# MARGINS 2009 Review

# 1. Executive Summary

# Executive Summary

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

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

These Initiatives address the mechanics, structure, and evolution of continental deformation at convergent and divergent margins, the mass and energy flux to resulting continents through subduction and the sedimentary mass transfer from them. Several guiding principles have characterized the existing program:

- *Broadly interdisciplinary communities*. Each initiative addresses a complex system affecting many types of observable phenomena. Understanding these systems requires a wide variety of expertise, and integration across a broad range of disciplines that often do not work together effectively.
- *Crossing the shoreline.* Any complete science program addressing continental margin evolution has to be amphibious, encompassing both marine and terrestrial elements. Thus, MARGINS crosses NSF division boundaries, and of necessity integrates both Earth and Ocean Sciences.
- *Active systems.* Dynamic systems are best studied where the processes take place today, so all field experiments occur in active systems.
- *Experiment, computation and theory.* Laboratory and numerical efforts provide critical independent approaches to help understand the diversity of observational evidence. These approaches also can have special roles in the integration and synthesis of observational results.
- *Focus sites.* To afford such ambitious multidisciplinary activities, major field exercises are concentrated in community-specified Focus Sites, one or two per Initiative. Most current sites are outside the U.S., so many international program partners have been leveraged in the process.

Achieving the science goals in this manner required an integrated program, able to build communities with access to a broad range of tools, resources, and scientific approaches. This has necessitated focusing research funding on targeted sites, and creating activities that provide oversight and foster integration within and between sites. Normal "core" funding mechanisms at NSF cannot achieve these goals. Some of the first major successes of the program were the thematic workshops that built the broad interdisciplinary communities that are active today, and stimulated successful proposals. This interaction among disparate scientific communities and clear, focused programmatic goals driven by compelling science remains a hallmark of the MARGINS program today.

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

**Growth of the MARGINS Community**

The first MARGINS workshop took place in 1988, in Irvine CA, with 75 participants. Its title captures a transformative advance of this program, the building of focused yet interdisciplinary research program wide: "A Research Initiative for Interdisciplinary Studies of the Processes Attending Lithospheric Extension and Convergence". Since then, the program has directly funded 182 proposals (94 distinct projects) to 118 different PIs, spanning many geosciences disciplines (not counting many studies inspired by the MARGINS Initiatives). A total of 908 different scientists have attended the 23 MARGINS-sponsored workshops since 2000, and 1360 receive the Newsletter worldwide. The community affected by the MARGINS-program is, no doubt, even larger, including students and audiences at MARGINS sponsored presentations. For example, MARGINS representatives organize special sessions at international meetings such as Fall AGU, where in 2006 MARGINS-related special sections made up 25% of all Tectonophysics submissions. The database of MARGINS-funded research articles exceeds 250 in peer-reviewed journals, with MARGINS-related research many times larger. The MARGINS program has also successfully leveraged large international collaborations, drawing funding and key personnel from other programs and international agencies. While many of the basic scientific questions addressed by MARGINS researchers have broad roots, there is no doubt that the MARGINS program has made significant intellectual contributions to this large, and still growing, interdisciplinary community.

**Major Accomplishments**

The four MARGINS Initiatives have demonstrated a great variety of scientific successes, which, in turn, have engendered a host of new opportunities. The major highlights from each are summarized here. In a chapter on Future Directions, several new opportunities are outlined, and each Initiative is discussed in detail in their Summaries.

***RCL.*** The accomplishments of the RCL initiative fall into three major themes: 1) Role of magmatism in rifting, 2) Strain partitioning in space and time and 3) Feedbacks between sedimentation, rift architecture, and melting. The presence or absence of magma is a primary control on strain distribution along and across the rift, vertically through the lithosphere and in time. Where and when magma appears in the system, in turn, is controlled by pre-rift mantle composition, temperature structure, and sediment loading effects. Large differences in strain distribution in space and time between the Gulf of California and Red Sea sites demonstrates the combined roles of lithospheric rheology and driving forces: widely distributed strain prior to seafloor spreading in the Gulf of California (post-orogenic rift) versus early strain localization in the Red Sea (cratonic rift). Field studies document the influence of pre-existing fabric inherited from a prolonged period of transtensional deformation on the along-axis segmentation during distributed strain and after seafloor spreading. Within the Gulf of California system, fundamental differences in rift to breakup architecture reveal domains of distinct rifting styles separated by abrupt transitions. The pre-rift history of magmatism and consequent mantle depletion may represent an important factor in controlling the evolution of rifts that develop out of convergent settings. These new 4D observations have motivated fundamental laboratory and numerical modeling experiments to isolate the feedbacks between the effects of magmatism, sedimentation and rheology, including lower crustal flow. These models show that 1) sediment loading plays a key role in the distribution of strain and magmatism from rift inception to breakup; 2) the presence of melt facilitates or drives lithospheric rupture and leads to strain partitioning during all stages of rifting.

***S2S.*** Transfer of sediment and solute mass from mountains to abyss plays a key role in the cycling of elements such as carbon, through ecosystems as a result of global change and sea-level rise, and in resource management of soils, wetlands, groundwater, and hydrocarbons. The Source-to-Sink Initiative consists of focused investigations on tectonically active convergent continental margins that produce large amounts of sediment deposited in adjacent basins, with the Waipaoa River System (NZ) and Gulf of Papua (PNG) as the research focus areas. Major advances have been made relative to the original program goals for both of the S2S focus areas. As one example, the NZ Waipaoa focus area represents an active margin setting where the fate of riverine inputs during current highstand conditions is strongly modulated by the changing sediment yield of the rivers, tectonic accommodation on narrow continental shelves, and energetic oceanographic conditions. MARGINS research shows that shelf accommodation and sediment input by the rivers was roughly in balance throughout most of the Holocene. However, huge sediment yield increases in response to historical deforestation result in roughly 75% of modern sediments discharged by the river escaping the Waipaoa shelf. Hence, human disturbance (which can mimic past natural disturbance through catastrophic volcanic eruptions or earthquakes) can radically alter the locus of sediment and organic carbon sequestration on the continental margin, thus having important implications for models of sequence stratigraphy and the global carbon cycle. Among many other advances in the PNG focus area, for the first time a clinothem has been investigated that has more than one sediment source – the Fly River in the south and a number of smaller rivers (the Purari being the largest) to the north. Lobe shifting of the clinothem probably results from climate change, but whether the change involves the source areas (e.g., northern vs. southern rivers) or circulation or climatic events (e.g., intensification of ENSO about 3-5 ka BP) is not presently known.

***SEIZE***. Major breakthroughs and key results in the SEIZE Initiative have come from both MARGINS funded science and integration of SEIZE efforts with those of the broader community. Most prominent are (1) new understandings of the controls of fault stability and distribution of seismicity, (2) evidence for a wide range of fault slip behaviors and rates, and (3) coupling of deformation and fluid processes. One of the defining questions driving seismogenic zone studies is the origin and nature of the updip limit to unstable sliding. Frictional sliding experiments carried out on clays of different compositions suggest that clay transformation alone, i.e., from smectite to illite, cannot account for the transition in stability. MARGINS investigations have also provided important evidence for strain transients within updip regions of the subduction zone faults, both at Nankai and Costa Rica; these results complement observations of correlated low-frequency earthquakes, tremor, and slip in the down-dip portions of many global subduction zones. Additionally, pore pressure transients have been detected in seafloor flowmeters and linked to seismic tremor, firmly linking fluid processes, forearc deformation, and fault slip. Our understanding of factors that control seismic segmentation of subducting margins has also advanced, especially the along-strike heterogeneity in both the downgoing plate and forearc. One major accomplishment for the entire SEIZE initiative has been the start of long-awaited NanTroSEIZE drilling over the Nankai accretionary prism. MARGINS contributions have included the commercial acquisition, processing, and interpretation of a large, 3D seismic volume, which reveals the frontal portion of the forearc, and in particular, the megasplay fault system which may be active coseismically. Logging and sampling of the shallow prism in 2008 is preparatory for planned deeper drilling and observatories, leading to direct observations of seismogenic zone fault rocks for detailed structural, lithologic, and experimental studies.

***SubFac.*** Results from the Subduction Factory Initiative have transformed our understanding of key processes active at all levels in subduction systems, including (1) mantle melting, (2) fluid and chemical fluxes, and (3) crustal evolution. These results have not merely added new knowledge; rather, they have fundamentally altered our approaches to subduction science by creating new conceptual frameworks that incorporate feedbacks and interactions among diverse physical, thermal, hydrologic, and chemical processes. For example, the amount of $H_2O$ dissolved in arc magmas was largely unknown for most volcanoes before MARGINS, and is now well constrained to vary within a small range of values from 2-6 wt%. This first-order result, combined with new experimental results, predicts a free fluid/melt phase in the mantle that exists from regions as cool as 800°C near the slab to 1300°C in the hot core of the mantle wedge. In addition, the seismic prediction of the mineral serpentine in the subducting plate has fundamentally changed our view on every aspect of the subduction factory, from the generation of earthquakes, to the transport of $H_2O$ into the mantle, to the geochemical composition of magmas and fluids in the upper plate. Nested seismic experiments have provided the first integrated images of the fluid/magma pathways that exist beneath volcanoes, from their magma chambers, through the crust, and even into the mantle to their slab source. A coordinated MARGINS effort has led to numerical models that now make useful predictions as to the thermal and flow field generated during subduction. Finally, volcanic gas measurements and thermodynamic models have converged to predict surprisingly poor recycling efficiency of $CO_2$ through the subduction zone (< 20%), implying that much surface carbon is lost to the deep mantle.

**Broader Impacts**

MARGINS has overseen the development of large publicly-accessible databases of geophysical and geochemical information, and began the process of refining them into user-friendly, community-vetted archives that go beyond mere compliance with NSF policies. MARGINS has prepared and begun to evaluate “Mini-lessons” that bring its research results into the university classroom at multiple levels, and has attracted a strong cohort of graduate students and early-career scientists accustomed to a multi-disciplinary approach. These Education and Outreach accomplishments are not add-ons: they are integral to the research programs, and to the professional life of MARGINS PIs. MARGINS also has enabled strong international collaborations that amplified its human and financial investments. None of this would have been nearly as successful through core programs.

**Prospects for the future**

The main motivation for a successor program to MARGINS is the continuing fundamental need to conduct interconnected suites of large, amphibious interdisciplinary projects to address first-order aspects of continental evolution. The last decade provides ample evidence of the benefits of coordination across the shoreline and disciplines. While the existing science plan includes several significant goals that are as relevant today as ten years ago, new discoveries and developments provide even more motivation. As one example, the discovery of strain transients over a range of time scales (creep events, tremor, etc.) in subduction zones suggests dynamic coupling between offshore inputs, the processes that regulate great earthquakes and the large-scale fluid cycling to the mantle. In addition, a growing body of evidence indicates that these phenomena occur in both shallow (offshore) portions of the subduction zone, and deep (onshore), perhaps reflecting similar underlying physics. A full understanding requires coordinated onshore and offshore investigations. New observations along rifted margins reveal that sedimentation and magmatism may regulate continental breakup; the mechanisms responsible can be clarified by numerical modeling, drilling and other observations, again demonstrating the need for integrated studies. Events in Sumatra and elsewhere have shown that fundamental scientific investigations have significant geohazards impacts, in particular, the genesis of tsunami during earthquakes and related slope failures. A wide array of geohazards acting over several time scales directly impact the coastlines, and can be studied best through joint marine- and land-based research. Many of these developments clearly crosscut current MARGINS Initiative boundaries, just as they crosscut traditional disciplinary boundaries, and highlight the importance of cross-MARGINS integration in the future.

MARGINS allows science to unfold in novel ways. The program's first major successes were meetings that built large, collaborative, and functional communities made of disciplinary groups that did not normally interact, educating across disciplinary lines. For example, seismologists now work closely with geochemists, geomorphologists studying upland erosion now interact more closely with offshore stratigraphers, and land-based geologists and paleoseismologists have developed close collaborations with marine geophysicists. These communities are now producing young scientists well versed at interdisciplinary science, such that it is the norm for major MARGINS papers to have authors from a variety of fields who present results that crosscut traditional boundaries. Similarly, MARGINS has made major international collaborations much easier, and has led to complementary programs in other countries that work closely with MARGINS scientists. These include major German and Japanese international programs as well as focused programs in most host countries. In the future, there is much to be gained by continuing to build new collaborations, in particular collaborations that cross the current MARGINS initiative structure.

The last decade has seen a rise in major U.S.-supported scientific facilities, and MARGINS provides a scientific focus for many onshore-offshore projects that make use of them, such as EarthScope, IODP and OOI. Some of these facilities are well placed to study problems in convergent margin dynamics, rifted and passive margin formation, or sediment generation and distribution of U.S. shelf sediment. The development of these facilities in and around the U.S. continental margins suggests that a MARGINS successor would have at least some footprint in the U.S., to the benefit of the nation. Also, parallel computational resources such as CIG and CSDMS have come on-line, facilities that will provide critical tools for integration and hypotheses development. These are well suited to MARGINS program goals, and in the case of CSDMS their development is in part attributable to MARGINS. Finally, as seen already, the breadth of MARGINS provides novel and easily exploitable opportunities for developing interdisciplinary material for undergraduate education and for outreach. We can expect these efforts to continue and grow.

Sections 7 and 8 of this report suggest some aspects for the Review Committee to consider as it thinks about the future. They highlight some of the organizational principles that have contributed to

MARGINS' success, and that could continue to do so. They identify scientific questions that a successor program might explore, both arising from the four present Initiatives and some crosscutting themes that unite them. Finally, they address some of the substantive issues that may affect planning for a successor program, such as how to promote integration and synthesis, and whether or not to continue with focus sites or only at active margins. The Steering Committee has initiated community-planning activities in which the next stages of planning might occur, pending feedback from this Review and from NSF.

**Closing Statement**

MARGINS research over the last ten years has contributed to many key findings in Earth Sciences, summarized here and in the following chapters, through a focused program of research that spans the shoreline across active continental margins. In so doing, it has built a large, interdisciplinary community, well situated to carry out transformative shoreline-crossing studies in the future. The last decade has also seen increased scientific excitement from new observations in the systems MARGINS studies, in fundamental science questions with prominent societal impacts, and has developed or defined the necessary tools and collaborations and tools to carry out the research. Overall, the program has been a success exceeding expectations, and much potential exists for new transformative discovery through a successor program.