GeoPRISMS
Draft Science Plan

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1. Executive Summary

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The decade of MARGINS research unquestionably fostered major discovery in solid Earth sciences. The program succeeded because it recognized that progress on many outstanding questions required coordinated, multidisciplinary efforts spanning the shoreline across active continental margins, and integrating those with experimental and theoretical work. In so doing, the program built a large, interdisciplinary community well situated to carry out transformative shoreline-crossing studies in the future. The last decade also saw increased scientific excitement from several remarkable, unexpected observations of the behavior of active plate boundaries, and tremendous investment into the infrastructure needed to carry out their investigation. Overall, MARGINS was a success exceeding expectations, paving the way for new discoveries through a successor program as recommended by the 2009 Decadal Review Committee (DRC). This document introduces a draft plan for such a successor program, here termed GeoPRISMS (Geodynamic Processes at RIfting and Subducting MarginS). It outlines the scientific challenges that such a program will address, the program structure, and the approaches it will use to implement it. It follows the community consensus reached at the MARGINS Successor Planning Workshop (MSPW) in February, 2010.

GeoPRISMS will expand the dimensions of the original program in several fundamental ways, following DRC and MSPW guidance: (1) integration of scientific emphases, defining two Initiatives (SCD and RIE) rather than the four within MARGINS, (2) further integration through emphasis on overarching scientific themes that cross-cut tectonic categories, (3) explicit inclusion of surface processes and their feedbacks in the evolution of continental margins, (4) consideration of ancient and exhumed margins, (5) implementing science objectives through a hybrid of focus-site and thematic-based investigations, (6) increased attention to US margins and facilities such as EarthScope and the Cascadia Amphibious Array, (7) expanded emphasis on issues with direct societal impact, and (8) a vertically-integrated education and outreach program supporting development from K-12 to early career scientists. It will continue to emphasize multidisciplinary research and studies that cross the shoreline, recognizing that the shoreline is where much of continental evolution takes place, and is also where the dynamics of the solid Earth have the largest impact on human populations. MARGINS built this interdisciplinary, collaborative community, accounting for the scientific breakthroughs it has achieved; GeoPRISMS will sustain it.

The GeoPRISMS Science Program includes two broadly integrated initiatives, distinguished by tectonic setting:

- *Subduction Cycles and Deformation (SCD)* takes a holistic approach to the deformation processes and material cycles governed by subduction. It integrates and expands the former SEIZE and SubFac Initiatives, building on a growing recognition that the two systems are tightly linked and responding to many of the same forcing functions, although manifest in different ways. The SCD Initiative will focus on the coupled processes responsible for both long-term margin evolution and material transfer and short-term plate boundary deformation and volcanism. In particular, it studies 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 thrust zone and sub-arc mantle, and the ways in which these processes affect the long-term growth and evolution of continents. In so doing, SCD will provide fundamental scientific understanding of the processes that generate some of the largest natural hazards on the planet, including great earthquakes, tsunamis, and explosive volcanic eruptions.
- *Rift Initiation and Evolution (RIE)* provides a new and broad perspective on the processes by which continents break apart. It expands the former RCL Initiative to include the full

spectrum of stages of continental breakup, with increased emphasis on the interplay between surface processes, sedimentation, and continental evolution. It will include early-stage rifts but also the study of passive margins, which archive the entire history of rift zone construction and evolution. This approach provides direct relevance to understanding both mineral and petroleum resources. The RIE Initiative will seek to determine the parameters and physical properties that control the process of continental evolution, with particular emphasis on the initiation of continental rift zones, feedbacks between tectonics, magmatism, and surficial processes, and the resulting stratigraphic and tectonic architecture of rifted margins.

Both initiatives highlight the interconnectedness among surficial, shallow crustal, and deep Earth processes and their roles in plate boundary deformation, mantle rheology, magmatic processes, and volatile fluxes. Both will engage interdisciplinary teams carrying out observational, experimental, and modeling studies to address their fundamental questions. These investigations have practical applications for sustainability in the face of climate change and sea level variation, resource management and availability, and hazard mitigation. Furthermore, the proposed studies provide unique opportunities to build an appropriately educated workforce, the next generation of GeoPRISMS scientists, and will yield new knowledge about processes that fascinate the public.

Implementation of GeoPRISMS will follow a “hybrid” approach, in which focus-site studies will be complemented by thematic investigations. While major field efforts will occur in designated focus sites, as in MARGINS, studies that address programmatic themes but cannot be done in those sites will be supported elsewhere. Examples could include study of a process or system where best expressed, global comparisons to establish the significance of focused observations, or studies that sample different stages of a temporally evolving process. The sites themselves will be chosen at community workshops held in the program’s first year. Finally, a suite of five Overarching Themes will serve as the basis for integrative studies and provide a framework for cross-initiative programs: (a) Origin and Evolution of Continental Crust; (b) Fluids, Magmas and Their Interactions; (c) Climate-Surface-Tectonic Feedbacks; (d) Geochemical Cycles; and (e) Plate Boundary Deformation and Geodynamics.

A broad array of tools and resources are now available to carry out GeoPRISMS scientific objectives, following a decade of infrastructure investment by NSF and other agencies. Observational facilities include new geophysical and geodetic facilities such as IODP, IRIS, UNAVCO, OBSIP, the *R/V Marcus Langseth*, and EarthScope. Computational infrastructure and software archives provided by CIG and CSDMS expand the numerical modeling potential within the new program. Strong international collaborations established during MARGINS will also transfer into the new program, as will new partnerships with domestic and foreign agencies.

The new directions outlined in this Science Plan will expand the broader impact of the program in several distinct ways. The explicit inclusion of sediment transport and deposition processes along both subducting and rifting margins will increase understanding of geologic hazards such as landslides and shoreline change, and provide natural links to the oil and gas industry. Continued emphasis on seismogenesis and a new focus on volcanic systems provides a springboard for study of hazards associated with megathrust earthquakes and volcanic eruptions, and potential linkages to mining and minerals. Furthermore, an emphasis on volatile exchanges, from weathering to the deep interior, will provide insight into the long-term evolution of the atmosphere and hydrosphere.

In concert with a new scientific agenda, a new and integrated educational program is envisioned, closely aligned with research priorities. The program is guided by the notion that GeoPRISMS science can impact education at all levels and in a diverse range of communities, starting with new partnership-based outreach to K-12, continued development of the highly successful Undergraduate Mini-Lesson program, an extension of the Distinguished Lecture Program to bring top-level lecturers to a wide range of colleges, a new dedicated REU program to foster undergraduate research, a new series of short courses aimed at graduate students, and continuation of a Post-doctoral Fellowship program. Facilitated by an Education and Outreach director within the GeoPRISMS Office, this spectrum of activities will allow research results to rapidly enter the classroom, and will provide enhanced mechanisms for training the next generation of scientists. It is expected that some of these activities will be funded through proposals outside of the regular science panel.

In the near term, GeoPRISMS should pursue several important opportunities, without waiting for site selection workshops. These include but are not limited to (a) theoretical, experimental, or global comparisons that address GeoPRISMS science objectives without requiring major field efforts; (b) field efforts needed to complete work in existing MARGINS Focus Sites that address GeoPRISMS priorities; (c) integrated investigations that parallel the deployment of geophysical infrastructure taking place now, particularly those complementing the OCE/EAR MARGINS-EarthScope Cascadia Amphibious Array, and other amphibious surveys coordinated with EarthScope's Transportable Array as it makes its way across the continental US. Collaborative research efforts could begin along the US Gulf Coast, East Coast, Alaska and Cascadia, all of which have direct ties to GeoPRISMS science objectives.

In summary, the potential for new discovery within GeoPRISMS is even greater than that envisioned in the successful MARGINS science plan, and many new resources can be brought to bear that were not available a decade ago. By planning the entire program at once, a thoroughly integrated science agenda has been devised, centered on many of the major overarching themes that are central to modern inquiry in the solid Earth sciences. They also provide many opportunities for impacts through increasing our understanding of geohazards of primary economic resources, and by providing novel educational opportunities. By capitalizing on the new opportunities summarized here, and by harnessing the public's excitement in understanding US continental margins and their potential, GeoPRISMS will lead us toward transformative discoveries in the nature and evolution of continental margins worldwide.

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2. Origin and Structure of GeoPRISMS

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The GeoPRISMS Draft Science Plan represents a community response to several fundamental scientific challenges. While the program is fundamentally new, it builds on the successes of the NSF MARGINS program and addresses the MARGINS Decadal Review. We provide a brief overview of the MARGINS Program to put GeoPRISMS in context, and summarize the proposed structure of the new program

2.1. Scope and Accomplishments of MARGINS

For the last decade or more, the MARGINS Program has provided a community focal point for science that aims to understand the origin and evolution of the continents through the investigation of their active margins. This was encapsulated in the MARGINS Program mission statement, "*to understand the complex interplay of processes that govern continental margin evolution globally,*" and encompasses what are perhaps some of the largest challenges in solid Earth science. The connection between global processes and continental evolution lies at ocean-continent margins, the sites of most processes that modify continents. The MARGINS program was divided into four major initiatives, which were designed to form inclusive and interdisciplinary vehicles for attacking these problems. The Initiatives and their respective Focus Sites were defined as:

- *RCL* – Rupturing Continental Lithosphere (Gulf of California/Salton Trough)
- *S2S* – Sediment Source to Sink (Waipaoa NZ; Fly River/Gulf of Papua)
- *SEIZE* – the Seismogenic Zone Experiment (Nankai; Central America)
- *SubFac* – the Subduction Factory (Izu-Bonin-Mariana; Central America)

These Initiatives addressed the mechanics, structure, and evolution of continental deformation at convergent and divergent margins, the mass and energy flux to resulting continents through subduction, and the sedimentary mass transfer from them. Several guiding principles characterized the program, many of which will continue in a modified form in GeoPRISMS:

- *Broadly interdisciplinary communities.* Each initiative addressed a complex system affecting many types of observable phenomena. Understanding these systems requires a wide variety of expertise, and integration across a broad range of disciplines.
- *Crossing the shoreline.* Any complete science program addressing continental margin evolution has to be amphibious, encompassing marine, coastal, and terrestrial elements. Thus, MARGINS crossed NSF division boundaries, and by necessity, integrated both Earth and Ocean Sciences.
- *Active systems.* Dynamic systems are best studied where the time and length scales, fluxes, and rates of processes are measurable today, so most field experiments occurred in active plate boundary systems.
- *Experiment, computation, and theory.* Laboratory, numerical, and analytical efforts provided critical independent approaches to help understand the diversity of observational evidence. These approaches also have special roles in the integration, synthesis, and visualization of observational results.
- *Focus sites.* To afford such ambitious multidisciplinary activities, major field exercises were concentrated in community-specified Focus Sites, one or two per Initiative. Most of the selected sites were outside of the U.S., so many international program partners were leveraged in the process.

Achieving the science goals within this framework in this manner required an integrated program, able to build communities with access to a broad range of tools, resources, and scientific approaches. This necessitated focusing research funding on targeted sites, and creating activities that provided oversight and fostered integration within and between sites. Normal "core" funding mechanisms at NSF could not achieve these goals. Some of the first major successes of the program were the thematic workshops that built the broad interdisciplinary communities that remain active today, and stimulated successful proposals. This interaction between disparate scientific communities and clear, focused programmatic goals driven by compelling science was a hallmark of the MARGINS program and will remain so for its successor GeoPRISMS outlined here.

MARGINS science has been funded through individual and collaborative proposals to the NSF panel. An independent MARGINS Steering Committee (MSC) provides guidance, support and evaluation for the program (but not science proposals), and forms the principal link to the broader scientific community. To support the varied activities, a MARGINS Office facilitates communications, meetings, and other planning or assessment activities. It also serves as a focal point for several MARGINS-related education programs, centered on undergraduate and graduate student development. The MSC and MARGINS Office thus serve as primary vehicles for encouraging and enabling communication and integration among the disparate scientific communities involved.

The four MARGINS Initiatives have resulted in a great variety of scientific successes, which, in turn, have engendered a host of new opportunities across the subduction-rift-sediments community. The major highlights from each of the Initiatives and the program as a whole were summarized in preparation for the 2009 Decadal Review, including community-contributed Research Nuggets. These documents can be downloaded from the MARGINS Web Site: *www.nsf-margins.org/Review2009*.

2.2. MARGINS Decadal Review and Planning for GeoPRISMS

In late 2008, as the MARGINS Program approached its tenth year, an external committee was organized to provide a review of the program in its entirety, including science goals and accomplishments, program management, and broader impacts. The Decadal Review Committee (DRC, Prof. Anthony Watts, chair) was asked to evaluate progress to date and plans and promise for the future, and to provide comments and recommendations to NSF, and advice on the potential structure of a successor program. The DRC met February 2-3, 2009 to carry out this review; see *www.nsf-margins.org/Review2009* for the full report, documentation and response.

The DRC offered a highly favorable review of the program, recognizing the success of several core approaches of the MARGINS Program, including the broad approach to community building, the importance of crossing the shoreline, the use of focus sites to concentrate resources, the added value in cultivating international partnerships, and the importance of integrating computational and experimental research with field observation. The DRC also recognized that such activities could not have succeeded without a science program separate from core funding. The committee offered a strong recommendation to NSF that a MARGINS-like special program should be continued, building upon the strengths of MARGINS (See Box 2.1). These recommendations form the starting point for this Draft Science Plan.

In response, the NSF accepted the DRC report in principle, and requested the MARGINS Steering Committee to engage the broader geosciences community to help plan the future directions of MARGINS research. An open community workshop was organized Feb 15-17, 2010 in San Antonio for this purpose, with over 200 participants attending. This MARGINS Successor Planning Workshop (MSPW) was designed specifically to

- Identify compelling science issues that the community would like to see addressed in a possible successor program;
- Decide whether to implement thematic vs "focus site (hereafter referred to as primary site)" approaches, and to consider the pros and cons of both;
- Establish stronger linkages between Earth and ocean sciences for even stronger partnership between EAR and OCE;
- Further justify the need for a special program with sequestered funding in the context of the proposed science;

Box 2.1. Primary recommendations of the MARGINS Decadal Review Committee

- Both the SEIZE and SubFac Initiatives should continue, guided by community workshops to define their science plans for the next phase of study;
- A new initiative should be developed that would incorporate a broader view of rifted margin evolution, including passive margins and analysis of sedimentary architecture as recorders of the progress of rifting;
- The S2S Initiative should not be continued as a stand-alone initiative, but rather the appropriate aspects of sedimentology and stratigraphy should be incorporated explicitly within the other initiatives;
- Passive and ancient exhumed margins should be considered, as well as active margins.
- The focus site concept should be continued, but expanded to allow flexibility;
- Large-scale modeling, lab and experimental studies of margin analogs in the rock record should continue to be important elements;
- The program should continue to work productively with other large-scale NSF facilities: such as EarthScope, OOI, IODP, and R/V Marcus Langseth;
- Enhanced links with societal issues such as climate, sea-level and environmental change, geo-hazards, and energy and resources should be highlighted in the new program.

- Develop a draft Science Plan for consideration by NSF for authorization of a successor program.

The document presented here represents the community consensus on priorities emerging from that Workshop, introduced here as GeoPRISMS (Geodynamic Processes at RIfting and Subducting MarginS). It was written in the two months following the MSPW by ~20 participants chosen by, and including members of the MSC, incorporating community feedback on an early draft solicited during a Public Comment Period. The widely circulated document provides an outline of future science directions, justifications for a renewal program, and a summary of how such a program would be implemented. NSF authorization for a new program, if given, will set the stage for subsequent planning workshops to take place, to prepare the final GeoPRISMS Science Plan, although some program elements could commence immediately (See Section 6.3).

2.3. Building GeoPRISMS beyond the MARGINS Brand

As recommended by the DRC, GeoPRISMS will maintain the focus of its predecessor on subducting and rifting margins, and research efforts will be organized around several fundamental scientific questions that have the highest potential for achieving transformative breakthroughs on a decadal time scale. It emphasizes interdisciplinary inquiry, and crosses the shoreline. However, GeoPRISMS is not a continuation of MARGINS. Instead it builds on the MARGINS "brand", taking advantage of the progress and community building done previously to focus on several new problems and processes. New researchers from a broadened range of disciplines will be attracted into research collaborations to investigate processes that take place at the Earth's surface, as well as within the crust and mantle, to better understand how these intertwined systems drive each other in space and time. New tools and new facilities will be exploited as much as possible to drive transformative breakthroughs, and discoveries of the last few years will feature prominently in science goals. To fully realize these potentials, GeoPRISMS will:

- Address complex coupled systems through an integrated approach, combining field research in structure and tectonics, marine geology, geomorphology, geochemistry, geophysics, sedimentology, stratigraphy, and satellite-

based methods, but also with a sound basis in experimental, analytical and numerical modeling investigations;
- Involve large amphibious field programs as well as smaller focused field and lab-based studies;
- Be guided by Overarching Themes, which address the coupled geodynamic, surficial, and climatic processes that build and modify continental margins over a wide range of timescales (from s to My); and
- Develop comprehensive systems-based models to understand margin evolution and dynamics, the construction of stratigraphic architecture, and the implications for the accumulation of economic resources, associated geologic hazards, climate change and environmental management.

Following recommendations by the DRC and the MSPW community input, GeoPRISMS will consist of two broad Initiatives. The new initiatives are Subduction Cycles and Deformation (SCD) and Rift Initiation and Evolution (RIE). The SCD initiative will encompass the former SEIZE and SubFac Initiatives, building on a growing recognition resulting from a decade of MARGINS research that the two systems are tightly linked and respond to many of the same forcing functions, albeit manifested in very different ways. The RIE Initiative will encompass the former RCL and aspects of the Source to Sink Initiatives. RIE will expand its purview to include the study of passive margins as archives of the entire history of rift zone construction and evolution, with direct relevance to understanding both mineral and petroleum resources. These initiatives will be integrated through five Overarching Science Themes, which serve as an intellectual focus to the tectonically-defined Initiatives (Box 2.2).

Following DRC and MSPW recommendations, GeoPRISMS reaches beyond MARGINS in several novel directions:

- Explicit inclusion of surface processes (e.g., climate modulated weathering, erosion, sediment dispersion, and deposition) and their feedbacks in the evolution of continental margins;
- Consideration of inactive and potentially exhumed margins, where a process has gone to completion or where observations of deeper systems can be made in the field;
- Implementation of science objectives by way of a "hybrid" approach, merging focus-site studies with a more flexible thematic approach, to enable detailed study of a process or system where best expressed, as well as global comparisons to establish the significance of focused observations, or their fit into a temporal framework;
- Close relationships with many new major facilities now in operation to maximize their scientific return, including increased attention on US-based facilities such as EarthScope and the Cascadia Initiative;
- Expanded relevance of GeoPRISMS research to issues with direct societal impact, including accumulation of economic resources, understanding geologic hazards, and managing coastal development; and
- Broadened educational and outreach programs to engage the new generation of scientists into exciting continental margins science.

Box 2.2. GeoPRISMS Overarching Themes (Described in Section 3)

- Origin and Evolution of Continental Crust
- Fluids, Melts and Their Interactions
- Tectonic-Sediment-Climate Interactions
- Geochemical Cycles
- Plate Boundary Deformation and Geo-dynamics

2.4. Initiative Structure

Subduction Cycles and Deformation (SCD) will address coupled processes active at subducting margins and explore linkages among them, spanning the updip limits of the accretionary wedge and incoming plate, to the deep mantle and plate boundary interface, and associated cycling of fluids and volatiles, their role in rheology, melting, and magmatism, and ultimately, arc processes that lead to the growth of continental crust. This new initiative formalizes the strong linkages between SEIZE and SubFac recognized during MARGINS, and will facilitate the interdisciplinary exchange of knowledge within the subduction zone community, enabling transformative discoveries of this highly coupled system. As elaborated in Section 4, the key questions guiding this initiative are:

- 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, from mantle geochemical reservoirs to the architecture of arc lithosphere, and how do these influence the formation of new continental crust?
- What are the physical and chemical conditions that control subduction zone initiation and the development of mature arc systems?
- What are the critical feedbacks between surface processes and subduction zone mechanics and dynamics?

Rift Initiation and Evolution (RIE) will focus on the fundamental processes active within rifts and rifted margins, from the initial localization of continental rupture, the structural, magmatic, and sedimentary processes that control the growth of rift zones, through the late stages of rifting and the transition to oceanic spreading, and the resulting stratigraphic and tectonic architecture of passive margins. This initiative will emphasize the interactions between climate, erosion, and sediment transport and deposition, and plate boundary deformation, including mantle dynamics, to gain a comprehensive understanding of lithospheric evolution along rifted margins. As detailed in Section 5, the key questions guiding this initiative are:

- Where and why do continental rifts initiate?
- 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 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?

2.5. Integrated GeoPRISMS Science and its Societal Impact

Both GeoPRISMS Initiatives embrace the interconnectedness among surface, tectonic, and magmatic processes, addressing the complex interactions and feedbacks induced by climate, erosion, sediment transport, and deposition in controlling continental margins dynamics, crustal growth, fault mechanics, volatile flux, and magmatic activity. This approach will enhance collaborations between marine and terrestrial geologists and geophysicists, and will help to build stronger partnerships across NSF divisions. The new initiatives will engage interdisciplinary teams carrying out observational, experimental, and modeling studies to address their fundamental questions. These investigations have practical applications for sustainability in the face of climate change and sea level variation, increased pressures on energy and water resource management and availability, and hazard mitigation. Not only are the proposed studies of both basic and applied value, but they also provide unique opportunities to build an appropriately educated workforce, the next generation of GeoPRISMS scientists, and new knowledge on subjects of great importance to the broader public.

2.6. Justification for a Stand-Alone Program: Why Not Core?

Strong arguments can be made to maintain GeoPRISMS as a focused program, distinct from the standard NSF core programs. Like MARGINS, GeoPRISMS remains tightly focused on understanding the complex coupled systems that control continental margins dynamics, structure, stratigraphy, and evolution, from top to bottom, as viewed from onshore and off, and from inside and out. The extraordinary cross-disciplinary nature of MARGINS and GeoPRISMS science could lead to transformative breakthroughs, but must attract geoscientists who can work in teams that span the traditional NSF divisions. Consistent with this model, fulfilling the GeoPRISMS vision will require:

- A combination of on-land and marine investigations to fully capture processes and products that cross the shoreline, for example, mantle and lithosphere dynamics that control plate boundary deformation, and the subaerial to submarine pathways that control sediment dispersal and accumulation.
- Strong interdisciplinary research teams, for example, promoting collaborations among geomorphologists, sedimentologists, geochemists, geophysicists, and geodynamicists to understand the complex development of stratigraphic architecture along rifted margins., and the dynamic interplay between tectonics uplift, erosion, sedimentation, and megathrust fault mechanics.
- Guidance from a cogent Science Plan, that can focus major projects to address clear scientific objectives vetted by the community.
- Interdisciplinary NSF panels able to evaluate the breadth and scope of GeoPRISMS scientific proposals, and in particular, synthesis activities that may span a broad range of data sets and research techniques, including experimental and/or theoretical studies.
- A well-informed scientific community, conversant in the wide range of geological phenomena that govern continental margin processes. Such a community is an outgrowth of coordinated efforts to enhance communication, education, and knowledge exchange, for example, through workshops, newsletters, websites, and the oversight and steering committee, which the GeoPRISMS Office will manage.
- Coordinated efforts to disseminate the significance and relevance of GeoPRISMS science, for example, its impacts on understanding geohazards and economic resources to the broader community, including students, the public, and policy makers. A focused and managed program will facilitate such efforts beyond the abilities of individual PIs.

GeoPRISMS will also continue the demonstrated benefits of the focused MARGINS program, which include engaging and leveraging major international partnerships, providing a framework for science that uses major infrastructure facilities, and developing broad education and outreach efforts from numerous individual research projects. Furthermore, the facilities for data archiving, rapid public release policies, and development of educational access tools are best managed within a focused program. These education and outreach tools have been shown to contribute significantly to the success of MARGINS, and are expected to continue to do so within GeoPRISMS.

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3. Overarching Scientific Topics and Themes

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The community has recognized five major research directions within solid-Earth geosciences, where transformative advances are likely to occur in the next decade, and where a concentrated scientific program could be most effective. These Overarching Themes transcend disciplinary and tectonic boundaries, so GeoPRISMS includes them as an integral part of the entire program, joining both major initiatives. As a benefit, identification of these themes should further build effective scientific partnerships. Much of the success of the present MARGINS has come from developing truly cross-disciplinary communities where none existed before. One of the main tasks in building a successor program will be to identify and mitigate other barriers to discovery, including those between the GeoPRISMS Initiatives.

Below we identify the five major cross-cutting themes that bridge the Initiative structure and provide a comprehensive framework for interdisciplinary understanding of fundamental processes that govern continental margin evolution (See Box 2.2). We view these themes as likely areas in which major breakthroughs will occur within GeoPRISMS. We expect that workshops and integrative products will be structured in part around these themes, complementing the Initiative-specific work that is at the center of GeoPRISMS.

3.1. Origin and Evolution of Continental Crust

Earth's continental crust appears to be unique in the solar system, yet the processes governing ITS creation, modification, and destruction are not fully understood. Continental margins are dynamic environments where the continental crust and lithosphere are created, destroyed, and modified, providing natural laboratories for integrated studies of lithospheric origin and evolution. New continental crust is accreted tectonically or magmatically to pre-existing crustal masses at subduction, transform, and rifted margins. Subsequent processes fundamentally change the composition and structure of the continental crust at these margins. In both active and passive margins, erosion and deposition transfer material from mountains to basins, altering the thickness, density, and stratification of the crust in time and space. Surficial chemical and mechanical weathering processes partition elements, and fluvial systems redistribute segregated material, further contributing to compositional changes that distinguish continental crust from evolved mantle-derived magma. Ultimately, subduction removes some of this material. These tectono-magmatic, metamorphic, and weathering processes also control the spatial distribution of mineral, carbon, and hydrocarbon resources.

Although the evolution of continental lithosphere spans many tectonic environments, volcanic arcs and rift zones represent key locations to study processes governing the creation, modification, and destruction of the continental lithosphere. The bulk composition of continental crust (equivalent to an andesite) is more evolved than the mantle-derived magmas (equivalent to a basalt), requiring shallower melting and differentiation, or processing within the continental lithosphere. Magmas may rise to the surface via dikes, or accumulate at the base of the crust, increasing its thickness through time. Magmas may also ascend to crustal magma chambers where fractional crystallization processes distill lighter elements. Mafic and ultramafic cumulates of differentiation can be denser than the underlying mantle and may delaminate or otherwise return to the mantle on short time scales. The processes and rates of evolution of mantle-derived materials to more differentiated continental crust through internal crustal differentiation and, perhaps, delamination of associated cumulates, remain important questions.

The transfer of magmatic material from mantle to crust, and dense residuum from crust to mantle, can also fundamentally alter plate structure, strength, and rheology, and may precondition zones of melting during subsequent tectonism or heating. The mantle lithosphere beneath continents is a distinct geochemical reservoir that is created and modified in subduction zones and continental rifts. The extraction of melt and the introduction of metasomatic components are important processes in both the mantle wedge at subduction zones and in the upwelling mantle beneath rifts, and pronounced feedbacks between fluids in the downgoing crust and circulation within the overlying mantle wedge trigger melting and magma rise. Feedbacks between pre-existing lithospheric heterogeneity, lithospheric stretching, and mantle upwelling also influence the distribution, composition, and volume of melts beneath rift zones. These crustal and mantle heterogeneities persist over long time scales, and play roles in subsequent episodes of deformation and magmatism, localizing fluid flow and strain. There is also a top-down effect: the timing and distribution of sediments may strongly influence the localization of strain and magmatism. These new discoveries and insights inform and guide a new generation of scientific exploration and investigation within subduction and rift settings.

3.2. Fluids, Magmas and Their Interactions

An understanding of the production and transport of magmas, fluids, and volatile species is central to the understanding of both rift and subduction systems. Processes mediated by fluids provide a focus for synergetic studies through combinations of theoretical, experimental, and observational approaches. At subduction zones, devolatilization of sediments and dehydration reactions influence the style of deformation along the plate interface and the rheology of the mantle wedge. At rifts, fluids influence the strength of the lithosphere, the style of rifting, and patterns of seismicity. Near the surface, interactions among sedimentation, compaction, and pore fluid pressure control fluid fluxes between the solid Earth and the hydrosphere, as well as geohazards associated with slope stability. Melting at subduction zones is a primary mechanism for generation of continental crust, and analyses of melts generated at both rifts and subduction zones are critical for understanding the chemical evolution of the Earth.

Significant advances in characterizing the thermodynamics of melting and metamorphic reactions in subduction input material and the mantle wedge has led to more quantitative approaches for investigating relationships among the thermal evolution of slabs, metamorphic reactions, fluid production, and seismic velocity structure. Within this framework, much current research is focusing on the spatial and temporal links between fluids and the earthquake cycle, and the recycling of volatiles into the solid Earth. In rifting environments, there is growing appreciation for the role of melting and diking during rift initiation. These insights motivate new investigations on the links between rifting mechanics and the spatial and temporal patterns of magmatism. Multi-disciplinary studies are transforming our understanding of magma generation and migration. In particular, rapid improvements in integrating seismic imaging, laboratory measurements, geochemical analyses and numerical modeling help to resolve the distribution of melt and the conditions under which it exists. Laboratory experiments provide critical information on the effects of volatiles on mantle melting. Geochemical analyses provide direct measurements of volatile species in magmatic glasses and precise magma chronologies. Theoretical models provide strong ties between solid flow and thermal structure of the mantle wedge in both 2D and 3D, particularly with new capabilities to incorporate feedbacks between melting, two-phase flow, and chemistry.

Although a myriad of links among fluid, mechanical, and chemical processes are recognized, their characterization through observations has generally been qualitative and incomplete. Understanding the processes that control the spectrum of fault slip styles at convergent margins, some of which have been linked to fluids, is primitive because many key observations were only made in the last several years and data coverage is limited by short time series. Furthermore, laboratory and theoretical investigations of rock properties at relevant P-T conditions have only initiated in the last few years. Likewise, while geochemical proxies linking devolatilization and magmatism are evident, the physical and chemical interactions between fluid production and melting are not well constrained. Making major advances beyond empirical correlations will require integration of new datasets from field seismology, long-term observatories, geophysical surveys, seafloor sampling, and laboratory experimental studies with thermal and hydrologic models. GeoPRISMS is poised to facilitate these advances.

3.3. Climate-Surface-Tectonic Feedbacks

Sediments archive information about surface, climatic, sedimentary and tectonic processes in a drainage and distributary network. These archives can be queried via integrative studies of the stratigraphy of a basin. Research discoveries of the last 20 years demonstrate the remarkable degree to which Earth surface processes impact lithospheric evolution and continental margin structure. Quantitative models that integrate depositional processes over geological timescales show promising potential in interpreting past tectonic subsidence rates, sediment discharge, and climatic conditions. GeoPRISMS can use technological innovations in imaging, geochronology, and physical and numerical simulation to elucidate the interactions between Earth surface processes and continental margin evolution.

At the core of unraveling lithospheric scale questions lies our need for a better understanding of how Earth surface processes interact with tectonics and climate to produce surface morphology. Specifically, we invert the stratigraphic record for history and morphology through time. Recent studies of the production of stratigraphy at continental margins have shown how the signals of external environmental variables (e.g., tectonic subsidence, eustatic sea-level, and climate) can be substantially overprinted by processes that are internal to the sediment-transporting systems. These internal or "autogenic" processes can dominate the routing of sediment and hence the construction of stratigraphy from seconds to 10^5 -10^6 years.

Sedimentary systems may be measured in terms of the relative flux of weathered and eroded material and fluid from the source region through the transport system to the sedimentary basin. Sedimentary basins are valuable and in some cases, unique, recorders of integrated weathering and flux history of the accumulated sediments. Surface processes convey materials and alter them as they are transported. Important questions remain about the relative roles of biological processes, climate, and erosion rate in modulating material flux and weathering rate and processes. In addition, large river systems draining continental margins, in particular island or volcanic arcs, remain significantly undersampled for geochemical purposes. The role of weathering on continental margins as a major volatile sink and in the global carbon cycle is central, yet relatively unexplored. Synoptic and high temporal and spatial resolution measures of precipitation and runoff are not available for most parts of the world, yet they are key metrics of process and fundamental controls on the rate and fate of dissolved and solid sediment load.

The interactions between Earth surface processes with climate and tectonics also have enormous societal implications, and many of the processes of greatest societal impact are co-located. For example, areas exposed to sea-level change are also impacted by landslide-induced tsunamis. The supply of sediments is now understood to influence the distribution and magnitudes of great subduction zone earthquakes. The surface processes that build continental margins also determine which continental margins are preconditioned for slope failure, and the interactions between sediment supply, climate, and tectonics control the position of the shoreline over time. At the largest scale, material fluxes govern the distribution of economic resources such as hydrocarbons, which ultimately has complex feedbacks with climate. Continuing study of the interplay between changing environmental forcing and the transport processes acting on Earth's surface will produce significant discoveries that transform our community's view of continental-margin evolution during the next ten years.

3.4. Geochemical Cycles

Elements cycle between the Earth's surface and interior at both rifting and subducting margins.

The transfer and exchange of matter between Earth's oceans and atmosphere, subducting plates, asthenospheric and lithospheric mantle, and arc and continental crust ultimately control the composition and evolution of Earth's major near-surface solid and fluid reservoirs.

At subduction zones, the downgoing plate is enriched in volatiles through seafloor deformation and weathering processes and distributes this cargo to the overriding plate and mantle, selectively releasing volatile-rich fluids over a range of depths. This progressive devolatilization of the subducting plate creates a broad range of geochemical transformations in the overriding material and geological expressions at the surface, including forearc serpentinite diapirism and volatile-rich arc and back-arc magmatism, unique products of volatile transport. At rifts, volatiles bound in the pre-existing continental crust and lithosphere may be released to the atmosphere and oceans, through deformation and magmatism, or could be removed from the oceans and atmosphere by weathering processes. Additionally, alteration of exposed mantle along faults near the continental ocean transition may serve as a substantial volatile sink.

To date, most attention has been focused on the influence of H_2O and CO_2 on melting in subduction zones, but the cycling of other volatile species (S, N, rare gases, halides) at plate margins is also critical for large scale geochemical cycles and the importance of all of these volatiles goes beyond their influence on melting. For example, fluxes of volatiles between the surface and Earth's interior at plate margins have a first order influence on planetary climate on time scales ranging from years to billions of years. Storage and sequestration of volatiles by weathering, sedimentation, and subduction limits near-surface supplies of climate-influencing volatiles, whereas magmatism and the hydrologic cycle transport them back to the surface.

The extent to which oceanic plates entering subduction zones are serpentinized may produce an important and unknown control on input budgets and fluxes of volatiles into the Earth's interior. Recent geophysical studies of oceanic plates suggest that faulting at the outer rise creates pathways by which low-temperature fluids circulate to up to 20 km into the oceanic lithosphere. The resulting hydration of the slab mantle could be a tremendous reservoir of water (and other volatiles) that can be transported to depth, given the high water content of serpentinite. Additionally, the cold corner of the mantle wedge may be serpentinized as slab-derived fluids flush through it, creating a large reservoir of H_2O and other volatiles in the overriding fore-arc mantle. As yet, the processes that allow volatile fluxes out of this critical region are poorly understood. Hydrated and carbonated peridotite has emerged as a potential central control on the behavior of the subduction system at intermediate depths. New approaches are needed to quantify its abundance and total volatile budget in the mantle slab and forearc crust, and to assess how volatiles return to the Earth's surface. Finally, we still have a very poor understanding of the sources, sinks, and fluxes of volatiles in rift systems. Are rifts net sources of volatiles owing to mantle degassing, or sinks due to sequestration by weathering, hydrothermal alteration and sedimentation? Quantifying volatile fluxes at rift zones will be a critical new avenue of research in the Earth's geochemical cycles.

3.5. Plate Boundary Deformation and Geodynamics

Deformation at continental margins depends on the rheologic properties of the crust and mantle. Continental rifting proceeds through a combination of elasto-plastic deformation in the lithosphere and viscous flow in the underlying asthenosphere. Similarly, deformation in the descending plate and the overlying mantle wedge at subduction zones is controlled by the behavior of the crust and mantle, as well as fault zone rheology along the subduction interface. Major breakthroughs in our understanding of plate boundary deformation and geodynamic processes have come in the last decade through new observations and models, as well as interdisciplinary understanding of the interplay between rheology, fluids, melts, and surface dynamics.

Continuous GPS, InSAR, and seismic data, as well as computation resources, have improved significantly in the past decade, facilitating many unanticipated discoveries. In particular, new seismic and geodetic observations have led to the recognition of a much wider spectrum of possible slip mechanisms. Episodic tremor and slip (ETS) and other slow slip processes were unknown ~10 years ago, and now represent a major frontier in our understanding of what controls slip on faults downdip from the seismogenic zone in a wide range of fault environments. New seismic, geologic and geodetic observations have improved our understanding of magma migration and storage within active rift systems, and have revealed episodes of active rifting and post-rifting transients in both space and time. Such deformation maps have provided constraints on magmatic plumbing systems, the relative role of seismic versus aseismic rifting, and rheologic properties of the host-rock. Increased computational power over the last decade has allowed the incorporation of complex rheologies into high resolution, three-dimensional geodynamic models of deformation averaged over multiple seismo-magmatic cycles, as well as over a single cycle.

There are still many unresolved questions, however, that will drive the next generation of study of plate boundary deformation at continental margins. For example, we still have a very limited understanding of the processes that lead to the wide spatial and temporal variations in deformation and slip behavior. These may relate to fluids and volatiles in important ways, which can only be resolved by remote characterization of the materials involved, combined with laboratory investigations. Spatial and temporal variations in slip behavior are also highly dependent upon stress transfer, fault zone properties, structure, and composition of the wall rocks, which remain to be documented in a range of settings. At the large scale, there are many fundamental questions about the effects of magmas, fluids, and volatiles on crust and mantle strength, and therefore patterns of mantle flow that govern plate boundary deformation. Within rift zones, the efficiency of melt extraction influences mantle rheology and composition, and melt accumulations may determine strain localization. Improved knowledge of the rheology in these regions will advance our understanding of how coupling between mantle and crustal processes shape margin evolution in the long term.

An important direction for GeoPRISMS research, inherent to the amphibious approach, is the integration of offshore observations of strain and displacement to complete the picture of continental margin deformation. Emerging technologies and resources have extraordinary potential to lead to transformative discoveries of combined onshore-offshore processes.

3.6. Integrating Overarching Themes Within GeoPRISMS Science

The overarching themes outlined above are not entirely unique to the GeoPRISMS program, but they highlight the key breakthroughs that have occurred in recent years, inside and outside of MARGINS, that can guide a new generation of scientific investigation. Given the emphasis of GeoPRISMS on rifting and subducting margins, where the critical geologic processes are most active and best expressed, the new program is poised to make transformative discoveries in the thematic areas outlined above, from the mantle to the surface of the Earth. The five overarching themes are tightly integrated into the Initiative science questions that follow (Sections 4 and 5), and provide the broader context within which to frame scientific investigations at specific settings and sites. Thus, the GeoPRISMS program provides a vehicle for making fundamental observations in the settings best suited for their study.

To enhance this potential, we also anticipate holding thematic workshops (e.g., Theoretical and Experimental Institutes, see Section 6) organized around one or more of these overarching themes and spanning both initiatives, and perhaps AGU Special Sessions, to bring researchers together from inside and outside of GeoPRISMS to exchange knowledge and approaches to best address the questions posed.

Ideally, such workshops will also lead to special volumes and publications relating recent results, building a resource available to the larger scientific community, and thereby expanding the impacts of GeoPRISMS research. Additionally, we anticipate proposals being written that emphasize these themes within the context of Initiative-based science priorities, also likely spanning both Initiatives. In these and other ways, detailed in following sections, these Overarching Themes serve as an intellectual framework for the GeoPRISMS scientific agenda.

GeoPRISMS
Draft Science Plan

4. Subduction Cycles and Deformation

4.1 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?
4.2 How does deformation across the subduction plate boundary evolve in space and time, through the seismic cycle and beyond?
4.3. 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?
4.4. How are volatiles, fluids, and melts stored, transferred, and released through the subduction system?
4.5. What are the geochemical products of subduction zones, from mantle geochemical reservoirs to the architecture of arc lithosphere, and how do these influence the formation of new continental crust?
4.6. What are the physical and chemical conditions that control subduction zone initiation and the development of mature arc systems?
4.7. What are the critical feedbacks between surface processes and subduction zone mechanics and dynamics?
4.8. SCD in the Next Decade

4. Subduction Cycles and Deformation

Subducting margins are the loci of many of the most fundamental Earth processes, from the accretion of island arcs to their eventual modification into continental crust, and the fluxing of fluids and volatiles from the surface into the mantle and back through arc volcanoes. The largest earthquakes on Earth occur on subduction zone megathrusts, and their occurrence and magnitude are strongly influenced by material properties, metamorphic and geodynamic processes, and rheology of the crust and mantle. Many of these processes can be perceived as cyclic, for example, the seismic cycle, material cycling through the Earth, and even long-term tectonic cycles, e.g., the Wilson cycle. These processes are also critical to understanding the feedbacks between volcanism, long-term climate change, and the thermal evolution of the Earth's interior. The research directions of the Subduction Cycles and Deformation (SCD) Initiative are closely linked to the overarching themes outlined in Section 3, and demonstrate the interconnectedness of surficial, crustal, and deep Earth processes and their roles in plate boundary deformation, megathrust seismicity, mantle rheology, magmatic processes, and elemental fluxes, particularly volatile and fluid-mobile elements, many of which are important for ore-formation.

The key questions that will be addressed within SCD 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, from mantle geochemical reservoirs to the architecture of arc lithosphere, and how do these influence the formation of new continental crust?
- What are the physical and chemical conditions that control subduction zone initiation and the development of mature arc systems?
- What are the critical feedbacks between surface processes and subduction zone mechanics and dynamics?

The successful resolution of these questions will require strong interdisciplinary research teams, including experts in surface processes, structural geology and geodynamics, rheology, geochemistry and geophysics, who will examine the full subduction system from the trench to the sub-arc, arc, and back-arc regions. High resolution geodynamic models, incorporating complex rheologic and thermodynamic data, will provide important tests of data-driven hypotheses, providing an integrated understanding of the long-term mechanical, thermal, and chemical evolution of the Earth. These models, in turn, will guide the future collection of data to advance the frontier of subduction zone knowledge. This approach builds on the SEIZE and SubFac initiatives of MARGINS as envisioned by the Decadal Review Committee, but extends them in new directions that are driven by discoveries over the last decade.

4.1. 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?

Recent large damaging earthquakes, such as the 2004 Sumatra and 2010 Chile events, not only demonstrate the societal importance of understanding the subduction megathrust, but also provide unprecedented new datasets to understand fault behavior. In addition, many exciting discoveries in the last ten years have revealed that subduction zone

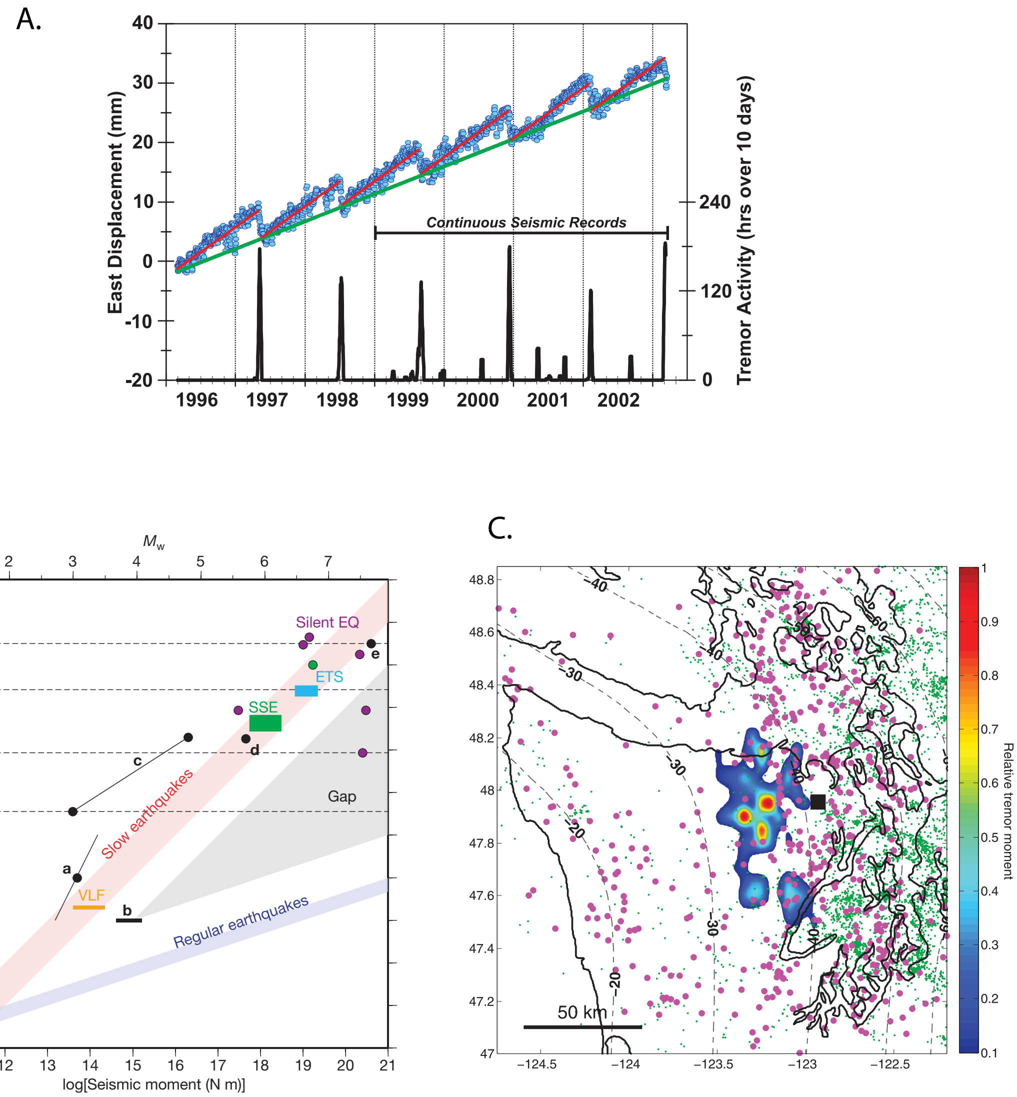


Figure 4.1. Highlights from observations of new slip processes made in the last decade. (A) Episodic tremor and slip observed over 7 years along the Cascadia margin shows correlation between the slow slip events observed in the geodetic record (upper) and timing of tremor activity during periods of slow slip [Rogers and Dragert, 2003]. (B) Time scale for ETS and slow earthquakes relative to "regular earthquakes" suggests a different scaling law and different behavior for these slip events with longer time constants [Ide et al., 2007]. (C) Moment release during May 2008 ETS episode with earthquake locations (1960-2008, pink and green circles near and away from subduction interface), showing that the tremor patches occur in areas without earthquakes [Ghosh et al., 2009].

faults show a wide range of previously unknown fault slip behaviors and rates, from coseismic slip to silent earthquakes, slow slip events (SSE), episodic tremor and slip (ETS), low frequency earthquakes (LFE), and very low frequency earthquakes (VLF), in addition to "normal" fast-slip earthquakes. Although our community has made some progress in characterizing these phenomena, we do not know if these new observations represent a fundamentally new type of seismic moment release, or fall along a continuum between normal earthquakes to creep [*e.g. Ide et al.*, 2007] (Figure 4.1). We also do not fully understand the underlying physical processes that give rise to these slip phenomena, in terms of intrinsic fault rock properties, fault architecture, and conditions (e.g., pore pressure, stress state, and temperature) on the fault interface, or how these other slip processes may influence great earthquake occurrence.

A major focus of the Subduction Cycles and Deformation Initiative will be obtaining key observational and experimental constraints on faulting processes across the entire range of slip conditions and sampling these at various stages over the earthquake cycle. This effort will require a combination of: (1) new seismic, geodetic, and other geophysical field observations; (2) long-term observations of in situ mechanical, geochemical, thermal, and hydrologic conditions relevant to these slip processes; (3) theoretical and laboratory-based experimental approaches that link observations and the underlying physical mechanisms; and (4) integration of observations across multiple study sites to sample the full range of slip behaviors and/or stages in the seismic cycle (as discussed in Section 4.2).

What controls the magnitude and recurrence interval of earthquakes?

Large megathrust earthquakes, such as the recent 2010 Chile earthquake (Figure 4.2), capture the public's attention like few other natural events. How and why do some subduction zones, such as Sumatra, Chile, and Cascadia, produce magnitude 9+ earthquakes whereas others such as Central Mariana are apparently limited to magnitudes <7 remains a major unanswered question of profound societal importance. Connections have been suggested between the occurrence and size of locked regions, and other subduction zone parameters, such as convergence rate [e.g. *Ruff and Kanamori*, 1980; *Stein and Okal*, 2007], incoming plate thermal structure and sediment content [e.g. Hyndman et al., 1997; *Spinelli and Saffer*, 2004, *Lay and Bilek*, 2007], upper plate structures [e.g., *Wells et al.*, 2003; *Collot et al.*, 2004; *Brudzinski and Allen*, 2007], hydration and weakening of the overriding forearc [*Peacock and Hyndman*, 1999; *Hyndman and Peacock*, 2003], and inhomogeneities such as subducting basement relief [e.g. *Bilek*, 2007; *Bangs et al.*, 2006; *Burgmann et al*. 2005; *McIntosh et al*., 2007].

Although it has been widely held that both the updip and downdip limits of seismicity are controlled by temperature along the megathrust [e.g., *Hyndman et al.*, 1997; *Oleskevich et al.*, 1999] identifying the underlying processes in terms of fault material physical properties, composition, or state variables, such as pore pressure or effective stress, has proven elusive [e.g., *Moore and Saffer*, 2001]. Furthermore, at some margins, recent observations indicate significant along-strike variability in both the downdip and updip limits of interseismic locking, suggesting that the association of the updip and downdip limits of interseismic locking with particular temperature

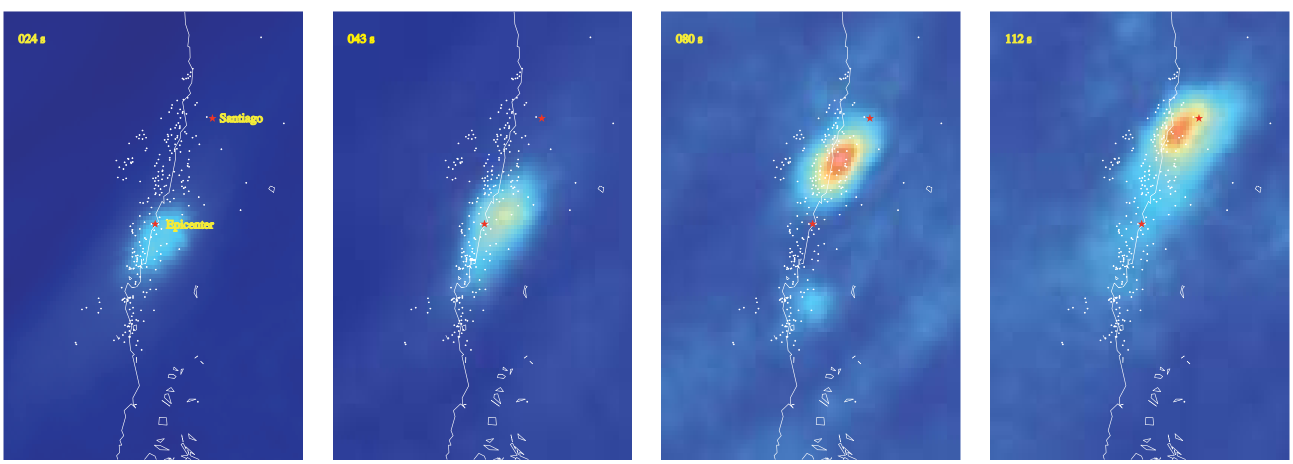


Figure 4.2. Slip of the 2010 Mw 8.8 Chile mainshock as a function of time, as imaged by stacking seismograms from the Japan Hi-Net network and USArray. Initial slip was lower amplitude and concentrated near the epicenter, but the rupture began propagating northward along the coastline about 40 s into the event, reached peak slip rate at about 80 s, and approached the Santiago Chile area near the end of the rupture. Small dots denote aftershock locations from the first few days after the mainshock. (Image courtesy of Eric Kiser and Miaki Ishii, Harvard University).

ranges is probably oversimplified [e.g., *McCaffrey et al*., 2008]. A second issue in correlating slip and locking behaviors with inferred fault conditions at depth is that considerable uncertainty remains in thermal and hydrologic models that are typically used to estimate temperatures and pore pressure. Quantifying these relationships will require seismic and geodetic studies to identify the locked sections of the faults combined with modeling studies to (1) define thermal and hydrologic state of the fault and (2) explore how variable fault zone conditions affect seismic rupture processes.

A significant new proposition in the last decade for understanding subduction zone seismogenesis, which needs to be verified by more observations, is that large earthquakes are correlated with large negative gravity anomalies and forearc basins [*Song and Simons*, 2003; *Wells et al*., 2003] and that maximum coseismic moment release tends to occur in local gravity minima, with slip decreasing along positive gravity gradients [*Llenos and McGuire*, 2007]. A theoretical understanding of the observed correlations is still in development – are the large earthquakes in some sense caused by the forearc basins [e.g., *Fuller et al*., 2006] or are these basins a consequence of the nature of plate coupling [e.g., *Wells et al*., 2003]? Are the correlations robust with respect to uncertainties in moment release distributions? Further progress will be enabled by detailed seismic and geodetic observations of large earthquakes and the geologic structure of forearc basins, as well as by theoretical models relating basins and earthquakes over many earthquake cycles.

What mechanical properties and/or fault zone conditions control the wide spectrum of slip rates observed on subduction megathrusts?

Recent observations from MARGINS and MARGINS-related studies have documented a wide spectrum of slip processes beyond simply aseismic creep and earthquake slip. These include tsunami earthquakes, very low frequency and slow slip events that occur in the outer forearc [*Ito and Obara*, 2006], episodic tremor and slip (ETS) and associated non-volcanic tremor activity (NVT) (Figure 4.1). A clearer picture of the physics controlling these processes and the conditions necessary for their occurrence will provide critical clues about the mechanics and moment release on subduction megathrusts, but our understanding of these phenomena is in its infancy. ETS, for example, has been observed in several subduction zones [e.g. *Rogers and Dragert*, 2003; *Obara*, 2002; *Shelly et al*., 2007], however, the fault zone conditions and intrinsic rock properties that are required to produce these events are not well understood. Tremor in particular has been observed in a wide variety of locations including both the downdip and updip limits of the subduction megathrust [e.g. *Schwartz and Rokosky*, 2007; *Brown et al*., 2009] and is proposed to be linked to the downdip edge of great earthquakes [*Chapman and Melbourne*, 2009]. The same is true for VLF events in the outer forearc, which may signal slip activity on major, potentially tsunamigenic, splay faults [e.g., *Ito and Obara*, 2006]. The effort to understand the connections between fault conditions and slip behavior will require additional seismic and geodetic observations of these signals, as well as laboratory and modeling efforts. Furthermore, many of the physical mechanisms that have been hypothesized to explain the occurrence of these phenomena involve linking fluid pressure variations with different frictional slip regimes [*Wada et al*., 2008; *Liu and Rice*, 2007; *Peacock*, 2009]. Thus a key component of the research in this area will involve investigating the interactions between subduction inputs (sediments and hydrothermally altered lithosphere), thermal structure, and metamorphism as described in Section 4.3.

4.2. How does deformation across the subduction plate boundary evolve in space and time, through the seismic cycle and beyond?

Although the subduction megathrust is a dynamic and important component of the subduction zone (Section 4.1), it is not the only locus of deformation in the subduction system. For example, secondary faults in the upper and lower plates exhibit coseismic slip and may accommodate substantial interseismic

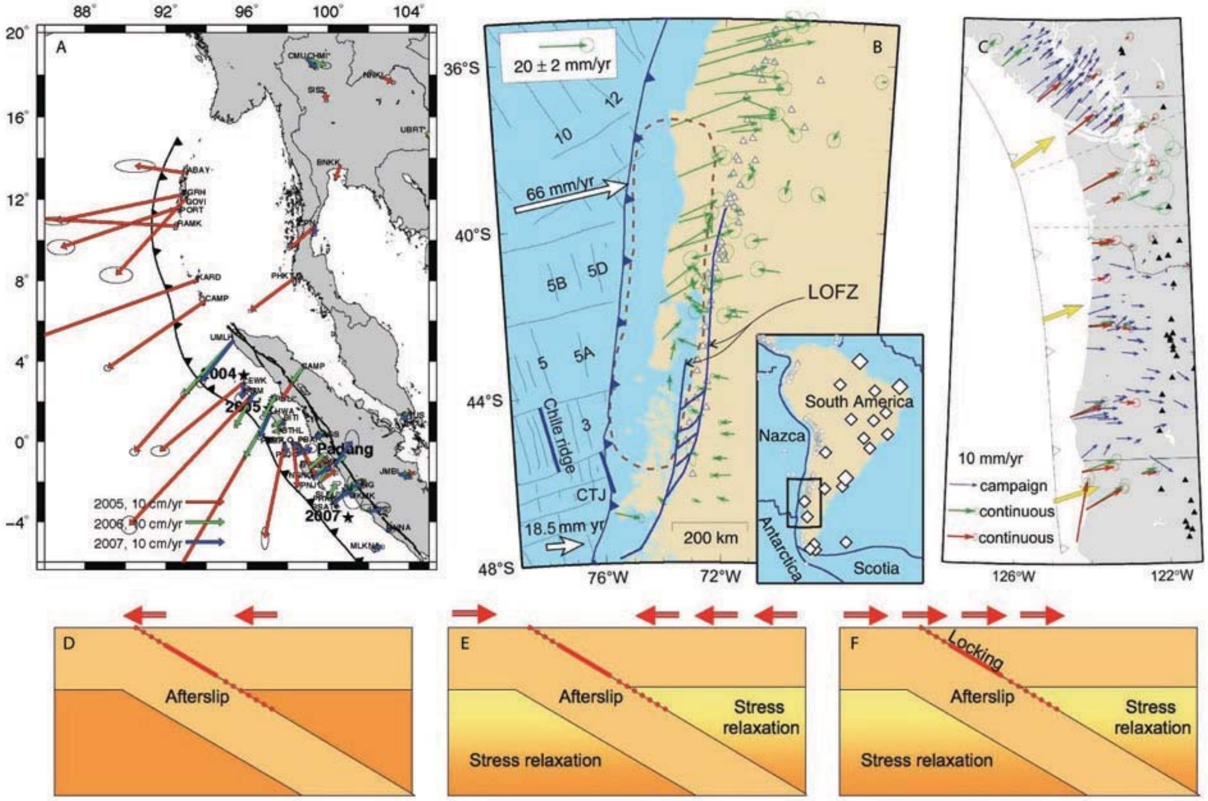


Figure 4.3. Schematic model for plate boundary displacements throughout the seismic cycle. Raw surface velocities for (A) Sumatra following 2004 earthquake, all sites move seaward [Grijalva et al., 2009]. (B) Chile ~40 years after M 9 earthquake, shows opposing motion of coastal and inland stations [Wang et al., 2007], (C) Cascadia, ~300 years after M ~9 earthquake, all sites move landward after oblique plate motions are removed [Wang, 2007]. Cartoon (modified from Wang [2007]) showing corresponding plate motions for (D) afterslip following rupture as both plates rebound elastically, (E) postseismic interval prior to full plate boundary locking as the mantle undergoes viscoelastic relaxation, and (F) plate boundary relocking, which forces the upper plate to move with the subducting plate.

strain; bulk viscoelastic movements of the upper plate and mantle can show varying responses dependent on the varying stress conditions along the margin. While these features and processes might be considered "secondary" in some respects, they are quite relevant for understanding earthquake and tsunami hazards, and the study of these features may in fact, provide a first-order understanding of what is happening on the megathrust (e.g., upper plate faults may limit where megathrust fault slip occurs [*Collot et al*., 2004]). A new direction for GeoPRISMS will be to combine onshore and offshore images of important fault structures, current observations of seismic and deformation activity, and a historical perspective preserved in sediment archives to assess the roles these "secondary" features and processes play in the evolution of subduction plate boundary zone during the earthquake cycle and over the course of multiple earthquake cycles.

What is the time history of surface displacements throughout the seismic cycle, and what are the respective contributions from mantle flow, upper and lower plate deformation, and the plate boundary interface?

Geodetic observations of plate boundary displacements demonstrate that relative plate motions vary with location and time, even along a single subduction zone. To first order, these differences can be understood within the context of the earthquake cycle and the variable decay of post-seismic deformation with time depending on the specific earthquake history and the subsurface rheology of an area (Figure 4.3) [e.g., *Wang*, 2007]. In practice, it is not possible to document the full time evolution of the deformation cycle due to the long recurrence time between earthquakes at any given margin. However, global comparisons of subducting margins at different stages in their seismic cycle offer the opportunity to construct a comprehensive picture of deformation throughout the entire cycle, and to relate these patterns to the responses of key components of the system – the megathrust fault, the oceanic and forearc crust, and the viscoelastic mantle. Although only a few such comparisons have been made to date [e.g., *Savage and Thatcher*, 1992; *Cohen*, 1996], the availability of inexpensive, but highly precise continuous geodetic instruments on land, and improvements in similar measurements offshore, now make if possible to fully constrain the patterns of deformation that accompany the full seismic cycle within a decadal time frame by working in several subduction zones simultaneously. Defining this framework will enable us to clarify the second order factors that govern the distribution and magnitudes of large earthquakes in these settings, including the spatial and temporal variations in strength and locking behavior of the megathrust fault, and the intracrustal deformation that may diffuse stress build up that drives fault slip.

As one example of the relevance of understanding plate boundary deformation throughout the seismic cycle, we note that discrepancies between observed geodetic displacements and predicted plate convergence rates have been interpreted to reflect partial locking of the plate interface during interseismic periods [e.g., *Wang and Dixon,* 2004; *Norabuena et al*., 2004, *Burgmann et al*., 2005; *Chlieh et al*., 2008] with implications for the potential size of megathrust earthquakes. In other settings, e.g., parts of Alaska [e.g. *Fournier and Freymueller*, 2007] and *Sumatra* [*Chlieh et al*., 2008], the plate boundary appears to be fully locked. The physical mechanisms behind this variability are still poorly defined. Is partial locking an indication of slow creep along the entire interface, at a rate slower than plate convergence, or is it a manifestation of a heterogeneous fault surface, parts of which are fully locked, and others fully creeping? How much interseismic strain is accommodated by faulting or folding within the forearc and how does it vary along and across strike, particularly in complexly faulted forearcs? Dense continuous geodetic data with broad spatial coverage over a range of convergent margins can offer critical observations to address these questions. The recent earthquakes in both Sumatra and Chile, and increasing attention applied to the Cascadia margin, make this a unique time to fulfill this objective, within the next decade of GeoPRISMS.

What is the role of secondary faulting in the upper and lower plates in accommodating strain accumulation and what are the potential earthquake and tsunami hazards from earthquakes on these faults?

At many subduction zones, numerous "secondary" faults both onshore and off-shore, and in both the upper and lower plates, may slip coseismically and/or accommodate an appreciable fraction of plate motion. Understanding the roles and slip rates of these faults is crucial to understanding the associated hazards. For example, major splay faults in the upper plate (Figure 4.4) may rupture coseismically during great earthquakes, and by efficiently transferring slip to the seafloor, could generate large tsunami [e.g., *Moore et al*., 2007; *Henstock et al*., 2006]. Normal faulting in the subducting plate is thought to have generated the large tsunami that inundated Samoa in 2009 [*Lay et al*., 2009]. Oblique convergence at subducting margins is commonly manifest by significant slip partitioning within the forearc, accounting for large seismogenic strike-slip faults, e.g., Chile's LOFZ and the Sumatra Fault. Complex forearc structures and kinematics both onshore and offshore, for example in Central America [e.g., *LaFemina et al*., 2002], Cascadia [e.g., *Goldfinger et al*., 1997; *Pratt et al*., 1997], Sumatra [*Mosher et al*., 2008], and the Aleutians [e.g., *Ave Lallemant and Oldow*, 2000], complicate the interpretations of strain accumulation and release on the megathrust fault [e.g., *Collot et al*., 2004; *McCaffrey*, 1992], and may also host slip triggered by megathrust earthquakes [e.g., *Delouis et al*., 1998]. Many of these structures cross the shoreline, and due to their proximity to populated areas, raise significant concern regarding seismic and tsunami hazards. Studies of these faults are important for developing a complete understanding of the long-term strain accumulation in the subduction system

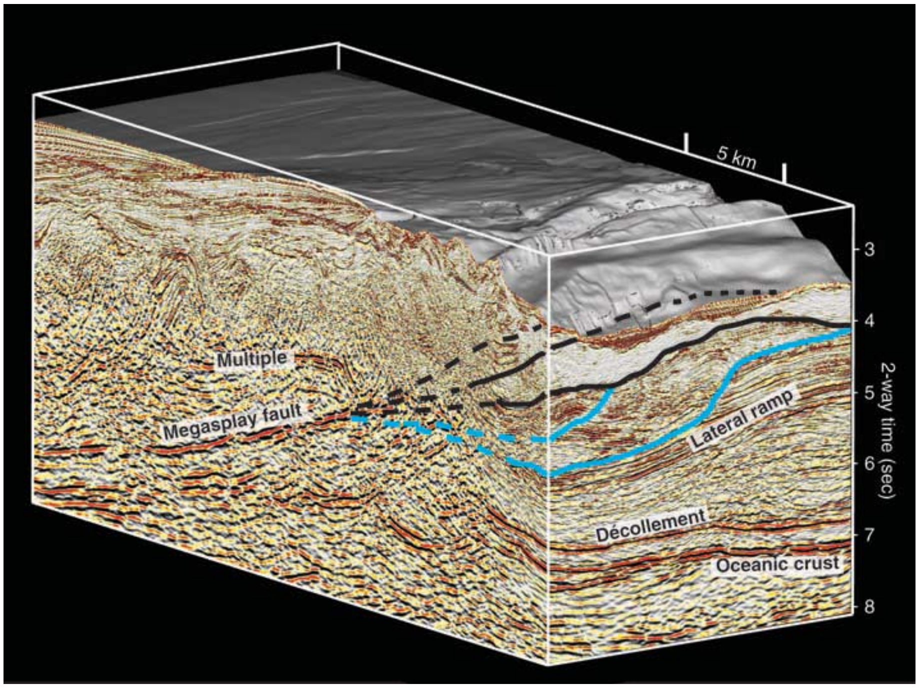


Figure 4.4. 3-D seismic data volume from the frontal accretionary prism along the Nankai margin, showing relations of in-sequence thrusts of the prism (blue lines) and younger out-of-sequence branches of the splay fault (black lines). The top of a thrust sheet that has been folded above a lateral ramp in the frontal prism is cut off by the younger megasplay fault. From Moore et al. [2007].

and seismogenesis on the megathrust. This can be accomplished through a combination of offshore seismic imaging and bathymetric surveys, onshore and offshore geodetic surveys, and geologic and paleoseismic studies.

4.3. 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?

Volatiles and melts play important roles in the dynamics of subduction systems from the shallowest levels of the plate interface to the greatest depths of arc melting source region (Figure 4.5). Numerous theoretical, experimental, and field campaigns over the last decade point to fundamental links between devolatilization, deformation, and fluid/melt transport. Several key questions have emerged from these studies: How does devolatilization affect the frictional properties and slip behavior of the shallow subduction interface where earthquakes occur, and does it modulate episodic tremor and slip? How do volatile release and serpentinization impact the rheology and the width of the slab-mantle wedge boundary? What are the relative importance of temperature, water content and melt content in controlling the viscosity of the mantle wedge? How does fluid move from the slab interface into the melting regime beneath arc volcanoes? A few selected examples of these exciting emerging questions are described below, followed by a description of evolving problems in linking slab volatile release to understanding geochemical fluxes in Section 4.4.

How does volatile release from the subducting sediments and igneous ocean crust affect the slip behavior of the subduction megathrust?

Fluids are known to affect the strength of faults in the brittle crust because they modulate the effective normal stress [e.g., *Hubbert and Rubey*, 1959]. However, only recently have fluids been recognized as potential controls on the nature of slip on faults. For example, at or near the down-dip edge of the seismogenic zone, where estimated temperatures are 350-450 C, numerical models suggest that the occurrence of slow slip events (SSE) and non-volcanic tremor (NVT) may arise owing to extremely low effective stresses, and thus elevated pore pressure [e.g., *Liu and Rice*, 2007]. The location of these processes may also coincide with slab dehydration reactions [*Wada et al*., 2008; *Wada and Wang*, 2009; *Rondenay et al*., 2008; *Abers et al*., 2009]. Near the trench, the low stress drops associated with very low frequency earthquakes (VLF) and SSE have also been attributed to elevated

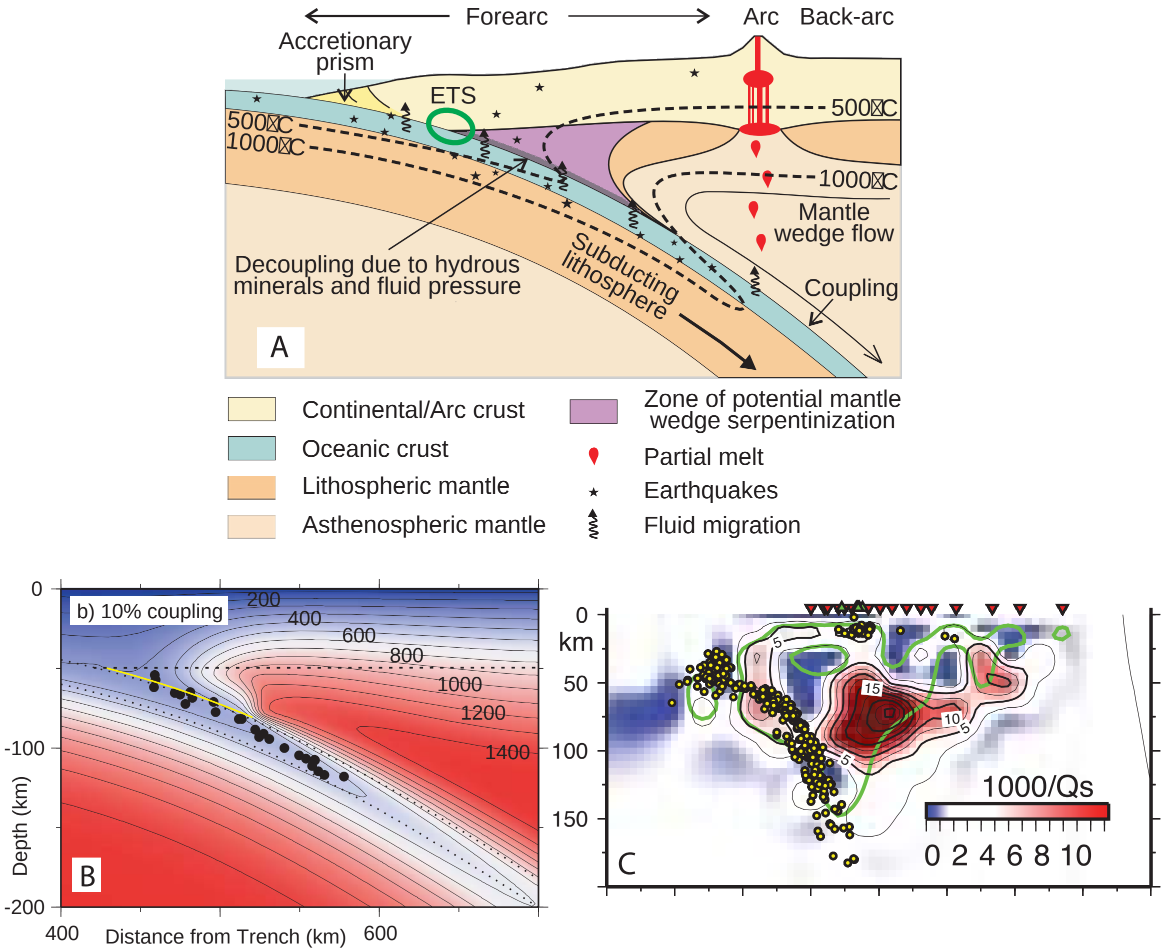


Figure 4.5. (A) Figure from Wada and Wang [2009] showing an example for a young slab subduction zone, and including the locations of slab dehydration relative to key mechanical and rheological transition along the subduction interface, including the seismogenic zone and its downdip edge where ETS has been observed, potential serpentinization of the mantle wedge , and kinematic coupling between the downgoing slab and mantle wedge. (B) Thermal modeling from Abers et al. [2006], showing the effects of coupling between the slab and mantle wedge on temperatures. (c) Shear wave attenuation result from Rychert et al. [2008] showing a "cold nose" consistent with hypothesized coupling of the slab and mantle wedge, and/or serpentinization.

pore pressure, possibly related to compaction or clay dehydration [*Ito and Obara*, 2006]. Despite these hypothesized connections, clear observations to constrain these slip behaviors and the corresponding in situ conditions are scarce. By combining new observations on the spectrum of seismic signals arising from the slab/wedge interface (described in Section 4.1) with constraints on the thermodynamics of metamorphic reactions in the slab and state-of-the-art numerical models of slab dynamics we are poised to made new advances in our understanding of the links between the thermal structure of the slab, mineral reactions and fault mechanics.

Sediments and the fluids they host can influence fault frictional behavior as diagenetic and metamorphic reactions alter sediment in the subduction zone, spurring compositional changes and/or fluid release. Fluid production can modify pore pressures that in turn affect fault strength and sliding behavior [*Moore and Saffer*, 2001; *Spinelli and Saffer*, 2004]. Mechanical behavior and diagenetic reactions are also related to subduction zone thermal structure [*Moore and Vrolijk*, 1992; *Spinelli and Wang*, 2008]. Some observations and theoretical reasoning suggest that the updip and downdip limits of the fast earthquake slip region correspond to about 150° C and 350-450° C (or where the slab encounters the upper plate Moho), respectively [e.g. *Hyndman and*

Wang, 1993; *Peacock*, 2003; *Spinelli and Wang*, 2008], but the specific processes, conditions, and fault compositions occurring at these temperatures, and the robustness of the link between locking and thermal structure remain unclear [e.g., *Moore and Saffer*, 2001; *Saffer and Marone*, 2003; *Spinelli and Wang*, 2008]. For example, at some subduction zones, e.g., Hikurangi, interseismic locking may occur at temperatures below 150° C [*McCaffrey et al*., 2007, 2008]. Along the Alaska subduction zone, at least one segment exhibits creep over the full depth range (no locked zone at all), and in other segments the locked zone abruptly narrows despite only minor changes in estimated temperature [*Fournier and Freymueller*, 2007; *Freymueller et al*., 2008]. Following the 2005 Sumatra earthquake, afterslip extended into the very shallow portion of the fault, possibly to the trench in portions of the rupture zone [*Hsu et al*., 2006]. Our understanding of the links between diagenesis and metamorphism, fluid release, and fault slip behavior that may produce this variability is highly incomplete. Observations at the Costa Rican margin suggest a tentative connection between slab metamorphism and the location of locked patches along the megathrust within the seismogenic zone where estimated temperature is ~250 C, but the processes controlling such behavior are poorly constrained [*Schwartz and DeShon*, 2007]. Additional geophysical datasets to be used in development of new thermal models are important for improving our estimates of temperature distribution on the plate boundary, which can then be used for comparison with seismic and geodetic datasets as well as with laboratory results.

What is the role of serpentinization in weakening the incoming plate and the plate interface?

Recent observations indicate that the incoming oceanic plate mantle at some subduction zones may be highly serpentinized, hypothesized to result from seawater circulation along inherited and reactivated normal faults generated at the spreading ridge [*Ranero et al*., 2003]. Although documentation of this phenomenon remains scarce, it provides a potential mechanism for transport of H_2O to subarc depths and possibly beyond. For example, geochemical signals of serpentine dehydration [*Savov et al*., 2007; *Barnes and Sharp*, 2006] may be observed in arc lavas [*Eiler et al*., 2005; *Straub and Layne*, 2003]. Although evidence for serpentinization of both the mantle wedge [e.g., *Bostock et al*., 2002] and the incoming oceanic plate upper mantle [e.g., *Ranero et al*., 2003] has been documented, the extent of alteration and its effects on the mechanics of the subduction system are poorly constrained. For example, does serpentinization of the incoming plate mantle significantly change its mechanical strength [e.g., *Faccenda et al.,* 2009] and its subsequent dehydration control the location of some intermediate depth seismicity? Likewise, serpentinization of the mantle wedge above the subducting slab has been hypothesized to partially control the downdip limit of interplate seismicity [*Hyndman et al*. 1997]. By combining constraints from seismic imaging, seismicity studies, and modeling informed by new experimental results, our community can make significant advances in understanding the links between serpentinization and subduction dynamics.

How does dehydration of the slab influence mantle wedge dynamics?

The strength or viscosity of the slab-wedge interface controls coupling of displacement between the mantle wedge and the downgoing slab. Integrative studies demonstrate that the degree of coupling is a key factor for controlling the thermal structure of the slab at depth and the mantle wedge beneath the arc. To match observed heat flow and to explain a range of other geophysical and geochemical observations, the interface must be mechanically decoupled to depths significantly beyond the down-dip limit of seismicity [e.g., *Wada et al*., 2008; *Wada and Wang*, 2009]; fluids released through deydration reactions may play a role in this phenomenon. However, the deformation processes and thermodynamic conditions that control the location of the “decoupled-coupled” transition are not understood. Another key aspect of subduction dynamics is the apparent requirement for a low viscosity mantle wedge [e.g., *Billen and Gurnis*, 2001]. Thus, the introduction of fluids into the wedge likely plays a key role, owing

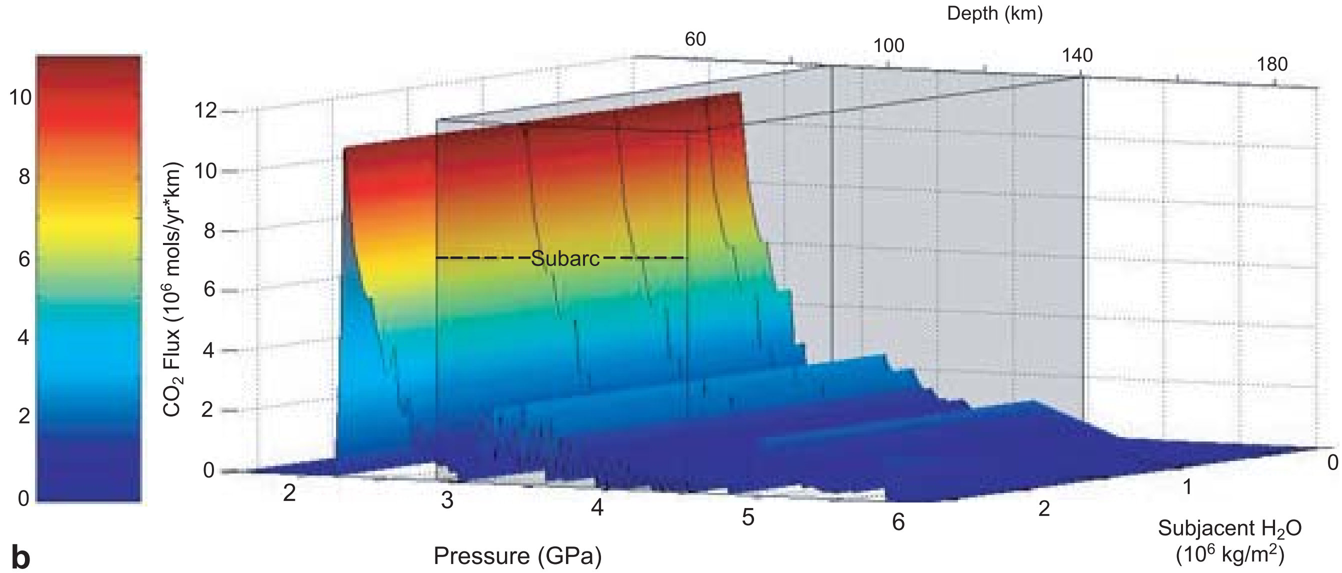


Figure 4.6. Modeled CO_2 and H_2O fluxes from the top of the subducting slab for Central America, assuming pervasive fluid flow [Gorman et al., 2006]. Note that the predicted CO_2 flux from the fore-arc region is significantly higher than the flux from the sub-arc region.

to the strong effect of water on the viscosity of the mantle. However, key questions remain regarding the path that fluids take from dehydration to melting [e.g., *Cagnioncle et al*., 2007]. How distributed is the fluid flow? Do fluids migrate along fractures? Are fluids advected via buoyant diapirs along the slab interface [e.g., *Gerya and Yuan*, 2003]? How is the change in water content during melting reflected in melt composition and recorded in melt inclusions? Multidisciplinary investigations of these problems will be significantly improved by new advancements in our understanding of the role of water on the seismic properties of the mantle [e.g., *Karato*, 2003; *Karato et al*., 2008] and geochemical constraints on the conditions of dehydration of the slab and hydrous melting in the wedge.

What physical processes are associated with intermediate and deep earthquakes?

Fault slip that occurs under high pressures corresponding to depths greater than ~70 km (i.e., where normal stresses should prohibit fault movement) have puzzled seismologists for decades. Based on constraints from deformation experiments, metamorphic phase equilibrium and thermal models of subduction zones, intermediate depth earthquakes (70-300 km depth) are related to dehydration reactions in the subducting slab [e.g., *Kirby et al*., 1996; *Hacker et al*., 2003; *Abers et al*., 2006]. However, the mechanical process of dehydration embrittlement and the widespread applicability of this model is still uncertain due to uncertainties in the feedbacks between reaction rate, permeability and the evolution of pore-fluid pressure [e.g., *Wong et al*., 1997; *Rutter et al*., 2009]. Alternatively, these earthquakes may arise owing to the viscous instabilities that nucleate within locally weak layers resulting from variations in temperature or grain size (which may actually be produced by dehydration reactions) [*Kelemen and Hirth*, 2007; *John et al*., 2009]. Resolution between these possibilities awaits new observational and theoretical constraints on the thermal and hydration state of the slab, the kinetics of dehydration reactions [e.g., *Rutter et al*., 2009; *Perrillat et al*., 2005] and their roles on the mechanics of faulting.

4.4. How are volatiles, fluids, and melts stored, transferred, and released through the subduction system?

The efficiency of mass cycling through subduction zones is controlled by the composition of the subducting lithologies and the processes by which volatiles are released from the subducting slab and transferred to the surface. Significant progress has been made over the last decade in quantifying sediment and crustal inputs at various subduction zones [e.g., *Plank and Langmuir*, 1998; *Kelley et al*., 2003; *Sadofsky and Bebout*, 2004; *Plank et al*., 2007], the extent of devolatilization during subduction [e.g., *Hacker*, 2008; *Shaw et al*., 2008], the geochemical, petrologic, and dynamic relationships between slab volatile fluxes and generation of magmas in the mantle wedge [e.g., *Grove et al*. 2006; *Kelley et al*. 2006, *Cagnioncle et al*. 2008], and the volcanic outputs of arcs [e.g., *Hilton et al*., 2002; *Fischer et al*., 2002; *Shaw et al*., 2003; *Gorman et al*., 2006] (Figure 4.6). These advances have raised a number of fundamental new questions about subduction volatile fluxes and cycling.

What is the role of serpentine in subduction and release of H_2O?

Recent work has suggested that serpentine may be a major carrier of volatiles and other trace elements into the subduction system [e.g., *Ranero et al*., 2003]. Serpentine can hold up to ~14 wt% H_2O [*O'Hanley*, 1996] - a factor of ~3 more than crustal and sedimentary lithologies [*Hacker*, 2008]. This has led to the recognition that serpentine dehydration may play a major role in mass transfer and arc magmatism. Serpentinization reactions also lead to carbonation of the downgoing plate and thus have the potential to influence the carbon budget of subduction zones. However, the extent of serpentinization of the incoming plate is largely unquantified. Likewise, the concentration of several major volatile components (e.g., C, S, F, Cl) in subducting mantle remain poorly characterized. Quantifying these inputs through geochemical analyses of drill cores on the incoming plate or studies of ancient lithospheric sections, or by seismological or other geophysical imaging, such as MT, is essential toward assessing volatile budgets through the subduction system.

Some of the subducted serpentine contributes to the flux of volatiles that returns to the surface through island arcs, but some may convert to high pressure hydrous phases, delivering H_2O to the deeper mantle [*Ohtani et al*. 2002; *Rupke et al*. 2004]. The fate of H_2O subducted in serpentine is therefore critical to the operation of the deep Earth H_2O cycle. Along with considerations of the proportion of subducted serpentine and its depth in the subducting plate, key considerations in evaluating the fate of subducted serpentine include improved understanding of temperature-depth trajectories of subducting slabs, experimental studies of phase equilibria and kinetics associated with dehydration reactions in subducting peridotite, seismic and other geophysical detection of the extent of hydration in subducting plates, and geochemical studies of tracers of serpentine in arc magmas, such as B and other light elements.

What is the relationship between dehydration reactions and the release of fluids and/or melts from the slab?

A range of techniques has been exploited to quantify the output flux of volatiles from subduction systems. These include remote sensing techniques to quantify present-day gas fluxes from some arc volcanoes (those with sufficiently large gas plumes), geochemical gas studies that have provided new insights into the sources of volatiles [e.g., *Snyder et al*., 2001; *Hilton et al*., 2002; *Fischer et al*., 2002; *Shaw et al*., 2003; *Hilton et al*., 2007], and new micro-analytical tools such as SIMS that allow the direct analysis of melt inclusions to constrain volatile compositions in relatively primitive melts [e.g., *Benjamin et al*., 2007; *Shaw et al*., 2008; *Sadofsky et al*., 2008] and clinopyroxene to infer volatile contents indirectly [*Wade et al*., 2008]. Comparison of water contents in olivine-hosted melt inclusions from Central America to slab fluid proxies such as Ba/La and B/La shows relatively good agreement and thus yields insight into fluid release processes [*Sadofsky et al*., 2008] (Figure 4.7). Likewise, through studies of the isotopic composition of subduction-related water trapped in melt inclusions, we have learned further details of slab dehydration and how water is exchanged between the mantle and its exospheric reservoirs over time [*Shaw et al*., 2008] (Figure 4.8). Significant progress has been made in understanding the role that water plays in generating arc and back arc melts and linking these melts to geophysical observables [e.g., *Wade et al.*, 2006; *Wiens et al.*, 2006; *Benjamin et al.*, 2007; *Shaw et al.*, 2008; *Sadofsky et al.*, 2008]. However, calculating volatile fluxes has been hindered by our inability to reliably estimate magma production rates at individual arcs. New research opportunities include: (1) integrating melt inclusion studies with better estimates of arc magma production rates, (2) estimating volatile fluxes in forearc and back arc regions, (3) determining fluxes of volatile species that have not been previously quantified (e.g., S, F, Cl, etc.) in a range of subducting settings, and (4) linking volcanic fluxes to climate models.

What are the melting reactions and loci and melt pathways from the mantle wedge to the surface?

The processes and pathways by which volatiles are released from the downgoing slab, and the extent to which they contribute to melting, are important new avenues for future study. Evidence for high temperatures at the slab-wedge interface from both geodynamic simulations [*van Keken*, 2003; *Kelemen et al.*, 2003; *Syracuse et al.*, 2010] and novel slab-top thermometers applied to arc lavas [*Plank et al.*, 2009] suggest that slab-derived fluxes are melts or silicate-rich fluids. Yet, melting reactions for slab-top lithologies and the compositions and properties of the fluids produced are incompletely known. New measurements of Fe^{3+}/Fe^{2+} ratios

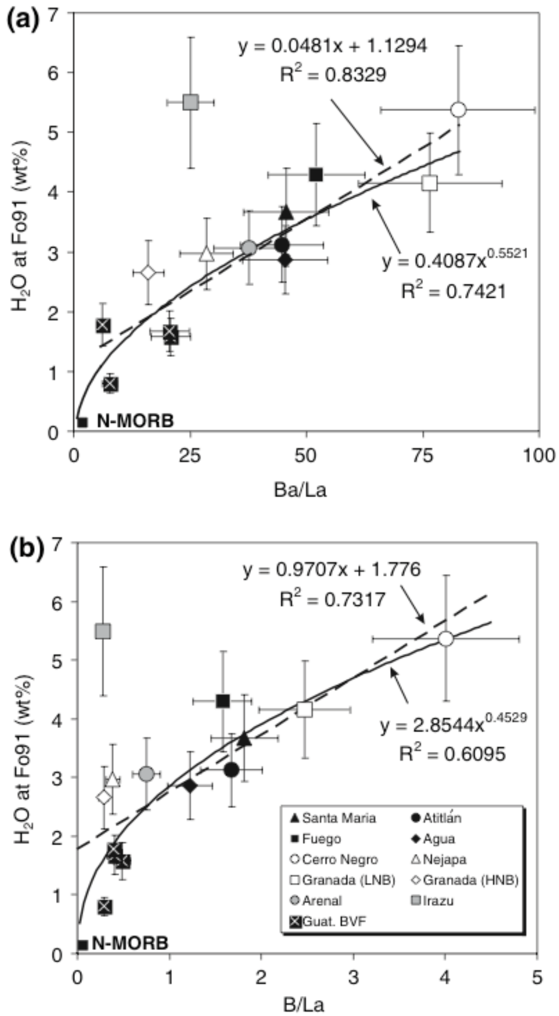


Figure 4.7: Correlations of water with (A) Ba/La and (B) B/La ratios in the mean parental melts of the Central American volcanoes [Sadofsky et al. 2008]

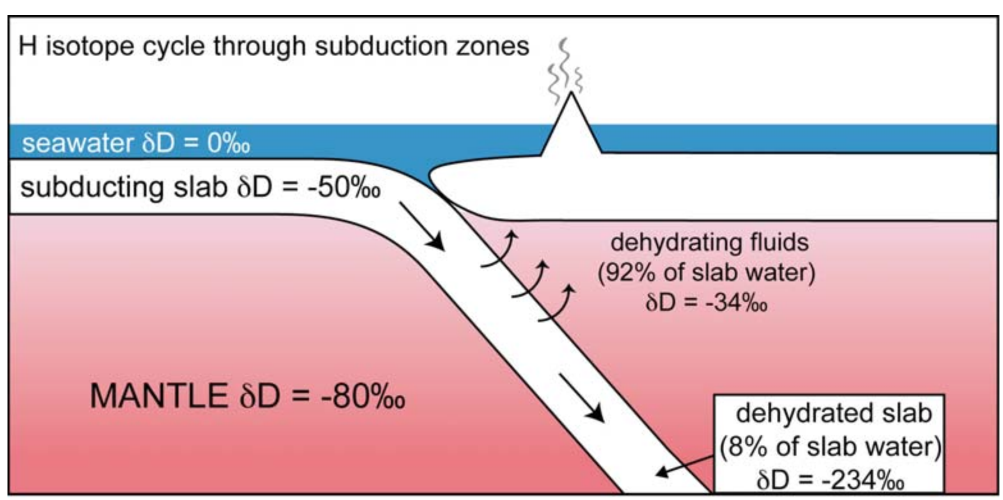


Figure 4.8. A schematic diagram showing a model for how H isotopes in Earth's reservoirs are cycled through subduction zone systems. The effect of the dehydration process on H isotopes is illustrated assuming 92% dehydration of the slab and a case where the fluids released have an average δD of -34 ‰. An important consequence of this process is that the down-going slab would have extremely low δD values and thus it is predicted that the recycled slab component found in ocean island basalts would also have low δD values [Shaw et al., 2008].

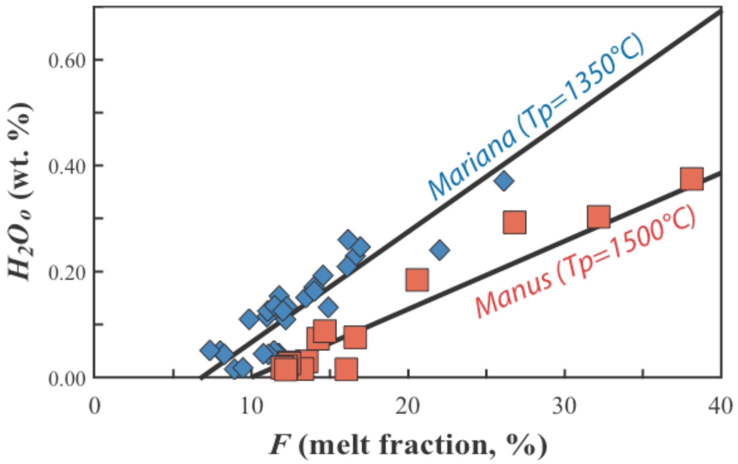


Figure 4.9. Melt fraction vs. H_2O content of the mantle source beneath the Mariana and Manus back-arc basins, modeled from erupted melt compositions [from Kelley et al., 2006]. The slope of each trend, which is an indicator of the productivity of hydrous melting, coincides with a contrast in mantle potential temperature, suggesting that the differing P-T conditions of melting beneath each basin relates to melt productivity.

in arc magmas indicate that upward migration of slab-derived fluids promotes relatively oxidizing conditions in the mantle wedge [*Kelley and Cottrell*, 2009], although alternative tracers of mantle wedge oxidation state, such as V/Sc ratios of arc magmas [*Lee et al*. 2005] yield conflicting conclusions. The effect of subduction fluids on wedge oxidation state therefore requires further investigation. New experiments are needed to constrain the petrologic and geochemical character of fluids and melts in equilibrium with appropriate lithologies over a range of oxidation conditions. Coupled with sophisticated models incorporating reaction kinetics, multiphase flow, and re-hydration of the overlying mantle, such work will fully characterize mass transport from the slab to the overlying mantle wedge.

Studies of arc and back arc lavas show that the proportion of melting of the wedge is a complex function of slab-derived H_2O, temperature, and pressure of melting, but that individual arcs have distinct, nearly-linear relationships between extents of melting and proportions of water in the wedge sources. These relationships have have been interpreted either as fluid addition to a nearly isothermal mantle or as mixing between two distinct melting regimes within the wedge [e.g., *Stolper and Newman*, 1994; *Gribble et al*. 1998; *Kelley et al*., 2006; *Langmuir et al*., 2006] (Figure 4.9). Increasingly realistic 2-D dynamic models of melt generation in the mantle wedge now incorporate inputs from the slab, as well as solid and melt transport [*Cagnioncle et al.* 2007] (Figure 4.10). However, the locus of melting in the mantle wedge remains highly uncertain and the models do not yet reproduce the linear H_2O-melt fraction trends or resolve their origin. New experiments [*Grove et al*., 2006] locate the H_2O-saturated peridotite solidus near 840° C, expanding considerably the area of the mantle wedge where partial melting is permissible, and suggesting that melting could initiate through breakdown of hydrous minerals such as chlorite. Melting reactions and mechanisms thus remain incompletely understood, opening new avenues

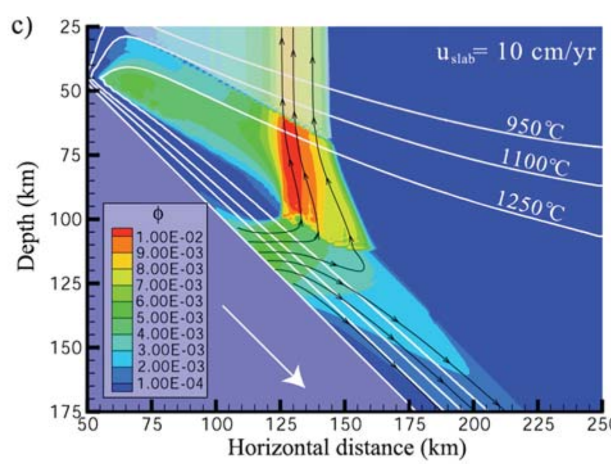


Figure 4.10. Geodynamic model of melting in the mantle wedge from Cagnioncle et al. [2007], demonstrating the interaction between fluid release from the slab, the temperatures and flow in the mantle wedge, and the production and segregation of partial melt.

of experimental study. New, high-resolution and 3-D models of flow and melting in the wedge must also incorporate this expanded locus, the potential new mechanism of hydrous peridotite melting, and anticipated sensitivity of melting processes to mantle P-T conditions. As most of the observational constraints derive from back-arc environments [e.g., *Stolper and Newman*, 1994; *Gribble et al*. 1998; *Kelley et al*., 2006], more comprehensive studies of melting beneath arcs, principally through examination of melt inclusions, are needed to better establish the relationship between fluid addition and the extent of melting.

Melt in the mantle beneath volcanic centers can be imaged seismically using Vp/Vs tomography [*Syracuse et al*. 2008] and it is clear that partially molten zones beneath volcanic centers extend through the mantle to the slab/wedge interface (Figure 4.11). Coupling of geophysical detection with petrologic documentation of the depths of formation and segregation of mantle-derived arc magmas from phase equilibria experiments [e.g., *Grove et al*. 2002] or using new petrologic geobarometers [*Lee et al*. 2009] will provide new constraints on the depths of origin of arc magmas.

Once magma ascends into the lithosphere, crystallization and differentiation creates feedbacks between thermal and rheological evolution, leading to variable amounts of sequestration in the crust and influencing the dynamics of melt transport, storage, and eruption. Seismic, geodetic, and potential field studies of arc volcanoes, including monitoring volcanic tremor and low frequency seismicity [e.g., *Konstantinou and Schlindwein*, 2003] and satellite-based observations of volcano inflation [e.g., *Pritchard and Simons*, 2002; *Hooper et al*., 2004], provide new opportunities to document location and movement of magma from the base of the lithosphere to sub-volcanic conduits. Integrating these with studies of erupted volcanic rocks, crystals, and melt inclusions to determine storage depths, volatile contents, and residence times of volcanic products may provide exciting opportunities for new cross-disciplinary understanding of the transport and storage of magma in the crust and shallow mantle. Dynamic models combined with petrologic and experimental investigations are also needed to better understand the parameters that determine the plutonic versus volcanic fates of arc magmas.

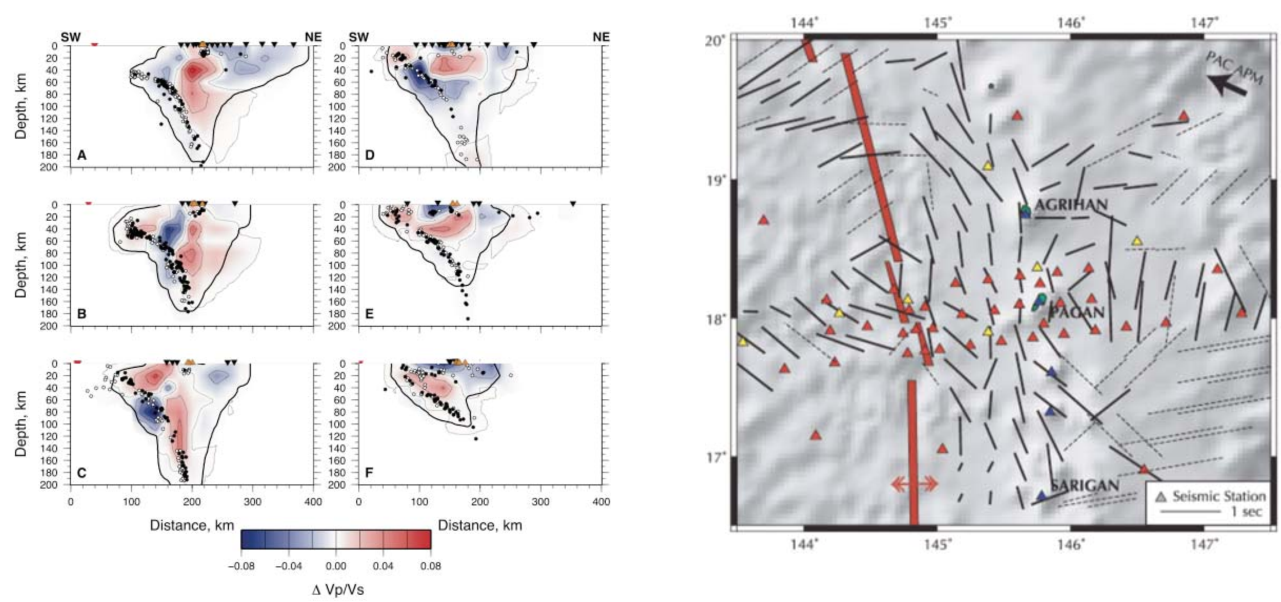


Figure 4.11. Seismic images of the mantle wedge in subduction zones, from MARGINS studies. (left) Vp/Vs tomography beneath Central America, imaging regions of melt beneath volcanic centers all the way down to the slab/wedge interface [Syracuse et al. 2008]. (right) Spatially averaged shear-wave splitting indicating anisotropy beneath the Central Mariana arc [Pozgay et al., 2007].

What are the fluxes of volatiles delivered to the mantle from the subducting slab and how are fluids and melts focused to the volcanic front?

Improved (although by no means complete) understanding of fluid release from the subducting slab to the overlying wedge [*Hacker*, 2008] demonstrates that fluxing components are added to the wedge over a range of depths and that these are not necessarily located directly below the volcanic front. Concentration of melt beneath volcanoes therefore requires significant melt focusing. Although it is clear that such focusing responds largely to the spatial distribution of fluid sources and the pressure and permeability fields, there is at present no robust predictive model that can be compared to observed volcanic outputs. Furthermore, understanding the pathways of melt ascent in the mantle wedge –in particular the 3-D and 4-D aspects – remains a challenging problem in mesoscale physics, as it requires dynamical models of interactions between solid and fluid flow in the wedge, as well as experimental and theoretical models of the influence of deformation on wedge permeability [e.g., *Holtzman et al*., 2003].

How do surface processes and climate modulate volatile inputs and outputs at subducting margins, and vice versa?

The surfaces of island and continental arcs are dynamic regions in which significant, but poorly quantified, mass transfer occurs. Arcs represent the largest fraction of juvenile volcanic exposures on Earth and, in particular, the largest proportion of such terranes in tropical and sub-tropical regions. Weathering of these terranes is of substantial importance to terrestrial weathering processes [*Allegre et al*., 2010], including those leading to fixing of atmospheric CO_2. The storage of CO_2 in weathered arc terranes ,as well as its transport to the ocean via riverine fluxes, is as yet poorly quantified, as is the influence of climate on these processes.

Other surface processes including erosion and glaciation/deglaciation on central volcanoes may also have significant influence on volcanic outputs owing, to decompression/compression of underlying mantle and/or of magma chambers, and these in turn may influence arc volatile fluxes and therefore climate. For example, Huybers and Langmuir [2009] showed a temporal correlation between arc volcanic eruptions and the end of the last glacial cycle and argued that enhanced volcanic output from deglaciation of arc stratovolcanoes was a significant source of atmospheric CO_2, an important feedback to the climatic shifts at glacial/interglacial transitions. Further quantification of the flux of CO_2 from arc volcanoes, improved chronometry of volcanic eruptions, and modeling of the feedbacks between deglaciation, eruption dynamics, and climatic effects are needed to explore this intriguing hypothesis.

On a longer time scale, delivery of volatile-rich sediments to oceanic trenches followed by subduction may be an important contributor to the flux of subducting volatiles. Consequently, the formation, transport, storage, and ultimately the delivery of sediments from the upper reaches of volcanic terranes to forearcs to trenches have direct influence on the subducting volatile fluxes. Quantifying the volumes and rates of material transfer, and mapping them through space and time in different settings, will clarify the magnitudes of such fluxes for mass balance calculations. This will require not only better inventories of subducted and volcanic volatile fluxes, but also improved accounting for subduction devolatilization in forearcs and its relationship to volatiles vented to the oceans and surface via submarine and terrestrial hydrologic systems [e.g., *Füri et al*. 2010]

4.5. What are the geochemical products of subduction zones, from mantle geochemical reservoirs to the architecture of arc lithosphere, and how do these influence the formation of new continental crust?

A principal focus of the MARGINS program was the functioning of the Subduction Factory, which aimed to examine how materials processed in subduction zones contributed to the ongoing large-scale geochemical differentiation of the Earth, including fluxes to the deeper mantle and formation of the continental crust. Improved understanding of the workings of the Subduction Factory was one of the principal achievements of the MARGINS program, but significant questions remain.

What are the geochemical characteristics of the materials that subduction returns to the Earth's mantle, and how are these related to the development of long-term mantle heterogeneity?

Subduction zones create a range of petrological products in the mantle, including multiple residual lithologies (metasediments, metabasalt, metaperidotite) in the subducted plate, depleted and metasomatized peridotite in the mantle wedge, and potentially, an ultramafic lower arc crust that may descend into the Earth's mantle but be geochemically distinct from it. The contributions of these lithologies to mantle geochemical evolution remains unclear. Following long residence times in the mantle, some of these lithologies may evolve into mantle isotopic heterogeneities that are detected at modern ocean island volcanoes [e.g., *Hoffman and White*, 1982]. Although coarse linkages can be drawn between isotopic signatures and hypothesized residues of subduction [e.g., *Jackson et al*., 2007; *Workman et al*., 2008; *Weaver*, 1991] (Figure 4.12), the elemental fractionations required to generate the oceanic island sources are potentially attributable to subduction processes, but are largely unconstrained and untested against actual geochemical characterizations of subduction zone mass transfer processes. Recent models show that subduction processes may be sufficient to explain certain mantle end-members [e.g., *HIMU*; *Kelley et al*., 2005], but significant uncertainties remain. Advancement of our understanding of the role of subduction in creating long-term mantle heterogeneity requires improved element budgets of altered gabbro and lithospheric mantle in the subducting plate, accurate constraints on arc crustal growth rates, high-precision geochemical analyses of arc volcanic and plutonic rocks, and petrological/geochemical studies of exhumed sections of subducted slabs, mantle wedges, and lower arc crust. These data will provide essential constraints on the magnitudes of elemental fluxes through subduction zones, and the critical geochemical fractionations that take place during subduction, in order to construct accurate mass balances that allow the long-term imprint of subducted residues to be quantitatively assessed.

What are the rates and processes of arc crust growth and differentiation and how is arc crust transformed to continental crust?

The formation and differentiation of arc crust is one of the central geochemical fluxes on Earth, but

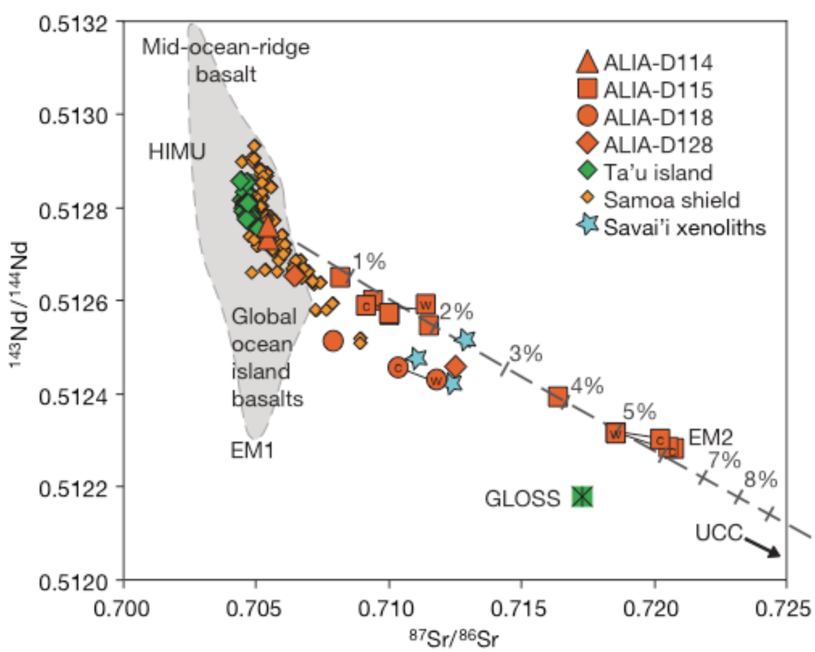


Figure 4.12. Isotopic composition of extremely enriched Samoan lavas [Jackson et al., 2007]. These extreme isotopic ratios point towards the involvement of bulk subducted sediment (GLOSS) or upper continental crust (UCC) in the Samoan mantle source.

the rates at which arc crust forms and at which it matures towards continental crust remain poorly known. Studies of the growth of volcanic edifices may be insufficient to characterize the rates of arc growth, as significant outputs take the form of tephra deposited far from volcanic sources [*Kutterolf et al*. 2008] (Figure 4.13) or large portions of arc magmas that do not erupt, but cool and crystallize as plutons. As arc crust differentiates and matures, some fraction is thought to transform to juvenile continental crust, although the rates and processes of this transformation in modern arcs are poorly understood.

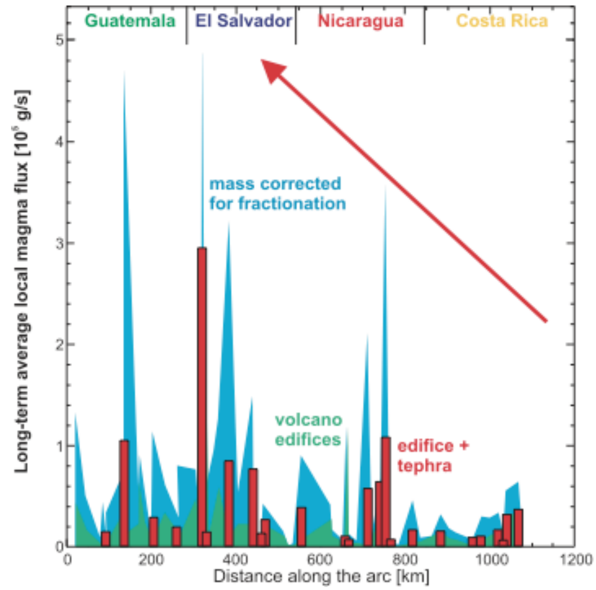


Figure 4.13. Average magmatic flux over the last 200 kyr at Central American volcanic centers as reconstructed from combining geologic mapping of exposed volcanic edifices with the offshore tephra record, with corrections for the proportion of cumulates required to account for the compositional differentiation evident in the volcanic compositions [Kutterolf et al. 2008].

Exhumed sections of arc crust show that significant fractions of arc magmas crystallize as plutons rather than erupting as volcanic products [*Bard et al*., 1980; *DeBari and Coleman*, 1989]. Some portions of arc plutonic rocks represent cumulates from differentiated magmas that ultimately erupt, and with estimates of the extent of differentiation, cumulate masses may potentially be computed from compositions and volumes of volcanic rocks [e.g., *Kutterolf et al*. 2008] (Figure 4.13) or from comparisons between growth rates of volcanic edifices and tracers of subduction fluxes such as SO_2 [*Sadofsky et al*. 2008]. Not all arc plutons are dominated by cumulates, however, and the magmas that solidify within arc crust may be a substantial fraction of juvenile arc crust. Estimates of the growth rates of plutonic arc crust, therefore ,must be approached either from field-based observations of sections of exhumed arc crust, including geochemical characterization and geochronometry, or from a combination of geophysical, geochemical, and geochronologic studies of active arcs. The former depends in part on developments in high precision geochronometry, chiefly from accessory minerals such as zircon. The latter may include seismic documentation of the volumes of arc crust of known age, or more focused geophysical and geochemical efforts to characterize the deep magmatic roots of modern volcanic systems as described in Section 4.4. A critical parameter to be sought is the ratio of erupted versus plutonic crustal material and constraints on how this ratio varies in different arc settings, which requires an understanding of how the dynamic and petrologic evolution of magma in the crust promotes or inhibits magma eruption versus in situ crystallization.

Along with growth of arc crust, a complementary set of problems pertains to the rates and processes of differentiation of arc crust and creation of juvenile continental crust. The continental crust shares many geochemical signatures with arc lavas, and the two have long been thought to be genetically linked. Yet the continents are andesitic in composition (~60 wt.% SiO_2)[*Rudnick and Fountain*, 1995; *Taylor and McLennan*, 1985; *Weaver and Tarney*, 1984] whereas the primary mantle-derived magmas at most mature subduction zones are basalts (~50 wt.% SiO_2). Intracrustal differentiation takes place over a range of spatial and temporal scales, from the local evolution of individual magmatic centers to large-scale development of distinct compositions of upper, middle, and lower continental crust. Intracrustal differentiation processes in arcs can create silicic or intermediate mid-crust, such as that documented in the Izu-Bonin arc [*Suyehiro et al*., 1996; *Koidara et al*. 2007] (Figure 4.14) and those evident from exposed crustal sections [*Bard et al*., 1980; *DeBari and Coleman*, 1989]. Intracrustal differentiation, however, cannot be solely responsible for formation of juvenile continental crust, and intermediate compositions are not seismically indicated at all modern arcs (e.g., the Aleutians [*Shillington et al*., 2004]). Many recent hypotheses attempt to explain continental compositions by invoking, for example, unique primary melts [e.g., *Kelemen et al*., 2003], co-evolving geophysical properties and petrological architecture of arc crust [e.g., *Tatsumi et al*., 2008], removal of ultramafic lower crust [e.g., *Rudnick and Fountain*, 1995], or geochemical evolution associated with surface processes such as weathering (as discussed below) to create continental crust from the magmatic products of subduction zones. Although there are models that can account for the return of cumulates to the mantle [e.g., *Jull and Kelemen* 2001], better petrologic and geophysical tools are required to document their formation and their impact on magmatic and crustal differentiation and on the structure of the Moho beneath arcs. Understanding creation of continental crust in arcs also requires careful trace element and isotopic discrimination between true juvenile components and those recycled from subducted sediments [*Plank*, 2005]. Moreover, although recent models offer a broad spectrum of hypotheses to explain the physical and petrological processes that may produce continental crust in arc settings, these remain largely untested against petrological, geochemical, and geochronological data of direct samples of exhumed or in situ arc crust, experimental/natural constraints on the petrological evolution of volatile-rich arc magmas in general or at individual volcanoes, or high-resolution investigations of the geophysical properties of mature arc crust.

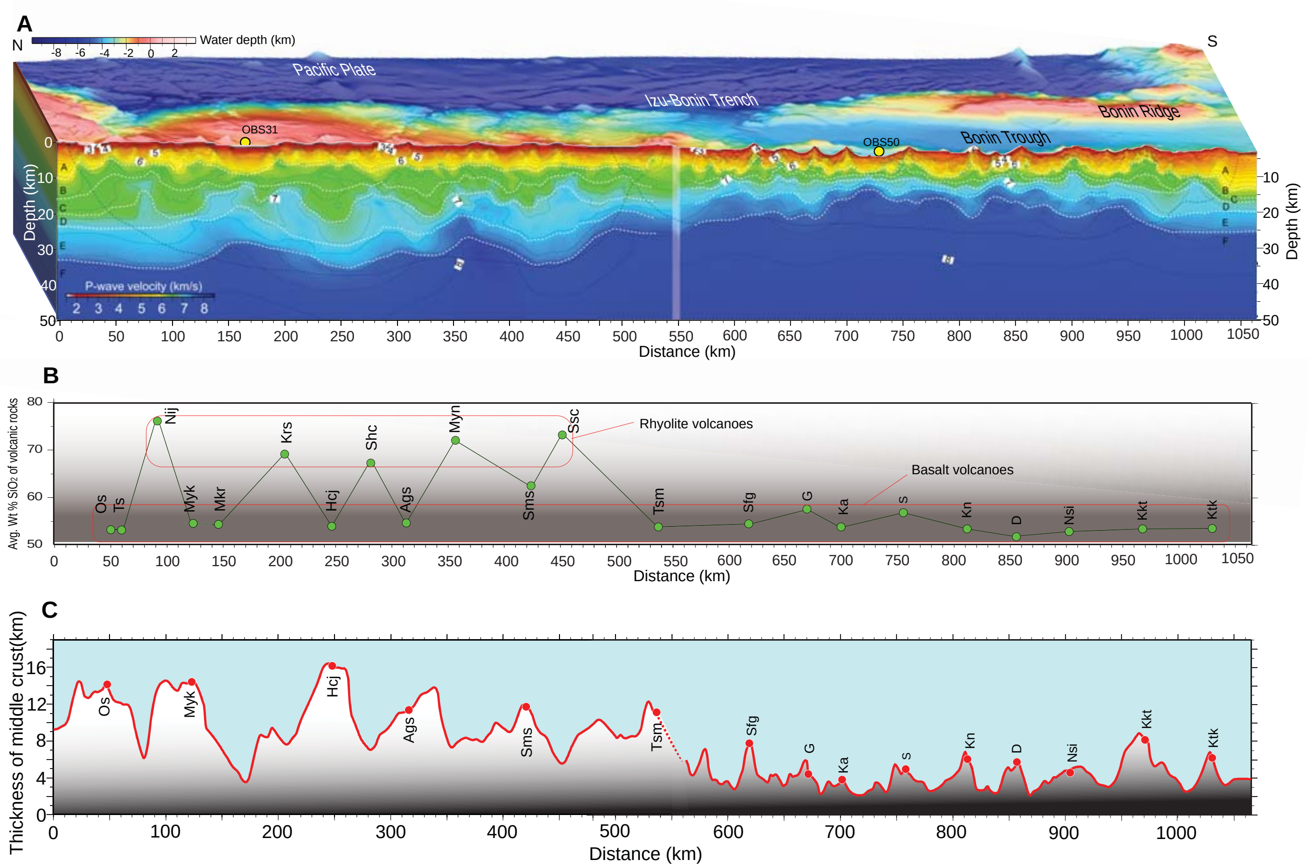


Figure 4.14. (A) Along-strike seismic velocity structure of arc crust in the Izu-Bonin arc [Kodaira et al., 2007], showing finely-resolved variations in crustal thickness. (B) The composition of lavas erupted at Izu-Bonin frontal arc volcanoes correlates with (C) the thickness of the low-velocity (Vp=6.0-6.5) middle crust beneath each volcanic center.

What role do weathering and erosion play in the compositional and dynamic evolution of volcanoes and volcanic arcs?

Recent comparisons of subducting sediment compositions and associated arc lava compositions suggest that many arcs may simply inherit the signatures of subducted sediments without any internal fractionations [e.g., *Plank*, 2005], raising the question of what other processes may be necessary to manufacture continental rocks. The formation of accessory minerals during magmatic differentiation may play an important role in modifying trace element signatures as magmas evolve chemically [e.g., *Wade et al*., 2005]. Weathering and erosion of arc or continental crust creates important physical and chemical fractionations that modify the composition of the source rocks and deposit seafloor sediments that are either consumed by subduction or accreted onto the overriding plate [e.g., *von Huene and Scholl*, 1991; *Beaumont et al*., 1999]. New studies of the chemical impacts of weathering of arc rocks and the mechanics of sediment transport, deposition, and accretion will improve the interconnections between surficial and solid Earth processes at subduction zones.

4.6. What are the physical and chemical conditions that control subduction zone initiation and the development of mature arc systems?

Subduction initiation is a major event in plate tectonics and the initial stages of subduction zone development are different from established, mature subduction zones. Initiation of new subduction zones may be associated with major rearrangement of the forces that drive and resist plate tectonics, and unique magmas are produced, which are limited in time to the earliest stages of subduction. As subduction zones mature through time, they may also evolve structurally and manufacture continental crust. Throughout the last decade, many geophysical, geochemical, petrological, and dynamical studies have aimed to address key aspects of the initial stages and temporal evolution of subduction systems, generating pivotal new questions:

How does the initial tectonic state control the initiation and subsequent evolution of subduction, and how do plate kinematics, deformation, and petrology change before, during, and after initiation of subduction?

The cold thermal structure and the formation of dense eclogite in the descending lithosphere may be primary drivers of plate motions, but these are counter-balanced by the strength of the bending oceanic plate, which could be the locus of the primary resisting force to plate tectonics [*Buffett and Rowley*, 2006]. The driving force behind the earliest inception stages of new subduction zones, whether by far-field forces or in situ with local forces (Figure 4.15), is unknown [*Gurnis et al*., 2004; Stern, 2004]. Indeed, whether the Eocene change in Pacific plate motion either caused or was caused by initiation of IBM and Tonga-Kermadec subduction zones is one of the most outstanding unsolved problems in plate tectonics. The question of how and why subduction initiates and then evolves into an arc involves substantial geophysical and petrological unknowns. These questions can only be answered through comparative studies between subduction zones at different phases of development (precursory to nascent through to fully developed). Such integrated studies will involve the interpretation of the petrological, structural, and stratigraphic history in terms of experimental and computational constraints on mineral equilibria and metamorphic phase transitions, plate motions, and dynamic modeling. Numerical models will play a key role in linking far-field plate dynamics and the initial tectonic state of a margin to the expected structural, stratigraphic, and petrological signatures in time and space. Already, dynamic models predict different vertical motion and volcanic histories for the far-field and in-situ nucleation hypotheses (Figure 4.15).

How do the early products of island arc magmatism relate to the dynamics and conditions of subduction initiation?

The fore-arc basalts (FABs) and boninites that characterize the earliest lavas erupted at subduction zones are also fundamentally different from the arc tholeiites, calc-alkaline basalts, and more silicic lavas that typify volcanism at most modern subduction zones. The first magmatic products of subduction are likely to be FABs (Figure 4.16; [*Reagan et al*., 2010]), which are chemically similar to mid-ocean ridge basalts and require decompression-driven melting of the mantle during the early stages of subduction. Following the FABs, boninites are hydrous melts of highly depleted mantle, which require a H_2O flux from the subducted plate. These early magmas are the products of unique mantle melting processes that occur predominantly during subduction zone infancy [e.g., *Crawford et al*., 1989; *Stern and Bloomer*, 1992; *Reagan et al*., 2010], yet the relationship of these distinctive magmas to the physical state of the mantle and slab as subduction begins is unknown. Stratigraphic sequences of early arc lavas preserve the age progression of these key magmatic transitions, thus petrological, geochemical, and geochronological studies of early arc lavas will provide important data for constraining the magmatic evolution during the early stages of subduction. Such data will also place important constraints on the presence and timing of physical processes active in the mantle wedge through the early stages of subduction (e.g., decompression-driven melting and the timing of the appearance of slab-derived fluxes in the mantle wedge). The relationships between the initiation of subduction, the onset of magmatism, and the very early co-evolution of subduction zone structure and magma composition are also central to constraining the origins and early architecture of arc crust.

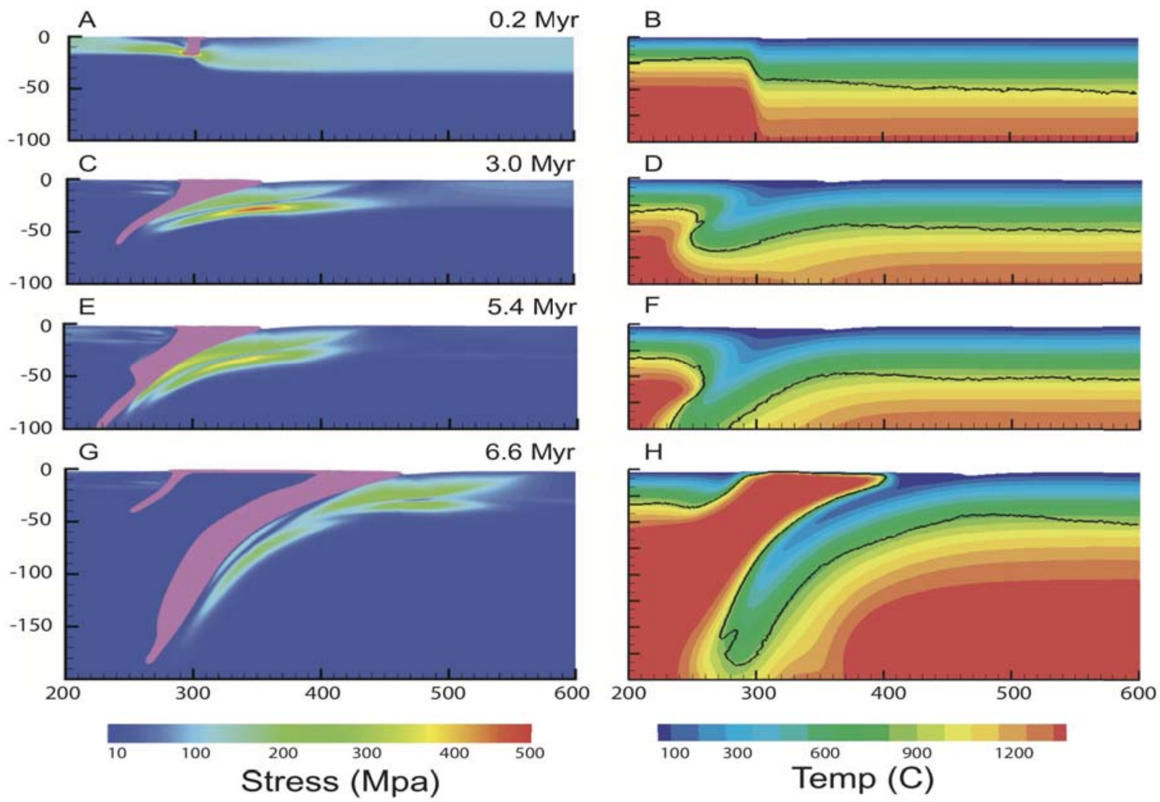


Figure 4.15. Dynamic model of initiation of a subduction zone at a pre-existing fracture zone that separates 10 Ma lithosphere from 40 Ma at four instants in time (with stress shown in the left column and temperature in the right). The new subduction zone is driven by a combination of convergence perpendicular to strike of the fracture zone and the buoyancy differences. The initial driving forces must first overcome substantial elastic bending before sufficient buoyancy exists beneath the plate to remain self-sustaining. The model predicts a distinct phase of rapid uplift of the margin before subsidence and subsequent rapid back-arc opening. (From Gurnis et al., [2004]).

What controls the rate of subduction and the 3-D structure and geometry of a subduction zone over time, and how are these related to magmatism at the surface?

To what extent an initially descending, forced slab affects the physical properties of the juvenile mantle wedge, how the initial melting and volatile release affect the properties of the plate (strength and buoyancy), and how these factors relate to volcanic expressions at the surface are entirely unknown. Dynamic models show that the rates of subduction and slab dip are controlled not only by the age of the incoming plate but also by the duration of subduction and the characteristics of the mantle wedge [*Manea and Gurnis*, 2007; *Billen*, 2008]. Moreover, volatile release from the slab changes the physical properties of the mantle wedge, such as effective viscosity, which also affects slab dip angle [e.g., *Manea and Gurnis*, 2007]. The rate of plate motion and subduction are potentially controlled by the strength of the bending plate [*Buffett and Rowley*, 2006], which may be governed not only by the initiation and growth of normal faults in the trench but also by the serpentinization of the mantle lithosphere. The recent correlation of mantle lithosphere seismic velocities with normal faulting on the outer rise [e.g., *Ivandic et al*., 2008] opens up new opportunities to determine the role of serpentinization in controlling the strength of the plate when combined with other geophysical observations. Seismic observations also suggest a significant component of 3-D, along-strike mantle wedge flow at many modern subduction zones [e.g., *Russo and Silver*, 1994; *Fouch and Fischer*, 1998; *Pozgay et al*., 2007; *Hoernle et al*., 2008; *Long and Silver*, 2009], yet most current models of subduction are 2-D. The structure and geometry of subduction zones in 3-D through time, may result from an intimate balance between volatile fluxing, melting in the wedge, and larger-scale geodynamic forces. Studies of the volatile and magmatic output of the arc in time and space augmented with constraints on the mechanical properties of the incoming lithosphere will prove essential in deconvolving the specific roles of each of these factors. Future dynamical models will need to be 3-D, incorporate melting and melt migration in a thermodynamically self-consistent way, and allow the plates to dynamically interact, and geophysical studies will provide 3-D snapshots of the structure and flow vectors of modern subduction zones that can be tested against dynamical models (e.g., Figure 4.11b).

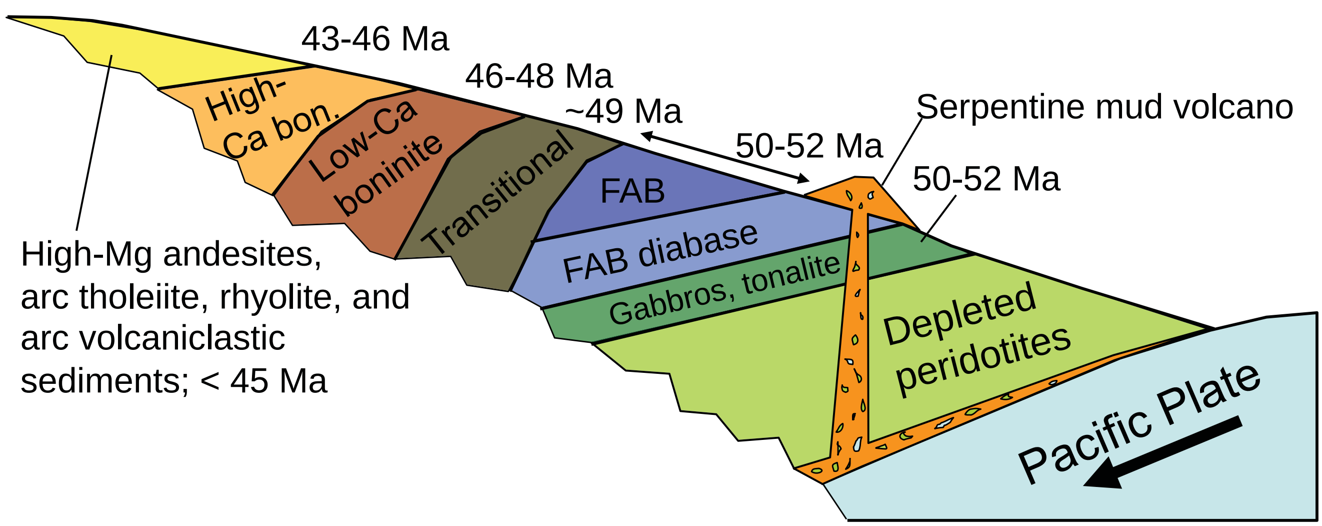


Figure 4.16. Schematic cross-section of volcanic stratigraphy in the Mariana fore-arc, showing the age progression of lava types from FAB to transitional lavas, to boninites (compiled by Reagan et al. [2010]).

What controls the distribution of volcanoes in space and time?

Recent studies examining the positioning of arc volcanoes above subducting plates suggest that volcano location may be related to the slab dip and descent rate [e.g., *England et al.*, 2004; *Syracuse and Abers*, 2006], but may also relate to the thermal structure of the mantle wedge [e.g., *Schmidt and Poli*, 1998; *Grove et al.*, 2009] and extensional forces in the overriding plate [e.g., *Alaniz-Alvarez et al.*, 1998]. Volcanic centers might not be permanent features of arcs, but may be replaced by newer centers elsewhere along the arc as subduction and arc kinematics evolve [e.g., *Honda et al.*, 2007]. Understanding the distribution of volcanic centers along arcs in space and time requires improved understanding of the 3-D and 4-D dynamics of subduction and the overlying plate at scales ranging from entire arcs to single volcanoes, and to volatile and melt pathways in the mantle wedge. Geophysical imaging of "hot fingers" in the mantle beneath Japan [*Tamura et al.*, 2002] shows that magma may be concentrated beneath major volcanic centers, and seismic studies of the crust in Izu-Bonin reveal significant along-strike variations in crustal structure that correlate with volcanic expressions at the surface (Figure 4.14) [*Kodaira et al.*, 2007], suggesting that the roots of volcanic centers remain stationary. Similar features have not yet been identified in other arcs, although recent studies suggest that significant focusing to volcanic centers may also occur in the crust [*Karlstrom et al.*, 2009]. Achieving a 4-D perspective on the evolution of melt focusing beneath volcanic arcs requires combining geodynamic modeling of the interactions between solid and fluid flow in mantle wedges with high-resolution geophysical documentation of the deep crustal and mantle roots of whole arcs and individual volcanic centers and geochemical and petrologic constraints on the depths and temperatures of primitive magmas.

4.7. What are the critical feedbacks between surface processes and subduction zone mechanics and dynamics?

The dynamics and resulting structural evolution of convergent margins is governed by the balance between tectonic and magmatic processes that build up the margin, and erosive and sediment dispersal processes that tear it down. The resulting distributions of sediments of different types also influence the distributions, geometries, and mechanisms of deformation and fault slip across the boundary, which in turn influence rates of uplift

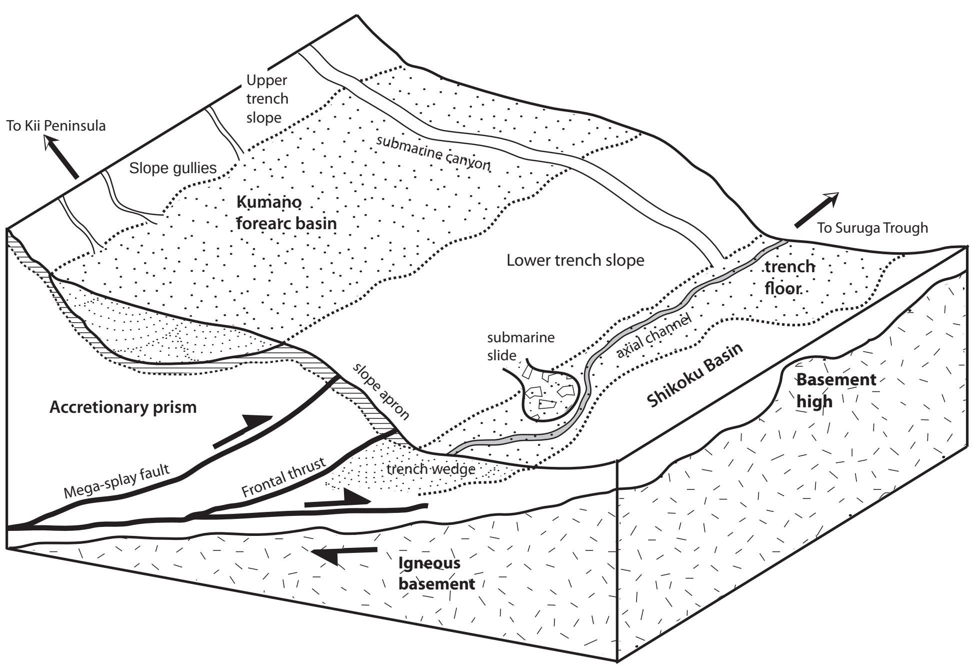


Figure 4.17. Schematic diagram of the interplay between sediment transport, deposition, and mechanics in the frontal parts of accretionary prisms based on the Nankai margin, offshore Japan (courtesy of M. Underwood).

and exhumation. Clarifying the interplay between surficial and deep-seated processes at subducting margins is fundamental to understanding the long-term evolution of plate boundaries, and interpreting ancient analogs. This approach follows the recommendation by the DRC to explicitly incorporate surface processes in the subduction studies. The key questions include:

How do erosion, sediment transfer, and deposition, interact with deformation and subduction geometry during plate boundary evolution?

Field studies of active [e.g., *Koons*, 1990, 1994] and ancient [e.g., *Hoffman and Grotzinger*, 1993] mountain ranges reveal how orographic precipitation and consequent erosion impact the distribution of deformation in mountain belts. These processes can now be understood in the context of critical Coulomb wedge theory [*Davis et al*., 1983; *Dahlen et al*., 1990; *Beaumont et al*., 1992; *Willett*, 1999]: forearc erosion and recycling back into the trench favors frontal accretion and uplift, whereas retroarc erosion enhances the exhumation of deep crustal material. Sediment deposition also influences the dynamic behavior of a margin. The addition of sediments above or in front of an active thrust belt restricts the initiation of new frontal thrusts in an attempt to balance the critical stresses [*Storti and McClay*, 1995; *Simpson*, 2006; *Berger et al*., 2008].

Most of these models have assumed steady-state conditions in 2-D. However, the Earth is 3-D and subject to variable conditions over time and space, which impact the evolution of convergent margins. We are only just beginning to understand this behavior. For example, climatic variations influence erosion rates through time, which can control the width of mountain belts [*McQuarrie et al*, 2008] and limit the convergence rate between plates [*Meade and Conrad*, 2008]. Complex 3-D landforms result from the formation and evolution of drainage systems and glaciation, which are themselves driven by tectonic uplift [e.g., *Whipple*, 2004; *Tomkin and Roe*, 2007; *Egholm et al*., 2009]. The time dependent evolution of these landforms significantly affects both local and regional stress conditions and resultant deformation patterns. Integrated onshore and offshore studies are necessary to more fully clarify these relationships, and to relate landform evolution, 3-D sediment dispersal patterns and accumulations within the stratigraphic record, and uplift and erosion rates within the forearc, arc, and back-arc regions. Comparative studies at contrasting margins will be needed to discern the relative importance of climatic and tectonic factors under different conditions.

How do sediment dispersal patterns influence forearc evolution?

In the offshore region, depositional processes impact the dynamics of the accretionary prism and the underlying megathrust fault. The thickness, texture, composition, facies distribution, and rate of sediments entering trenches are highly variable, which results in a heterogeneous distribution of strata that are accreted or underplated (Figure 4.17). This configuration impacts pore fluid pressure, stress state, wedge geometry, and the strength of the plate boundary fault [*Morley*, 2007; *Underwood*, 2007]. As a result, the form of accretionary prisms may be controlled in 4-D by the heterogeneous properties of sediment input [*Saffer and Bekins,* 2002]. To understand this heterogeneity, we must understand how surface processes and accommodation space interact to form stratigraphy in convergent settings. For example: (1) What defines the size, spacing, and location of submarine canyons, and how does this impact the distribution of sediment types? (2) Do canyons debouch in mid-slope forearc basins or continue to the base of slope? (3) Are sandy trench-wedge facies spatially restricted to channel-levee complexes or evolve into broad sheet-flow systems? (4) How does sedimentation interact with basement topography? The evolution of forearc basins and smaller trench slope basins may also be intimately coupled to the initiation of slip and subsequent uplift history along imbricate thrusts and major out-of-sequence thrust faults (e.g., megasplays) within the accretionary prism [*Underwood et al*., 2003; *Strasser et al*., 2009; *Simpson*, 2010]. In turn, the thickness of sediment in a forearc basin, itself driven by surface processes, may control the degree of mechanical coupling between the upper and lower plate and hence the magnitude of subduction zone earthquakes [*Fuller et al*., 2006; *Wells et al*., 2003]. Detailed 3-D seismic data combined with direct sampling and in-situ measurement (e.g., through coring and logging) will be necessary to map out the stratigraphic and structural packages that control this system, while coupled 3-D numerical models can test these dynamic feedbacks.

4.8. SCD in the Next Decade

The Subduction Cycles and Deformation Initiative is poised to make rapid progress on the questions outlined above, by building on the successes of both the SEIZE and SubFac Initiatives, capitalizing on the realized connections between the two original initiatives, and entraining new participation from other communities to examine the role of surface processes and sedimentation at subducting margins. The integration of communities will promote strong collaborative investigations of both shallow and deep controls on plate boundary deformation and megathrust seismogenesis, and the role of sediments, fluids, and volatiles in mass transfer, fault processes, and crustal growth. Substantial data already have been collected at the three main focus sites for the two initiatives: Nankai, Central America, and Izu-Bonin Marianas. As noted in Section 6.1, future research will probably take place in different locations, either newly defined focus sites (i.e., primary sites) or a broader array of sites selected for comparative studies. Joint EarthScope-MARGINS deployments of seismometers and GPS stations at Cascadia, and the migration of the USArray Transportable Array to Alaska in 2014, define clear opportunities for more focused studies (Section 6.3). The quality and volume of observations at the current MARGINS focus sites define a baseline of knowledge that will transfer into the new program, allowing for important comparisons to test the significance of the observations made at the focus sites.

Additionally, the MARGINS subduction community has established strong international collaborations, in particular, with Japanese, German, and Central American researchers, and IODP drilling efforts (Section 8.2). In fact, IODP drilling is entering its third phase at Nankai (NanTroSEIZE), and is projected to continue well into the next decade, providing key constraints on the physical state and behavior of the megathrust. IODP drilling offshore Costa Rica (CRISP) is entering its first phase, augmented by observatories both on land and offshore, which will continue to provide geodetic, hydrologic, and seismological data for the Middle America subduction zone. Thus, both SEIZE focus sites will continue to attract researchers within or outside of GeoPRISMS, contributing to our growing understanding of seismogenic zone processes in both locations. IBM drilling has also been proposed, addressing some of the crustal objectives of the SubFac community highly relevant to GeoPRISMS.

The structure of the GeoPRISMS program fosters interdisciplinary studies that can take advantage of the latest advances in numerical modeling, integrated geophysical observations (seismic structure, earthquake parameters, geodesy gravity/geoid, electrical conductivity, bathymetry, magnetics and heat flow), integrated geochemical and petrological studies using state of the art analytical equipment of both subduction inputs (i.e., sediments, fluids, altered oceanic crust), and outputs (plutonic rocks, lavas, and gasses). The GeoPRISMS structure will also provide the motivation for new experimental studies on both key physical and chemical properties of subduction zone materials. Finally, the advancements made in MARGINS provide the context for focused studies on unique exposures of plutonic lower crustal and mantle rocks, ultra-high-pressure metamorphic rocks, and accretionary prism exposures that can help constrain key parameters inferred from observational and experimental studies.

GeoPRISMS
Draft Science Plan

5. Rift Initiation and Evolution (RIE)

5. Rift Initiation and Evolution (RIE) Initiative

Continental rifts and their end products, passive margins, are the expression of fundamental processes continually shaping planetary surfaces. Rifts are sites of magmatic fluid and volatile transfer from the mantle to the surface through flood basalt and alkaline magmatism, and from the surface to the mantle via surface weathering, hydrothermal systems and serpentinization. Sedimentary sequences contained within the segmented rift systems record the interplay between tectonics and climate throughout basin evolution, and they may sequester large volumes of CO_2 and hydrocarbons. Like subduction margins, rifts may be sites of voluminous and explosive volcanism. Passive margins are sites of enormous landslides and destructive earthquakes. 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 (Figure 5.1). These objectives tie directly into the overarching themes, as rifts are primary locations where new continental crust is formed and modified, where fluids, and particularly magmas, are generated and transferred, influencing the modes of rift opening, where climatic and surface processes govern mass transfer and tectonic activity, and where volcanic activity and the exposure and alteration of mantle rocks result in poorly understood volatile exchange. 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 the following key questions that build on MARGINS discoveries within the new GeoPRISMS program:

- Where and why do continental rifts initiate?
- 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 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?

These fundamental questions propel our inquiry, which builds on significant achievements over the last decade by the scientific community, harnesses the power of observational, experimental, and geodynamical modeling technology, and is strengthened by focused GeoPRISMS activity. The questions are interwoven and guided by the Overarching Themes of Section 3, they share common foundations and approaches with the SCD Initiative, and they intersect the goals of the energy industry. Resolution of RIE questions requires a multi-disciplinary team of geologists, geophysicists, geochemists, and geodynamical modelers employing a multi-pronged approach of data acquisition in key active and ancient rifts, experimental studies to constrain plate rheology and fluxes, and the development and implementation of 3-D geodynamical models constrained by thermal and rheological data. This approach follows the recommendations of the Decadal Review Committee, in that the rifting Initiative expands emphasis on sediment and fluids, incorporates passive margins, and features enhanced links to geohazards and the energy industry.

5.1 Where and why do continental rifts initiate?

Although the concept that thick continental lithosphere extends and ultimately breaks apart has been accepted for over 50 years, the conditions required for the initiation of rifting remain controversial. Many studies have pointed out that the forces that drive plate tectonics may be insufficient to rupture normal continental lithosphere in many cases (e.g., plates that are not attached to slabs [*White and McKenzie*, 1989; *Bott*, 1991; *Buck*, 2004]). The fact that some modern active rifts (e.g., East Africa Rift system) are surrounded largely by mid-ocean ridges rather than subduction zones begs the question of how rifting initiates in these settings. Our poor understanding of rift initiation is partly due to the fact that extensive stretching, syn- and post-rift magmatism, and post-breakup sedimentation usually overprint and bury the record of incipient extension at mature rifts and rifted margins. Understanding how, why, and when

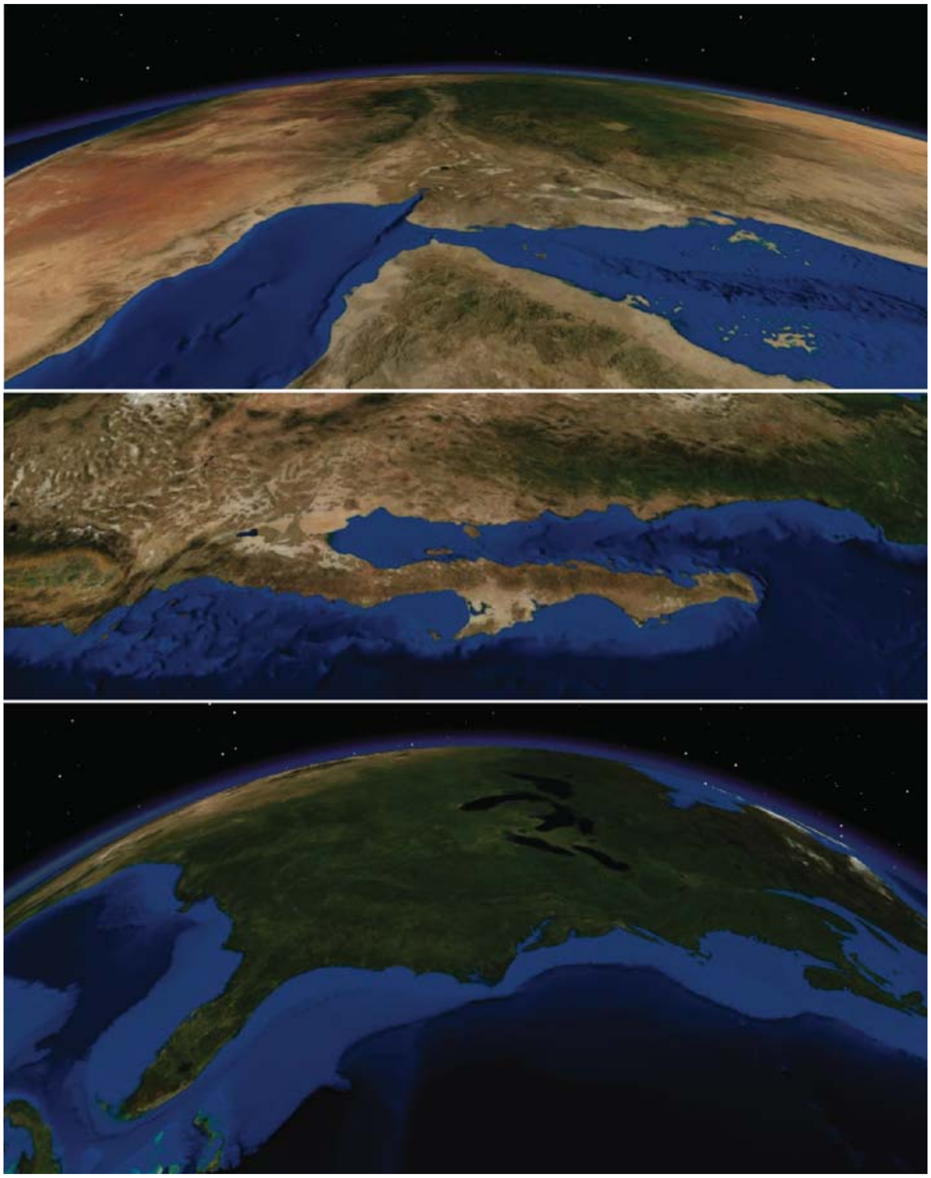


Figure 5.1. Active rifting (above shown looking south at the Afar Triple Junction and down the East African Rift), transtension in the Gulf of California (middle), and evolved rifted margins of southern and eastern North America (below) are spectacularly and diversely manifest. They represent opportunities for developing fundamental understanding about the interaction between the atmosphere, hydrosphere, biosphere and lithosphere. They are also targets for resource management, assessment of sustainable civilization along the coasts in the face of climate change and sea level rise, and for the mitigation of natural hazards. (Images from Next Generation Blue Marble (NASA's Earth Observatory) rendered using ArcGlobe.)

rifts initiate and localize is important for gaining a broader understanding of the forces controlling lithospheric motions, the global geochemical cycles, and ultimately the timing and mechanisms of the Wilson Cycle.

What are the relative roles of magmatism and pre-existing structures in rift initiation?

The theoretical inability of plate tectonic forces to overcome the strength of normal continental lithosphere in regions such as East Africa implies that either some active process weakens the lithosphere (e.g., the introduction of magma and metasomatising fluids) or that rifting begins along pre-existing weaknesses in the lithosphere. However, the relative importance of these factors during the inception and earliest development of a new rift are controversial. Dike intrusion can occur at lower tectonic forces than the formation of new faults [e.g., *Buck*, 2004] (Figure 5.2). On the time scale of individual rifting events, the largest proportion of strain is accommodated by magmatic intrusions in some late-stage [*Wright et al*., 2006] and magma-rich early-stage rifts [*Calais et al.*, 2008]. Magma may also contribute to rift initiation by infiltrating and/or thermally or chemically eroding the mantle lithosphere [e.g., *Harte*, 1983; *Menzies*, 1983; *Vauchez et al*., 2005; *Aulbach et al*., 2008]. However, the extent to which magmatism actively promotes rift initiation worldwide is unknown. The source of magma at the onset of rifting is also enigmatic, as very little decompression melting is expected for small amounts of extension [*White et al*., 1987; *McKenzie and Bickle*, 1988]. Thus, early stage magmatism requires other mechanisms, such as a deep-seated thermal anomaly, the presence of volatiles, and/or a pre-existing chemical heterogeneity in the asthenosphere or continental lithosphere.

Pre-existing variations in crust and mantle lithospheric composition and structure could allow rifting to occur in otherwise strong lithosphere [e.g., *Dunbar and Sawyer*, 1989] or to initiate small-scale convection and magmatism [e.g., *Sleep*, 1996; *King*, 2000]. Continental rifts develop within heterogeneous lithosphere in response to forces that may be at any orientation to pre-existing structural fabric or compositional heterogeneity. Favorably oriented pre-existing faults and fabrics may promote early localization and partially control the length and polarity of new faults [e.g., *van Wijk*, 2005]. Pre-existing lithospheric thickness variations, thermal perturbations, and compositional heterogeneities can also promote the initiation of melting [*Petit and Ebinger*, 2000; *Watts and Burov*, 2003]. A major question, therefore, is whether pre-existing structures are more important during rift initiation, with magma only becoming important later [e.g., *Keranen and Klemperer*, 2008]. A corollary concerns the role of thermal erosion of mantle lithosphere in recycling lithospheric material to the mantle, and implications for the stability of continental lithosphere and mantle flow [*Class and LeRoex*, 2006; *Hanan et al*., 2004]. Combined active source-passive source seismic, InSAR and GPS, magneto-telluric (MT), seismicity, magma chemistry, fluid inclusion, and groundwater geochemistry studies within incipient rift zones would allow us to unravel the relative importance of magmatism, pre-existing weaknesses, and other factors in facilitating rift initiation, and they would constitute a first step towards constraining the tectonic forces required for rifting to begin.

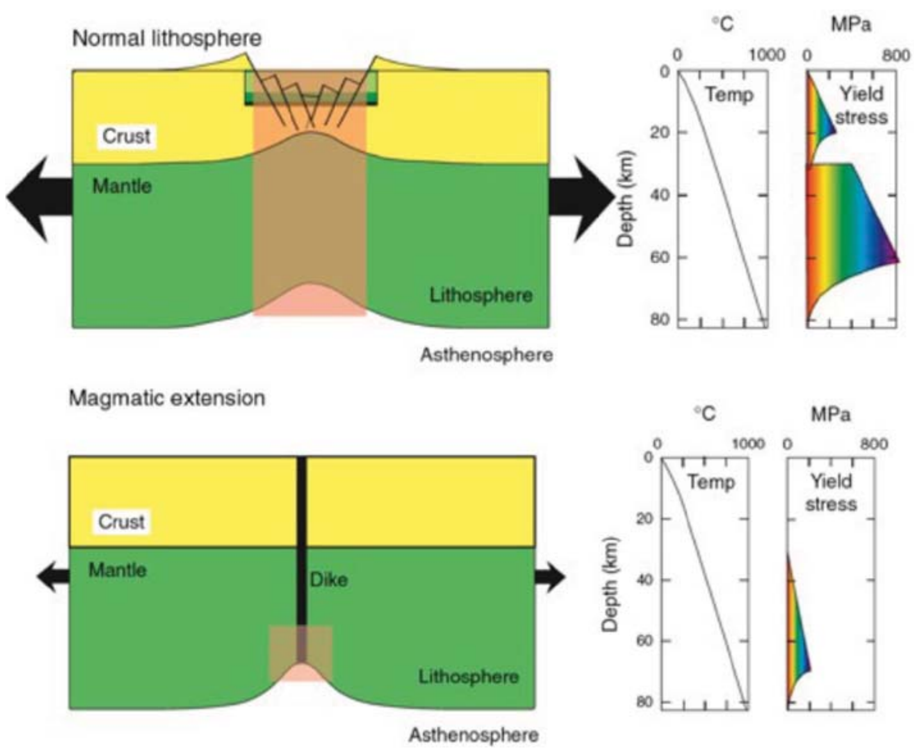


Figure 5.2. The strength of normal lithosphere is hypothesized to exceed plate motion forces available for rifting (top), but dike intrusion can significantly decrease lithospheric strength (bottom), thus focusing the initiation of rifting [Buck, 2004].

How do border fault segments form, and how is strain distributed throughout the lithosphere beneath and along early rift stage border faults?

Tectonic segmentation is a fundamental characteristic of nearly all divergent plate boundaries and is strongly controlled by lithospheric rheology. The earliest segmentation in rifts occurs when deformation localizes along border faults, which appear to accommodate >70% of upper crustal extension during early rifting (Figure 5.3). Models and limited observations show that border faults grow from shorter segments that propagate along strike, or shorter segments that link to other faults during progressive rifting episodes [e.g., *Cowie and Shipton*, 1998; *Densmore et al*., 2007]. Observations from the Gulf of Suez and East Africa indicate that this linkage occurs during the first 1-2 are needed to reveal how strain is accommodated along and between these systems during rifting crises as well as the inter-rifting cycle.

Likewise, the style of deformation at depth in the lower crust and upper mantle beneath border faults remains unknown. Do border faults observed at the surface penetrate the entire crust and take up a large portion of extension

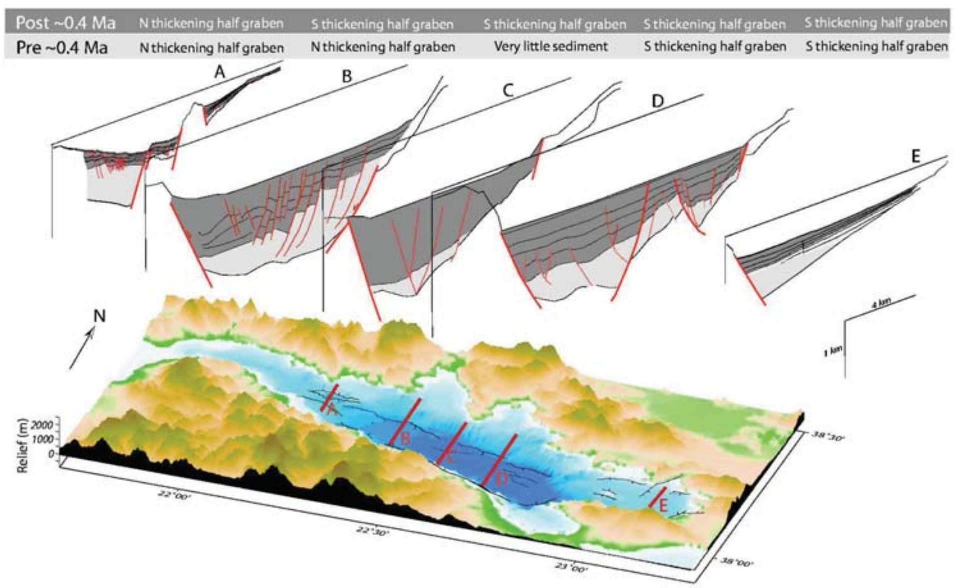
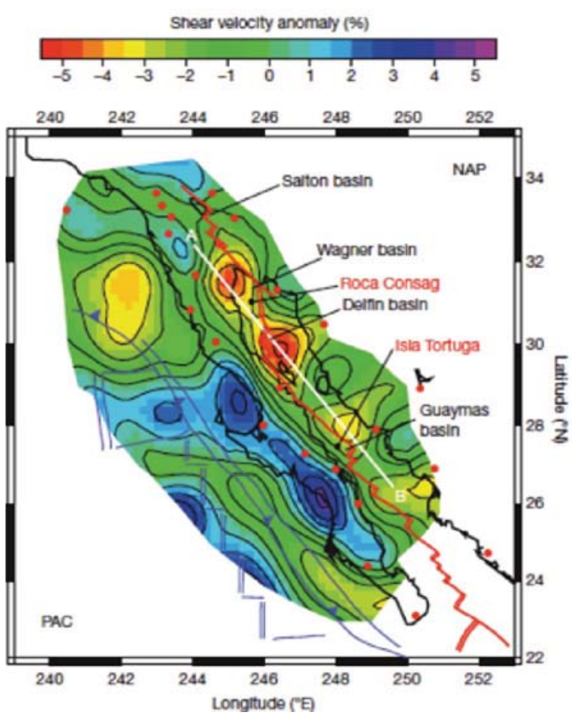


Figure 5.3. Temporal and spatial changes in faulting and basin geometry during early-stage continental rifting in the Gulf of Corinth imaged with seismic reflection data [after Bell et al., 2009].

My of basin evolution [*Morley*, 1999; *Kinabo et al*., 2007; *Gawthorpe et al*., 2003]. Border faults may achieve a maximum length that scales with plate strength as measured through maximum seismic rupture lengths and flexural rigidity [e.g., *Jackson and Blenkinsop*, 1997; *Hayward and Ebinger*, 1996]. But many questions remain. How is strain partitioned between border faults, intrabasinal faults, and magmatism across incipient rift basins? How are fault dip, displacement/length ratios, and earthquake rupture patterns modulated by magmatism and pre-existing structure [e.g., *Abers et al*., 1997; *Hayward and Ebinger*, 1996]? Field structural geologic, stratigraphic, and geomorphic studies combined with upper crustal imaging could elucidate the border fault structure and the linkages between them, while GPS, seismicity and InSAR throughout the crust [e.g., *Jackson and Blenkinsop*, 1997] or do they sole out in the middle crust such that either distributed deformation, separate fault system(s), lower crustal flow, or magmatic addition accommodate extension at depth in the lower crust [*Kusznir et al*., 1991; *Lavier and Manatschal*, 2006; *Persaud et al*., 2004; *Thybo and Nielsen*, 2009]? Lower crustal or possibly upper mantle focal depths of earthquakes in cratonic lithosphere have been interpreted as evidence for crustal-scale normal faults [e.g., *Nyblade et al*., 1996; *Albaric et al*., 2009], yet crustal thickness is poorly constrained in most areas of deep seismicity. Observations from discrete rifting events provide clues. *Jackson and Blenkinsop* [1997] document a ~100 km-long contiguous fault scarp in southern Malawi with a 15 m-high scarp that may correspond to a single Mw 8 event. These observations and the historical record of Mw > 7 earthquakes in Africa suggest that large sections of border faults slip in single earthquake sequences, but the paucity of seismic and geodetic instrumentation in areas of incipient rifting provide few additional constraints. Furthermore, if significant magma intrusion occurs at depth, how does it influence faulting at shallower levels? Do aqueous or magmatic fluids weaken crust and mantle rocks, enabling slow-slip and/or creep? The large discrepancy between aseismic and seismic strain during the 2007 fault slip-dike intrusion-carbonatitic volcanic eruption sequence in the < 5 My Natron, Ethiopia rift suggest that high volatile contents and magma intrusion facilitate rift opening [*Calais et al*., 2008]. Yet, how representative is this single event? How do fault slip and fluids contribute to time-averaged strain patterns? Answering these questions requires integrated seismic and geodetic studies of the co- and post-seismic response of the lithosphere to discrete rifting episodes, and fully integrated geochemical studies of erupted rocks. Combined with geodynamic modeling, such studies will provide new constraints on the spatial and temporal distribution of strain and thermal erosion of mantle lithosphere along and between rift segments, and will help to quantify the relative importance of tectonic versus magmatic strain accommodation as a function of depth.



5.2 How do fundamental rifting processes (such as tectonics, magmatism, and erosion, transport, and sedimentation), and the feedbacks between them, evolve in time and space?

The temporal and spatial development of extensional systems responds to a range of interrelated variables including strain rate, lithospheric rheology (a function of composition and cumulative thermal and deformation history), the distribution, source composition, and volume of melts and other fluids, structural and topographic relief, and many other factors. The most prominent surface manifestation of early-stage extension is a rift valley defined by a system of normal faults, punctuated by volcanic centers. These faults and magmatic centers contribute to the total strain budget across the rift, create a landscape that focuses surface drainage systems, control sedimentation patterns and the distribution of volcanic products, and create enclaves for human habitation. The rift system is also capable of potentially large magnitude earthquakes and/or explosive volcanic eruptions in relatively thick, strong continental lithosphere [e.g., *Jackson and Blenkinsop*, 1997; *Yang and Chen*, 2008; *Carn et al*., 2008].

As rifting progresses to seafloor spreading, the relative partitioning of strain between faulting and

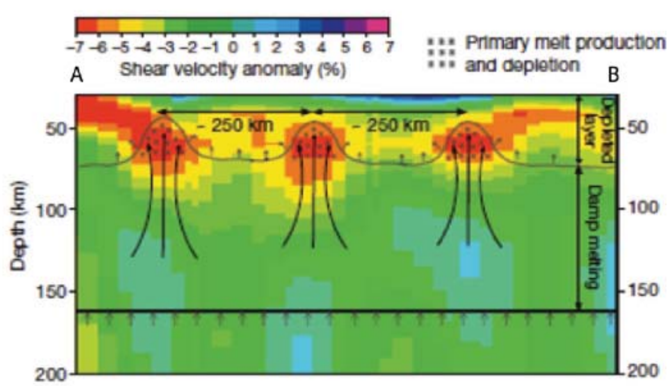


Figure 5.4. Shear-wave velocity structure beneath the Gulf of California [Wang et al., 2009]. Areas of low shear-wave velocities with spacing of ~250 km have been interpreted as regions of enhanced melt and upwelling.

magmatism may shift, depending on the thermal structure and composition of the mantle, as well as crustal properties [e.g., *Keranen and Klemperer*, 2008; *Ebinger and Casey*, 2001]. The evolution of a rift system varies spatially and temporally. Fault patterns show distinct variability along the length of a rift that reflects the initial formation and subsequent interaction and linkage of rift segments [e.g., *Densmore et al.*, 2007]. This evolution is strongly coupled with the migration, storage, and eruption of magma throughout rifting. The underlying magma reservoir(s) may or may not be segmented at the length scales of the border faults, creating feedbacks between magmatism and faulting that influence the morphology (including topography) of the rift through time (Figure 5.4).

A remaining challenge lies in our lack of understanding of how a rift may change from fault-dominated to intrusion-dominated extension (ultimately culminating in seafloor spreading); we also do not understand how the mantle may control or be influenced by such a transition. Similarly, we have few constraints on the mantle lithosphere thinning and mass transfer via thermal erosion and/or delamination during rifting [e.g., *Jull and Kelemen*, 2001; *Rooney*, 2010]. To fully articulate the evolution of a rift system, the relative roles, spatial patterns, and temporal evolution of the tectonic and magmatic elements must be characterized and placed into a context of predictable behaviors and quantifiable processes.

What is the relationship between deformation and magmatism at all levels of the lithosphere?

A key breakthrough in the last decade is the recognition that there is an intimate linkage between deformation and magmatism in extensional systems at a variety of time and length scales (Figure 5.5) [*Buck*, 2004; *Lizarralde et al.*, 2007; *Holtzman et al.*, 2003; *Thybo et al.*, 2009; *Wang et al.*, 2009]. However, the nature of this relationship at all levels of the lithosphere and its evolution

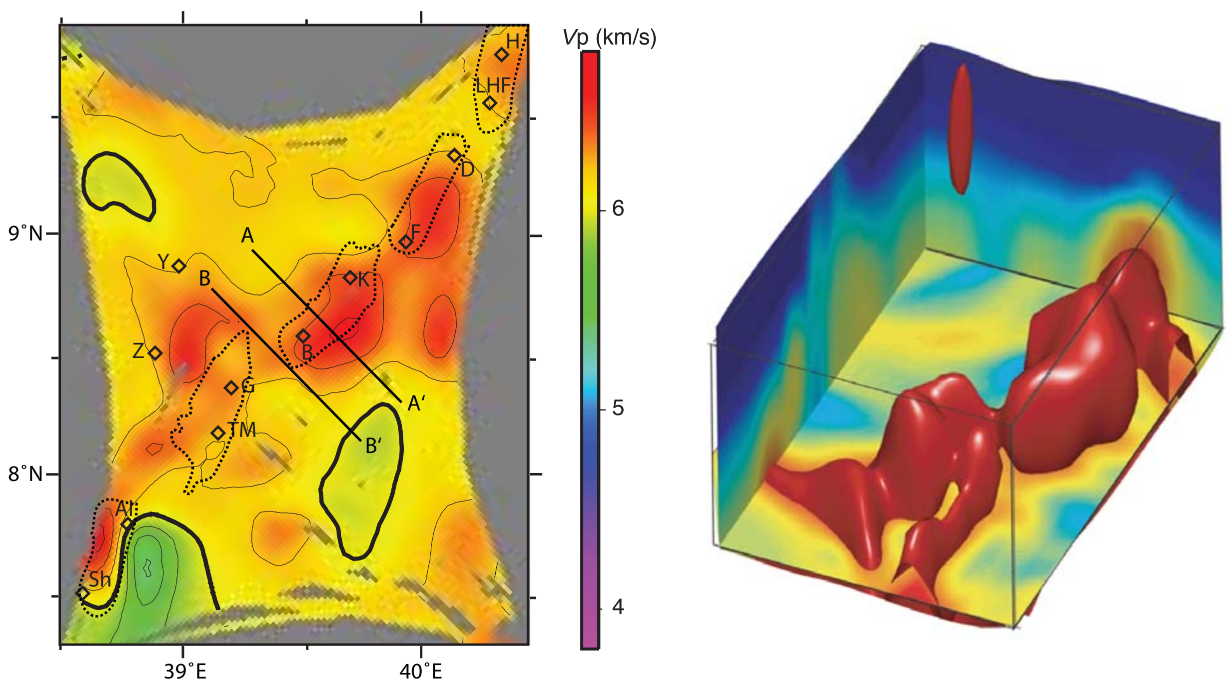


Figure 5.5. Three-dimensional seismic velocity model (10 km depth level horizontal slice) from the Main Ethiopian rift clearly images mid-crustal intrusions and shows that below about 7 km depth, extension is probably controlled by magmatic intrusion in a ductile middle to lower crust, whereas normal faulting and dike intrusion in a narrow rift axis position control and segment extension in the brittle upper crust [Keranen, et al., 2004].

through time remain controversial. In the shallow lithosphere, there are feedbacks between faulting, sedimentation, and the magmatic plumbing systems beneath volcanic centers and elsewhere along the rift [e.g., *Keranen et al*., 2004; *Keir et al*., 2009; *Bialas et al*., 2010]. Seismic reflection and surface mapping reveal pervasive faulting in some rift zones, yet the number and distribution of faults active during discrete rifting episodes remain unclear. In many rifts, few dikes reach the surface and faults accommodate strain above the intrusion level of dikes; existing faults are reactivated in late-stage rift zones [*Rowland et al*., 2007]. When eruption does occur, the controls on whether magmas migrate to the surface along existing faults, or if they generate new fractures during their rise [e.g., *Rubin*, 1995; *Baer et al*., 2007; *Calais et al*., 2008; *Biggs et al*., 2009] remains poorly understood.

The manifestation of deformation and magmatic systems at depth is also enigmatic. Rifting lithosphere may thin by more than a factor of 5 prior to the onset of seafloor spreading [*van Avendonk et al*., 2009; *d'Acremont et al*., 2005], although in some cases much less [e.g., *Taylor et al*., 1999]. The shallow and deep fault systems that facilitate this extension, and the linkage between them, remain poorly understood [e.g., *Lavier and Manatschal*, 2006; *Persaud et al*., 2004; *Keranen and Klemperer*, 2008; *Thybo and Nielsen*, 2009]. For example, what is the importance of rolling-hinge and/or detachment faulting, and what are the roles of lithospheric thermal structure, mantle serpentinization and other factors in the initiation and duration of these fault systems [*Abers et al*., 1997; *Pérez-Gussinye et al*., 2001; *Axen*, 2004; *Sachpazi et al*., 2007; *Reston et al*., 2007]? What conditions are required for the initiation of low angle faults?

Likewise, the role of magma at depth is enigmatic. Melt infiltration in the lithosphere may play a key role in weakening the lithosphere even in rifts that exhibit scarce magmatism at the surface due to inefficient melt extraction as postulated for the Iberian margin [e.g., *Muntener and Manatschal*, 2006; *Cannat et al*., 2009], ancient margins exposed in the Alps [*Müntener et al*., 2010] and in slow-spreading mid-ocean ridges [*Lizarralde et al*., 2004; *Kelemen et al*., 2006]. In magma-rich systems, the rheological consequences of magmatic intrusions into the crust, large mafic underplates, and extensive melt extraction from the lithosphere for the evolving rift also remain poorly understood. Recent large-scale studies have revealed a correspondence between variations in the style of crustal extension, the volume of magmatism, sediment input, and the pre-rift deformational and melt extraction history of the lithosphere [*Kendall et al*., 2005; *Lizarralde et al*., 2007; *Thybo and Nielsen*, 2009; *Dorsey*, 2010], raising important questions about how rift deformation changes through time in response to changes in the magmatic and sedimentary systems. Finally, it is unclear how and when all magmatism and deformation becomes concentrated at the ridge axis. Studies in the Gulf of California and elsewhere indicate that off-axis faulting and seismicity [*Fletcher and Munguía*, 2000, *Péron-Pinvidic et al*., 2007] and magmatism [*Jagoutz et al*., 2007; *d'Acremont et al*., 2010; *Lizarralde et al*., in review] may continue long after the establishment of an incipient spreading center.

Future studies should investigate how faulting and melt production and extraction vary from rift initiation to breakup to the onset of mature seafloor spreading, and how they respond to and influence deformation throughout the lithosphere. For example, the relationship of seismic observables to the distribution of melt and deformation at depth has advanced significantly [e.g., *Holtzman et al*., 2003; *van Wijk et al*., 2008], as has our ability to image smaller, more subtle features in the lithosphere using novel techniques like noise tomography [e.g., *Shapiro and Campillo*, 2004]. Advances in the acquisition and analysis of EM and MT data both onshore and offshore provide excellent opportunities to better constrain the distribution of fluids throughout the sediments, crust and lithosphere [*Whaler and Hautot*, 2006], especially when combined with other geophysical datasets [e.g., *Chen et al*., 2009; *Keir et al*., 2009]. Newly developed thermobarometers combined with isotope studies give unprecedented opportunity for understanding the development of magmatism throughout rifting [e.g., *Fischer et al*., 2009; *Lee et al*., 2009]. Furthermore, GeoPRISMS can take advantage of EarthScope's onshore Transportable Array and new seismic techniques to provide unprecedented constraints on variations in melt extraction and composition of the lithosphere beneath active and ancient rifts, and passive margins in North America.

What controls the evolution of segmentation and along-strike variations in extensional style and magmatism in rifts?

Continental rifting and breakup occurs in fundamentally 3-D systems. One of the core expressions of along-strike variability is tectonic and magmatic segmentation [e.g., *Keranen et al*., 2004; *Keir et al*., 2006; *Martinez et al*., 1999] (e.g., Figure 5.4), but many questions remain about how segmentation evolves over the life of the rift with progressive thinning and heating of the lithosphere, and how it relates to transform-bound segments in the eventual mid-ocean ridge. In early-stage rifts, segmentation is marked by border faults [e.g., *Scholz et al*., 1990; *Kinabo et al*., 2007]. However, the controls on the relationship of border faults to deformation and magmatism at depth, the scales of segmentation, and the segment linkage history (which has significance for rift weakening as well as consequences for maximum earthquake magnitudes), remain poorly understood. Some authors propose that border faults are abandoned during later-stage rifting, after which magma defines and maintains segments [*Ebinger and Casey*, 2001; *Keir et al*., 2009], but the evolution of this coupled magmatic/tectonic system is not well constrained. Moreover, in settings such as the Gulf of California (Figure 5.5), profound along-strike changes in crustal stretching, are correlated with variations in magmatism, sedimentation, and mantle properties [e.g., *Lizarralde et al.,* 2007; *Van Avendonk et al*., 2009; *Wang et al*., 2009]. In some cases, abrupt changes in these properties appear to occur at (proto-) transform faults [*Shillington et al*., 2009]. One question that arises from these observations is how and when during rift evolution do the focused magma accretion zones and segment linking transform faults giving rise to mid-ocean ridge segments initiate, and does the segmentation evolve differently in magma-rich versus magma-limited systems?

The fundamentally segmented structure of continental rifts, and the potential role of volatiles and magma, demand a fully 3-D geophysical imaging approach at the scale of the entire lithosphere and across a range of stages in rift to breakup evolution. With combined active-passive source seismic and MT experiments, the GeoPRISMS community can image melt depleted or enriched zones in the mantle and the corresponding strain patterns of the crust and mantle lithosphere required to test current models. Comparison of along-strike variations in crust and mantle structure in magma-rich and magma poor rift zones, and in differing stages of development, are key to discriminating between models for 3-D strain localization as rifting proceeds to rupture. Likewise, geodetic, seismic, heat flow, and MT studies of actively deforming rift segments provide fundamental insights into the origin, rise, and storage of magma throughout rifting: these active deformation studies require a rapid response initiative to capture unpredictable and unprecedented rifting events [e.g., *Lohman and McGuire*, 2006; *Nooner et al*., 2009]. Advances in the acquisition and analysis of electro-magnetic (EM) and MT data both onshore and offshore provide excellent opportunities to better constrain the distribution of fluids throughout the sediments, crust and lithosphere [*Whaler and Hautot*, 2006], especially when combined with other geophysical datasets [e.g., *Chen et al*., 2009; *Keir et al*., 2009]. Finally, where magmas have reached the surface or are degassing to water systems, we can also evaluate along-strike variability in the role of volatiles [e.g., *Chen et al*., 2009].

What is the relative importance of discrete rifting events versus continuous deformation in accounting for plate divergence?

Most of our understanding of the rifting process arises from geological and geophysical observations (e.g., seismic estimates of crustal thinning, or geochemical constraints on magma-source composition) that are integrated over million-year time scales. What portion of plate divergence occurs seismically versus aseismically, and what are the implications for fault slip rates and hazards? How do these strain patterns relate to the episodicity of magmatism? Recent geodetic and seismic observations of extensional deformation with time scales of seconds to years suggest that the majority of strain accommodation at fast-spreading ridges [e.g., *Tolstoy et al*., 2006] and late-stage rifts [*Wright et al*., 2006; *Ebinger et al*., 2008] may occur during discrete seismic and magmatic diking events, often followed by aseismic periods of magmatic re-inflation [e.g., *Nooner and Chadwick*, 2009], but very few observations are available on the time scales of these processes. Seismo-magmatic diking may be more important during early-stage rifting, based on a study of a magma-rich system [*Calais et al*., 2008], but again we are observation limited (except for recent results such as Keir et al. [2009]; Figure 5.6). Slow-slip, VLF, and tremor accompany dike-induced normal faulting, as in subduction zones, underlining the role of fluids in earthquake rupture processes in rift settings [e.g., *Lohman and McGuire*, 2006; *Ebinger et al*., 2008]. Developing a better understanding of the episodicity of deformation at all stages of rifting, the proportion of plate divergence taken up by magmatic addition, and the spatial distribution of this behavior in relation to tectonic and magmatic segmentation, will improve our understanding of the underlying processes and feedbacks controlling rift evolution. New technologies are now available that are capable of quantifying topography, displacements, deformation, or fluxes in unprecedented detail and accuracy, such as InSAR and airborne laser swath mapping (LiDAR) that can see through vegetation [e.g., *Zielke et al*., 2010], not to mention maturing geochronologic tools such as optically stimulated luminescence and cosmogenic radionuclides which provide ages on Quaternary landforms and deposits to critically constrain deformation, erosion, and deposition rates. Co-located GPS and seismic stations provide the time resolution lacking in the satellite data acquisition; together the space-based geodetic and seismic tools enable full quantification of strain partitioning in time and space, and improved constraints on the movement of magma and volatiles through the plates.

How do erosion, sediment transport, and deposition vary with climatic and tectonic forcing in rifts?

Studies of geomorphology, thermochronology, and mechanical modeling have only started to address the effects of climate and erosion on the mechanics of rift basins. Even modest topographic elevation on rift flanks can have a substantial impact on patterns and intensity of rainfall and consequently erosion of source areas [*Zehnder*, 2004]. Studies of low temperature thermochronology suggest that uplift on the flanks of the east African rift led to Neogene aridification in Africa and intensification of monsoonal circulation in Asia [e.g., *Spiegel et al*., 2007]. *Chapin* [2008] proposed that initial opening of the Gulf of California caused enhanced

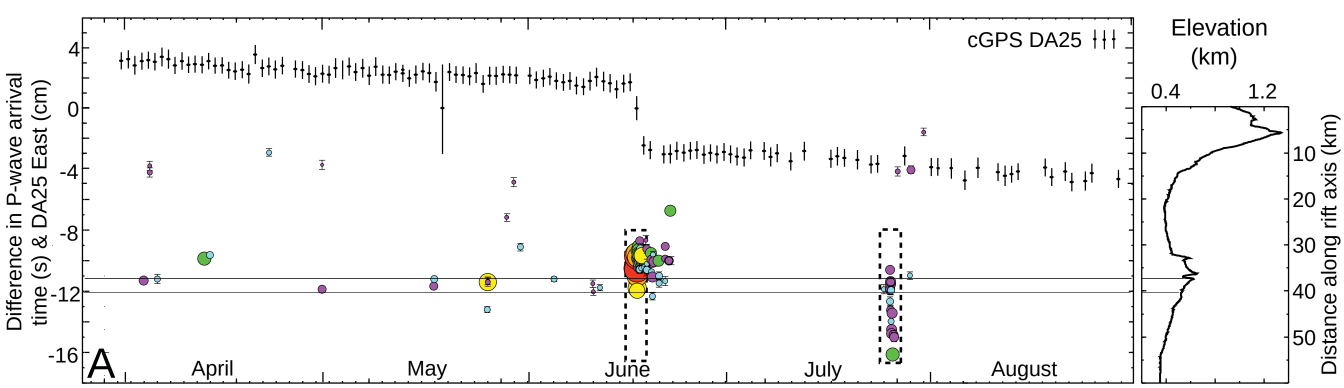


Figure 5.6. Injection of lateral dikes fed from magma reservoirs beneath rift segment centers is a key component in creating and maintaining regular along-axis rift segmentation. Image shows east-west motion from continuous global position system location and along axis position of migrating earthquake sequence [Keir et al., 2009].

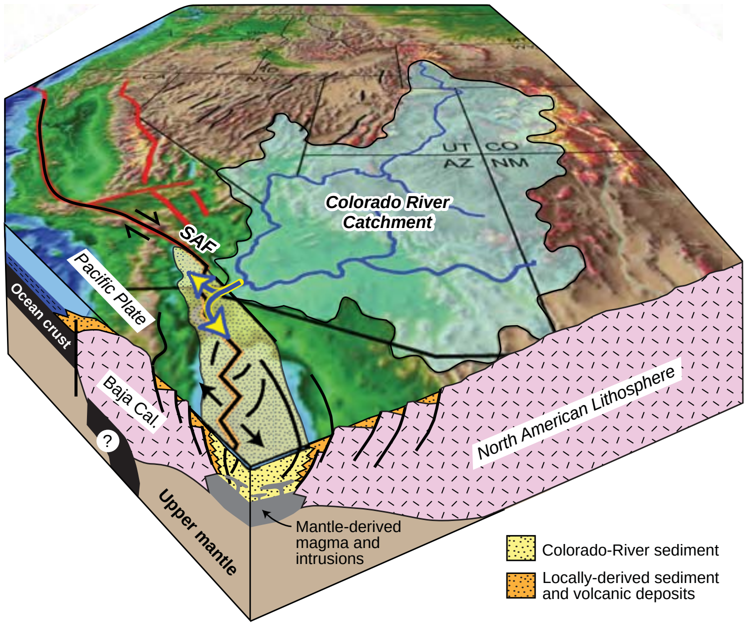


Figure 5.7. Lithospheric rupture and crustal recycling along the oblique-divergent plate boundary in the Salton Trough and northern Gulf of California. From Dorsey [2010].

monsoonal flow from the Pacific Ocean, which triggered integration of the Colorado River and subsequent large flux of sediment into the Salton Trough and Gulf of California. *Mack et al.* [2009] showed that footwall incision and basin filling in the Megara Gulf, Greece, were driven by increased catchment runoff related to Pleistocene climate change. Methanogenesis due to magma intrusion in rift-related sediments has been proposed to produce significant consequences for climate in the past [e.g, *Dickens*, 2004]. These studies point to important but poorly understood feedbacks among rift-related deformation, climate change, erosion, subsidence, and transfer of sediments from eroding highlands to rift basins.

Once in the basin, sedimentation impacts thermal structure, lithospheric rheology, and rift architecture. Accumulation of sediment was recognized over 30 years ago as a mechanism of crustal formation in deep continental rifts [*Moore*, 1973; *Fuis et al.*, 1984; *Nicolas*, 1985], yet this process has been largely overlooked in modern studies of rifted margins. For example, in the past 5-6 m.y., as much as 2-3 x 10^5 km^3 of crust has been eroded from the Colorado Plateau and transferred to deep oblique-rift basins in southern California and NW Mexico, where the sediment is converted to new crust at growth rates similar to those documented for subduction-related magmatic arcs and seafloor spreading centers [*Dorsey*, 2010] (Figure 5.7). Known and suggested effects of rift zone sedimentation include: (1) rapid transformation of sediments to metasedimentary rock, providing a possible explanation for "transitional" crust at many rifted margins [e.g., *Contrucci et al*., 2004; *Wu et al*., 2006]; (2) suppression of eruptive volcanism, with low-density silicic melts rising through sediment to the terrestrial surface or seafloor while mafic melts remain intrusive [*Schmitt and Vazquez*, 2006]; (3) thermal blanketing and suppression of hydrothermal circulation which leads to enhanced extraction of mantle melt and early transition to narrow rifting [*Lizarralde et al*., 2007]; (4) redistribution of crustal loads and buoyancy forces that also promote an early transition to narrow rift mode [*Bialas and Buck*, 2009]; thick, rapid sedimentation onto stretched and heated continental crust not only traps heat within the plate, but the light sediments lead to a higher integrated buoyancy force across the rift, promoting extension and adiabatic decompression melting [*Bialas and Buck*, 2009]; and (5) broad diffuse deformation after lithospheric rupture and transition to narrow rifting [*Persaud et al*., 2003]. While these studies point to the significant influence of sediment input on lithospheric processes in evolving rifts, many aspects of this mechanism remain controversial and poorly understood. New research is needed to fill this gap, and should include integrated studies of erosion, transport and deposition in modern fluvial and deltaic systems, regional sediment budgets to track long-term rates and volumes of accumulation in active rifts, seismic reflection and refraction surveys to image the response of and influence of sediment to lithospheric structure and composition, and geochronologic studies of rift-basin sequences to assess the timing and rates of crustal recycling via linked surficial and lithospheric processes.

5.3 What controls the structural and stratigraphic architecture of rifted continental margins during and after breakup?

The full architecture of a rifted continental margin provides a record of processes over the life of the margin. Stratigraphy both records and interacts with the evolution of rifted margins. The crust and mantle lithosphere on rifted margins are the product of inherited structure and composition prior to rifting, thinning, sedimentation and magmatic addition during rifting, and thermal equilibration and sediment loading after rifting. Below, we consider some fundamental questions that need to be answered to understand the evolution of rifted continental margins.

What controls the large scale form of evolving rifted margins?

Rifted margins have extraordinarily variable forms resulting from the feedback of sediment supply, tectonics, magmatism, deformation rates, pre-existing lithospheric architecture and climate (Figure 5.8). Some of the most widely recognized first-order differences in margin form are manifested in crustal structure. Rifted margins worldwide exhibit substantial variability in the width of extended continental crust, degree of crustal stretching prior to breakup, style of brittle deformation and the apparent volume and composition of synrift magmatism [e.g., *Wu et al.*, 2006; *Lizarralde et al.*, 2007, *Autin et al.*, 2009, *Shillington et al.*, 2009; *Goodliffe and Taylor*, 2007]. The variability of all of these aspects of rifted margin crustal structure arises from the interplay between strain rate, thermal and compositional structure of the crust and mantle lithosphere, and influence of fluids and the overlying sediments. Although previous studies have identified substantial variations in the crustal structure worldwide, our understanding is impeded by uncertainties in the interpretation of certain crustal features, and the limited information from the lower crust and upper mantle beneath

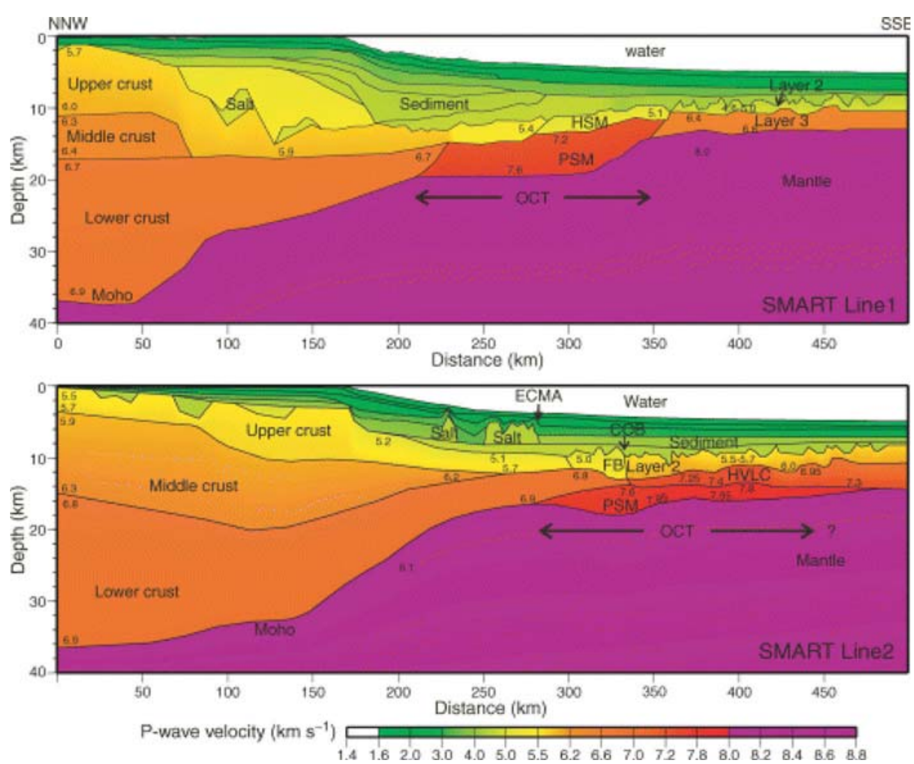


Figure 5.8. Crustal cross sections from wide-angle seismic data offshore Nova Scotia in a region of along-strike changes in the style of crustal thinning, magmatism and sedimentation [Wu et al., 2006]. Observations of along-strike changes in fundamental rift structure here and elsewhere (Gulf of California, offshore Australia, Black Sea, etc.) highlight the need for better constraints on the 3-D evolution of rifting, and the causes of such variability.

continental rift zones. For example, are high-velocity bodies at the edges of many margins composed of new magmatic material [*Holbrook et al*., 2001; *White et al*., 2009], inherited gabbroic bodies [e.g., *Gernigon et al*, 2004; *Van Avendonk et al*., 2009], or serpentinized mantle [*Dean et al*., 2000, *Contrucci et al*., 2004]? In some cases, one or more of these interpretations can be excluded, but ambiguity often remains. Furthermore, what is the nature of 'transitional' crust on the outer parts of some rifted margins—is it denuded, altered subcontinental mantle [e.g., *Dean et al*., 2000], highly thinned, possibly intruded continental crust [e.g., *Van Avendonk et al*., 2006], and/or new crust created by a mixture of magma and sediments [e.g., *Dorsey et al*., 2010]? These questions and others can be addressed with a combination of (1) higher resolution geophysical studies (magnetic, seismic, etc) that capture the three-dimensionality of margin structure at a variety of scales (e.g., 3-D reflection imaging of fault structures and 3-D crustal tomography), (2) constraints from S-wave velocity structure and other geophysical attributes, (3) drilling and characterization of ancient margins exposed onshore, and (4) direct comparison with comparable profiles from early and middle stage rift basins, as outlined in 5.1 and 5.2.

The structure of the mantle lithosphere at rifted margins is also a recorder of the history of deformation, melt retention and extraction, and thermal and compositional perturbations before, during and after rifting. In addition to lateral variations in velocity and attenuation, measurements of seismic anisotropy in the mantle and crust reveal inherited strain fabrics from earlier deformation [e.g., *Tommasi and Vauchez*, 2001]. Thus, mantle fabrics provide constraints on, and the strain history and planform of, mantle convection at breakup. Furthermore, the lithospheric structure is influenced by the production and distribution of melts at depth. For example, in addition to the melt extracted to form new magmatic crust, some melts may stall in the overlying lithosphere and refertilize it [e.g., *Piccardo et al*., 2007; *Cannat et al*. 2009; *Müntener et al*., 2010]. Not only does this suite of synrift processes shape the composition and thickness of the mantle lithosphere itself, it interacts with crustal deformation and sedimentation to control vertical motions during rifting and influence the thermal evolution of sediments, both of which are of keen interest to energy companies. Finally, the mantle lithosphere evolves after rifting in response to off-axis magmatism [e.g., *Jagoutz et al*., 2007], cooling [*McKenzie*, 1978], sediment loading, as well as passage over a dynamic mantle [e.g., *Spasojevic et al*., 2008]. However, in comparison to crustal structure, the corresponding variability in the underlying mantle lithosphere at passive margins is relatively poorly constrained.

The mostly widely available information on the mantle lithosphere beneath rifted margins comes from controlled source seismic studies of late-stage rifts and passive margins, and ancient margins exposed onshore. Unfortunately, these studies often produce ambiguous results. For example, seismic studies reveal variations in upper mantle velocity along and across magma-poor margins [e.g., *Dean et al.* 2000; *Van Avendonk et al*., 2006] that could be explained either by variations in serpentinization or melt extraction/retention. Moreover, there are few seismic anisotropy studies along passive margins to distinguish between models for mantle lithospheric thinning. Understanding the structure of the mantle lithosphere at rifted margins requires integrated onshore/offshore passive and active seismic imaging and anisotropy studies, as well as MT and magnetic studies of intact rifted margins, combined with structural and petrological studies of xenoliths, and direct comparisons with mantle velocity and of ancient margins exposed onshore. These studies offer excellent opportunities to understand spatial variations in mantle composition beneath rifted margins, because geophysical attributes can be interpreted solely in terms of compositional variations as melts and thermal anomalies are not present. Improvements in data quality and the number of broadband ocean bottom seismometers offer a tremendous opportunity to probe the deep record of margin development, particularly with the unparalleled onshore opportunities afforded by EarthScope's transportable array. GeoPRISMS could leverage NSF funding to augment EarthScope

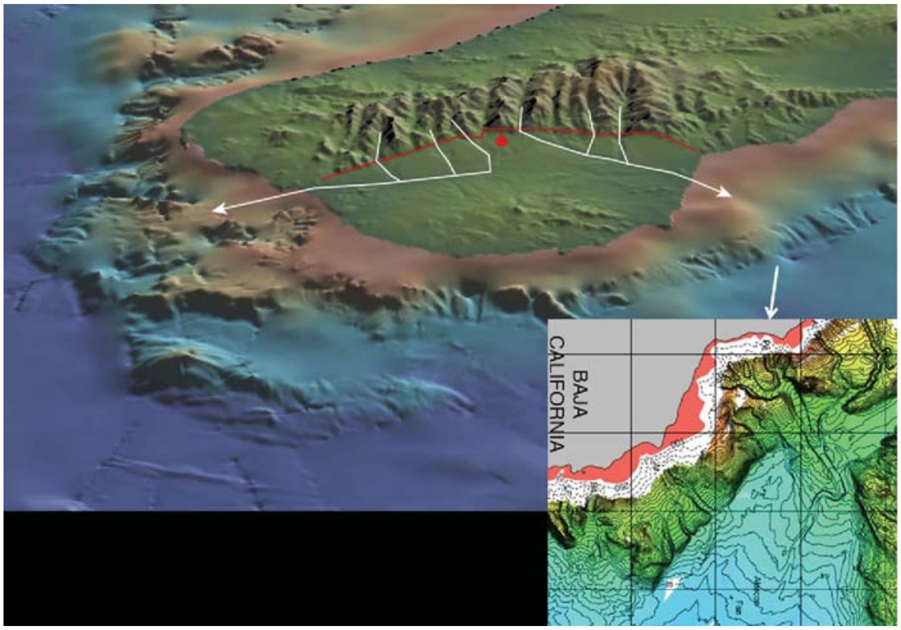


Figure 5.9. Oblique view west-northwest at bathymetry and topography of the southernmost Baja California Peninsula. Sediment is routed from the uplifting Sierra La Laguna across the active San Juan de Los Cabos fault (red) and the terrestrial piedmont into the adjacent marine system with important climate modulation in this tropical monsoonal setting [Arrowsmith et al., RCL workshop 2009; Arrowsmith, et al., 2009]. Inset bathymetry of the Alarcon Fan is unpublished data, courtesy of P. Lonsdale et al.

imaging of the East and Gulf Coasts. Characterizing the mantle lithosphere on successfully rifted margins completes the spectrum of rift evolution in 5.1 and 5.2.

How does evolving rift architecture modify and interact with subaerial and submarine sediment-dispersal pathways through time?

Prevailing models of erosion and sediment dispersal in rift settings involve transport away from the rift in the footwall of normal faults, and funneling of sediment into rifts via topographic lows in accommodation zones [*Leeder and Jackson*, 1993; *Jackson and Leeder*, 1994; *Driscoll and Hogg*, 1995; *Gupta et al*., 1999; *Densmore et al*., 2004] (Figure 5.9). Some rifts experience sediment transport along the rift axis by fluvial, deltaic and submarine systems, while others are sediment-starved and receive input primarily from small footwall catchments. Studies in the Gulf of Suez, East Africa, North Sea, and the Gulf of Corinth indicate that rifting initiates in isolated depocenters that later become connected by growth and linkage of basin-bounding normal faults [*Gupta et al*., 1998; *Dawers and Underhill*, 2000; *Morley*, 2002; *Bell et al*., 2009]. However, it is not well understood what factors control the difference in fault geometries and time required for fault integration at different rifted margins. It also is not clear how 3-D sediment dispersal patterns change in space and through time in response to evolving structural controls such as fault migration and lateral linkages, how fluvial erosion modulates that response, and how these processes vary in marine versus nonmarine environments, in particular as modulated by climate variation in sea level and precipitation magnitude and distribution (Figure 5.9). High resolution topography (derived from LiDAR for example) enables detailed stratigraphic and geologic investigations of drainage systems; and new cosmogenic and other surface dating methods provide unprecedented detail in dating exposed sedimentary packages that record rift evolution. Investigation of 3-D seismic datasets on rifted and post-rift sedimentary sequences will better constrain the sedimentary system's interactions with the evolving rift structure. In addition, laboratory studies that explore the linkages between sedimentation and faulting will illuminate how sediment dispersal patterns evolve [e.g. *Kim et al*., 2010]. Finally, numerical capabilities have become sufficient to explore the broad parameter spaces of these phenomena.

What are the rates, processes, and timescales of delta transport across shelves into deep basins and how are the signals of these variations expressed in the stratigraphic record?

To understand the evolution of rifted margins, we must understand how surface processes are

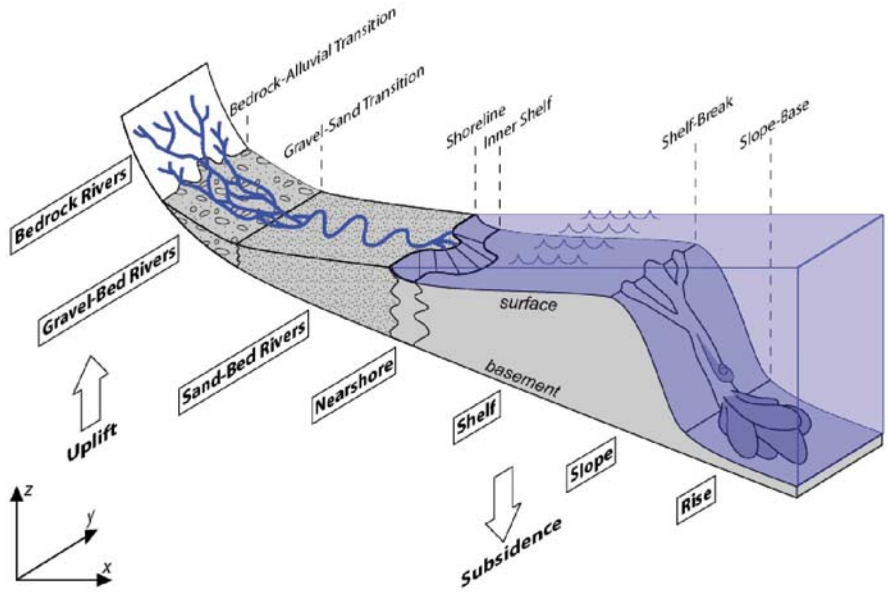


Figure 5.10. Idealized landscape crossing the shoreline with sedimentary environments indicated by boxed labels and interfaces between them indicated by dashed lines. What are the appropriate flux laws in each landscape domain? What controls the "interface" between each domain? On geologic timescales, the interface position strongly controls the partitioning of sediment between the adjoining environments; at the same time, the partitioning of sediment drives movement of the interface. These moving boundary problems are investigated by coupling morphodynamic and geodynamic equations for processes at the interfaces between the environments and along the boundaries of the system (drawn by Matthew A. Wolinsky).

integrated through time to create the stratigraphy we observe (Figures 5.10 and 5.11). A critical issue is to understand how surface-transport dynamics and subsidence couple. However, the depositional response varies widely depending on the time scale of the external perturbation (e.g., change in tectonics, sea level) relative to the response time of the landscape [*Allen*, 2008]. For example, an imposed basement deformation will clearly influence sediment transport and deposition patterns, causing flow to deviate around the uplifts and be drawn into the subsidence maximum. The extent to which flow is deflected will vary due to internal processes of the sediment-transporting system itself. *Kim and Paola* [2007] have shown that the time period of this internally generated surface process can be substantially lengthened in the linked erosion-fan system and can induce long-term alternations between embayed versus straight coastlines despite steady external forcing (Figures 5.10 and 5.11). These stratal patterns could be inaccurately interpreted as the product of change in the tectonic, sea level or climate forcing. Finally, the spatial and temporal scales for lithospheric response to sedimentation will depend on lithospheric rheology.

There is growing recognition that autogenic processes (e.g., floodplain deposition, channel avulsion, delta lobe progradation) play major roles in generating sedimentary deposits (Figure 5.11) [e.g., *Strong and Paola*, 2008; *Martin et al.*, 2009]. 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 [e.g. *Dorsey et al.*, 1997; *Dorsey and Umhoefer*, 2000]. Processes that decrease the avulsion frequency and/or increase the autogenic length scale (lobe size) increase the possibility of overlap between autogenic and tectonic time and length scales. Finally, dynamic processes in the mantle exert a direct control on the evolution and morphology of stratigraphy on passive margins [*Spasojevic et al*., 2008], but little is known about the spatial and temporal scales of these response functions.

New work is needed to understand these processes and clarify the dynamic links between global scale geodynamic models of plate motion and the preserved stratigraphic record. Field studies of exposed strata can be used to constrain both the timing and patterns of crustal deformation associated with evolving margins. The timing and patterns of crustal deformation can often be even better constrained through analysis of seismic and well data defining buried stratigraphy. Reflection seismic data have been collected along most of Earth's continental margins and an ever increasing amount of these data is in the form of 3D seismic volumes that provide unparalleled definition of evolving margins. Analysis of these data sets can define the longer wavelength deformation associated with the geodynamics of plate margins and refine the stratigraphic signals of "autogenic" and "allogenic" processes in margin stratigraphy [e.g., *Straub et al*, 2009]. Analysis of existing data sets can also guide the collection of new geophysical data to test predictions regarding the signals of margin dynamics that are preserved in the stratigraphic record.

Insight from both the field and subsurface studies will guide development of new numerical models for surface evolution of continental margins. The Computational Infrastructure for Geodynamics (CIG) and Community Surface Dynamics Modeling System (CSDMS) facilitate the general use of coupled numerical models and computational abilities for rheological, mechanical, and coupled

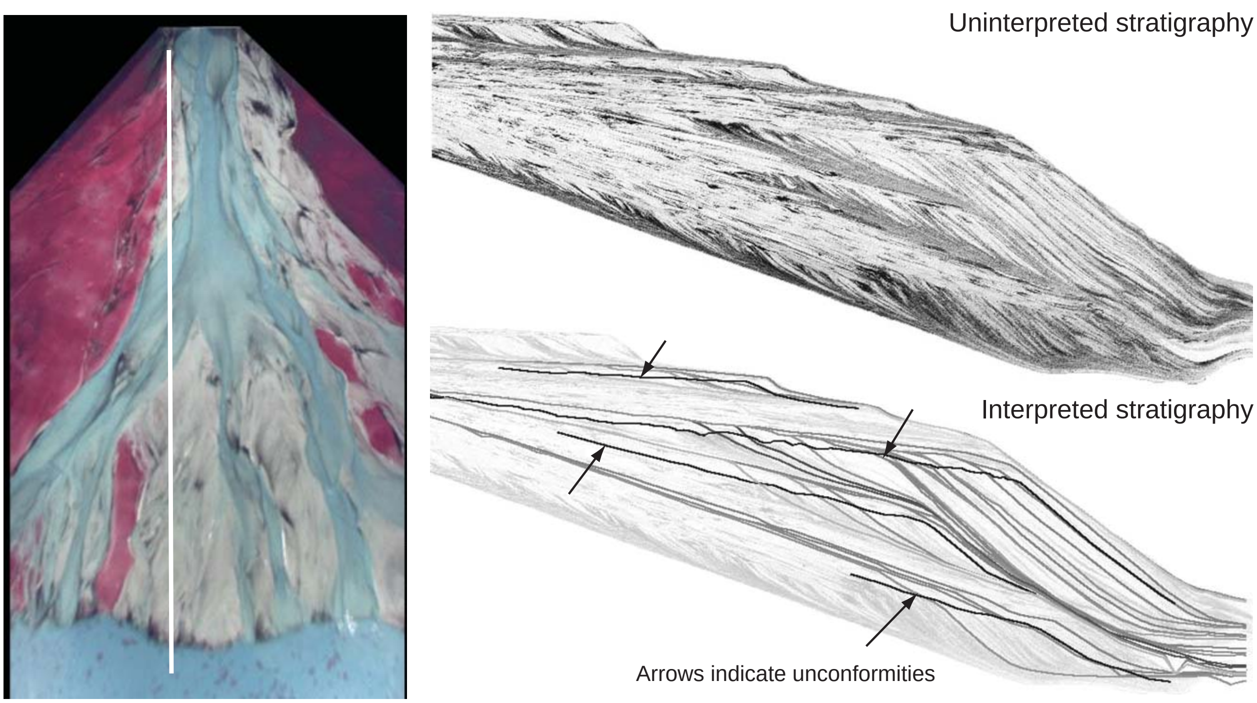


Figure 5.11. Stratigraphic evolution as seen through the depositional filter via experiment, with scans of surface topography (gray) compared against mapped unconformities and sequence boundaries (black). A significant challenge in linking process to form is the connection between instantaneous surface 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].

surface evolution problems (deformation, fluid flow, etc.) relevant to continental margins problems. Such models will be informed by field observations, both onshore and offshore, to clarify sedimentation rates and tectonic linkages. GeoPRISMS will aim to leverage existing computational infrastructure developed by NSF funding for geodynamics, sediment transport, and landscape evolution, as well as take advantage of geoinformatics and encourage open-access databases for new data collected under the GeoPRISMS program (See Sections 8.1 and 10.4)

What active processes influence the form of the post-rift continental margin?

Post-rift continental slopes in rapidly loaded systems are controlled by the same critical wedge mechanics that underlies our understanding of collisional convergent margins [*Bilotti and Shaw*, 2005]. Sedimentation and the interaction of sedimentation with rift geometry (along with gravitational spreading and salt tectonics in places) can drive the entire evolution of the margin [*Morency et al.*, 2007; *Gradmann et al.*, 2009; *Ings and Beaumont*, in press]. Continental margins are constantly sculpted by submarine landslides and distributary channel networks [*McAdoo et al.*, 2000]. The large-scale topographic and bathymetric slope of the continental margin results from the balance between sediment loading, thermal subsidence that creates accommodation space, deformation from relatively buoyant salt and mud, and gravitationally driven topographic stresses and strength variation due to elevated pore pressures [*Gradmann, et al.*, 2009; *Flemings et al.*, 2008] (Figure 5.12). It is not clear how glacial-interglacial climate cycles such as sea-level change and related changes in loading influence margin dynamics, and how these are expressed in the resulting stratigraphic and structural architecture. A multidisciplinary approach that includes laboratory experiments, field observations, and synthesis in multi-scale coupled models, is needed to successfully address the above questions. For example, seismic reflection and chirp data can be used to infer ongoing deformation at the continental margin. Direct measurements through coring can be used to constrain in-situ

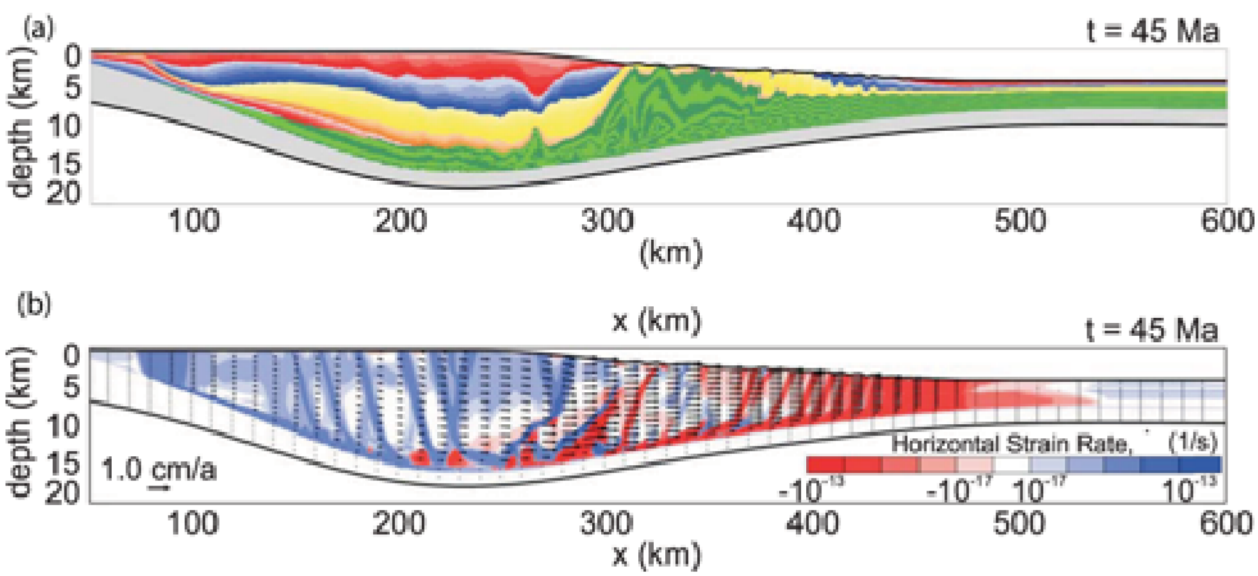


Figure 5.12. Representative numerical simulation of evolution of a passive margin in response to differential loading of thinned continental crust assuming visco-plastic sediment behavior. The combined fluid and mechanical calculations describe large deformation flows and include dynamic pore fluid pressures. Simulation of evolution of passive margin after 45 m.y. (top) Lithology: shale is shown in light and dark green and the sand-dominated material is shown in red, orange, yellow, and blue. Crust is shown in light gray. (bottom) Horizontal component of the strain rate and flow velocities. Coupled upslope extension, intermediate translation, and downslope contraction above a deforming shale layer is shown.The vertical exaggeration (VE) is 6. [modified from Ings and Beaumont, in press].

conditions and material properties. These data can be fed to coupled mechanical and fluid flow models to understand the driving processes controlling the geometry of continental margins.

How do fluxes of sediment to margins, and the landscapes they support, respond to changes in climate and land-use? How can these insights be used to predict future changes expected for large, heavily populated, low-lying deltas?

The shoreline position is a delicate function of multiple complexly interacting natural processes [e.g., *Blum et al*., 2008; *Blum and Roberts*, 2009], yet it is the focus of significant human population, modification, and infrastructure. Understanding these processes is critically needed in order to anticipate shoreline changes and manage our responses to them. The land loss rate on the Mississippi delta is estimated to be 44 km^2/year, and at this rate it is estimate that New Orleans will be exposed to the open sea by 2090 [Fischetti, 2001]. Since Hurricane Katrina (August 29, 2005) highlighted the deleterious effects of the loss of a land buffer between New Orleans and the sea, arguments have been presented for opening the levees and creating engineered river diversions to build new land. Recently a physically based model of deltaic river sedimentation predicted that 700-1200 km2 of new land (exposed surface and in-channel freshwater habitat) could be built over a century using a conservative sediment supply rate and a reasonable range of rates of sea-level rise and subsidence (Figure 5.13) [*Kim et al*., 2009]. To better predict this behavior, we need to understand how deltaic morphodynamics respond to spatially variable subsidence, which can be driven by long-term lithospheric processes, as well as surface processes such as more frequent coastal storms, sediment load reduction and compositional changes due to upstream dams, and dynamic ecosystem evolution. Continental margins around the globe are subject to rising sea level with the consequence that many of these margins are pre-conditioned for significant impact from storms or waves. Ultimately, we must determine the resiliency of margins to perturbations in climate forcing, sediment fluxes, and land-use. We should thoroughly decipher sedimentary archives to provide a predictive science to prepare for better use and management of continental margins in the near future. This can be accomplished by combining targeted studies of modern coastal systems with expressions of past coastal zones that are defined using shallow geophysical tools and wells. For example, studies of modern systems can provide information critical to developing numerical models

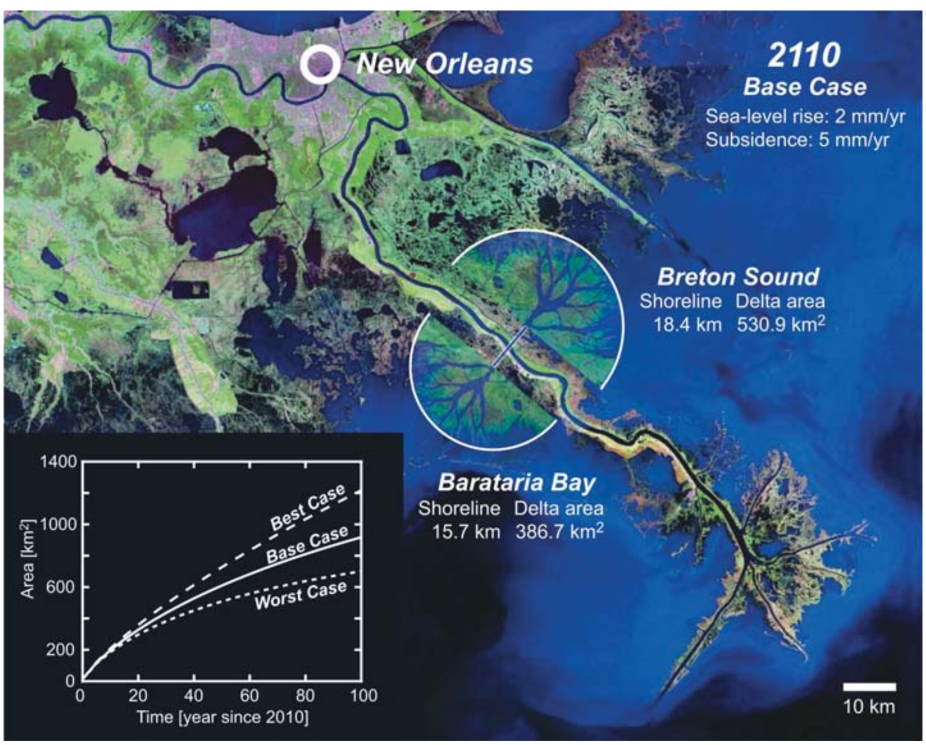


Figure 5.13. Application of scientific understanding of balances between sedimentation, production of accommodation space, and process transitions to the prediction of future changes expected for large, heavily populated, low-lying deltas. This schematized prediction of the lower Mississippi River below New Orleans shows the predicted new land (delta surface) that could be built over the next 100 years depending on sediment flux, sea level rise, and subsidence rate [from Kim, et al., 2009a based on Kim, et al., 2009b].

that accurately characterize shoreline adjustments associated with large cyclonic storms, as well as models that accurately route land-building sediment through distributary networks of delta channels. Study of shoreline and coastal deposits throughout the Quaternary will provide quantitative definitions of coastal adjustments connected to a range of changes in both climate and sea level.

5.4 What are the mechanisms and consequences of fluid and volatile exchange between the Earth, oceans, & atmosphere at rifted continental margins, and between the lithosphere and the mantle?

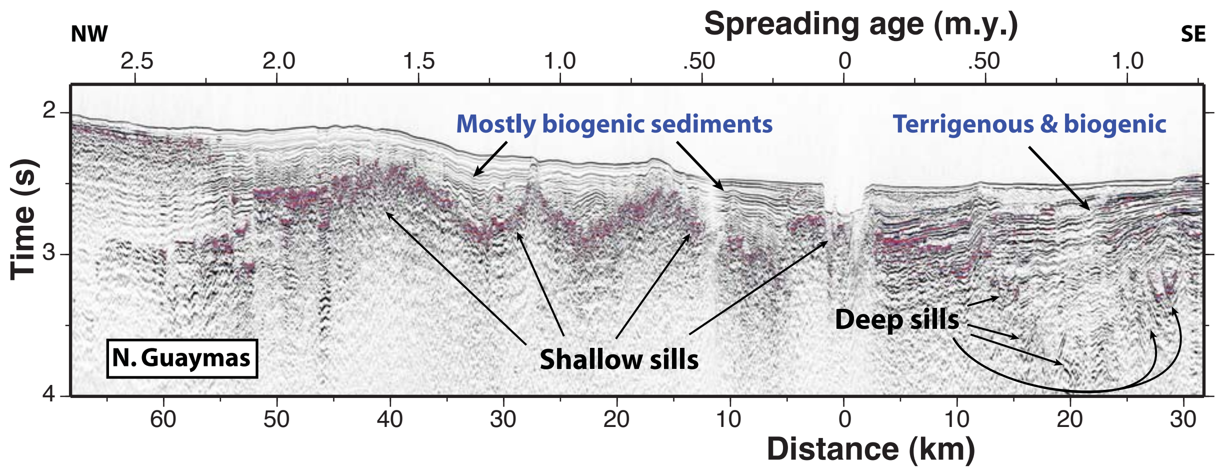
Continental rifts are key sites where volatiles are exchanged between the deep Earth and its surface reservoirs. Crustal and mantle materials may also be recycled to the mantle via thermal erosion and delamination processes, subsequently changing magma sources in rifts and incipient ridges. Volatiles play a critical role in controlling the physical mechanisms by which rifts initiate, the spatial and temporal distribution of magmatism, biological processes, and geologic hazards. However, to date relatively few studies have focused on quantifying the fluxes of volatiles during rift evolution.

What are the net volatile fluxes at continental rifts?

At continental rifts and passive margins, volatile exchange between the Earth's mantle and its exospheric reservoirs is controlled by the rate of magmatic degassing and the rate of chemical sequestration due to alteration (e.g., serpentinization) and precipitation [e.g., *Marty and Pik*, 1996; *Karner et al*., 2007]. The relative importance of these processes is likely controlled by the style of rifting (magma-poor versus magma-rich). For example, in volcanic rift zones, rift initiation is typically accompanied by large amounts of igneous activity, which is often attributed to the presence of a thermal or chemical anomaly at depth [e.g., *White and McKenzie*, 1989]. In this scenario, the large outpouring of magma would likely be accompanied by significant degassing of volatile species including CO_2, SO_2, and H_2O; high SO_2 fluxes are observed in satellite-based remote sensing measurements of degassing volcanoes in the cratonic lithosphere of East Africa [e.g., *Carn et al*., 2008]. Furthermore, magmatic intrusions into sediments can also cause degassing (see below [*Svensen et al*., 2004; *Lizarralde et al*., in review]. Volatile measurements and flux estimates for magma-poor rifts are limited; however, recent volatile studies at ultra-slow spreading ridges can yield insight into processes that may be analogous to the early stages of rifting in continental settings. Recent estimates for volatile fluxes from the ultra-slow spreading Gakkel Ridge based on melt inclusion studies show that although volatile release is likely episodic, the absolute volatile fluxes from these settings may be globally significant [*Shaw et al*., 2010]. The caveat is that magma-poor rifts frequently expose lower crustal and upper mantle rocks at the seafloor [*Boillot et al*., 1998; *Whitmarsh et al*., 2001]. Weathering and subsequent alteration of these rock types (particularly serpentinization of mantle peridotite) have the potential to sequester significant amounts of CO_2 and other volatiles. A major byproduct of serpentinization is methane. Future geochemical studies to quantify volatile release during rifting and the rates of sequestration during alteration are necessary to determine the relative importance of these competing processes at both magma-rich and magma-poor continental rifts to assess whether these systems are net sources or sinks for different volatile species.

What are the reservoirs and release mechanisms for volatiles from rift inception to breakup?

Rifting promotes erosion and weathering and creates depositional accommodation space. Sediment deposition into rift basins may represent a net atmosphere-to-ocean carbon flux, with rift basins being a carbon sink and long-term sequestration site. Subsequent intrusion of these basins by rift magmas represents an atmospheric C source via thermogenic alteration of C-rich sediments and the release of CO_2 and CH_4, as hypothesized for the Paleocene-Eocene boundary in the North Atlantic [*Svensen et al*., 2004] and in Siberia at the end of the Permian [*Svensen, et al*., 2009]. Such methanogenesis that



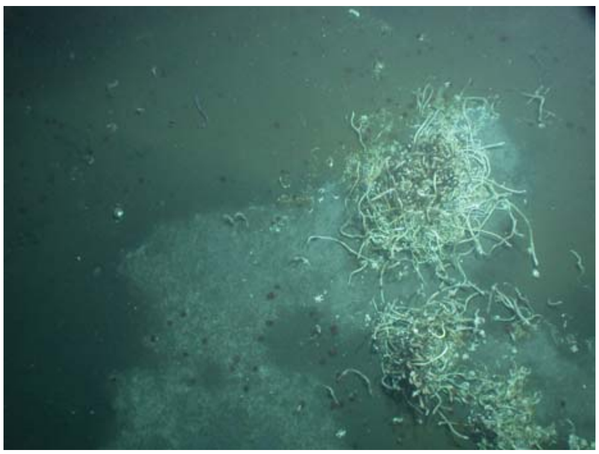


Figure 5.14. (top) Multi-channel seismic profile showing shallow sills intruded into biogenic sediments in the northern Guaymas Basin, Gulf of California. (left) Tube worms observed with deep-tow camera system located above a prominent sill ~27 km northwest of the rift axis in the top panel. Figure courtesy of Dan Lizarralde.

might be caused by magma intrusion in sediments has the potential for significant consequences for climate in the past [*Dickens*, 2004],. Recent active source seismic studies in the Guaymas Basin of the Gulf of California suggest that magmatic sills are intruded into thick piles of organic-rich sediment significant distances from the rift axis (Figure 5.14). Presumably, these intrusions heat the surrounding sediments thereby releasing volatiles and driving active venting at the seafloor [*von Damm et al*., 1990; *Lizarralde et al*., in review; *Svensen et al*., 2004]. However, the cause of the off-axis volcanism in the Guaymas Basin and Gulf of Aden [*Lucazeau et al*., 2008] and its relationship to the high sedimentation rates in the former are unknown. And, sedimentation and magmatic intrusion are occurring at the same time, so the sink and the source may cancel each other out to some poorly known extent. Future seismic and geochemical studies can investigate whether volatile release associated with off-axis sill intrusion is a common process at highly sedimented continental rift zones and to estimate the magnitude of these volatile fluxes. Understanding the linkage between magmatism, gas storage, and volatile release within rift basins is necessary to make progress towards evaluating volatile fluxes, geohazard mitigation, and alternative energy sources.

Another potentially important sink for CO_2 in rift systems is through the carbonation of mantle peridotite in regions where the upper mantle is exhumed during rifting [e.g., *Kelemen and Matter*, 2008]. However, the efficiency of this process is controlled by the rate of carbonation, which remains poorly constrained in natural systems. In particular, laboratory studies are required to address the kinetics of carbonation reactions as well as the evolution of permeability during alteration. These studies can then be linked to rates of mantle exhumation during rifting in order to place bounds on the total amount of CO_2 sequestered during rift evolution.

What role do volatiles play in the initiation and evolution of rifting?

Volatile species such as H_2O and CO_2 significantly reduce the melting point of mantle peridotite [e.g., *Mysen and Boettcher*, 1975; *Dasgupta and Hirschmann*, 2006; *Grove et al*., 2006]. Thus, the presence of volatiles in the mantle prior to rift inception has the potential to promote melting, which in turn has been shown to facilitate continental rifting (Figure 5.14). In the Gulf of California it has been suggested that volatiles released as the relict Farallon slab descended into the mantle and heated may have contributed to later melt production beneath the Gulf [*Wang et al*., 2009], and limited data suggest that melting during the onset of the Woodlark Rift opening may likewise reflect influence of prior subduction [e.g., *Lackschweitz et al*., 2003]. Likewise, volatile contents of melt inclusions from volcanoes in the East African rift show elevated water contents and this excess water could play an important role in generating melts and potentially initiating rifting [*Head et al*., 2009]. Satellite-based remote sensing studies of SO_2 in the East African Rift also argue for enhanced volatile contributions in rift settings; measured SO_2 fluxes at Nyamuragira volcano are comparable to other high gas flux volcanoes (e.g., Kilauea, Etna) [*Carn and Bluth*, 2003]. However, despite these observations, recent volcanic gas studies based on N_2, CO_2 and noble gases at Oldoinyo Lengai, located in the eastern branch of the East Africa Rift, suggest that the source of volatiles is indistinguishable from the mid-ocean ridge source [*Fischer et al.*, 2009]. Further geochemical analyses of volatiles in volcanic glasses, melt inclusions, and fumaroles are necessary to identify magmatic inputs, volatile fluxes, and to assess the role of volatiles in promoting melting during rift evolution.

Not only are volatile fluxes from the mantle to the surface important in controlling lithospheric rheology during the early stages of rifting, hydration reactions at the surface may also influence deformation patterns, particularly during late-stage rifting and after plate rupture. Fluid flow along faults can cause the formation of weak, hydrous minerals and/or elevated pore pressures, which may allow faulting at lower stresses than would otherwise be possible [*Shipboard Scientific Party*, 1999; *Floyd et al*., 2001]. Once enough extension has occurred for embrittlement of the entire crust, fluids may be able to transit through the crust along faults and cause serpentinization of the upper mantle [*Pérez-Gussinye et al*, 2001]. Even small amounts of serpentinite can result in significant reduction in strength [*Escartin et al.*, 1997], which might allow deformation to localize at the crust-mantle boundary and facilitate the formation of detachment faults and/or rolling hinge faults [*Lavier and Manatschal*, 2006; *Reston et al*., 2007]. Such faults are thought to expose large tracks of mantle rocks on magma-poor rifted margins [e.g., *Whitmarsh et al*., 2001] and at slow-spreading and ultra-slow-spreading mid-ocean ridges [e.g., *Blackman*, 2010], at which point they can undergo more pervasive serpentinization. Serpentinization produces H_2 and CH_4, which may in turn influence ocean chemistry, facilitate carbon precipitation and fuel ecosystems [e.g., *Kelley et al*., 2005].

The rates of fluid flow and subsequent alteration of the mantle during rifting are poorly constrained. Seismic and drilling studies are required to assess the extent of alteration at depth in different rift settings. Further, geodynamic modeling studies are required to evaluate the importance of key feedbacks between volatiles, melting, and crust and mantle rheology during rifting.

5.5 RIE in the Next Decade

The questions posed above for the Rift Initiation and Evolution (RIE) Initiative represent maturation in the approach to understanding rifted margin processes and evolution in GeoPRISMS relative to MARGINS. These questions build on important findings arising from intense collaborative investigations at the MARGINS focus sites, primarily along the Gulf of California, as well as a range of studies conducted outside of MARGINS in passive margin settings and non-focus site locales; all provide fundamental insights into the range of processes and problems active during and following rifting, and demonstrate the prominent interplay between surface processes, lithospheric dynamics, rift zone deformation, and magmatism at rifted margins from initiation to conclusion. A good part of this history lies in the sedimentary record so well preserved along passive margins, and which continues to be modified by gravitational, climatic, and anthropogenic processes. RIE will enable integrated studies of tectonic and surficial processes along the entire spectrum of rifted margins, to clarify the rates of important processes through time and their contributions to rift zone evolution and the development of lithospheric and stratigraphic architecture and geomorphic configuration through time.

The RIE Initiative is poised to make headway on the ambitious questions above by testing specific predictions that have been made by recent modeling and experimental work, for example regarding the distribution and styles of extensional deformation throughout the lithosphere over time [e.g., *Nagel and Buck*, 2004; *Lavier and Manatschal*, 2006, *Huismans et al*., 2008], the volume of magmatism involved in rift initiation and development [*Van Avendonk et al*., 2009; *Bialis and Buck*, 2010], and its interactions with lithospheric deformation. These predictions can be tested using a combination of geophysical imaging, geochemical analysis and geological observations.

The extensive list of resources and methods necessary to address the RIE questions, and the complexity of Earth system interactions in the evolution of rifted margins, highlight the need for integrated investigations offered by the GeoPRISMS program. The study of these complex interactions, which occur over a wide range of spatial and temporal scales, and are often incompletely recorded by the geology, becomes truly interdisciplinary as we harness many observational and experimental/modeling tools to build a predictive understanding. Not only do these systems cross disciplinary boundaries, but also the fundamental boundary of the shoreline. A coordinated GeoPRISMS program brings together the intellectual capacity of the diverse and vibrant communities interested in these problems, ever-improving observational and experimental/modeling technologies, and the resources to build basic and useful understanding of these systems. The results of RIE investigations will have applications to the sustainability of human civilization living close to the shoreline, the search for economic resources that lie along these margins, and the mitigation of nearshore geologic hazards.

GeoPRISMS
Draft Science Plan

6. Implementation of Science Objectives

6. Program Implementation

This Draft Science Plan describes the overall goals and architecture of GeoPRISMS, with the intent that a final Plan and full implementation will await further community workshops where specifics are fleshed out and prioritized, including any site selection. Here, we describe the proposed implementation structure for GeoPRISMS best suited to meet the scientific goals, then detail the overall timeline for generating a complete Science Plan vetted by the community. However, several recent and ongoing observational programs, including those launched under MARGINS or ARRA funds, already have strong community support and are compatible with GeoPRISMS objectives. These realities dictate that maximum scientific return will occur if some of these activities can commence immediately under proposals funded by the FY11 budget, and are part of the motivation for rapidly submitting this Draft Science Plan shortly after the MSPW. We justify these opportunities below.

6.1. Proposed Implementation Structure for GeoPRISMS

Achievement of the scientific objectives of the GeoPRISMS Program will require a new approach, modified slightly from the successful focus site approach of MARGINS. The selection of up to two focus sites for each initiative under the MARGINS program allowed for the concentration of resources and expertise, and enabled rich interdisciplinary selection of many non-US locales. These sites encouraged strong international collaborations as well as productive ODP and IODP drilling efforts in Nankai and Central America. Clearly, a great deal of research has, and continues to be, accomplished at these focus sites beyond that originally envisioned. The benefits of such concentrations of resources and effort at the MARGINS focus sites will carry into GeoPRISMS, defining strong reference data sets upon which subsequent research can be built. By default, the new "Primary" sites for the GeoPRISMS program will differ from the previous ones, unless strong justifications are made to the contrary.

Several of the science questions outlined above, however, also clearly reveal that there are many scientific questions integral to GeoPRISMS objectives that cannot be completely addressed at one or two research locales, but require more global comparisons. For example, rifting proceeds from early continental extension through lithospheric rupture to the generation of an ocean basin, and understanding the full evolution may be clearer by comparing a suite of archetypical sites. Similarly, the seismic cycle on plate-boundary thrusts can last hundreds of years, therefore much may be gained by contrasting multiple sites at different stages of the seismic cycle. In a rather different way, understanding the global volatile and mass fluxes at subduction zones seems likely to require global comparisons and different sites to constrain the fluxes to the deep Earth, or to constrain the conditions controlling arc growth rates. Finally, our understanding of the metamorphic reactions occurring along the downgoing-overriding plate boundary in subduction zones, and volatile-rock interactions associated with serpentinization requires close coupling and investigations of active processes and corresponding ancient, exposed rock sequences wherever they occur. These arguments lend support to including a thematic component in the new program, emphasizing community-selected, well-formulated, and tractable themes.

To achieve the scientific objectives of GeoPRISMS, we propose a "hybrid" approach, in which major field efforts predominantly take place at 1-2 Primary Sites per initiative, generally different from previous MARGINS focus sites. However, the program will fund critical efforts at other sites that provide essential observations not otherwise attainable at the Primary Sites, but which are central to Science Plan objectives, for example:

- *Sites that represent endmembers of critical parameters;*
- *Sites that supply critical components of global comparisons*

- *Sites that uniquely exhibit certain phenomena obscured at Primary Sites;*
- *Sites that typify different stages of margin evolution.*

Some of the MARGINS focus sites can serve as reference sites for such studies, benefiting from abundant baseline data or time series; comparative or complementary studies can evaluate their global or evolutionary significance. Research released from the constraints of focus sites also allows a broader community to participate, rather than favoring those most vested in a specific locale. This will serve to grow and strengthen the GeoPRISMS community. Major initiative workshops, described in Section 6.2, will be held to organize Primary Site and Theme selection and to coordinate research plans. The chosen models implemented for carrying out the science objectives for the GeoPRISMS program can also vary between the initiatives. These decisions will be made at the community workshops to ensure the best science in the most appropriate locations. This approach builds on the MARGINS Focus Site approach but extends it, as recommended by the 2009 DRC Report.

Given the availability of new near-US facilities (EarthScope, OOI, etc.), enthusiasm for the study of US coastal systems and geohazards, and basic logistical considerations, it seems likely that at least part of the successor program's focus will lie near North America. However, scientific needs, strong international partnerships, and critical infrastructure at present outside of North America (e.g., the next few years of riser drilling) will motivate some non-US sites. The appropriate balance between these opportunities will be made at directed community workshops.

As with MARGINS, outstanding research proposals that address the broad themes and initiative goals of GeoPRISMS, but fall outside the specific Primary Site and thematic topics identified by the community, could also be considered for funding. Examples include broad laboratory, modeling and theoretical studies as a basis for synthesizing and generalizing Primary Site field efforts. Such studies have been critical to the success at MARGINS in integrating observations from distant disciplines. Also, the theoretical results provide a strong basis for generalizing results from individual sites to understand the underlying processes, including the over-arching themes that span the SCD and RIE initiatives. New facilities and resources, such as CIG and CSDMS, provide new opportunities for increased rigor and community participation in these efforts.

6.2. Approach and timetable for finalizing the GeoPRISMS Science Plan

The SCD and RIE initiative plans, key scientific questions, and implementation methods outlined above represent preliminary consensus, based primarily on the outcome of the MARGINS Successor Planning Workshop. While these discussions offer a strong basis for proposing the GeoPRISMS successor program, there are clearly many details still to be resolved. In particular, the community must agree upon the specific themes that will be tackled, as well as how and where the research will be carried out. Primary Sites, where deemed necessary, will have to be selected based on the best science and the strength of the available or acquirable data sets. These decisions will impact future interactions with international partners and industry colleagues, as well as with other NSF programs and facilities such as EarthScope. The ultimate decisions and selections will certainly factor into the feasibility and fundability of the GeoPRISMS program.

To make these final decisions, initiative-based planning workshops will be organized as soon as possible, and announced after the hoped-for NSF approval of GeoPRISMS. The call for workshop applications will tap the wider community, independent of previous participation in the MSPW or MARGINS, to ensure the broadest input, with the anticipation of two workshops, one for each Initiative. Workshop objectives will include:

- Refine the initiative themes and key unanswered questions outlined here
- Resolve which themes require Primary Sites to answer

- Prioritize the scientific objectives, themes, and questions
- Identify, justify, and select 1-2 Primary Sites per initiative
- Finalize plans for ramping down work at existing MARGINS Focus Sites
- Identify international partners and national collaborative agencies
- Outline research approaches and timetables for each theme and focus site
- Identify and charge the final Science Plan writing team

Smaller workshops may be organized around overarching themes to help clarify the specific questions and scientific approaches required for each initiative, and to guide the initiative-based workshops.

Pending NSF approval and funding availability, these planning workshops will be organized for Fall 2010, providing the necessary input for the final Science Plan to be drafted by the end of 2010. This timetable could lead to a full solicitation in 2011, in time for FY12 funds, should NSF allow.

6.3. Immediate (FY11) Opportunities for GeoPRISMS

A number of ongoing and new data collection efforts provide critical and immediate opportunities for GeoPRISMS. As a result, there is great community momentum and need for a focused program in the short term, taking advantage of these facilities and the excitement they have engendered. Hence, there are several opportunities and reasons to begin support of some activities immediately, on the basis of this Draft Science Plan and the recommendations of the DRC. As detailed below, these include:

(1) activities in existing MARGINS Focus Sites that ramp down efforts but bridge to GeoPRISMS priorities, including syntheses and continuation of long-lead-activities;
(2) multidisciplinary and amphibious activities taking advantage of the joint ARRA-funded MARGINS-EarthScope Cascadia Facility Enhancement (2010-2014);
(3) studies that complement the USArray Transportable Array deployment as it reaches US passive margins (2010-2013);
(4) collaborations with the USGS and NOAA in Law of the Sea activities (2010-2015);
(5) and relevant rapid response surveys, should they occur.

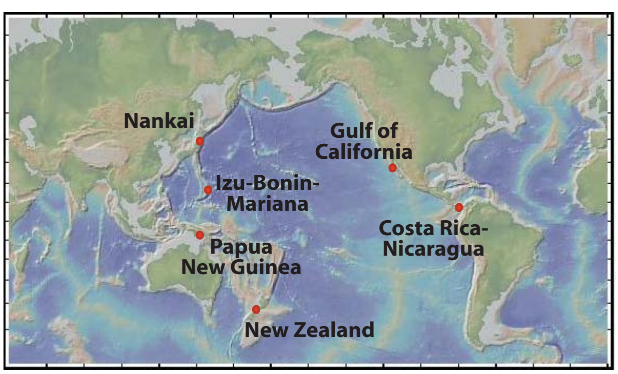


Figure 6.1. 2000-2010 MARGINS Focus Sites.

Other time-sensitive activities in subsequent years (after 2011) might include complements to Alaska-Aleutian deployment of the USArray and activities that complement priorities of an IODP successor; these can be specified in future Science Plan revisions. The priorities elucidated here should form sufficient motivation to institute funding as soon as approved by NSF without substantial hiatus.

6.3.1 Time-sensitive Opportunities at Existing MARGINS Focus Sites and Integration Activities

While it is expected that work at existing MARGINS Focus Sites (Figure 6.1) will wind down, as envisioned in that program's decadal science plan and recommended by the DRC, certain activities form a natural bridge to GeoPRISMS and should be supported. As recommended by the DRC, there are uncollected data sets at several of the MARGINS focus sites that are still needed to answer the fundamental initiative questions (e.g., Gulf of California/Salton Trough), whereas others have gained stature as international focus sites for IODP drilling (e.g., Nankai, Izu-Bonin and Central America). At some sites, new infrastructure provided by other programs (e.g. EarthScope at

Salton Trough; IODP at Nankai) will produce new major data sets regardless, and GeoPRISMS could play a critical role in providing a complementary multidisciplinary perspective and broad intellectual framework for studies of these data. Also, some priorities of GeoPRISMS (e.g. understanding strain and deformation; understanding eruptive outputs of volcanoes) are best addressed via long-term records, many of which have been started at SubFac, SEIZE and RCL focus sites. Such long-term records seem worth continuing in many cases, and in most cases, it would be inappropriate to abandon ongoing research begun under MARGINS, not all of which have reached completion. Within the next year, it is expected that initiative communities will establish final priorities for supporting continuing research projects vs. initiating surveys in new locations.

In addition, work that does not involve a large investment in field campaigns could begin immediately. It is envisioned that GeoPRISMS will incorporate a host of computational, experimental and analytical studies, as did MARGINS, and such laboratory-based projects could begin before specific research sites are selected. In particular, it seems likely that global comparisons or broad theoretical studies could go far toward quantifying a framework of specific hypotheses that could be tested at old and new focus sites. Examples of such global and theoretical comparisons abound in both the SCD and RIE descriptions above.

6.3.2. Cascadia Initiative

NSF's Earth Sciences (EAR) and Ocean Sciences (OCE) divisions each received $5M in facility-related investment from the 2009 American Recovery and Reinvestment Act (ARRA) spending to support EarthScope and MARGINS science objectives in the Cascadia region. The resulting amphibious geophysical facility (Figure 6.2) enhances EarthScope/PBO GPS stations, deploys 27 USArray-style Transportable Array (TA) stations, and builds a pool of 60 shallow and intermediate depth Ocean Bottom Seismographs (OBS's) that will be deployed offshore of the Cascadia margin starting in May/June 2011. After an initial 3-5 year Cascadia deployment, the OBS and TA stations will become part of the OBS and PASSCAL Instrument Pools to be deployed elsewhere. Additionally, nodes of the Ocean Observatories Initiative (OOI) will be installed off Cascadia in the coming years, making this margin one of the best-instrumented subduction zones on the planet.

To guide this facility, in July 2009 the chairs of the EarthScope and MARGINS Steering Committees convened a 24-person Planning

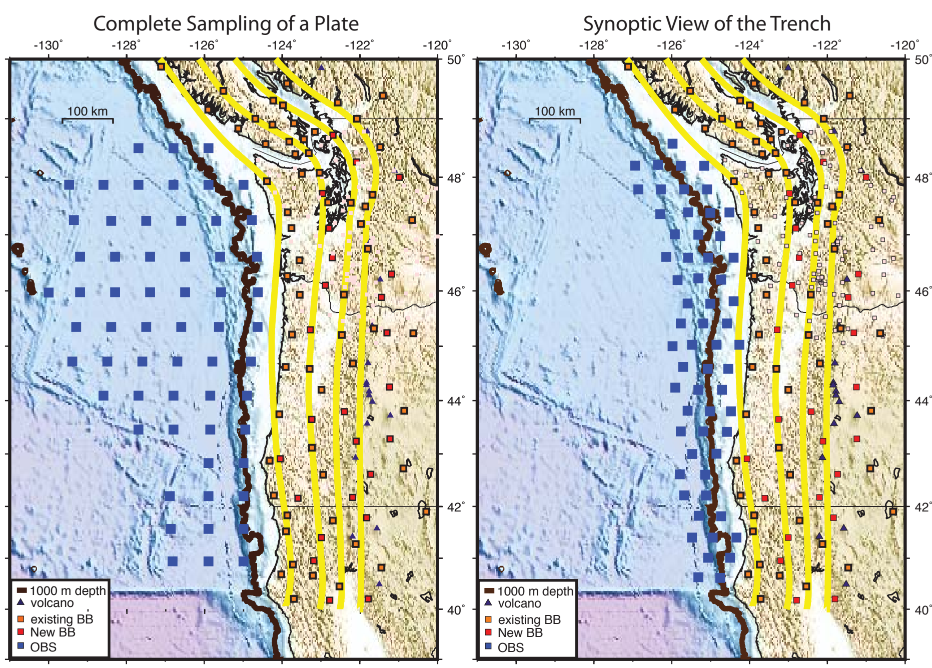


Figure 6.2. Possible deployment options for Cascadia Amphibious Array (2009 Whitepaper).

Group (see whitepaper: *www.nsf-margins.org/Cascadia/09meeting*). Subsequently, a smaller Amphibious Array Steering Committee (AASC) was formed to provide advice and facilitate coordination between the facilities and the community, and to convene a community-wide workshop in October 2010 to elucidate scientific objectives and implementation plans.

Most of the science objectives initially identified have significant overlap with those of MARGINS and GeoPRISMS. These include: (1) understanding the connections between thermal structure, fault zone composition, metamorphic dehydration, pore pressure, fault strength and fault slip behavior; (2) determining water transport in a young subduction zones; (3) identifying melt production and the plumbing system of volcanoes; (4) understanding seismic anisotropy and mantle flow patterns and the segmentation at subduction zones. Even without the large infrastructure investment, Cascadia is a high-priority subduction zone site, for several reasons. As recognized in the MARGINS Science Plan, Cascadia represents an extreme thermal endmember of subduction. The subducting Juan de Fuca plate is the youngest to subduct anywhere and still generate a volcanic arc. It is also one of the first margins at which Episodic Tremor and Slip (ETS) have been observed, and still has arguably the strongest and most extensive ETS record. Thus, this is likely a high-priority site for GeoPRISMS.

GeoPRISMS can complement EarthScope support of science in Cascadia in several ways. It provides a global framework for subduction zone studies. It also provides access to a deeply interdisciplinary community, who can bring tools that complement the geophysical facility investment and can put discoveries in broader context. Finally, it provides a natural means for crossing the shoreline, conducting marine and amphibious studies that complement terrestrial observations of EarthScope.

Because this facility is being deployed in 2010-2011, and is expected to move after 3-5 years, urgency exists in funding any projects making use of it.

6.3.3. USArray Studies of Other US Margins

The EarthScope facility represents a major investment in the Geosciences in generating data streams of high relevance to GeoPRISMS. The multiple components of the EarthScope program provide open-access, commonly real-time data from seismic, geodetic, electro-magnetic, and borehole data to measure the multiple time and length scales of plate boundary deformation (PBO), to recover rock samples from the seismogenic zone (SAFOD), and to seismically image continental lithospheric and deep Earth structure (TA). As the TA marches across North America from west to east, it serves as a natural focus on a variety of scientific problems. In particular, its swaths of ~400 broadband seismographs reach the Texas Gulf Coast and northern East Coast passive margin areas beginning in 2010 and 2013, respectively (*http://www.usarray.org/maps*). Thus the window for concurrent complementary studies across these margins is fairly short, and planning activities should begin immediately.

The Gulf Coast and Atlantic Coast targets are areas of interest to RIE, given the potential to understand the full history of the opening of the Gulf of Mexico and Atlantic Ocean, through the study of the crustal structure of both passive margins. Such inquiry is a natural complement to what was learned from the Gulf of California MARGINS focus site, as recognized by the Decadal Review Committee. For example, comparison of the non-volcanic eastern and magmatic western Gulf of Mexico margins, East Coast margins, Gulf of California, and other margins worldwide allows for an unprecedented study of the role of inherited tectonic features on their magmatic and structural evolution, and also allows for a direct comparison of the role of sediment flux on margin evolution. The Gulf of Mexico also allows leveraging of a large industry dataset, enhancing industry ties as emphasized by the DRC, and will impact ongoing petroleum exploration efforts in the Gulf. Thus, studies of these margins fit in well with GeoPRISMS priorities outlined previously, and the infrastructure investment provided by EarthScope has potential to foster significant new discovery.

The partnership here between the EarthScope science program and GeoPRISMS seems natural and probably necessary to achieve both program's goals. The full import of the EarthScope experiment can only be achieved through combined offshore-onshore efforts, both with seismic and MT experiments, and in 3-D. Both programs have major elements that integrate lithosphere-scale Earth structure with deformation on its surface, and with near-surface geologic processes. Research opportunities are enhanced by vintage industry seismic and borehole data sets along the US East Coast, as well as onshore well and seismic data. GeoPRISMS and EarthScope can leverage industry in a common partnership, as in the Gulf Coast.

TA's west-to-east imaging swaths conclude in 2015 when instrumentation is scheduled to move to Alaska. The potential for innovative and compelling SCD Initiative science in onshore-offshore experiments in Alaska are tremendous, and will be clearly an important topic at a Subduction Initiative workshop expected in late 2010.

There is some sense of urgency to TA and GeoPRISMS linkages on the East Coast passive margins, given the ca. 3 year lead time for the OBS equipment pool.

6.3.4. Law of the Sea - the US ECS Project

The U.S. multi-agency Extended Continental Shelf (ECS) Project was created to establish the full extent of the nation's "continental shelf" consistent with international law. The United Nations Convention on Law of the Sea (UNCLOS) provides the criteria for defining this region beyond 200 nmi from the territorial baselines, based upon knowledge of bathymetry, sediment thickness and geologic context. The US Department of State, US Geological Survey, and NOAA are the primary partners in this effort.

The ECS Project has identified a dozen regions with potential for ECS along the margins of the US and its Pacific Islands (Figure 6.3; *http://continentalshelf.gov/*). New 2D seismic reflection data are required for the Arctic, the Bering Sea, the Gulf of Alaska, the Atlantic margin, and possibly also the Northern Marianas region and the Line Islands collected by the USGS. Targeted OBS refraction data are also needed in each of these potential ECS regions. New

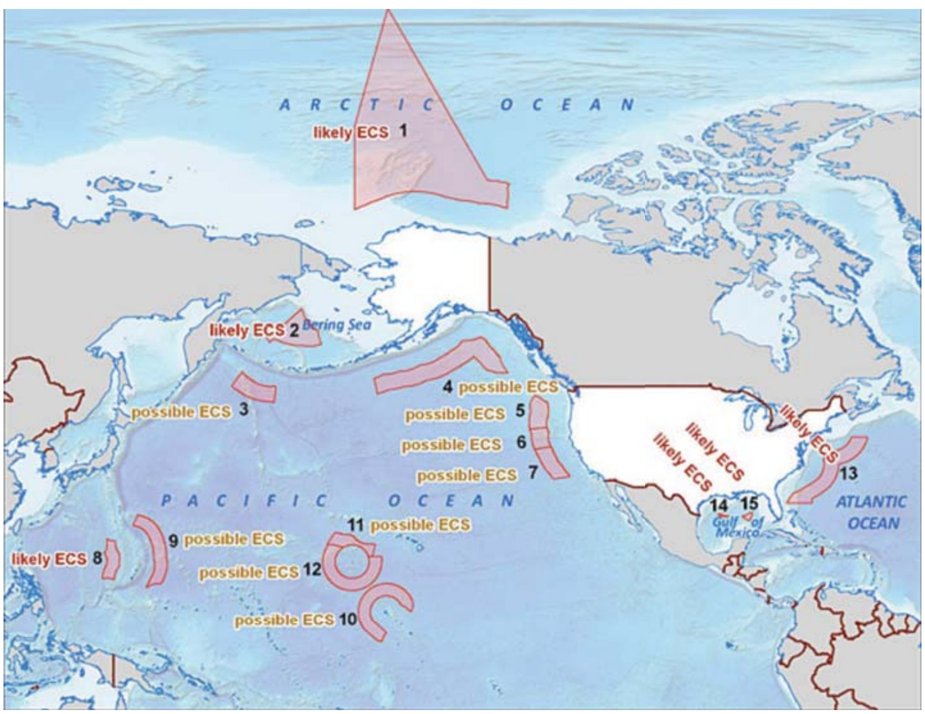


Figure 6.3. Areas where the U.S. is considering collecting and analyzing data as part of the ECS program (continentalshelf.gov).

multibeam bathymetry data have also been collected or are planned to meet specific ECS objectives in each of these regions, by NOAA and Univ. New Hampshire (*http://ccom.unh.edu/*).

The time line for the ECS project is to complete all necessary data acquisition within ~5 more years (e.g. by ~2015). The planning of ECS-specific data acquisition is inherently governmental, but the funded ECS program provides an opportunity to plan coordinated studies that will enhance the value of both ECS and academic programs. The regions of ECS interest have significant overlap with previous and proposed GeoPRISMS study areas and USArray focus areas in both rifts and subduction zones. In general, the ECS studies will focus on deep-water regions to 350 nmi from the coast. Data collected by the US for the ECS project will generally be non-proprietary and will be publicly available. Analysis for ECS purposes may be highly specific, and further use of these data for academic studies is encouraged. Thus, the ECS studies offer opportunities for broad synergy between the ECS project work and GeoPRISMS, including potential access to tremendous new data sets in critical areas.

6.3.5 Rapid Response Research Opportunities

Potentially transformative scientific opportunities exist through a dedicated Rapid Response Plan. Many of the motivating questions posed in this Science Plan bear directly on the occurrence of unpredictable phenomena, such as large megathrust earthquakes and volcanic eruptions. The 2004 and 2005 Sumatra earthquakes, as well as the Feb 27, 2010 Chile earthquake offered rare and unique opportunities to acquire data immediately following a great earthquake, including aftershock distributions, postseismic surface displacements, and offshore bathymetric and/or seismic surveys to identify the rupture zone. Rapid responses to volcanic eruptions provide critical insights as well. NSF has readily promoted such rapid response surveys where feasible, often building on existing projects and leveraging research teams with appropriate international collaborations to facilitate logistical issues, now covered by the RAPID program. Data sets arising from such efforts will play an increasing role in clarifying the fundamental geologic processes of interest to GeoPRISMS research.

MARGINS researchers have been prominent participants in two major rapid response activities, during the 2003 Anatahan volcanic eruption [*Wiens et al*., 2005; *Wade et al*., 2005], and the recent boninite eruption in northern Tonga [*Todd et al*., 2009]. The successes of these two endeavors demonstrate the importance of mobilizing research activities in response to rare or extraordinary events, and the MARGINS-GeoPRISMS community affords an unparalleled nimbleness in this regard. GeoPRISMS is also ideally poised to offer new insights into a separate, but fundamentally important process: fluid-involved fault slip and seismically ‘silent’ dike intrusions, such as the Afar 2005 mega-dike intrusion. These events accommodate a significant but poorly quantified proportion of plate boundary strain, and involve complex relations between magma, volatiles and rocks (dikes) and metamorphic reactions, volatiles, and rocks (ETS). GeoPRISMS rapid response efforts will also support studies of seismically quiet, magma-involved rifting and subduction episodes to ensure measurements of volatile and magma flux, strain accommodation throughout the plate, and rheology of the crust and mantle.

Independent of the timeline for initial funding for the successor program, we recommend that a protocol exist for submission and approval of event-driven rapid response surveys of direct relevance to GeoPRISMS, which would enable rapid acquisition and release of data and observations to further advance GeoPRISMS scientific objectives. As such events are, by their nature, unpredictable, they offer immediate opportunities for GeoPRISMS-related investigations outside of the normal call for proposals, and should be considered in the near term.

GeoPRISMS
Draft Science Plan

7. Research Strategies

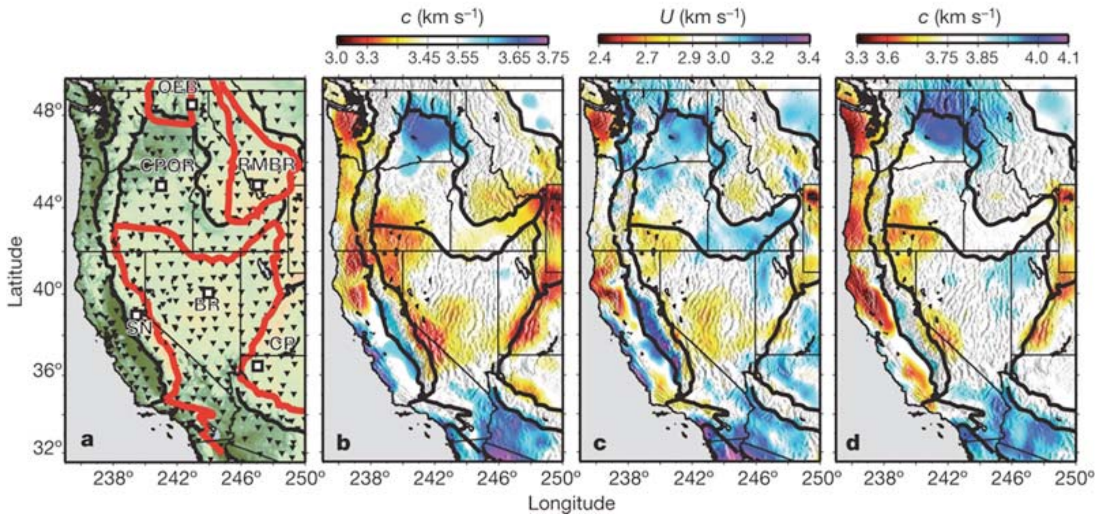


Figure 7.1. Results of ambient noise tomography in the (a)western U.S., showing at 20 s period maps of Rayleigh wave phase (b) and group(c) velocity, and Love wave phase speed (d)[Moschetti et al., 2010]. These methods are providing some of the first strong constraints on fabric within the lower crust, here interpreted to indicate significant anisotropy in extensional regions.

7.1. Seismology Research Strategies

Seismology is a core tool for executing GeoPRISMS science in both the SCD and RIE Initiatives. Seismic data acquisition takes the form of either passive seismic arrays that record natural seismic sources for periods of weeks to years, or active seismic experiments in which very dense arrays of short period seismographs or hydrophones record seismic signals generated by explosions or airguns. Combined, these datasets provide constraints on locations and properties of subsurface interfaces, variations in temperature, composition and architecture of the crust and mantle lithosphere that can be integrated with other geophysical, geological and geochemical constraints, and they provide direct observations of seismic sources that characterize deformation.

Passive seismic methods will be used for studies of natural seismic sources such as earthquakes and tremor, as well as larger-scale imaging studies. Discovery of the menagerie of seismic signals associated with subduction thrust faults (and possibly other tectonic settings) and magma-involved normal faulting, such as very low frequency earthquakes, slow-slip, and non-volcanic tremor, demonstrates the importance of collecting and archiving continuous broadband seismic data in active tectonic regions. Future study of slip properties along the subduction megathrust and other faults at both divergent and convergent plate boundaries will require the deployment of temporary dense seismic arrays for targeted study of seismic sources. In addition, deployments of broadband seismographs will be required to determine crustal and mantle seismic structure in the forearc and arc regions, as well as beneath rift flanks and fault-bounded valleys. For example, variations in P- and S-wave seismic velocity, velocity anisotropy, and attenuation will be used to understand the properties of the mantle source region for volcanic arc and rift magmas, and to quantify their spatial variability using tomographic methods. These variations will also be used to help constrain the pathways and transport mechanisms of fluids through arcs and rifts, and the strain fabrics of the deforming rocks. New analysis methods for passive data, such as ambient noise tomography, will constrain properties such as crustal S-wave velocity at greatly enhanced resolution (Figure 7.1). Interpretation of seismological structures from such studies will also inform and rely on experimental studies of rock properties at mantle temperatures and pressures, and geochemical analyses of volatile content and source P-T conditions.

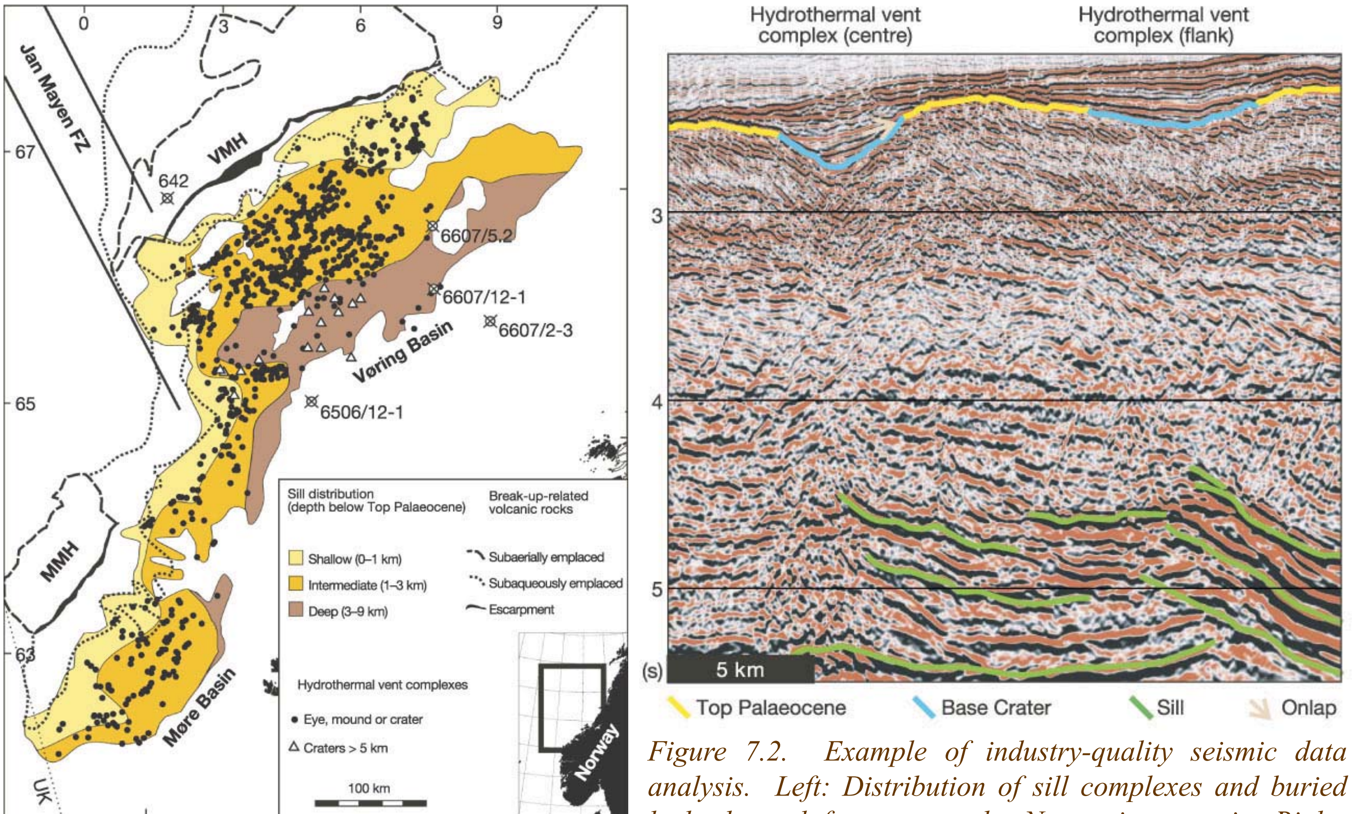


Figure 7.2. Example of industry-quality seismic data analysis. Left: Distribution of sill complexes and buried hydrothermal features on the Norwegian margin. Right: Seismic reflection profile demonstrating relationship between sills (green) and hydrothermal vent complexes (blue). Sediment degassing due to sill injection has been linked to dramatic climate change at the Paleocene-Eocene boundary [Svensen et al., 2004].

Active source seismic methods provide high-resolution constraints on sedimentary, crustal, and upper mantle structure that complement imaging with passive methods described above (e.g., Figure 7.2). There exist a variety of sources for such data sets that could be of great value to GeoPRISMS studies, including previously acquired academic seismic data archived within databases (Section 10.4), as well as 2-D and 3-D industry seismic data in areas no longer being explored or produced (Section 8.3). Additionally, the academic community now has the capability of carrying out marine 3-D seismic reflection surveys using the R/V Marcus Langseth (Section 8.1.2), offering unprecedented detail on, for example, the relative timing and interaction of faults in 3-D in both compressional and extensional settings, magmatic plumbing systems in the crust and their relationship to deformation, and the architecture and sequence stratigraphy of sedimentary systems, and the distribution of gas and other fluids in sedimentary basins. Furthermore, the 2-D seismic reflection data acquired with long streamers (8 km) and large, clean sources can yield deep images of faults in the crust and upper mantle (e.g., megathrusts and splays, border faults, and detachments) and provide excellent velocity constraints in sediments and the upper crust. Two and three dimensional wide-angle seismic surveys can provide constraints on the composition and physical properties of the crust and upper mantle, including magmatic intrusions into the crust, the composition and thickness of mafic magmatic lower crust in arcs and rifts, variations in crustal thickness due to thinning or shortening, and serpentinization of the upper mantle. Integrated analysis of active and passive source seismic data (particularly seismic anisotropy, local seismicity, receiver functions, and noise tomography) offers the opportunities for unprecedented imaging of the upper lithosphere.

As detailed in Section 8.1, the National Science Foundation has already made a significant investment in the advanced facilities required for seismological research, to the benefit of programs like GeoPRISMS. These include investments in state-of-the-art marine imaging vessels (R/V Langseth), earthquake seismology infrastructure through the Incorporated Research Institutions in Seismology (IRIS) , a growing pool of Ocean Bottom Seismographs (OBS) through the OBS Instrument Pool (OBSIP), and the joint MARGINS/EarthScope Cascadia initiative supported by ARRA funds.

7.2. Geodesy and Remote Sensing

Changes in the shape of the Earth (part of the field of geodesy) can provide important clues to processes occurring in the subsurface related to faulting and the movement of fluids (magmatic or otherwise). GPS geodesy made important contributions to the past MARGINS program in documenting the existence of slow earthquakes in Costa Rica and rift kinematics in the Gulf of California, for example. Clearly, geodesy could play a much larger role in making new discoveries along active continental margins in GeoPRISMS, taking advantage of a multi-faceted approach including measurements made in the sea, on land and from space.

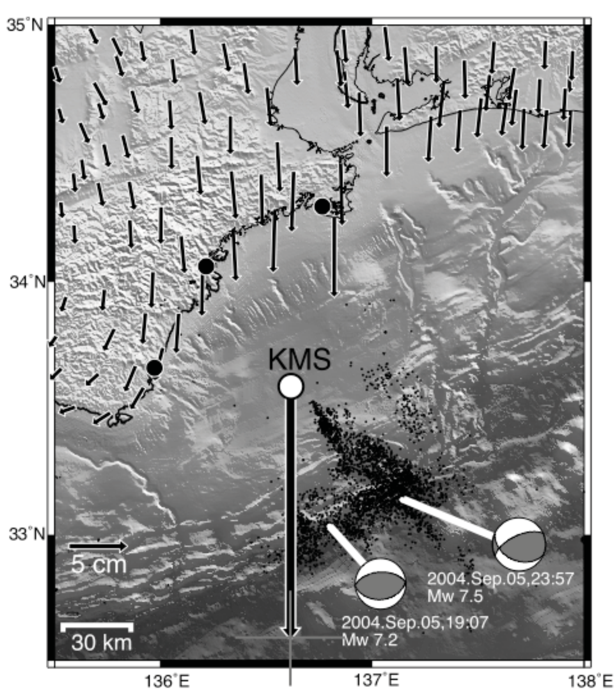


Figure 7.3. Coseismic slip for a Mw 7.5 Kumano Trough (Nankai) earthquake determined from a novel sea floor GPS-acoustic system (large arrow) [Ikuta et al., 2008].

Submarine Geodesy: There are several different systems for making geodetic measurements of movements of the seafloor, and the error bounds on some of these observations are small enough to make the techniques geophysically interesting. For example, continuous GPS-Acoustic buoy/seafloor transponder systems measure vertical and horizontal seafloor motions with cm-scale resolution (e.g. Figure 7.3); these could provide the first clues to constrain offshore strain accumulation during the seismic cycle [e.g., *Gagnon et al*., 2005]. Offshore geodetic measurements, combined with continuous monitoring of strain, pore pressure, and seismicity in boreholes, provide a powerful suite of tools for characterizing the nature and causes of offshore fault and volcano movements [e.g., *Spiess et al*., 1998; *Nooner and Chadwick*, 2009]. While there is currently no national facility for seafloor geodesy, there has been significant NSF and other investment in developing the technique. Internationally, the DONET system in the NanTroSEIZE study area (Japan) and the OOI/NEPTUNE-Canada system offshore Cascadia are scheduled to come online in 2010. Multiple methods might be pursued, including buoy systems, autonomous underwater vehicles, moored monuments that can be revisited in different campaigns, and cabled network systems that will provide data for both early warning systems and long-term focused studies targeting convergent, rifting and magmatic processes.

Land-based geodesy: Continuous GPS arrays around the world are being continually expanded, offering outstanding opportunities to observe plate motions at active margins directly. In subduction zones, a collaborative international circum-Pacific/Indian Ocean network could be used for real-time tsunami warnings (obviously in collaboration with many other agencies). Such a facility would also help to characterize the tectonic settings of slow slip events with implications for understanding the basic physics behind this enigmatic process. Surface displacement measurements from different subduction zones would also allow for a comparison of the nature and extent of ground deformation during different stages in the earthquake cycle that would be impossible in a single focus site over the timescale of a decade. Measurements during different parts of the earthquake cycle are necessary to determine a first order understanding of the physical processes and properties involved – for example, the frictional characteristics of the megathrust and the spatial variations in crustal and mantle viscosity [e.g., *Wang*, 2007]. Active rifting margins also exhibit complicated displacement fields, in response to seismic and aseismic fault slip and dike intrusions; GPS surveys are critical for discriminating the relative contributions of each process, and for resolving the spatial and temporal variability of rift zone deformation [e.g., *Calais et al.*, 2008].

Geodetic Imaging: An exciting new dataset to address the next decade of GeoPRISMS questions is Interferometric Synthetic Aperture Radar (InSAR), which can image sub-centimeter deformation of the Earth's surface on a 20 m scale for hundreds to thousands of kilometers. For example, InSAR can quantify the flux and location of magma and fluid movements in subduction zone volcanic arcs [e.g., *Wicks et al*., 2002; *Lu et al*., 2005; *Fournier et al*., 2010]; provide detailed images of fault slip in space and time on the subduction megathrust [e.g., *Pritchard et al*., 2002; *Chlieh et al*., 2004; *Pritchard and Simons*, 2006; Konca et al., 2008], and constrain the relative role of magma intrusion and earthquakes during rifting [e.g., *Wright et al*., 2006; *Biggs et al*., 2009; *Baer and Hamiel*, 2009]. To date, access to data from the nine InSAR satellites has been limited due to the need to purchase the data or restrictions from the data providers. However, it is planned that satellites launched in the next decade will have open data access, including the European Space Agencies Sentinel satellites and NASA's DESDynI satellite. While Sentinel will provide a great advance in the availability of InSAR data, the data from the DESDynI satellite will be essential to GeoPRISMS science for resolving time dependent deformational processes with its shorter revisit time (8 days) and for actually observing the ground surface in areas of vegetation with its longer radar wavelength. GeoPRISMS science goals also could be advanced by opening up the archives of past satellite missions (going back to 1992) to the U.S. GeoPRISMS community through a "Supersite"-like

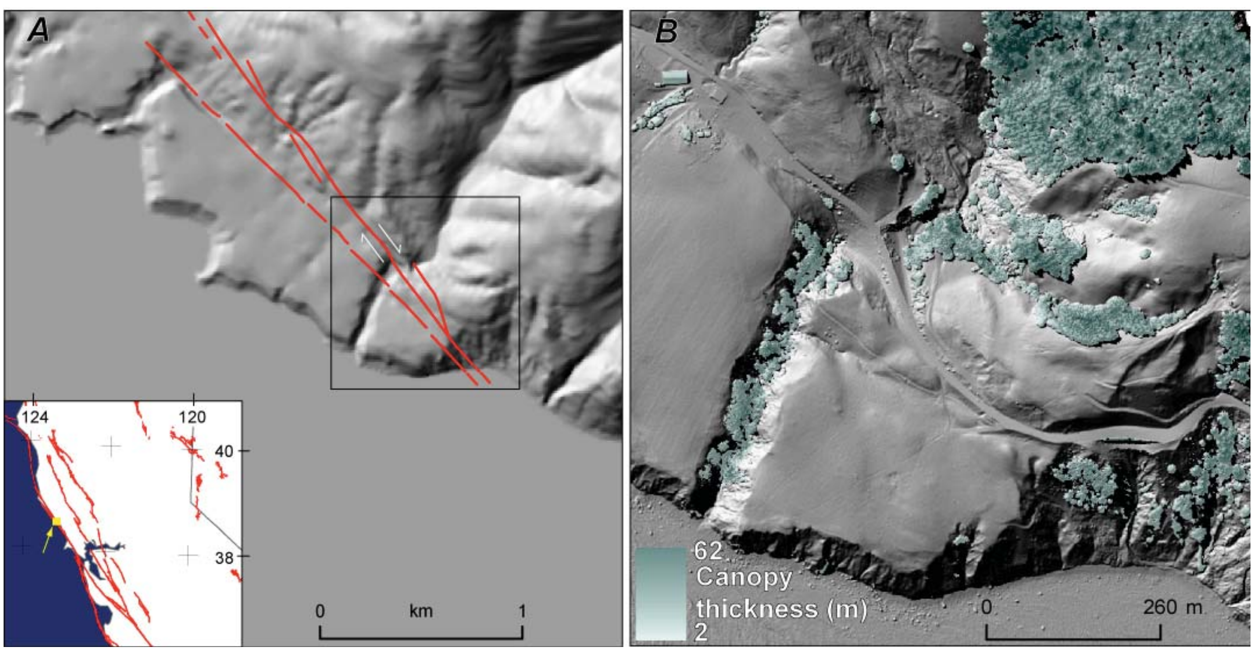


Figure 7.4. High-resolution topography characterizes landform geometry at scales at which geomorphic processes operate. A) Widely available 10 m per pixel National Elevation Data (NED) with San Andreas Fault (SAF) traces (last slippage here in 1906 of 1-2 m) overlain in the Fort Ross area of coastal northern California (inset yellow rectangle). Box shows location of B. B) 1 m per pixel full feature airborn laser swath mapping (ALSM) digital elevation model with canopy thickness in green. NED data are from US Geological Survey. EarthScope ASLM data are from http://www.opentopography.org. Figure by Ramón Arrowsmith

portal (supersites.unavco.org) in areas of interest to the GeoPRISMS community (e.g., East Africa, various subduction zones). The National Science Foundation (along with NASA and the USGS) funds several archives of InSAR data available to U.S. researchers through UNAVCO (the WInSAR and GeoEarthscope archives over North America) and the Alaska Satellite Facility (spanning the globe).

Remote Sensing: Remote sensing technologies have continued to improve and become more broadly available over the MARGINS time frame. These improvements, from spaceborne, airborne, seaborne and ground based perspectives, include higher spatial, temporal, and spectral resolutions. Compositional mapping of near surface materials and their changes continues to be a powerful constraint for surficial geological and volcanological monitoring activities. Synthetic aperture radar has provided global topographic data in great detail (*http://srtm.csi.cgiar.org/*) and is now powerfully deployed in interferometric mode from space and the air to measure surface displacement fields from volcanic phenomena, (a) seis-mic slip, and landslides. High resolution topography from airborne and ground based laser scanning characterizes landform geometry and surface displacements (in differential mode) at the cm to dm level and thus characterizes processes at the appropriate fine scale (Figure 7.4). Similarly, bathymetric imaging (discussed further below) has changed our view of the seafloor, in particular, for shallow settings with rapid erosion and deposition as well as along active faults and submarine vents.

7.3. Other Geophysical Methods

Heat flow measurements at both subducting and rifting/rifted margins are needed to constrain temperature-dependent processes and lithospheric rheology. Recognition of strong along-strike variations in heat flow offshore both Costa Rica and Nankai as well as the recognition of continuing hydrothermal circulation in young subducting oceanic crust demonstrates the danger of predicting the thermal state of incoming oceanic crust from conductive reference models. Series of strategically arranged heat flow profiles along strike may help estimate the relative roles of temperature, fluids, and basement relief influencing transitions between frictional behavior on the subduction thrust. Heat flow measurements over the margin wedge and through volcanic arcs hold the potential for identifying signals associated with the mantle source region, fluid migration and melting regions and better understanding the dynamics of wedge flow [e.g., *Wada et al*., 2008; *Cagnioncle et al*., 2007; *Syracuse et al*., 2010]. Across and along the segmented length of continental rifts and passive margins, heat flow observations are needed to quantify heat transfer from asthenospheric upwelling, magma intrusions, and to determine the time and length scales of hydrothermal circulation within faulted crust from rift onset to rupture. These observations are vital to predictive models of rift basin structure and stratigraphy, and hydrocarbon maturation processes, and will be needed to better understand the evolving strength of rifted margins.

Magnetotelluric (MT) and electromagnetic (EM) surveys constrain the electrical resistivity structure of the subsurface. The presence of fluids strongly influences the resistive structure, so these techniques are particularly powerful in mapping out the subsurface distribution of magmas and fluids, especially when combined with other geophysical and geological constraints. The distribution of magmas and fluids and their influence on rheology and deformation constitutes an identified Overarching Theme to GeoPRISMS, making these techniques extremely relevant. These methods can be used to provide further constraints on the compositional evolution of the mantle (e.g., regions of enhanced metasomatism [*Chen et al*., 2009]). Recent advances in data acquisition and analysis of onshore and offshore EM and MT offer the opportunity to yield transformative new insights into GeoPRISMS questions. Controlled source EM techniques involve recording electromagnetic signals generated by a dipole source on an array of sensors; methods for acquiring marine EM are an area of intense research. These data can provide relatively high-resolution constraints on the shallow distribution of melts and fluids [e.g., *MacGregor et*

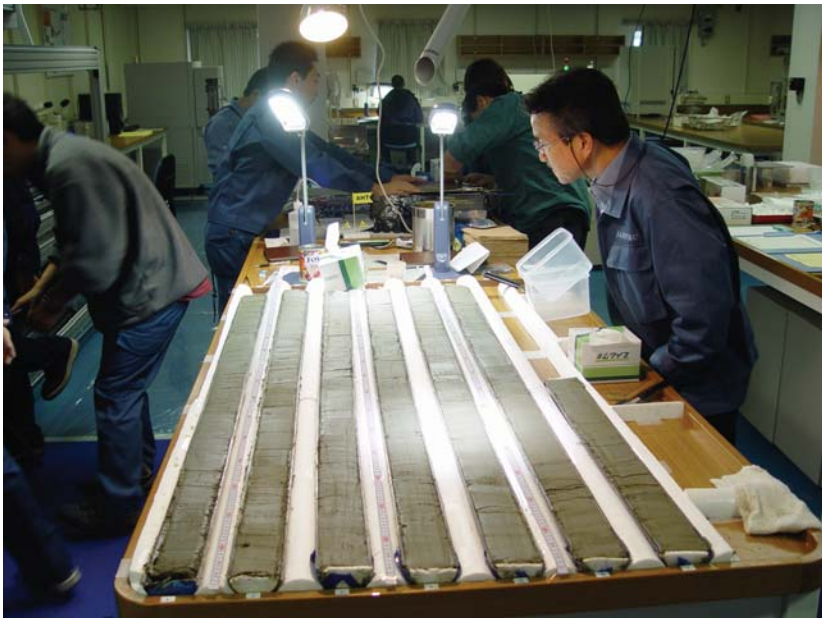


Figure 7.5. IODP drill core inspection (from IODP web pages).

al., 2001], which could be applied to understand dike injection in extensional zones, fluids at convergent margins, and magmatic plumbing below volcanoes in arcs and rifts. Magnetotelluric data provide information on the deep resistivity structure of the crust and mantle by measuring naturally varying magnetic and electrical fields using sensors positioned onshore or on the seafloor, which can be used to constrain the distribution of magmas [e.g., *Sinha et al*., 1998; *Evans et al*., 1999, *Whaler and Hautot*, 2006], fluids [e.g., *Wannamaker et al*., 2009] and compositional anomalies [e.g., *Chen et al*., 2009] at depth. EM and MT data are particularly powerful when combined with other geophysical information, such as active and/or passive source seismic data, and with each other [e.g., *Sinha et al*., 1998; *Keir et al*., 2009].

7.4. Drilling, Coring, and Logging Strategies

Ocean drilling through the Integrated Ocean Drilling Program (IODP), as well as continental drilling coordinated by ICDP, can be a key component in GeoPRISMS research in submarine settings, providing critical ground truth of the subsurface unavailable by any other means. Drill cores (Figure 7.5) are necessary to constrain sediment age and composition, micropaleontology, paleo-bathymetry and -environments, geochemical characteristics, microstructural features, and physical properties, and to validate 2-D and 3-D seismic interpretations. Cored samples can be studied in detail in the laboratory, and continuous in-situ properties and conditions can be obtained through borehole logging tools or logging-while-drilling (LWD) capabilities, yielding gamma ray, resistivity, neutron density, porsity, and pressure while drilling. Borehole installations, such as Circulation Obviation Retrofit Kits (CORKs), permit long time series pore pressure measurements, yielding estimates for in-situ effective stress conditions relevant to understanding failure conditions on active fault zones. Other borehole installations, such as geodetic sensors (e.g., tilt meters) and seismometers can provide measures of seafloor and deeper deformation at resolutions not possible remotely. Ideally, a transect or grid of boreholes, well-placed with respect to the features of interest, will allow a fairly complete characterization of the properties and composition of the subsurface.

Technological advances in borehole observatories can also allow critical real-time data acquisition and can detect transient signals, providing unique understanding of coupled fluid-deformation processes [e.g., *Brown et al*., 2005]. Multiple co-located data sets, deployed along drilling transects, would yield necessary information about the underlying physics of the system, as well as observations to constrain complex numerical models to address the underlying driving processes.

7.5. Field Observations

Field observations and interpretation along continental margins, both onshore and offshore, create an important bridge between geological, geophysical, remote imaging and laboratory studies, enabling full characterization of the system from top to bottom through geologic time. Indeed, many of the strategies outlined above require substantial field components, which could include seagoing cruises or onshore instrument deployments. The scope of such observation is vast, and is loosely categorized here by core community.

Terrestrial Geological Investigations. Structurally oriented field investigations (Figure 7.6) permit direct measurement of features and fabrics that record dynamic processes of lithospheric deformation. These studies include geometric assessment of structural features (e.g., orientations and deformation styles), observation and quantification of kinematic indicators (to characterize motions within the system at a range of scales), determination of rates of strain (e.g., paleoseismological investigations of subaerial and submarine fault zones, exhumation rates via low temperature thermochronology, and ages of deformed minerals), and unraveling the deformation mechanics. Field studies allow a higher resolution constraint on spatial and temporal scales of analysis than can be obtained through indirect techniques. For example, field mapping allows the geometric patterns of rocks and structures in exhumed portions of a system to be characterized at a level of detail that cannot be gleaned through other means. In addition, field data are needed to constrain stress and strain conditions crucial for the validation of geodynamic models and the interpretation of experiments.

Such studies are likely to be particularly relevant in exhumed ancient systems, which provide for the interpretation of seismic data from accretionary prisms, arc sections, and sedimentary basins. For example, field observations of metamorphic assemblages allow quantification of fluid redistribution and its effect on downdip megathrust rupture extent in subduction zones. High resolution geochronological and thermochronological data from field sites can be used to bridge the gap between differing temporal scales of analysis, as well as quantifying rates of processes and changes in these rates during the evolution of the system. A fundamental component of all 4-D studies is age constraints on rates of plate margin processes.

Marine Geological Investigations. Basic marine investigation, including but not limited to sea floor mapping, remains a critical step in characterizing GeoPRISMS field sites. Improved swath mapping techniques (Figure7.7) are providing detailed and evocative bathymetric and side-scan sonar images of deep-sea trenches, forearcs, and the axes of rifted

Figure 7.6. Field geologists evaluating structural relationships (photo courtesy J. Morgan).

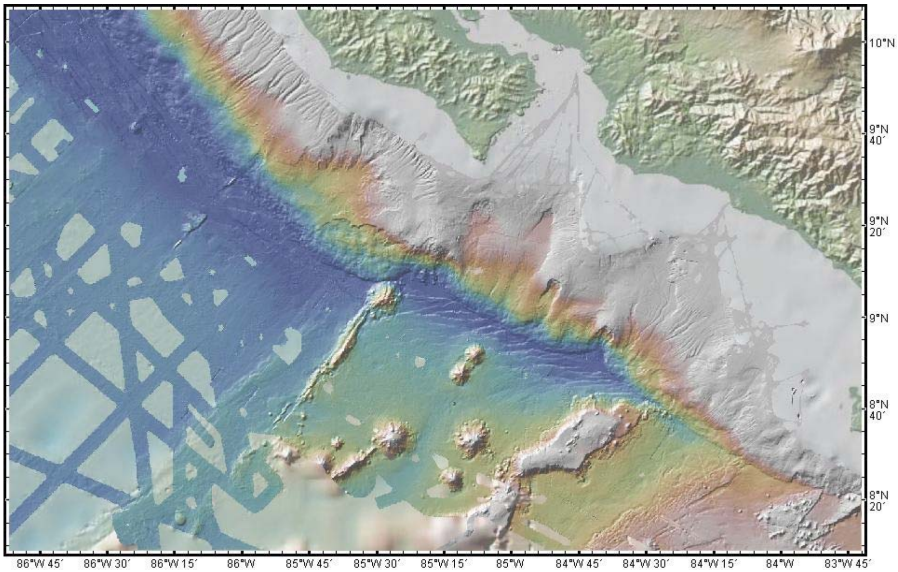


Figure 7.7. High-resolution bathymetric map from multibeam surveys, Middle America Trench off Costa Rica, showing faults and other deformational structures [GeoMapApp; from Ranero et al. 2003 and other sources].

margins. Such images are extremely useful for GeoPRISMS research in a number of ways. They can identify fault scarps, for example associated with the bending of plates seaward of trenches, that can act as important fluid conduits. Bathymetric images help to identify variations in sea floor roughness, which in subduction zones characterizes the material entering trenches and perhaps the extent to which the plate interface can sustain great earthquakes. Spatially limited depositional systems, e.g., lobate deposits, and submarine channels are also well resolved, providing fundamental information about transport pathways and zones of accumulation. In all settings, the images provide clues to deformational and geomorphic processes, locations of fluid venting and submarine magmatism, and distribution of past mass-wasting events. Finally, such mapping is an important complement to subsurface seismic imaging, and a requirement for drilling. In areas with limited subsurface imaging, seafloor bathymetry allows 1-D and 2-D structures to be extrapolated into 3-D, clarifying the surficial fabric of an area.

A variety of complementary ship-based techniques enable direct sampling of materials on the sea floor, including dredging, gravity coring, and piston coring. In complex terrains, manned or remotely operated submersible surveys are invaluable, allowing observers to make outcrop scale observations and to identify and collect samples in context. Deep-towed vehicles can be used to obtain intermediate scale maps or images of features of interest, facilitating subsequent submersible studies or other sampling approaches. More extensive subsurface sampling expeditions require deep sea drilling, coring, and logging techniques described above, which will continue to play a big role in GeoPRISMS investigations.

Petrology and Geochemistry: Field campaigns are necessary to obtain fundamental data on lithology, mineralogy, petrography, major and trace elements, and stable and radiogenic isotopes of all rock types. The techniques and methodologies used vary with the underlying research goals and strategies, and some must be carried out in the lab. As examples, field studies allow direct observation and sampling of igneous rocks that provide constraints on the evolution of magmatic systems and characterization of metamorphic grades that allow insights into the pressure and temperature conditions at depth within the system. Field surveys are the only way to obtain direct measurements of fluxes (solids, fluids, and melts) and estimates of fluxes through proxies (volumes, compositions). Uplift rates and exposure times can be estimated through geochronology and thermochronology (e.g., $Ar^{40/39}$, U-Pb, etc.), providing important bounds to tectonic and erosional processes.

Sediment and Surface Process Investigations: Field studies of exposed sedimentary systems provide important information about the rates and processes of basin subsidence (and later inversion and uplift), basin-bounding faults, ancient environments and climate, paleogeography of shifting depositional systems (e.g. rivers, deltas, shorelines), and the sedimentary response to interactions between internal (autogenic) and external (allogenic) processes. Detailed facies maps and measured sections are used to document the spatial and temporal distribution of sedimentary deposits, unconformities, and important architectural elements. Paleocurrent data combined with sedimentary petrology permit the reconstruction of ancient sediment-dispersal pathways and changes in those pathways due to changing tectonic and climatic boundary conditions. Field stratigraphic studies also provide the context for allied studies in paleontology, paleomagnetism, geochemistry, geochronology, and cosmogenic isotopes, which are used to further elucidate the timing, rates and dynamic controls on the evolution of exposed sedimentary systems. Onland sedimentologic and stratigraphic studies are also readily linked with related offshore investigations, and thus represent a critical component of integrated, shoreline-crossing studies of the GeoPRISMS program. Buried stratigraphy, both onshore and off, can be analyzed using seismic and well data, providing constraints on the timing and patterns of crustal deformation, and distinguishing the stratigraphic signals of “autogenic” and “allogenic” processes in margin stratigraphy. Such targeted studies provide information critical to developing numerical models that accurately characterize the depositional response to climate, sea level, and tectonics.

The effects of surface processes, fundamentally modulated by varying climate and responding to variations in tectonic surface displacements and rock resistance, are manifest in directly observable topography and bathymetry. The spatial variation in geomorphic processes is often recorded in the stratigraphic successions mentioned above. Over the prior MARGINS decade, it has become increasingly apparent that over 10s to 100s of km (i.e., orogenic scales) geomorphically driven mass redistribution has direct influence on the evolving structural architecture of active tectonic systems [e.g., *Whipple*, 2009]. At the same time, increasingly high resolution global and regional topographic datasets have become available, enhancing our ability to characterize landscape form and interpret the distribution and action of surface processes through the use of innovative process-based topographic metrics [e.g, *Perron et al.*, 2009]. Furthermore, improved quantification of surface process rates has become possible using various techniques, such as low temperature thermochronology, cosmogenic radionuclides, ^{230}Th/U, Optically Stimulated Luminescence, and extensive ^{14}C dating. Tracking the varying flux of rock and water as these materials move across terrestrial landscapes, the shoreline, and into the marine sedimentary system, along with the corresponding process transitions, represents a powerful new perspective for GeoPRISMS.

7.6. Experimental and Analytical Strategies

Experimental Studies: Experimental laboratory studies will play a key role in GeoPRISMS science, as a reliable means to more fully constrain material properties and to test hypotheses. These efforts are essential toward understanding deformation and rheology, metamorphic reaction rates, melting behavior, solubility, and transport of fluids and magmas. Controlled experiments provide a means to link observations with the underlying physical and chemical processes, to test hypotheses developed from field data, define and quantify mechanisms for observed phenomena, and inform numerical modeling studies.

Laboratory measurements of rock and fault gouge frictional behavior are fundamental in evaluating the role of rock composition and physical properties, as well as state variables (pressure, fluid chemistry, and temperature) on fault sliding stability. These laboratory results also feed in to theoretical studies designed to test the rock properties and in situ conditions that give rise to specific slip behaviors, including episodic tremor and slip and slow slip . Laboratory experiments can also provide great insight into the linkages between surface processes and accommodation, and can be linked to both field and theoretical studies [e.g. *Kim et al*., 2010]. Similarly, laboratory experiments provide a direct approach to quantify the effects of hydrous fluids and melts on mantle rheology relevant to a wide range of major questions at both subduction zones and rifting margins. In this respect, experimental studies of rheology and the roles of fluids and melts also provide a natural link between the two initiatives, and thus provide a powerful vehicle for integration and synthesis. Incorporation of laboratory data into geodynamic models has proven instrumental for constraining a wide range of GeoPRISMS processes, ranging from the dynamics controlling slab dip, anisotropy and flow in the mantle wedge, the foundering of lower crust beneath the arc, the dynamics of continental rifting, and the slip behavior of the slab/mantle interface.

Although progress has been made in the last decade, laboratory measurements of observable physical properties remain few, and should continue to be made. Images of seismic velocity, attenuation and anisotropy remain ambiguous to the extent that the effects of composition, temperature melt and pore geometry remain uncertain. Similarly, as MT and other EM data become available, it becomes increasingly important to constrain the relationships between geodynamically interesting properties and observable features. This can be done with some emphasis on both laboratory and theoretical measurements of physical properties, particularly under conditions of high temperature, partial melt, varying strain conditions, and varying pore fluid pressure.

Experimental investigations are also required to unravel the chemical processes associated with mass transfer in subduction zones and rifts. These include determination of key metamorphic reactions, particularly those involving devolatilization and including major and trace element compositions of the coexisting fluids, investigation of the loci of melting reactions and the quantity and composition of partial melts produced for a range of crustal, mantle, and subducted lithogies, particularly in the presence of mixed volatiles, experiments documenting major and trace element compositions of partial melts are critical for evaluating geochemical fluxes associated with subduction. Further, experiments are required to interpret diverse analytical studies. Three of many possible examples include: Interpretation of compositions of melt inclusions requires experimental studies of volatile solubilities, mineral/melt partitioning of key trace elements, and the time scale of interactions between melt inclusions and their hosts. Similarly, geochronometry and thermochronometry requires laboratory determinations of diffusion rates of parent and daughter nuclides. And laboratory investigations of weathering rates are required to understand geochemical fluxes associated with surface processes.

Analytical Studies: A wide range of analytical studies are needed to document subduction and rift processes, including those that help quantify geochemical fluxes, mass transfer, and the timing and rates of critical processes. These include both laboratory-based analyses of samples collected in the field as well as in situ measurements, such as those associated with monitoring volcanic volatile fluxes (Figure 7.8). The increased availability of very high resolution microbeam techniques (SIMS, LA-ICP-MS, XANES, synchrotron-based FTIR,

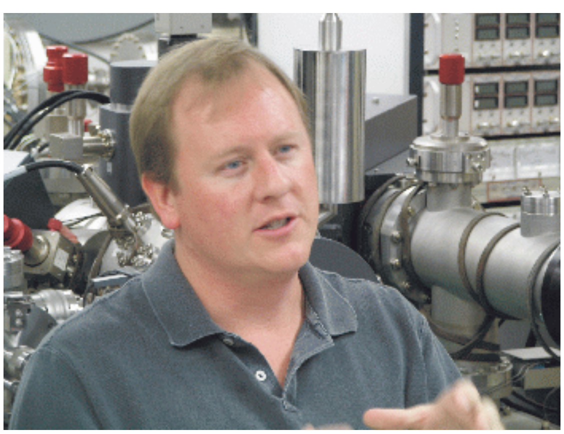


Figure 7.8. Erik Hauri in the geochemistry lab at DTM.

EBSD, MRI) now allow detailed probes of the chemical and textural characteristics samples at high spatial scales ranging from the volatile contents of melt inclusions to the oxygen fugacity of basalt source regions to chronometry of metamorphic exhumation or surface denudation to the deformation history of rocks. Increasingly sensitive isotopic measurements, including microbeam methods, multi-collector and gas source mass spectrometry allows unprecedend precision in the chronometry of magmatic and tectonic events and more detailed tracing of mass transport involving fluids, melts, sediments, and rocks. EBSD and MRI analyses allow detailed characteristics of microfabrics, including lattice preferred orientations and the 3-D distribution of mineral grains or fluids in both natural and experimentally-annealed rocks, thereby greatly aiding understanding of deformation mechanisms, seismic anisotropy, and the flow of fluids and melts through the mantle and crust.

7.7. Numerical Modeling Strategies

The GeoPRISMS program provides opportunities for interdisciplinary syntheses of geology, geophysics, and geochemistry. Geodynamics modeling facilitates such integration by offering quantitative ways to interface between these disciplines and to develop observational tests of conceptual models [e.g., *Billen,* 2008; *Karato et al*, 2008; *Wiens et al*., 2008]. Thus, geodynamic modeling will be an integral part of GeoPRISMS.

The scientific goals of the GeoPRISMS community require the development of multiphysics models that couple solid-state deformation, fluid migration – including magma migration – and chemical reaction. In the shallower portions of the crust and lithosphere, modeling approaches are required that incorporate (1) the hydrological cycle in sediments, and both continental and oceanic crust, (2) the influence of fault pressurization and friction on dynamic behavior, and (3) coupling between elasto-plastic behavior and surface processes. Deeper in GeoPRISMS systems, different approaches are needed, including hydration, dehydration and melting, melt migration, and coupling with viscous behavior (Figure 7.9). Coupling thermodynamics with both fluid and solid flow will make it possible to integrate experimental, geochemical, and geophysical constraints on key processes that cross the GeoPRISMS initiatives (e.g., melting and melt migration at rifts or subduction zones; Figure 7.9).

Addressing the wide range of spatial and temporal scales required by GeoPRISMS science will inspire a new generation of models that adopt multiscale/multiphysics modeling and upscaling techniques such as adaptive mesh refinement and representative volume strategies. Addressing the linkage between deformation within individual fault zones and plate margins up to the largest scales of plate motions require new generations of adaptive mesh refinement technologies. Robust, accurate, multiscale and multiphysics models are at the cutting edge of scientific computing [*van Keken et al*., 2008; *Burstedde,et al*., 2008] and the development of such models will benefit scientific initiatives beyond GeoPRISMS.

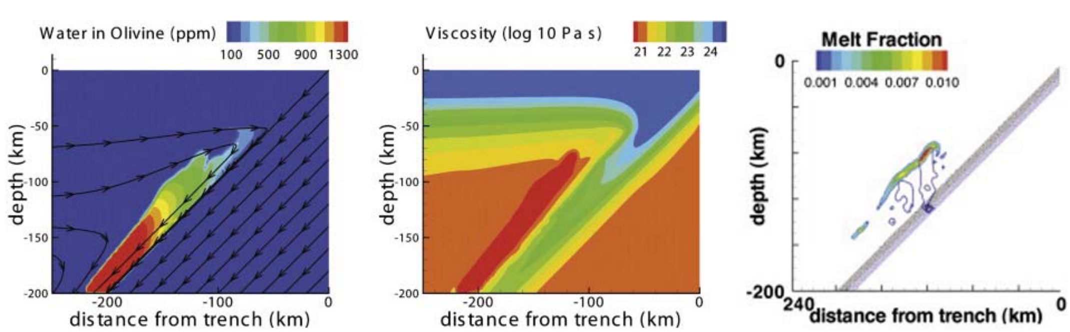


Figure 7.9. Coupled model of deformation, fluid flow, and melting representing the Central Costa Rica. Such coupled models predict the development of a hydrated low viscosity zone on top of the slab and self consistent mantle flow field and melt fraction [after Hebert et al., 2009].

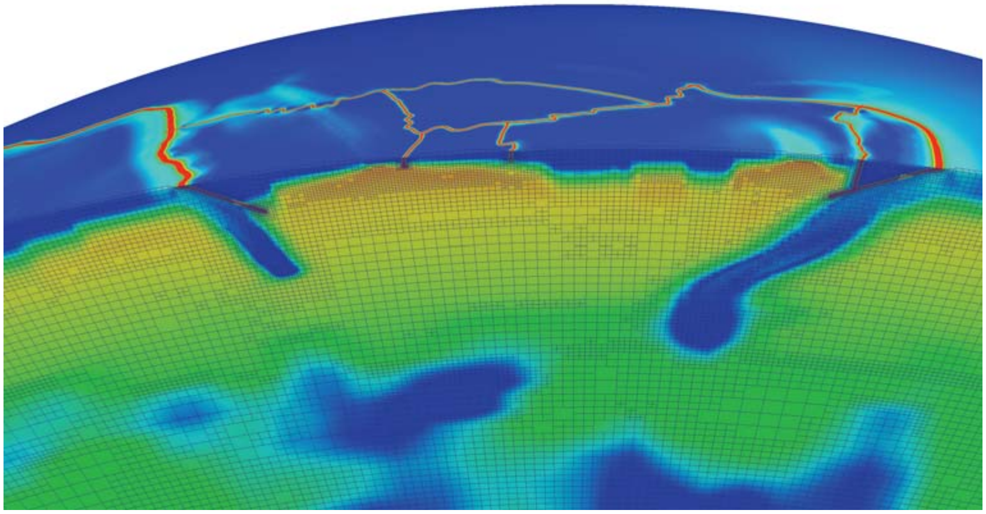


Figure 7.10. The latest advances in computational science now allow resolutions at sub 1-km scales as shown in this zoom-in of the New Hebrides and Tonga slabs in a global model of mantle flow. Such models incorporate laboratory-based rheology models, assimilate data at a variety of scales and can made predictions in deformation and state of stress at fines scales while also predicting global plate motions. From Stadler et al. [2010].

Specific code development is necessary to enable GeoPRISMS scientific goals. However, the most effective strategy for code development is for GeoPRISMS researchers to interact closely with modeling-oriented communities and initiatives, such as the Computational Infrastructure for Geodynamics (CIG; *www.geodynamics.org*) – for solid earth geodynamics and melt migration, and the Community Surface Dynamics Modeling System (*CSDMS; csdms.colorado.edu*) – for surface processes (See Section 8.1.7). GeoPRISMS could also reach out to hydrogeologic and reservoir modeling communities, including Los Alamos National Laboratory and the US Geological Survey, who are already developing sophisticated models for fluid transport and the production and storage of petroleum resources at continental margins. Interdisciplinary workshops appealing to field and experimental scientists as well as modelers, for example the upcoming CIG-EarthScope workshop, will help to train the next generation of GeoPRISMS modelers and encourage the formulation of collaborative proposals integrating numerical modeling to test competing field or laboratory based hypotheses and interpretations.

Interactive visualization (e.g., KeckCAVES) also facilitates the integration of datasets, comparison with models, and development of Education and Outreach products (e.g., Figure 7.10). Both the proposed SCD and RIE Initiatives of the GeoPRISMS program embrace 3-D and 4-D (time evolution) aspects of margin evolution. Interactive Visualization is crucial for complete, effective and efficient analysis of large, complex and multi-parameter data and model results [*Kellogg et al*., 2008; *Billen et al*., 2008]. The KeckCAVES group at the University of California, Davis, has developed flexible Interactive Visualization tools (3DVisualizer), which run on laptops, CAVEs, and 3DTVs. GeoPRISMS can seize the opportunity to use this and other similar capacities to integrate geodynamics models and observations into a unified framework to enable interdisciplinary integration and discoveries.

7.8. Integrative Research Strategies

Throughout this document, we have emphasized the fundamental role of interdisciplinary research within GeoPRISMS, based on community prioritization of scientific objectives. As a demonstration of what could be achieved through such focused research efforts in the new program, we outline one example motivated by substantial community input and discussion before, during, and after the MSPW - that of understanding volcanoes from bottom to top. The concept of holistic, integrative studies of an individual volcano (perhaps complemented by a comparable exhumed pluton) was outlined in three separate contributed white papers (Appendix E), demonstrating a strong community sentiment for this avenue of research. The description below does not condone any particular site for study, nor imply that this is the most important target for GeoPRISMS research. Such decisions must be made during the upcoming Initiative and/or thematic planning workshops. Nevertheless the strong support from independent whitepapers suggests this direction may emerge in final science plans, along with many other types of integrative investigations guided by community priorities. GeoPRISMS stands in a unique position to make inroads into a comprehensive understanding of natural Earth systems along continental margins, of interest to a broad cross-section of the scientific community and society.

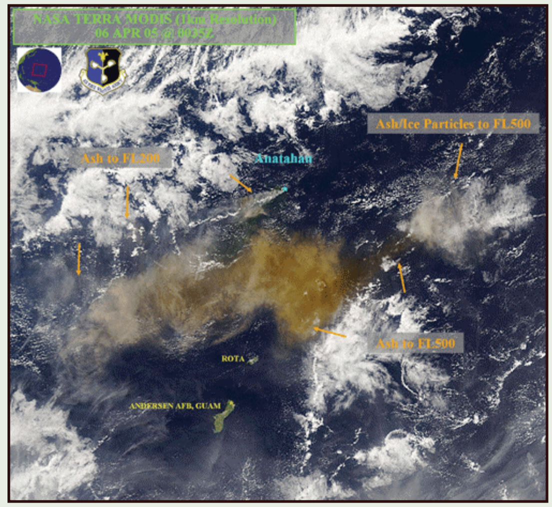


Figure 7.11. (left) Arenal volcano, Costa Rica has erupted nearly continuously since 1968. (right) MODIS image of ash plume from April 2005 Anatahan eruption, Mariana Islands (NASA).

An Example: Volcanoes From Bottom to Top:

The GeoPRISMS program is uniquely suited as a multi-disciplinary platform that will illuminate the inner workings of arc volcanic systems beyond what can be achieved through single PI led projects. The focus would be how arc volcanoes work, from bottom to top, but with emphasis on the processes and conditions that trigger magmatic ascent in the crust and control the transport pathways. Seismology (passive and active, on-land and ocean-bottom), geodesy, and potential field and electromagnetic studies together can provide powerful geophysical constraints on the depths and geometries of magma storage zones at a variety of spatial scales, as well as resolve temporal changes. Among other things, such observations would improve our understanding of the processes leading up to eruptive activity. Cross-correlations between different geophysical data sets will, for example, greatly improve our understanding of how fluid and magma movement are linked with deep crustal long-period earthquakes and volcanic tremor, two common eruption precursors. Petrology, geochemistry and experimental studies quantifying magma storage conditions, ascent rates, and magma mixing and mingling timescales also provide spatial and temporal "images" of the magma systems. Moreover, geochemical investigation of a geochronologically-constrained suite of lavas from an active arc volcano can constrain the long-term record of eruptive and crustal processes and provides an opportunity to quantify the timescales and kinetics of these processes. Geochemistry and petrology studies of active magma systems, compared with analogous plutonic bodies, can provide a much longer timescale view of the evolution of arc magmatic systems, which cannot be addressed by geophysical studies alone. Such studies could address, for example, the longevity and geochemical evolution of arc volcanic systems, their importance as an outcome of primary subduction zone geochemical processes, volatiles recycling, and the production of continental crust. The GeoPRISMS program is thus uniquely suited to bring the geochemistry/petrology and geophysics communities together to focus on the same volcanic phenomena from different angles, laying the groundwork for many new, and potentially paradigm-changing discoveries.

Clearly, there is great potential for synergistic work on this theme across disciplinary boundaries through such investigations, and the approach outlined above touches on essentially all of the overarching themes laid out in Section 3. Furthermore, studies in Cascadia and Alaska can take advantage of recent ARRA initiatives, future USArray deployments, and cooperation with U.S. volcano observatories. This program of research would also have direct societal relevance in terms of providing a deeper understanding of volcano behavior, and thereby, volcanic hazards and their environmental impacts.

GeoPRISMS
Draft Science Plan

8. Partnerships and Collaborations

8. GeoPRISMS Collaborations and Partnerships

Over the last decade, the National Science Foundation has invested heavily in infrastructure and national facilities for conducting research. GeoPRISMS is well positioned to leverage these investments, by providing an intellectual framework for their application toward the scientific problems outlined here, and by bringing to bear an interdisciplinary community that can give broad context for observations made within a discipline. Furthermore, the global scope of GeoPRISMS makes it a natural vehicle for expanding international partnerships began under MARGINS, and several areas of new emphasis make partnerships with several industries more attractive. All of these linkages, to NSF facilities, industry and international partners, were seen as strengths by the DRC and encouraged strongly. These collaborations and partnerships result in much greater scientific return than would be possible otherwise.

8.1. Relationships to Other NSF-Supported Programs & Facilities

8.1.1. EarthScope

GeoPRISMS and EarthScope are distinct but complementary programs; their similar time scales and combined scientific vision promise to revolutionize our understanding of plate tectonics and mantle dynamics, and the implementation of Earth Systems research. Future GeoPRISMS investigations, guided by the Overarching Themes and Initiative questions outlined in this Science Plan, will clearly benefit from strong synergies with the EarthScope community and facilities, and vice versa.

EarthScope (*www.earthscope.org*) aims to investigate the structure, dynamics, and history of the North American continent, using North America as a natural laboratory to gain fundamental insight into Earth processes [*Williams et al.*, 2010]. EarthScope's vision extends to data dissemination, developing data processing and distribution facilities to rapidly and freely provide researchers everywhere with raw and processed data, thereby building and strengthening the synergism and scientific community.

The EarthScope Facility consists of three main components:

- The Transportable Array (TA; Figure 8.1) is a land-based, telemetered broadband seismometer array deployed on a roughly 70-km grid that is imaging crust and mantle structure beneath North America. Stations in the grid are moved every two years, with instrumentation maintained and supported by IRIS. The magneto-telluric array is much coarser, involves much shorter observation periods and is focused on particular targets. TA has imaged the Rio Grande rift, and is currently deployed around the Mid-Continent rift system. The N-S oriented swaths of ~400 instruments will reach the Texas Gulf Coast and northern East Coast passive margin areas

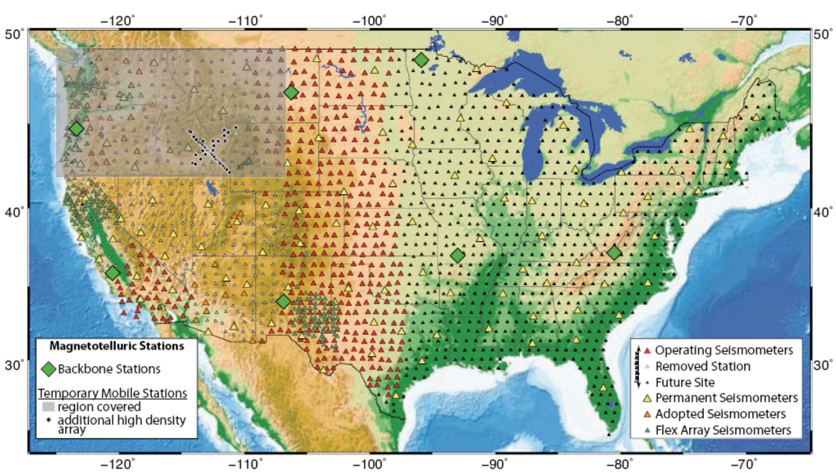


Figure 8.1. The EarthScope-USArray Transportable Array as of January 2010.

beginning in 2010 and 2013, respectively, and Alaska in 2014 (*www.usarray.org/maps*).

- The Plate Boundary Observatory (PBO), which aims to study, in 4-D, the strain field of the active plate boundary along the Western United States. Telemetered data from continuously recording GPS, borehole seismometers, tiltmeters and strainmeter data capture the broad spectrum of plate boundary deformation signals. These permanent instrumentation sites are supported by UNAVCO.
- The San Andreas Fault Observatory at Depth (SAFOD) deep drilling along a portion of the San Andreas fault near Parkfield, California where deformation occurs both by creep and repeating microearthquakes. This effort is in collaboration with the USGS and the International Continental Drilling Project. In addition to providing critical constraints on the properties of rocks within fault zones and the interactions with fluids, the SAFOD project has led to the development of high-resolution tomographic imaging methods that exploit the superb seismic data sets [e.g., *Zhang et al*., 2009]. These new methods and fault zone studies provide new tools for use in GeoPRISMS studies worldwide.

The EarthScope Flexible Array program allows for more focused studies on particular targets of interest, within the ~70 km spacing of USArray. This program supports an additional 400 x 3-component seismometers and 2000 single-channel systems for active and passive source seismic experiments, plus 100 GPS receivers for rapid response efforts (e.g, Cascadia, Alaska). These instruments are available through proposals to NSF. Obvious sites of GeoPRISMS collaborations include onshore-offshore active source seismic experiments to image crust and upper mantle thinning and magma intrusion/extraction zones along the eastern and western Gulf of Mexico margins, the Atlantic margin, continued focus studies in Cascadia, the western U.S. rift systems, and Alaska.

MARGINS has built a broad interdisciplinary community in which observational geophysicists work closely with geochemists, geodynamicists, sedimentologists, marine geologists, metamorphic and igneous petrologists. EarthScope began as largely a community of geophysicists studying North America, but recent results and data access policies have broadened the aims [*Williams et al*., 2010]. All three EarthScope facilities complement the onshore-offshore nature of MARGINS-GeoPRISMS studies and their emphasis on global comparisons of active and ancient processes. Growing collaborations between MARGINS and EarthScope have gone some way toward building a joint interdisciplinary research community, through the large Salton Trough rifting geophysical experiment and the new Cascadia Facilities Initiative. Both efforts also engage the USGS, a clear partner on the earthquake and volcanic hazards and natural resources aspects of MARGINS and EarthScope. Similar synergies are anticipated within the new GeoPRISMS program as well.

8.1.2. UNOLS Fleet and R/V Marcus G Langseth

The University-National Oceanographic Laboratory System (UNOLS) is an organization of 61 academic institutions and National Laboratories involved in oceanographic research and joined for the purpose of coordinating oceanographic ships' schedules and research facilities. The program mission is to provide a primary forum through which the ocean research and education community, research facility operators and the supporting Federal agencies can work cooperatively to improve access, scheduling, operation, and capabilities of current and future academic oceanographic facilities. Currently, the UNOLS fleet consists of 21 research vessels located at 16 operating institutions in the UNOLS organization. The UNOLS office, located at the University of Rhode Island Graduate School of Oceanography. More details are available on the UNOLS website (*www.unols.org*). Ships of the Fleet range in size from 20 meters to 85 meters and operate in coastal waters of the United States, the Great Lakes and the oceans of the world. In combination, these vessels enable a full suite of marine geological studies of interest to GeoPRISMS, including single-channel and multi-channel seismic capabilities, multibeam bathymetry mapping or backscatter imagery, and

Figure 8.2. The R/V Marcus G. Langseth

sample recovery by way of dredging, piston coring, and gravity coring operations. Several vessels support submersible manned or remotely operated vehicles of the National Deep Submergence Facility (e.g., HOV Alvin, ROV Jason), as well as Autonomous Underwater Vehicles (AUV ABE/ Sentry) and towed vehicles equipped with a variety of sensors and able to operate at various water depths, providing critical in-situ observations of submarine features.

The R/V *Marcus G. Langseth* (Figure 8.2), a relatively recent addition to the UNOLS fleet, is the first and only academic vessel capable of acquiring 3D seismic reflection data with 6 streamers, a 40-element airgun array as well as long (8 km)-offset 2D seismic reflection data. She has been owned by the NSF and operated by Lamont-Doherty Earth Observatory of Columbia University since 2008. The *Langseth* also possesses a 1x1º beam multibeam swath mapping system providing high-resolution bathymetric data as well as the deck space and equipment to acquire many other complementary marine data sets, including wide-angle seismic refraction data and passive seismic data using ocean-bottom seismometers. The *Langseth* successfully acquired her first 3D volume in the summer of 2008 on the East Pacific Rise near 9º50'N successfully imaging magma bodies, and has also been employed in the acquisition of several large onshore/offshore seismic studies comprising 2D deep-penetration seismic reflection profiles using long streamers and wide-angle seismic reflection/refraction data, including the 2008 MARGINS project to image the crustal structure of the Costa Rica subduction system [e.g., *Van Avendonk et al*., 2008]. The *Langseth's* ability to provide constraints on the deep, 3D configuration of magmatic and deformational systems is also essential for acquiring and analyzing data sets with other emerging marine technologies including seafloor geodesy, seafloor monitoring of seismicity and other signals (e.g., tremor), and marine MT and EM studies.

The recent NSF-sponsored workshop "Challenges and Opportunities in Academic Marine Seismology Workshop" held in March, 2010, explored potential changes in the funding and scheduling structure for Langseth usage, with the likelihood of more community-driven scientific proposals, as well as more open data policies. Such approaches are highly compatible with MARGINS-GeoPRISMS, whose community may play an important role in defining research priorities for the vessel. The Langseth seismic vessel will clearly continue to be an important resource for future GeoPRISMS investigations of rifting and subducting margins.

8.1.3. Scientific Ocean Drilling through IODP

Ocean drilling through IODP (Integrated Ocean Drilling Program) and its potential successor program will continue to be a major tool to address important GeoPRISMS objectives. Ocean drilling results can be used to sample offshore portions of the system, in order to test models, provide

Figure 8.3. The riser drill ship D/V Chikyu

otherwise unobtainable samples, and build long-term observatories addressing central GeoPRISMS initiative goals. Examples from the past decade include drilling and sampling of subduction inputs at the Costa Rica margin, installation of borehole observatories near the trench at both the Nankai and Costa Rican margins, and the ongoing NanTroSEIZE project to drill into the seismogenic zone at the Nankai Trough, the first scientific riser drilling program. The NanTroSEIZE concept was developed as a completely integrated MARGINS SEIZE and IODP project. Currently active new drilling proposals include boreholes offshore Costa Rica and the IBM arc system, among others, that would require the ultra-deep drilling capability of the riser drillship *D/V Chikyu* (Figure 8.3). A proposed industry-supported drilling program for the *D/V JOIDES Resolution* could provide critical data for the studies of sediment, basin architecture, and crustal processes at rifted margins such as the Gulf of Mexico.

Development and implementation of IODP drilling proposals requires committed effort by many investigators representing a wide range of disciplines, who cooperate to focus on a particular problem in a particular location. There is therefore a natural parallel and synergy between IODP and MARGINS and GeoPRISMS activities, which also require cooperative and multidisciplinary coordination. The development of IODP drilling proposals often stimulates extensive pre-drilling geophysical and geological study of potential targets, and historically the NSF MARGINS and ODP programs have cooperated closely in this regard. Furthermore, the goals of IODP proposals increasingly include long-term monitoring of active processes through emplacement of borehole observatories. Because the instrumentation and post-drilling monitoring must be supported by third parties in the IODP framework, they represent especially fertile avenues for GeoPRISMS – IODP synergy.

8.1.4. Seismological Facilities and Equipment.

The Incorporated Research Institutions for Seismology (IRIS) manages facilities for the acquisition, management and distribution of seismic data, including the Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) fleet of portable seismometers at all period bands (Figure 8.4). This instrumentation covers a broad spectrum of onshore seismic investigations,

Figure 8.4. Installing a PASSCAL broadband seismograph in Costa Rica.

including deep imaging using teleseismic arrivals, monitoring of seismicity and other signals and active source seismic studies. IRIS also manages an extensive database of diverse seismic datasets and champions significant outreach and education activities. To facilitate Rapid Response, such as envisoned in GeoPRISMS, PASSCAL has a dedicated fleet of 'RAMP' instruments for rapid response efforts to earthquakes. The dissemination of data through the IRIS Data Management System (DMS) provides one possible avenue for making GeoPRISMS data and results available to as large a community as possible.

The US National Ocean Bottom Seismograph Instrument Pool (OBSIP) was established by the National Science Foundation to expand the access to instrumentation for marine seismology beyond large oceanographic research centers to a wider range of users. Three facilities, located at Lamont-Doherty Earth Observatory at Columbia University, Institute of Geophysics and Planetary Physics at Scripps Institution of Oceanography and Woods Hole Oceanographic Institution, maintain and operate a fleet consisting of about 100 broadband and 100 short-period ocean bottom seismometers (OBSs). This diverse set of OBSs is capable of recording signals across much of the seismic spectrum, at a fidelity comparable to land instruments, for periods of a year or more, autonomously on the seafloor. The Cascadia Initiative will lead to a further expansion of the broadband capabilities, including the design and construction of instruments that are trawl-resistant and thus can be deployed in shallow water. The instrumentation and expertise of OBSIP can facilitate the acquisition of new, exciting observations that are critical to achieving the goals of GeoPRISMS. Examples include dense deployments of short-period instruments for 2D and 3D crustal imaging using active-source seismology and long-term deployments of arrays of broadband instruments to record local, regional and teleseismic events for monitoring seismicity and other signals and for deep imaging of the lithosphere and asthenosphere.

8.1.5. Geodetic Facilities and Equipment

UNAVCO is a university consortium that manages facilities for research using high precision geodesy, including a large pool of GPS equipment that can be loaned to researchers for NSF-supported research projects (Figure 8.5), and related technical support. UNAVCO is the primary archive for all NSF-supported research using GPS, and a wealth of data from measurement campaigns and continuous instruments is available to the community through the UNAVCO data archive. UNAVCO operates the Plate Boundary Observatory and SAFOD components of EarthScope, including the real-time GPS upgrades that are part of the Cascadia

Figure 8.5. A UNAVCO-supported GPS facility.

Initiative, and hosts the WInSAR and EarthScope archives of SAR and LiDAR data for research using imaging geodesy.

There are abundant opportunities for synergy between UNAVCO and GeoPRISMS. UNAVCO's instrumentation and expertise can facilitate the acquisition of diverse geodetic datasets that address core objectives of GeoPRISMS. Another aim of GeoPRISMS is to better understand hazards in subduction and rift zones, and the UNAVCO instrumentation pool and field engineers can support rapid deployments of instrumentation following major earthquakes. UNAVCO is hosting archives of geodetic imagery for major earthquakes and volcanic eruptions as part of the "supersites" efforts supported by the European Space Agency and other space agencies. Education and Outreach efforts can be coordinated between GeoPRISMS, UNAVCO and IRIS, tapping a broad range of expertise at the facilities and reaching out to a wide audience. UNAVCO provides discussion forum and other means of reaching the entire community of geodetic researchers, including many researchers outside the US.

8.1.6. Ocean Observatories Initiative (OOI)

The Ocean Observatories Initiative represents a new, major investment by NSF in long-term infrastructure of science-driven sensor systems to measure the physical, chemical, geological and biological variables in the ocean and seafloor. OOI is funded through the Major Research Equipment and Facilities Construction (MREFC) program, with funding starting in FY2010 and construction continuing through 2014. The facility consists of three major components, a Global Observatory network of four buoys placed at high-latitude remote sites, a Regional Observatory accessed by high bandwidth cables traversing the Juan de Fuca plate, and a Coastal observatory of shallow-water sampling (information from OOI Final Network Design Document, Ocean Leadership, 2009). While most of the resource is dedicated to water-column and atmospheric measurement, some facilities particularly on the Regional Observatory provide direct support for sea floor geophysical and other measurement. It features one primary node at Hydrate Ridge on the Cascadia forearc, providing facilities that complement well the Cascadia Amphibious Facility (Section 6.3.2), as well as a primary node on the Juan de Fuca ridge and potential for expansion elsewhere nearby. These primary nodes provide power and high-bandwidth communication, and are planned to include arrays of seismometers, pressure gages, hydrophones, and a host of other instruments of potential use, all available freely and in near real time. As well, the Endurance Coastal Array will provide water-column data along two transects off Cascadia, some of great utility to sediment transport studies. Similar facilities are planned for the Pioneer Array initially deployed off the northeast United States in shallow water (<500 m). It is easy to envision GeoPRISMS scientists being able to take advantage of these major new data streams, and likewise helping drive the optimal use of these facilities. For more information, see *www.oceanleadership.org/programs-and-partnerships/ocean-observing/ooi/*.

8.1.7. Computational Infrastructural Facilities

The Computational Infrastructure for Geodynamics (CIG) and the Community Surface Dynamics Modeling System (CSDMS) are two cyberinfrastructure programs that complement and support MARGINS-GeoPRISMS by developing, supporting, and disseminating software for use by researchers. CIG provides open-source software for the greater geodynamics community, focussing primarily on the solid-earth including short and long-term tectonics, mantle dynamics, and seismology. CSDMS focuses on earth surface processes including the movement of fluids, and the flux of sediment and solutes. Both groups nurture, develop and maintain high-level participation for the benefit of the entire Geoscience community through open collaboration and cooperation. CSDMS is based at the University of Colorado and is midway through their first five years of operation. CIG has just been renewed for another five years as it moves from Caltech to the University of California at Davis. As organizations facilitating computational research within different parts of the geosciences, they have been and will continue to be outstanding resources for the GeoPRISMS community.

CIG: CIG develops and maintains software for problems ranging widely from mantle, crustal and earthquake dynamics, magma migration, and seismology, important components of the GeoPRISMS initiatives. CIG has been able to introduce a number of important stand alone codes that has been used widely in margins-related research, *PyLith* for the entire earthquake cycle from tectonic loading and unloading to dynamic rupture, or *Gale* for the spontaneous initiation and evolution of faulted rift and compressional margins. One of the underlying computational challenges spanning nearly all of geodynamics is the need to resolve fine-scale features (such as faults) embedded in a larger domain (such as a plate). The computational challenge is the need to resolve the fine features as they form, evolve and entirely disappear. CIG has pursued a multiple approach to bring useful software to the geoscience community that involves explicit collaborations with the larger world of computational sciences with both an in-house CIG staff as well as members of the geodynamics community.

The CIG vision for the future is on one of interoperable software that allows users to seamlessly move from data to dynamic models and back to data using computational models that are able to handle the extreme variations in material processes and multi-physics, while respecting the complex geometry of geological processes (Figure 8.6).

CSDMS: The CSDMS Model Repository offers more than 100 open-source models (e.g. basin

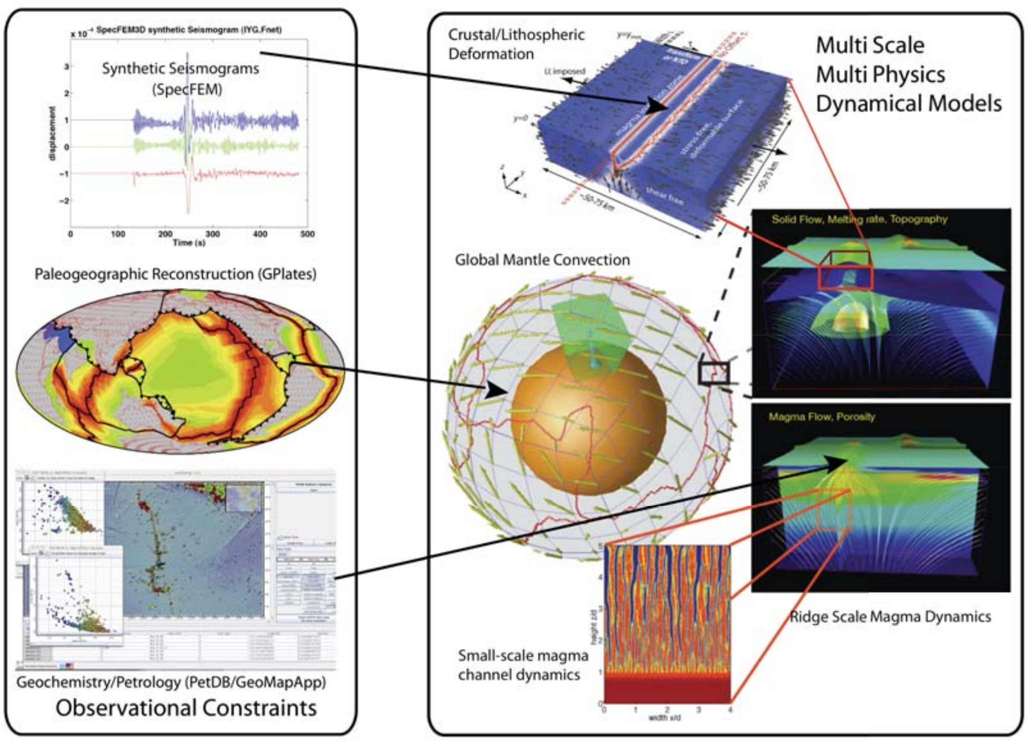


Figure 8.6. A Vision being pursued by CIG during its next five years of funding. Examples of computations and data available to help us understand solid earth dynamics at a range of scales. In this case, the dynamics of plate boundary processes and their interaction with global mantle flow. RIGHT PANEL: Example output of computational codes for global mantle convection (CitcomS), midocean ridge flow with melting and melt transport, crustal scale magma injection and faulting (Gale), and small scale reactive melt channel formation. Each model was designed to consider a particular scale or set of processes. The challenge is how to permit users to combine these models, as needed, to explore the dynamics of the coupled interactions and use them to make inferences from geophysical and geochemical data. LEFT PANEL: Example data used to test and drive models, including seismic waveforms (SPECFEM), plate reconstructions (GPlates), and geochemistry (PetDB).

evolution, morphodynamics, transport, hydrology, climate and ocean). CSDMS employs state-of-the-art architectures, interface standards and frameworks that make it possible to convert these stand-alone models into flexible, "plug-and-play" components that can be assembled into larger applications. The CSDMS model-coupling environment offers language interoperability, structured and unstructured grids, and serves as a migration pathway for surface dynamics modelers towards High-Performance Computing (HPC). In support of the GeoPRISMS program, CSDMS would be pleased to add to its growing library, open-source code contributions that relate to the Earth's surface - the ever-changing, dynamic interface between lithosphere, hydrosphere, cryosphere, and atmosphere. Further CSDMS would help migrate high-priority contributions in the CSDMS architecture so to make it a plug and play component.

The CSDMS Data Repository offers access to global databases for model initializations and boundary conditions, laboratory data for bench-marking. CSDMS supports the linkage between what is predicted by CSDMS codes and what is observed, both in nature and in physical experiments. In that regard, the GeoPRISMS program could position itself to provide integrated observational data that could be used to test individual CSDMS code and fully coupled source to sink models. The Education and Knowledge Transfer (EKT) Repository offers undergraduate and graduate modeling courses, educational modules, modeling labs, and process and simulation movies. CSDMS would be pleased to work with the GeoPRISMS program to host appropriate EKT products developed by the MARGINS community.

8.2. International and Multi-Institutional Partnerships

One of the great successes of MARGINS has been the catalyst for partnerships with large international programs. These have provided substantial opportunities both for U.S. and foreign scientists, and have led to efficient use of resources beyond NSF's direct contribution. They have also led to major discoveries, as evidenced by the multinational nature of author lists in recent Science and Nature papers. Major international partnerships formed during the previous program that are likely to continue include:

- *Japan* - A significant part of the MARGINS Seismogenic zone effort was focused on study of the Nankai subduction zone in cooperation with the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). The goal of this effort is seismogenic zone riser drilling by the IODP D/V Chikyu operated by JAMSTEC. In addition, MARGINS Subduction Factory efforts to understand the origin of Izu-Bonin-Mariana arc crust were coordinated with Institute for Frontier Research on Earth's Evolution (IFREE) at JAMSTEC, with joint ocean bottom seismograph deployments and data exchange.
- *Germany* - A fruitful international relationship developed with the German SFB-574 "Volatiles and Fluids in Subduction Zones" headquartered at IFM-GEOMAR and Christian-Albrechts Universitat Kiel. Collaboration included joint field programs in Central America, data exchange, joint publications and joint workshops.
- *Costa Rica* - Margins efforts in Central America benefited greatly from collaboration with Costa Rican scientists from Universidad Nacional Autónoma and other universities and agencies. Activities included joint fieldwork, joint data analysis, and several MARGINS workshops in Costa Rica, attended by many Costa Rican scientists and students.
- *Mexico* - The MARGINS Rifting of Continental Lithosphere program partnered with several Mexican institutions in the Gulf of California project, including UNAM (Universidad Nacional Autónoma de México) and CICESE (Centro de Investigación Científica y de Educación Superior de Ensenada).
- *New Zealand* – Two institutes in New Zealand partnered with the Source to Sink initiative in the Waipaoa Focus Site, North Island. NIWA (National Institute of Water & Atmospheric

Research) provided expertise and much field resources for offshore studies, while GNS (Institute of Geological and Nuclear Sciences) conducted complementary research onshore, and both cosponsored joint publications and workshops.

International collaborations will be a key part of the new GeoPRISMS program, enabling the U.S. to pool resources with other countries. Increased collaboration with Canadian scientists is already happening in response to the Cascadia Initiative along the Pacific coasts of North America, and through EarthScope studies of the Atlantic margins. MARGINS was vital in the initiation of Euro-Margins, UK-Margins, and the ongoing Marges (France) programs, and this international community remains closely knit through ongoing MARGINS activities. One goal of GeoPRISMS will be to renew these ties to develop a more formal international partnership, such as originally envisioned for the now-defunct InterMARGINS consortium. In addition, the potential for comparisons between active and ancient rifting events in the new GeoPRISMS science plan suggests extensive possibilities for collaboration with the UK, France, and other EU partners in onshore-offshore studies along the Atlantic margins. China, Korea, and India are becoming stronger players in global geoscience research and may also play strong collaborative roles in the new program. Finally many of the existing partnerships should continue, for example the long-term drilling in Japan waters will keep some focus there, the SFB-574 leadership has expressed interest in continued joint efforts at comparing different subduction zones, and partnerships in Central America, Mexico and New Zealand all have potential to continue.

Within the U.S., several agencies outside the NSF form natural partners. USGS is a clear partner on the earthquake and volcanic hazards and natural resources aspects of GeoPRISMS, as well as economic assessment of passive margins, particularly as U.S. margins become more emphasized. Similarly, as described in Section 6.3.4, the USGS and NOAA are potential partners in analysis of data collected in regard to Law of the Sea. The Los Alamos National Lab and USGS (among other agencies) are already developing sophisticated models for fluid transport and the production and storage of petroleum resources at continental margins, and are partnering with CSDMS in sediment dynamics research, so could form GeoPRISMS partners.

8.3. Collaborations with the Energy Industry

As recommended by the Decadal Review Committee, GeoPRISMS will seek a stronger partnership with the petroleum industry. A quantitative, process-based, understanding of margin evolution is fundamental to discovering and exploiting energy and minerals. The energy industry has now moved into frontier settings such as deepwater basins, forearc basins, poorly explored deeply buried parts of mature basins that are strongly influenced by syn- and early post- tectonic processes, and unconventional resources such as gas hydrates and shale-gas environments. Successful and cost-effective exploration strategies in these frontier areas are enhanced through understanding of the tectonic, stratigraphic, and fluid flow processes operating during the formation and evolution of continental margin basins as well as their placement within the correct paleogeographic, paleoclimatic, and paloeoceanographic environments. A better understanding of tectonic, sedimentological, and fluid flow processes in active marginal basins is also critical to strategies for the discovery and exploitation of mineral deposits and geothermal energy.

The energy (wind, thermal, hydrocarbons) and telecommunications industries face new challenges as they build infrastructures along the world's continental margins in increasingly deeper water environments. In these settings, an accurate understanding of hazards posed by earthquakes, tsunamis, submarine landslides, and the impact of large storms. At the critical land-sea interface, rapid changes in the land surface are impacting access to water, exposure to major storms, and forcing agricultural change. Industry must adapt and serve this rapidly changing environment.

There are opportunities for GeoPRISMS and the energy industry to collaborate in both the deepwater and coastal settings. Successful collaboration will depend on industry and the scientific community achieving mutual benefit. At the core of this collaboration will be the goal of achieving a better understanding of margin processes with a common aim of predictive modeling of margin evolution. Beyond strengthening our scientific understanding, corporations will benefit as we train the next generation of technical leaders, some of whom will join them. The clearest benefits to the GeoPRISMS program is to leverage our research program through the use of industry-acquired data and through specific cost-sharing by industry for our research projects. The most obvious example is access to high quality 3-D and 4-D seismic reflection data sets across the world's continental margins for use in specific GeoPRISMS activities. The benefits extend beyond sharing data and specific cost-sharing arrangements. There is an excellent reservoir of knowledge in industry; access to this "in-house" detailed knowledge of certain basins and tectonostratigraphic environments can help focus and refine our research programs, and enhance training for GeoPRISMS students and researchers. Finally, development of broad familiarity with private sector practices for dealing with spatially dense multidisciplinary datasets will greatly benefit our science.

A successful collaboration will benefit from the interactions both in focus site decisions, as well as program steering. A factor to consider in decision-making is the intersection of sites enabling the best quality science and industry interest. Thus, the availability of extensive industry data and/or industry passion for particular regions should weigh in our decision-making. Second, we need to actively develop specific collaborations between industry and the GeoPRISMS Program. Obvious examples include data-sharing and service in kind agreements wherein GeoPRISMS uses existing geophysical or well data to further refine our own experiments. The relationship between academia and industry is often delicate. It must be recognized that GeoPRISMS research is an open enterprise; on the other hand, we must put in place the proper protections for industry to be able to share information they have previously acquired that are of some proprietary value. The industry-GeoPRISMS collaboration will be facilitated by a spokesperson on the GeoPRISMS Steering Committee, as recommended by the DRC. We will also hold regular collaborative workshops to facilitate the exchange of data and knowledge and to enhance prospects for establishing academic/industry consortia related to GeoPRISMS activities.

GeoPRISMS
Draft Science Plan

9. Education & Outreach for the GeoPRISMS Program

9. Education & Outreach for the GeoPRISMS Program

9.1. Focus and Goals of the GeoPRISMS Education and Outreach Program

MARGINS research over the last decade, and the enhanced GeoPRISMS Program, create a number of opportunities for enhancing geoscience education and public understanding of the Earth and nature of geoscience. Key assets are a thriving interdisciplinary research community, science that integrates theoretical, experimental, and observational approaches, and amphibious study of key solid Earth processes. Based on recent experience, enhancements to education efforts can be accomplished most effectively through

- A set of programs that engage and support students in the GeoPRISMS community. These programs should not only contribute to the successful professional growth of the students but also enhance the community's diversity.
- Activities that provide leveraged opportunities for enhancing the broader impact of individual projects. In particular, establish a new GeoPRISMS wide REU program and continuation of the mini-lesson program, again with renewed emphasis on reaching a diverse audience.
- Partnerships with existing programs to extend the reach of GeoPRISMS science into informal, K-12, and undergraduate education.
- Continuation of the Distinguished Lectureship Program as a mechanism for disseminating GeoPRISMS science throughout the geoscience community.

Accomplishing these goals will require a full-time Education and Outreach Coordinator who will oversee GeoPRISMS-wide student activities, the REU program and mini-lesson infrastructure. In many cases, additional funds to operate these and other programs will be sought from external sources, including relevant NSF education and outreach programs, as detailed below. The E&O Coordinator will work within the central office to manage the core education and outreach activities, support the PI community in leveraging the efforts of their education and outreach efforts, and facilitate partnerships with geoscience education and outreach activities more broadly. This strategy will ensure the needed support both for the GeoPRISMS student community to foster their successful growth into the GeoPRISMS research leadership of the future, and for the GeoPRISMS PI community to develop highly effective broader impacts that in aggregate create a robust education and outreach program. The proposals below are based on a well-thought out Vision Statement developed by the MARGINS Education Advisory Committee (MEAC), presented in full in Appendix D.

9.2. Focus on Undergraduates: REU and Other Programs

The GeoPRISMS Program will sustain and grow the present undergraduate-centered efforts, with goals of entraining students and faculty in geoscience departments not currently engaged in MARGINS or GeoPRISMS research and increasing the diversity of the GeoPRISMS community. These activities will provide opportunities to experience interdisciplinary science and will create a natural pipeline into graduate education.

The most effective vehicle for bringing undergraduate students and their departments into GeoPRISMS is a Research Experience for Undergraduates (REU) program. GeoPRISMS can provide strong opportunities for students to engage in large scale, interdisciplinary, amphibious research focused on understanding plate boundary processes in a systemic way. Much of the science described in this Science Plan is accessible and exciting to undergraduates and provides opportunities to engage students in experiences that complement those currently offered through the REU program and other solid earth consortia such as IRIS. The GeoPRISMS program will be based on the successful IRIS model of distributed hosts with important modifications for the unique aspects of the GeoPRISMS community. Key features will be:

- At least 2-3 distributed sites will host individuals or groups of students.
- Freshmen, sophomores and juniors will be eligible to participate, allowing students to learn about geoscience with enough time to major in the field. Special attention will be paid to recruiting students from institutions that have not been involved in GeoPRISMS research, including those from 2-year, 4-year, and minority serving institutions, and to recruiting a diverse pool of student participants.
- The students are encouraged to have advisors at their home institutions be actively involved in the research.. This will provide a pathway for new faculty to enter the research program, expand awareness of GeoPRISMS, and provide needed staffing for the REU sites. It may be valuable to engage graduate students in advising and mentoring the students as well. Funding for graduate students might motivate researcher participation.
- Cohort building of the entire REU group across the sites will be emphasized through a week of introductory activities at a central site, which may include the novel use of ship-based or field camp-based experiences.
- Support from the GeoPRISMS central office or designated affiliate will coordinate activities. One possible model would be to link the initial GeoPRISMS REU to the IRIS site REU or similar programs.
- The GeoPRISMS Office will track the REU students after their summer program so that that community can be encouraged to participate in the bridge programs (see Section 9.8.2).

Funding mechanisms will be explored with NSF. It is anticipated that funding for specific research sites or students can be included in individual research proposals or obtained through proposals to the NSF-REU program, while coordination activities will be as part of the GeoPRISMS E&O Coordinator's responsibility.

9.3. Building the Student / Post-doc / Early Career Community

MARGINS and GeoPRISMS research involves an interdisciplinary team-based approach to studying systems using multiple methods, with notable success in fostering this approach in graduate students who then continue on to become GeoPRISMS PIs. These efforts will be enhanced by further development of two programs, the Postdoctoral Program and a new Graduate Student Forum funded and managed by the Education and Outreach Coordinator at the GeoPRISMS central office.

9.3.1 .Student Forum and Pre-Meeting Symposium

Current graduate student community building events supported by the MARGINS Program include a student forum and student prizes at the fall AGU meeting. Since 2003, 39 students have been honored as winners or honorable mentions. The awards are viewed as honors that are highly valuable on students' CVs. This program should continue. More undergraduate students should be encouraged to apply.

To further provide students with opportunities for interaction, the GeoPRISMS Program could develop a structured 1-day student symposium, typically occurring before a larger GeoPRISMS meeting or workshop. As one model, this symposium could include oral and poster presentations, organized by senior graduate students or mentors. The experience will provide leadership opportunities for senior students and first-exposure opportunities for more junior students, which will help in developing independent scientists and effective communicators within both groups. The meetings could include career development opportunities, such as talks on proposal writing or postdoctoral opportunities (especially the postdoctoral program), as well as group discussions about how to succeed as a graduate student. Post-doctoral fellows could be an important source of speakers and information for this activity. Online social networking (e.g., Facebook, twitter) could be promoted as an additional low-to-no-cost avenue for student communication and enhanced program awareness.

9.3.2. Postdoctoral Program

The MARGINS postdoctoral program has been highly successful in providing a pathway between graduate school and academic positions. To the awardees, the named postdoctoral fellowship is viewed as a prestigious honor, and is recognition of early independence, established capability, and high scientific potential. This program should continue, as recommended by the DRC. Although participants have done exceedingly well, there has been a small applicant pool that should be expanded. Participation might be increased by communicating more thoroughly with the graduate student population (see Section 9.3.1). Special attention should be paid to maximizing the diversity of the applicant pool. Also, the NSF solicitation process could be modified to increase its competitiveness in two ways:

- Increasing application deadlines to twice per year (autumn and spring), with expedited review and decision process, thus removing direct competition between regular GeoPRISMS PIs and the postdoctoral applicants. Potential postdocs, after identifying a prospective advisor, will write and submit the fellowship application directly to NSF. A fellowship issued directly to the student (postdoc to-be) will greatly enhance a CV. The newly developed NSF-EAR postdoc program may serve as a good model.

The GeoPRISMS postdocs could be integrated more specifically in supporting GeoPRISMS students. For example, they could be required to participate in symposia. GeoPRISMS could also provide more support for their professional development, for example, capitalizing on the On the Cutting Edge workshop for post-docs and graduate students. (*http://serc.carleton.edu/NAGTWorkshops/careerprep/index.html*) In addition to benefiting the post-docs, this approach could build broader awareness of the GeoPRISMS program. These mentoring efforts would directly complement the mentoring requirements now put in place by NSF.

9.4. Develop Educational Resources and Foster Faculty Involvement: Mini-Lessons

Over the last 5 years, efforts to integrate discoveries from MARGINS science with the teaching of fundamental concepts in geoscience have been propelled by development of web-accessible classroom and teaching laboratory activities and visualizations called 'mini-lessons' (*http://serc.carleton.edu/margins/index.html*). Mini-lessons capitalize on cyberinfrastructure resources to integrate MARGINS-GeoPRISMS data and research findings into broadly accessible educational materials. The engagement of undergraduate educators has ensured that the materials developed are well-suited to their audience, while participation by MARGINS PIs ensured cutting-edge content.

This program model capitalizes on the natural tendency of faculty to incorporate their research into their teaching, and is particularly well suited to supporting individual projects in moving their research results into undergraduate teaching. In addition, mini-lessons can form the foundation for independently funded projects addressing specific educational needs (e.g., adaptation for middle school Earth Science). Both of these approaches have already been adopted. Two synthesis project proposals in the 2009 MARGINS competition included creation of mini-lessons as mechanisms to broaden the impact of the projects. Independently but following the MARGINS model, an education grant has been awarded to IRIS to develop a set of mini-lessons to teach seismologic concepts.

Several approaches could enhance the effectiveness of mini-lessons:

- Mini-lessons should address curriculum needs as defined by educators.

- Team approaches to the development of mini-lessons, or curricula comprising mini-lessons, could be fostered to engage career and 2-year college faculty.
- Gaps in the existing mini-lesson collection should identified and filled.
- Some mini-lessons should be designed for easy adoption into lower division, gateway courses. Such courses are often taught by faculty outside of their expertise, therefore, these mini-lessons must be self-contained educational resources.
- Interested graduate students could be engaged with faculty in developing mini-lessons enhancing their preparation for faculty appointments that involve teaching.
- Continue formalizing the assessment of materials across the undergraduate curriculum for content accuracy and pedagogical effectiveness.
- Improve dissemination of mini-lessons through professional organizations, meetings, workshops, professional journals, and education and outreach resources.
- Construct a Developer's Toolkit compiling best pedagogical practices and resources for developers (e.g., GeoMapApp, EarthChem) and access points to basic research results.

These types of activities could be funded either as broader impacts proposed by PIs as part of their scientific proposals or by proposals to appropriate NSF education programs (TUES, GeoED, OGED) for sets of mini-lessons. To enable distributed improvements to the collection through this variety of mechanisms, the GeoPRISMS core funding will support the cyberinfrastructure for ongoing creation and dissemination of mini-lessons, although other support for significant program enhancements will be explored (the original MARGINS Mini-Lessons development was supported by a grant from the NSF's Division of Undergraduate Education). The Education and Outreach Coordinator will work with individual PIs to identify opportunities to enhance the mini-lesson collection. The GeoPRISMS Education Advisory Committee (GEAC) will provide oversight and review the overall health of the collection, and make recommendations for needed developments such as those outlined above.

9.5. Expand Education and Outreach Through Strategic Partnerships

Informal (e.g. museum) and/ or K-12 education components are important new direction for the GeoPRISMS Education and Outreach program, and one identified by the DRC. The arena is large, and a program is best developed through partnerships with existing science organizations, consortia, and/or PIs of long-term geoscience education projects, who have existing informal or formal education programs. This approach will yield a major increase in the visibility of MARGINS and GeoPRISMS science and scientists for a relatively modest investment.

9.5.1. Partnered "Event- Based" Presentations

One promising model for this approach is the development of "event-based" presentations, planned informal/formal educational events featuring audience-appropriate and engaging GeoPRISMS science concepts, scientists-in-action, interesting investigative techniques, and/or exploration efforts. Developed through partnerships with groups focused on outreach, the GeoPRISMS Office would coordinate the science content with PIs for these events. The partner organization would be responsible for the event itself, including advertising and organization, and logistics. An example of such an event might be the GeoPRISMS Office initiating a web-based live interview from a drill ship working in a GeoPRISMS area, but using the IODP resources and connections with the educational (principally K-12) community. The goal of the event is both the communication of science content and the formation of science career role models for K-12 students, undergraduates, graduate students and the general public.

Engaging events for informal education could include live communications with scientists, and opportunities for event participants to control or provide input on investigations. Additional materials, such as podcasts and video-clips could be captured and incorporated during the event. The central GeoPRISMS Office can coordinate the collection of material from PIs, whereas the partner organization would contribute their expertise in designing and presenting content. Possible partners include: GLOBE, IODP, the JASON Project, COSEE, TXESS Revolution, and the National Ocean Sciences Bowl. PIs on individual proposals who anticipate that they will have important materials for this type of outreach could include funding for the development of materials in their proposals and emphasize this contribution as part of their broader impacts.

9.5.2. Other Partnership Opportunities

There are opportunities to partner with geoscience education programs and education PIs to bring GeoPRISMS science into the middle and high school curriculum. Partnerships with other geoscience research initiatives (e.g. IRIS, UNAVCO, EarthScope, OOI) professional societies, curriculum development projects, and professional development programs could provide opportunities to adapt mini-lessons (Section 8.4) to the K-12 audience for use by teachers, to incorporate GeoPRISMS science in textbooks and teacher professional development programs (e.g. GIFT workshops, Research Experiences for Teachers). Opportunities also exist to partner with geoscience education researchers and educational psychologists who could initiate and carry out projects to measure the impact of this type of educational outreach on teachers and students, and museum audiences.

9.6. Distinguished Lectureship Program

The existing Distinguished Lectureship Program has been very successful in raising awareness of the MARGINS program and its contributions to scientific understanding of tectonic processes. The program is oversubscribed and has reached a wide variety of institutions. This program should be continued with core support, as recommended by the Decadal Review Committee (DRC), and its impact extended by

- Requiring that speakers be willing to give a public lecture and emphasizing the value of a public lecture. To some extent this is already being done, but the opportunity could be better emphasized and more appropriate venues selected (museums, etc.). Speakers could be supported with professional development opportunities to improve their speaking.
- Incorporating information about the MARGINS and GeoPRISMS mini-lessons. This could include demonstrations of mini-lessons for area teachers.
- Advertising opportunities to participate in GeoPRISMS through the REU program, graduate programs, and post-doctoral program.

The Education Advisory Committee was eager over the long term to explore ways to expand this program internationally, as recommended by the DRC. This likely would require some other source of funding than present, which is aimed at educating the domestic student body, but there may be opportunities in conjunction with GeoPRISMS International Partnerships (Section 8.2).

9.7. Managing and Supporting an Effective Education Program

The 2009 Decadal Review Committee recommended greater visibility and awareness of the successor program both within the broader geosciences community and the general public. The program enhancements proposed above address these recommendations directly, and define a roadmap for expanding the educational impacts of the GeoPRISMS Program. Currently, a half-time education staff position in the MARGINS Office has responsibility for all of the educational programs described in Section 8.1, as well as less formal activities (managing online presentation material and other educational content on the web site: e.g., coordinating with the data management group, and writing education pieces in the twice yearly newsletter). Increasing the scope of the GeoPRISMS Education and Outreach program as described above will require added responsibilities, including:

- Providing a support structure and services for potential PIs in designing and achieving broader

impacts in their proposals including building partnerships between GeoPRISMS PIs and experts in educational activities and outreach.
- Managing the core support for the REU program (or overseeing a contract for this management) including GeoPRISMS wide activities for participating students.
- Managing new programs supporting students and post-docs within the GeoPRISMS community including the Graduate Student Forum.
- Coordinating with other research initiatives and programs and in particular seeking out and serving as contact point for partnerships in informal and K-12 education and outreach.
- Coordination of a more formal Education and Outreach advisory structure.
- Assisting in attracting external grant funds to support the expanded programs.

In addition, it will be desirable for the Education and Outreach Coordinator to explore new opportunities to bring GeoPRISMS science into wider use in education and outreach. GeoPRISMS education and outreach efforts will be best achieved through one dedicated full-time education specialist within the office of the GeoPRISMS Program, along with direct support for basic program functions as done presently (e.g., the Distinguished Lectureship Program, the mini-lesson Collection, the Graduate Student Forum, and Student Prizes. More ambitious expansions of the program will be achieved through additional grants, for example to the REU programs, TUES for development of sets of mini-lessons (original development was funded separately by CCLI), and the IGERT program for mentoring and graduate traineeships.

Location of the education and outreach program in an office that changes location every three years presents a substantial challenge to program continuity. However, the strength of the program to date reflects the engagement of the research community in the education efforts. This has been accomplished by extensive involvement of the MARGINS Office and research leadership in the education programming, which is made possible by the management of these programs in the central office. The partnership with SERC in creation of the mini-lessons provides a model for bringing stability to long-term programs. SERC can continue to host the mini-lesson collection and cyberinfrastructure supporting the contribution, review and dissemination of mini-lessons while the GeoPRISMS Office moves from place to place. Concurrently the MARGINS Office, and ultimately, the GeoPRISMS Office, remains responsible for engaging the community in the development of these lessons, for decisions regarding their content, and for the scheduling of workshops or other faculty development opportunities.

The Margins Education Advisory Committee (MEAC) has played a critical role in the development of MARGINS education activities by bringing together leadership in education and in the use of MARGINS science in education to advise the Steering Committee and the MARGINS Office. A new GeoPRISMS Educaton and Advisory Committee (GEAC) will be put in place to continue to provide such guidance. Membership will be selected to provide needed expertise in undergraduate education, mentoring students, increasing diversity, and expanding the reach of programming to K-12 and informal venues through partnerships.

9.8. Opportunities for Future Growth

Two additional areas for programming were identified in the development of the Education and Outreach plan. These ideas could be implemented in the future as opportunities arise.

9.8.1. International Experiences

The GeoPRISMS program will have activities in many countries with numerous international colleagues. New programs could encourage and help PIs in obtaining International Research Experiences for Students (IRES) or Doctoral Dissertation Enhancement Projects (DDEP) grants. An IRES or DDEP grant would support a coordinated group of undergraduate and/or graduate students working on GeoPRISMS-related research in the partner country as they work directly with their international collaborators and students. There are also opportunities in the area of International Service Learning. One example is the USAID Higher Education for Development (HED) program that fosters partnerships between USA universities and their partner institutions in host countries. The GeoPRISMS Office can provide coordination and support to facilitate obtaining grants, and to encourage education and outreach activities by individual PIs at international sites and with international collaborators.

9.8.2. Bridging Experiences

Some "bridge" experiences could fill the gap between undergraduate and graduate school. Current programs generally overlook this interval, funding for research opportunities is scarce and few career-building activities have been developed at this stage. GeoPRISMS could organize a short course or summer field camp that students would take immediately after they graduate with their B.S. degree. A field camp could emphasize the hands-on interdisciplinary tools and data acquisition that students will use in their graduate research. The activity could include both land-based and ship-based experiences, perhaps supported by external funds (e.g., CCLI, now TUES). Another bridge activity would be to help PIs to obtain supplemental grants to fund incoming graduate students during the summer before they start their graduate career.

9.9. Summary Statement and Unifying Vision

The GeoPRISMS program will be uniquely positioned to help train the next generation of interdisciplinary scientists, while expanding the reach of MARGINS and GeoPRISMS science into the broader community. The programs outlined above will form a unifying broader impacts strategy for the successor program and will create a pipeline of students that reaches from within the K-12 community all the way to early career faculty. We foresee that K-12 outreach will utilize partnerships with already successful programs. At the undergraduate level, the MARGINS program has been successful at introducing students to MARGINS science through vehicles such as mini-lessons. Additional experiences such as a GeoPRISMS REU program and opportunities to participate in international research and service learning programs further enhance the undergraduate experience. Engagement in the mini-lessons program of early career and 2-year college faculty at institutions not currently engaged in GeoPRISMS research will provide a mechanism for broadening the pool of students benefiting from these programs and entering the pipeline. Graduate students entering GeoPRISMS research fields will have new peer-mentoring opportunities at dedicated meetings and throughout the year via social networking sites. The GeoPRISMS student prize will continue to reward the top graduate students for their exemplary work. At the end of the pipeline, Ph.D. students will be encouraged to apply for the highly successful GeoPRISMS postdoctoral program, and early-career scientists will be provided with tools to create proposals with strong broader impacts. This comprehensive vision rests primarily on the engagement of the GeoPRISMS community and a growing community of GeoPRISMS geoscience educators in PI-driven activities and proposals.

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10. Other Impacts of the GeoPRISMS Program

10. Other Impacts of the GeoPRISMS Program

10.1. Interdisciplinary Science and Community Building

One of the extraordinary accomplishments of the MARGINS Program was the development of a large, interdisciplinary community over a decade's time. A major vehicle for this achievement was sponsorship of workshops. The GeoPRISMS Program will continue in this role, building on the successful model of MARGINS. Four workshop classes will be sustained:

- *Initiative Planning Workshops*, which will take place in the first year of GeoPRISMS to clarify the scientific objectives of the new initiatives, define the specific themes and primary sites for initiative studies, to direct the science, and to complete the detailed GeoPRISMS Science Plan.
- *Theoretical and Experimental Institutes (TEIs)*, which provide broad education across the disciplines, and are designed to cross-educate diverse groups of scientists about controversies, approaches, techniques, and problems in a spectrum of disciplines relevant to the problem at hand. TEIs lead to new collaborations and multidisciplinary proposals, entrain new scientists from outside of the GeoPRISMS community, and train a generation of young scientists to approach problems in an interdisciplinary manner.
- *Thematic Workshops*, which will address specific problems of interest to a number of GeoPRISMS investigators, guided by the Overarching Themes detailed in Section 3.
- *Primary Site Workshops*, which will be used to delineate new research objectives and outline approaches at Initiative Primary Sites, and subsequently, to exchange knowledge, guide new ventures, and synthesize the work done at these sites.

Workshop participation will be open to the broader U.S. community (not just GeoPRISMS PIs), including researchers within national agencies, as well as members of the international community with continuing interests in GeoPRISMS activities. This will ensure that GeoPRISMS continues to build the strong national and international partnerships necessary to carry out global science, thereby broadening the pool of ideas within the community, and leveraging resources and knowledge to strengthen it. Workshops outcomes will include new research collaborations to carry out the science objectives, along with special volumes of research papers and special sessions at scientific meetings, to disseminate results. In addition, the GeoPRISMS Steering & Oversight Committee will be proactive in organizing large special sessions at major national meetings (AGU, etc.), following a very successful MARGINS practice, to enhance rapid communication of new discoveries.

10.2. Understanding Geohazards

Much of the world's population lives along coastlines, and many of the natural hazards that affect society occur at this critical interface between the oceans and continents (Figure 10.1). Recent events, such as great earthquakes, tsunamis, explosive volcanism, marine and terrestrial mass wasting events, great storms such as Hurricane Katrina, and floods and sediment-transport that accompany them, all demonstrate the importance of understanding the solid Earth at continental margins. What GeoPRISMS can contribute are the fundamental scientific underpinnings of any educated approach to these and other critical societal concerns. GeoPRISMS is poised to make major contributions to our scientific understanding of such hazardous phenomena, their causes, and their consequences. Highlighting these connections will be a significant new program element, as recommended by the DRC.

Seismogenic zone studies within the SCD Initiative, focused on the properties and processes that govern the planet's largest earthquakes, define an obvious connection, highlighted by the devastating 2004 Sumatra earthquake and tsunami and the more

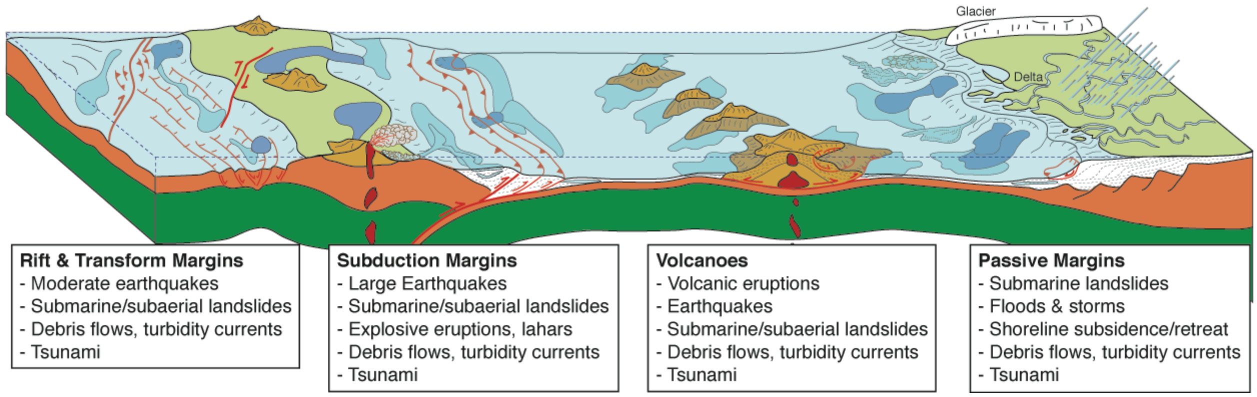

Figure 10.1: Representative geohazards that can originate along continental and volcanic margins. (Figure modified from Morgan et al. [2009]).

recent 2010 Haiti and Chile earthquakes. Seismic surveys carried out over continental margins subject to earthquakes, direct sampling and instrumentation of active fault zones, and both onshore and offshore paleoseismology can provide critical observations. Further research should also allow better evaluation of proposed triggering of large earthquakes by slow slip events. Such data could eventually assist operational agencies worldwide in improving earthquake hazard assessment.

GeoPRISMS investigations will also provide new insights into arc volcanism, in a setting that includes most of the planet's most deadly explosive volcanoes. These events are devastating locally and can have regional or even global impacts on the earth's atmosphere, affecting phenomena from short-term climate to global air travel (e.g., Iceland, April 2010). GeoPRISMS studies will provide valuable data to define the eruptive histories of volcanoes, and constrain the geochemical evolution that might influence eruptive behavior. Ash layers that accumulate in ocean trenches are often the key to dating turbidite records used to reconstruct subduction zone earthquake histories, as well as explosive eruptions. New information and interpretations generated by GeoPRISMS can be expected to assist the U.S. Geological Survey in its responsibility to advise the public of earthquake and volcanic hazards, through integrative and focused studies of both seismogenic faults and active magmatic systems.

The GeoPRISMS program addresses geohazards at rift margins. Studies of active coastal and slope processes provide emphasis on the erosion, transport, and transfer of sediments across the shoreline, and their storage in the marine setting (Section 5). These studies will take into account the role of both long-term and short-term sediment transfer and depositional processes that contribute to the architecture along passive margins controlled by coastal subsidence and climate-induced changes. Slope instability and consequent landsliding on all types of margins can be initiated by floods, storms, earthquakes, and eruptions, and GeoPRISMS provides the means to study the mechanisms of mobilization and transport, and potentially, precursory phenomena indicative of failure. Beyond sedimentary processes, measurements of deformation and fault activity will clarify earthquake hazards that affect populations living along active rifting margins.

In both Initiatives, the systems approach of GeoPRISMS provides vital constraints on the complex interplay and feedbacks between tectonics, sediment generation and transport, and global climate change. For example, compressional and extensional tectonics can lead to broad plateau uplift that deflects continental scale drainage networks, and that serves as a topographic barrier to atmospheric circulation, with feedbacks to the ocean circulation pattern. Continental rupture culminates in the formation of new ocean basins that fundamentally change ocean circulation, with clear atmospheric feedbacks and climate change. Because of their mix of organic rich muds, narrow oceans, and moderate to rapid sediment rates, rifts in their early stages are the ideal setting for formation of large gas hydrates which later may be destabilized. In addition, thermal uplift may disrupt the connection between seaways, thereby further altering ocean circulation and climate (Section 5). Over time scales of years, some of the most profound effects on the climate come from explosive volcanic eruptions that eject aerosols high into the atmospheres. While most of these effects diminish after a few years, the largest historic eruptions have had profound consequences for humanity. New gas and volatile measurements from arc volcanoes are helping to quantify these processes better, and better understand such effects.

10.3. Economic Resources

The impacts of an improved understanding of continental margins upon our economic resources cannot be understated. An extraordinary fraction of the world's population lives along continental margins and depends on the resources of these margins, including water and food. They are directly affected by both onshore and offshore habitat loss, due to changing coastal conditions and riverine influx, and the hazards described above. At the same time, these margins are undergoing major changes in real time (e.g., Section 5.2-5.4). The GeoPRISMS program can make substantial contributions to understanding the processes that affect these settings and how their change through time will impact economic resources of many types.

A quantitative, process-based, understanding of margin evolution is also proving fundamental to discovery and exploitation of energy and minerals. The petroleum industry has now moved into frontier settings such as deepwater basins, forearc basins, poorly explored deeply buried parts of mature basins, and unconventional resources such as gas hydrates and shale-gas environments. In the deepwater environment, a single exploration well can cost $200,000,000 and a production facility can cost an order of magnitude more. Any increase in our understanding of margin processes that can incrementally impact risk in this environment can have enormous impact. Successful and cost-effective exploration strategies in these frontier areas are enhanced through understanding of the tectonic, stratigraphic, and fluid flow processes operating during formation and evolution of margin basins.

Submarine active margins are also sites where large precious and base metal deposits formed in the past, and are even forming today. Active submarine hydrothermal venting has been discovered throughout western Pacific arcs, in part through MARGINS. Almost half of current global mineral exploration is for gold and the largest new deposits are in subduction environments, such as the caldera of Lihir volcano and at 1500 mbsl in the northeast Manus Basin, both in Papua New Guinea. The metals in these deposits are mostly derived from subduction zone magmas and volcanic rocks, and are transported in saline fluids similar to those responsible for metasomatizing arc magma sources and for the explosive eruption of arc volcanoes. Consequently, understanding the origin and setting of the metal deposits is directly related to the origin and evolution of mantle, crust, and fluids in subduction zones at many scales, goals that figure prominently in GeoPRISMS.

For these reasons, the new program will feature strong links to energy and resource issues, as recommended by the DRC. While direct linkages depend upon the ultimate form that agreements and partnerships take (see Section 8.3), increased emphasis on relevance will be a high priority.

10.4. Data Management in GeoPRISMS

The first decade of MARGINS has involved marine and terrestrial field programs across a wide range of scales, from small-scale fieldwork by individual PIs to complex multinational experiments. At the initiation of the MARGINS program, facilities existed to accommodate some types of data, but in many cases data sets resided primarily with individual scientists. To ensure long-term data preservation and to provide broad data access and distribution, the MARGINS data management system (*www.marine-geo.org/MARGINS*) was initiated in Fall 2003 at Lamont-Doherty Earth Observatory. It includes a central, searchable metadata catalog with links to download data files, hosted locally or in remote archives including UNAVCO, IRIS and EarthChem. Data system tools include the visualization and analysis applications GeoMapApp and Virtual Ocean. The data system has become well integrated with the MARGINS program, forms the basis of significant outreach activities (Section 9), and provides field data and documentation for all MARGINS expeditions.

It is expected that the range of field programs and data collected in GeoPRISMS will broadly resemble that in MARGINS, but opportunities exist to provide greater support for integration and education through added facilities. Data management discussions at the MSPW suggested several possible areas of high priority growth potential, described below. Some of these opportunities can be easily managed, while others will require community discussion and vetting. It is expected that a small Data Management Task Force will be convened early in GeoPRISMS to evaluate and prioritize these opportunities.

Existing infrastructure and an expanded GeoPRISMS data system: Considerable data infrastructure currently exists to facilitate GeoPRISMS program science and should be built upon. New capabilities to support multi-PI collaborations could be developed, such as common work space for data analysis, where PIs working in a similar region or on a common process could easily share a wide variety of observations. A central data system could also serve as a hub for distributing more integrative data products and analysis tools. Some of this capability exists in CIG and CSDMS, and partnerships with these programs could advance this goal. Currently, there is no infrastructure for the archiving of experimental data such as lab-based rheological studies and sediment flux models, but possibly such data could be archived under an expanded data system. GeoPRISMS will also continue forging strong ties to the EarthScope facility, and expanding the underlying existing data management links to IRIS and UNAVCO for seismic and geodetic data, respectively.

Data policy compliance: NSF requires the long-term preservation of and broad access to digital data and physical samples acquired with NSF funding. While compliance with the MARGINS data policy was successfully achieved for field data sets, challenges remain for data types with no obvious home archive. Also, the existing MARGINS data policy (dating from 2005) should be reviewed to ensure that it adequately addresses the requirements of GeoPRISMS and current NSF practices.

Incorporating secondary data: Derived and analytic data can be of broadest use for the multi-disciplinary and integrative studies that are likely under the GeoPRISMS program, but are not routinely archived. However, easy access to such secondary data has potential to revolutionize the synthesis of multidisciplinary observations. Many of these data do not have standard repositories or homes, therefore a goal for the community will be to establish a suitable framework in which such data could be more widely distributed.

Data Citation: Creating citations for field data will allow scientists to refer to it soon after acquisition in a consistent and long-lasting manner. The database group is developing capacity to publish data sets with digital object identifiers (DOIs) within the international STD-DOI system. IRIS is currently pursuing another model of data set citation through Seismological Research Letters. These data citation and tracking systems need to be evaluated and should be pursued in the data management plan for GeoPRISMS.

Physical samples: At present there is no formal structure for the routine archiving of physical samples (rocks, fluids) collected under most NSF awards, with samples historically housed at PI host institutions. The curation of physical samples needs to be addressed at the NSF agency level, perhaps through partnerships with national museums such as the Smithsonian and American Museum of Natural History.

Numerical models: The CIG and CSDMS computational facilities provide infrastructure for the archiving and dissemination of certain types of modeling source code (See Section 8.1.7). GeoPRISMS PIs will be encouraged to submit relevant software.

Industry data: Availability of industry-collected 3-D seismic and downhole data sets could greatly benefit future GeoPRISMS science. Gaining access for broad use and publication within the research community is likely to present challenges and may require development of formal industry-academic partnerships. GeoPRISMS should also work with industry partners to find solutions for preservation of industry data sets that are no longer viewed as commercially valuable, for example within the data management system.

Primary Site/Thematic Data Compilation: As primary sites are identified for the GeoPRISMS program, early priority should be given to identify and assemble key existing data sets for the region. Compiling these data sets and making them available to the community through an expanded MARGINS-GeoPRISMS data portal would help with field work planning, for example. Compilation of the existing data may not be trivial, particularly for terrestrial data sets and geochemical data, and dedicated support may be needed for this initial task.

By these many different means, the GeoPRISMS program will be able to contribute to the much broader scientific community in a timely manner, allowing other researchers invested in related studies to access the data for their investigations. This approach is compatible with an increasing emphasis on open (or rapid) data access through many other organizations, initiatives and facilities, including EarthScope and potentially R/V Marcus Langseth acquired seismic data.

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11. Program Management

11. Program Management

11.1. Program Structure

The successful MARGINS program provides a strong model upon which to outline the program structure for GeoPRISMS. Key elements will include

- A national Office to coordinate meetings and workshops, to disseminate information (by way of newsletters, listserv announcements, etc.) including workshop summaries and reports on funded research, to manage educational and database activities, and to assist with logistics and scientific efforts not supported by funding to PIs. The GeoPRISMS Office will be directed by the GeoPRISMS Steering and Oversight Committee Chair, and hosted at his/her institution, rotating every 3-4 years; proposed activities are listed in Section 11.2.
- A GeoPRISMS Steering and Oversight Committee (GSOC), composed of ~12 members representing the community, to help guide program activities. The GeoPRISMS Chair will oversee the GSOC:
  - o Similar to the MARGINS Steering Committee (MSC), GSOC's activities will include reviewing progress toward scientific goals, organizing and running workshops, preparing white papers and initiative summaries, promoting national and international collaborations and opportunities, fostering communication within the broader community, and providing advice and feedback to NSF program managers and GeoPRISMS chairs.
  - o Upon the recommendation of the DRC, GSOC also will continually monitor and review progress towards the stated goals within each Initiative's science plan, and encourage attempts to integrate and synthesize results. The GSOC will also have one or more members who represent the perspectives of industry, the climate and geohazards community, and state or national surveys.
- A GeoPRISMS Education Advisory Committee (GEAC), which will provide advice and guidance on educational programs coordinated by GeoPRISMS (see Section 9), with 1-2 members also serving on the GSOC. GEAC will help to oversee the activities of the educational coordinator housed in the GeoPRISMS Office.
- An annual NSF solicitation for GeoPRISMS proposals, each of which should address priorities outlined within the community-approved Science Plan. To avoid potential conflicts of interest, the GSOC will have no direct input into the proposal evaluation.
- An independent NSF review panel, with expertise spanning the EAR and OCE communities, to evaluate proposals in the context of the GeoPRISMS Science Plan.

11.2. Proposed Office Activities

The GeoPRISMS Office, operating under the direction of the Chair of the GSOC and subject to the advice of that body, will serve to facilitate and coordinate the research program, including the following activities (again modeled after the MARGINS Office):

1. **Program Planning and Coordination**. The Office will schedule, organize and provide logistical support for regular GSOC meetings, twice yearly, along with gatherings at AGU and smaller working groups. The Office will prepare pre-meeting materials, produce and distribute meeting minutes, arrange travel, and invite relevant visitors to provide content. The Chair of the Office will also be available to attend meetings and workshops to aid in program planning, internationally, at NSF and elsewhere in the U.S.

2. **Workshop Support.** The Office will provide encouragement, guidance and logistical support to proponents willing to organize major conferences within the purview of PRISMS, and will organize smaller meetings necessary to attain GeoPRISMS objectives. These workshops have been the cornerstone of the MARGINS effort at building large, new interdisciplinary science communities, and nurturing creative new proposals, and will continue into GeoPRISMS. To ensure that these workshops focus on programmatic goals, at least 1-2 GSOC members will be encouraged to serve as Conveners for any major workshop.

3. **Communication.** While research is done at individual institutions, integration and synthesis requires a good understanding of all other aspects of the program, and requires an informed community. One primary vehicle is the program web site (see for example, *www.nsf-margins.org*), and the associated e-mail list server, which will be maintained and moderated by the GeoPRISMS Office. These vehicles provide information on science planning, research, job opportunities, funding, meetings, and documents, both nationally and internationally. The web site will also continue to serve as an easily-found portal to science planning documents, database servers, reports on Initiative progress, and educational resources. A twice-yearly Newsletter will continue to provide summaries of GeoPRISMS-related activities and to alert the community to events, new opportunities and other issues of interest. Finally, GeoPRISMS will host receptions, forums and town-hall meetings at major international functions such as Fall AGU.

4. **International Collaboration.** As in the past, the Office will facilitate international collaborations by co-sponsoring workshops with international participants, by assisting in coordination of collaborative agreements, and by participation of the GeoPRISMS Chair or GSOC members in international planning committees. One priority will be to foster a replacement for the now defunct InterMARGINS consortium.

5. **Event Response.** The GeoPRISMS Office will follow MARGINS lead by serving as a point of contact to facilitate rapid response when critical events occur. In the past, rapid responses were supported through the MARGINS Office and NSF, after a short informal written request and approval by both MSC and NSF. GeoPRISMS proposes that this approach continue into the new program, allowing the rapid turnaround needed for sudden events, and the proactive engagement of a broad range of scientists through Office coordination. The NSF "RAPID" program facilitates such activities.

6. **Data Management.** Broad, cross-disciplinary scientific syntheses depend on easy data archival, retrieval and exchange between many communities. The MARGINS database hosted by MGDS is now well-populated and will transfer into the GeoPRISMS Program, while retaining the MARGINS label. The Office will continue to assist in efforts to improve both the access and completeness of the collection, as outlined in Section 10.4. The Office will also foster interaction between the scientific community and the database developers.

7. **Education and Outreach.** The MARGINS Office currently operates several components of the Education program, in consultation of the MARGINS Education Advisory Committee. The Education and Outreach component of GeoPRISMS includes some enhancements, detailed in Section 9, and will be overseen by GEAC as described above. All program elements also will be coordinated largely through the GeoPRISMS Office, and the Education Coordinator who works there. In many cases the programs will be operated elsewhere in cooperation with other well-established programs and funded separately, as outlined in Section 9, but close coordination within the Office will be needed to ensure that

educational and research priorities are well integrated.

Office Operations

Since 2003, the MARGINS Office has had two full-time equivalent (FTE) staff members, typically a full-time Administrator who handles operations and a full-time PhD-level Science Coordinator who deals with larger-scale issues. If the enhanced E&O activities (Section 9) are approved, the currently half-time education-related staff position should be increased to a full-time Education Coordinator to manage these operations, under the advisement of the GEAC. The Office will continue to be supported by a 3-year grant to the Chair that covers salaries and routine operating costs, including GSOC meetings. The Office will manage supplemental funding requests through proposals or a Cooperative Agreement, in order to support workshops and related activities.