MARGINS 2009 Review

8. Overarching Themes for the Future

8.1 Rheology and Deformation

Deformation at continental margins depends critically on the rheologic properties of the crust and mantle. Continental rifting proceeds through a combination of 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. The Earth's rheology, therefore, forms a common thread between RCL, SubFac and SEIZE.

Frictional behavior and viscous flow can be studied directly in the laboratory, however a key challenge for geoscientists is extrapolating these experimental conditions to the Earth. Integrated observations, such as those available at the MARGINS focus sites, provide the necessary constraints for understanding the large-scale behavior of the Earth. For example, new observations in the past decade show styles of frictional behavior within a single fault zone ranging from seismic to aseismic. The transition zone between these types of behavior is important given the newly observed slip processes, such as slow slip, tremor, low-frequency earthquakes, and afterslip, which frequently occur within these regions. However, the transition in both space and time between these frictional regimes remains poorly understood. 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 are critical for understanding the conditions required for the spatial and temporal variations in the fault slip processes. Further, integrated seismic and geodetic observations at future MARGINS study sites will help apply these models to the large-scale behavior of the Earth.

Increased computational power over the last decade allows the incorporation of complex rheologies into high-resolution, three-dimensional geodynamic models. 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. Such integrated approaches are key for understanding not only the mechanical, but also the thermal and chemical evolution of the Earth. Finally, it is important to emphasize that because these rheological questions apply to a wide range of fault zones and deformational regimes beyond those at continental margins, a future focus on these issues will help expand and diversify the MARGINS community.

8.2 Fluids and Magmas

The production and transport of fluids, including magmas, H_2O, and CO_2, are fundamental processes controlling the thermal, compositional, and mechanical evolution of both active and passive continental margins. Fluids affect rock rheology and deformation throughout the crust, and at subduction zones devolatilization of the slab and sediments is tightly linked with mass fluxes throughout the forearc, the mechanics of slip along the plate boundary, and magma generation. At shallower depths, interactions between sedimentation, compaction, and pore fluid pressure are central to understanding geohazards associated with slope stability. Magmas are fluids that also affect the strength of the lithosphere, and supply volatile species to the atmosphere. Melt generation in both rifts and subduction zones is the primary mechanism of continent formation and therefore of fundamental importance to the long-term chemical evolution of the Earth.

Although studies at continental margins have led to recognition of myriad links between fluid, mechanical, and chemical processes, their characterization has generally been qualitative. Our understanding of the causation and underlying physics for a range of deformation events at convergent margins is primitive, because many key observations are recent (i.e. in the last 5-6 years or less) and are fundamentally limited by data coverage and short time series of data collection, and because laboratory constraints on relevant rock behaviors under appropriate P-T conditions are lacking. Likewise, signals linking devolatilization and magmatism are evident in geochemical data, but the interactions between fluids, melt, and wall rock are not well constrained. To date, significant steps in our understanding have been accomplished by noting the spatial coincidence of modeled variables (pore pressure or temperature), and the approximate locations of observables like earthquake activity, anomalously low seismic velocity, and the egress of exotic fluids. Making major advances 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.

As one example, rapid sedimentation and delayed compaction at passive margins lead to pore fluid overpressures, which are a key factor in submarine slope failures [e.g., *Dugan and Flemings*, 2000]. Similarly, at depths beginning < 1 km within and beneath the forearc of subduction zones, fluids (H_2O and CO_2) are a key agent linking the Subduction Factory and SEIZE, because fluid release by early dehydration reactions in this region is the primary driver of elevated pore pressures. These pressures both drive fluid migration and associated chemical fluxes [e.g., *Kastner et al.*, 1991; *Hensen et al.*, 2004], and influence the strength and slip behavior of plate boundary faults [*Spinelli* and *Saffer*, 2004; *Ranero et al.*, 2008]. Fluid-rock interactions also modify rock physical properties via cementation and dissolution, and may contribute to progressive downdip changes that govern the wide spectrum of observed fault slip behaviors. Similarly, near the downdip edge of the seismogenic zone at temperatures of ~350° C, the occurrence of episodic tremor and slip (ETS) and non-volcanic tremor (NVT) has been linked to elevated pore pressure by numerical models [e.g., *Liu and Rice*, 2007]. The newest thermal models provides a path forward to explore spatial correlations between the predicted locations of dehydration reactions and the observed loci of ETS [*Wada et al.*, 2008; *Spinelli and Wang*, 2008].

At greater depths, devolatilization of the subducting slab serpentinizes the overlying mantle wedge, affecting the mechanics and thermal state of the slab-mantle interface, and driving fluxes of exotic fluid and mud that extrude from serpentine seamounts observed up to ~70 km above the slab [*Mottl et al*., 2004; *Oakley et al*., 2007]. Recent observations indicate that serpentinization of the incoming oceanic plate mantle, hypothesized to result from seawater circulation along inherited normal faults generated at the spreading ridge, may play a major role in the global water cycle [*Ranero et al*., 2003]. Although documentation of this phenomenon is scarce, it provides a plausible mechanism for transport of H_2O to subarc depths and possibly beyond; for example, geochemical signals of serpentinite dehydration [*Savov et al.*, 2007; *Barnes and Sharp*, 2006] may be observed in arc lavas [*Eiler et al*., 2005; *Straub and Layne*, 2003]. Decarbonation in the forearc and subarc likely acts in combination with H_2O to generate elevated pore fluid pressures, and holds implications for both climate change and volcanic fluxes of CO_2 [*Kerrick and Connolly*, 2001a-b; *Gorman et al*., 2006].

Magmas are at once generated by fluids - water drives melting in the earth by lowering melting points by hundreds of degrees - and also are fluids themselves, transporting heat and mass upward from the mantle to the crust. Completing the cycle, as magmas ascend, fluid components exsolve as vapor, fueling eruptions and feeding the atmosphere. Thus, magmas and fluids are intimately related during different tectonic processes at continental margins.

While magma generation at mid-ocean ridges is well understood, the situation is significantly more complicated at incipient rifts and in subduction zones. At rifts, it remains unclear whether the influence of melt on rifting is controlled from the top by the lithosphere or from the bottom by the asthenosphere. At subduction zones, volatile-induced melting dominates magma formation in the mantle wedge, but major questions remain regarding the interaction between melt, volatiles and the surrounding solid. The presence of melt in turn will influence the tectonic evolution of the crust and upper mantle. Melt weakens the lithosphere, and may control the location and style of rifting and volcanism. The physical controls on where magma stalls, cools and differentiates are poorly understood, but critical in driving the compositional stratification of the continents and the dynamics of explosive eruptions.

Multi-disciplinary focus is required to transform our understanding of magma generation and migration. MARGINS has seen rapid improvements in seismic imaging, laboratory measurements, geochemical measurements and integrative numerical models, which motivate future studies. 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 [*Syracuse et al*., 2008]. Ongoing and future work will rely on the improvements in imaging techniques of elastic wave velocities, anelasticity, and anisotropy, combined with deeper EM imaging of volatile rich zones. Laboratory experiments have provided critical new information on the effect of volatiles on mantle melting [*Grove et al*., 2006; *Dasgupta and Hirschmann*, 2007; *Hauri et al*., 2006], but new work is needed on the physical and rheological properties of partially molten mantle under ambient conditions. Geochemical techniques now provide direct measurements of volatile species in magmatic glasses [e.g., *Shaw et al*., 2008; *Benjamin et al*., 2007] and provide precise magma chronologies [e.g., *Carr et al.*, 2007] over the lifetime of a volcano (order 10^5 yrs), but new approaches are needed to constrain the total volcanic and intrusive mass fluxes for entire arc systems. Finally, theoretical models have provided a strong tie to solid flow and thermal structure of the mantle wedge [*Conder et al*., 2002; *van Keken et al*., 2002; *Kelemen et al*., 2003; *Peacock et al.*, 2003], with 3D capabilities starting to be realized [*Kneller and van Keken,* 2007]. Significant improvements in both computational resources and algorithmic development are needed to incorporate feedbacks between melting, two-phase flow, and chemistry.

8.3 Sediment Fluxes

The source-to-sink approach provides a framework for understanding and predicting the fluxes and chemical transformations of sediment and solutes in earth systems, and the resulting sedimentary sequences. The complex interplay between sediment transport, climate and tectonic processes dictates the partitioning of inorganic and organic sedimentary constituents across the margin. Deformation creates and modulates the highlands and basins, with faulting, magmatism, and ecological processes acting as barriers or conduits to sediment transport. Recent observations indicate other feedbacks, for example between sedimentation and rift magmatism. These systems are climate-modified and modify climate. Furthermore, erosion and sedimentation play an important role in subduction and the cycling of material to the deep mantle. The theme of sedimentation, climate, and deformation has the potential to bring in numerous new researchers to the MARGINS community.

Upscaling

A fundamental challenge to progress in understanding transfer and transformations of sediment and solutes in earth systems is the issue of ‘upscaling’ physical processes from the time scale of individual events such as floods and storms to the times cales that create landforms and the strata of sedimentary basins. As the spatial and temporal scales of the system increase, our ability to develop and test approximations for sediment flux laws diminishes accordingly. Further complicating the problem, but enriching its scientific challenge, is the role of external phenomena, e.g. earthquake clustering and active faulting, volcanic eruptions, river avulsions, and the interaction of ecology with sediment dynamics. Progress in this arena will involve significant advances in how we parameterize and explore the equations describing sediment transport, chemical reactions, and ecology on these longer time scales. This will require a multi-disciplinary approach that combines observational, modeling, and experimental studies designed to inform and test these approximations. Given the inherent complexities, the issue of upscaling is likely to remain a key area of transformative research in the coming decade. Another crucial challenge to understanding of both the stratigraphic record and hazardous events is to define the connections between sediment transport processes that cross the critical boundaries at continental margins, such as the transitions between lowland reaches of rivers and the marine environment and the shelf-to-slope transition.

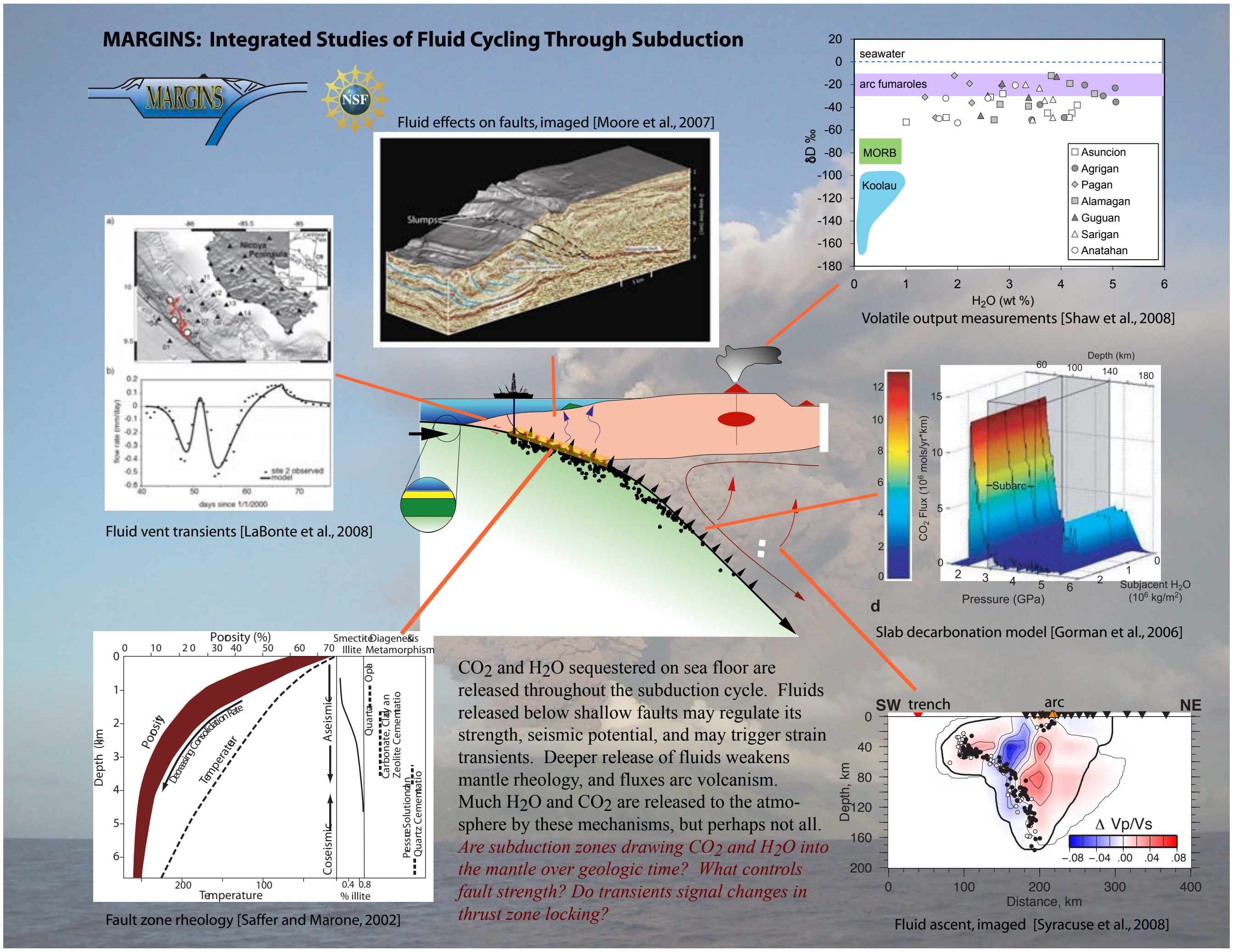
Shelf-to-Slope Transition

Whereas many stratigraphic models use sea level as the overarching control of the ultimate fate (sink) of terrestrial material on the margin, studies of a number of contemporary margins present a much more complicated picture, where shelf trapping or bypassing depends on the complex interplay between sediment transport processes and longer-term changes in sea level, sediment input, tectonics and accommodation on the shelf which together control when/how material is transferred to and across the slope and beyond. Furthermore, it appears that relatively small perturbations in these controlling factors can have profound effects on shelf bypassing over very short (decadal to century) time scales. Beyond refining stratigraphic models of active and passive margin development, a mechanistic understanding of shelf bypassing is also key to understanding carbon cycling and burial on the margin. Furthermore, on convergent margins, the mode, timing and rates of inputs to deep sea trenches can control the rheological properties of sediments and, in turn, have a first order effect on plate slippage during subduction. Therefore, this focus would offer the possibility of integrating disciplinary interests within the MARGINS program. In addition, focusing on the shelf-slope transition offers the successor program other collaborative opportunities afforded by cabled observatories that cross the margin, such as the Ocean Observatories Initiative (OOI) and the Canadian VENUS program.

Sedimentation, Climate, and Surface Processes in Rifting

There is a growing recognition over the past decade that continental lithospheric rupture is controlled in novel ways by feedbacks among and between tectonic deformation, drainage capture, sediment flux, and climate. Earlier workers proposed that lithospheric temperature, strain rate, and initial geologic conditions were the main controls on rift architecture and evolution. Recent work on sedimentation during rifting suggests the existence of feedback, whereby sediments modify the thermal and mechanical properties of the rifting lithosphere [*Bialas and Buck*, submitted; *Lizarralde et al*., 2007]. Thus, sediment fluxes and sedimentation, formerly thought of as a consequence of tectonic deformation, actually may act to amplify or damp rifting, depending upon such factors as the character of the rift drainage network, the rate of uplift and erosion of the rift margins, and the loci of deposition. These exciting new directions of research will require a MARGINS perspective in which the rift-tectonics and sedimentary process communities collaborate with the broader surface processes communities, to recruit recently-developed tools (e.g. cosmogenic isotope measures of sediment production) and approaches (e.g. integrated mathematical modeling of deformation and landscape evolution; quantification of stochastic landscape sediment budgets) to probe the stratigraphic record. The theme of sedimentation, climate, and rifting has the potential to bring in numerous new researchers to the MARGINS community. The analysis of the genesis, geometry, and properties of deep sedimentary formations in continental settings has direct societal relevance for issues ranging from carbon sequestration to ore genesis to mitigation of slope failure hazards to the location and management of groundwater resources.

8.4 Example: Integrated Subduction Studies in Central America



CO_2 and H_2O sequestered on sea floor are released throughout the subduction cycle. Fluids released below shallow faults may regulate its strength, seismic potential, and may trigger strain transients. Deeper release of fluids weakens mantle rheology, and fluxes arc volcanism. Much H_2O and CO_2 are released to the atmosphere by these mechanisms, but perhaps not all. *Are subduction zones drawing CO_2 and H_2O into the mantle over geologic time? What controls fault strength? Do transients signal changes in thrust zone locking?*

Figure: Fluid cycling through a subduction zone, integrating MARGINS observations.

Synergies between different research disciplines can produce scientific results with far greater impact than the individual efforts. Such synergism is a vital strength of the MARGINS Focus Site funding model. A concrete example of this is the significant scientific results that emerged from the combined SEIZE and SubFac focus site in Central America, integrating multiple seismological field campaigns (CRSEIZE, TUCAN) with the TicoFlux effort at establishing fluid and thermal inputs, solid-flow modeling efforts to establish the mantle thermal regime, and geochemical sampling of volatiles within primary arc magmas.

TicoFlux (2001-2002 field expeditions) was designed to establish the heat, sediment and fluid fluxes into the subduction system. TicoFlux identified a sharp along-strike thermal transition within the downgoing plate, and constrained the subducting sediment composition and distribution. These observations were used to generate subduction thermal models and to calculate fluid source distribution and fluid pressures on the plate boundary fault (Spinelli and Saffer, 2004). CRSEIZE (1999-2001) was carried out to define and compare the pattern of strain accumulation and the distribution of seismicity on the plate boundary (DeShon and Schwartz, 2004; DeShon et al., 2006). Significant results include the identification of distinct regions of strain accumulation and microseismicity, with a locked plate boundary located at ~14 km depth, updip of the primary microseismicity zone (Norabuena et al., 2004). Along-strike variations in the updip edge of seismicity were also tied to thermal state, as there is a shift to shallower microseismicity in the region where warm oceanic crust from the Cocos-Nazca spreading center subducts relative to seismicity in the region of cooler EPR crust subduction (Newman et al., 2002). The TicoFlux and CRSEIZE data were further integrated into more advanced thermal and fluid flow models to test the hypothesis that transitions between stable sliding to stick-slip behavior are thermally controlled (Schwartz and DeShon, 2007). At the up dip limit, the authors concluded that the transition, including along strike variations, coincides with declining fluid pressure related to thermally controlled diagenetic fluid sources. At the down dip limit the deepest microseismicity corresponds with the 350°C isotherm.

The TUCAN seismic array (2004-2006) was designed to image the regional slab dehydration and magma production in the mantle wedge; its design seamlessly extended the CRSEIZE footprint across the volcanic arc to the Caribbean coast. The integrated arrays are allowing imaging and seismicity studies to be carried across the downdip end of the locked zone and past the volcanic arc, defining accurately the geometry of the Wadati-Benioff zone, imaging the crust of the overriding plate, particularly in the transition from the seismogenic zone to the mantle wedge where significant slab-derived water may be sequestered as serpentinite in the overriding mantle wedge (DeShon and Schwartz, 2004; MacKenzie et al., 2008; Syracuse et al., 2008a). Comparison with seismic attenuation, another temperature proxy (Rychert et al., 2008), and changes in anisotropy fabric within the mantle wedge (Abt and Fischer, 2008) place in situ constraints on the resulting thermal structure; when combined with estimates of water release from the volcanic arc (Benjamin et al., 2007; Sadofsky et al., 2008) they suggest that much of the along-strike variations in arc output (Carr et al. 2003,2007) reflect changes in water content more than thermal structure. Preliminary 2D thermal modeling of the entire subduction system (Peacock et al., 2005) suggests that along-strike variations in slab-surface temperature are small at subarc depths, but that study did not account for the variations in near-surface thermal structure found by TicoFlux.

The next step to closing the loop is to reconcile the observations and modeling of thermal structure offshore by TicoFlux with the seismic and geochemical constraints; these efforts are beginning (e.g., Syracuse et al., 2008b), and are likely to continue. International partnerships play a key role in this process; German participation was critical for the CRSEIZE OBS deployment, and more recently, the German program SFB574 complements many of the offshore and onshore projects funded by MARGINS and have resulted in several joint efforts (e.g., Ranero et al., 2003; Hoernle et al. 2008) and complementary data efforts such as magnetotelluric surveys (Brasse et al., submitted). Because these multiple experiments were supported within the MARGINS structure, these synergistic results have emerged and integrated to an exceptional level.