GeoPRISMS
Draft Science Plan

Appendix D. Vision Statements

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Education & Outreach for a MARGINS Successor Program

MARGINS MEAC members and participants of the Education Planning meeting

On October 29-30, 2009, nineteen scientists and educators met in Northfield, MN to provide guidance to the possible form of an educational component in a MARGINS successor program. The meeting was motivated by recommendations from the MARGINS Decadal Review that encouraged enhanced educational activities, with a goal to prepare this Vision Statement in advance of the MARGINS Successor Planning Workshop scheduled for Feb. 2010. Participants consisted of members of the MARGINS Education Advisory Committee, Steering Committee, past participants in MARGINS Educational workshops, as well as leaders of partner programs and earth science education experts. This Vision Statement summarizes their recommendations.

I. Focus and Goals of a MARGINS Successor Education and Outreach Program

The NSF MARGINS program has been effective in bringing together multi-disciplinary communities to work across the shoreline on complex earth systems investigations. Education and outreach (E&O) activities in a successor program to MARGINS should support the research community of PIs in achieving coordinated broader impacts, and should contribute to public understanding of the Earth and the nature of geoscience. Based on recent experience, this can be accomplished most effectively by targeting audiences at the undergraduate and graduate level. This approach capitalizes on scientific achievement within the program and takes advantage of the university setting of most PIs. In the K-12 and informal arenas, an exploratory set of activities could be developed through partnerships with existing programs.

The first decade of MARGINS served the graduate student community well, given the small resources devoted to education. MARGINS educational activities have resulted in a suite of "mini-lessons" that bring MARGINS discoveries and major research datasets into undergraduate classroom instruction; a popular Distinguished Lecturer series that targets a diverse set of institutions that would otherwise have had limited exposure to the program; a post-doctoral fellowship program that has helped foster a new generation of MARGINS PIs; and a variety of efforts at workshops and professional meetings to provide professional development to several generations of geoscience graduate students. As a sign of success, many individuals who started in the MARGINS community as students are now leading MARGINS scientists.

We suggest that the successor program should enhance current successful efforts, and expand in a few key directions:

- Produce a series of experiences in the pathway from undergraduate to graduate education including an REU program, expanded international experiences and a "bridge" spanning the transition from undergraduate to graduate education.
- Build a vital next-generation interdisciplinary community of independent scientific leaders through graduate student awards, new programs of graduate symposia, and the postdoctoral fellowship program.
- Support PI activities: directly help develop broader impacts for proposals and projects, sponsor faculty development activities, and expand the mini-lessons portfolio to reflect the full scope of research and teaching opportunities afforded by the undergraduate curriculum.
- Explore opportunities to expand MARGINS successor E&O to public and K-12 audiences through strategic partnerships and event-based science presentations.

These enhancements will complete the "student to PI to community leader" professional development trajectory.

Accomplishing these goals will probably require a full-time staff member dedicated to educational activities, and likely outside funding for some more ambitious undertakings. This person should work within the central office to support both the investigator and student community, and work with education specialists to grow the strong partnership between basic science and earth science educators.

II. Focus on Undergraduates - REU and Other Programs for Undergraduates

A MARGINS successor program should sustain and grow the present undergraduate-centered efforts, with a goal to entrain students and faculty in geoscience departments that do not have graduate programs. Also, it could promote undergraduate research in interdisciplinary science that would create a natural pipeline into graduate education.

IIa. REU Program

We recommend that the flagship program for undergraduate education be an REU program introducing students to MARGINS strengths in interdisciplinary research. Our REU program will be based on the successful IRIS model of distributed hosts with important modifications for the unique aspects of the MARGINS community. Key features will be:

- At least 2-3 distributed sites will host individual or groups of students.
- Sophomores and juniors will participate in order to include students and instructors from 2-year colleges and colleges without graduate programs.
- The students' advisors from home institutions will be actively involved in the research.
- Cohort building of the entire REU group across the sites will be emphasized through a week of introductory activities at a central site, which may include the novel use of ship-based or field camp-based experiences.
- Support from a central Office or designated affiliate will coordinate activities. One possible model would be to link the initial MARGINS successor REU to the IRIS site REU or similar programs.
- The MARGINS successor office will track the REU students after their summer program so that that community can be encouraged to participate in the bridge programs (see section IIc).

IIb. International Experiences

A successor MARGINS program will have activities in many countries with numerous international colleagues. New programs could encourage and help PIs in obtaining

International Research Experiences for Students (IRES) or Doctoral Dissertation Enhancement Projects (DDEP) grants. An IRES or DDEP grant would support a coordinated group of undergraduate and/or graduate students working on MARGINS-related research in the partner country as they work directly with their international collaborators and students. There are also opportunities in the area of International Service Learning. One example is the USAID Higher Education for Development (HED) program that fosters partnerships between USA universities and their partner institutions in host countries. The MARGINS successor office can provide coordination and support to facilitate obtaining grants, and encourage education and outreach activities by individual PIs at international sites and with international collaborators.

IIc. Bridging Experiences

Some "bridge" experiences could fill the gap between undergraduate and graduate school. Current programs generally overlook this interval, funding for research opportunities is scarce and few career-building activities have been developed at this stage. A MARGINS successor could organize a short course or summer field camp that students would take immediately after they graduate with their B.S. degree. A field camp could emphasize the hands on, interdisciplinary tools and data acquisition that students will use in their graduate research. The activity could include both land-based and ship-based experiences, perhaps supported by external funds (e.g., CCLI). Another bridge activity would be to help PIs to obtain supplemental grants to fund incoming graduate students during the summer before they start their graduate career.

III. Build Student / Post-doc / Early-Career Community

MARGINS research involves an interdisciplinary team-based approach to studying systems using multiple methods, with notable success in fostering this approach in graduate students who then continue on to become MARGINS PIs. These efforts could be enhanced by further development of two programs, the Postdoctoral Program and a new Graduate Student Forum.

IIIa. Graduate Student Forum and Pre-Meeting Symposium

Current graduate student community building events supported by the MARGINS program include a student forum and, notably, student prizes at the fall AGU meeting. Since 2003, 25 students have been selected by judges as winners or honorable mentions. The Student Prize awards are viewed as honors that are highly valuable on students' CVs. This program should continue.

To further provide students with opportunities for interaction, the MARGINS successor program could develop a structured 1-day graduate symposium, typically occurring before a larger MARGINS meeting or workshop. As one model, this symposium could include oral and poster presentations, organized by more senior graduate students or mentors. The experience will provide leadership opportunities for senior students and first-exposure opportunities for more junior students, which will help in developing both groups as independent scientists and effective communicators. The meetings could include career development opportunities, such as talks on proposal writing or postdoctoral opportunities (especially the MARGINS postdoctoral program) as well as group discussions about how to succeed as a graduate student. Online social networking (e.g., Facebook, Twitter) could be promoted as an additional low-to-no-cost avenue for student communication and enhanced program awareness.

Funding opportunities in the IGERT (Integrated Graduate and Research Traineeship) program could be explored for student workshops and graduate fellowships.

IIIb. Postdoctoral Program

The MARGINS postdoctoral program has been highly successful in providing a pathway between graduate school and academic positions. To the awardees, the named postdoctoral fellowship is viewed as a prestigious honor, and is recognition of early independence, established capability, and high scientific potential. Although participants have done exceedingly well, there has been a small applicant pool which should be expanded. Participation might be increased by communicating more thoroughly with the graduate student population (see IIIa). Also, the NSF solicitation process could be modified in two ways to increase its competitiveness:

- Increasing application deadlines to twice per year (autumn and spring), with expedited review and decision process, thus removing direct competition between regular MARGINS PIs and the postdoctoral applicants.
- Ensuring that applications be written by the graduate student and submitted directly to NSF. The newly developed NSF-EAR postdoc program may serve as a good structure.

IV. Develop Educational Resources and Foster Faculty Involvement: Mini-Lessons

Over the last 5 years of the MARGINS program, efforts to integrate discoveries from MARGINS science with teaching fundamental concepts in geoscience have been propelled by development of web-accessible classroom and teaching laboratory activities and visualizations called 'mini-lessons'. Mini-lessons capitalize on cyberinfrastructure resources to integrate MARGINS data and research findings into broadly applicable educational materials. The engagement of undergraduate educators has ensured that the materials developed were well-suited to their audience, and participation by MARGINS PIs ensured cutting-edge content.

Several approaches could enhance the effectiveness of mini-lessons:

- Mini-lessons should address curriculum needs.
- Team approaches to the development of mini-lessons, or curricula comprising mini-lessons, could be fostered to engage career and 2-year college faculty.
- Gaps in the existing mini-lesson collection should be filled.
- Some mini-lessons should be designed for easy adoption into lower division, gateway courses. Such courses are often taught by faculty outside of their expertise, therefore, these mini-lessons must be self-contained educational resources.
- Continue formalizing the assessment of materials across the undergraduate curriculum for content accuracy and pedagogical effectiveness.
- Improve dissemination of mini-lessons through professional organizations, meetings, workshops, professional journals, and education and outreach resources.
- Construct a Developer's Toolkit compiling best pedagogical practices and resources for developers (e.g., GeoMapApp, EarthChem) and access points to basic research results.

V. Expand E&O Through Strategic Partnerships

An informal (e.g. museum) and/or K-12 education component could be an exciting new direction for the E&O program. The arena is large, and a program is probably best developed through partnerships with existing science organizations, consortia, and/or PIs of long-term geoscience education projects who have existing informal or formal education programs. This approach could yield a major increase in the visibility of MARGINS and MARGINS successor science and scientists for a relatively modest investment.

Va. Partnered "Event- Based" Presentations

One promising model for this approach is the development of "event-based" presentations, planned informal/formal educational events featuring audience-appropriate and engaging MARGINS successor science concepts, scientists-in-action, interesting investigative techniques, and/or exploration efforts. Developed through partnerships with groups focused on outreach, the MARGINS successor office would coordinate the science content with PIs for these events. The partner organization would be responsible for the event itself, including advertising and organization, and logistics. The goal of the event is both the communication of science content and the formation of science career role models for K-12 students, undergraduates, graduate students and the general public.

Engaging events for informal education could include live communications with scientists, and opportunities for event participants to control or provide input on investigations. Additional materials, such as podcasts and video-clips could be captured and incorporated in the event. The central office can coordinate the collection of material from PIs, whereas the partner organization would contribute its expertise in designing and presenting content. Possible partners include: GLOBE, IODP, the JASON Project, COSEE, TXESS Revolution, and the National Ocean Sciences Bowl.

Vb. Other Partnership Opportunities

This expanded effort also provides opportunities to partner with geoscience education programs and education PIs (curriculum developers and professional development providers) to adapt mini-lessons (section IV) to the K-12 audience for use by teachers to prepare their students to understand an event. In addition, the central office could collaborate with teacher networks to offer training (face-to-face or online) to teachers who will host these events so that they are equipped with a deeper understanding of the science, and thus better able to communicate content and describe career paths to their students. Opportunities also exist to partner with geoscience education researchers and educational psychologists who could initiate and carry out projects to measure the impact of this type of educational outreach on teachers and students, and museum audiences. Examples of potential K-12 education partners include national and international teacher networks such as NSTA, the National Earth Science Teachers Association (NESTA), and GLOBE, as well as museums.

VI. Managing and Supporting an Effective Education Program

An enhanced commitment to education and outreach by the MARGINS successor program is contingent on effective coordination by the central office. MARGINS began efforts in education and outreach in 2004, first by adding education representatives to the steering committee, then by developing the MARGINS Education Advisory Committee (MEAC) coordinated by a half time office staff member. Much of the educational effort has been a bottom-up approach, involving only those PIs who have an interest in this type of outreach.

The 2009 Decadal Review Committee recommends greater visibility and awareness of the program both within the broader geosciences community and the general public. Currently, a half-time education staff position in the MARGINS office has responsibility for all educational programs described in Section I, as well as less formal activities (managing online presentation material and other educational content on the web site; coordination with the data management group; writing education pieces in the twice yearly newsletter; etc.). Increasing the scope of an E&O program as described above requires added responsibilities including:

- Establishing partnerships between MARGINS PIs and experts in educational activities and outreach;
- Coordinating with other research init
- iatives and programs and in particular seek out and serve as contact point for partnerships in informal and K-12 E&O;
- Providing a support structure and services for potential PIs in designing and achieving broader impacts in their proposals;
- Provide logistical and administrative support for the REU effort and possible "bridge" activities;
- Coordinate Graduate Forums and other graduate cohort-building activities;
- Initiate pilot programs to leverage new research into exploratory educational vehicles; and

- Coordination of a more formal E&O advisory structure.

We believe that this effort will be best achieved through one dedicated full-time education specialist within the Office of the MARGINS successor program. Also, many of the more ambitious programs will require additional funds outside the regular MARGINS program, for example for Site REU programs, through the CCLI for course content improvement, and perhaps through IGERT for graduate mentoring and traineeships. As demonstration of this approach, MARGINS successfully obtained CCLI funding to support the present mini-lessons program.

We recognize the challenge of this commitment in an office that changes location every three years. However, the strength of the program to date reflects the engagement of the research community in the education efforts. This has been accomplished by extensive involvement of the MARGINS office and research leadership in the education programming, which is made possible by the management of these programs in the central office. The partnership with SERC in creation of the mini-lessons provides a model for bringing stability to long-term programs. SERC can continue to host the mini-lesson collection and cyberinfrastructure supporting the contribution, review and dissemination of mini-lessons while the MARGINS office moves from place to place. Concurrently the MARGINS office remains responsible for engaging the community in the development of these lessons, for decisions regarding their content, and for the scheduling of workshops or other faculty development opportunities. A similar model might be used for management of the other large programs envisioned above.

VII. Summary Statement

The successor MARGINS program will be uniquely positioned to help train the next generation of interdisciplinary scientists, while expanding the reach of MARGINS science into the broader community. The programs outlined in this vision statement will form a unifying broader impacts strategy for the successor program and will create a pipeline of students that reaches from within the K-12 community all the way to early-career faculty. We foresee that K-12 outreach will utilize partnerships with already successful programs. At the undergraduate level, the MARGINS program has been successful at introducing students to MARGINS science through vehicles such as mini-lessons. Additional experiences such as a MARGINS REU program and opportunities to participate in international research and service learning programs further enhance the undergraduate experience. Engagement in the mini-lessons program of early-career and 2-year college faculty at institutions not currently engaged in MARGINS research will provide a mechanism for broadening the pool of students benefiting from these programs and entering the pipeline. Graduate students entering MARGINS research fields will have new peer-mentoring opportunities at dedicated meetings and throughout the year via social networking sites. The MARGINS student prize will continue to reward the top graduate students for their exemplary work. At the end of the pipeline, Ph.D. students will be encouraged to apply for the highly successful MARGINS postdoctoral program, and early-career scientists will be provided with tools to create proposals with strong broader impacts. This comprehensive vision rests primarily on the engagement of the MARGINS community and a growing community of MARGINS geoscience educators in PI-driven activities and proposals.

RCL Vision Statement – Outcomes from the 2009 Charleston Workshop

Conveners and Participants of the RCL Synthesis Workshop
(*www.nsf-margins.org/RCL/2009*)

Introduction

Over the past decade, the Rupturing Continental Lithosphere (RCL) initiative of the MARGINS program has fostered a multidisciplinary research community examining rifting and rupture processes within the Gulf of California and Red Sea focus sites. A workshop of the RCL community was held on April 30–May 2, 2009 in Charleston, SC to discuss the major findings from the focus sites and complementary theoretical and laboratory studies, and to evaluate these results within the context of global studies. 83 students, post-docs, and scientists from a total of 9 countries participated in the workshop, including many from outside the traditional RCL community. A workshop report summarizing the results described in the oral and poster presentations was published in the Fall 2009 MARGINS Newsletter and can be found online at *www.nsf-margins.org/Publications/Newsletters/Newsletter.html*. The final day of the workshop was focused on outlining the key scientific questions that should motivate a successor MARGINS program.

Early career scientists led breakout groups to establish the future science objectives as well as to provide recommendations for designing a successor program to most effectively address these objectives (e.g., thematic vs. focus site approach). The breakout and plenary discussions were guided by the recommendations of the MARGINS Decadal Review Committee, who proposed that the RCL initiative be transformed into a Rifts, Sediments, and Fluids (RSF) initiative with a greater emphasis on integrating surface and sedimentary processes with the overall evolution of the margin. Presented below are the 5 major scientific questions derived from this workshop that could drive a future RSF initiative. We stress that these represent a consensus view of those present at the workshop, and thus are not meant to fully encompass all viewpoints. As the planning toward a MARGINS successor program continues, we encourage members of the community to expand upon these science objectives by submitting 2-page white papers for discussion at the MARGINS Successor Planning Workshop to be held in San Antonio, TX in February, 2010. Guidelines for submitting white papers can be found at *http://www.nsf-margins.org/SuccessorProgram/whitepapers.html* .

Shaping the Future of RCL/RSF

Many new and fundamental scientific questions have arisen regarding the development and evolution of continental margins stemming from the advances made during the last decade of MARGINS research. The systems-science approach required to answer these questions requires interdisciplinary science that "crosses-the-shoreline". The RCL initiative of the MARGINS program fostered such an interdisciplinary community as well as facilitating international collaborations that would otherwise be unlikely to crystallize. Early career scientists have been, and will continue to be integral to the success of a successor MARGINS program.

Articulating our emerging goal

At the Charleston workshop, breakout group and general discussions converged on the overarching goal of a successor program: To understand the forces, responses, and feedbacks between continental rifting, mantle melting, and sedimentation (Fig. 1). This requires studies that span the full range of time (seconds to millennia) and spatial (10-6 to 108 m) scales. Below we identify 5 key scientific questions that were posed, which require integration of short-term and long-term observations, theory, and laboratory studies to fully understand processes acting at rifted continental margins:

1. What are the mechanisms and feedbacks that cause lithospheric thinning and weakening, which in turn

lead to continental rifting? Specifically, what are the roles of magmatic and aqueous fluids in initial lithospheric strength reduction, and what are the feedbacks between sedimentation, climate and strain in space and time?

2. What are the mechanisms and feedbacks controlling the along-axis segmentation of continental rifts from initiation to breakup, with an emphasis on understanding the generation and focusing of magmas, and determining the timescales and rates associated with these processes?
3. What are the implications of these processes for societally-relevant issues such as earthquake and volcanic hazards, and the storage and release of hydrocarbons and greenhouse gases?
4. What are the rates, processes and timescales of delta transport across shelves into deep basins? How do these processes vary with climatic and tectonic forcing in continental rifts, and how are the signals of these variations expressed in the stratigraphic record?
5. What are the dynamic feedbacks between crustal deformation, erosion, climate, and sedimentation in and adjacent to continental rifts?

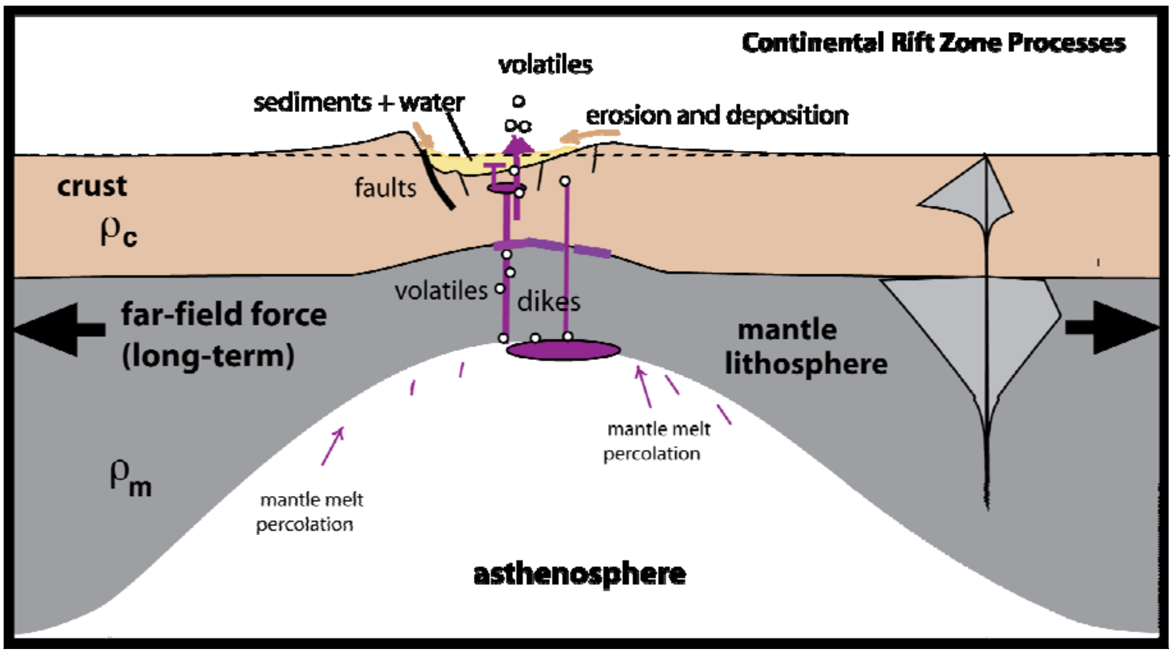

Figure 1: Schematic diagram illustrating feedbacks between key processes influencing the evolution of rifted continental margins.

What infrastructure and approaches are needed to achieve goals?

Sequestered funds within a MARGINS successor program allow the development and use of large-scale infrastructure investments to study scientific problems that are unlikely to arise from a core NSF program. Such a program will catalyze the development of large interdisciplinary projects and international collaborations that benefit from this infrastructure. The current MARGINS program promotes informed collaboration rather than competition, and thus leverages infrastructure to benefit scientific advancement. For example, the active involvement of scientists in different disciplines who communicate and address fundamental questions synergistically would be impossible without an umbrella program like MARGINS. Regular thematic meetings and theoretical institutes build a community of 'Rifting' researchers, and they maximize scientific productivity and synergy. These meetings are particularly beneficial for students, post-docs, and early career researchers. Further, the short time-scales of many of the processes occurring at continental margins can require a rapid response that is best orchestrated through a program such as MARGINS. Examples include the recent boninite eruption at the Tonga trench, funded through a partnership between MARGINS and RIDGE 2000 (*www.nsf-margins.org/SF/Lau/Lau2009.html*).

As with the current MARGINS program, a successor program seeks to "cross-the-shoreline" with joint observations based on marine seismic (and other geophysical datasets), sampling, drilling (onland and offshore), terrestrial field observations, satellite based studies, geochemical analyses, new geochronologic methods, experimental approaches, and numerical models. A MARGINS successor program is well positioned to take advantage of new technologies (SAR satellite data or other space-based technologies that can see through vegetation; quantify displacements, deformation, or fluxes) as well as advances in established techniques. The rapid growth and success of the Computational Infrastructure for Geodynamics (CIG), for example, facilitates the general use of coupled numerical models and computational abilities for rheological, mechanical, and coupled surface evolution problems (deformation, fluid flow, etc.) relevant to continental margins problems. A successor program should aim to leverage existing computational infrastructure developed by NSF funding for geodynamics and landscape evolution, as well as take advantage of geoinformatics and encourage open-access databases for new data collected under the MARGINS program. An outcome of the current and successor program is fully developed proposals to IODP; OOI; Earthscope; and evolving partnerships with industry to provide a substantial element of subsurface characterization.

Structure of a Successor Program

The MARGINS Decadal Review stressed that a successor program could not continue with a "business as usual" approach and must move beyond the current focus sites. Meeting participants debated the pros and cons of focus sites, thematic programs, and hybrid theme and focus site options. Answers to the fundamental rifting questions presented above necessarily require new observations from, and new models of, multiple locations globally spanning the evolution of rifts from inception to breakup. There was a clear consensus that 1) a future Rifting, Sedimentation, and Fluids initiative should include studies at active margins where processes can be examined as they are happening, as well as successfully rifted margins with experiments that span the continent-ocean divide, and 2) that focus sites should enable characterization of 4D strain processes. The merit of a coupled active-ancient program stems from new technologies to probe ancient margins in 3D, and to develop strong IODP proposals and links with industry. The final choice of future focus sites should build on existing major experiments and infrastructure, allowing us to apply RCL experience to future sites. Exploitation of well-sampled sites (e.g., drill sites) using new technologies and analytical techniques will enhance the cost-to-benefit ratio, and integrate with newly collected data.

Concluding Remarks

The Charleston RCL meeting achieved consensus on core themes for the MARGINS successor program. These scientific aims, and programs to achieve these aims will be honed and structured at the MARGINS Successor Planning Workshop in San Antonio, TX in February, 2010 (http://www.nsf-margins.org/SuccessorProgram/index.html). We encourage members of the community to attend this workshop and/or to submit white papers expanding on the scientific objectives discussed at the Charleston workshop.

SEIZE Vision Statement – Consensus views from the 2008 SEIZE workshop on the next decade of the Seismogenic Zone Experiment

Nathan Bangs, Demian Saffer, Susan Schwartz, Don Reed and Susan Bilek

Draft: 15 December 2009

Introduction

During the past decade, the MARGINS SEIZE program has led a campaign of focused field studies in Nankai and Central America with complementary laboratory and theoretical work to address fundamental questions about slip behavior during major subduction zone earthquakes. These questions included: What controls energy release in great subduction earthquakes?; where does slip occur, and what controls the spatial limits of coseismic slip and interseismic locking?; and how do stress, fluid pressure and strain vary throughout the seismic cycle? SEIZE has greatly facilitated long-term integrated studies of seismicity, seafloor bathymetry, geodesy, and fluxes of heat and fluids at these focus sites that would not be possible without a dedicated program at NSF. A workshop held on September 23-26, 2008, gathered 80 scientists from around the world at Timberline Lodge on Mt. Hood, OR to summarize progress and discuss future directions for the SEIZE initiative. A report on the outcome of the workshop is available at: *http://www.nsf-margins.org/SEIZE/2008/index.html*. The 3 day workshop: assessed the progress made in the last decade on major SEIZE science objectives, defined critical gaps or unanswered questions, and identified new fundamental questions about subduction zone behavior, many of which have emerged from MARGINS and related studies over the past decade. In addition, we discussed the need for new facilities and technological developments to address the core science questions, the relative merits of focus sites vs. a thematic-based initiative, and the need for a dedicated program at NSF to adequately address key SEIZE science objectives.

The upcoming MARGINS Successor Planning Workshop in San Antonio, TX in February 2010 will serve to refine the SEIZE workshop outcomes and integrate them with those of the other MARGINS initiatives to formulate a new program. Here we review the consensus opinions at the Mt. Hood workshop to lay groundwork for discussions in San Antonio.

New and Emerging SEIZE questions

One key outcome of the workshop was the definition of a new generation of core science questions that have emerged from new discoveries during the last decade of SEIZE-related research. These new questions are largely motivated by new datasets and theoretical studies that have documented a wide spectrum of fault slip behaviors in both space and time, ranging from "normal" earthquakes, to episodic tremor and slip (ETS), to tsunami earthquakes and slow slip events (Figure 1). Detailed observations in a variety of major plate boundary fault zones, but in particular, subduction zones, show that fault slip occurs over time scales from seconds (earthquakes) to months (silent earthquakes, ETS, low and very low frequency (VLF) earthquakes). It is unclear what controls the broad range in slip behavior and particularly how these slower time constant events relate to strain accumulation and release on subduction megathrusts, or what processes or rock properties facilitate them (e.g., rock composition, stress state, and pore fluid pressure).

Specifically:

1. What is the role of fluids in controlling fault rheology?

It has been hypothesized that metamorphic dehydration, pore pressure, and their distribution affect slip behavior (specifically the locations of ETS, VLF, and the updip limit of interseismic locking) and fault strength. Fluid release and pore pressure evolution, possibly mediated by sediment composition and thickness, basement topography, or thermal structure, may play defining roles in controlling fault rheology. New observations, theoretical studies, and

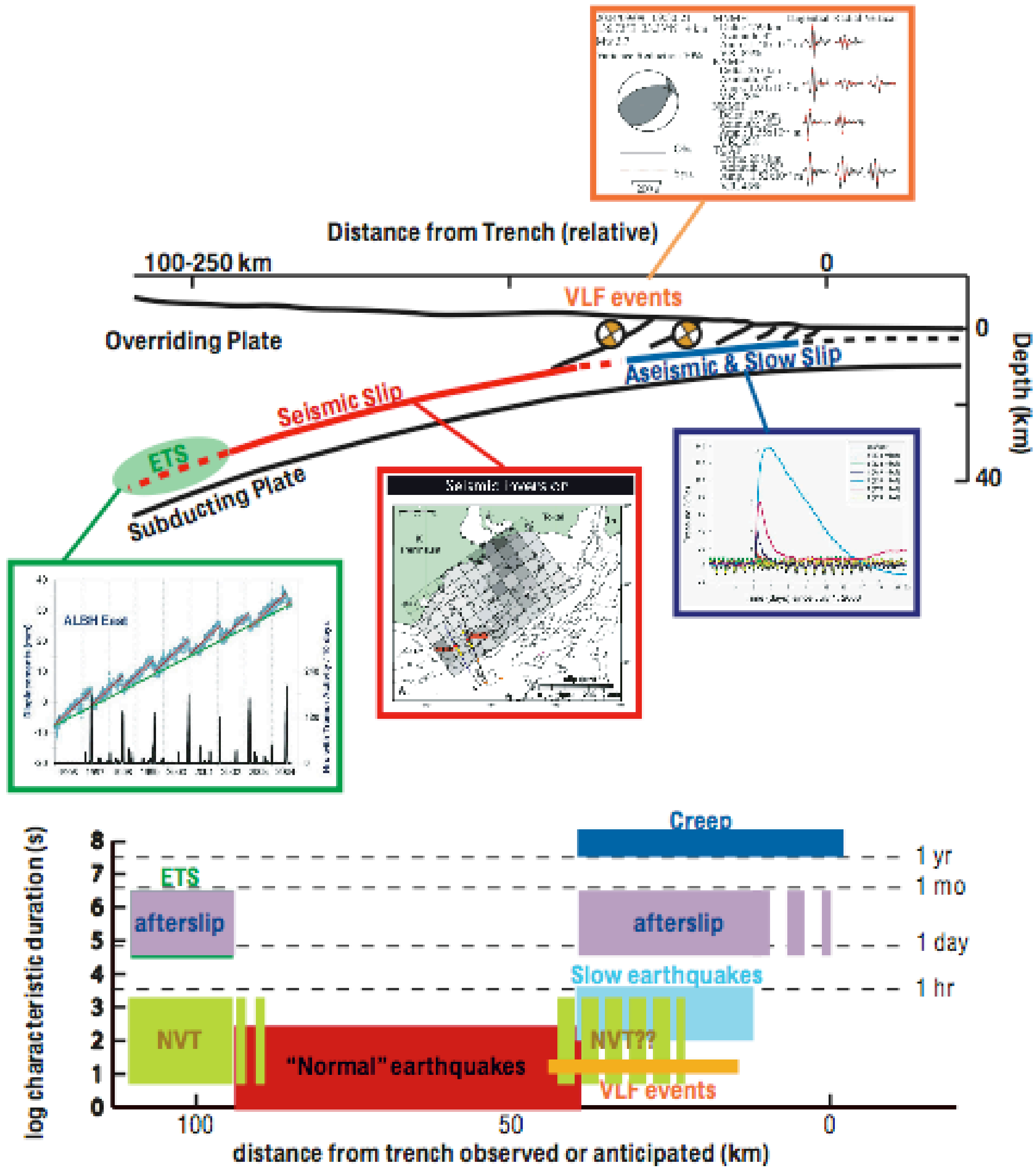

Figure 1. Recent observations over many different time and length scales demonstrate a wide range of slip behaviors on active fault zones, particularly near the updip and downdip limits of normal earthquakes.

experimental efforts are needed to test these ideas.

2. What governs along-strike variations in moment release in great earthquakes, and similar variations in interseismic locking?

Variations in seismicity and interseismic deformation along- and across-strike have been correlated with subducting plate roughness and age, upper plate structure and lithology, and contrasting properties and processes within the fault zone. Are these correlations universal or local? Are there other factors (e.g., pore pressure distributions or thermal state) that strongly influence or control these variations, and if so, how?

3. What causes the observed temporal variations in seismogenic zone behavior and plate boundary deformation in interseismic, coseismic, and post-seismic periods?

Integrated onshore-offshore surveys at Nicoya, Nankai, Cascadia, and elsewhere demonstrate distinct fault behaviors and surface deformation in each setting, often varying along strike. These regions are all at different points within the seismic cycle. How do the observed variations relate to the time since the last earthquake, and what controls this temporal variation? Comparative studies along several margins at different stages within the seismic cycle can help to establish a unified understanding of evolving processes at subduction margins.

4. What are the state of stress and absolute strength of subduction faults and wall rock?

New results suggest strong spatial variations in stress at the Nankai margin from borehole breakouts, extremely low apparent stress drops (< 0.1 MPa) for VLF events, and dynamic triggering of tremor at Cascadia suggestive of low effective stresses. How are these observations related to overall fault strength, fault composition and subduction inputs, and fluid pressure?

5. What is the geology of the seismogenic zone and its transitions?

In particular, what is the character of the upper plate, and the composition, fabric, architecture, and physical properties of fault rock, and how does it influence fault mechanics and rheology, and strain accumulation and release? Is strain accumulated in an extremely localized zone, as observed in some continental fault systems?

New technologies, methods, and scientific strategies

The new science questions listed above will guide future program development; however, new methods, technologies and strategies with respect to program structure and focus sites will be critical to assure future success. A future program will implement a broad application of existing scientific techniques and emerging new ones. Recent studies at the Costa Rica SEIZE focus site have made direct connections between fluid flow and seismic activity from a campaign deploying new instrumentation to measure fluid flow and seismicity simultaneously. Similarly, paleoseismological studies have delineated rupture history and segmentation in great detail along the Cascadia margin, which will be key to unraveling long-term rupture patterns at a variety of margins. Both of these and other recently developed, promising techniques will need to be broadly employed. Coordination and collaboration of facilities and technologies between ongoing, complementary programs, such as long-term observatory efforts with OOI, SAFOD and others, will be a key component of future efforts to span the shoreline and expand the range of observations.

In addition, several emerging technologies have the potential for transformative breakthroughs to address the new SEIZE-related science questions. For example, continuous GPS-Acoustic buoy/seafloor transponder systems for continuous monitoring of seafloor vertical and horizontal motions with cm-scale resolution is in development and could provide a critical complement to onshore stations that have been instrumental in unraveling strain accumulation during the seismic cycle. Offshore geodetic measurements combined with continuous monitoring of strain, pore pressure, and seismicity in boreholes provide a powerful suite of tools for characterizing strain over a range of magnitudes, and spatial and temporal scales. For example, fluid pressure can now be measured in borehole observatories to +/- 0.5 Pa and at frequencies up to 1 Hz. These offer promising new ways to measure strain within hydrologically isolated formations, especially where they can be tied to cabled networks and monitored in real time. Ultimately, buoy systems will complement permanent cabled network systems that will provide similar data for both early warning systems and long-term focused studies, such as the DONET system scheduled to come on line in 2010 in the NanTroSEIZE study area and the OOI/NEPTUNE-Canada system offshore Cascadia.

Programmatic strategies

In order to adequately address the next generation of SEIZE questions enumerated above, a future SEIZE program (1) will require branching out to new locations beyond the current focus sites; and (2) incorporate a continued role for co-located crossdisciplinary and complementary studies at the current focus sites. Understanding the fundamental controls on the observed spectrum of fault slip behaviors requires efforts along several subduction margins, because no single site exhibits all of these behaviors. Similarly, addressing the causes of observed temporal variations in seismogenic zone behavior can be achieved only through studying multiple systems at various stages in the seismic cycle, and by examining along-strike variations at individual margins. Notably, many important and relevant datasets have come from studies outside of the current focus sites, such as Cascadia, Alaska, and Sumatra, and from laboratory and theoretical studies. A continued presence at existing focus sites will take advantage of valuable infrastructure developed during the past decade, and generate time series data critical for events during the seismic cycle.

The MARGINS program, including the SEIZE Initiative, require a separate program outside of the NSF Core program for several reasons. In particular, studies focused on subduction zone seismogenesis require integrated studies that span the shoreline, a mechanism for long term data collection over multiple co-located field campaigns, complementary laboratory and theoretical studies, and a mechanism to foster broad collaboration and data synthesis between programs. As an example, the CRSEIZE Program along Costa Rica defined and compared the pattern of strain accumulation to the distribution of seismicity, while the collocated TicoFlux Program identified along-strike thermal transitions and constrained the subducting sediment composition and distribution. Results from TicoFlux and CRSEIZE were combined to test the hypothesis that transitions between stable sliding to stick-slip behavior are thermally controlled. At the up dip limit, they 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 estimated location of the 350oC isotherm. Integrated studies and broad syntheses are critical for future SEIZE progress. Development of a programmatic structure for SEIZE that fosters integration and synergy with other emerging MARGINS programs, such as SUBFAC, will add value to SEIZE and strengthen both programs.

Concluding Remarks

The discussions at the Mt. Hood workshop laid out the foundation for the future SEIZE scientific goals and addressed the critical issues for achieving those goals within the MARGINS program. The MARGINS Successor Planning Workshop in San Antonio, TX in February 2010 will enable us to further refine the SEIZE program and develop a strategy to achieve our scientific goals. We encourage the SEIZE community to shape the future of SEIZE by submitting white papers to the workshop to guide discussions and by attending in San Antonio.

MARGINS Theoretical & Experimental Institute: Volatiles In The Subduction Factory Sponsored by the NSF MARGINS Program (September 28 – October 1, Mt. Hood, OR)

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Vision Statement – draft updated 1/7/10

Introduction

Subduction zones play a primary role in mediating the cycling of volatiles on Earth. The volatile constituents that are carried into subduction zones in minerals and pore fluids are dominated volumetrically by H_2O. Water exerts a fundamental control on a wide range of geophysical and geochemical processes in subduction zones. This includes the seismic coupling and the generation of earthquakes, aqueous fluid release and element transfer from the subducting slab, generation of serpentine and chlorite in the forearc and mantle wedge, stabilization of hydrous minerals in the slab and mantle wedge, mantle-wedge convection, melting of sub-arc mantle, and explosive volcanism. The pattern and amount of water-rich fluid released from subducting oceanic lithosphere has a first-order influence on the locations, volumes and eruptive style of arc volcanoes and the generation of juvenile continental crust. Though other volatile components are less voluminous than water, they nevertheless contribute to key geologic processes as well. For example, along with H_2O, carbon dioxide, reduced low-weight hydrocarbons, and sulfur- and halogen-bearing compounds contribute to the greenhouse gases when they are emitted from subduction zone volcanoes, and thus have a significant influence on climate at local to global scales. Carbon combines with water to exert a direct influence on the depths at which the mantle melts to yield arc magmas, on primary melt compositions, the nature of arc magma crystallization, and the rheology, conductivity and seismic velocity of the sub-arc mantle. Chlorine, fluorine and sulfur strongly modify the solubility and transport of other elements in the dynamic hydrologic settings of the slab and mantle wedge.

In the autumn of 2009, approximately 90 researchers gathered at Timberline Lodge on Mt. Hood, Oregon at a MARGINS Theoretical and Experimental Institute (TEI) focused on the behavior, mass-balance, and influence of volatiles in subduction zones. This meeting brought together geochemists and geophysicists to examine and discuss the current state of our knowledge on the budget of H_2O, CO_2, N, F, S, Cl, and noble gases in the two SubFac focus sites (Izu-Bonin-Mariana and Central America), to examine the role of these volatiles in major geochemical and geophysical observations, and to deepen our understanding of the influence of volatile elements on geologic processes fundamental to our understanding of subduction zones. The attendees at this meeting spent the final day in breakout groups discussing outstanding issues in subduction zone science that remain as unsolved problems. From these breakout groups, a coherent set of directions for future research emerged; these scientific directions are multidisciplinary and global in their significance, and they should form an important part of the future trajectory of any successor program to the current MARGINS initiative.

Future Directions in Subduction Zone Research

In the original Subduction Factory science plan incorporated as a part of MARGINS in 2000, fifteen major scientific questions were posed to guide the selection of focus sites and the directions of research within the scope of the program. Two-thirds of those questions dealt directly with the abundance and role of H_2O, CO_2 and other volatiles in subduction zone processes. This testifies strongly to the importance of volatiles in controlling what happens at subduction zones. Simply put, volatiles make subduction zones what they are, and this is no less true today than it was ten years ago.

The abundance of volatiles on Earth is likely the single major reason why Earth is the only planet in the solar system with subduction zones. The active plate tectonic cycle that now characterizes the surface expression of mantle convection depends critically on the strong impact that water has on the strength of mantle and crustal rocks. One need look no further than Venus or Mars to imagine how different Earth's tectonics would be on a dry one-plate planet without subduction zones. Beneath the plates, water influences mantle convection to a degree that belies its abundance. As little as 150 ppm H_2O (by weight) is sufficient to lower the viscosity of the mantle by three orders of magnitude below that of dry mantle. Volatiles also have a direct influence on the behavior of megathrust faults and the earthquakes they generate, as well as the overall thermal structure of the mantle wedge. In the upper 150 km of the mantle, the melting point drops by 200-300°C upon addition of as little as 0.1% of H_2O. This allows normal mantle beneath subduction zones to melt at depths where it would otherwise never melt in the absence of water. Volatiles are thus directly responsible for the existence and location of subduction zone volcanoes and the generation of new continental crust. When magma reaches the Earth's surface, the risk of explosive and violent eruptions depends almost entirely on its volatile content. In addition the volatile components released can have direct impact on short- and long-term climate evolution. Because of its strong influence on mantle convection, and the location and style of surface volcanism, and the impact of volcanoes on climate and public safety, the origin, distribution and influence of volatiles in subduction zones are among the most important issues in all of Earth science.

In order to understand the dynamics and structure of subduction zones and their influence on the chemical and physical evolution of the planet it is critical to understand the role of volatiles. This was strongly reflected in the key scientific questions that emerged from the breakout groups at the Volatiles TEI meeting. These questions are multidisciplinary in nature, and by necessity require a coordinated approach to field geology, volatile geochemistry, high-pressure experimentation, geophysical field experiments and data analysis, and convection and melt transport modeling that has been a strong hallmark of the existing MARGINS initiative.

Volatile cycling – Ocean Drilling Program (ODP) drill holes have given a first-order idea of the composition of sediments entering subduction zones around the world, but ODP hole locations have not yet been concentrated in any one area to a degree necessary to delineate along-strike variations in the composition of the plate entering any single subduction system. Sampling of fluids that emerge from convergent margin megathrusts and the forearc is similarly limited. These two near-surface observations place first-order constraints on the overall budget of volatiles entering subduction zones and advection of these volatiles into the sub-arc mantle. They are also subject to the greatest uncertainties among all the terms in budget calculations.

Various hydrous minerals are the carrier phases for volatiles into subduction zones and magmas are responsible for the return of these volatiles to the Earth's surface. It is therefore critical to be able to accurately predict the phase assemblages of subducting plates across the global array of subduction zones. Seismic imaging can test these predictions. For example, evidence is emerging for significant serpentinization of the slab mantle pre- and post-trench, and multi-scale layering at the top of the slab likely reflects volatile-influenced crustal mineralogies, and, in some cases fluid-filled fractures. The stability limits of slab minerals are first-order determinants on where fluids emerge from the downgoing plate. They also likely determine the mode of slip at the interface between the downgoing and overriding plates (e.g. earthquakes versus episodic tremor and slip) and the location of intermediate-depth seismicity.

Important questions remain on the role of volatiles once they are released at sub-arc depths from the descending slab. How do melts and volatiles transit, interact with, and modify the surrounding mantle and crust from the slab to eruption? Geophysical imaging is making progress in placing bounds on the form and amount of volatiles in the slab, melting region, and beneath the arc. Dense arrays of seismometers in the IBM and Central American subduction systems have resolved the velocity and attenuation structure of the slab and wedge with sufficient resolution that the competing effects of temperature, volatiles, and partial melt are beginning to be distinguished. Nonetheless, still higher resolution is required, particularly to illuminate the form of melt pathways from the wedge to the arc. Correlation with conductivity structure, although in a nascent stage, has the potential to yield important complementary constraints. However, interpretations of geophysical images are at present limited by uncertainties in the effects of volatiles and melt on geophysical observables, and further experimental studies are essential.

Magma volatile contents are now amenable to direct measurement in submarine glasses and melt inclusions, but large uncertainties remain in the magma generation and crustal growth rates at magmatic arcs. Remote atmospheric sensing of volatile gas output at arc volcanoes is limited to major eruptions, while direct sampling of volcanic gases is limited to occasional sampling at obvious fumaroles, often separated by many years and thus not amenable to time-series studies of gas output evolution. What is the partitioning of volcano degassing between major eruptions and passive quiescent venting?

Geodynamical modeling that accounts for volatile and melt transport and their rheological feedbacks is key to integrating geochemical and geophysical data and testing models of volatile cycling through subduction systems. However, basic questions remain regarding the geometry of mantle flow in subduction zones, and how the subducting plate couples to the surrounding mantle. The depth at which slab/mantle coupling terminates exercises a key control on the thermal structure of the subducting slab and hence on the locus of slab dehydration and of flux-melting in the overlying wedge. What controls the termination depth of slab/wedge coupling?

Volcano vigor– Magmatic arcs are the locations of the most spectacular, explosive and destructive volcanic eruptions that have occurred during recorded history. What are the geochemical and geophysical features that contribute to the wide variety of volcanic eruptive vigor? Magmatic water has an obvious influence on volcano explosivity, but most degassing of water from magma occurs in the upper few kilometers of the volcanic edifice. Do other less-abundant but also less-soluble volatiles also play a role in the accumulation of gas beneath explosive volcanoes? What is the feedback between stress changes (static and dynamic), local earthquakes, volcano degassing, and ultimately eruption? What aspects of volcano structure and composition can be used to help forecast volcano vigor in populated areas?

Climate - Along with H_2O, carbon dioxide, reduced low-weight hydrocarbons, and sulfur- and halogen-bearing compounds contribute to the global budget of greenhouse gases when they are emitted from subduction zone volcanoes, and thus have a significant influence on climate at local to global scales. Subduction zone volcanoes are the primary path for degassing of these volatiles directly into the atmosphere. Compared with anthropogenic input to the atmosphere, conventional wisdom holds that the flux of various volatiles from volcanoes is small, yet measurement of these fluxes is erratic and sparsely distributed. The lack of adequate sampling therefore causes an important failure to accurately capture the emanation of magmatic gas during volcano quiescence between major eruptions which likely dominates the total degassing flux. What is the real contribution of volcanic gas to climate change? How does the flux of magmatic gas from subduction zones vary with magma production and tectonic changes at convergent margins?

Growth Rate – The growth rate of magmatic arcs at subduction zones provides first-order estimates for magma-based flux calculations for volatile transport from the mantle to the exosphere and is the primary means by which we can calculate modern growth rates for continental crust. At spreading centers, magma generation rate is readily calculated from the kinematics of plate spreading. However, at convergent margins the plate geometry is less simple, addition of arc magma may be difficult to differentiate from pre-existing crust, and the stronger influence of volatiles on magma generation make it a significantly more complex phenomenon than at spreading centers. What insights into fluid formation, fluid flow, magma generation and mantle convection in subduction zones are required in order to advance our understanding of crustal growth in arcs? How does arc magma generation depend on tectonic forcing functions such as slab structure, age, convergence rate and nature of the overriding plate? How fast do arcs grow, and how precisely do arcs turn into continents? What is the partitioning of intrusive versus extrusive magmatic products at individual arcs, and how can this be determined? What are the mass and chemical balances of arc formation and evolution, and how do they relate to formation of continental crust?

Structure and Evolution of Arcs –Few compelling dynamic models exist for the initiation of a convergent margin and no sites have been clearly identified where nascent formation of a subduction zone is imminent or ongoing. How does subduction begin? What is the tectonic and structural transition to mature subduction zones? The large diversity of subduction zones raises further questions. What causes the heterogeneity in subduction zone structure? What factors result in the formation of back arc basins, and what are the interactions between the main arc and back arc? Why does strain partitioning between the plate interface and the upper plate vary so widely between subduction zones, and what are the implications for arc rheology? What is the long-term evolution of tectonics and magma mass flux over time during the lifetime of an individual arc? How do arcs and subduction processes vary in space and time, and what are the processes and dynamics that control those variations?

Deep Mantle Recycling - What is the physical and chemical state of the slab after subduction zone processing? What quantity of volatiles passes below the subduction zone factory? How does the rheology of the residual slab contribute to the generation of very deep earthquakes? How does the residual slab relate to mantle heterogeneity, and what role do subduction zones play in global-scale geochemical and volatile cycles, from the core to the atmosphere?

Deep Time - How does subduction influence the long-term geochemical evolution of the planet – mantle and atmosphere? What is the role of subduction zones in determining the deep-mantle budget of volatiles?

Hydrous minerals – Serpentine and chlorite are two important hydrous minerals that have great capacity for storing water. Their predicted stability fields suggest that they could be present in many key parts of the subduction system (the wedge corner, below the slab Moho, above the dewatering slab, at the base of the upper-plate Moho) and that therefore they may exert important controls on the dynamics of subduction zones. The ability to detect the presence of these minerals thus becomes important. What are the physical, rheological, seismic, and conductive properties of serpentine and chlorite? What is the abundance of these minerals at the predicted locations of their stability? Do other hydrous minerals, such as Phase A, the 10 Angstrom phase, or humite minerals, also play important roles in the storage and release of H_2O in or above subducting slabs? What is the role of hydrous minerals in plate locking at convergent margin megathrusts, and in decoupling between the slab and the mantle wedge? What is the role of these minerals in delivering volatiles to the zone of arc magma generation, and what is the chemical signature of their involvement? How does their importance at convergent margins vary with thermal state, along-strike, and at local and regional scales?

Convergent Margin Forcing Functions – We now have estimates of the concentration of H_2O in the magmas of most of the volcanoes in the two SubFac focus sites (IBM and Central America). In both areas there appears to be a clear signal of flux melting, with water contributing to increasing the degree of mantle melting in proportion to its abundance in the mantle. Yet water also shows a dichotomy in its behavior at these two subduction zones, with clear along-strike correlations in geochemical and geophysical variables in Central America but not at IBM. Equally perplexing, depth to slab below the arc, depth to apparent slab decoupling, and water output are relatively constant among arcs, while many properties of the subducting slab vary widely. What physical processes control this lack of correlation?

Infrastructure Required to Address Future Subduction Zone Research

Parallel multidisciplinary efforts in sea- and land-based field programs, experimental petrology and geochemistry, numerical modeling efforts, and geochemical-isotopic-volatile analytical programs have been a hallmark of the MARGINS program as a whole and of SubFac in particular.

- IODP drill cores are essential to obtain the composition of the incoming slab and provide the primary means by which sediment compositions and alteration state of the upper MORB crust are determined.
- Field programs to sample volcanic gases and melt inclusions have been a critical component in determining the volcanic output of volatiles at subduction zone volcanoes, as well as providing a means to examine how magmas differentiate in the crust and contribute to a vertical stratification in crustal composition.
- Deployments of seismometers and MT instruments, including ship-based support for ocean-bottom deployments, have been crucial to determining the seismic velocity and attenuation and conductivity structure of the mantle wedge and subducting slab, as well as imaging the thickness of arc crust along-strike

and the state of fracturing and potential hydration of the incoming plate at the outer rise.

- Labs where high pressure and temperature experiments are conducted provide the fundamental data on magma composition, melt production, melting temperatures, volatile and trace element partitioning, and seismic velocity, and conductivity properties that permit us to turn geochemical and geophysical observations into realistic interpretations of deep-Earth structure, temperature and composition.
- Shore-based facilities for geochemical analysis and computational networks for modeling of earthquakes, convection, fluid and melt transport and seismic wave propagation are essential for an integrated approach to MARGINS science progress.

The Importance of a Coordinated Multidisciplinary Approach

A commonality of purpose among these multidisciplinary activities in SubFac has achieved a synergy of scientific results that would not have been possible in the absence of focus sites. The collocation of research efforts sponsored by the governments of Germany (in Central America) and Japan (in IBM) has greatly enhanced the scientific productivity and efficiently leveraged US funding. From a logistical point of view, coordination of field campaigns in geophysics and sampling (for gases and melt inclusions for geochemistry) has been achieved with an economy of both effort and cost at both focus sites. Scientifically, in both IBM and Central America, we now have constraints on sedimentary input, observations and measurements of forearc fluid flux, magma geochemistry and volatile content both along strike and across the arc, images of seismic velocity and attenuation variations, and dynamic models that are constrained by geophysical observables. From these coordinated efforts, it is now possible to make much more accurate interpretations of the geophysics and geochemistry than ever before possible at any subduction zone. Focus sites have made this happen in a way that would not have occurred by serendipity, without a concentration on specific active margins.

To contrast, through core EAR and OCE funding, there exist separate pieces of this scientific puzzle in places like the Aleutians, Tonga and South America – but the lack of a coordinated effort like SubFac has isolated the results of these individual studies, and as a result they lack the kind of multidisciplinary impact that has been achieved, and is continuing to emerge, from the focus of ideas and resources at a few specific sites. A combination of multidisciplinary efforts, concentrated at a few focus sites, has maximized the scientific impact of MARGINS funding.