GeoPRISMS
Draft Science Plan

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.