5. Rift Initiation and Evolution (RIE)

5.1 Where and why do continental rifts initiate?
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?
5.3 What controls the structural and stratigraphic architecture of rifted continental margins during and after breakup?
5.4 What are the mechanisms and consequences of fluid and volatile exchange between the Earth, oceans, and atmosphere at rifted continental margins, and between the lithosphere and the mantle?
5.5 RIE in the Next Decade
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 serpentinitization. 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 CO₂ 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
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 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

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

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.)
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.

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 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

![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].](image-url)
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
migmatism 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...
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. Rifiting 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., Lavie 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 deformatinal 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 Munguia, 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
What controls the evolution of segmentation and along-strike variations in extensional style and magmatism in rifts?

Continental rifting and breakup occur 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
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.](image-url)
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; Münntener
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
deforamation 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
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
The 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.,]
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 “alloigenic” 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 km²/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 CO₂, SO₂, and H₂O; high SO₂ 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 CO₂ 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 CO₂ and CH₄, 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
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 H₂O and CO₂ 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 SO₂ in the East African Rift also argue for enhanced volatile contributions in rift settings; measured SO₂ 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 N₂, CO₂ 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 H₂ and CH₄, 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.