4. Overarching Scientific Topics and Themes

Much of the success of the present MARGINS has come from developing true 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 PRISMS Initiatives. Below we identify 5 major cross-cutting themes that bridge the Initiative structure: (1) origin and evolution of the continental crust; (2) fluids, magmas and their interactions; (3) climate-surface-tectonic feedbacks; (4) geochemical cycles; and (5) plate boundary deformation and geodynamics. We view these themes as likely areas in which major breakthroughs will occur within PRISMS.

4.1. Origin and Evolution of Continental Crust

Earth's continental crust appears to be unique in the solar system, yet the processes and rates of its creation and consequent implications for composition and stability of the mantle lithosphere 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 tectonic, metamorphic, surficial, and magmatic processes fundamentally change the composition and structure of the continental crust at these margins. In both active and passive margins, erosion and deposition processes transfer material from mountains to basins, altering the thickness, density, and bulk composition 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. 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, rift zones, and flood basalt provinces are 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 a 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 on short time scales [e.g., Kay and Kay, 1993; Jull and Kelemen, 2001]. Although most mantle-derived magmas are basaltic, more differentiated magmas (andesites) can be produced directly from the mantle in the right circumstances [e.g., Kelemen, 1995; Yogodzinski et al., 1995; Tatsumi, 2001]. 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.
A key breakthrough of MARGINS and collaborative programs is the documentation of the crustal distillation process in the Izu-Bonin trench region through co-located geochemical and geophysical studies. For example, Kodaira et al. [2007] and Calvert et al. [2008] imaged 3D along- and across-strike variations in the thickness of a middle crust with velocities appropriate for andesite and a complementary high-velocity lower crust. They also observed along-arc crustal thickness variations that likely arise from variations in magmatic productivity, crustal differentiation, and/or crustal delamination of denser residuum. The production of intermediate middle crust from mafic, mantle derived melts is significant since it resembles the average seismic velocity structure and bulk chemical properties of continental crust [e.g., Christensen and Mooney, 1995; Rudnick, 1995], and it requires the formation of dense, mafic cumulates, which may be transferred to the mantle or downgoing slab by lower crustal foundering, or dynamic processes [e.g., Jull and Kelemen, 2001; Behn and Kelemen, 2006]. The presence of a thick middle crust with velocities attributable to intermediate compositions distinguishes IBM from some other intra-oceanic island arcs, which show a higher velocity middle crust [Holbrook et al., 1999; Lizarralde et al., 2002; Shillington et al., 2004]. No comparably dense, 3D datasets exist in other arcs that can reveal whether or not the along-strike variability observed in the IBM is typical of arcs worldwide.

Continental rift settings are regions of potentially voluminous magmatism where substantial volumes of new, mafic and differentiated felsic material may be added to the crust. Less well established is the potential for lithospheric materials to be recycled back into the mantle in these rift settings [e.g. Class and LeRoex, 2006; Wallner and Schmeling, 2010]. MARGINS studies confirm profound along-strike variations in the volume and composition of the rift-related magmatic additions to the crust, as well as variations in the mantle structure associated with melt extraction and retention. MARGINS and other studies worldwide are revealing the 3D magmatic plumbing system that supplies melt through the crust from rift inception to rupture, and volumes of fractionated basaltic material from upper crustal magma chambers [e.g., Keranen et al., 2004; White et al., 2009; Rooney et al., 2007; Keir et al., 2009].

The transfer of magmatic material from mantle to crust and dense residuum from crust to mantle fundamentally alters 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. Numerical modeling, laboratory, seismic and geochemical studies document the feedbacks between fluids in the downgoing crust and circulation within the overlying mantle wedge that trigger melting and subsequent rise of magmas to the plates [e.g., Grove et al., 2006; Cagnioncle et al., 2007; Rychert et al., 2008; Syracuse et al., 2008; Hebert et al., 2009]. Models and observations also document the feedbacks between pre-existing lithospheric heterogeneity, lithospheric stretching, and mantle upwelling on the distribution, composition, and volume of melts beneath rift zones [e.g., van Wijk et al., 2005; King, 2000; Bialas et al., 2010; Holtzman and Kendall, in press]. These crustal and mantle heterogeneities persist over long time scales, and play a role 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 strongly influence the localization of strain and magmatism [Lizarralde et al., 2007; Bialas and Buck,
2009]. These new discoveries and insights inform and guide a new generation of scientific exploration and investigation within subduction and rift settings.

4.2. 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.

MARGINS researchers have made significant advancements in characterizing the thermodynamics of melting and metamorphic reactions in subduction input material and the mantle wedge. This led to a more quantitative approach for investigating relationships among the thermal evolution of slabs, metamorphic reactions, fluid production, and seismic velocity structure. Within this framework, 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. MARGINS facilitated rapid improvements in integrating seismic imaging, laboratory measurements, geochemical analyses and numerical modeling. Two examples that highlight such improvements are the demonstrated link between style of rifting and magmatism in the Gulf of California [Lizarralde et al., 2007] and the imaging of fluid and melt pathways in the Costa Rica-Nicaragua subduction zone [Rychert et al., 2008; Syracuse et al., 2008]. Future work will rely on continued innovation in imaging techniques that integrate seismic velocities, attenuation, and anisotropy, as well as EM imaging of volatile rich zones. Laboratory experiments provide critical information on the effect of volatiles on mantle melting [Grove et al., 2006; Dasgupta and Hirschmann, 2007; Hauri et al., 2006], but continued work is needed on the petrological, physical and rheological properties of partially molten mantle under ambient conditions [e.g., Takei and Holtzman, 2009; Faul and Jackson, 2005]. Geochemical analyses provide direct measurements of volatile species in magmatic glasses [e.g., Shaw et al., 2008; Benjamin et al., 2007] and precise magma chronologies [e.g., Carr et al., 2007], but new approaches are required to constrain the volcanic and intrusive fluxes for entire arc systems. Finally, theoretical models provide a strong tie to solid flow and thermal structure of the mantle wedge in both 2D [Conder et al., 2002; van Keken et al., 2002; Kelemen et al., 2003; Cagnioncle et al., 2007; Hebert et al., 2009] and 3D [Kneller and van Keken, 2007]. A new generation of models that incorporate
feedbacks between melting, two-phase flow, and chemistry can be realized by capitalizing on recent advances in computational resources and algorithmic development.

Although a myriad of links among fluid, mechanical, and chemical processes are recognized, their characterization through observations has generally been qualitative. Understanding of processes that control the spectrum of fault slip styles at convergent margins, some of which have been linked to fluids [e.g., Dragert et al., 2001; Shelley et al., 2006], 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 [e.g., Liu and Rice, 2007, 2009; Rubin, 2008]. 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. PRISMS is poised to facilitate rapid advances in our understanding of fluids and their impacts at both subduction zones and rifts through multidisciplinary approaches, newly acquired data, new observational tools, and integrated modeling.

4.3. Climate-Surface-Tectonic Feedbacks

Sediments are archives that provide 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. There is promising potential in interpreting past tectonic subsidence rates, sediment discharge, and climatic conditions from quantitative models that integrate depositional processes over geological timescales [Fedele, 2007]. We are poised to use technological innovations in imaging, geochronology, and physical and numerical simulation to elucidate the interactions between earth surface processes and continental margin evolution.

We are only beginning to understand how surface processes impact modern rifted margins. Sediment input may favor an early transition to narrow-rift mode due to changes in heat flow and magmatism [Lizarralde et al., 2007] and crustal buoyancy [Bialis and Buck, 2009], while also promoting diffuse deformation after lithospheric rupture [Penaud et al., 2003]. Recent studies of low-T thermochronology [Spiegel et al., 2007], tectonically induced climate change [Chapin, 2008], and climatic controls on incision rate and rift architecture [Mack et al., 2009; Kluesner et al., 2009], all point to poorly understood feedbacks among crustal extension, climate, erosion, subsidence, and sedimentation. The geometry of mature rifted margins is thought to be controlled by sediment input through both critical wedge geometries [Bilotti and Shaw, 2005], and through development of an equilibrium topography controlled by slope stability that is in turn controlled by pore-pressure modulated sedimentation [Flemings et al., 2008].

Recent studies integrate geomorphology, thermochronology, and numerical modeling to investigate how climate and erosion impact the mechanical development of thrust belts and related orographic effects [Willett, 1999; Montgomery et al., 2001; Whipple, 2009].
Convergent-margin dynamics are governed by feed-forward and feed-backward relationships among uplift and deformation, forearc tectonic erosion, climate dynamics, erosion, sediment delivery to the margin, dehydration of clays during subduction, cycling of fluids and gases through the accretionary prism, upper mantle dynamics, and upper-plate magmatism. The thickness of incoming sediments at trenches is highly variable and controls large variations in the materials brought into contact with the mantle wedge, pore fluid pressure, stress conditions, and mechanics of accretionary wedges [Morley, 2007; Underwood, 2007]. The form of accretionary prisms may be controlled by sediment input [Saffer & Bekins, 2002] and the presence or lack of sediment in a forearc basin may exert a strong control on the degree of mechanical coupling between the upper and lower plate, and hence the magnitude of subduction zone earthquakes [Simpson, 2010; Fuller et al., 2006]. The existence of great earthquakes on convergent margins appears to be more likely when thick sediments are subducted [Song and Simons, 2003].

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 from the stratigraphic record to the morphology through time. Recent studies of the production of stratigraphy at continental margins have generated a series of quantitative insights into 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 [Allen, 2008; Straub, 2009]. 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.

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 cases, unique, recorders of integrated weathering and flux history of the accumulated sediments. Surface processes convey and alter materials 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 [e.g., Gaillardet et al., 1999; Derry et al., 2005]. 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 [Derry and Schopka, 2010]. 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 interaction of Earth surface processes with climate and tectonics has enormous societal implication. Many of the processes of greatest societal impact are collocated. For example, areas most exposed to sea-level change are also impacted by landslide-induced tsunamis. We are beginning to understand the extraordinary impact that subducting sediments have on great earthquakes and the degree to which sediment supply in convergent zones drives the location and magnitude of great earthquakes. A better understanding of how earth surface processes build
continental margins will help us understand what continental margins are preconditioned for slope failure. In turn a better understanding of the interactions between sediment supply, climate, and tectonics will allow us to better understand shoreline position [Kim et al., 2009]. At the largest scale, we study the fluxes of material. The flux of hydrocarbons both impacts energy usage but also climate.

### 4.4. Geochemical Cycles

The cycling of elements between the Earth’s surface and interior is a common theme bridging investigations of active processes at rifting and subduction 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.

The cycling of volatile elements (e.g., H$_2$O, CO$_2$, S, N, Cl) through subducting and rifting tectonic settings is a key factor in the behavior of both systems. 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, that are unique products of this volatile transport process. Significant progress has also been made in quantifying volatile inputs and outputs at subduction zones, particularly in providing constraints on pre-eruptive H$_2$O contents of arc and back arc magmas [e.g., Shaw et al., 2008; Newman et al., 2000; Benjamin et al., 2007; Wade et al., 2008; Wade et al., 2006; Sadofsky et al., 2008; Walker et al., 2003; Wallace, 2005], and in constraining magmatic outgassing fluxes through direct studies of volcanic gases [e.g., Hilton et al., 2002; Hilton et al., 2007; Fischer et al., 2007; Fischer et al., 2002; Zimmer et al., 2004; Shaw et al., 2003; Shaw et al., 2006]. 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.

To date, most attention has been focused on the influence of H$_2$O 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 may be serpentinized is an important and unknown control on input budgets and fluxes of volatiles into the Earth’s interior. Recent geophysical studies of oceanic plates at the outer rise of subduction zones suggest that deformation associated with the plate bending creates pathways by which low-temperature fluids circulate to >20 km into the oceanic lithosphere [e.g., Ranero et al., 2003]. Such faulting
provides a mechanism for hydrating the lithospheric mantle of the slab through formation of serpentine minerals, which can bind up to ~12 wt% H$_2$O, and would therefore provide a tremendous and previously unconsidered reservoir of water (and potentially other volatiles through formation of carbonate, sulfides, etc.) to be transported to depth by subduction. Further, the cold corner of the mantle wedge overlying the subducting plate can become serpentinized as slab-derived fluids flush through it, creating a large reservoir of H$_2$O and other volatiles in the overriding fore-arc mantle. However, the processes that allow volatile fluxes out of this critical region are poorly understood. Serpentine has thus emerged as a possible central control on the behavior of the subduction system at intermediate depths, and new approaches are needed to quantify its abundance and total volatile budget in the mantle section of the downgoing slab, the nose of the mantle wedge, and in the forearc crust, and how these reservoirs relate to the return of volatiles from the subducted plate to the Earth’s surface. Moreover, we do not well the sources, sinks, and fluxes of volatiles in rift systems. For example, it is not known whether rifts are net sources of volatiles owing to mantle degassing, or sinks, owing to sequestration by weathering, hydrothermal alteration, and sedimentation.

4.5 Plate Boundary Deformation and Geodynamics

Deformation at continental margins depends critically 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 the fault zone rheology along the subduction interface.

Major breakthroughs in our understanding of plate boundary deformation and geodynamical processes have come in the last decade through new observations and models that span a range of disciplines. Continuous GPS, InSAR, and seismic data, petrology databases, and computation resources [e.g. Carbotte et al., 2004; http://iris.washington.edu; http://supersites.unavco.org; Olsen et al., 2010] have all improved significantly in the past decade, enabling new tools and facilitated unanticipated discoveries. Observations of spatial and temporal variations in structure and process over multiple scales at plate boundaries provide descriptions of 3D spatial structural variations at subduction zones and variations in slip throughout the seismic cycle [e.g. Moore et al., 2007]; studies of rift zones are less well advanced [e.g., Thatcher, 2009; Ebinger et al., 2010]. New seismic and geodetic observations have led to the development of a much wider spectrum of possible slip processes. 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, from subduction zones, rift zones, and transform [e.g. Rogers and Dragert, 2003; Wright et al. 2006, Schwartz and Rokosky, 2007, Calais et al. 2008, Ito et al., 2009, Shelly et al., 2009]. New seismic, geologic and geodetic observations have improved our understanding of magma migration and storage within active rift systems, and documented episodes of largely aseismic slip [e.g., Dixon et al., 2002; Wright et al., 2006]. For example, combined InSAR and GPS map the deformation of active rift events and post-rifting transients in both space and time [e.g., Biggs et al., 2009; Nooner et al., 2009]. These deformation maps provide 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 allows the incorporation of complex rheologies into high resolution, three-dimensional geodynamic models of both deformation averaged over multiple seismo-magmatic cycles, and a single cycle [e.g. Billen and Hirth, 2007; Kneller and van Keken, 2008; Billen, 2008; Aagaard et al., 2008]. Such models are now being used to apply laboratory constraints on the influence of grain-size, volatile content, and melt on mantle rheology to flow in the mantle at both subduction zones and continental rifts.

There are still many unresolved questions, however, linked to our limited understanding of the processes leading to the spatial and temporal variations in deformation. Our understanding of magma and volatile distributions in the lithosphere and their effects on plate deformation, strength, and geodynamics is still lacking. In order to understand the variability in slip behavior, we must improve our understanding of the roles of fluids and rheology in these slip processes. With the newly observed spectrum of slip processes on faults, we need to resolve how to extend the known coupling of fluid pressure and stress to fault slip in field settings at depth. Spatial and temporal variations in slip behavior should also be explored in terms of stress transfer, fault zone properties, structure, and composition of the host-rock. In many of these environments, the offshore component of deformation and hydration/dehydration reactions is critical to the understanding of shallow slip processes, and emerging resources and technologies should be leveraged to make these offshore observations. Rheology of the crust and mantle is important for the behavior of rifts and influences subsidence patterns and strain distribution; it is strongly dependent on the distribution of fluids [e.g., Takei and Holtzman]. For example, rheology and properties of shallow subduction zone influences mode and distribution of plate locking, slip, seismicity, and influences mantle wedge/mantle flow. Within rift zones, the efficiency of melt extraction influences mantle rheology and composition, and melt accumulations may determine strain localization [e.g., Buck, 2004; Lizarralde et al., 2007; Jagoutz et al., 2007]. Improved knowledge of the rheology in these regions will advance our understanding of how coupling between mantle and crustal processes shape margin evolution.

We can also improve our understanding of these processes through efforts that connect observations from the lab to macro-scale, seismic to geologic timescales. Efforts that provide sampling and testing of materials in the natural laboratories of fault zones, experimental work in the lab on fault zone samples at realistic slip velocities, and theoretical developments on fault dynamics [e.g. Brodsky et al., 2009; Escartin et al., 2008; Liu and Rice, 2007, 2009] are critical for understanding the conditions required for the spatial and temporal variations in the fault slip processes. Geodynamic models, used to integrate laboratory-based studies of viscoelastic and poroelastic properties and rate-state friction, will be critical to better understand coseismic, postseismic, and interseismic stress accumulation processes of the seismic cycle. Such integrated approaches are key for understanding the mechanical, thermal, and chemical evolution of the Earth, as well as better understanding and ultimately forecasting natural hazards events.