority to engage a broad cross-section of investigators, from those with established reputations designing and running large onshore and/or offshore experiments, to early-career scientists. This will require maintaining a mix of funding levels and mechanisms, and soliciting and funding both large and small projects. Proposal pressure, guided by peer review, will ensure that the best science is supported. Without question, several of the scientific targets outlined in the GeoPRISMS implementation plan will benefit from large community experiments (e.g., USArray, the Cascadia Amphibious Array). Such community experiments and other projects that yield open data will also build a powerful framework with many hooks for complementary PI-driven projects. MARGINS succeeded largely because it built a large community of collaborative investigators accustomed to carrying out broadly interdisciplinary research. These collaborations, however, depended upon funding opportunities that encouraged newcomers to join and strengthen the research community. To sustain and grow this community, GeoPRISMS must ensure that such opportunities continue to exist for all researchers interested in contributing to GeoPRISMS science goals, and must confirm that there is room for innovative new approaches to achieving these goals.

Support for science, planning and educational workshops must also remain a cornerstone of GeoPRISMS funding, as these facilitate communication, knowledge transfer, and data exchange, while also encouraging new interdisciplinary collaborations. Workshops are also an important means to educate new members of the community, in particular, students and early career scientists, helping them to identify research pathways that contribute to the common cause. These avenues must be kept open and inviting to ensure the continued growth of the community, and the greatest research achievements.

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5. References

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(Updated December 23, 2013)

Allibone, A., Milan, L.A., Daczko, N.R., and Turnbull, I.M., 2009, Granulite facies thermal aureoles and metastable amphibolite facies assemblages adjacent to the Western Fiordland Orthogneiss in southwest Fiordland, New Zealand: Journal of Metamorphic Geology, v. 27, p. 349-369.

Aulbach, S., Rudnick, R.L., and McDonough, W.F., 2011, Evolution of the lithospheric mantle beneath the East African Rift in Tanzania and its potential signatures in rift magmas, Geological Society of America Special Papers, v. 478, p. 105-125.

Atwater, T. M., J. P. Severinghaus, Tectonic maps of the North Pacific, The Eastern Pacific Ocean and Hawaii, Geol. of North Am., N, E. L. Winterer, D. M. Hussong, R. W. Decker, 15–20, Geological Society of America, Boulder, Colo., 1989.

Baker, J., Chazot, G., Menzies, M., and Thirlwall, M., 1998, Metasomatism of the shallow mantle beneath Yemen by the Afar plume - Implications for mantle plumes, flood volcanism, and intraplate volcanism, Geology, v. 26, p. 431-434

Bangs, N.L.B., Moore, G.F., Gulick, S.P.S., Pangborn, E.M., Tobin, H.J., Kuramoto, S., and Taira, A., 2009, Broad, weak regions of the Nankai Megathrust and implications for shallow coseismic slip: Earth Planet. Sci. Lett., v. 284, p. 44-49, doi:10.1016/j.epsl.2009.04.026.

Barnes, P.M., Lamarche, Bialas, G.J., Henrys, S., Pecher, I., Netzeband, G.L., Greinert, J., Mountjoy, J.J., Pedley, K., Crutchley, G., 2010, Tectonic and geological framework for gas hydrates and cold seeps on the Hikurangi subduction margin, New Zealand, Marine Geology, 272, 26–48.

Beccaluva, L., Bianchini, G., Ellam, R.M., Natali, C., Santato, A., Siena, F., and Stuart, F.M., 2011, Peridotite xenoliths from Ethiopia: Inferences about mantle processes from plume to rift settings, in Beccaluva, L., Bianchini, G., and Wilson, M., eds., Geological Society of America Special Papers, Volume 478: Boulder, CO, p. 77-104

Bell R.E., Sutherland R., Barker D.H.N., et al., 2010, Seismic reflection character of the Hikurangi subduction interface, New Zealand, in the region of repeated Gisborne slow slip events, Geophysical Journal International, v.180, 34-48.

Biggs J. E.Y. Anthony, and C.J. Ebinger, 2009, Multiple inflation and deflation events at Kenyan volcanoes, East African Rift, Geology, 37, 979-982, doi:10.1130/G30133A.1.

Brudzinski, M.R., and Allen, R.M., 2007, Segmentation in episodic tremor and slip all along Cascadia, Geology, 35(10), 907–910; doi: 10.1130/G23740A.1.

Calvert, A.J., 2011, The seismic structure of island arc crust, in Brown, D., and Ryan, P., eds., Arc-Continent Collision: The Making of an Orogen: Frontiers in Earth Sciences: New York, Springer-Verlag, p. 87-120, doi: 10.1007/978-3-540-88558-0_4

Cook, F. A. and Vasudevan, K., 2006, Reprocessing and enhanced interpretation of the initial COCORP southern Appalachians traverse: Tectonophysics, 420, 161-174.

Cook, F.A., Albaugh, D.S., Brown, L.D., Kaufman, S., Oliver, J.E., Hatcher Jr., R.D., 1979. Thin-skinned tectonics in the crystalline Southern Appalachians: COCORP seismic reflection profiling of the Blue Ridge and Piedmont. Geology 7, 563–567McHone, J. G., 2000, Non-plume magmatism and rifting during the opening of the central Atlantic Ocean: Tectonophysics, 316, 287-296.

Danielson, S., M. Johnson, S. Solomon & W. Perrie, 1 km Gridded Bathymetric Dataset Based on Ship Soundings: A research tool for the waters of eastern Russia, Alaska & western Canada, 2008, Poster presentation at the 2008 Alaska Marine Science Symposium, Anchorage, Alaska. http://mather.sfos.uaf.edu/~seth/bathy/

DeMets, C., Gordon, R. G. and Argus, D. F., 2010, Geologically current plate motions. Geophysical Journal International, 181: 1–80. doi: 10.1111/j.1365-246X.2009.04491.x.

Eberhart-Philips, D., Christensen, D.H., Brocher, T.M., Hansen, R., Ruppert, N.A., Haeussler, P.J., and Abers, G.A., 2006. Imaging the transition from Aleutian subduction to Yakutat collision in central Alaska, with local earthquakes and active source data. J. Geophys. Res., [Solid Earth], 111:B11303–B11333. doi:10.1029/2005JB004240

Elliott, J., C. F. Larsen, J. T. Freymueller, and R. J. Motyka, 2010. Tectonic Block Motion and Glacial Isostatic Adjustment in Southeast Alaska and Adjacent Canada Constrained by GPS Measurements, J. Geophys. Res., doi:10.1029/2009JB007139.

Enachescu, M., 2007, Digital seismic dilemma, ownership and copyright of offshore data: Why is government policy regarding offshore seismic data so important for the Atlantic oil and gas industry? CSEG Recorder. (Download from: https://www.cseg.ca/publications/recorder/2007/05may/may2007-digital-seismic-dilemma.pdf).

Expedition 313 Scientists, 2010, Shallow-water drilling of the New Jersey continental shelf: global sea level and architecture of passive margin sediments, *IODP Prel. Rept.,* 313. doi:10.2204/iodp.pr.313.2010.

Forsyth, D.W., Lay, T., Aster, R.C., and Romanowicz, B., 2009, Grand challenges for seismology: Eos (Transactions, American Geophysical Union), v. 90, p. 361– 362, doi: 10.1029/2009EO410001.

Furman, T., Kaleta, K.M., Bryce, J.G., and Hanan, B.B., 2006, Tertiary mafic lavas of Turkana, Kenya: Constraints on East African plume structure and the occurrence of high-mu volcanism in Africa, Journal of Petrology, v. 47, p. 1221-124.

GLOBE Task Team and others (Hastings, David A., Paula K. Dunbar, Gerald M. Elphingstone, Mark Bootz, Hiroshi Murakami, Hiroshi Maruyama, Hiroshi Masaharu, Peter Holland, John Payne, Nevin A. Bryant, Thomas L. Logan, J.-P. Muller, Gunter Schreier, and John S. MacDonald), eds., 1999. The Global Land One-kilometer Base Elevation (GLOBE) Digital Elevation Model, Version 1.0. National Oceanic and Atmospheric Administration, National Geophysical Data Center, 325 Broadway, Boulder, Colorado 80303, U.S.A. Digital data base on the World Wide Web (URL: http://www.ngdc.noaa.gov/mgg/topo/globe.html) and CD-ROMs.

Goldfinger, C., Nelson, C.H., Morey, A.E., Johnson, J.E., Patton, J.R., Karabanov, E., Gutiérrez-Pastor, J., Eriksson, A.T., Gràcia, E., Dunhill, G., Enkin, R.J., Dallimore, A., and Vallier, T., 2012, Turbidite event history—Methods and implications for Holocene paleoseismicity of the Cascadia subduction zone: U.S. Geological Survey Professional Paper 1661–F, 170 p. (Available at http://pubs.usgs.gov/pp/pp1661f/).

Hansen, S.E., A.A. Nyblade, and M.H. Benoit, 2012, Mantle structure beneath Africa and Arabia from adaptively parameterized P-wave tomography: Implications for the origin of Cenozoic Afro-Arabian tectonism, Earth and Planetary Science Letters, 319-320, 23-24.

Kelemen, P.B., Hanghøj, K., and Greene, A.R., 2003, One view of the geochemistry of subduction-related magmatic arcs, with an emphasis on primitive andesite and lower crust in Holland, H.D., and Turekian, K.K., eds., Treatise on Geochemistry: New York, Elsevier, p. 593-659.

Klepeis, K.A. and Clarke, G.L., 2004, Evolution of an exposed lower crustal attachment zone in Fiordland, New Zealand, In: *Vertical coupling and decoupling in the lithosphere*, Grocott, J., McCaffrey, K., Taylor, G., Tikoff, B. (eds), Geological Society, London, Special Publications, **227**, 197-229.

Klepeis, K.A, Clarke, G.L., Rushmer, T., 2003, Magma transport and coupling between deformation and magmatism in the continental lithosphere, *GSA Today*, **13**(1), 4-11.
Kodaira, S., Sato, T., Takahashi, N., Miura, S., Tamura, Y., Tatsumi, Y., and Kaneda, Y., 2007, New seismological constraints on growth of continental crust in the Izu-Bonin intra-oceanic arc: Geology, v. 35, doi: 10.1130/G23901A.1, p. 1031-1034.
Küster, D., and Harms, U., 1998, Post-collisional potassic granitoids from the southern and northwestern parts of the Late Neoproterozoic East African Orogen: a review, Lithos, v. 45, p. 177-195
Leonard, G.S., Begg, J.G. and Wilson, C.J.N. (compilers), 2010, Geology of the Rotorua area: scale 1:250,000. Lower Hutt: Institute of Geological & Nuclear Sciences Limited. Institute of Geological & Nuclear Sciences 1:250,000 geological map 5. 99 p. + 1 fold. Map.
Lucassen, F., Franz, G., Romer, R.L., Pudlo, D., and Dulski, P., 2008, Nd, Pb, and Sr isotope composition of Late Mesozoic to Quaternary intra-plate magmatism in NE-Africa (Sudan, Egypt): high-mu signatures from the mantle lithosphere, Contributions to Mineralogy and Petrology, v. 156, p. 765-784.
Maguire, P.K.H, C.J. Swain, R. Masotti, and M.A. Khan, 1994, A crustal and uppermost mantle cross-sectional model of the Kenya Rift derived from seismic and gravity data, Tectonophysics, 236, 217-249.
Martin, J., C. Paola, V. Abrea, J. Neal, B. Sheets, 2009, Sequence stratigraphy of experimental strata under known conditions of differential subsidence and variable base level, *AAPG Bulletin*, *93*(4), 503-533; doi: 10.1306/12110808057.
Manley, W., and Kaufman, D.S., 2002. Alaska Paleoglacier Atlas: Boulder, CO (Inst. Arct. Alp. Res., Univ. Colorado). http://instaar.colorado.edu/QGISL/ak_paleoglacier_atlas/
McCaffrey, R., Qamar, A., King, R.W., Wells, R.W., Khazaradze, G., and Williams, C., 2007, Deformation in the Pacific Northwest: Geophysical Journal International, v. 169, p. 1315–1340, doi: 10.1111/j.1365-246X.2007.03371.x.
Miller, R.B., and Snoke, A.W., eds., 2009, Crustal cross-sections from the western North American Cordillera and elsewhere: Implications for tectonic and petrologic processes: Boulder, Colorado, Geological Society of America Special Paper 456, vi + CD + 314 p. ISBN 978-0-8137-2456-0.
Moore J.C., Diebold J.B., Fisher M.A., Sample J.C., Brocher T.M., Talwani M., Ewing J.I., von Huene R., Rowe C., Stone D., Stevens C., Sawyer D.S., 1991, EDGE deep seismic reflection transect of the eastern Aleutian arc-trench layered lower crust reveals underplating and continental growth: Geology, v. 19, p. 420–424, doi: 10.1130/0091-7613(1991)019<0420:EDSRTO>2.3.CO;2.
Moore, G.F., Bangs, N.L., Taira, A., Kuramoto, S. Pangborn, E., and Tobin, H.J., 2007, Three-dimensional splay fault geometry and implications for tsunami generation: Science, v. 318, p. 1128-1131.doi: 10.1126/science.1147195
Ohta, Y., J. T. Freymueller, S. Hreinsdóttir, and H. Suito,, 2006. A Large Slow Slip Event and the depth of the seismogenic zone in the south central Alaska subduction zone, Earth Planet. Sci. Lett., Volume 247, Issues 1-2, 15 July, Pages 108-116.
Peterson, C. L., and D. H. Christensen (2009). Possible relationship between nonvolcanic tremor and the 1998–2001 slow slip event, south central Alaska, J. Geophys. Res., 114, B06302, doi:10.1029/2008JB006096.
Priest, G.R., 1990, Volcanic and tectonic evolution of the Cascade volcanic arc, Central Oregon, J. Geophysical Research, 95, B12, 19,583-19,599.

Reece, R., S. Gulick, B. Horton, G. Christeson, L. Worthington, 2011, Tectonic and climatic influence on the evolution of the Surveyor Fan and Channel System, Gulf of Alaska, Geosphere, v. 7, no. 4, p. 830-844, doi: 10.1130/GES00654.1.

Ryan et al. (in review, USGS OFR).

Schulte, S.M., and Mooney, W.D., 2005, An updated global earthquake catalogue for stable continental regions: reassessing the correlation with ancient rifts, Geophysical Journal International. Volume 161, Issue 3, pages 707–721, DOI: 10.1111/j.1365-246X.2005.02554.x.

Shillington, D.J., Van Avendonk, J.A., Holbrook, S.W., Kelemen, P.B., and Hornbach, M.J., 2004, Composition and structure of the central Aleutian island arc from arc-parallel wide-angle seismic data: Geochemistry Geophysics Geosystems, v. 5(Q10006), doi: 10.1029/2004GC000715

Stern, R.J., 2002, Crustal evolution in the East African Orogen: a neodymium isotopic perspective, Journal of African Earth Sciences, v. 34, p. 109-117.

Stevenson, A.J., D.W. Scholl, and T.L. Vallier, 1983. Tectonic and geologic implications of the Zodiac Fan, Aleutian abyssal plain, Northeast Pacific. Geological Society of America Bulletin, 94(2):259-273.

Stock, J., and P. Molnar, 1988, Uncertainties and implications of the Late Cretaceous and Tertiary position of North America relative to the Farallon, Kula, and Pacific Plates, Tectonics, 7(6), 1339–1384, doi:10.1029/TC007i006p01339.

Strong, N., and C. Paola (2008), Valleys that never were: Time surfaces versus stratigraphic surfaces, *J. Sed. Res., 78*, 579–593.

Sutherland, R., M. Gurnis, P. J. J. Kamp, and M. A. House, Regional exhumation history of brittle crust during subduction initiation, Fiordland, southwest New Zealand, and implications for thermochronologic sampling and analysis strategies, Geosphere, 5, doi:10.1130/GES00225.1, 409-425, 2009.

Syamsir, Z., Durcanin, M., Withjack, M., Schische, R., and Monteverde, D., 2010, The Mesozoic Orpheus rift basin, offshore Nova Scotia and Newfoundland, Canada: Synrift and early postrift evolution of a well-imaged North Atlantic rift basin: Porceedings II Central & North Atlantic Conjugate Margins Conference, Lisbon, Portugal (http://metododirecto.pt/CM2010).

Syracuse, E.M, van Keken, P.E. and Abers, G.A., 2010, The global range of subduction zone thermal models, Physics Earth Planetary Interiors, doi:10.1016/j.pepi.2010.1002.1004.

Teklay, M., Scherer, E., Mezger, K., and Danyushevsky, L., 2010, Geochemical characteristics and Sr-Nd-Hf isotope compositions of mantle xenoliths and host basalts from Assab, Eritrea: implications for the composition and thermal structure of the lithosphere beneath the Afar Depression, Contributions to Mineralogy and Petrology, v. 159, p. 731-751.

Twichell, D. C., Chaytor, J. D., ten Brink, U. S., and Buczkowski, B., 2009, Morphology of late Quaternary submarine landslide along the U.S. Atlantic continental margin: Marine Geology, 264, 4-15

Verplank, E.P., and Duncan, R.A., 1987, Temporal variations in plate convergence and eruption rates in the Western Cascades, Oregon, Tectonics, 6, 2, 197-209.

Wallace, L. M., and J. Beavan, 2010, Diverse slow slip behavior at the Hikurangi subduction margin, New Zealand, J. Geophys Res., 115(B12402), doi:10.1029/2010JB007717.

Wech, A.G., & Creager, K.C., 2011, A continuum of stress, strength and slip in the Cascadia subduction zone. *Nature Geoscience, 4,* 624-628.

Whiteside J.H., Olsen P.E., Kent D.V., Fowell S.J., Et-Touhami M., 2007, Synchrony between the Central Atlantic magmatic province and the Triassic-Jurassic mass-extinction event?: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 244, p. 345–367, doi: 10.1016/j.palaeo.2006.06.035.
Withjack, M.O., Schlische, R.W. and Olsen, P.E., 2012, Development of the passive margin of Eastern North America: Mesozoic rifting, igneous activity, and breakup, in D. Roberts and A.W. Bally (editors), Phanerozoic Rift Systems and Sedimentary Basins, Elsevier Press, pp. 301-335.
Withjack, M.O., and Schlische, R.W., 2005, A review of tectonic events on the passive margin of eastern North America, *in* Post, P., ed., Petroleum Systems of Divergent Continental Margin Basins: 25th Bob S. Perkins Research Conference, Gulf Coast Section of SEPM, p. 203-235.
Yogodzinski, G.M., Vervoort, J.D., Brown, S.T., and Gerseny, M., 2010, Subduction controls of Hf and Nd isotopes in lavas of the Aleutian island arc: Earth and Planetary Science Letters, v. 300, p. 226-238, doi: 10.1007/s00410-010-0565-4
Zimmer, M.M., Plank, T., Hauri, E.H., Yogodzinski, G.M., Stelling, P., Larsen, J., Singer, B., Jicha, B., Mandeville, C., and Nye, C.J., 2010, The role of water in generating the calc-alkaline trend: New volatile data for Aleutian magmas and a new tholeiitic index: Journal of Petrology, v. 51, p. 2411-2444, doi: 10.1093/petrology/egq062

GeoPRISMS
Implementation Plan

Appendices

Appendix A. Implementation Plan Writing Team

Appendix B. GeoPRISMS and Related Workshops

Appendix C. Implementation Plan Updates

Appendix A. Implementation Plan Writing Team *(Updated December 23, 2013)*

The Implementation Plan writing began after the RIE Implementation Workshop (November 4-6, 2010), and the SCD Implementation Workshop (January 5-7, 2011), based upon input received from the more than 250 participants of those workshops, as well white paper contributors. Updates and revisions to the Implementation Plan are made following relevant GeoPRISMS planning workshops and discussions, as logged in Appendix C. Many people contributed to this community document, most prominently, the lead writers listed below, many of whom also served on the GeoPRISMS Steering and Oversight Committee and/or served as conveners for GeoPRISMS-sponsored workshops. We are also especially grateful for the ready assistance of the many people we called upon for their expertise, who are also listed below. Finally, this document is the product of enriching discussions among the workshop attendees and the members of the GeoPRISMS community. The GeoPRISMS Implementation Plan is truly a community effort!

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Appendix B. GeoPRISMS and Related Planning Workshops *(Updated December 23, 2013)*

The initial draft and subsequent updates to the GeoPRISMS Implementation Plan reflect community discussions and decisions arising from GeoPRISMS planning workshops. Workshop participants, agendas, and white paper contributions can be found on the web pages indicated.

<u>MARGINS/GeoPRISMS Workshops</u>

GeoPRISMS Planning Workshop for New Zealand
April 15-17, 2013, Wellington, NZ
http://www.geoprisms.org/past-meetings/newzealand-apr2013.html

GeoPRISMS Planning Workshop for East Africa Rift System
October 25-27, 2012, Morristown, NJ
http://www.geoprisms.org/past-meetings/ears-oct2012.html

GeoPRISMS-EarthScope Science Workshop for Cascadia
April 5-6, 2012, Portland, OR
http://www.geoprisms.org/past-meetings/207-cascadia-apr2012.html

EarthScope-GeoPRISMS Science Workshop for Eastern North America
October 27-29, 2011, Bethlehem, PA
http://www.geoprisms.org/past-meetings/124-enam-oct2011.html

GeoPRISMS-EarthScope Planning Workshop for Alaska
September 22-24, 2011, Portland, OR
http://www.geoprisms.org/past-meetings/123-alaska-sep2011.html

EarthScope-GeoPRISMS Planning Workshop for Eastern North America
May 20-21, 2011, Bastrop, TX
http://www.geoprisms.org/past-meetings/116-enam-may2011.html

GeoPRISMS SCD Implementation Workshop
January 5-7, 2011, Bastrop, TX
http://www.geoprisms.org/past-meetings/43-scd2011.html

GeoPRISMS RIE Implementation Workshop
November 4-6, 2010, Santa Fe, NM
http://www.geoprisms.org/past-meetings/45-rie2010.html

MARGINS Successor Planning Workshop
February 15-17, 2010, San Antonio, TX
http://www.nsf-margins.org/SuccessorProgram/index.html

Appendix C. Implementation Plan Updates and Revisions *(Updated December 23, 2013)*

As a "living document", the GeoPRISMS Implementation Plan is subject to ongoing revisions and updates, which are logged below. Date of most recent version is indicated in italics after each section heading. Be sure to refer to the most current version of the Implementation Plan.

Date:	Status:
March 02, 2011	Draft of Implementation Plan released and approved by NSF
March 24, 2012	Section 2.2 (SCD Alaska Primary Site) completely replaced following September 2011 Alaska Planning Workshop. Section 2.1 (SCD Introduction and Overview) given minor updates. Appendix A (List of Writers) updated to include Section 2.2 writers. Appendix B (List of Planning Workshops) added. Appendix C. (Updates and Revisions) added.
May 29, 2012	Section 3.3 (RIE ENAM Primary Site) completely replaced following October 2011 ENAM Science Workshop. Section 3.1 (RIE Introduction and Overview) given minor updates. Section 5 (References) added to include Sections 2.2 and 3.3 references. TOC (Table of Contents) updated. Appendix A (List of Writers) updated to include Section 3.3 writers. Appendix B (List of Planning Workshops) updated. Appendix C. (Updates and Revisions) updated.
June 20, 2012	Section 2.3 (SCD Cascadia Primary Site) completely replaced following April 2012 Cascadia Science Workshop. Section 2.1 (SCD Introduction and Overview) given minor updates. Section 5 (References) updated to include Section 2.3 references. TOC (Table of Contents) updated. Appendix A (List of Writers) updated to include Section 2.3 writers. Appendix C. (Updates and Revisions) updated.
May 15, 2013	Section 3.2 (RIE EARS Primary Site) completely replaced following October 2012 EARS Planning Workshop. Section 3.1 (RIE Introduction and Overview) given minor updates. Section 5 (References) updated to include Sections 3.2 references. TOC (Table of Contents) updated. Appendix A (List of Writers) updated to include Section 3.2 writers. Appendix B (List of Planning Workshops) updated. Appendix C. (Updates and Revisions) updated

December 23, 2013	Section 2.4 (SCD New Zealand Primary Site) completely replaced following April 2013 New Zealand Planning Workshop. Section 2.1 (SCD Introduction and Overview) given minor updates. Section 3.2 (RIE EARS Primary Site) given minor updates. Section 3.3 (RIE ENAM Primary Site) given minor updates. Section 5 (References) added to include Sections 2.4 references. TOC (Table of Contents) updated. Appendix A (List of Writers) updated to include Section 2.4 writers. Appendix B (List of Planning Workshops) updated. Appendix C. (Updates and Revisions) updated