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MARGINS Program

Science Plans

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Preface

Any major new research initiative requires a period of intellectual gestation during which the community gathers and assimilates a list of major scientific questions to be addressed, the most practical ways to approach the issues and the technical and fiscal resources needed to make a meaningful impact. The US MARGINS Program was no exception. It took the geosciences community a decade of workshops and planning sessions to achieve this goal. The MARGINS' community recognized early that a relatively small range of physical and chemical processes (e.g., lithospheric deformation, magmatism, other mass/energy fluxes, sedimentation and fluid flow) were fundamental to the evolution of all margins. Studying these processes wherever they were best expressed and extant today would therefore provide a logical and most expedient line of inquiry for understanding the complex nature of continental margins. The process-oriented and holistic approach to understanding the entire system of margin evolution also meant that broadly based interdisciplinary studies would have to be undertaken and a new class of major experiments would have to be designed to achieve these goals. National Science Foundation's MARGINS Program, first initiated in 1998, has the explicit goal of elevating the current, largely descriptive, view of the ocean margins to a level where theory, modeling, field observation and experiment can yield a more systemic understanding of processes that control continental margin creation and evolution. The essential amphibious nature of almost all MARGINS' studies also lends itself ideally for support from both the Division of Earth Sciences and the Division of Ocean Sciences.

The publication of the updated MARGINS Science Plan in the fifth year of funding represents an important milestone for the Program. The individual science plans for four MARGINS initiatives (Rupture of Continental Lithosphere, Seismogenic Zone, Subduction Factory, and Source to Sink) represent the results of the often long and lively discussions within each sub-community of MARGINS. They summarize the current thinking about the major scientific issues and define the state-of-the-science in each initiative as well as outline the progress made so far. This document will serve an important purpose as a planning document within NSF and will be used for reviews of the Program and for budgetary purposes. Major programs have to be continuously appraised and their future growth justified at several levels – this document will form the basis of such activity for the MARGINS Program. But more importantly, it is hoped that the document will serve the community as a focal point for proposing future research and new experiments in each area.

Over the past five years the Program has clearly seen an accelerating interest in MARGINS and MARGINS-related research. Five years of MARGINS funding, and through its sponsored workshops and symposia and synergistic development of MARGINS-type programs in other countries, a generation of geoscientists have been trained and grown accustomed to think holistically about the entire system, beyond their own disciplines. This alone is bound to positively influence all future continental margin research in allowing investigators to think broadly and propose bold new experiments. The Program has already seen an improvement in the quality of experiments proposed to study areas outside the MARGINS "focus sites" with this holistic approach. MARGINS research and planning is also providing some of the basic studies and arguments for drilling along the ocean margins in the new Integrated Ocean Drilling Program.

Many active scientists and champions for individual initiatives have worked hard to produce this document. They received valuable guidance from the MARGINS Steering Committee, many of whose members volunteered or were conscripted into producing the initial drafts of the science plans based on the various workshops and symposia. Others from the community at large were sometime called upon to help out at short notice. All did so cheerfully. The MARGINS Office worked tirelessly to produce the final document. NSF acknowledges their hard work in producing this important revision of the Science Plan for the benefit of the entire Earth Science community.

Bilal Haq
For NSF MARGINS Program

The NSF-MARGINS Program: Executive Summary

The NSF-MARGINS program began because of a community perception that continental margin science could benefit from increased communication, cooperation, and integration between scientists engaged in a wide variety of observations, experiments, and theoretical modeling in studies crossing the shoreline. With an emphasis on studying active processes, the objective of MARGINS is to develop a self-consistent understanding of the processes that are fundamental to margin formation and evolution, comprising lithospheric deformation, magmatism and mass fluxes, sedimentation, and fluid flow, together with their interactions and feedbacks. The MARGINS process has been to work with the community to identify major areas of important research that could benefit from this approach, leading to four major initiatives. These are: *Rupturing of the Continental Lithosphere* (*RCL*) and the birth of an ocean; *Subduction Factory* (*SubFac*), to understand the processes controlling the chemical cycle in subduction zones and the geodynamic information contained therein; *SEIZE*, the *Seismogenic Zone Experiment* to investigate the great earthquakes occurring along the plate boundary in subduction zones; and *Source-to-Sink* (*S2S*), which links geomorphology, erosion and transport by the sedimentary processes that form the stratigraphic record from nearly instantaneous to geologic timescales. Within each initiative, widely advertised and attended NSF-supported workshops helped to identify key scientific issues, developed criteria essential for successful studies, evaluated candidate geographical localities and sought consensus on optimal focus sites, and summarized the aspirations of the research community in the various Science Plans, which have been widely disseminated by NSF and the MARGINS Office. Implementation of these Science Plans is achieved by concentrating resources on focus sites targeted for intense, multidisciplinary programs of research in which an ongoing dialogue among field experiment, numerical simulation, and laboratory analysis researchers is fundamental and symbiotic, and is facilitated by a continuing series of science and planning workshops. The MARGINS program seeks a quantum leap in our quantitative knowledge and predictability of Earth system behavior in order to enhance Earth Science research for scientific advancement, but also for societal relevance, exploitation, exploration, and hazard mitigation. In the first half of its decadal existence, a fundamental objective of the MARGINS program has already been attained - the building of a large community of scientists who are well-informed across a broad range of disciplines and sub-disciplines not related to their own.

Following are thumbnail sketches of each initiative:

1) RCL - the initiation, evolution, and eventual destruction of continent- ocean margins involve the coupled interaction of mechanical, fluid, chemical, and biological processes. These processes result in the accumulation of most of the Earth's valuable resources and the focusing of the principal geologic hazards at margins; the locus of the greatest population density. The Rupturing of Continental Lithosphere (and birth of an ocean) experiment

will proceed by focused investigations of the four-dimensional style, distribution, and depth partitioning of extension within continental lithosphere to determine the spatial and temporal variations in the rheology of the lithosphere, why rifts form where they do, and the forces required to sever continental lithosphere.

2) SubFac - Subduction of oceanic plates causes earthquakes, tsunamis, and explosive volcanism, and also gives rise to ore deposits, geothermal energy, and the continental crust we live on. The Subduction Factory Initiative focuses research on two contrasting subduction zones to address fundamental questions about forcing functions for magmatism and fluid flow, volatile cycles through convergent margins, and mass balance and growth of the continents.

3) SEIZE - Subduction zones also generate the world's largest and most destructive earthquakes and tsunamis, and host much of the world's population The Seismogenic Zone Experiment studies the shallow subduction plate interface that is locked and accumulates elastic strain, periodically released in large or great earthquakes. Questions focus on the controls on the distribution of seismic energy release, on the heterogeneities in the locking behavior of the interface, on the rate of propagation and slip rates of earthquakes, and on the nature of temporal changes in strain, fluid pressure and stress during the seismic cycle.

4) S2S - The Source-to-Sink initiative will provide a comprehensive study of linked, terrestrial and marine sediment dispersal systems over the range of time scales for which sedimentary processes operate. Observational, laboratory and theoretical studies will be integrated to allow the modeling of entire, linked sedimentary systems as opposed to only their components. Questions center around the role of changing tectonics, climate and sea level as forcing functions in the production, transport and storage of sediments and solutes; processes initiating erosion and sediment transfer, and their interactions; and the interplay of sedimentary processes and forcing functions in creating the stratigraphic record.

With the maturing of the science plans and implementation proceeding in all initiatives, the MARGINS program can focus more attention on data management and education and outreach. Data policies for the archiving and timely release of MARGINS funded data are now in place and dedicated focus site database design, schema, and template experiments are underway. The MARGINS Office now has a half-time FTE to pursue Education and Outreach activities. Reflecting the strengths of the MARGINS Steering Committee and Office, efforts will focus on undergraduate and informal education. Early activities include the creation of a MARGINS post-doctoral fellowship scheme, a MARGINS Images library for undergraduate instructors, and collaboration with the St. Louis Science Center with the ultimate goal of developing MARGINS related exhibits. All products will be made available to the MARGINS science community for adaptation and use nationwide. Collectively, the formal MARGINS publications, the products of the Education and Outreach efforts, and the databases of the MARGINS focus sites represent an important legacy and resource for future researchers-NSF's "investment in the future".

The NSF-MARGINS Program: A reflective overview

by Garry D. Karner and Julie D. Morris

The MARGINS initiative was conceived in its first working form in 1988. Then, as now, its orientation was towards scientifically driven, process oriented and interdisciplinary studies of active processes that cross the shoreline along continental margins. An initial objective was to construct a way to tackle first-order, fundamental research questions of Earth Sciences, the solution of which would advance significantly the science in a single, concerted step. Not surprisingly, then, the mission statement of the MARGINS Program is "*to understand the complex interplay of processes that govern continental margin evolution globally*". Members of the steering committee generated proposals to host five open NSF-sponsored workshops between 1988 and 1993, in order to engage the community and to define the scope of the overall research initiative, and determine how best (and most efficiently) to focus MARGINS research on scientific questions. The proceedings of a workshop sponsored by the National Research Council (NRC) in Irvine, California, defined, outlined and presented the MARGINS concept: the report was entitled "*MARGINS: A research initiative for interdisciplinary studies of processes attending lithospheric extension and convergence*". The crucial message of this workshop was the following:

> "The primary scientific objective of the initiative will be to develop programs aimed at understanding the processes that control the initiation and evolution of continental margins"

"The outcome of the workshop indicates widespread support and enthusiasm for a new direction in margins research that would focus on interdisciplinary studies of the fundamental processes of margin evolution. Interdisciplinary studies, as a new direction, are demonstrated by the working group reports, which show a remarkable similarity in focus despite the wide diversity of topics addressed and the degree of separation usually present between investigators from different disciplines. Many of the scientific problems that were identified, and their suggested solutions, were common to several working group topics. These similarities define a commonality of direction that belies traditional boundaries based on discipline, geography, or methodology. The principal reason for these similarities is that fluid flow, magmatism, and sedimentation, are not unique to either divergent or convergent margins. Instead, they are fundamental global processes that control the ways in which continents grow and deform with time.

The MARGINS Initiative is proposed as a means of nurturing this new direction. The primary scientific objective of the initiative will be to develop programs aimed at understanding the processes that control the initiation and evolution of continental margins."

Birth of MARGINS

Mission statement

Founding philosophy

With these words, the founding philosophy of the MARGINS program was established.

The original MARGINS science plan was published in 1996 by the MARGINS Planning Office, then at the Department of Geology and Geophysics, Rice University, Texas. The original MARGINS science plan outlined a program of multidisciplinary investigations (including theory, observation, and experiment) to be carried out in a complementary fashion in order to advance our understanding of the processes controlling continental margin evolution and development, at a quantitative level. The proposed approach was process-oriented because similar processes occur at all active continental margins, regardless of the exact kinematics of the setting (i.e., convergent, divergent, or transform). A few key processes were identified as important in controlling the evolution of all margins. As such, these were envisioned as the targets for MARGINS investigations. It was proposed that efforts be concentrated in a few optimal locations where the processes are active and where theory, observations, and experiments could be synergistically combined to address one or more of the problems identified as key to understanding margin evolution.

Original science plan

Developing scientific objectives

The scientific objectives of the MARGINS program build on a large body of continuing research that has, and is, being conducted using core funding from NSF and other agencies. Achieving the MARGINS objectives requires an experimental approach that includes: developing multidisciplinary case studies, focusing on active systems, studying whole systems (implying an amphibious approach with research spanning the shoreline), establishing scaling relations, including comparative global studies, and establishing event response strategies.

Five general areas of investigation were identified by community workshops and outlined in the original MARGINS Science Plan (1996): 1) the low-strength paradox of lithospheric deformation, i.e., what are the stresses and fluid flow conditions on active faults and how are these related to laboratory observations of the strength of rocks? Under what circumstances can the entire lithosphere rupture?; 2) Strain partitioning during deformation, and in particular, vertical strain partitioning, i.e., is the lower crust of a sufficiently different rheology than the upper crust such that it can accommodate a different strain pattern at depth than that is visible at the surface?; 3) Magma genesis and recycling, that is, can we develop a theory that can explain the chemical, temporal and spatial aspects of melt production and migration?; 4) How is the stratigraphy of geological events preserved?; 5) What are the effects of fluids and fluid fluxes on rock geochemistry, lithospheric rheology, and volcanism? These general questions are applicable to all types of margins. The 1996 science plan did not identify exact locations where these studies would take place—this would be done via a series of NSF-supported community workshops that presented and assessed suitable locales (focus sites) to best address and investigate the various research objectives. However, the science plan did suggest some notional experiments as models that were considered crucial to the success of the MARGINS program.

In the late 1990s, the MARGINS steering committee began to further organize the program and to detail the science plan. At the same time, well-organized groups in the community had been planning major research themes, such as the detailed petrological plumbing of subduction systems and the factors governing the nucleation of seismogenic earthquakes, which could be integrated into the general MARGINS science plan. Thus, the general science plan acquired a number of first-order research initiatives, the philosophies of which required the same multi-disciplinary, coordinated and focused study of active systems advanced by the MARGINS science plan. These four initiatives were: Rupturing of the Continental Lithosphere (RCL) and the birth of an ocean; Subduction Factory (SubFac), SEIZE, the Seismogenic Zone Experiment, and Source-to-Sink (S2S).

This publication, a collection of the recently updated science plans of each of the MARGINS Initiatives, is the result of an immense amount of work by the community, champions within each initiative to organize workshops and finalize their respective science plans, the MARGINS Steering Committee, individuals who worked with their communities to create executive summary documents, and the MARGINS Office. Particular thanks go to Dr. Olaf Svenningsen, who developed the graphic design and layout for the entire book, redrafted innumerable figures, revamped sections of text, and spent an eternity looking for missing references. The fact that this book exists at all is in large part due to his determination and enthusiasm.

These science plans should be viewed as dynamic documents, reflecting increasing knowledge and an evolving scientific community. One fundamental objective of MARGINS has already been attained—the building of a community of scientists who are well-informed across a broad range of disciplines and sub-disciplines not related to their own. This was achieved by way of many interdisciplinary workshops, theoretical institutes, symposia, AGU town meetings, and professional meetings fostered by the MARGINS program. With the community now so engaged, there needs to be a commensurate awareness within NSF of this "community collaborative spirit" in addition to a marked increase in the MARGINS budget (with contributions from NSF-OCE, NSF-ODP and NSF-EAR) in order for the program to address the research objectives outlined in the science plans over the lifespan of the program.

"One fundamental objective of MARGINS has already been attained—the building of a community of scientists who are well-informed across a broad range of disciplines and sub-disciplines not related to their own"

Rupturing Continental Lithosphere (and the birth of an ocean) Initiative

We will begin this science plan introduction with a detailed account of the RCL science plan, as MARGINS had its origins in attempting to study, characterize, and understand the deformation of the continental lithosphere. The evolution of the MARGINS program since 1988 saw dramatic changes in content and focus, augmenting RCL with SEIZE, SubFac and S2S, while retaining its original strategy. Further, the intense discussions, interactions, and "pain" experienced by RCL in extracting a consensus from the community in terms of research objectives and focus sites is common to all the initiatives; what we learned from RCL occurred in each and every initiative in its early days of planning.

A fundamental and accepted aspect of the MARGINS program revolves around the axiom to focus on active and "complete" systems. MARGINS concentrates on active systems because it becomes tractable to characterize the boundary conditions and the initial physical and chemical states of materials in the system.

Furthermore, one or more of its characteristics may have changed during the active-passive transition, with paleo-conditions being potentially difficult to infer from the rock record. The "complete" system approach is deemed critical because of the need to study the margin as a large, complex, interactive dynamic system.

RCL goals and development

The RCL science plan was the outcome of an NSF-sponsored Theoretical and Experimental Workshop on "Rheology and deformation of the lithosphere at continental margins" in January, 2000. The purpose of the workshop was to review the status of the fundamental objectives defined in the initial science plan and to select focus sites for the investigation of faulting, strain partitioning, and magma emplacement at sites of active continental rifting, where there is a transition to initial seafloor spreading.

For the RCL initiative, the main goals have evolved into:

1) To understand the driving forces of rift initiation and continuation,
2) To determine the controls on the locus of rifting, and to understand the conditions of initial rifting in different environments,
3) To characterize the rift as a thermo-mechanical system (rheological flow laws, and the role of brittle failure, including low-angle normal faults),
4) To determine the scale of deformation of the lower crust during the rifting process,
5) To quantify the transfer of heat into and within the lithosphere during rifting,
6) To understand the distribution of the extensional (and transcurrent) strain with depth, in map view, and in time,
7) To understand the controls on rift architecture,
8) To determine the role of fluids and volatiles during rifting,
9) To understand the timing, kinematics, and rheology of the transition from continental extension to seafloor spreading,
10) To determine the composition and origin of transitional crust formed during the process of completely rifting a continent.

Given the MARGINS strategy to concentrate on both active and complete extensional systems, for the RCL initiative there are actually only a handful of potential candidate sites around the world, such as the Gulf of Aden/Gulf of Tadjura (Arabia-Somalia), the Gulf of California/Salton Sea (Mexico/USA), Red Sea/Gulf of Suez (Arabia-Nubia), and the western Woodlark Basin (Papua New Guinea). In order to assess each region, Focus Site Criteria were devised representing essential, desirable, and logistic characteristics required of the study regions. The sites were evaluated in terms of their scientific merits with some consideration given to political feasibility and the likelihood of partnership with scientists from other countries. Two of the sites (the Gulf of California and Northern and Central Red Sea) were selected by the community, one to represent rifting in old cratonic lithosphere (the Red Sea) and the other to represent rifting in young orogenic lithosphere (the Gulf of California). In addition, these two rifts have different degrees of obliquity: the Red Sea is a nearly orthogonal rift whereas the Gulf of California is highly oblique. In October 2000 and March 2001, NSF-sponsored workshops specifically focused on the more detailed science questions for each of the focus sites. Most importantly, these workshops were designed so that investigators who had not worked previously in the focus sites could familiarize themselves with the current status of research efforts in the region, thereby allowing then to explore what scientific opportunities exist and to learn what studies have already been undertaken.

Although it has been only two proposal cycles since RCL proposals have been funded within the MARGINS program, certain aspects of the proposed studies have already been accomplished, due in part to projects that were underway but funded outside the MARGINS program itself. The RCL science plan has been updated to reflect these studies and reviews the latest information on observational findings from the two focus sites, as well as the latest thinking on these issues coming from both laboratory and theoretical studies. Unfortunately, political and military instabilities in the Middle East and judicial issues stemming from active seismic-source experiments and the Marine Mammals Protection Act has slowed our ability to work in the RCL focus sites.

"A fundamental and accepted aspect of the MARGINS program revolves around the axiom to focus on active and 'complete' systems"

Subduction Factory (SubFac) Initiative

Subduction of oceanic plates causes earthquakes, tsunamis, and explosive volcanism, together with changes in the composition of the mantle, including its abundance of volatile and heat-producing elements. Subduction also gives rise to beneficial products, such as ore deposits, geothermal energy, and the ground we live on. Thus, subduction is one of the Earth's most important dynamic processes. It also is one of the least well understood because of the limited accessibility, the complexity, and the immense length-scales of subduction zones. The goal of the *Subduction Factory Initiative* is to focus research on two contrasting subduction zones to address fundamental questions about how this process works. The community-selected focus sites are the Izu-Bonin-Marianas and Nicaragua-Costa Rica subduction systems.

The "Subduction Factory" recycles raw materials from the subducting lithosphere to the surface and deep Earth. SubFac aims to study this recycling process by imaging subduction zones with a variety of techniques and quantifying fluxes of subducted materials through the mantle to the surface in the form of melts, aqueous fluids and gases. Embedded within this approach are essential links to the thermal and viscosity structure of the slab and mantle wedge, the nature of mantle flow through the wedge, and the timescales of magma generation and transport.

SubFac Initiative

Three fundamental science themes are addressed by this initiative:

Science themes

1) How do forcing functions such as convergence rate, age of the subducting plate, sediment dynamics, and upper plate thickness influence the production of magma and fluid from the Subduction Factory?
2) How do subducted volatiles (mostly H_2O and CO_2) impact biological, physical, and chemical processes from the trench to the volcanic arc and back-arc as well as the deep mantle?
3) What is the mass balance of chemical species and material across the Subduction Factory, and how does this balance affect continental growth and evolution?

Ongoing projects funded by NSF and contributing to SubFac combine mapping of the incoming plate and fore-arc slope with both active and passive seismic experiments to image structures and composition of the upper plate, mantle wedge, and subducting slab. Heat flow measurements and GPS deformation rate estimates are being combined with other geophysical data to constrain the physical operation of the subduction system. Riserless drilling continues to provide samples of the input material seaward of the trench and output material in the forearc (e.g., fluids, possibly accreted sediments and hydrated forearc mantle) and arc (fluids, gases, extrusive and intrusive rocks). With the recent launching of the Japanese riser drill ship, Chikyu, deeper holes into the incoming crust and upper plate will more thoroughly chart the inputs and outputs of the system. A record of volcanic evolution and fluxes on the upper plate will also be provided by on-land drilling into the arc. On-land and offshore boreholes will be exploited to sample fluid outputs from the system.

SubFac studies and focus sites

Field and analytical studies of the arc system focus on the mass fluxes of constituents through the Subduction Factory by measuring chemical compositions of lavas, melt inclusions, and gases. Laboratory studies provide element partitioning relationships, phase equilibria, and calibrations for rheological and seismological properties. A wide array of in situ observatories and multiple re-occupation campaigns, coupled with a strategy for rapidly responding to major events, round out the data collection strategy. These diverse field and lab measurements are being integrated with physico-chemical models for subduction, fluid flow, melting and melt flow. Phenomena predicted from geodynamic models are guiding the data acquisition efforts, and the data collected will provide constraints for future generations of models. In this way, modeling and observations will complement and motivate each other.

The Central American and Izu-Bonin-Mariana (IBM) subduction zones were chosen as focus sites for these studies. These sites provide ample volcanic and seismic activity, accessibility to input and output samples for geochemical analyses, along-strike variations in forcing functions, cross-arc and historical perspectives, and minimal upper plate contamination of magmas. Central America features variations in forcing functions along-strike from Nicaragua to Costa Rica, including the age and surface morphology of the subducting plate and the variation in the quantity of sediment transported to depth. These are matched by sympathetic chemical gradients in the volcanic output, which allows the mass-flux through the system to be thoroughly examined. Extensive carbonate subduction and extremely volatile element-rich eruptions enable investigation of the carbon and water cycles through subduction zones. High-fidelity tracer studies in Recent to Miocene igneous rocks will constrain a mass balance of chemical constituents through the arc with time. Many of the Subduction Factory objectives link naturally with those of the SEIZE science plan in Central America. The IBM margin is an excellent complement to Central America. The oldest and presumably coldest crust on the planet subducts beneath the IBM with relatively little, and carbonate-absent, sediment. Active back-arc volcanism allows output to be accessed across strike and through time, and provides a framework with which to test the effects of back-arc flow on subduction dynamics. Vigorous fluid venting from trench to rear-arc provides samples for studying volatile cycling across the entire margin.

SEIZE Initiative

The *Seismogenic Zone Experiment* (SEIZE) was developed to study the shallow subduction plate interface that is locked and accumulates elastic strain, periodically released in large or great earthquakes, often tsunamigenic. Considerable progress has been achieved on many of the underlying objectives of the Seismogenic Zone Experiment, which sets the foundations for future work. As of March 2003, 10 programs (consisting of multiple proposals) have been funded directly by MARGINS, of which approximately seven are mostly complete. The MARGINS program has stimulated considerable interest in the US science community as demonstrated by MARGINS-related science funded by Earth and Ocean Sciences core programs and internationally, principally with German, Japanese, Costa Rican, and Nicaraguan scientists engaging in complementary work. The focus sites, Nankai and Central America (Nicaragua-Costa Rica) complement each other, with shallow seismogenic zones, possibly reachable by riser drilling, in both areas. Central America is characterized by basement topography and sediment thickness that vary greatly along strike, with "patchy" seamount distribution, possibly related to patchy locking. Characteristic earthquakes tend to be smaller in magnitude (M~7-7.5) with a limited slip distribution, possibly controlled by bathymetry; slow tsunamigenic earthquakes have occurred off Nicaragua. Nankai is characterized by larger magnitude (M~8-8.5) earthquakes, with relatively uniform fault properties and only small lateral changes; large areas are fully locked most of the time.

A major accomplishment at this point has been the construction of a functioning community of scientists across major subdisciplines of Earth Sciences. This community, by way of several workshops, theoretical institutes, symposia and professional meetings, most fostered by the MARGINS program, now share a common understanding of the complexity of the earthquake cycle, share a common vocabulary, and have been developing a clearer and sharper focus on the most important issues as reflected in the revised SEIZE science plan. There is a much greater appreciation of the theoretical, experimental, and modeling contributions and of critical observations, including their limitations, necessary to test and foster our understanding of seismogenesis. The IODP drilling community, which overlaps substantially with MARGINS-SEIZE, are using these developments to hone deep drilling objectives for the Japanese riser ship, Chikyu, in Costa Rica and Nankai, with fault targeted drilling, sampling and monitoring possible as early as 2007.

SEIZE Initiative

State of the first initiative to "take off"

The SEIZE initiative was the first to get started, having its roots in a 1995 workshop in Japan, "Dynamics of Lithosphere Convergence," sponsored by the International Lithosphere Program, followed by an NSF-sponsored workshop in 1997 to flesh out the science plans and identify focus sites. The planning and precursor efforts of SEIZE thus began long before the first direct MARGINS funding in 1999. A great deal of seismic reflection data has been obtained, sufficient to image the entire seismogenic zone beneath Nicaragua, Costa Rica, and Southeastern Japan. Two 3-D reflection surveys have been done off Japan, and one 3-D in Central America. Much geodetic work has been carried out in both regions and we have significantly better understanding of locked vs. slipping zones. The Ocean Drilling Program installed a long-term sea floor observatory sampling deeply sourced fluids within the décollement zone off Costa Rica, to monitor fluid pressures, temperatures, flow rates and compositions and their changes through time. The importance of transient strain events, possibly related to fluid flow, has been recognized. Integration of heat flow data, thermal modeling and laboratory studies has led to a new set of questions about the controls on the updip limit of seismicity at convergent margins.

Recently, a revised science plan was commissioned as part of a SEIZE Theoretical and Experimental Institute in March

2003. The science plan derived from the 1997 meeting focused on the following questions:

A. What is the physical nature of asperities?
B. What are the temporal relationships among stress, strain and pore fluid composition throughout the earthquake cycle?
C. What controls the updip and downdip limits of the seismogenic zone of subduction thrusts?
D. What is the nature of tsunamigenic earthquake zones?
E. What is the role of large thrust earthquakes in mass flux?

Based on work done since, the science plan has been updated with these supplemental questions:

1) What controls the overall distribution of seismic energy release during a subduction zone earthquake (up, down, and sideways). Is there one P-T-X condition that defines the onset and down dip limit, or do they vary with the material properties and fault geometry in the subduction system?

2) What controls the sometimes heterogeneous distribution of locking patterns on the plate interface and subsequent variations of energy release ? Are such "asperities" linked by common physical processes within the fault region or governed by separate, unrelated phenomenon? Do they vary in time, and if so, over what time scale?

3) What controls the rate of propagation and slip rates of earthquakes and the distribution of fast, slow, tsunamigenic, and silent earthquakes in time and space?

4) What is the nature of temporal changes in strain, fluid pressure, and stress during the seismic cycle? Do these change gradually during the seismic cycle or are there transient interseismic phenomena that lead to strain and energy release at various times during the seismic cycle?

5) What are the prediction errors associated with typical mechanical models?

Earthquake questions for MARGINS

Source-to-Sink (S2S) Initiative

S2S Initiative

A major goal of the Earth Science community is to provide quantitative explanations and predictions of the effects of perturbations on surface environments and on the geologic record preserved in sedimentary strata of continental margins. In past decades, margins have been investigated piecemeal, by researchers who have tended to focus on a particular segment (from a disciplinary perspective), and eschewed the broader perspective of the margin as an interconnected whole. Recognizing this shortcoming, NSF was instrumental in initiating the MARGINS *Source-to-Sink* Program which, for the first time, will attempt to understand the functioning of entire margin systems through dedicated observational and community modeling studies.

The Source-to-Sink Initiative seeks to make significant advances in our predictive capability of sediment and solute fluxes across the Earth's continental margins. Improved predictions of sediment and solute mass from source to sink are needed now because this transfer plays a key role in the cycling of elements such as carbon, in ecosystem change caused by climate change and sea-level rise, and in resource management of soils, wetlands, groundwater, and hydrocarbons. Yet, we are presently unable to anticipate how perturbations in one part of the source to sink system will affect another.

It is for this reason that the S2S science plan calls for an unprecedented coupling of physical and numerical modeling and integrated field studies. A suite of inter-connectable numerical and physical-process models with shifting boundaries is to be constructed to test hypotheses concerning process connections and to predict the behavior of these source to sink systems on time scales ranging from individual events to millions of years. Rates and mechanisms of sediment production, transport, and accumulation will be monitored using high-resolution digital elevation models, new dating and tracer techniques using cosmogenic isotopes and optically stimulated luminescence, and field acoustic and optical velocimeters for measuring sediment velocity and concentration. High-resolution records of sedimentary deposits are to be collected through swath mapping and CHIRP, combined with sediment coring involving logging tools such as GRAPE and FMS. Ultimately, IODP drilling may provide the best test of S2S concepts and working hypotheses as the work continues in the defined focus sites; the Fly River/Gulf of Papua system of Papua-New Guinea and the Waipaoa River system of the North Island, New Zealand.

The key scientific issues that, if answered, would produce a quantum leap in our quantitative understanding of geomorphological, hydrological, and geological Earth Systems were identified at two community-wide MARGINS Source-to-Sink Workshops (Lake Quinault and Lake Tahoe) and an AGU MARGINS town meeting. These meetings helped to define the concept of a Community Sediment Modeling Environment. The scientific issues are encapsulated in the following three questions:

1) How do tectonics, climate, sea level fluctuations, and other forcing parameters regulate the production, transfer, and storage of sediments and solutes from their sources to their sinks?
2) What processes initiate erosion and sediment transfer, and how are these processes linked through feedbacks?
3) How do variations in sediment processes and fluxes and longer-term variations such as tectonics and sea level build the stratigraphic record to create a history of global change?

S2S questions

The Source-to-Sink Initiative focuses on two active convergent continental margins that produce large amounts of sediment deposited in adjacent, closed basins, as their focus sites. Following community-wide discussions, the Fly River and adjacent Gulf of Papua (Papua-New Guinea) and the Waipaoa River System on the east coast of New Zealand's North Island were chosen for focused research. The Fly River and Gulf of Papua constitute one of the few modern examples of a developing foreland basin, and the Waipaoa drainage basin reflects growth of a terrain by volcanism and vertical uplift. The Fly/Gulf System experiences a tropical environment, whereas the Waipaoa is sub-tropical/ temperate. Because of differences in oceanographic environments, the Gulf of Papua possesses both siliciclastic and carbonate sedimentary environments, whereas the Waipaoa margin contains only siliciclastic sediments. The Fly drainage basin (75,000 km^2) experiences relatively constant discharge, the main perturbations being linked to ENSO-related droughts, and it is practically unaffected by human activity, although recent mining on the Ok Tedi has provided a sediment spike that can be monitored farther downstream. In contrast, the Waipaoa system (2000 km^2) is strongly affected by seasonal variations in discharge and (particularly) by tropical cyclones; and for the past 100 years it has been affected by the impact of European

Field studies and physical and numerical modeling land-use and (to a lesser extent) by dam construction.

At the Fly/GOP focus site, historic measurements along the river are relatively few. Consequently, the community decided that we need first to understand how changes in water discharge and sediment loading impact floodplain and shelf-clinoform sedimentary sinks, and how escaping sediments impact carbonate production by coral/algal communities on the shelf and in deeper water. A dedicated Waipaoa workshop held in Gisborne, Palmerston North and Wellington, New Zealand, helped to hone the research objectives for the Waipaoa focus site. For this focus site, shallow and deep coring of lacustrine and shelf environments along with chronostratigraphic analyses are needed to define the inputs and sedimentary architecture. Geophysical characterization of the shelf needs to be carried out, principally by swath bathymetry and high-resolution seismic profiling, with limited ground-truthing. Monitoring and modeling studies are required to understand the mechanisms of sediment dispersal from Poverty Bay to the open shelf, and the resulting depositional signatures.

S2S Focus Sites

A new approach to geoscience research

Concluding remarks

In conclusion, the **development of MARGINS programs** in the US and abroad promotes a changing and challenging approach to research in the Earth Sciences. **The MARGINS objective** was, and remains, to develop a self-consistent understanding of the processes that are fundamental to margin formation and evolution. **The MARGINS approach** involves concentration on several study areas targeted for intense, multidisciplinary programs of research in which an ongoing dialogue among field experiment, numerical simulation, and laboratory analysis researchers is fundamental and symbiotic. The various **science plans of the MARGINS Program** all define methodologies for investigating those processes that fundamentally govern the evolution of margins, which comprise lithospheric deformation, magmatism and mass fluxes, sedimentation, and fluid flow. The **goal of the MARGINS Program** is to provide a focus for the coordinated, interdisciplinary investigation of these processes that are the foundation of the **MARGINS Initiatives**.

The need to integrate multiple lines of evidence to better understand complex dynamical systems requires both interdisciplinary approaches and a concentration of resources in areas likely to yield outstanding results. Within the MARGINS framework, implementation workshops, AGU and GSA special sessions and town meetings, and Theoretical and Experimental Institutes provide opportunity for explicitly synthesizing field, observational and analytical studies with theoretical and experimental approaches to frame next-generation studies. This overview shows the commonality of approaches in the four MARGINS initiatives and the frequent transcendence of the processes under study, often irrespective of tectonic setting. A corollary is that progress in one initiative will frequently benefit another.

Rupturing Continental Lithosphere (RCL)

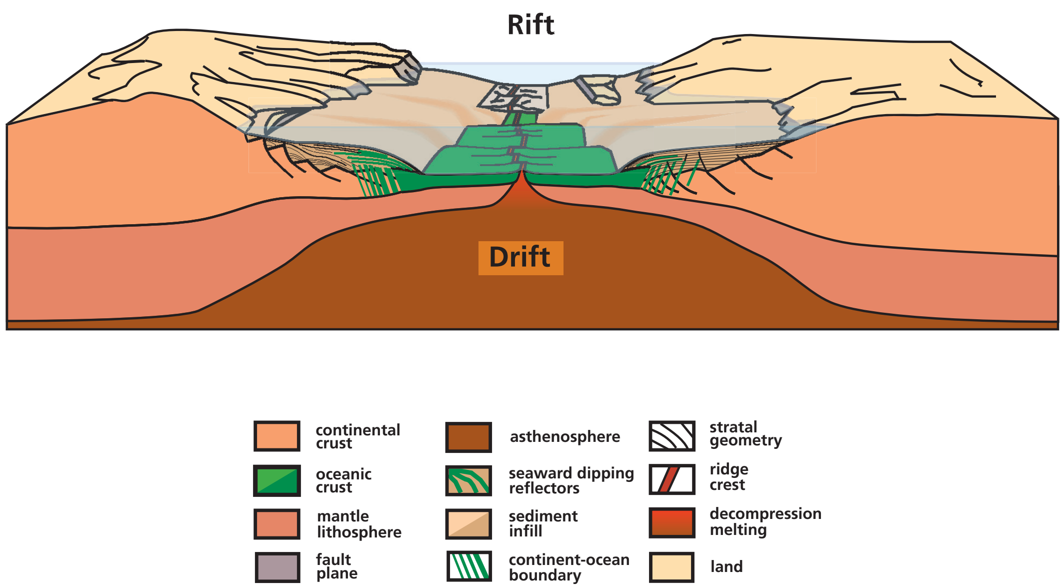


Figure 1. Schematic overview of the major elements of an active continental extensional system where there is a lateral transition to initial seafloor spreading that will provide a spatial proxy for temporal variability.

1.Executive Summary

Continental margins mark the Earth's principal locus of past and present lithospheric deformation, as represented by both their structural architecture and the preserved basin infill. Most importantly, the preserved basin stratigraphy is a proxy for the history of vertical motion of the lithosphere surface and thus represents a "tape recording" of the deformation of the lithosphere but of "variable fidelity". Consequently, to understand the nature and origin of continental margins requires an understanding of the physical processes associated with lithosphere-scale deformation. Limits to understanding deformational phenomena and margin evolution have arisen in two ways. First, since the mid-1960s, when the plate tectonic paradigm was advanced, we have witnessed an enormous growth in our descriptive knowledge of the many expressions of deformational processes, but our understanding of the responsible mechanisms has not grown apace. In many instances we have no theory at all, or an incomplete physical theory to account for observed phenomena. The converse situation has also arisen—considerable advances have been made in describing deformational processes in rock physics laboratories and through computer simulations of prescribed model structures, but the specific predictions they make about the Earth are currently unsupported, in general, by the observational data base. In both cases major paradoxes have arisen—the Earth appears to behave in ways we believe to be theoretically impossible.

The "Rupturing Continental Lithosphere (RCL)" scientific community has accepted and strongly endorsed, through a series of workshops and Theoretical Institutes, the MARGINS paradigm of concentrating resources in selected critical or *focus* regions in order to define a process-oriented approach to study active extensional systems. Although much progress has been made over the last few years in understanding the kinematics of continental lithosphere deformation, it is agreed by the community that the mechanics by which the continental lithosphere deforms is not well understood, nor is the manner in which strain is partitioned and magma distributed. Five overarching research themes have been recognized:

RCL research themes

- How does the strength of the lithosphere evolve during rupturing?
- How is strain partitioned during lithospheric rupturing?
- What is the role of magmatism (and volatiles) during extension and in the transition to sea-floor spreading and what is the relationship between magma petrogenesis and the deformation magnitude and history?
- What is the stratigraphic response to lithospheric rupturing?
- How are fluid fluxes modified or controlled by lithospheric rupturing?

The respective focus sites are the Gulf of California/Salton Trough, a region of orogenic crustal rifting, and the complementary central and northern Red Sea/Gulf of Suez, a rift system characterized by cratonic continental crustal extension. Defining criteria for selecting the focus sites require that:

- active continental rifting culminates laterally in seafloor spreading,
- conjugate margins are identifiable,
- pre-rift sediments and or basement and syn-rift sediments and associated fault geometries can be adequately imaged and sampled,
- the crustal structure of the entire rift system and its transition to seafloor spreading can be imaged at kilometer scales,
- highly thinned continental, transitional and young oceanic crust is accessible to sampling,
- the plate-tectonic kinematic framework is/can be well-resolved.

> "Although much progress has been made, […] the mechanics by which the continental lithosphere deforms is not well understood, nor is the manner in which strain is partitioned and magma distributed"

Allied field studies for "Rupturing Continental Lithosphere" will concentrate on outcrops that can be used to map and/or define the deformation, metamorphism and magmatism of the lower continental crust and upper mantle exhumed within rift settings. Geological, geophysical and petrological characterization of the focus sites will be accomplished by a series of transects, one group focussing on the early stages of continental rifting and the other group concentrating on the transition from late-stage continental extension to the earliest stages of oceanic crust generation and seafloor spreading.

The "Rupturing Continental Lithosphere" initiative will proceed by focused investigations combining seismic reflection and refraction imaging across the entire zone of extension and initial seafloor generation - the geophysical characterization phase. This regional phase will comprise active and passive seismic experiments to image the deformed upper and lower crust and underlying mantle structure of the rift and adjacent regions. Subsequent phases will consist of detailed geological field studies of the deformed zone, primarily to map the surface expression of deformation, to map the distribution, style and timing of deformation, and to ascertain the changing role of lowangle and high-angle fault systems. Additional studies will consist of regional and detailed geophysical, geological, geochemical, petrological and geodetic studies. Gravity and geoid data, heat flow measurements and GPS-determined deformation rate estimates will provide crucial constraints on sub-surface crustal and mantle flow and plastic deformation. ODP and IODP drilling in both shallow and deep water environments will allow the bounding surfaces of stratigraphic packages to be sampled in order to define unconformity and correlative conformity age, sedimentary facies, and depositional environment (including information on paleo-water depth), and bounding fault gouge composition and geotechnical information. Drilling will also allow direct sampling of rift-related volcanics and basement composition to be determined. Laboratory studies will be crucial in providing calibrations and a framework for the rheological properties (i.e., constitutive laws) and scaling relationships of deforming crustal and mantle rocks as functions of composition, temperature, and strain rate, in addition to controls on rock strength and permissible ranges in stress difference as a function of depth. These various disparate data sets will be integrated through numerical simulations of the four-dimensional style, distribution, and depth partitioning of extension within continental lithosphere to determine the spatial and temporal rheology of the lithosphere, why rifts form where they do, and the forces required to sever continental lithosphere.

"To understand the complex interplay of processes that govern continental margin evolution globally"

The RCL initiative is a decadal-scale program, initiated by geophysical characterizations of the focus sites using regional geological and geophysical field experiments, and converted to a research program through MARGINS workshops, AGU and GSA special sessions, town meetings and theoretical institutes. Implementation of the RCL Science Plan, via the NSF MARGINS program, primarily facilitates competitive proposal-driven research in those focus areas considered by the community to have the best promise of solving the first-order problems related to the extensional deformation of the lithosphere. A website listing of on-going programs and successful proposals will form a basis for other synergistic projects in the RCL focus areas. The MARGINS website will also serve as data custodian for project data well before publication, in addition to providing a bibliography of work completed by US and foreign collaborators. Results will be communicated through international and national meetings and workshops.

2. The MARGINS Philosophy

The MARGINS research program can be encapsulated by the following mission statement: "To understand the complex interplay of processes that govern continental margin evolution globally". The program was initiated by the scientific community and the National Science Foundation and has been designed to elevate our present largely descriptive and qualitative knowledge of continental margins to a level where theory, modeling and simulation, together with field observation and experiment, can yield a clearer and quantitative understanding of the processes that control margin genesis and evolution.

> "This process-oriented approach to understanding the entire system of margin evolution requires broadly based interdisciplinary studies and a new class of major experiments."

Process-oriented Approach

Although continental margins have been traditionally assigned to three distinct tectonic settings, i.e., convergent, divergent and translational, the approach used by the MARGINS program recognizes that a range of fundamental physical and chemical processes that form and deform the surface of the Earth operate at all margins. Tectonic setting may govern the specific expression of a particular process that may vary in different environments. However, a relatively small number of processes, i.e., lithospheric deformation, magmatism, other mass/energy fluxes, sedimentation, and fluid flow, are fundamental to the evolution of margins. Study of these basic processes, wherever they are best expressed, provides a more logical line of inquiry for understanding the complex nature of continental margins. This process-oriented approach to understanding the entire system of margin evolution requires broadly based interdisciplinary studies and a new class of major experiments. The Rupturing Continental Lithosphere MARGINS science plan, developed from a series of well attended workshops over the past decade and finishing with the Puerto Vallarta and Sharm el-Sheikh workshops, advocates concentrating on several study areas (Focus Sites) targeted for intensive, multidisciplinary programs of research in which interaction between field experimentalists, numerical modelers and laboratory analysts would occur. Geological, geophysical and petrological characterization of the focus sites should be accomplished by a series of transects, one group focussing on the early stages of continental rifting and another concentrating on the transition from late-stage continental extension to the earliest stages of oceanic crust generation and seafloor spreading.

MARGINS plans to foster the involvement of a broad cross-section of research in focused, multidisciplinary experiments, to achieve the objectives that could not be accomplished otherwise.

3. What are the main processes to be studied in the "Rupturing Continental Lithosphere" initiative and how will they be studied?

Although much progress has been made over the last few years in understanding the kinematics of continental lithosphere deformation, it is agreed that the physics by which the continental lithosphere deforms is not well understood, nor is the manner in which strain is partitioned (either spatially or temporally) or the timing, composition, spatial distribution and melting depth of rift-related magmas. These processes control the fundamental architecture of margins and hence the location and magnitude of resources and geologic hazards. They are best studied by a suite of nested and multidisciplinary investigations at various space and time scales utilizing field studies, laboratory experiments and numerical simulations.

Five overarching themes, also part of the original MARGINS Draft Science Plan and re-endorsed by the RCL community, comprise:

- How does the strength of the lithosphere evolve during rupturing?
- How is strain partitioned during lithospheric rupturing?
- What is the role of magmatism (and volatiles) during extension and in the transition to sea-floor spreading and what is the relationship between magma petrogenesis and the deformation magnitude and history?
- What is the stratigraphic response to lithospheric rupturing?
- How are fluid fluxes modified or controlled by lithospheric rupturing?

RCL overarching themes

A particularly powerful way to address and solve these problems is to focus a comprehensive investigation on faulting, strain partitioning and magma emplacement at sites of active continental rifting where there is a lateral transition to initial seafloor spreading that will provide a spatial proxy for temporal variability. Structural targets within extensional systems include: 1) Determine the local and regional states of stress, the distribution and rate of strain, the pressures and temperatures, and the physical and chemical properties of rocks and fluids associated with a well-imaged and seismically active low-angle normal detachments (the extreme case of the weak fault paradox). Measurements of these in situ parameters made by drilling, instrumenting and long-term monitoring will be used to determine how such faults move at resolved shear stresses far smaller than those expected based on laboratory observations and Coulomb rheologies. 2) Determine the spatial and temporal distribution of strain by (i) mapping the geometry and offset of faults, (ii) inverting and modeling the stratigraphic and structural record to resolve the history of strain variation and its control on topography/erosion/deposition, (iii) using seismic, gravity/geoid and geothermal methods to obtain an integrated sum of the deformation and a measure of the ductile thinning of the lower crust, and (iv) evaluating the heterogeneity of the continental lithosphere prior to rifting. 3) Determine the pattern of mantle flow, the extent of melt generation, and the style of melt migration and emplacement during continental rifting and the early stages of seafloor spreading by imaging with seismic and electromagnetic methods an active rift-spreading transition, by measuring the heat flow distribution, and by analyzing the chemistry and petrology of magmas emplaced in these regions.

4. What do we need to know about "Rupturing Continental Lithosphere"?

In more detail, the fundamental questions that the MARGINS "Rupturing Continental Lithosphere" program is attempting to answer include:

- What are the driving forces of rift initiation and continuation?

  How do these forces evolve during rifting? What are the positive and negative feedbacks during rifting that cause some rifts to succeed and others to fail? What controls the locus and conditions of initial rifting (intra-continental versus intraorogen/ intra-arc)?

- How do rifts behave as thermo-mechanical systems?

  What mechanisms allow continental lithosphere to extend and rupture (e.g., what are the specific rheological flow laws and what is the role of low-angle normal faults)? What are the interactions between upper mantle thermo-mechanical processes and rifting of the continental lithosphere? What is the scale of deformation of the lower crust? How is heat transferred into and within the lithosphere during rifting? How is extensional strain partitioned, both in depth and in map view (including strain localization, the possible role of low-angle normal faults, the role of strike-slip faults and vertical-axis rotation in oblique extension)? What controls the amount, location and episodicity of strain and magmatism?

- How does the rift architecture evolve? What are the processes that control the locus of initial rifting? How do fluids (magma, volatiles) affect the lithosphere during rifting and in the transition to sea-floor spreading? What controls basin architecture/geometry, including segmentation, asymmetry, and its evolution during rifting? How do erosion and sedimentation affect tectonism and vice versa? Can correlating "strain markers" be unequivocally identified on either side of the rift system, thereby providing an absolute constraint on the amount, transport direction, and location of total strain across the rift system?

- What processes are important in the transition from rifting to initial seafloor spreading? How are these processes reflected in the structures/ geology of the continent-ocean transition? What controls the width of rifting and its ultimate focussing to seafloor spreading? What controls the locus of the continent-ocean boundary, the character and origin of transitional lithosphere (crust and/or mantle), and the manner in which extension is transferred from continental lithosphere to the mid-ocean ridge?

Rupture mechanisms

Locus of rifting

Rift-to-drift transition

5. Scientific strategies required in studying "Rupturing Continental Lithosphere"

5.1. Mapping the rheological zonation of the lithosphere, the role of décollements (detachments) and accommodation zones, and the mechanical behavior of deforming crust and mantle

The scientific objectives outlined above build on a large body of continuing research that has been conducted with core funding from NSF and other agencies. For example, geophysical data from many conjugate margins document the existence of large regional subsidence with only minor accompanying brittle deformation and erosional truncation. To explain the amplitude of the regional subsidence with little or no attendant brittle deformation requires significant lower crustal and mantle extension across these margins and may possibly involve mantle dynamic effects. A suitable model requires that a diffuse zone separates the brittle and ductile deformation in the crust (i.e., an intracrustal décollement), which shoals in the region of maximum heat input. Therefore, depending on the location of athenospheric upwelling

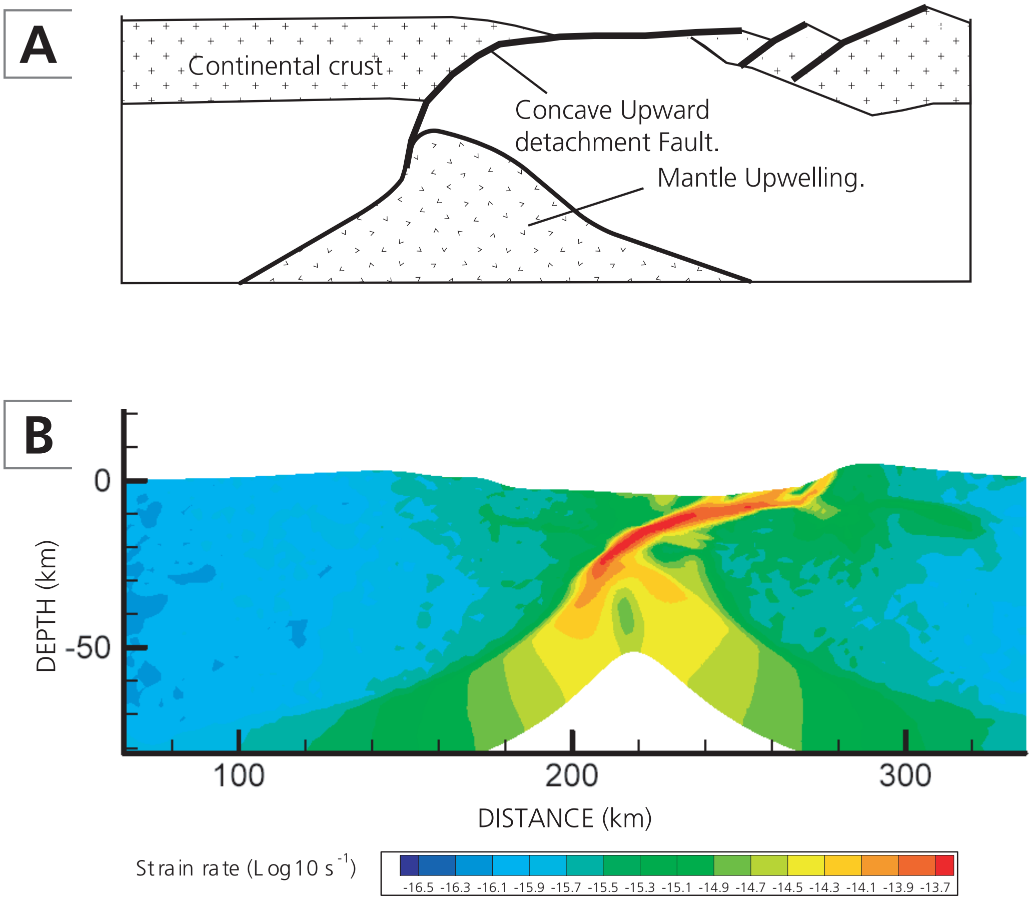


Figure 2. A. Conceptual lithospheric scale model of the transition between continental rifting and ocean floor spreading (after Whitmarsh et a., 2001). B. Numerical model of strain rate distribution, showing the exhumation of the upper mantle by a rolling hinge fault with a concave upward shape. In this model, the state of strain and stress is coupled dynamically to the thermal field. The "cold parts" of the numerical model are brittle (elastic-plastic Mohr-Coulomb) and the "warm parts" are ductile (Maxwell visco-elastic with creep rheology). Illustration courtesy of Luc Lavier, UTIG.

(e.g., the future ocean/continent boundary), the detachment will dip towards both margins, thereby solving a long-lived problem of passive margins, dubbed the "upper plate paradox", in which geological and geophysical studies suggested that rift geometries and structure were inherently asymmetric but whose subsidence patterns both tended to be symmetric and identified them as upper plate margins. The balancing brittle deformation is focused in a narrow region adjacent to the continent/ocean boundary and soles into the detachment. The deformed continental crust in this region is highly intruded and overprinted by volcanism associated with rift-induced decompression melting. The depth of the detachment migrates throughout the history of the rifting in response to the input of heat. The lower crustal extension appears to be most dominant during the late stages of the rifting phase just prior to continental breakup because the upwelling of asthenospheric heat causes the lower crust to deform plastically. This is itself paradoxical as modeling studies using yield-stress envelopes suggest that the late stages of rifting should be characterized

Rheological zonation of the lithosphere

by brittle deformation irrespective of the amount of advected heat.

Requiring a major change in the behavior of extending continental crust as breakup in approached is a tantalizing hypothesis. It is nevertheless unclear if this is a common feature of rift systems that have experienced large degrees of extension. For example, while this same non-brittle, supposedly plastic deformation-induced subsidence is a feature of the western Woodlark basin, the measured present-day heat flow across the extending region completely fails to support the idea of enhanced lower crustal temperatures required to modify the mechanical properties of the extending crust. The late stages of Woodlark basin extension is indeed characterized by brittle deformation, as evidenced by the late installation of the Moresby low-angle fault system.

Rheology of the lithosphere in rifts

Addressing this rheology problem requires complete three-dimensional seismic, tomographic and geologic mapping across, along and through the zone of actively extending continental lithosphere. Achieving MARGINS research objectives such as the example above will require new experimental approaches that include developing multidisciplinary case studies, focusing on active systems, studying whole systems, establishing scaling relations and developing comparative global studies. The system volume may be on the order of 100's by 100's km (width and length) by 100 km (depth). Within this volume, sedimentary basins will have a characteristic rift structure and architecture coupled with a stratigraphic record of the deformation history of the continental lithosphere. Normal and low-angle faults help to define the upper crustal, brittle deformation associated with the collapse of the hanging wall blocks and ultimately the thinning of the continental crust. The footwalls of these faults, where exhumed, will provide dating, geothermometry, geobarometry, structural fabric, and hydrologic histories, all of which bear upon the nature of the deformation mechanisms at depth as modified by the exhumation process. The region would include along-strike variations in the magnitude of fault slip, as well as non-slipped regions, so that stress and strength parameters can be studied as a function of fault development and total slip.

Low-angle normal faults

Low-angle normal faults continue to be a source of controversy in that a number of studies of large fault structures of extensional systems indicate fault movement at resolved shear stresses smaller than those expected to cause failure. Further, it is not clear at what time during the rifting process low-angle faults play a crucial role in the crustal thinning process. Observations thus far are conflicting. Whereas low-angle faulting occurs in the late stages of extension in the western Woodlark basin, deformation in the Gulf of California/Salton Trough region has low-angle faults active both early and late in the history. Although in some locations, low-angle faults are thought to be active now, in other places the extension appears to have initiated along low-angle faults that have since been abandoned and dissected by high-angle normal faults. Although fault zone lithologic composition may play a pivotal role in facilitating slip on low-angle fault systems, the time-temperature-pressure relationships that are conducive to low-angle fault movement need to be incorporated into a viable theory to account for this mode of failure. Help with this apparent paradox will require studies of major active faults that characterize their in-situ properties and determine their evolution in space and time, together with studies of the exhumed roots of major fault systems, experimental studies of rock mechanical properties, plus modeling and theoretical studies of deforming systems. Normal slip on low-angle faults represents the extreme case of the low stress paradox and would therefore be the focus of an ideal case study. Such a study would first obtain a 3-D image of the active low-angle fault and the encompassing geological system. This would include:

- geologic and topographic/bathymetric mapping, as well as visual/radar/sonar imaging of the surface,
- heat flow, gravity and magnetic measurements,
- geodetic measurements of strain, including tilt,
- geophysical images (seismic reflection-refraction; earthquake seismicity, tomography, and shear-wave splitting; electrical resistivity) of the subsurface.

Following the initial characterization of the study volume, drilling to and through the active fault zone will be required to make in-situ measurements to determine the state of stress, fluid pressure and composition, permeability, deformation and P-T history. These measurements are required both within and away from the fault zone to understand the factors that control fault zone localization and the development of low stress, and to understand how the active fault zone compares with exhumed sections (both locally and globally). The origin, type and flux of fluids are critical parameters to be determined. Direct sampling of the fault zone at depth will provide materials for lab-based studies of physical properties and failure modes. Boreholes will also allow long term monitoring of fluid geochemistry, seismicity and strain.

In addition to this field-based case study, laboratory studies would focus on the details of the behavior of fault zone rock types at confining pressures, strain rates, temperatures and fluid pressures that are appropriate for both shallow and deep segments of major active faults.

Understanding the kinetics of mineral precipitation out of the fluid phase may be crucial in evaluating the role of rapid void production in maintaining high permeability near active faults. An important component of the laboratory studies would be determination of the physical processes responsible for the observed laboratory behavior to aid in assessing whether the processes operate on natural faults. Detailed three-dimensional mechanical models would be constructed of any areas chosen for intensive field studies. These should include constitutive relations based on laboratory data and the distribution of rock types, and physical conditions inferred from field studies. These models will be useful in guiding experimental and field work as well as in interpreting and integrating results from these other approaches. In addition, modeling studies will play an important role in planning experiments that can best differentiate between competing hypotheses about the processes active in fault zones.

Integrated study of fault zones

Strain partitioning through space and time

5.2. Determining how strain is partitioned as a function of space (across and through the lithosphere) and with time

Understanding the partitioning of strain in the lithosphere requires multidisciplinary experiments with the objective of establishing the deformational history of a margin over the full volume of the deforming structures. Such experiments must bring to bear a diversity of geological and geophysical measurements in a single region, at scales appropriate to the active processes and at denser spatial sampling than currently available. The experiments must extend across-strike from undeformed crust inboard of the margin to uninvolved oceanic crust outboard, along-strike over distances sufficient to characterize more than one segment of the margin, and vertically to the base of the lithosphere.

The overall goal of these experiments will be to determine the spatial and temporal distribution of strain in an active rift and young passive margin with the ultimate goal to identify the parameters that control strain distribution. This goal implies specific experimental targets at all levels within the lithosphere requiring:

Targets and requirements to estimate strain partioning

- the mapping of definitive deformation structures in three dimensions;
- locating boundaries between regions of contrasting rheological and structural behavior, such as décollements and transfer zones;
- measuring the stress field that drives deformation;
- defining the mass balance of the deforming system, including magmatism, delamination, sedimentation, and erosion;
- determining how strain is partitioned by deformation mechanism as well as in space; and
- quantifying the roles of the parameters that control deformational processes, including thermal state, strain rate, state of stress, lithology, and lithospheric structure.

Clearly it will be difficult to directly map and observe the mode, amplitude and depth-partitioning of extension in actively deforming extensional systems, a task necessarily relegated to allied field studies. However, a variety of experimental and field approaches will be necessary to overcome these observational difficulties in order to achieve the above goals, and will include:

- Onshore geologic studies, including surface mapping, petrological, geochronological, and paleo-elevation studies, to provide relative and absolute dating, structural and uplift/subsidence history, Holocene fault motions, and the fundamental lithological framework.
- Acquiring high-resolution DEMs via SPOT (or equivalent) images and transformation software for structural mapping; draping of DEMs with LANDSAT, ASTER and other remote sensing bands to measure absolute dips, plunges, etc.
- Active-source seismic methods (multichannel and wide-angle) to define basic lithospheric geometries and Moho depth, constrain magmatic additions to the system, and image faults, offset geological markers, and (perhaps) strain fabrics within plastically deforming layers.
- Passive seismic arrays to provide insight into local seismicity, the ambient stress field and rheology, as well as lithospheric thickness, mantle velocity structure, and anisotropy.
- Surface geodetic studies, where possible, to provide boundary conditions on deformation.
- Downhole stress measurements to provide information on the stress field.
- Potential field data, including gravity, magnetic and electrical measurements, to constrain lithospheric structure and lithological interpretations.
- Heat flow and magnetotelluric surveys,
- Onshore and offshore drilling may be required, to provide detailed sampling to define sediment and basement type, volcanic rock composition, the age of the surfaces bounding stratigaphic packages, paleo-waterdepth measurements, sediment and basement porosity and permeability, and stress measurements.

Stratigraphic proxies provide first-order information on the amplitude, timing and depth-partitioning of extension, but say nothing about mechanism. For example, exten-

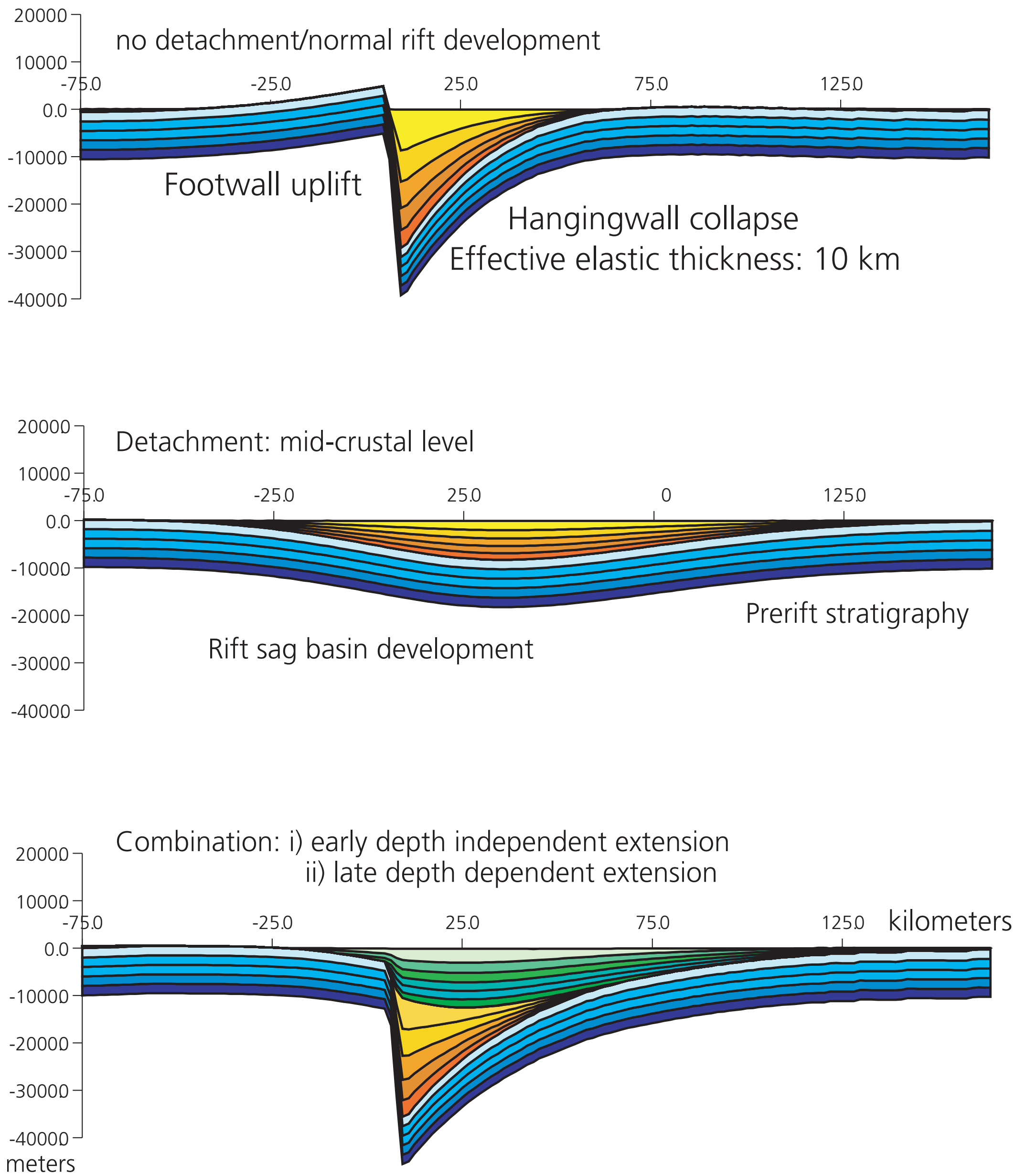


Figure 3. Modeled stratigraphic and structural response to lithospheric extension. A) Sag basin development characterized by mid-crustal detachments that facilitate lower crustal and lithospheric mantle in the absence of upper crustal extension. B) Normal rift basin development when lithosperic extension involves both the crust and lithospheric mantle. C) Complicating effects when earlier brittle deformation is overprinted by later plastic rifting of the lower crust and lithospheric mantle. This configuration poses a problem because the syn-rift sag phase is easily misinterpreted as simply the post-rift sedimentation associated with the first phase of rifting (modified from Driscoll & Karner, 1998; Karner & Driscoll, 1999). While thinning of the lithospheric mantle generates transient uplift, crustal extension creates permanent accommodation.

sional strain partitioning at mid-crustal levels compared to depth dependent extension leads to completely different syn-rift stratigraphic geometries (Figure 3); regional sag basin development characterized by a lack of brittle deformation in contrast to the more usual configuration of a basin-bounding normal fault, hangingwall collapse and rollover, and footwall uplift, respectively. Recognizing depth-dependent extension or a strain partitioning component can be complicated during polyphase extension, when earlier brittle deformation of the crust is overprinted by a later "plastic" phase of rifting. Most importantly, lower crust and mantle extensional thinning and depth-dependent lithospheric extension are both equivalent representations of the rifting process except that one involves plastic deformation of the lower crust and the other brittle deformation of the upper crust/middle crust (and possibly plastic deformation of the lower crust). The standard definition of rifting, that is, the active period of normal faulting, needs to be broadened to include possible plastic deformation of the lower crust. Rifting is thus more appropriately viewed as the process during which the crust is being thinned, albeit by upper (brittle) and/or lower crustal (plastic) thinning. Why brittle deformation of the crust should be abandoned and replaced by plastic deformation during the rifting process is not clear, and understanding and predicting this mechanical behavior and its rheological implications will be a major goal of the RCL initiative.

Rifting dynamics

Focus Site criteria

In addition to the various field approaches outlined above, laboratory and theoretical work will be crucial to designing the field experiments and understanding the data collected in them. Laboratory studies of the mechanical properties of rocks under a wide range of conditions must be undertaken to constrain such poorly understood variables as the effects of fluids, diagenesis, strain history and partial melt. Theoretical analysis will include numerical simulation of geodynamic processes and three-dimensional palinspastic reconstructions of margin geometries. Ideally, these will be jointly applied to a given extensional system. Recent advances in computational capabilities should allow numerical simulations at a small enough scale to attempt to reproduce the detailed geological evolution of extensional systems, and to thus provide constraints on the range of dynamic parameters and rheological behavior that are consistent with the observed geological history.

6. Where will we study "Rupturing Continental Lithosphere"?

The research objectives outlined earlier can best be addressed at margins where the following criteria can be met:

- Sites of active continental rifting that culminate laterally in seafloor spreading.
- Identifiable conjugate margin segments.
- Syn-rift stratal and associated fault geometry can be imaged, and the sediments sampled.
- Pre-rift surface/strata can be imaged at 100-m scales and sampled.
- Entire crustal structure can be imaged at kilometer scales.
- Pre-rift continental basement is accessible to sampling.
- Transitional crust is accessible to sampling.
- Oceanic basement is accessible to sampling.
- Plate-tectonic kinematic framework can be well-resolved.
- Access to geological and geophysical data (reflection and refraction seismics, potential field, drilling and logging data, and field observations).
- Accessibility (logistically, politically and culturally).

Using these criteria, the RCL community selected the Gulf of California and the central/northern Red Sea region as focus sites for detailed and integrated research on rifting processes. Some discussion should be made concerning why the Afar and Gulf of Aden are not part of the RCL focus sites. During the Snowbird meeting (January, 2000) in which the community deliberated on the RCL focus sites, the Red Sea and the Afar/Gulf of Aden were kept separate because of the nature of the science considered important in these two areas. The MARGINS program seeks to concentrate resources on several study areas targeted for intensive, multidisciplinary programs of research, implying that the physical size of the focus site needs to be amenable to research efforts within a reasonable timeframe. With the unanimous choice of orogenic rifting in the Gulf of California, the cratonic rifting candidates become the central/northern Red Sea and the Afar/Gulf of Aden. Workshop participants were asked to further vote between the two cratonic focus sites again using the following criteria: Which sites will produce science that will have the greatest impact? Which sites are ready now to start work (as opposed to first enhancing an aging or poorly developed geological and/or geophysical data base and framework)? Which sites are logistically viable (i.e. if the best science sites are located in war ravaged regions, is there any point in investing MARGINS funds in such regions)? The Afar/Gulf of Aden candidate was rejected based primarily on perceived logistical problems of working onshore in Somalia and Aden, the political instability of Aden, and the then-war between Eritrea and Ethiopia.

The MARGINS community is very aware of the political and potentially negative implications of a large US program suddenly appearing in a foreign country in order to conduct so-called collaborative research. For this, our foreign colleagues must be involved at all levels of the science planning and implementation stages of the MARGINS work. Workshops in Mexico and Egypt have already informed and involved colleagues from these countries concerning the overall goals of the MARGINS program, the types of problems to be addressed by the Rupturing of Continental Lithosphere initiative, and our need for meaningful collaborations and interactions with Mexican, Egyptian, and Saudi universities and institutes. "Meaningful collaborations" imply the building on foundations already established, especially by foreign researchers, and engaging interested foreign collaborators in the formulation of both proposals and research objectives. It is imperative therefore that proposed work in Mexico, Egypt, and Saudi Arabia should involve co-principal investigators from these countries. Although a MARGINS post-doctoral fellowship scheme has been implemented, funds should also be included within proposals for the engagement of foreign senior and post-doctoral researchers in addition to students and the visit of foreign principal investigators.

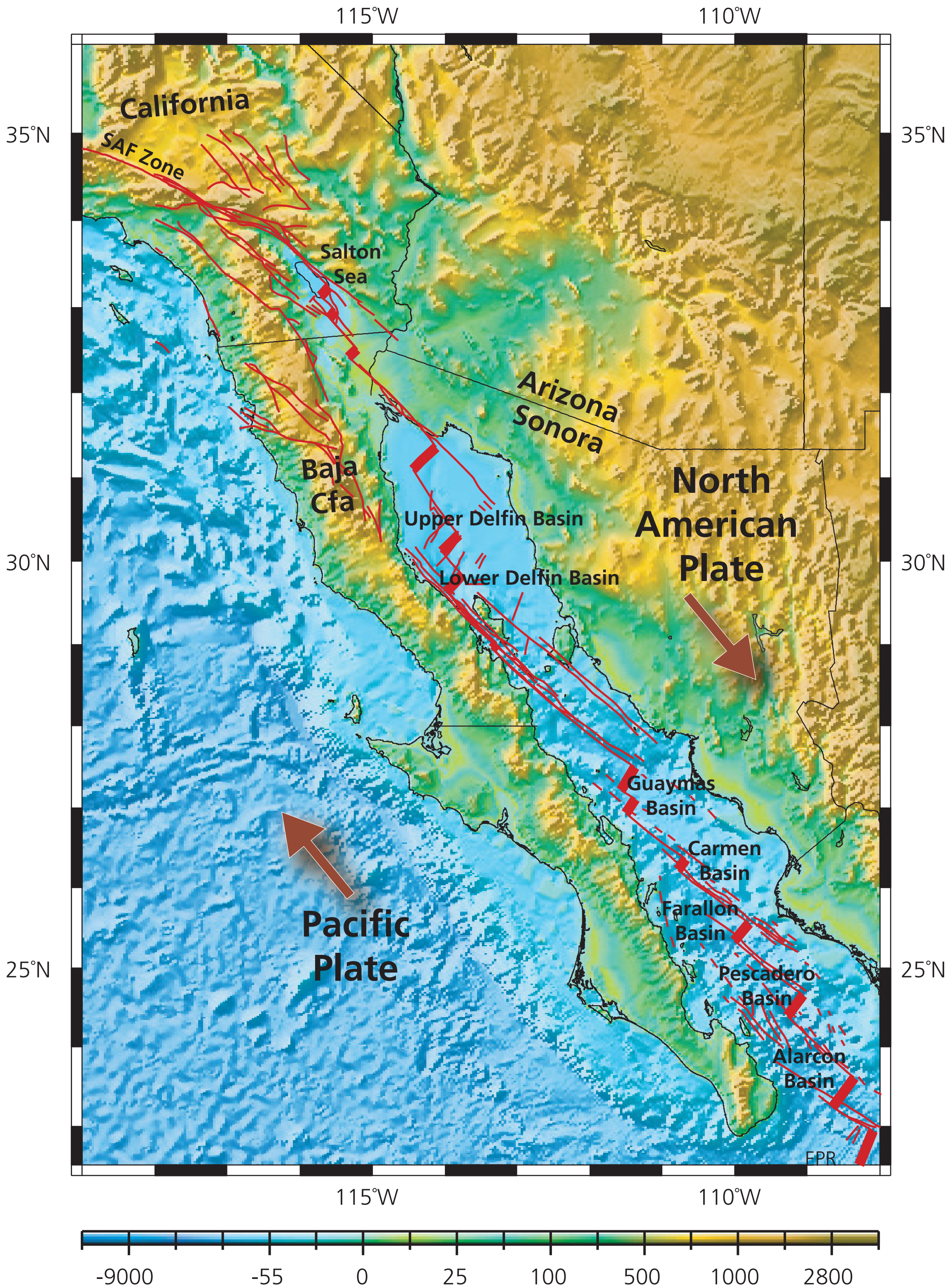
RCL Focus Sites

Gulf of California/
Salton Trough

6.1 Focus Site 1: Gulf of California/ Salton Trough

6.1.1 Introduction

The Gulf of California/Salton Trough focus site encompasses the zone of the Pacific-North America plate boundary, in southern California and western Mexico, where the boundary changes along strike from oceanic to continental in nature. In the southernmost sections, the continental lithosphere has been fully ruptured, leading to the creation of new seafloor, whereas in the more northern sections new seafloor is not yet forming and the plate displacement is occurring by continental extensional deformation.



Gulf of California

The study area encompasses the modern, active plate boundary and the surrounding region where rift-related processes have been operating during the time of opening of the Gulf (since about 12 Ma). The region of continental extension surrounding the Gulf has been labeled the "Gulf Extensional Province". However, it merges with the somewhat older Basin and Range province of southern California and western Mexico at its northern edge (in California, Arizona, and Sonora) and along a part of its southeastern margin (in Nayarit; Henry and Aranda-Gómez, 2000).

6.1.2 Location and nature of the modern plate boundary

The modern Pacific-North America plate boundary in the Gulf of California extends from the Pacific-North America-Rivera triple junction (near the Tamayo transform fault) north-northwestward along the length of the Gulf. It is a highly oblique boundary, comprising short spreading centers or pull-aparts separated by long transform faults. For a very complete summary of this region, see Lonsdale (1991). The segment of the Pacific-North America plate boundary north of the Tamayo transform fault, the Alarcon basin, has a typical mid-ocean ridge crest (the Alarcon Rise) and symmetric marine magnetic anomalies back to chron 2a (3.4 Ma) (corresponding to a total width of 180 km of oceanic crust formed in this segment). Basement depths in this basin are also consistent with it being normal oceanic crust.

Basins in the central Gulf (e.g., Farallon and Guaymas) have narrow axial magnetic anomalies, inferred to be produced by young, mainly intrusive mafic igneous rocks, such as those drilled on DSDP leg 64. Nevertheless it has proved difficult to recognize symmetric magnetic anomalies within these basins. Basins in the northern Gulf (Wagner, Upper Delfín, Lower Delfín) have very shallow bathymetry, with water depths generally less than 1000 m. These basins are sediment-filled sags with distributed normal faults controlling them, and only rare exposures of volcanic rocks at the seafloor. They lack the symmetric pattern of magnetic anomalies that would be typical of oceanic crust (Figure 5). The Salton Trough region of the plate boundary, which is the northern limit of the area discussed here, contains basins that are so filled with sediment that they are now subaerial. Here, the process of new crustal formation consists of mafic dikes intruding and metamorphosing sediment, and normal oceanic crust is absent.

Figure 4. General topography of the Gulf of California/Salton Trough focus sites with the Pacific-North American plate boundary.

The nature of the transform boundaries also changes character from south to north. The transform faults of the southern Gulf appear to be "oceanic" in character (in the sense that most of the plate boundary slip is localized along them) from the Tamayo transform fault northwards to the Ballenas transform system. However, northward of the Ballenas transform system, the various extensional basins are not separated by discrete transform structures. Rather, the basins appear to partly overlap, with complicated fault zones separating them, often with an orientation oblique to the direction of plate motion.

6.1.3 Locations and styles of lithospheric rupture

The architecture of the rift is probably best known (at the present time) for the southernmost and northernmost segments. For the southernmost segment (the Alarcon basin) oceanic crust has been forming since 3.4 Ma. However since there is a maximum of 180 km of oceanic crust in this segment, there

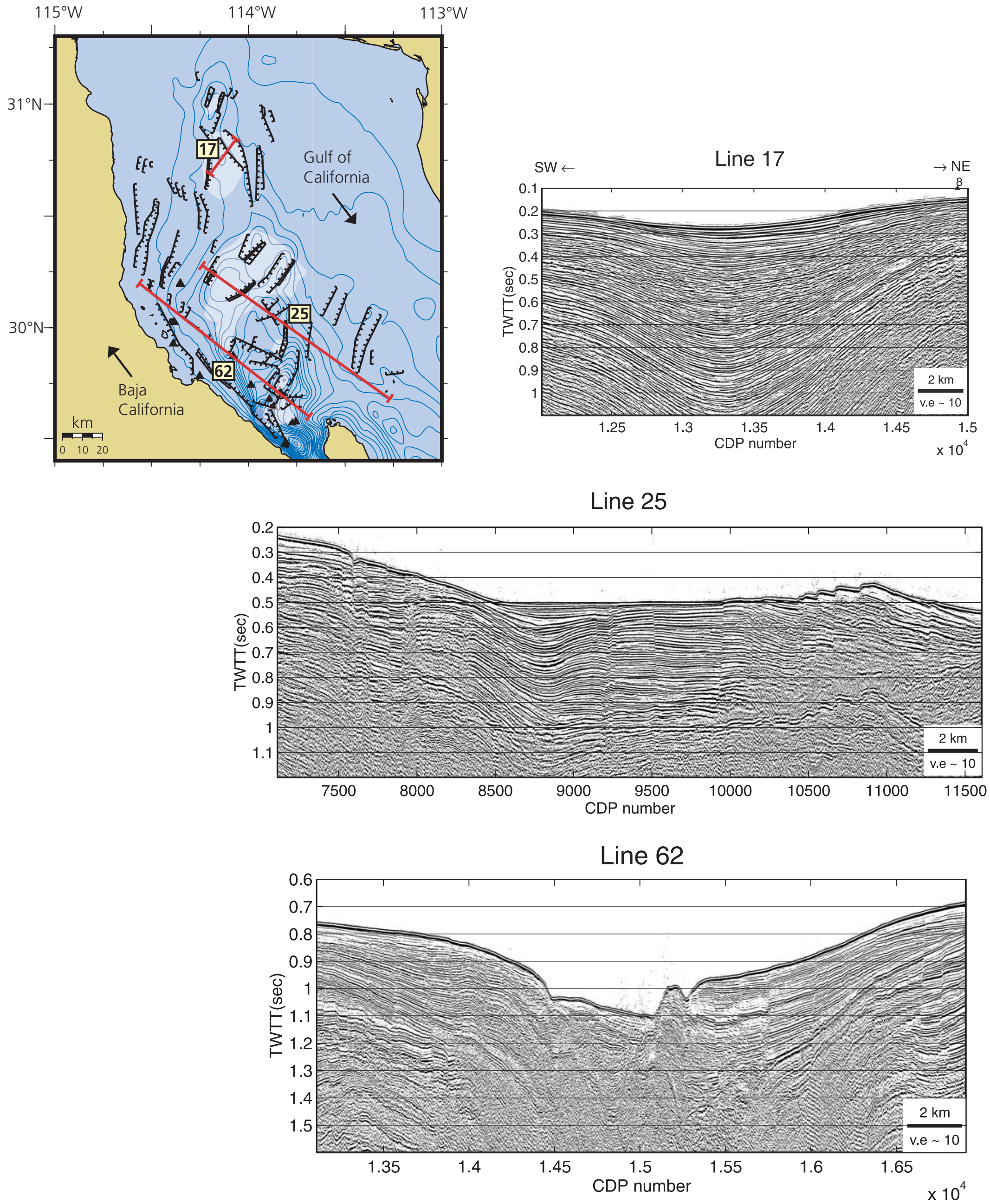


Figure 5. Summary map showing the faults in the northern Gulf of California interpreted from high-resolution multi-channel seismic data, bathymetric contours every 50 m (thin blue lines), and major spreading centers shown in red (after Persaud et al., 2002). Location of multichannel seismic lines are indicated with red lines. In Line 17 across the southern Wagner Basin, the stratigraphic form accurately describes where and when accommodation is developed across the region because sedimentation from the Colorado River has paced active subsidence. Lines 25 and 62 across the southern Upper Delfin basin, showing high-angle, closely spaced normal faults taking up strain within the sedimentary section.

must be additional motion that was taken up as continental extension during the rifting process, and the details of this strain partitioning remain a first-order objective of the RCL initiative.

In the Salton Trough, geophysical and geological observations (both at the surface and at depth) are consistent with new crust having been formed here, but with a thickness exceeding 20 km and consisting of mafic magmas intruding a very thick sedimentary succession. Further, the amount and distribution of new crust produced is not well constrained (Lewis et al., 2001). Thus, the partitioning of the plate motions in space and time between the formation of new crust and the extension of the continental lithosphere adjacent to this region is still not well constrained (Oskin et al., 2001).

In the northern Gulf basins (Wagner and Delfín), the nature and composition of the crust and lithosphere are also not well known. Limited information on Moho depths suggests thicknesses of 15 km or more. The material forming the crust of the basins may be similar to the new crust in the Salton Trough, or it may be extended continental crust, or some combination of the two. However, it appears that at least across the upper Delfín basin there cannot be much area of submerged continental upper crust because of the constraints provided from geological re-constructions of the Miocene rocks that correlate on either side of the gulf (Figure 5).

The segmentation of the present plate boundary system in some cases may be related to the structural segmentation that developed during the earliest stages of rifting in the region. Axen (1995) proposed a model for structural segmentation of the western rift margin. The connection between the structural segmentation of the rift margin and the subsequent evolution of the fracture zones has been discussed by Stock (2000) for the northern Gulf basins but remains to be addressed for much of the length of the Gulf.

6.1.4 Amount of slip in the gulf

It is generally thought that the amount of opening in the Gulf of California is about 300 km. This is based on several lines of reasoning:

- The offset along the San Andreas fault system in central California, where it is best determined, is 315±10 km. This fault system is kinematically connected to the northern Gulf; although there are various faults, zones of vertical-axis rotations, etc. that may cause the net amount of displacement to differ between here and the northern Gulf (see discussion by Dickinson, 1996).
- A distinctive Tertiary conglomerate deposit is correlated from the Santa Rosa Basin (in NE Baja California) to the coast in Sonora near Isla Tiburón (Gastil et al., 1973). The locations of these outcrops suggest about 290 km of offset across the Upper Delfin basin. This is consistent with more recent studies of Miocene ignimbrites that correlate from near these two locations and suggest 255±10 km of shoreline separation (Oskin et al., 2000).
- The Alarcon basin has opened by seafloor spreading at an average rate of 45 mm/a since 3.58 Ma (DeMets, 1995). If it is assumed that this rate can be extrapolated back to 6 Ma, then the amount of total opening would be 270 km.
- There is a greater width of seafloor present south of the Tamayo Transform fault, in the mouth of the Gulf (e.g., Lonsdale, 1989). However since much of this seafloor was formed by Pacific-

Rivera motion and not Pacific-North America motion, it is not necessarily straightforward to relate the amount of spreading in the mouth of the Gulf of California to the kinematics farther north in the gulf.

- There are no major Miocene or younger trans-peninsular faults on the Baja California peninsula south of the Agua Blanca fault. Thus the Baja California peninsula is inferred to have behaved as a rigid block (south of the Agua Blanca fault) during the time of opening of the Gulf of California (e.g., Umhoefer and Dorsey, 1997). Any differential extension along strike in the Gulf and its Extensional Province would thus be due to geometric effects (e.g., distance from the pole of relative plate motion).

Timing of opening of the rift

If it is assumed that all of these observations are correct, then the amount of opening of the Gulf would be approximately the same along strike and the variations in structural style of the rift system and the nature of the continent-ocean transition are necessarily independent of spreading. In this case, exactly what is controlling the structural variation along strike remains to be identified.

6.1.5 Timing of opening of the Gulf of California/Salton Trough rift

The timing of opening of the rift is constrained from various observations: timing of extensional faulting around the margins; magmatic history; and history of marine sedimentation. There has long been a notion of a “Proto-gulf” (Karig and Jensky, 1972), an early marine incursion in middle Miocene time, followed by the “modern Gulf phase” starting at ca. 6 Ma. For the peninsular side of the Gulf, Helenes and Carreño (1999) recently summarized the Neogene sedimentary history. Studies presently underway suggest that most of the well-constrained dates for initiation of marine sedimentation in the Gulf region are 8 Ma and younger. One site that had long been considered good evidence for the proto-gulf, with marine strata thought to be ~12 Ma, is Isla Tiburón (Gastil et al., 1999) but a reinterpretation of geological relationships there suggests that the marine rocks more likely are latest Miocene in age (Oskin and Stock, 2003). Basin histories have been reconstructed from Pliocene sedimentary rocks in the Salton Trough (Winker and Kidwell, 1996), the Puertecitos area (Martin-Barajas et al., 1997) and in the Loreto region (Dorsey and Umhoefer, 2000).

Both the rift-related volcanism and the extensional faulting around the Gulf predate the majority of the known marine sedimentary rocks. The history of volcanism and extension has been recently summarized by Martín-Barajas (2000). Extensional faulting within the Gulf Extensional Province has been active in various localities prior to 6 Ma and as far back as pre-11 Ma in Baja California (Lee et al., 1996). Much of this was high-angle faulting although some low-angle normal faults have been identified in northern Baja California and the Salton Trough (Bryant, 1986; Axen and Fletcher, 1998; Axen et al., 2000). Early Miocene detachment faulting has been documented in the Basin and Range province of Sonora (Nourse et al., 1994, Gans, 1997); in the Mexican Basin and Range province, there is also middle-late Miocene normal faulting that is “proto-Gulf” in age (Henry and Aranda-Gomez, 2000).

The magmatic history of the Gulf region has been the subject of several extensive summaries (Martín-Barajas, 2000; Sawlan, 1991). Prior to the opening of the Gulf, there was a subduction-related andesitic magmatic arc along the eastern side of the peninsula, from perhaps 22 to 16 Ma in the northern part of the peninsula and from about 22 to 12 Ma in the southern part of the peninsula. The earlier cessation of this arc volcanism in the north is attributed to the earlier cessation of the subduction of Farallon plate fragments there. The andesitic arc volcanism was followed by bimodal volcanism (basalt-rhyolite, including ignimbrite eruptions) as well as by locally diverse volcanic fields containing both alkalic and tholeiitic compositions. Some of these have continued to be active into Pliocene and even Quaternary time. In addition, locally, calc-alkaline volcanism has continued to the present day (e.g., Puertecitos Volcanic Province, Tres Virgenes volcano).

6.1.6 Rift evolution in the context of plate boundary slip

Onland geological observations suggest that the direction of opening of the Gulf of California rift has changed through time, with the early rift phase (late Miocene) being more orthogonal and the later rift phase being more oblique (e.g., Angelier et al., 1981; Umhoefer et al., 1994). It has been proposed that the Gulf has a two-stage tectonic history (e.g, Stock and Hodges, 1989). During the first phase, Baja California acted as a microplate caught between North America and the Pacific plate, so that the opening of the Gulf represented part of the total Pacific-North America plate motion, with the remainder of the motion being strike-slip in nature and accommodated elsewhere. During the second phase, Baja California would have been essentially attached to the Pacific plate, so that the later opening in the Gulf represents Pacific-North America plate motion.

One constraint on the overall kinematics of the region is the motion between the Pacific and North America plates, determined from global plate circuits (e.g., Atwater and Stock, 1998). The plate circuit calculations show a total of 600 km of relative displacement of the Pacific plate relative to North America since 12 Ma (for a point now near the Salton trough). If the Gulf only contains about 300 km of opening during that interval, the remainder of the plate motion must have been accommodated somewhere else. A common assumption is that several hundred km of this missing motion occurred by margin-parallel strike-slip displacement in the California Borderland west of the Peninsula, on structures of the Tosco-Abreojos-San Benito fault system (Spencer and Normark, 1979). This is inferred from the displacement of the Magdalena fan from its probable source area (Yeats and Haq, 1981). However, the exact amount of displacement of the Magdalena fan, as well as the timing of this displacement, has come under scrutiny (Fletcher et al., 2000). Even if the total offset of several hundred km is correct, there is still some additional extension, younger than 12 Ma, that is needed between Pacific and North America at the latitude of the Gulf of California. This motion may be represented by extension within the Mexican Basin and Range province, as suggested by Henry and Aranda- Gomez (2000).

Another overall kinematic constraint is that geological observations on the conjugate margins of the Upper Delfín basin require most of the displacement of the two sides to be post-6.1 Ma (Oskin et al., 2000). Thus it appears that Baja California was moving at nearly the Pacific rate relative to North America through most of Pliocene time, but that between 6 and 12 Ma the average rate of opening of the Gulf must have been very slow.

Magmatism and plate motion in Gulf of California

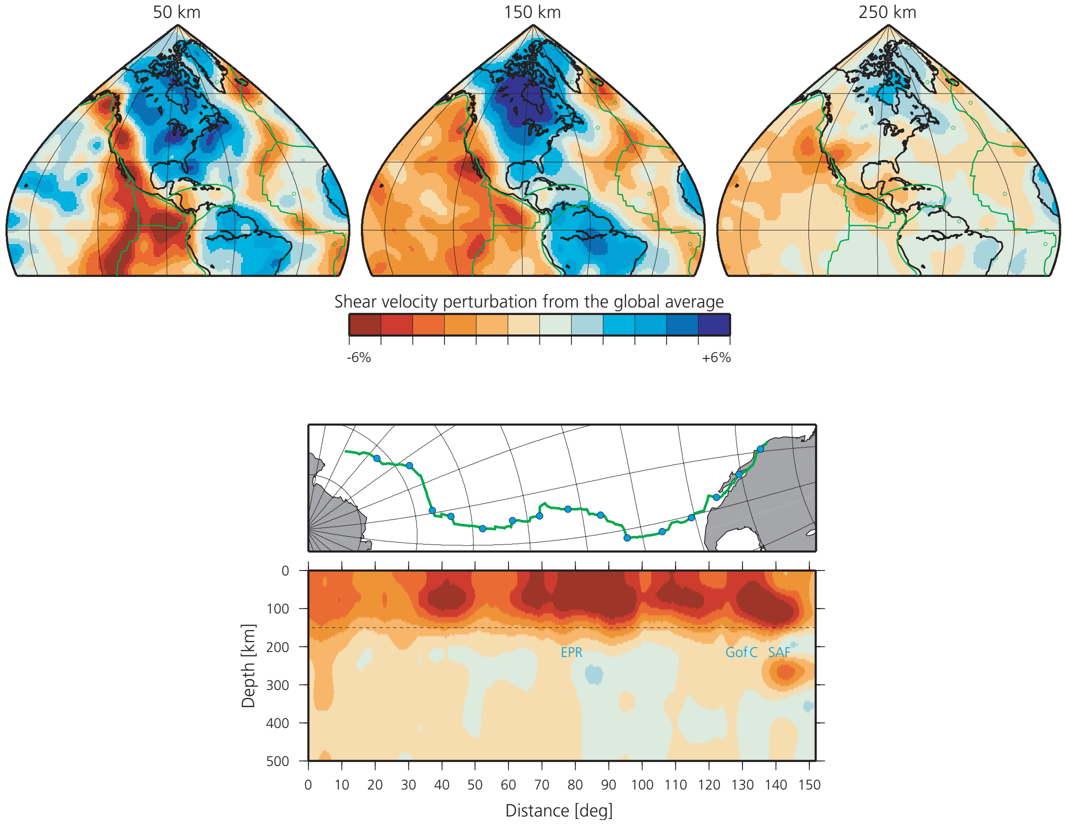


Figure 6. Shear velocity heterogeneity at different depths underneath North America, and cross section along the spreading ridges of the southeastern Pacific. Gulf of California is marked by a significant negative anomaly. Illustration courtesy of Jeroen Ritsema (CalTech).

6.1.7 Geodynamic setting of the Gulf of California at the start of rifting

Prior to the development of the Gulf of California, there was a long history of eastward subduction at these latitudes, with the oceanic Farallon plate converging with western North America. The Pacific-Farallon ridge approached North America during Tertiary time, until it reached the trench and the Pacific and North America plates came into direct contact at about 28 Ma. At this point the subduction zone contained two independent plates (Juan de Fuca and Nazca) separated by the Pacific-North America boundary. This boundary zone lengthened with time because its northern end (the Mendocino triple junction) migrated northwards with the Pacific plate, and its southern end (the Rivera triple junction) jumped discontinuously southward due to progressive extinction of spreading between the Pacific plate and the microplates. As the Rivera triple junction migrated southward, subduction west of Baja California would have ceased, and the subduction-related volcanic arc in Mexico was progressively extinguished from north to south.

Plate reconstructions show that by about 16 Ma the Rivera triple junction was adjacent to Central Baja California (Stock and Lee, 1994). At this time, the Baja California continental borderland north of the Vizcaino peninsula was taking up much of the deformation of the Pacific-North

America boundary. Arc volcanism in northern Baja was waning, whereas subduction related volcanism was still continuing in the region of southern Baja California. The Magdalena and Guadalupe plates, which were being subducted adjacent to southern Baja California, had broken from the Cocos plate, which itself had broken from the northern part of the Nazca plate (Lonsdale, 1991).

The Magdalena and Guadalupe microplates stopped spreading with respect to the Pacific, and became attached to the Pacific plate, at about 12 Ma. Thus, the Rivera Triple Junction jumped down to approximately its present location, and the entire length of boundary west of southern Baja California experienced a major tectonic change, from a microplate-North America subduction zone to a transtensional zone of motion between the Pacific and North America plates. Nearly all of the extension in the Gulf extensional province in Baja California happened after this tectonic change. However, some extension east of the Gulf occurred prior to this time and hence would have been taking place in a back-arc setting.

After this major tectonic change, the Pacific-North America plate boundary motion at the latitude of the Gulf of California must have been accommodated largely outside the Gulf region (either west of the Baja California Peninsula, or east of the Gulf in mainland Mexico, or both). There was a delay of roughly 6 m.y. from when subduction stopped adjacent to the Baja California peninsula until the Gulf began to move at nearly the full Pacific-North America plate rate. The kinematics and dynamics of the plate boundary history during this interval (12-6 Ma) are debated but are certainly important to a full understanding of how the Gulf of California rift developed.

6.1.8 Outstanding problems of the Gulf of California/Salton Trough region

Numerous aspects of the Gulf of California/ Salton Trough region lend it to investigation within the Rupturing of the Continental Lithosphere Initiative. This brief discussion cannot hope to touch on everything but rather highlights a few of the important issues. First, the Gulf of California contains a transition along strike from what is clearly oceanic spreading, in the south, to active continental extension that is clearly not oceanic spreading, in the north. This transition does not appear to be related to the timing, the net amount, or the rate, of the extension, as these parameters do not vary much along the length of the rift (insofar as we know at the present time). This transition needs to be better characterized and the factors controlling it need to be identified and understood.

Outstanding problems in Gulf of California

The crust in the "transitional" region has only been studied in the Salton Trough area. Elsewhere it may be similar in nature to that found in the Salton Trough, but this is not known. One of the outstanding questions for this rift system concerns the degree to which lower continental crustal material may have flowed out from under the marginal areas into the region of the rift, as has been documented farther north in the Basin and Range province.

The lithospheric architecture of the margins of the rift is incompletely known, but identifiable conjugate margin segments can be studied to determine the complete architecture of given segments of the rift and their evolution through time. These conjugate margins are accessible on land on both sides. The distribution of water and land offers much potential for well-designed studies to constrain the Moho depth, the seismic velocity structure, and other parameters that will be necessary for modeling the rift evolution and for understanding its present geometry and structure.

Syn-rift stratal and associated fault geometries can be imaged in the Gulf of California/Salton Trough region, and the sediments are within reach to be sampled by the drill in order to constrain the rift evolution, both in surface exposures and in submarine settings. The syn-rift sedimentation rate generally decreases from north to south due to the high sediment input of the Colorado River at the northern end of the system, and the character of the sediments changes accordingly, providing, at the north end of the Gulf, a very high fidelity record of the faulting and sedimentation history, and farther south in the Gulf, thinner sequences that can provide information farther back in time. The region has not been significantly overprinted by any post-rifting tectonics or buried by excessive volcanism. The accessibility of the onland geology means that the evolution of rift segmentation with time, and the changes in strain partitioning with time during rifting, can be addressed.

Stratal geometry of Gulf of California

RCL Focus Site Red Sea/Gulf of Suez

Finally, there is great potential for addressing the thermomechanical history of the rift and its present thermal state. Although the rift is not yet blanketed by volcanics, there are pre- and syn-rift volcanic rocks in various areas in and around the rift. These have the potential to provide information on the nature of mantle source regions beneath the rift, the nature of the mantle lithosphere (if xenoliths are present) as well as constraints on the thermomechanical evolution of the rift. Very few heat flow measurements are available for the rift but the correct conditions certainly exist for such measurements to be made. In addition, there are definite (slow) upper mantle shear velocity anomalies beneath the Gulf of California and Basin and Range Range that may reflect the present-day thermal structure of the lithosphere (Figure 6).

6.2 Focus Site 2: Central and northern Red Sea/Gulf of Suez

6.2.1 Introduction

The Red Sea and Gulf of Aden (Figure 7) are the closest modern analogs to the rifting and rupturing of continental lithosphere which formed the vast majority of "Atlantic-type" continental margins, and are the location where the processes that shaped the early development of rifted continental margins can be studied with the fewest tectonic complications. Nearly all of the passive continental margins of the Atlantic, Indian and Arctic Oceans were formed by the nucleation of an oceanic spreading center within a continental rift following an extended period of rifting. This process is presently occurring in the Gulf of Aden and Red Sea. The Gulf of Aden and Red Sea spreading centers developed within continental rift valleys cutting for 3500 km through the interior of a once contiguous craton (Beydoun, 1970; 1981; Stoeser and Camp, 1985) following a 15-30 m.y. period of continental rifting (Purser and Hötzl, 1988; Davison et al., 1994; Fantozzi, 1996; Omar and Steckler, 1995).

The opening in both rifts has been primarily extensional rather than transtensional (Joffe and Garfunkel, 1987; Jestin et al., 1994; Cochran, 1981; 1982; Colletta et al., 1988). Other than a single episode of dike emplacement dated at ~22 Ma (Bartov et al., 1980; Eyal et al., 1981), there has been virtually no volcanic activity within the northern Red sea rift and extension in the northern Red Sea has been accommodated primarily by rotation of large crustal fault blocks. It has only been recently with the establishment of localized centers of intrusion (deeps) that significant volcanic activity has occurred within the northern Red Sea Rift (Martinez and Cochran, 1988). In the very northern Red Sea, the deeps are localized centers of intrusion within the continental rift (Pautot et al., 1984; Cochran

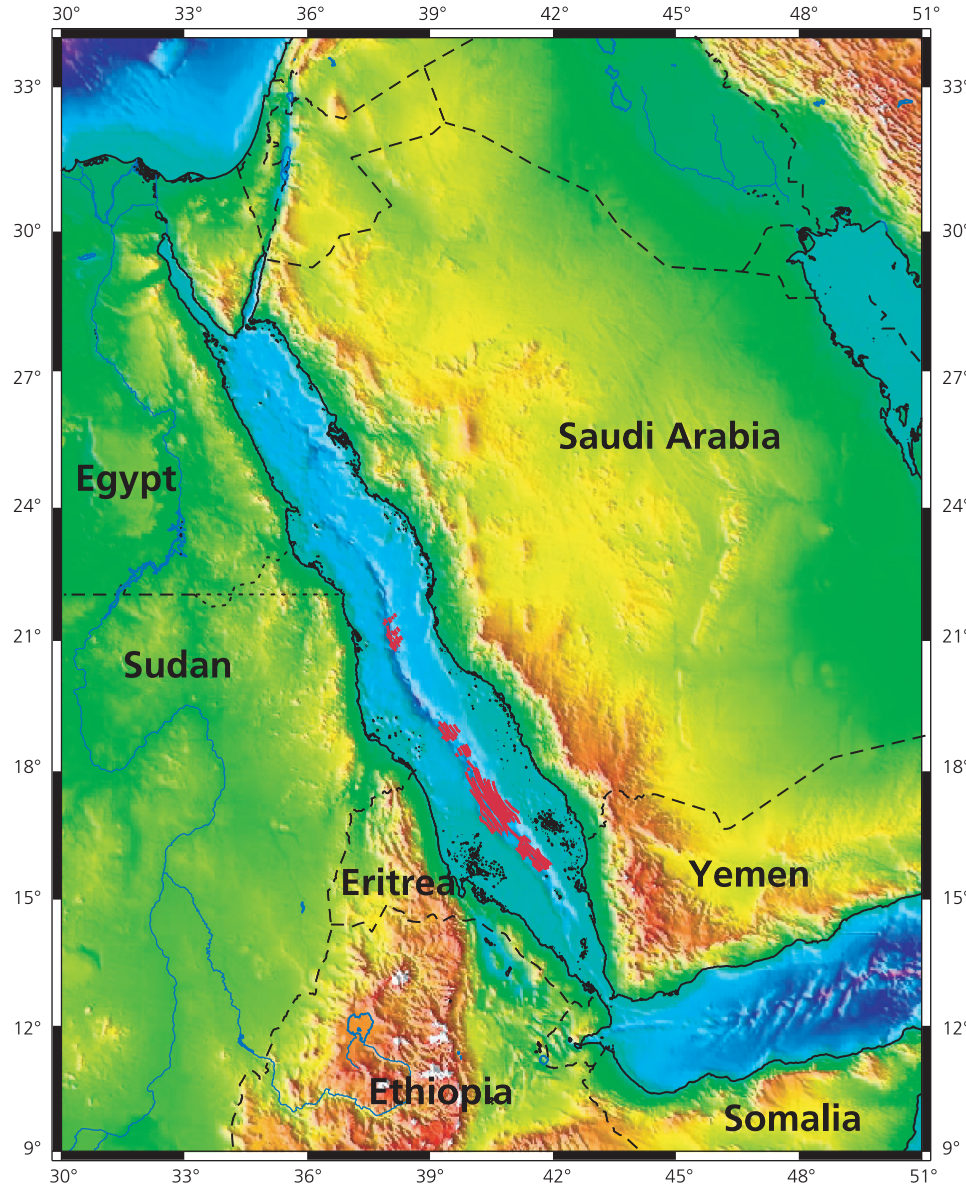


Figure 7. Topographic DEM for the Red Sea/Gulf of Aden region, showing the key countries bordering the central & northern Red Sea; Egypt, Saudi Arabia, and Sudan. Scientists from these countries are playing a fundamental role in co-developing the research proposals for studies of rupturing continental lithosphere.

et al., 1991) while further south they have evolved into well developed seafloor spreading cells actively lengthening and propagating toward each other (Pautot, 1983; Bonatti et al., 1984; Cochran, 1983). The northern Red Sea is thus a non-volcanic continental margin at which both seafloor spreading has recently begun and the mid-ocean ridge is in the process of becoming established.

Thus, the Gulf of Suez and northern/central Red Sea allow the development of a non-volcanic continental margin to be observed and

Continental rifting to seafloor spreading

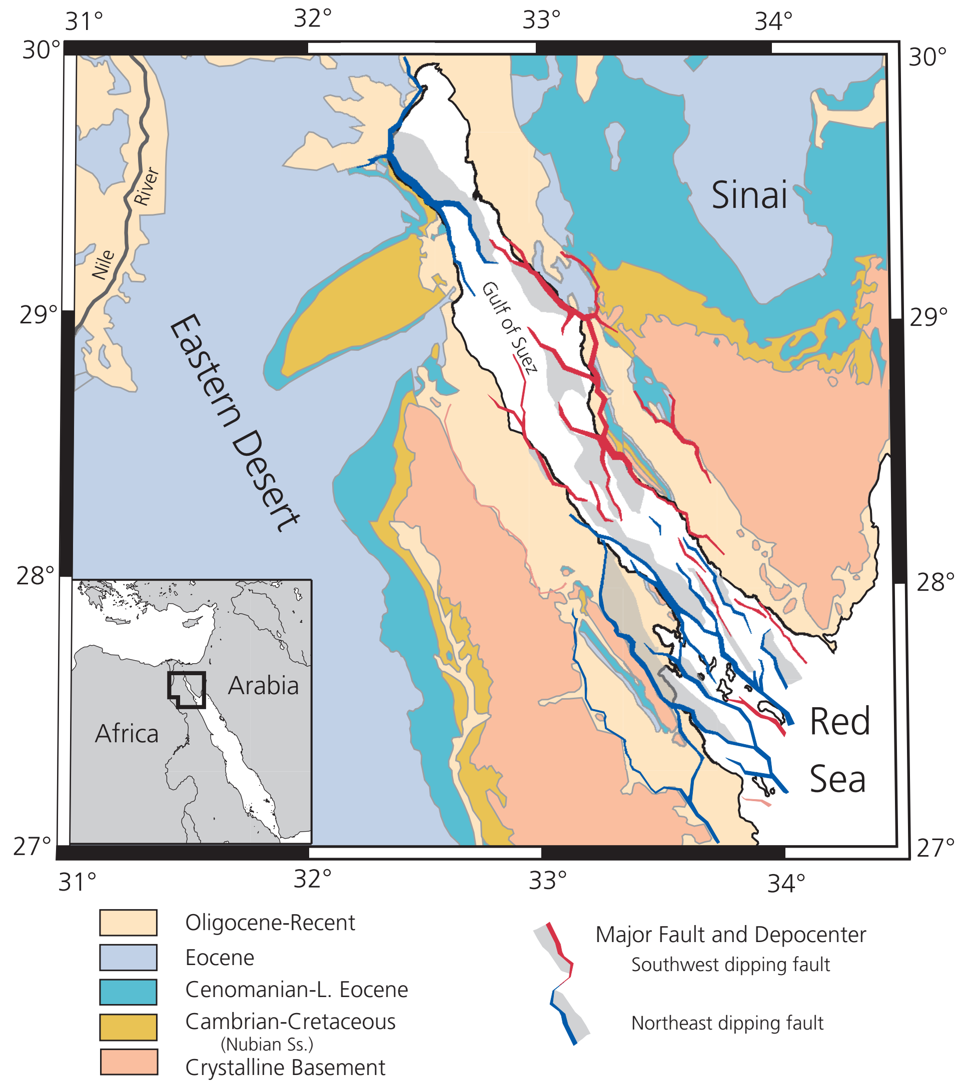


Figure 8. Border fault structure of the Gulf of Suez showing fault dip alternation and rift basin segmentation (modified from Moustafa, 1993, and Patton et al., 1994).

Non-volcanic rifting in northern Red Sea

studied from late-stage continental rifting through the establishment of a mid-ocean ridge system to a well-developed young continental margin and ocean basin in a tectonic setting similar to that which has produced the majority of such margins throughout the geologic record. Furthermore, it is important to restate the need for correlating unequivocal "strain markers" across the Gulf of Suez and the northern/central Red Sea rift systems, thereby providing absolute constraints on the amount, transport direction, and location of total strain across the rifts (e.g., Sultan et al., 1993).

On the other hand, the rifting process in the southern Red Sea and westernmost Gulf of Aden has been dominated by the presence of the Afar hot spot (Mohr, 1970; 1978; Schilling, 1973; Morton and Black, 1975). As a result, rifting in the southern Red Sea and westernmost Gulf of Aden has been accompanied by copious volcanism (Coleman et al., 1975; 1983). In particular the southern

Red Sea (south of ~22°N) is a volcanic margin where extension prior to the establishment of a localized oceanic spreading center at about 5 Ma was primarily accomplished through large-scale intrusion of new volcanic material (Gettings et al., 1986; Bohannon, 1986). Both the Red Sea and Gulf of Aden spreading centers are presently propagating into Afar (as the Erta Ale and Asal rifts respectively) (Mohr, 1970; Courtillot, 1980; Manighetti et al., 1998; Audin, 1999). The southern Red Sea thus presents the single best opportunity to study a recently formed volcanic continental margin and the Afar area presents an unparalleled opportunity to study hot spot - rift interactions.

The following summary of the Gulf of Suez is from Bosworth and McClay (2001). The structural and stratigraphic development of the Gulf of Suez reflects the interplay of five principal factors: 1) The presence of preexisting fault systems, penetrative fabrics and basement terrane boundaries, 2) eustatic variations, 3) changes in basin connectivity to the Mediterranean Sea and Indian Ocean, 4) rapid changes in African intra-plate stress fields, and 5) activation of the Levant-Aqaba transform plate boundary. The Gulf of Suez rift initiated in the late Oligocene as a result of the northeastward separation of the Arabia from the African Plate. North of Suez, extension is more diffuse but mostly focused on the Manzala rift buried beneath the Nile Delta. Microearthquakes and teleseismic events attest to continuing extension along major normal faults in the Gulf of Suez, Gulf of Aqaba and northern Red Sea regions.

The Gulf of Suez is the northern termination of the Gulf of Aden/Red Sea rift system, and the earliest syn-rift sediments are predominantly continental red beds with minor basalts. By the earliest Miocene, a shallow to marginal marine environment prevailed for most of the rift. The late early Miocene highstand allowed marine waters to mix between the Red Sea and the Mediterranean. Thick halite deposits formed in the late Miocene, and later sediment loading resulted in the formation of salt diapirs and salt walls.

Analysis of fault geometries, fault kinematics and syn-rift stratal relationships indicate that rift-normal extension predominated throughout the Oligocene to early middle Miocene development of the rift. In the middle Miocene, the Levant-Gulf of Aqaba transform boundary was established, linking the Red Sea extensional plate boundary to the convergent Bitlis-Zagros compressional plate boundary (Figure 7).

The northwest-trending Gulf of Suez is about 300 km long and the complete basin width, including onshore border fault systems, varies from 50 km at its northern end to ~90km at its southern end where it merges with the Red Sea (Figure 8). The rift is characterized by a zig-zag fault pattern, composed of north-south to north northeast-south southwest, east-west and northwest-southeast striking extensional fault systems both at the rift borders and within the rift basin proper. The fact that syn-rift sediments crop out on the both the Sinai Peninsula and western Egyptian desert implies that the focus of rifting likely propagated towards the center of the Suez rift, allowing flexural rebound engendered by later extensional faulting to expose the earlier syn-rift sediments (Figure 8).

There are three distinct rift segments or depocenters within the overall Gulf of Suez; the Darag basin at the northern end, the central basin or Belayim Province, and the southern Amal-Zeit Province (Figure 8). Each subbasin is asymmetric, bounded on one side by a major northwest-trending border fault system with large throws (4-6 km in general) together with a dominant stratal dip direction toward the border fault system. Structurally complex accommodation zones, oblique to the rift trend, separate the three depocenters. The accommodation zones ap-

Propagating rifts

Volcanic rifting in southern Red Sea

Gulf of Suez

pear to be wide (up to 20 km) areas of complexly faulted blocks of variable dips and interlocking "flip-flop" conjugate fault systems. Within each of the three main half-graben there are second-order sub-basins formed by individual fault blocks, each of which has its own characteristic syn-rift stratigraphy.

6.2.2 Selecting the central-northern Red Sea/Gulf of Suez focus site

There are three areas of active rifting that have been foci for recent studies dealing with the development of an oceanic spreading center within a continental realm in addition to being viable locations for a focussed study of the rupturing of continental lithosphere; the Gulf of California/Salton Trough, the Woodlark Basin, and the Red Sea/Gulf of Suez/Gulf of Aden region. Each of these geographic areas represents a very different setting for continental rifting.

Red Sea is the only on-going Atlantic-type rift

The Gulf of California developed by oblique extension in a primarily strike-slip regime (e.g., Larson et al., 1968; Larson et al., 1972; Moore and Buffingham, 1968; Lonsdale, 1989) just landward of the continental margin. Slicing a thin sliver off of a continent may be a relatively common phenomenon (Steckler and ten Brink, 1986) and represents a mechanism for the creation of exotic terranes (e.g., Coney et al., 1980; Churkin et al., 1982). However, the Gulf of California is a very different tectonic regime compared with the rift settings responsible for the majority of "Atlantic-type" continental margins.

Woodlark Basin rifting appears to have originated in response to a change in stress regime related to plate convergence and subduction of the Australian plate (Weissel et al., 1982; Benes et al., 1994). The present Woodlark Basin spreading center extends from the Simbo transform (which extends to the Solomon Trench; Crook and Taylor, 1994) to the Papuan Peninsula of New Guinea, into which the rift is propagating (Crook and Taylor,1994; Taylor et al., 1995). The time period over which the continental rifting stage developed prior to the establishment of the oceanic spreading center is rather short (< 4 m.y., Taylor et al., 1995) compared to the rifting phases at most passive continental margins that typically last for 15 m.y. or longer. Recent work has shown that the bathymetry and structure of the western Woodlark Basin has been significantly shaped by the thermal consequences of subduction processes (Fang et al., 1997), especially the addition of subduction-related fluids that, in turn, have modified significantly the rheology of the fore-arc and back-arc crusts. The Woodlark Basin thus represents a special and unusual tectonic setting and the extent to which observations from the Woodlark Basin can be used to understand the development and structure of other margins is not clear.

Only the Red Sea and Gulf of Aden present an opportunity to observe and study the initiation of a young rifted continental margin that formed by the deformation of stable cratonic continental crust. As such, the Red Sea and Gulf of Aden represent rift settings characteristic of the vast majority of continental margins around the world. During the Snowbird meeting (January, 2000) in which the community deliberated on the RCL focus sites, the Red Sea and the Afar/Gulf of Aden were kept separate because of the nature of the science considered important in these two areas. Following the unanimous choice of orogenic rifting in the Gulf of California by the Snowbird meeting participants, the cratonic rifting choice become the central/northern Red Sea region, with the Afar/ Gulf of Aden region being rejected based primarily on logistical problems of working onshore in Somalia and Aden, the political instability of Aden, and the then-war between Eritrea and Ethiopia.§

6.2.3 Geophysical data available from the central-northern Red Sea

Geophysical surveys of the central and northern Red Sea have been conducted by the oil industry and also by a number of academic institutions. A relatively large geophysical database has been collected by various institutions over the last 25 years. The total amount of digital data presently in our data base amounts to 243,418 depth, 178,980 gravity, and 155,544 magnetic measurements.

The largest blocks of geophysical data were collected during multichannel seismic surveys of the Egyptian side of the Red Sea from 25°N to 27°40'N carried out by Exxon and Phillips Petroleum in the mid to late 1970s. These surveys consisted of dip lines at 2- 4 km spacings nearshore and ~8 km spacing away from the coast with strike lines at 5-8 km spacing. We have obtained the bathymetry, gravity and magnetics data from the Exxon and Phillips surveys and have permission from the Egyptian government to publish it. Some Exxon data are also available, but only in analog form. A few additional Exxon seismic lines were published by Miller and Barakat (1988).

A similar survey was carried out on the Saudi Arabian side north of 24°N by Preussag AG for the Saudi government in the early 1980s. As Preussag has closed its marine survey division, inquiries have indicated that the data no longer exist in digital form in Germany. It is unclear whether it exists in Saudi Arabia. The German BGR has released copies of detailed bathymetric and magnetics maps, as well as maps of depth to various seismic horizons. These maps are at scales ranging from 1:100,000 to 1:250,000. Degraded "simplified" versions of some of these maps have been published by Richter et al., (1991).

In addition to the industry data, data from surveys carried out by U.S (LDEO and WHOI), French (IFREMER and Ecole Normale Supérieure), British, Italian, Russian and Israeli academic institutions as well as bathymetry data from about 20 British and U.S. Navy transits of the northern Red Sea are also available. The two most extensive academic surveys were those carried out by LDEO on Conrad and by IFREMER on Charcot. Track charts for these individual cruises as well as the details of data acquisition can be found in Martinez and Cochran (1988) and Guennoc et al., (1988). Both the Conrad and Charcot surveys collected 24 beam SeaBeam and single-channel seismic reflection data.

Seismic refraction lines across the region were collected between 1978 and 1986 by two research groups. A German group from Hamburg carried out several experiments using"MARS-66" portable seismometers and explosives for on-shore lines in Egypt and Saudi Arabia and OBSs and either explosives or airguns for marine lines. These profiles are summarized by Rihm et al., (1991) and discussed in more detail in the "grey" literature (Makris et al., 1979; 1983) and in University of Hamburg theses. A series of expanding spread profiles were carried out by the French École Normale Supérieure off Egypt in 1986. This work was reported by Gaulier et al., (1988). The seismic data shows fairly typical crustal thicknesses of 30-40 km onshore away from the Red Sea. The crustal thickness decreases slightly to 20-30 km within the onshore por-

§ Since the Sharm el-Sheik meeting, it has become clear that organized seafloor spreading is indeed occurring to the north of the Eritrean border. To conform with the original Snowbird 2000 meeting intent of the central/northern Red Sea study region, Eritrea is not part of this region. If, and only if, it can be demonstrated that rifting has not progressed to seafloor spreading in the Sudanese/Saudi section of the Red Sea is there a need to expand the research region to include northern Eritrea and the Sudan.

Geophysical data from the Red Sea

tion of the rift and then abruptly decreases to less than 10 km seaward of the coast. Thermal gradients, conductivities and heat flow values were published in Martinez and Cochran (1989), which, when combined with onshore measurements in Egypt published by Morgan et al., (1985), give a good picture of the variation in heat flow from the unrifted craton completely across the rift.

State of geophysical database

The majority of the available geophysical data from the northern Red Sea was obtained between 1975 and 1990. The data is well located using a combination of satellite and LORAN navigation and the bathymetry, gravity and magnetics data are generally of very good quality. As mentioned earlier, several cruises in the mid and late 1980s included SeaBeam data. However, in all cases this was the older SeaBeam system. As a result of the shallow water depths, the swath width was generally less than 1 km and the SeaBeam data were of limited value for general surveying although it was very useful for surveys of specific features such as deeps (Pautot, 1983; Pautot et al., 1984; Cochran et al., 1986). However, the density and generally high quality of the available data has allowed an understanding to be obtained of the structure of the northern Red Sea and is more than adequate to use in planning further experiments using the more sophisticated geophysical instrumentation now available.

The salt problem

6.2.4 The "Salt Problem" in the central-northern Red Sea

The main exception to the conclusion of the previous paragraph deals with the quality of multichannel seismic reflection data. The Exxon seismic sections published by Miller and Barakat (1988) show the base of the Miocene evaporites in many places but very little structure below the evaporites. This has led to a general opinion that the thick Miocene evaporites prevent imaging of deeper structure and basement within the Red Sea.

In reality, this is not quite accurate. Izzeldin (1987) presents a seismic section off of Sudan in which he is able to image a reflector, interpreted as basement, through the salt to a depth of 2.9 sec (two-way travel time). Also Preussag was able to prepare maps of the depth to a number of sub-salt horizons along the Saudi coast (see summary chart in Richter et al., 1991).

Much of the difficulty with MCS data from the Red Sea is that all of the available or published data was acquired 20-25 years ago using what is now very antiquated equipment. The Exxon survey was carried out with a 48-channel, 2350 m-long streamer, while the Preussag Saudi survey utilized 24-channel, 2400m and 30-channel, 3000 m streamers with a DFS V recording unit.

Geology of the Red Sea

6.2.5 Geologic background of the Red Sea

The Red Sea occupies a 2000-km long rift bounded depression (Figure 7). The rift shoulders average between 1000 m and 3000 m in elevation and expose a variety of Pan-African (late Proterozoic) granitic, metamorphic and mafic igneous rocks (Shackleton et al., 1980; Stern, 1984). Continental rifting appears to have begun nearly simultaneously along the entire length of the Red Sea in the Oligocene at ~ 34 Ma with the main phase of extension beginning at about 22 Ma (Omar and Steckler, 1995).

The morphology of the Red Sea consists of narrow marginal shelves and coastal plains, and a broad "main trough" with depths of about 400-1100 m. In the southern Red Sea, the main trough is bisected by an axial trough ~60 km wide with depths of up to 2000 m. A mid-ocean ridge spreading center with well developed seafloor spreading magnetic anomalies occupies the axial trough

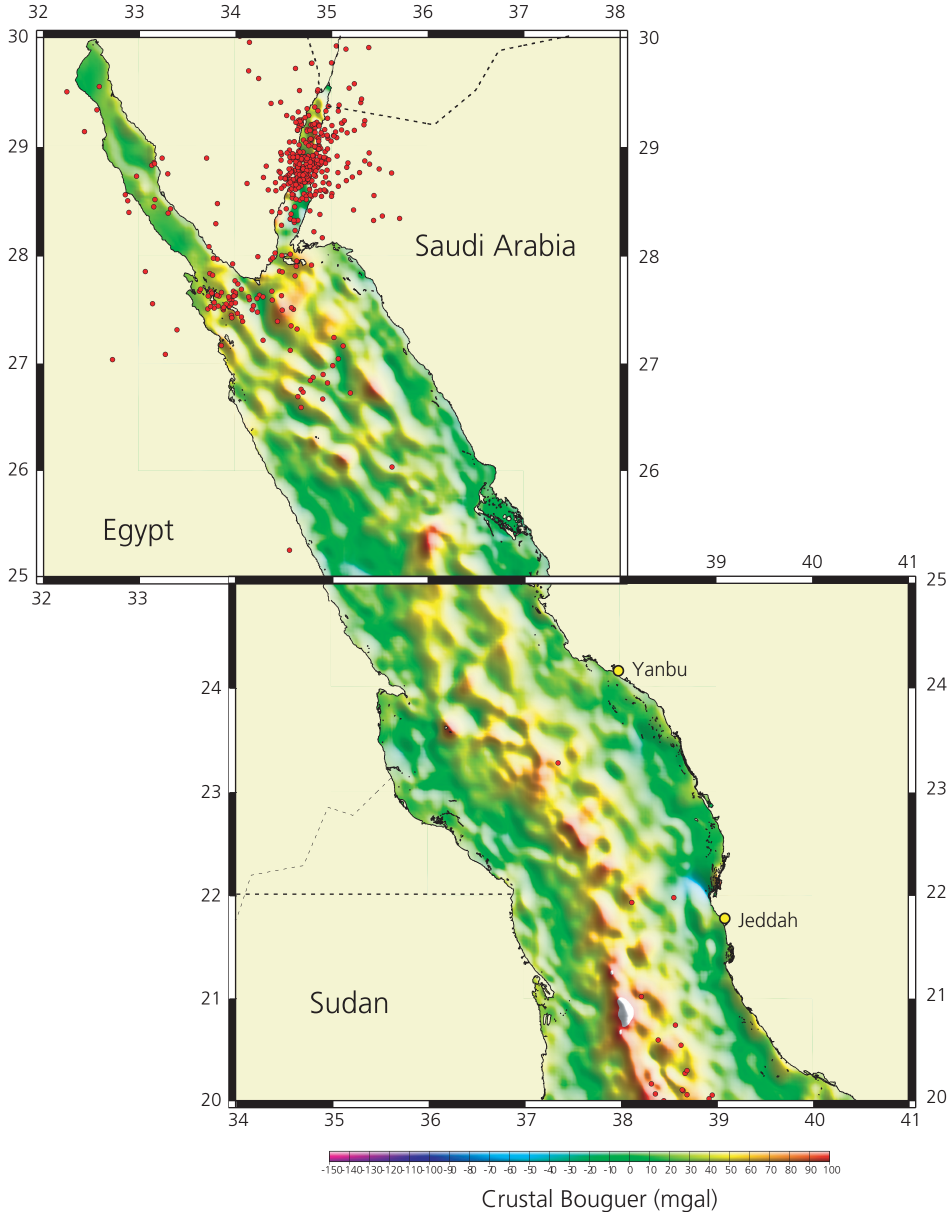


Figure 9. Filtered Bouguer gravity of the Northern Red Sea. The filtered Bouguer accentuates regions of deep bathymetry and thinned continental crust and major depocenters. Red dots represent the locations of earthquakes.

from about 15°N to 19°30'N (Roeser, 1975; Cochran, 1983; Miller et al., 1985; Garfunkel et al., 1987). Spreading appears to have nucleated at about 17°N at ~ 5 Ma and to have propagated north and south from there (Roeser, 1975; Courtillot, 1982; Cochran, 1983). The spreading center becomes discontinuous north of 19°30'N and passes into a transition zone made up of a series of isolated seafloor spreading cells (Cochran, 1983; Pautot, 1983; Bonatti, 1985; Bicknell et al., 1986). These "deeps" are separated by "intertrough zones" which are shallower, broader, and covered with highly faulted sediments including both the Miocene evaporites and post-Miocene pelagic sediments (Searle and Ross, 1975; Izzeldin, 1989).

An organized mid-ocean ridge is not observed in the northern 500 km of the Red Sea (Figure 9). The region is characterized by terraced bathymetry stepping down to an axis of deep water which is characterized by faulted and deformed sediments (Martinez and Cochran, 1988). Small deeps, generally associated with large dipolar magnetic anomalies are spaced along the axial depression (Pautot et al., 1986; Guennoc et al., 1988; Cochran et al., 1986). These deeps are much smaller than the central Red Sea transition zone deeps and usually are floored by sediments, although a volcanic peak is found in Shaban Deep near 26 10'N (Pautot et al., 1984).

Seaflor spreading in the Red Sea

Structure and bathymetry

6.2.6 Structure of the Red Sea

The central-northern Red Sea can be divided into two distinct regions (Figure 9), a main trough often referred to as "marginal areas" although they actually occupy most of basin, and a 15-30 km-wide "axial depression" (Martinez and Cochran, 1988; Cochran and Martinez, 1988). The bathymetry of the marginal areas forms a series of terraces 20-30 km wide, generally at depths of about 600 m, 800 m, and 950 m. These terraces are separated by steeper slopes or escarpments which often appear to be fault controlled.

Free-air gravity anomalies form a pattern of elongate high-amplitude (50 mGal) highs and lows which are oriented subparallel to the trend of the rift and extend for 50-70 km along strike. The free-air gravity anomaly highs are persistently located on the seaward edges of the bathymetric terraces Gravity contours are systematically terminated or offset across NE-SW trending zones. Bathymetric contours often are also offset at locations where the gravity contours are offset or terminate (Martinez and Cochran, 1988; Cochran et al., 1991). The gravity anomalies display the pattern of basement relief, interpreted as a series of tilted fault blocks 15-30 km across and roughly 60 km in length separated by accommodation zones which absorb the differential motion between adjacent sets of fault blocks (Martinez and Cochran, 1988).

A region of deep water 1100-1300 m deep and from 15 to 30 km wide referred to as the "axial depression" (Cochran et al., 1986) is a consistent feature of the northern Red Sea. The axial depression differs from the oceanic "axial trough" of the southern Red Sea in that sedimentary sequences, including both the Miocene evaporites and the post-Miocene pelagics, are continuous across it, lineated magnetic anomalies are not present and it is shallower. The axial depression often appears to be fault bounded, particularly in the vicinity of deeps. It is marked by a free-air gravity minimum with a relative amplitude of 30-60 mGal and is the location of the maximum heat flow on each of our heat flow traverses (Martinez and Cochran, 1989). Deformation of the sediments in the axial depression is more intense and concentrated than in the marginal areas and frequently extends to the seafloor. Martínez and Cochran (1988; 1989) argue that both the distribution of faulting and numerical modeling of heat flow data require that deformation previously occurred over a wide area, but has relatively recently become focused in the axial depression.

The axial depression is not only the locus of recent deformation, but is also the location of a series of axial deeps spaced at 50-75 km intervals along it. These are all small northern Red Sea type deeps (Pautot et al., 1984; 1986; Cochran et al., 1986;

Guennoc et al., 1988). In the area north of 26°N, where accommodation zones have been identified, the deeps are located almost exactly at the midpoint of segments, halfway between the accommodation zones. Except for the northernmost deep, near 27°20N, 34°20’E, the deeps are associated with large normally magnetized, dipolar magnetic anomalies which appear to result from recent, localized intrusions (Cochran et al., 1986). In the majority of cases, there is not a single anomaly over the deeps, but rather a pair of dipolar anomalies. A detailed study of Conrad Deep showed that the bodies responsible for the magnetic anomalies are not located under the deep itself, but rather are beneath the base of the fault scarps on either side of the deep and are elongated parallel to the fault scarps (Cochran et al., 1986), which strongly suggests that the faults bounding the axial depression have been used for the ascent of the magma.

It appears on both bathymetry and gravity maps that the axial depression is not simply a continuous axis of deep water as suggested in published descriptions (Pautot et al., 1984; Guennoc et al., 1988; Martinez and Cochran, 1988; Cochran et al., 1991), but is systematically segmented (Figure 9). Bathymetric depth and the amplitude of the gravity lows both decrease away from the deeps with minima at the accommodation zones identified by Martinez and Cochran (1988). The accommodation zones are not simply saddle points, but also offset the axial depression. The bathymetric and gravity lows associated with deeps do not intersect, but rather overlap without joining. This can be seen, for example, in Figure 9 where the gravity lows centered at Conrad Deep (27°03’N) and the 26°36’N deep curve away from each other as they approach the accommodation zone between the two deeps. The two gravity minima are separated by a 10 km-wide, 15 mGal relative high. The axial depression thus appears to be divided into discrete, independent segments separated by the same accommodation zones that define the geometry of the basement fault blocks within the marginal areas. Within each segment, there is an axial deep located almost exactly half way between the accommodation zones and associated with high-amplitude normally-magnetized dipolar magnetic anomalies which appear to result from large recent intrusions (Pautot et al., 1984; Cochran et al., 1986).

Axial deeps, gravity, and magnetic anomalies

Initiation and segmentation of the rift

Models have been developed for the establishment of an oceanic spreading center in a continental rift based on the present geophysical observations (Martinez and Cochran, 1988). It is hypothesized that the Red Sea rift began in the Oligocene as a series of linked half graben as presently observed in the East African Rift (Bosworth, 1985; 1994; Ebinger et al., 1987; Ebinger, 1989). By the mid-Miocene, the initial half-graben had evolved into sets of rotated fault blocks as presently observed in the Gulf of Suez (Garfunkel and Bartov, 1977; Colletta et al., 1988; Bosworth, 1994). In this stage, referred to by Bosworth (1995) as a “high-strain rift”, deformation and subsidence became more focused along the basin axis, with extension occurring along a new system of higher angle, planar faults (Bosworth, 1994; 1995). The Gulf of Suez rift is still segmented by accommodation zones and all of the blocks in a segment have a consistent sense of dip (Colletta et al., 1988; Bosworth, 1994).

An additional 100 km of extension has occurred in the northern Red Sea since the Gulf of Suez was cut off in the mid-Miocene. Buck et al., (1988) and Martínez and Cochran (1989) have argued the heat flow in the northern Red Sea requires that extension (with thinning of the crust and lithosphere) was spread throughout the rift but has recently become focused near the axis. This is consistent with the model developed by

Extension and melting in the Red Sea rift

Bosworth (1994; 1995) for the Gulf of Suez. It is also consistent with the more symmetric appearance of the northern Red Sea and with the observation of more intense sediment deformation in the axial depression (Martinez and Cochran, 1988). It appears that in this process, the basic tectonic framework of the rift has remained sets of rotated fault blocks separated by accommodation zones.

Thermal modeling (Buck et al., 1988; Martinez and Cochran, 1989) also suggests that as the extension becomes concentrated, some degree of partial melt will be generated beneath the axis. This melt appears to have reached the surface at the deeps which are characterized by large amplitude dipolar magnetic anomalies. Most of the deeps do not have a single magnetic anomaly but rather pairs of anomalies centered over each of the faults bounding the axial depression implying that the magma was intruded along the faults (Cochran et al., 1986). We hypothesize that the deeps develop into small seafloor spreading cells which propagate and grow together to form an oceanic spreading center. The segmentation of the newly formed mid-ocean ridge is thus hypothesized to be inherited from the geometry established during continental rifting.

Allied studies: deeply exhumed extended terrains

6.3 Allied field studies: Studies of deeply-exhumed extended terrains

Deeply-exhumed extended terrains are important for a full understanding of the processes of lithospheric rupture and extension. Such terrains, where well exposed, can offer an accessible 3-D geometrical picture of fossil fault systems and shear zones, rock and mineral fabrics, metamorphism or melting, and alteration down to very small scales. They can be sampled in whatever level of detail is necessary for each technique and problem. Similar information at depth in active systems is hard to obtain in such detail, because the rocks can only be accessed in very limited locations (i.e. occasional boreholes). Therefore, deeply exhumed extended terrains are important locations for addressing certain key questions of rupturing of the continental lithosphere.

The questions that can be addressed in these terrains will vary according to the rock types and their preservation or subsequent alteration, but ideally will include some or all of the following: unroofing history determined by geochronology, geothermometry, petrology (if melts were formed) and geobarometry; extensional deformation history from mineral fabrics, shear sense indicators, fractures, and veins; the nature of the crust and mantle involved in the deformation (from compositions of basement and/or syntectonic igneous rocks); the nature of any previous deformation that may be unrelated to the later extensional deformation that has affected the region; and the lithospheric-scale geometry of extensional systems.

One question that remains in some cases of exhumed extensional fault systems is, how is the deformation in a "metamorphic core complex" (i.e. the mylonite zone) actually related to the extension and the low-angle fault that unroofed the system? Similarly, in at least one case where the ocean-continent transition is exhumed, it is thought to be a zone of continental mantle (see summary by Whitmarsh et al., 2001). This appears to differ from what is present in either of our focus sites; yet, detailed study of this or other regions of transitional crust will help to establish constraints on composition, fabric, and timing of deformation. These can be compared with the focus areas to yield a fuller understanding of the range of possible behaviors as continental lithosphere ruptures to form an ocean basin.

7. Critical Field, Laboratory, and Experimental Efforts

7.1. Active-source seismology

Images and seismic velocities are obtainable at scales useful for probing the RCL Focus Sites to depths of about 50 km using newer experimental facilities and focused observational programs. Below the crust, depth and resolution are limited by the difficulty in propagating energy to great depths, and passive-seismic methods become the more powerful tools.

Conventional industry-style exploration reflection seismology will be essential for imaging the stratigraphic response to lithosphere rupturing, and for mapping the three-dimensional patterns of faulting in the brittle crust. The basin subsidence history, preserved in the basin-filling stratigraphic sequences, is the most sensitive record of lithospheric extension and thermal evolution during rupturing. Significant numbers of 2D profiles already exist for both Focus Sites, but some 3D data volumes may be necessary to properly understand areas of complex fault interactions, particularly perhaps those between strike-slip and normal faults, or between faults and active magmatic intrusion. Should it prove possible to identify, and appropriate to drill into, an active low-angle normal fault, 3D seismic data will be required before drilling. Some 2D datasets should be available from the hydrocarbon industry for the Red Sea focus site, and other data-sets have been and must continue to be acquired with NSF funding in both focus sites. For example, a 2D "high-resolution" profile in the northern Gulf of California shows well the complex stratigraphic and faulting record preserved in the Delfin Basin (Figure 4), and other profiles in the Gulf of California seem to show uppercrustal intrusions (Gonzalez-Fernandez, 2000, MARGINS abstracts). Reflection imaging will also be important to study the lower crust, since prominent, laminated lower-crustal reflectivity is believed to be a signature of extensional strain and magmatism (e.g., Reston, 1990; Warner, 1998).

Reflection and refraction techniques become more powerful when combined. Closely spaced seismographs (or ocean-bottom seismometers/hydrophones (OBS/H) offshore) along modern normal-incidence reflection lines have been used to extend structural imaging to depth as well as provide unique velocity data. Tomographic analysis of these data also provides the crustal and upper-mantle velocity field to combine with the structural analysis possible from near-vertical reflections. Velocity measurement is the best way to identify mafic intrusions ("rift pillows") formed at the base of the crust in some active rifts, including the Salton Trough (Fuis et al., 1984).

Imaging the deep rift: seismology

7.2. Earthquake-source seismology

The greater energy release and global distribution of earthquake sources allows their signals to be used to extend both structural and velocity mapping beneath the crust. Most analogous to the refraction profiles of active-source seismology are the 3D velocity tomograms of the mantle (some from surface wave analysis, others from body-waves), which show unusually low upper-mantle velocities, ascribed to unusually high upper mantle temperatures, below both western North America (Gulf of California, Basin and Range province) and the Red Sea/East African rift system (e.g., Dziewonski, 2000). Most analogous to the normal-incidence multichannel seismic sections are the receiver functions that extract P-to-S and S-to-P conversions formed at the 660-km, 410-km and Moho discontinuities, or other relatively abrupt velocity changes. Dense arrays of broadband seismographs deployed for months or years now collect data from enough sources to allow stacking and migration of receiver functions, with the same increase in resolving power that multi-channel seismic data shows over single-channel seismics. Preliminary receiver-function studies have already been carried out to map Moho depths in part of the northern Gulf of California (Lewis et al., 2000; in press), but more such work will surely prove necessary in both Focus Sites.

Passive source seismology

Other passive seismic techniques provide information that is very different from active-source techniques. Careful hypocentral location using local seismograph networks can delineate active faults and zones of active magmatism in both the crust and mantle (e.g., Rebollar, 2000; MARGINS abstract). Passive seismic arrays using portable PASSCAL-type deployments are rapidly expanding our understanding of the Earth's deep interior in many ways. Attenuation studies can provide constraints on temperature variations beneath rifts independent of those provided by velocity tomography or heatflow and xenolith studies. Shear-wave splitting measurements can determine the anisotropy of the upper mantle and crust (Savage and Sheehan, 2000 for Basin and Range Province). The splitting observations constrain the flow-induced fabric of the mantle to the extent that olivine crystals align and produce bulk anisotropy, and provide tests of dynamical models of rifting. Because this anisotropy typically includes components of both modern asthenospheric flow and fossil lithospheric anisotropy, passive seismic deployments must be broad enough to capture the areal variation of flow, and long-term enough to record sufficient suitable earthquakes at a range of back-azimuths to enable resolution of multi-layer anisotropy, if present. A seismic-related project is already funded to carry out an appropriate teleseismic study around the Gulf of Suez; despite the recent establishment of the NARS-Baja seismic array (Trampert et al., 2003), additional portable instrument deployments will be necessary for more detailed studies in the Gulf of California. Although mantle anisotropy is now routinely determined by passive arrays, determination of crustal anisotropy is much more difficult because the layer thickness in which such anisotropy is developed is much smaller (c. 10 km) than in the upper mantle (c. 100 km). Yet knowledge of lower-crustal anisotropy may yet prove the best determinant of the way the weak lower crust is responding to the boundary forces that ultimately control rifting.

7.3. Geodesy

Plate motion through geodesy

Space geodesy (GPS, DORIS, VLBI, SLR) gives us a present-day "snapshot" of plate motion and lithospheric deformation, and has the potential to contribute to our understanding of rift initiation and evolution in several ways.

First, space geodesy can provide information on kinematic boundary conditions: What are the motions of adjacent plates or blocks, and how might these motions help or hinder the rifting process? These boundary conditions may be crucial to determining the long term fate of a rift, in terms of eventual development of sea floor spreading and oceanic crust. Consider the modern Red Sea, formed by northward motion of the Arabian plate relative to the Nubian plate (Africa west of the East African Rift). Comparison of modern Arabia-Nubia motion (from space geodesy) to a several million year average (from sea floor magnetic anomalies or from geological models that uses these and other data) indicates that Red Sea spreading is slowing down. One explanation is that Arabia is colliding with the Eurasian plate to the north, and the resulting thickened crust and excess elevation of the Zagros and Caucasus Mountains exerts south-directed gravitational body forces on the Arabian plate that act to slow rifting in the Red Sea. Since the history of Red Sea opening is reasonably well described, one way to test this would be to investigate the history of crustal shortening in the fold and thrust belts on the northern boundary of the Arabian plate.

The mechanics and thermodyamics of ultra-slow sea floor spreading is another area of interest in rift development, since rifting of continental lithosphere may start out slowly, but presumably must accelerate to some minimum speed if sea floor spreading is to be achieved. By obtaining accurate measures of present day spreading rates for comparison with other geologic data, we may gain some useful insights. Using the Red Sea example, the GPS-determined angular velocity for Arabia-Nubia accurately defines the spreading rate increase from north to south. Sea floor spreading in the modern Red Sea seems to occur when the spreading rate reaches about 10 mm/a (full rate). At rates slower than this, isolated zones of magma upwelling occur, but do not coalesce into organized spreading centers.

The partitioning of strain in developing continental rifts is also of interest, in part because it may help us to understand how rifts develop. A current paradox is that the stresses available to break continental lithosphere seem to be too small, given current estimates of lithospheric strength. GPS in particular is well suited to defining in some detail the surface deformation field around active rifts. By comparing measured deformation to mechanical models of deforming lithosphere, we can gain insight into the deformation mechanisms. As GPS data become more precise, it is apparent that mechanical models of the lithosphere must go beyond the simple elastic half space formulation that are the mainstay of current crustal deformation models for geodetic data. Developing improved mechanical models will require constraints from heat flow, geological mapping, paleoseismic studies, and laboratory data on the strength of common crustal materials as a function of temperature and strain rate.

Plate motion

Ultra-slow seafloor spreading

Modeling rift processes

7.4. Geodynamic modeling

Geodynamic models are crucial to our understanding of the physical processes governing rifting of continental lithosphere and subsequent initiation of seafloor spreading. Models will provide the framework within which diverse onshore and offshore datasets may be synthesized to illuminate the intricacies of processes such as: strain localization and the evolution of fault systems; magma emplacement and how it interacts with deformation; hydrous fluid flow and sediment dynamics; strain partitioning during extensional and transtensional rifting; vertical partitioning of strain within the lithosphere and interactions between crust and mantle during continental rupture.

The ultimate goal of geodynamic models, however, will be to answer broad-scale questions regarding how continental extension in a localized zone of rifting leads to the initiation of seafloor spreading and thus to the birth of new plate margins. Fundamental to this goal is an assessment of the relative importance of plate-tectonic forces versus locally-derived body forces in driving the rupture of continental lithosphere. This question is intimately related to the stress conditions under which continental lithosphere ruptures and thus to the fundamental "low-strength" paradox in continental deformation (extreme examples of which include low-angle detachment faults). Additionally, in order to understand forces driving continental rupture, it is crucial to understand the extent to which previous tectonism "pre-conditions" the lithosphere and may enhance processes leading to rifting and the initiation of seafloor spreading.

Geodynamic models must, therefore, integrate surficial constraints on continental rupture processes (onshore and offshore geodetic strain rates, geologic slip estimates, strain partitioning as observed in the upper crust, conjugate margin geometry, fault segmentation, and magma emplacement) together with constraints on the threedimensional architecture and deformation of the plate margin (crust and mantle lithosphere thickness, seismic velocities, electrical conductivity, heatflow, petrology of crust and mantle xenoliths, inferred deformation fabrics from seismic anisotropy). Important issues to be addressed by geodynamic modeling include:

- The initiation and evolution of onshore fault systems during continental rifting and their relations to the offshore ridge-transform system following the transition to seafloor spreading
- Strain partitioning in the upper continental and oceanic crust during oblique transtension
- Strain partitioning within continental crust (decoupling of upper and lower crust) and the importance of low-angle detachment faulting
- Interactions between crustal extension, crust or mantle flow, and magma emplacement
- The relative importance of plate tectonic versus local body forces in governing continental rifting and the transition to seafloor spreading.

In both the Gulf of California/Salton Sea and the Red Sea/Gulf of Suez focus sites, the lateral variations in the transition to sea-floor spreading might be exploited in geodynamic models as a proxy for the temporal evolution of the process of continental rupture.

Electrical resistivity, heatflow, and lithospheric plate flexure

7.5. Magnetotellurics, heatflow, flexural strength and seismic attenuation

Magnetotellurics (MT) is an electromagnetic prospecting method in which orthogonal components of the horizontal electric and magnetic fields, induced by natural primary sources, are measured simultaneously as a function of frequency and are used to image the Earth's electrical resistivity structure from depths of a few 100 meters to several 100 kilometers. The MT method is based on frequencies in the order of 10^{-3} Hz to 1 Hz. In general, rocks containing fluids such as water or rocks at high temperature will have a low resistivity. Similarly, dry and cold rocks will have high resistivities. In contrast, seismic Q values are a measure of seismic energy dissipation and relate to the presence of fluids and augmented by temperature variations. Enhanced electrical conductivity at subsolidus temperatures is principally caused by the presence of fluids. Consequently, conductive pathways serve as a geophysical tracer for the distribution of fluids and/or large temperature variations in the lower crust and mantle. Likewise, strain anisotropy may also affect both fluid permeability and electrical and seismic transmission pathways, thereby helping to determine the directions of preferential extension and plastic strain in the lower crust and mantle.

Perhaps the best proxy to help decipher the amplitude of involvement of the lithospheric mantle, especially when coupled with the patterns of regional subsidence, magnetotellurics and seismic attenuation, will be patterns and magnitudes of the surface heatflow. In general, high-quality heat flow, when coupled with measurements of sediment thermal conductivities, provides crucial information on the pre-deformed and deformed thermal structure of the continental lithosphere, which in term provides an important constraint or state variable for seismological, petrological and rheological models for the deforming lithosphere.

Plate flexure helps to redistribute the loads created by the extension process and therefore is a critical factor in controlling the regional geometry of extended lithosphere. In order to estimate the total extension of the upper crust (from, for example, the distribution of surface faulting as mapped from surface mapping or reflection seismics), the lithospheric strength as a function of space and time needs to be determined. As demonstrated by Karner et al., (2000), extension and lithospheric strength inversely interact to produce a given basin geometry; equivalent basin geometries are obtained for either low flexural strength and large extension or high flexural strength and small extension. The best way to constrain the flexural strength of the lithosphere is by forward modeling the free-air and Bouguer gravity of the basin system, both in terms of the basin architecture and the adjacent rift flank topography. Because gravity anomaly amplitudes are very sensitive to the mechanical or flexural strength of the lithosphere, it is thus imperative to collect high-resolution gravity across the Gulfs of California and Suez deformation zones and adjacent regions.

8. Databases and the hydrocarbon industry

Over the last few decades, there has been a steady but irreversible shift with respect to the ownership of extensive Earth Scientific data bases. Thirty to forty years ago, it was the academic institutions like Lamont and Scripps that were the custodians of worldwide data sets. These data consisted primarily of underway geophysical data such as single-channel seismics, gravity, magnetics, and bathymetry, in addition to dredge, core, and box-core samples. Nevertheless, these data represented important if not the only data available across many continental margins for subsequent hypothesis development or defining the "state of knowledge" of a region. However, the rapid growth of the oil industry over this same period, the drilling of onshore and offshore wells within virtually all of the world's basins and margins, reconnaissance and detailed field mapping, geotechnical laboratory experiments and field sampling, reservoir characterization, remote sensing surveys, all coupled with the major advances in 2-D, 3-D and 4-D reflection seismic acquisition and processing, have resulted in the generation of immense geological and geophysical data bases that reside within the oil industry. The traditional funding organizations are not in a position to compete with industry in terms of data quality, coverage and rate of data acquisition, nor can the funding agencies afford to duplicate the acquisition of these data sets.

Data management

It is clear that MARGINS needs to facilitate collaboration between the oil industry and university researchers on problems of mutual interest. The MARGINS Office can play a prime role here by acting as a liaison between researchers and the oil industry in trying to facilitate the release of critical data sets. An excellent way of fostering this collaboration is via offering interested oil companies (non-voting) membership on the MARGINS or InterMARGINS Steering Committees.

Industry interaction

9. National and International cooperative programs

A number of major NSF Earth Science initiatives and international MARGINS programs are currently being planned and will potentially impact the various MARGINS initiatives. For example, a major NSF-requested Major Research Equipment for the Earth Sciences (EAR), termed Earthscope, was recently funded in part by Congress. In contrast, the UK and European Earth scientific communities have organized themselves to solve first-order problems considered important for both academia and the oil industry.

9.1 Earthscope

Earthscope comprises four facility-based components; PBO, USArray, SAFOD and InSAR, all of which overlap in either technique or scientific endeavor with RCL objectives. The challenge is to take advantage of these "facility initiatives" during the execution of the MARGINS program. In order to highlight these overlaps, a summary of each of the Earthscope components are briefly summarized.

The goal of the USArray facility will be to routinely image the crust and mantle beneath the U.S. (and overlapping areas in Canada and Mexico), using an array of portable seismic instruments, thereby providing subsurface imaging of the plate boundary zone, obtaining high-quality constraints on the deformation processes; mechanical (fault zone), thermal (topography), mantle (anisotropy), and density (tomography and gravity).

The objective of the Plate Boundary Observatory (PBO) facility is to supply primarily geodetic data to characterize the 3D deformation (velocity) field of the western U.S., Alaska, and Baja California. It will thus define plate boundary dynamics and crustal rheology, define distribution and timing of the active tectonic processes and their relation relation to geology, and aid in understanding the physics of the earthquake process, and of volcanic processes.

The objective of the San Andreas fault observatory at depth (SAFOD) facility is to oversee drilling into the seismogenic portion of the San Andreas fault. The SAFOD mandate is to provide "hard" constraints on seismic, physical, and rheological properties of the San Andreas crust by drilling a 4 km-deep hole close to the hypocenter of the 1996 magnitude 6 Parkfield earthquake, where the San Andreas fault slips through a combination of small-to-moderate magnitude earthquakes and aseismic creep.

Although strictly a NASA initiative, the Synthetic aperture radar interferometry (InSAR) project will be used as a satellite tool to provide spatially continuous maps of the displacement field over the 100 km-swath width imaged by the satellite radar in those areas be investigated with USArray and PBO.

9.2 UK Ocean Margins LINK Program

EarthScope and Ocean Margins LINK interaction

The UK together with Ireland shares an ocean margin over 1500 km in length containing valuable oil and gas reserves but the economic benefits of this huge area have not yet been fully determined. UK MARGINS program, formally termed the Ocean Margins LINK program and funded by the Natural Environment Research Council (NERC) and the UK hydrocarbon industry, will focus on three main themes: 1) Deep structure and rifting processes; 2) Sedimentary processes, sediment movement and slope stability; and 3) Fluid flow particularly into and out of the seabed, including its relationship with and effect on deep-water faunas. The model presented by the LINK program is novel and one that the US MARGINS program should attempt to emulate.

In addition, the Ocean Margins LINK program is also designed to focus the research capabilities of the UK science base, working in partnership with industry on the challenges facing the industry in exploring for, and developing deep-water oil fields. Specifically, the Ocean Margins LINK program will contribute to the following industry "challenges":

1) Improved prediction in exploration and reservoir characterization on the UK margin and globally; 2) Gas hydrates as a hazard and potential energy source; 3) Prediction of deepwater geohazards; and 4) Sustainable management of hydrocarbon resources and the deep-water environment.

The program is intended to stimulate industry and academic community partnership in key technological sectors and in doing so, enhance the competitiveness of UK industry and quality of life through the support of managed programs. LINK aims to accelerate commercial exploitation of science, engineering and technology. The program also helps stimulate industry to increase the resource of R&D within universities. A LINK project must have at least one university and one company, with access to data related to the project being granted by the collaborating companies.

9.3 EuroMARGINS

EuroMARGINS was created to address fundamental scientific questions concerning the origin, structure and evolution of passive continental margins concentrating on the following thematic issues: Rifting processes, sedimentary processes and products, and subsea floor fluid flow systems. As such, EuroMARGINS shares a common goal with the US MARGINS program in many of its objectives. Both active and inactive systems plan to be studied, with the various North Sea and Mediterranean margins and basins being sites of focussed research. EuroMARGINS research necessarily needs to be of societal importance, especially as it relates to hydrocarbon exploration and production, the economic potential of gas hydrates, deep-sea biota and, the occurrence of natural hazards.

With funding through the European Science Foundation (which acts as a financial broker for monies paid by member European countries for MARGINS research), implementation of the EUROMARGINS program will be carried out in two main phases. Phase I will focus on two "target" areas that are of immediate priority for Europe - one on the Northwest European margin and the other in the Mediterranean Sea. The centerpiece of Phase I will be the first 3-D seismic tomography and imaging of the crust and upper mantle in the transitional region between the continent and ocean. The seismic studies will be accompanied by sonar studies of the mechanics and kinematics of slope instabilities; the dynamics and variability of turbidite systems; and by chemical, biological and physical studies of fluid flow, gas hydrates and deep-water seeps and biota.

Phase II is envisioned to extend the work off Europe to other margin systems that are also of interest to European scientists. Particular target areas include the conjugate margins of the North Atlantic (e.g., Labrador, Greenland and west Iberia), the young margins of the Gulf of Aden and, the highly segmented margins of the South Atlantic (Brazil, Gabon and the Congo).

EuroMARGINS

InterMARGINS

9.4 InterMARGINS

Over the past few years, continental margins research has become a major focus of the international geoscience community. New national research programs have been initiated in many countries, for example in France, UK, USA, and Japan. To foster a greater degree of international coordination of margins research activities, to focus sufficient resources on some common, large interdisciplinary investigations, and to help leverage funding for multi- and inter-disciplinary research projects, a new international geoscience initiative dedicated to continental margins research was recently formed. The result is a steering committee, termed InterMARGINS, that is an international and interdisciplinary group of researchers concerned with coordinating continental MARGINS research between the various national MARGINS programs. It is designed to encourage scientific and logistical coordination, with particular focus on problems that cannot be addressed as efficiently by nations or national institutions acting along or in limited partnerships.

The scientific planning and direction of InterMARGINS is the responsibility of its steering committee and various InterMARGINS working groups. Each country with a paid subscription to InterMARGINS is represented by a voting member on the steering committee. The role of the steering committee will be to: 1) define and at times update the program plan, 2) propose and oversee specific InterMARGINS projects, 3) consider and prioritize proposals for new program elements, workshops and other appropriate activities, 4) liaise with the leaders of national MARGINS programs, 5) determine the membership in InterMARGINS and its working groups and committees, 6) approve the InterMARGINS budget and oversee the operation of the InterMARGINS office, and 7) select the InterMARGINS chairman and the host country for the InterMARGINS office. The chair of the office is presently Dr. Robert Whitmarsh of the Southampton Oceanography Center (SOC).

The most important role of InterMARGINS is to foster and enhance communication between national MARGINS-related research programs. It will develop and maintain metadatabases of ongoing national and multinational projects and research activities, initiate and carry out workshops, and disseminate information to members through newsletters and other forms of communication.

RCL implementation

Workshops

10. "Rupturing Continental Lithosphere" implementation plan

Study of the RCL initiative requires an integrated effort over a decadal timescale. The emphasis of research activities will evolve over these years, progressing from early integrated data gathering and characterization, experimentation and model formulation to more logistically complex field studies and integrated laboratory and numerical experiments. Later activities will stress synthesis and formulation of improved models for lithospheric deformation. The following timeline is illustrative, the details of actual activities and the exact sequence of events will be dictated by the proposals written and funded and by logistical and programmatic considerations.

Planning workshops for the Gulf of California/Salton Trough and northern Red Sea/Gulf of Suez focus sites were held in Puerto Vallarta at the end of October, 2000, and Sharm el-Sheikh during March, 2001, respectively. It is envisaged that the initial phases of work be concentrated in the Gulf of California and the Gulf of Suez portions of the focus sites with the geophysical characterization of each focus site at a scale and resolution necessary to generate an adequate foundation for future geological, geodetic and geochemical studies.

The second phase of reconnaissance work would represent geophysical characterization of the Salton Trough and the central Red Sea regions of each focus site. In all cases, this characterization should include the production of detailed topographic datasets obtained by merging onshore DEM information with offshore seafloor swath mapping, regional and high-resolution multichannel reflection seismic data, measuring surface heatflow variations across the focus sites, using lithospheric tomography to map possible lower crustal and lithospheric mantle flow regimes, regional refraction surveys to determine crustal and mantle velocities and Moho geometry, and the construction of regional but high resolution magnetic and gravity grids of onshore and offshore regions to define sub-surface structural trends, depocenter location and subbasin segmentation, and as a critical constraint on the spatial variations in the flexural strength of the extended lithosphere.

This framework will be crucial for guiding subsequent large-scale geological and tectonic syntheses, onshore geological mapping of syn-rift stratigraphy, border fault development and segmentation, continued radiometric dating of rift-related volcanics, and ultimately, the identification of crucial sites for testing hypotheses using dredging and IODP drilling.

Other critical activities in the early stages of the RCL program include developing databases for rapid dissemination of information, establishing local seismic arrays to define the depth-distribution and focal mechanisms of crustal deformation, and establishing geodetic monitoring stations. Theoretical institutes and workshops will help to inform, educate and reflect on the evolving RCL program, facilitating the construction of both a well-informed community knowledgeable of RCL objectives and feedback to the steering committee concerning the need for possible midcourse changes of the program. At the minimum, a mid-term review of the entire RCL program and science plan will be held as a public workshop. During the final years of the program, shallow-water and on-riser drilling and subsequent data analysis will ultimately test predictions about the rheological zonation of the crust and mantle, the partitioning of strain in the deforming lithosphere, and the local and far-field effect of stresses in driving lithospheric extension.

Numerical modeling and laboratory experiments will be critical throughout the program to interpret and synthesize the causes and consequences associated with the spatial and temporal variations of strain through the lithospher. These models will necessarily be constrained the results from the various observational datasets, both regional and local. This marriage of theory with observation will be a fundamental aspect of RCL numerical experiments.

A comprehensive study of the RCL initiative is estimated to cost $20-25 million, exclusive of ship time and drilling costs and facility-related projects associated with geodetic, land, and ocean bottom seismometers. The probability of international cooperation with collaborating organizations and synergism and input from EuroMARGINS and InterMARGINS should help reduce data acquisition and field logistic costs. It is believed that the synergism of nested and focussed multidisciplinary studies should yield a greater benefit/dollar investment that the usual single approach. Having said this though, it is expected that RCL-related proposals submitted to NSF core programs will provide invaluable complementary information on either the themes of RCL or insights from studying other (i.e. non-focus site) margin systems.

Establishing a geological and geophysical framework

Costs

11. How will we communicate results and opportunities for cooperation?

A RCL web site is maintained as part of the duties of the MARGINS Office with the prime purpose of distributing MARGINS-related results and data sets significantly prior to publication. The RCL web site will provide the following: 1) information concerning upcoming field expeditions and experiments, 2) access to databases and recently acquired data, and 3) a news bulletin board to foster communication across the different disciplines in the RCL community in addition to listing the abstracts of published work supported by MARGINS funds.

By making information concerning upcoming cruises and field experiments available in a timely fashion, other researchers can capitalize on these opportunities and secure funds to participate in these projects or design piggy-back experiments. In addition, acquired RCL data and/or pathways to access data will be available on the web soon after acquisition. The actual timeframes for data availability will vary for different data types. Existing data from RCL focus sites will be compiled, catalogued and entered on the web database. Rapid dissemination of data and new ideas will help focus the community which in turn should lead to a more interdisciplinary approach towards studying RCL. Data availability, together with the news bulletin board, will improve communication between observationalists, experimentalists and theoreticians.

Dissemination of results

Theoretical institutes will similarly allow interdisciplinary interaction. Enhanced communication will allow rapid determination of the critical observations and experiments necessary for constraining models for RCL. In this way, first-order model predictions can be immediately tested. Such an iterative approach between modeling and data analysis is the necessary first step towards developing realistic quantitative models of RCL.

In addition to the web site, international meetings and publications will promptly communicate the results of RCL. Workshops on the main scientific themes will also be an important component to focusing efforts within the broad community. These workshops will bring together the diverse community of researchers needed to cross-fertilize ideas and develop multi- and inter-disciplinary approaches to make progress on the RCL scientific objectives. Further, topic-specific workshops will be augmented by AGU and GSA town meetings and special sessions, by Theoretical and Experimental Institutes and associated publications, and by mid-program planning workshops.

Finally, an important component of RCL science execution and communication will be in the training of US and foreign students and developing exchange programs with foreign collaborators. Funds for this research and training will be earmarked in the overall MARGINS budget and will be distributed via successful student and foreign proposals to NSF-MARGINS.

12. How will "Rupturing Continental Lithosphere" be evaluated?

Evaluation of RCL

We anticipate that the RCL initiative will progress through a series of peer-reviewed and competitive proposals. This funding mechanism, that of funding the best science as defined by peer review and NSF Panel deliberations, provides continual evaluation of the initiative. Further, the initiative will be compared against the milestones set out for all MARGINS initiatives by the MARGINS Steering Committee in consultation with NSF-MARGINS Program Managers. The milestones will be supplemented by progress reports distributed by the MARGINS Office. These reviews will summarize the research of MARGINS-funded research and some evaluation of the effectiveness of interdisciplinary and international activities. Proposal pressure, MARGINS-related publications and community attendance at RCL workshops and theoretical institutes will all be effective measures of the progress and value of RCL research. A mid-term review in the form of a public workshop will allow the progress of RCL to be assessed in addition to allowing the community to reflect on the progress and possibly redirect/redefine the future direction of the initiative.

The Subduction Factory (SubFac)

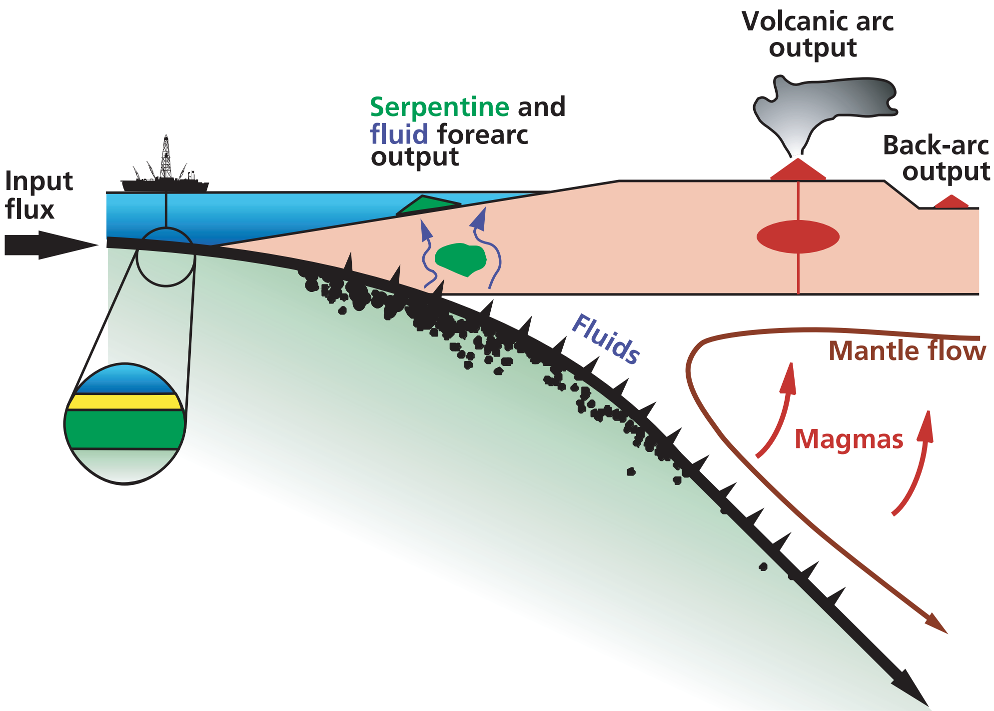


Figure 1. The Subduction Factory Initiative aims to study fluxes through the subduction zone to address three fundamental science themes: 1) How do forcing functions such as convergence rate and upper plate thickness regulate production of magma and fluid? 2) How does the volatile cycle (H_2O and CO_2) impact biological, physical and chemical processes from trench to deep mantle? 3) What is the mass balance of chemical species and material, and how does this balance affect continental growth and evolution?

1. Executive Summary

Subduction of oceanic plates causes earthquakes, tsunamis and explosive volcanism. Subduction also gives rise to beneficial products, such as ore deposits, geothermal energy and the very ground we live on. The Subduction Factory recycles raw materials from the subducting seafloor and overlying mantle, and creates products on the upper plate in the form of melts, aqueous fluids and gases. The Subduction Factory Initiative aims to study fluxes through the subduction zone to address three fundamental science themes: 1) How do forcing functions such as convergence rate and upper plate thickness regulate production of magma and fluid from the Subduction Factory? 2) How does the volatile cycle (H_2O and CO_2) impact biological, physical and chemical processes from trench to deep mantle? 3) What is the mass balance of chemical species and material across Subduction Factory, and how does this balance affect continental growth and evolution?

The Subduction Factory Initiative will proceed by focused investigations combining swath mapping of the incoming plate and fore-arc slope with both active and passive seismic experiments to image accretionary and slab structures, respectively. Heatflow measurements, magnetotelluric investigations and GPS plate and deformation rate estimates will combine with the other geophysical data to constrain the physical operation of the subduction system. Riserless drilling will provide samples of the input material seaward of the trench and output material in the forearc and arc. Riser drilling would permit deeper holes into the altered incoming crust, and riser or on-land drilling into the arc would sample a record of volcanic evolution and fluxes on the upper plate. Boreholes will be exploited to sample fluid outputs from the system. Field and analytical studies of the arc system will focus on the chemical composition and mass fluxes of lavas, melt inclusions and gases. Laboratory studies will provide element partitioning relationships, phase equilibria, and calibrations for rheological and seismological properties. A wide array of in situ observatories and multiple re-occupation GPS campaigns, coupled with a strategy for rapidly responding to major events, round out the data collection strategy.

Experiments

These diverse field and lab measurements will be integrated at every level with physico-chemical models for subduction, fluid flow, melting and melt flow. Phenomena predicted from geodynamic models will guide the early data acquisition efforts, and the data collected will provide constraints for further generations of models. In this way, modeling and observations will complement and propel each other.

Focus sites

Criteria for selection of subduction zones to be studied include the following: the margin should provide ample volcanic and seismic activity, accessibility to both input and output, along-strike variations in forcing functions, cross-arc and historical perspectives, minimal upper plate contamination of magmas, and ability to address the primary science objectives. These criteria are best met by studying two convergent margins, Central America and one of the intra-oceanic convergent margins of the Western Pacific—the Izu-Bonin-Mariana (IBM) system.

Central America is a high priority location because it satisfies the criteria and provides excellent opportunities to address all of the science themes. Forcing functions and volcanic response vary systematically and dramatically along-strike from Nicaragua to Costa Rica. Extensive carbonate subduction and extremely water-rich eruptions enable unparalleled investigation of the carbon and water cycles through subduction zones. Lower crustal exposures and high-fidelity tracer studies will pave the way to element and mass balance. Many of the Subduction Factory objectives link very naturally with those of the SEIZE science plan in Central America.

> "The Subduction Factory recycles raw materials from the subducting seafloor and overlying mantle, and creates products on the upper plate in the form of melts, aqueous fluids and gases."

Western Pacific margins provide ideal counterpoints to Central America. The slab subducting beneath Central America is relatively young, and parts of the fore-arc are sedimented. Central America offers excellent along-strike variations, but a weak cross-arc perspective. Western Pacific arcs are complementary, being characterized by old/cold slabs, carbonate-absent sediment subduction, and accessible outputs from fore-arc to back-arc. The IBM system, chosen as the other focus site, is also characterized by vigorous fluid venting from trench to rear-arc, providing samples for studying volatiles across the entire margin.

The Subduction Factory Initiative will extend over ten years from its inception, with earlier geological and geophysical field programs and theoretical institutes paving the way for later drilling, arc refraction, slab seismic and geochemical efforts. A fully integrated study of the Subduction Factory will cost $15-20M, excluding shiptime and drilling. Extensive international cooperation has and will distribute some of these costs over a number of nations. A web site listing on-going programs attracts other synergistic projects in the same area; the web site posts data before formal publication. Results are also communicated through international meetings and workshops the special publications these will produce. This science plan was updated in association with the SubFac TEI held in Eugene, Oregon, in August, 2000.

> "The rumblings and emissions at convergent margins reveal the inner workings of the Subduction Factory"

2. What is the Subduction Factory?

The rumblings and emissions at convergent margins reveal the inner workings of the Subduction Factory (Figure 1). The term Subduction Factory is used to encompass the fluxes of material into and out of subduction zones, together with the thermal, chemical and mechanical processes that shape convergent plate boundaries, the deep mantle beyond, and the air and water above. Raw materials—seafloor sediments, oceanic crust, and mantle lithosphere —are fed into the Subduction Factory at deep sea trenches. In the wedge above the slab, subducted materials are mixed with mantle, supplied by convection from the landward side of the arc. Output products—melts, aqueous fluids, metalliferous deposits, serpentine diapirs, volcanics, continental crust, gases, organic material, back-arc seafloor—emerge from the Factory on the upper plate. The remainder of the material that is processed in the Subduction Factory sinks deep into the mantle, someday to be resurrected as mantle plumes. The Subduction Factory is thus powerful but well-hidden. We can examine its raw materials and its products, but the Factory itself is hidden from view.

Subduction of oceanic plates triggers a wide array of scientifically and societally important processes. It impacts society directly because it causes earthquakes and explosive volcanism, and whereas earthquakes (and the tsunamis they spawn) kill more people, explosive volcanism can change climate, potentially affecting the global population. Most of the world's important ore deposits and continental crust—the very ground we live on—have been formed in the past by the factory. An important potential new form of energy—gas hydrates—are generated by the factory.

From a scientific perspective, the Subduction Factory is central to the operation and evolution of the Earth System. Subduction of pore fluids and hydrous minerals in oceanic sediments and altered basalt, their distillation at depth, transport through the mantle, and re-emission from arcs represents Earth's deepest hydrologic cycle, one which has a profound impact on the global budgets

Duration of the SubFac Initiative

Raw materials and products

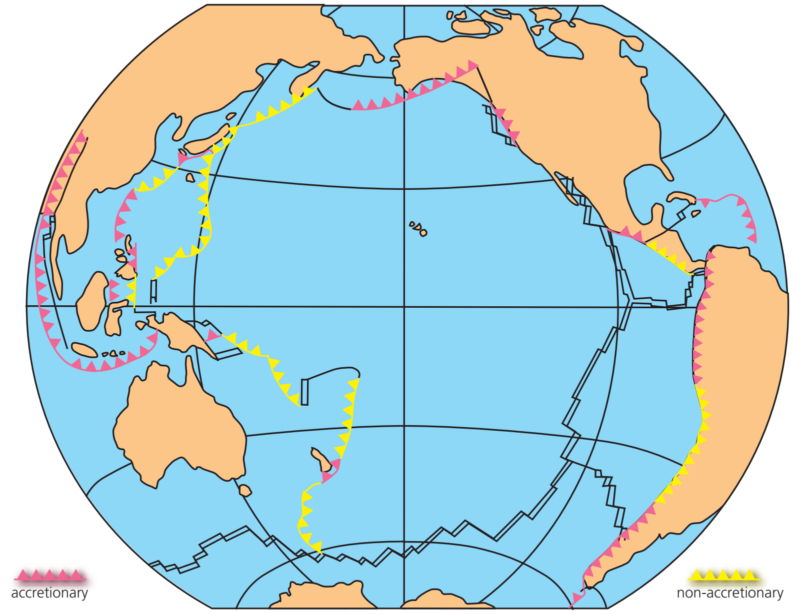


Figure 2: Trenches (barbed lines) associated with convergent margins of the Pacific, Caribbean, and eastern Indian Ocean. Red barbs identify accreting margins, where the forearc is growing seaward by offscraping of trench-floor deposits. Yellow barbs are non-accreting margins with no modern growth of sedimentary prisms. About 44% of Earth's aggregate convergent margin length of 43,000 km is non-accretionary and about 56% is accretionary. Each year a total of about 1 km^3 of upper plate material returns to the mantle, although recently recognized effects of subduction erosion may increase this volume.

of volatiles such as H_2O and CO_2. The return of subducted fluids and gases such as methane to the surface supports chemosynthetic biota, affects seawater chemistry, partially controls prism deformation, and serpentinizes shallow lithospheric mantle. Subducted ocean crust and sediments contribute to the chemistry of arc and some back-arc volcanoes, which contribute to crustal growth and provide a probe of physical and chemical processes operating deeper than can be drilled or imaged seismically. Subducted materials not returned to the surface by the Factory are carried into the deep mantle, where they alter its chemistry and rheology. And despite the central role for subduction in the evolution of the Earth and the fact that ours is the only planet where plate tectonics occurs now, how subduction begins is understood in only the broadest terms.

The Subduction Factory is the dynamic site of mass and energy exchange between the asthenosphere, lithosphere, hydrosphere, atmosphere, and biosphere, with profound implications for the evolution of the Earth's surface and interior. It is huge, operates at depth, and involves complex physical and chemical interactions, the resolution of which requires close co-operation between scientists who do not usually work together. Thus, it has been difficult to investigate processes and measure fluxes through the factory owing to the sheer scale of the problem and the poor constraints on volumes of magmas, aqueous fluids and volatiles produced. The MARGINS approach is to focus an interdisciplinary study at convergent boundaries where geological and geophysical measurements promise to constrain processes within the Subduction Factory in real time.

3. What Do We Need to Know about the Subduction Factory?

Studies of subduction zones attract a wide range of scientists because the questions are globally significant. A number of key scientific themes to be addressed at subduction zones have been identified at various MARGIN workshops, the NSF FUMAGES workshop, the CONCORD conference on riser drilling, the Avalon JOI/USSAC workshop on Crustal Recycling, and the ODP COMPLEX meeting: (1) How, why and where are new subduction zones started? (2) How are volatiles cycled through the subduction system? (3) What is the rate and mechanism of continental growth at convergent margins? (4) What is the impact of subduction on mantle evolution? (5) How does subduction lead to uni-directional changes in the composition of the continental crust? Answers to all these questions are the ultimate goal of Subduction Factory studies. Here we focus on a subset of these first-order questions that are increasingly tractable now, or that are necessary to pave the way for subsequent high priority science. At the Subduction Factory Workshop in June 1998, participants recognized the following three areas as critical for further progress.

3.1. Subduction Parameters as Forcing Functions on Factory Output

Sinking lithosphere powers the Subduction Factory, stirring the overriding mantle and bringing in mantle hot enough to melt, while also delivering ingredients essential for continental crust formation. The rate and angle of subduction and the physical and chemical properties of the subducting plate, such as its thermal structure, alteration profile, sediment load and volatile content are all likely to affect the type and quantity of Subduction Factory products. There are as many as 26 different physical parameters which vary among the world's 39 subduction zones. We still do not understand how the many independent and dependent variables control the factory output. Neither do we understand how these parameters affect intermediate and deep seismicity in subduction zones. Assessing the role of these various "forcing functions" is an important part of the Subduction Factory initiative. Along-strike variations in forcing functions within a single margin provide an efficient way to study cause and effect in the Subduction Factory. An alternative is to investigate paired margins with contrasting forcing functions.

Key scientific questions

Forcing functions

Convergence Vectors: The behavior of the subducted lithosphere can be described as a vector, defining convergence rate and dip. The convergence rate should control the rate at which many processes operate within the Subduction Factory. The most obvious connection is with input parameters, such as the flux of material and volatiles in the subducting plate delivered to the factory. Other important processes that should be simply related to convergence rates include rates of induced convection in the mantle wedge, shear heating along the slab-mantle interface, conductive heating of the subducted slab, and seismic moment.

Plate convergence rate

A looming question is whether faster convergence leads to faster growth of the arc crust. The existing growth rate estimates do not support such a connection, but they are also poorly known. In order to examine subduction rate as a forcing function, we need new approaches for measuring melt production and arc growth rates, and for using lava compositions to constrain thermal models. We also need an increasingly realistic geodynamic picture of convergent margins that includes dynamic rather than kinematic models, and a rheology

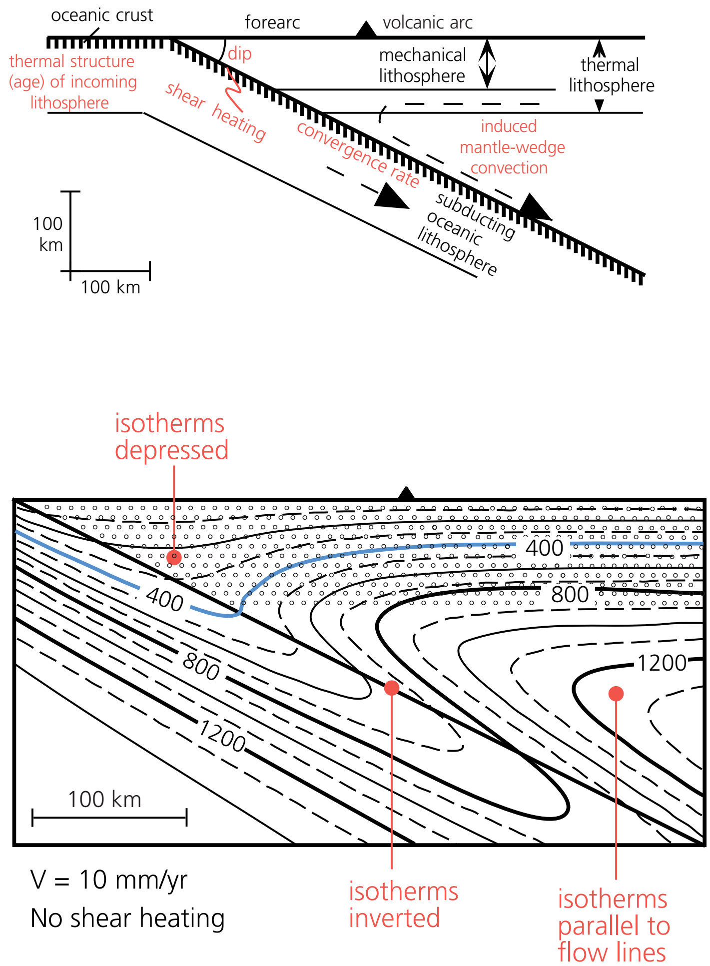


Figure 3: Controls on thermal structure of subduction zones. Upper portion shows some of the important variables in red. Lower portion is a model of subduction zone thermal structure for a plate convergence rate of 1cm/year, with important features shown in red. Modified after Peacock (1996).

Slab temperature

structure that incorporates the effects of both temperature and volatiles.

The dip of the subducted slab defines the path-length of the slab from the trench to beneath the arc. Some theoretical models also predict different mantle and fluid flow fields associated with different subduction angles. Such models should be tested by comparing their predicted behavior with lava compositions and gravity and heatflow data from well-characterized arcs.

Slab Temperature: In addition to the convergence vector, the other major control on the thermal structure of the subduction zone is the age of the subducted lithosphere.

This is because conduction - the least efficient mode of heat transfer - largely controls heating of the subducted lithosphere. Old lithospheres are thick and cold through their upper part, leading to development of an entirely different thermal structure than young lithospheres, which are thin and hot (Figure 3). Existing models predict that such different thermal structures will cause different loci in the slab for important metamorphic reactions, directly affecting fluid flow through the Subduction Factory. We know, for example, that hotter slabs lose most of their fluid mobile elements (e.g., B, Cs, Sb) before they can be delivered to the melt generation zone, but it is unknown what metamorphic reactions control this distillation of elements out of the slab. We also do not know how water behaves during this distillation, and if mantle melts are different above slabs of different ages. Very young slabs may melt and produce distinctive lavas known as adakites, but we do not know what thermal thresholds must be crossed before slab melting occurs. Since mantle and slab temperatures are central to the subduction factory output, it is desirable to study arcs with a range of parameters critical to these temperatures. A combination of geochemical tracer studies, slab metamorphic studies, thermal measurements and modeling, and seismic inversion techniques are needed to understand how slab thermal structure affects Subduction Factory operations.

Subduction Dynamics and Mass Transport to Depth: The crustal inputs to the Subduction Factory are another clear factor in controlling the mass, composition and distribution of outputs. The crustal inputs, in turn, depend not only on the supply to the trench, but also the dynamic processes that occur during subduction. Sediments may be bulldozed from the downgoing plate to form accretionary wedges, underplated beneath the fore-arc, subducted to the depths of magma generation or even joined by older material eroded from the fore-arc. The behavior of material through the upper 40 km of the subduction zone is intimately linked to the nature of the incoming sediment and rock sequence, its compaction dewatering, diagenesis and cementation, fore-arc deformation, and the nature of the seismogenic zone. Understanding all of these processes are objectives of both the Subduction Factory and SEIZE initiatives. The balance between accretion and subduction of sediments is also essential to resolving whether the continents are growing or shrinking, and to determining the flux of sediment-hosted chemical species into the mantle and back out the arc.

Many tools are required to estimate the material balance across the convergent margin. Seismic imaging can reveal the presence of a wedge-shaped sediment pile, or underplated sediment packets, but constrains neither the age of the sediments nor their source. Drilling and subsequent analyses can show if fore-arc sediment wedges are paleo-accre-

Slab melts

Fate of subducted material

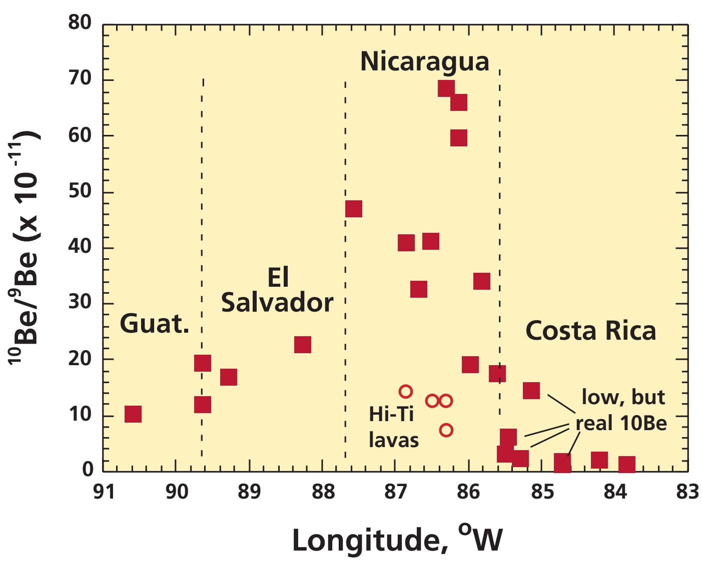


Figure 4: Plot of $^{10}Be/^{9}Be$ for very young Central American basalts and andesites, plotted as a function of longitude (see Figure 12a for location). Because ^{10}Be is produced cosmogenically in the upper atmosphere, high ratios of $^{10}Be/^{9}Be$ in fresh young lavas from Nicaragua indicate that virtually all the sediments carried into this trench are subducted to where magmas are generated, more than 100 km deep. Low $^{10}Be/^{9}Be$ in young Costa Rican lavas indicates that such sediments are not being delivered to the deep mantle beneath this arc segment, or are being diluted by eroded material.

tionary prisms, deformed piles of arc-derived sediments, or imbricate thrust packets of offscraped sediments. Neither technique can sample or image deeply enough, however, to constrain the full extent of accretionary prism dynamics, even with riser drilling. To investigate processes at greater depths, geochemical "imaging" is helpful. For example, only the youngest part of the subducting sediment column (<8-10Ma) contains ^{10}Be, and so high ^{10}Be concentrations in arc volcanoes indicate sediments subducted to depths appropriate for melt generation (Figure 4). It is also possible to infer the partitioning of ^{10}Be between frontally accreted and subducted sediment. If a discrepancy exists between what issues from arc volcanoes and what is thought to be subducted, then the geochemistry, drilling and seismic imaging may be used together to infer underplating or forearc erosion. In this way, volcanoes become flow monitors for material subducted past the seismogenic zone, into the Subduction Factory and beyond.

Role of the upper plate

Upper Plate Thickness: The thickness of the overlying plate, including both lithosphere and crust, is another forcing function because it affects asthenospheric flow in the mantle wedge and its thermal regime. The overlying plate also controls the height of the mantle melting column beneath the arc, and so limits the amount of melting that can occur through decompression (Figure 5). Arc lavas are consistently the most fractionated and petrographically complex on earth. This must be in part a reflection of the structure of overriding lithosphere. Aside from crustal thickness variations, we know little about the thickness of the upper plate, mostly because traditional seismic methods do not resolve well lithospheric thickness at convergent margins. This partly reflects the complex rheologies and thermal structures expected. For example, lithosphere is typically cold but strong, while asthenosphere is relatively hot but weak. The forearc mantle, however, may consist largely of serpentine, which is both cold and weak and so is not well described by this terminology. It may be more useful for understanding convergent margins to characterize the asthenosphere as the convecting portion of the mantle. Given these complications, how can we best map the boundary between the asthenosphere and lithosphere in the mantle wedge?

3.2. The Volatile Cycle through the Subduction Factory

Volatiles in subduction

A major goal of the Subduction Factory is to understand the deep water cycle of the blue planet and the role of subduction on Earth's natural carbon cycle. Water and to a lesser extent CO_2 control the physical and chemical behavior of subduction. The effects of water on deformation, development of the décollement and behavior of the seismogenic zone in the 0-40 km depth interval are discussed extensively in the SEIZE Science Plan. Subduction Factory efforts will complement those of SEIZE at shallow depths, and extend to greater depths along the slab, to the arc and back-arc melting regimes, and to the deep mantle.

What is the distribution of water and CO_2-bearing alteration phases in the incoming ocean plate? The proportion of volatiles delivered to the subduction factory from the igneous slab is poorly known, but is expected to be larger than that in the sedimentary veneer when considering bound volatiles subducted to sub-arc depths. Paired CORKed sites on ocean ridge flanks reveal shallow sea floor hydrology, which can be combined with petrological and seismological studies to better investigate alteration and volatile budgets of the oceanic crust. ODP sites in exposed oceanic peridotites indicate that sea-

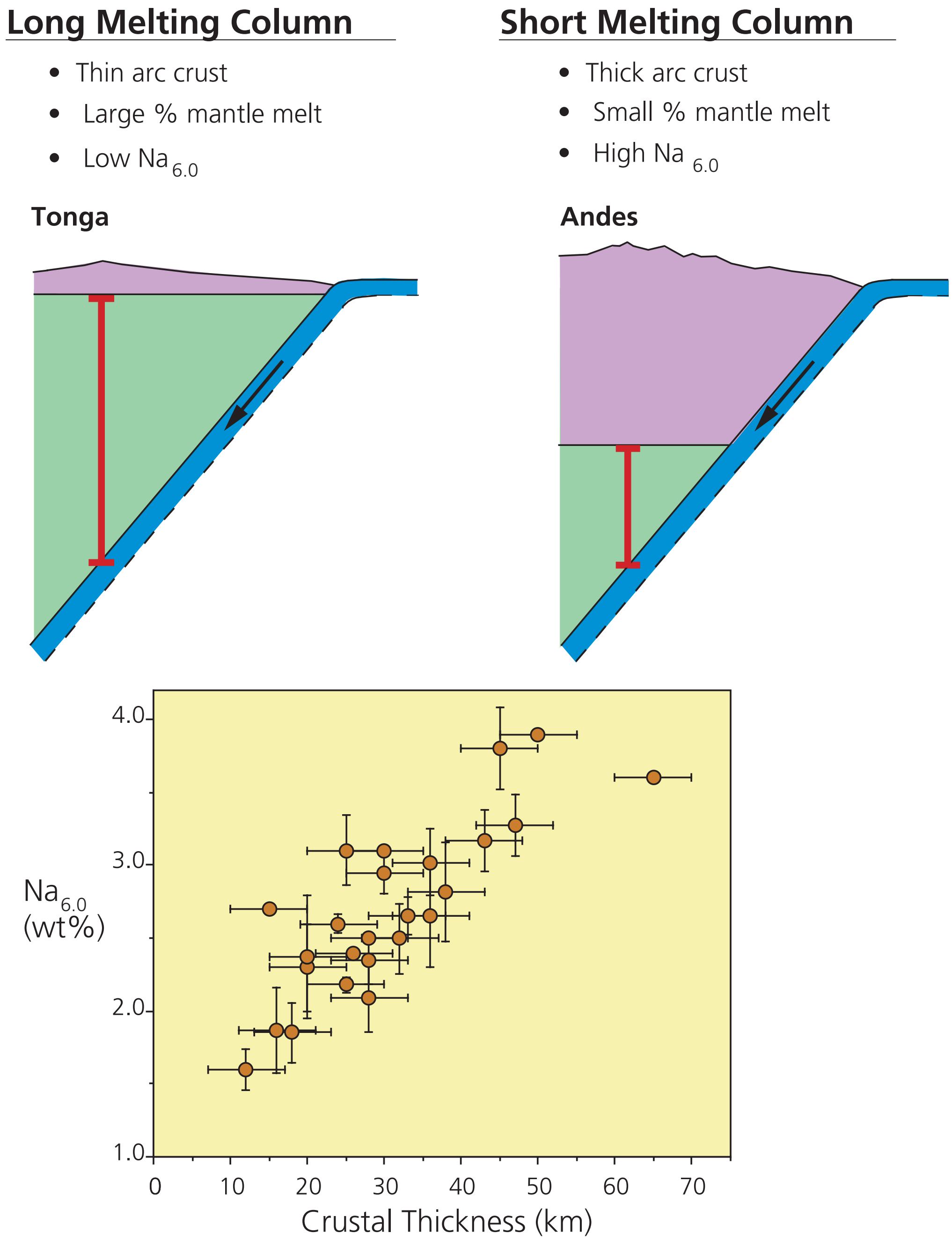


Figure 5: The melting column concept for volcanic arcs, where the amount of melting reflects the ascent height through the asthenosphere. Thin arc crust and lithosphere allow long melting columns and high degrees of melting in the mantle wedge. High degrees of melting, in turn, produce low Na basalts, as at mid-ocean ridges. Conversely, thick arc crust and lithosphere leads to short melting columns and less melting. This model could explain the global correlation between arc crustal thickness and the average Na content of arc basalts ($Na_{6.0}$ is the Na_2O concentration for basalts with 6% MgO). From Plank and Langmuir (1988).

Melting column

water penetrates to great depth. Heat flow and pore water chemistry from ODP sites outboard of some trenches indicate that seawater circulates to basement, presumably along fractures reactivated as the slab bends into the trench.

Aging of the oceanic crust

Understanding aging of the oceanic crust, in general, is critical for reconstructing the volatile cycle at convergent margins. In particular, a focused experiment must include good heat flow surveys and drilling at least 300 meters into oceanic basement (the upper oxidative alteration zone) at more than one locality outboard of the trench.

Compaction in the uppermost part of the subduction zone wrings from the slab water that is trapped in pores and fractures. More water is released as minerals in the slab breakdown and reform in response to increasing pressure. These reactions also add selected elements, including hydrocarbons, to the water making its way back to the surface along faults and through diffuse fluid flow.

Gas hydrates

Hydrological and geochemical studies of aqueous fluids venting in the fore-arc are critical for investigating gas hydrate composition and stability on convergent margins, the deep biosphere, the distribution of chemosynthetic vent communities and deformation within the seismogenic zone. Such studies are also essential to constrain the fluxes subducted to greater depth. Experimental studies of element partitioning between aqueous fluids and solid phases in the slab at low P and T are especially critical if we are to use aqueous fluids to interpret conditions occurring at depth. We also need dehydration experiments on natural mineral mixtures, including clay-rich, carbonate-rich, silica-rich, and carbonaceous sediments.

What is the extent of fore-arc serpentinization? While the serpentinization of the

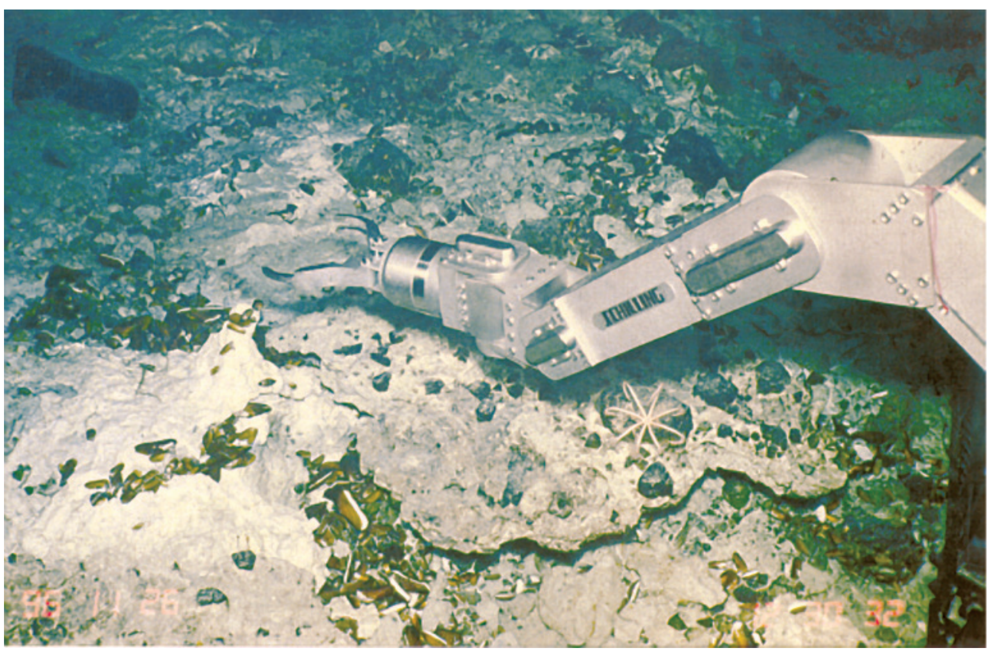


Figure 6: Shinkai 6500 submersible bottom photograph of biological communities at the summit of a serpentine mud volcano in the Mariana forearc. Slab-derived fluids issuing from the seamount support communities of mussels, gastropods, worm tubes and galatheid crabs. The base of the manipulator arm is ~15 cm in diameter. Photo provided by the Japan Marine Science and Technology Center (JAMSTEC), courtesy of Dr. Kantaro Fujioka.

shallow fore-arc mantle may be critical in controlling slip behavior across the seismogenic zone, it is also critical for material processing through the Subduction Factory. Serpentinite bodies are exposed across a wide section of the Izu-Bonin and Mariana forearcs, and represent a major sink for water distilled out of the slab (Figure 6). Any effort to quantify the flux of water delivered to the depths of magma generation will need to account for the volatile flux out of the slab to the overlying serpentinized mantle. This leads to several key questions. Is sub-surface serpentinization typical of all arcs, but imaged and sampled easily only in sediment-starved and structurally distressed margins? Can laboratory calibration of P and S wave velocities for serpentinite, amphibolite and tonalite lead to seismic methods for determining the subsurface distribution of serpentinite?

The serpentinites, and the aqueous fluids they host, record the volatile and chemical losses from the slab at about 20-50 km. They thus provide an important constraint on the effects of shallow subduction processes on the composition of the slab as it descends to greater depths. The effects of subduction on the shallow lithospheric mantle may be as profound as on the deeper mantle downstream of the volcanic arc.

What is the effect of subducted volatiles on mantle seismic velocity and viscosity, slab embrittlement, and intermediate depth earthquakes? Subducting slabs acts as heat sinks for the overlying mantle, and cool the adjacent mantle. The sub-arc asthenospheric mantle thus has an unusual thermal structure: it is hottest in the middle of the convecting mantle wedge and cools towards both the overlying lithosphere and downgoing slab. P-wave tomography across Japan shows an inclined layer parallel to and just above the subducting slab at about 75 to >150 km depth, which is lower velocity than the slab, but higher velocity than the shallower parts of the wedge (Figure 7). Convection models that use a temperature-dependent viscosity structure show a higher viscosity layer in this cooled mantle, creating a halo of cold, stiff mantle that couples effectively to the down going slab. But what is the effect, if any, of volatiles from the slab on the seismic properties and viscosity structure of the mantle wedge? Identifying either the presence or absence of a volatile signature on the physical properties of the mantle wedge would be extremely useful if this information could be translated to limits on volatile form (hydrous minerals, free aqueous fluids), concentration or distribution. Realistic experiments, particularly those that examine the combined effects of temperature, melt, and volatile distribution are difficult, but essential.

Volatiles and seismicity

The Seismogenic Zone initiative focuses on earthquakes occurring shallower than about 50 km. A significant fraction of seismic energy at convergent margins, however, is released in deeper events that occur within the subducting plate. Intermediate depth earthquakes, between about 50 and 350 km, often appear to be located near the top of the subducting plate. Are these earthquakes due to slab embrittlement during prograde metamorphism and dehydration of the altered oceanic crust? If so, then the frequency and depth distribution of intermediate depth earthquakes in subduction zones with different thermal parameters provides important clues about slab metamorphism, dewatering and rheology beneath, and also deeper than, the volcanic arc.

What is the stability of key hydrous and calcareous phases in the subducting slab and mantle wedge? Most existing models of arc magmagenesis emphasize the role of amphibole dehydration in the subducting basaltic crust and of amphibole and phlogo-

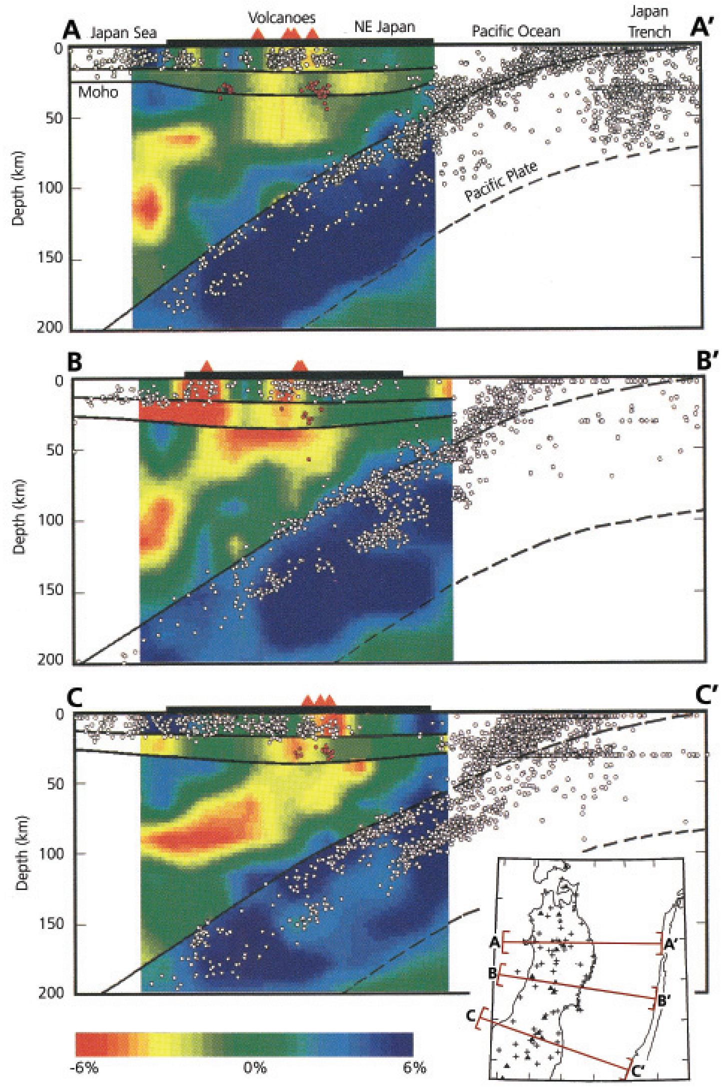


Figure 7: Mantle wedge tomography across Honshu, Japan, after Zhao et al. (1992). Earthquake loci are projected as small open circles, relative mantle Pwave velocities are shown in colors, from red (slow) to blue (fast). Note that there are two parallel zones of earthquakes, with the upper one defining the upper part of the plate. Note that the zone of "slow" mantle, inferred to reflect partially molten zones, lie several tens of km above the subducted slab.

pite stability in the overlying mantle. Recent experimental work, however, has revealed a menagerie of minerals that are stable in sediments, altered basalt and mantle peridotite compositions to relevant pressures and temperatures. Minerals such as phengite, lawsonite, aragonite, zoisite and chloritoid may be hosts for water and CO_2 in the subducting slab. It is critical that we understand the stability of phases in real systems during prograde metamorphism, as well as the partitioning of elements between these phases. In additional to laboratory experiments, seismic methods may also help to reveal the mineral reactions occurring in subducting slabs (Figure 8).

What is the role of water in arc magma generation and volcanic explosivity? Of all the volatile species, water most affects the mantle solidus. It is clear that arc lavas are richer in water than lavas from other tectonic settings, and that water's depression of the mantle solidus abets melt generation in the mantle wedge. The recent discovery of water-poor (but non-degassed) arc magmas, however, means that melting is sometimes anhydrous, probably driven by decompression melting as in other tectonic settings. This raises questions as to the different roles of water and decompression in driving mantle melting in the subduction factory. Further analytical studies of the intrinsic water content of arc magmas, combined with further experimental studies of the effect of water on peridotite melting, are needed to better understand the role of fluids and mantle flow in arc magma generation and crustal growth.

In addition to melting in the mantle, water also affects magmatic evolution in the crust and the explosivity of volcanic eruptions. Because the solubility of water in melts decreases rapidly at pressures below 1-2 kilobars, much water may be lost as melts ascend. This leads to rapid crystallization of minerals and further degassing. At some point, the crystallizing melt is unable to release its water peacefully, leading to violent eruptions. Violent eruptions severely impact nearby populations, and hazard mitigation requires understanding the links between melt chemistry, dissolved water, and how melt ascent and cooling affects degassing. Direct correlations have been found between water content and explosivity. Further analytical studies, along with studies of the dynamics of magma degassing, are needed to develop models that show how magmatic water controls shallow fractionation and explosive eruptions.

Volatiles and the dynamics of volcanism

How is CO_2 recycled in subduction zones? Arc magmas are clearly enriched in $CO_2/^3He$ relative to midocean ridge basalts and ocean island basalts, and more than 80% of the CO_2 in arc magmas may be derived from the subducting slab. CO_2 released from arcs is a major return flux of subducted CO_2 to the atmosphere, comparable to the ocean ridge flux, and as such, is a potential driver of intermediate-term climate fluctuation. The mass of carbonate and organic material subducted, however, is extremely variable among convergent margins. Do arc magmas contain more CO_2 where more sedimentary carbon is subducting? How much volcanic CO_2 is derived from carbonate subducted as veins in the oceanic crust? Where do decarbonation reactions happen in the slab? What proportion of the subducted carbonate is recycled into the deep mantle? In order to answer these fundamental questions, integrated studies are needed of volcanic gases and melt inclusions, CO_2 solubility and degassing, carbonate metamorphism, and carbon budgets in the subducting plate.

Ore formation

What is the role of subducted volatiles and trace metals in ore-forming processes at convergent margins? Hydrothermal activity and ore-formation have been observed in the Kermadec, Hellenic, Izu-Bonin, Tonga, Mariana, and Bismarck arc systems. Isotopes and trace elements indicate that a significant fraction of the ore-forming fluids and the metals they carry have been exsolved from volatile-rich arc magmas rather than leached by seawater during hydrothermal circulation through the crust, as for ocean ridge deposits. These ore deposits thus represent a little known aspect of the mass and element fluxes out of the subduction factory. They also provide a unique window into economically significant ore-forming processes. Many world class ore deposits from the Tertiary through the Archean (e.g., Kuroko, Noranda, and Sulfur Springs) are hosted by felsic volcanics that may have formed in a convergent margin setting.

3.3. Towards Mass Balance

An ultimate goal of Subduction Factory research is to understand how subduction builds the continents and affects mantle composition through time. A quantitative mass and element balance through the Subduction Factory would achieve this goal. To realize mass balance, however, we need to better understand how

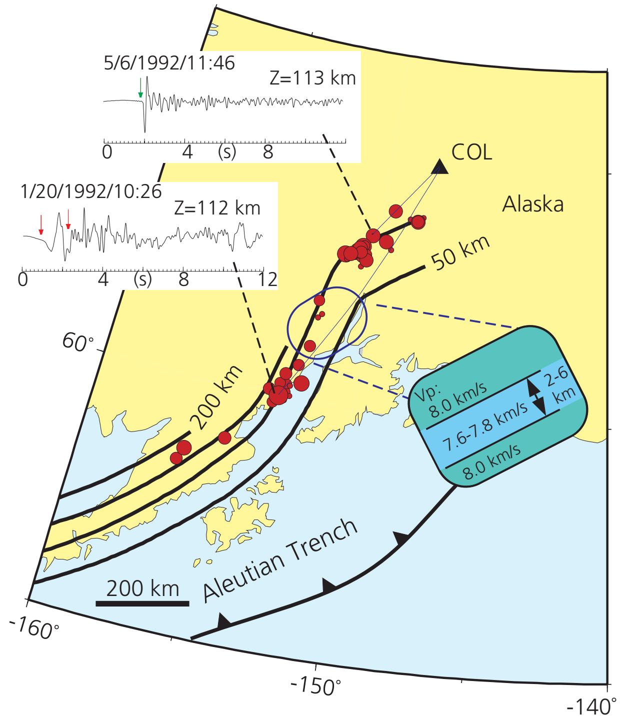


Figure 8a: Effect of the subducted slab beneath Alaska on regional seismic waveforms that travel along the subducted crust (Abers and Sarker, 1996). Red circles denote earthquakes at 100-150 km depth within the slab. Seismograms recorded at COL are simple for P waves that do not travel along the slab (green arrow), but pulse dispersion characterizes waves that travel along the slab (red arrows). Inset shows structure needed to produce this effect, a layer of subducted crust, ~5% slower than surrounding mantle. Velocities are consistent with lawsonite blueschist (Helffrich, 1996) but not gabbro or eclogite.

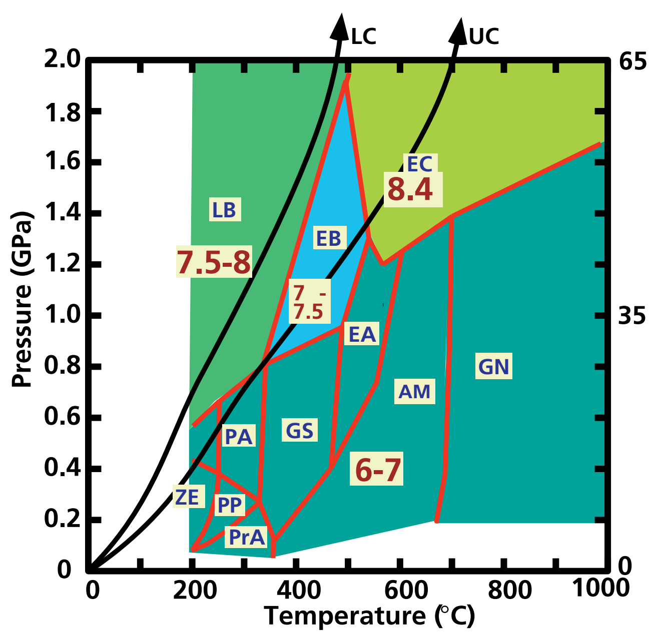


Figure 8b: Metamorphic facies for wet basalt, showing seismic P-wave velocities (km/s), from Peacock (1993) and Helffrich (1996). Black lines show P-T trajectories of subducting material for upper (UC) and lower (LC) crust. For comparison, mantle peridotite should have velocities of 8.0-8.2 km/s under similar conditions, and unaltered crust near 6.5 - 7.0 km/s. The seismic wave distortion measurements shown in Figure 8a are consistent with lawsonite blueschist (LB) or with mixtures of eclogite and basalt (EB).

energy and matter move through the Subduction Factory. The greatest uncertainty is in the estimates of material output rates, such as fluid fluxes to the forearc and magma fluxes to the arc crust. In particular, there is a critical need to know the volumes and compositions of middle and lower arc crust. Crustal growth and mantle evolution models also rely, in part, on correct interpretation of the geochemical and petrological signatures of arc lavas. Many studies show that chemical components are fractionated from each other during distillation from the slab and transport through the mantle to the site of melt generation. Using element fluxes to obtain mass fluxes requires a better understanding of element partitioning than currently available. Thus the route to mass balance is paved through studies of lower and middle arc crust and experimental and theoretical studies of geochemical tracers.

Mass balance

What are the volume and production rates of middle and lower arc crust? Volumes and production rates of arc crust are critical for determining the fluxes out of the Subduction Factory, as well as for understanding how the continents grow. Estimating volcanic volumes is relatively straightforward, and requires integrating the volume of the volcanic edifice and surrounding volcaniclastic apron. On the other hand, the intrusive contribution to the arc is obtained from crude estimates of proportionality to the extrusive volume. Recent seismic refraction studies, with improved resolution, provide some new constraints. The seismic structure of the Izu-Bonin arc includes a mid-lower crustal layer with Vp=6 km/sec, which, based on seismic properties as well as exposures of correlative rocks in the Tanzawa Mountains of Japan, may consist largely of tonalite (Figure 9). Seismic imaging of the Kyushu-Palau Ridge, a remnant arc isolated by Shikoku Basin spreading, reveals a similar Vp=6 km/sec layer, but only 2/3 the thickness of that imaged in the Izu-Bonin arc. These possibly tonalitic layers are in contrast to the largely basaltic lavas that erupt, and the mafic cumulates that are expected. Seismic studies of crustal structure, and experimental calibration of relevant seismic velocities, will be essential for constraining the volume of buried arc crust and crudely averaging its bulk composition. Direct sampling and analysis of this layer where tectonically exposed will be necessary. Mapping and dating of volcanic and plutonic rocks is also necessary to convert volumes to production rates.

Crust composition

What is the composition of the middle and lower arc crust? Numerous studies of the volcanic veneer of the arc crust show that the primary melt extracted from the mantle is mafic. The few exposed middle and lower arc crustal sections studied, however, are highly heterogeneous in composition. In some localities, lower and middle crust have compositions similar to the lavas, while in others they do not. Evidence from the Aleutians indicates that while the parental lavas are dominantly basaltic, the exposed plutons are mainly intermediate to felsic; this is consistent with seismic structure of the Izu-Bonin arc discussed above. Thus different processes or different primary magmas may produce intrusive and extrusive rocks. This is important for understanding continental genesis, because the tonalitic plutonic rocks have compositions similar to average continental crust, whereas basaltic lavas do not. Field studies, geochronology, petrology and tracer geochemistry studies will be central in addressing this issue. Exposed plutons in the Aleutians, the Cordillera de Talamanca in Costa Rica, Kamchatka, the Tanzawa Mountains of Japan, the Kohistan terrane of Pakistan, and the accreted Talkeetna arc in Alaska are places where deeper crustal sections can be studied.

What is necessary to translate element fluxes to mass fluxes? Some mass balances

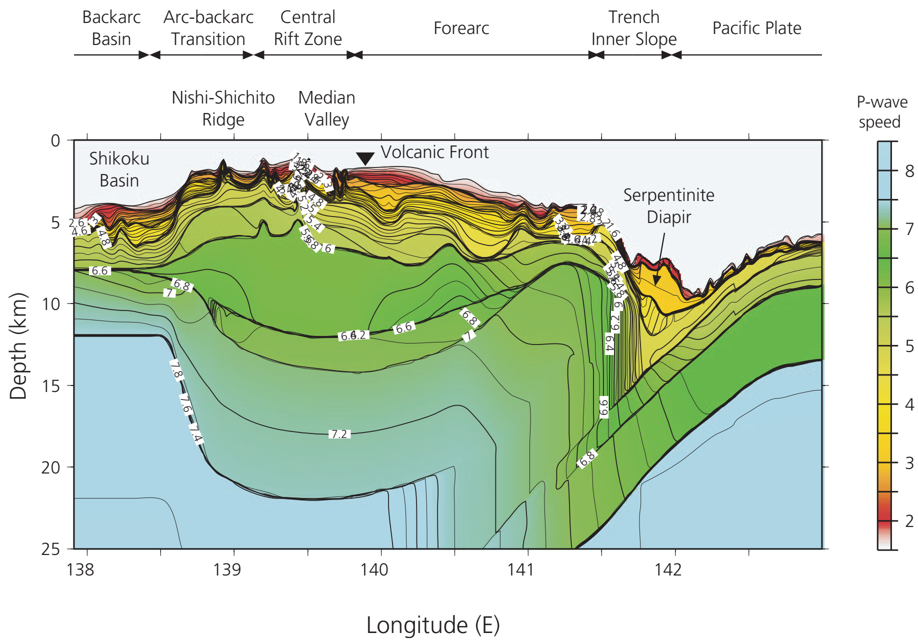


Figure 9: P-wave velocity structure of a typical intra-oceanic arc, measured by detailed OBS studies across the IBM arc at 32° 15' N. Contours represent lines of constant velocity (C.I. = 0.1 km/s; drawn thicker at 0.5 km/s intervals). Velocity structure is color-coded (after Suyehiro et al., 1996). See Figure 14 for approximate location.

Mass fluxes and geochemical tracers

are already available for a few chemical species at a few convergent margins. Various estimates indicate 20-50% of some elements (Th, Be, etc.) in subducted sediment are recycled to the arc. How do these elemental fluxes relate to the flux of mass from the slab to the mantle wedge? In theory, every geochemical process must obey mass balance, where the starting composition and fluid composition are related by the partition coefficient and fluid fraction. If we know the starting and final compositions and the partition coefficients, then we can calculate the mass fraction. In this way, geochemical tracers can constrain the mass fluxes of processes. In order to approach mass balance in this way, however, we need to determine the partition coefficients of crucial tracers in melts, solids, melts, and aqueous fluids through a wide range of P, T and composition space. High priority tracers that require better partitioning data are stable isotopes (B, Li, Cl, Be) the U-series nuclides (U, Th, Ra, Pa) and radiogenic parent-daughters. We also require experimental and partitioning studies of key high pressure phases in the subducting slab, such as lawsonite, phengite, and carbonates.

4. How Will We Study the Subduction Factory?

4.1. The MARGINS Philosophy

The Subduction Factory Initiative is a component of the MARGINS program. The MARGINS approach concentrates resources on areas targeted for intense, multidisciplinary research. In these focus areas, interaction between researchers involved in field data collection, numerical simulation and laboratory analysis promises unparalleled synergism necessary to understand complex natural systems such as the Subduction Factory. The operation of the Subduction Factory involves lithospheric deformation, mass fluxes, sedimentation, melts, and aqueous fluids. The MARGINS philosophy is realizing the goals of the Subduction Factory Initiative by sponsoring coordinated, interdisciplinary investigations in these areas.

4.2. Strategy for Implementation of the Subduction Factory Initiative

The fundamental goal of the Subduction Factory Initiative is to understand relationships between input and output mass and energy fluxes through a subduction zone, and to use this information to address the fundamental science questions outlined above. Realizing these goals requires a theoretical framework that quantitatively reproduces the observable consequences of plate subduction. Because subduction zones are among the most complex components of the solid earth system, achieving this goal will require a coordinated effort by a wide range of earth scientists interacting as members of an interdisciplinary team. The purpose of this section is to suggest guidelines for organizing the wide range of necessary studies.

Integration of the diverse science activities at a given convergent margin should lead to a robust physico-chemical model for how the Subduction Factory operates. We see the next generation of Subduction Factory models as progressing from preliminary model development to data acquisition to construction of refined models. For several convergent margins, sufficient data exist such that work can begin to develop specific physical and chemical models. Models will reveal areas of uncertainty to be addressed by subsequent field campaigns, laboratory analyses, and experiments. These results will constrain the construction, testing, and refinement of the next generation of models. The ultimate success of the Subduction Factory Experiment will be judged by the extent to which models become increasingly comprehensive, can be tested from the observables, and are able to predict behavior at other subduction zones. This requires an interdisciplinary scientific dialogue that promises to result in a quantum leap in our understanding of forcing functions, volatile cycling and mass balance in the Subduction Factory.

A series of early Subduction Factory Theoretical Institutes should focus on how best to develop the physical and chemical models. The Institutes should result in discussions of what geochemical and geophysical data are needed to drive the field and laboratory efforts. Periodic Subduction Factory Theoretical Institutes will maximize scientific team efficiency and recruit new team members. The first of these was held in Eugene, OR in August 2000; the special volume is now in proof.

Guidelines for organizing SubFac studies

4.3. Field, Laboratory, and Experimental Efforts

A wide range of data is needed to constrain and test physical and chemical models. Coverage for many of the geophysical methods should extend seaward of the trench to include the incoming plate. This is necessary for completeness, but more importantly as a means to evaluate possible deep hydration and serpentinization of the llithospheric mantle of the incoming plate.

4.3.1. Bathymetry and Swath Mapping

Improved swath mapping techniques are providing detailed and evocative bathymetric images of the subducting plate and the leading edge of the upper plate, along with submarine portions of the arc and backarc (cross-chains and spreading centers). Such images are extremely useful for Subduction Factory research in a number of ways. They can identify fault scarps formed as the plate bends into the trench, where downdropped grabens may become sediment-filled buckets, and horsts may affect the faulting structure of the upper plate. The faults themselves may be conduits for seawater flow to basement. Bathymetric images also help to identify places where smooth sedimented sea-floor vs. rougher topography (seamounts or ridges) is being subducted. Swath mapping reveals the response of the leading edge of the upper plate to topographic perturbations on the incoming plate. The images provide clues to processes such as prism evolution, frontal accretion, development of the deformation front, and subduction erosion, all important for understanding subduction dynamics and mass transport to depth. In non-accretionary margins, swath mapping can reveal the size, distribution, and to some extent structural setting of serpentinite mud volcanoes. In either case, swath mapping is a useful tool for identifying regions likely to be structurally complex enough that 3-D seismic surveys are important.

Bathymetric imaging

4.3.2. Seismic Methods

Active source seismology

Active-Source Seismology: Images and seismic velocities are obtainable at scales useful for probing the Subduction Factory to depths of about 25 km using newer experimental techniques and focused observational programs. Below 25 km, depth and resolution are limited by the difficulty in propagating broadband sound to great depths, and passive sources (seismicity) becomes the more powerful tool. Active source imaging can elucidate the top of the down-going slab, delineate structures within the base of the overriding plate, and define structural and velocity details within the forearc and parts of the arc-mantle wedge. This is true for accretionary margins, where the subducted material may either be underplated or carried deep into the Subduction Factory. For many non-accretionary forearcs, imaging will be difficult, but low velocities associated with serpentinite bodies should be mappable. In addition, the initial volatile losses within the upper part of the oceanic crust will be detectable given sufficient velocity resolution. Recent seismic programs to study ocean ridges are applicable to the subduction factory, including active-source tomography.

3-D seismic imaging

Seismic sources must be large to penetrate to the needed depths and contain a broad-band spectrum of energy to preserve resolution and allow waveform inversions of the reflections. The best way to obtain high-quality images and velocities is by using 3-D seismic reflection acquisition methods and prestack depth migration. These techniques require high quality data as well as high-performance computing capability. Multichannel seismics, particularly 3-D acquisition and processing, have been shown to provide high-quality images of the décollement and structures above and below. For instance a 3-D data set from Barbados directly mapped the location of aqueous fluids along the décollement as well as in fault ramps splaying into the overlying accretionary prism (Figure 10). Where the structures above the seismogenic zone are more complex, 3-D methods provide the essential first order corrections for the overlying structure. If the shallow structure is not properly accounted for, reflection amplitudes and waveforms of deeper events will be severely distorted.

Reflection and refraction techniques become more powerful when combined. Closely spaced ocean bottom seismographs/hydrophones (OBS/H) along modern normal incidence reflection lines have been used to extend structural imaging to depth as well as provide unique velocity data. These data also provide background velocities to combine with reflection waveform analysis. Active-

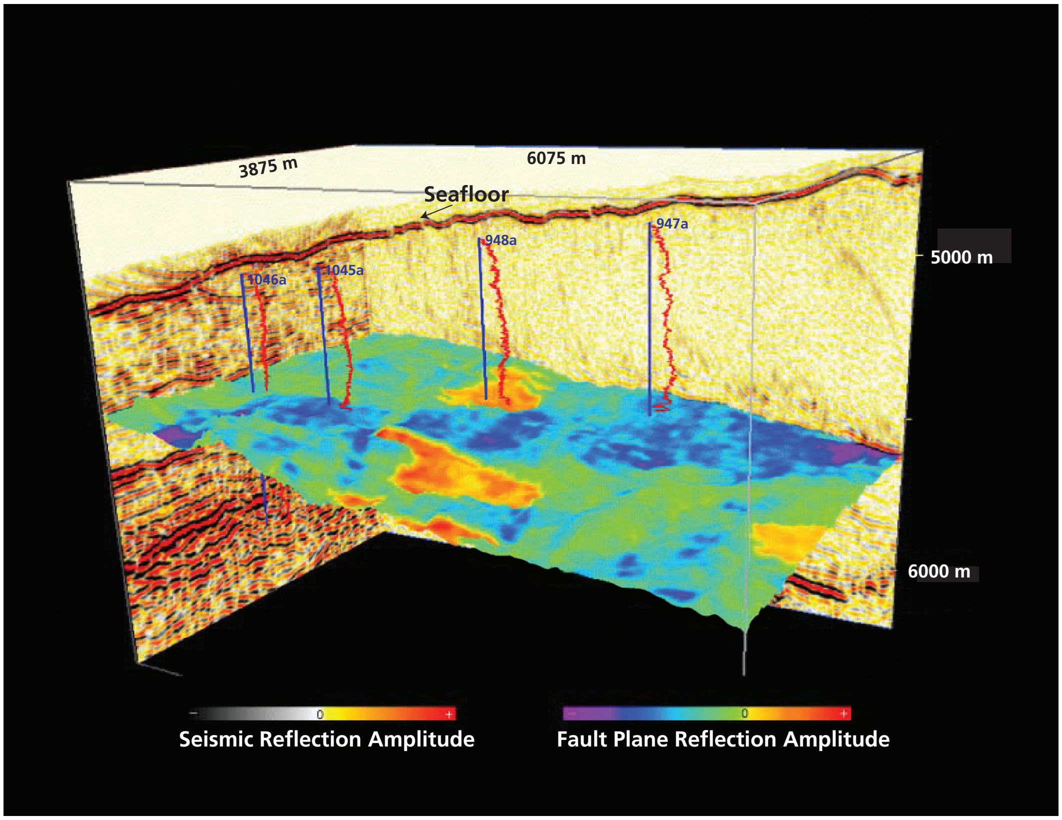


Figure 10a: Three-dimensional representation of a portion (approximately 4x6x6 km) of an accretionary prism using offshore Barbados in the Lesser Antilles as an example. Variations in the amplitude of seismic reflections reveal the shallowly-dipping plate boundary between the Caribbean (above) and the subducting Atlantic seafloor of the underlying North American Plate which allow subtle variations in fluid-rich and fluid-poor parts of the plate boundary to be studied. Modeling of reflection amplitudes and results from borehole density logs from ODP Legs 156 and 171A (red curves) indicate that the purple-green-blue reflection response is from a thin layer of low density and seismic velocity within the fault zone that probably corresponds to fluid-rich parts of the fault. Orange and yellow define areas dominated by positive-polarity waveforms, and may be areas of the fault that are relatively strong and free of fluids (Shipley et al. 1994).

source tomography has been used to map the structure of a seamounts, young oceanic crust, and rifted oceanic crust using 3-D arrays of closely-spaced OBSs with either conventional surface sources or explosive bottom sources. Similar experiments can help constrain shallow volatile losses from the subducting plate and the degree of serpentinization of non-accretionary forearcs.

Passive-Source Seismology: The wave trains of seismic signals sampling slabs can provide unique information about the structure and composition of subduction zones, at depths relevant to magmagenesis and tectonic driving forces. The development of high-fidelity broadband recording has made it possible to gain far more information from earthquake recordings than previously, particularly from the late parts of seismic signals.

At regional event-receiver distances, subduction zones produce several unusual

Passive source seismology

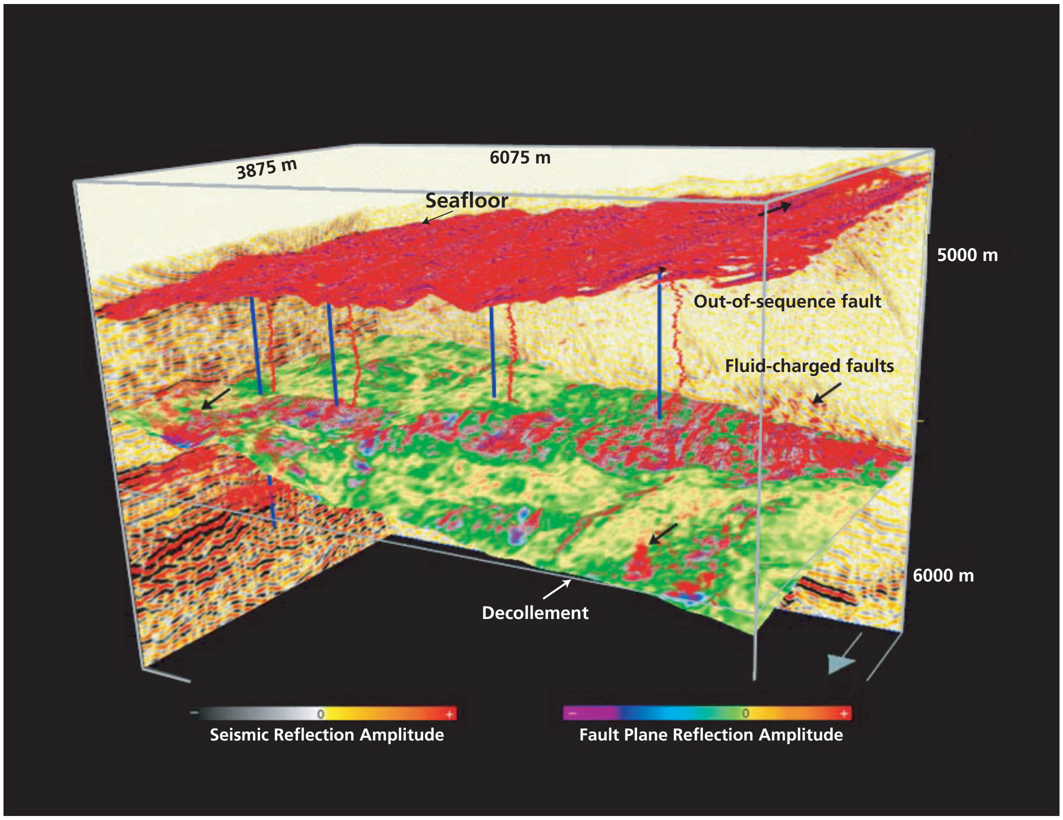


Figure 10b: Three-dimensional volume display of opacity along the plate boundary (décollement) of the Barbados accretionary prism. Seismic modeling and density legs from ODP Leg 156 and 171A (red curves) indicate that the purple-green-blue reflection response is from a thin layer of low density and seismic velocity within the fault zone. The reddish zones show the location of similar reflection waveforms in the overlying sediment volume. Speculation is that water is leaking from water-rich portions of the décollement rich (the purple-blue regions), charging the overlying sediments (Bangs et al., 1998; submitted).

Teleseismic wave trains

seismic phenomena. Large P-to-S and S-to-P conversions are commonly observed, which reveal boundaries of the subducted crust and the associated material contrasts. These conversions map boundary locations at accuracies of a few km, and provide a good picture of the relationship between the earthquakes usually used to define subducting slabs and the actual material boundaries at depth. Body waves traveling along slabs are also severely distorted or dispersed, a phenomenon that is used to constrain otherwise inaccessible properties of the subducted plate such as seismic velocities within subducted crust and the thickness of that layer. These measures can provide in situ constraints on the extent to which the basaltic crust metamorphoses to eclogite, and the depths to which it persists at blueschist facies. Finally, large temperature variations in the subducting slab and mantle wedge generate strong changes in seismic attenuation, which is now observable over a wide range of frequencies. Attenuation studies can provide constraints on temperature variations beneath arc volcanoes independent of those provided by velocity tomography.

Teleseismic wave trains reveal strong

converted-wave signals from the subducting slab at overlying stations, such as P-to-S and S-to-P conversions. These signals, usually analyzed as receiver functions, provide direct information on the location of the slab and other discontinuities, and on their impedance contrasts. They also provide sensitive measures of Poisson's ratio—useful because serpentinite has a anomalously high Poisson's ratio. Another kind of observation is provided by shear-wave splitting measurements, which constrain the flow-induced fabric of the mantle to the extent that olivine crystals align and produce bulk anisotropy. These observations provide tests of dynamical models in the mantle wedge and elsewhere. Both of these measurements are now being made routinely from portable PASSCAL-type deployments, and are rapidly expanding our understanding of the Earth's deep interior.

Requirements for Seismic Imaging of the Mantle Wedge: A good distribution of earthquakes and locations for seismic stations is essential for passive imaging of upper mantle structure associated with the Subduction Factory. Ideally, an arc would show a high level of seismic activity throughout the upper mantle to depths of ~600 km, and a broad land region for operating a land seismic network. In practice, the sub-arc magma production region can be well imaged as long as earthquake activity extends beneath the volcanic front to depths of 150-200 km. In addition, ocean bottom seismographs (OBSs) may be used in lieu of land seismic stations for arcs with limited land exposure, if seismicity rates are high. Some OBS deployment in the forearc and backarc are generally necessary in most arcs to image a wide region. Table 1 lists the seismicity rates at various depths for the arcs under consideration.

Tonga shows the highest seismicity rate, with seismicity distributed throughout the upper mantle, but would require an OBS deployment. The Mariana and Izu-Bonin slabs also show seismicity throughout the upper mantle, but have lower seismicity rates, and would also require OBSs. Japan has good intermediate depth seismicity and an exceptionally dense seismic network, allowing the best detail in tomographic images (Figure 7), although offshore areas are not well imaged. The Aleutians and Central America lack deep seismicity, but have adequate intermediate depth seismicity, and good local networks in place at some locations along strike. Cascadia lacks seismicity deeper than 60 km, and thus does not permit detailed imaging, although the dense land network permits some tomography with teleseismic rays.

Annual seismic events per degree length of subduction zone

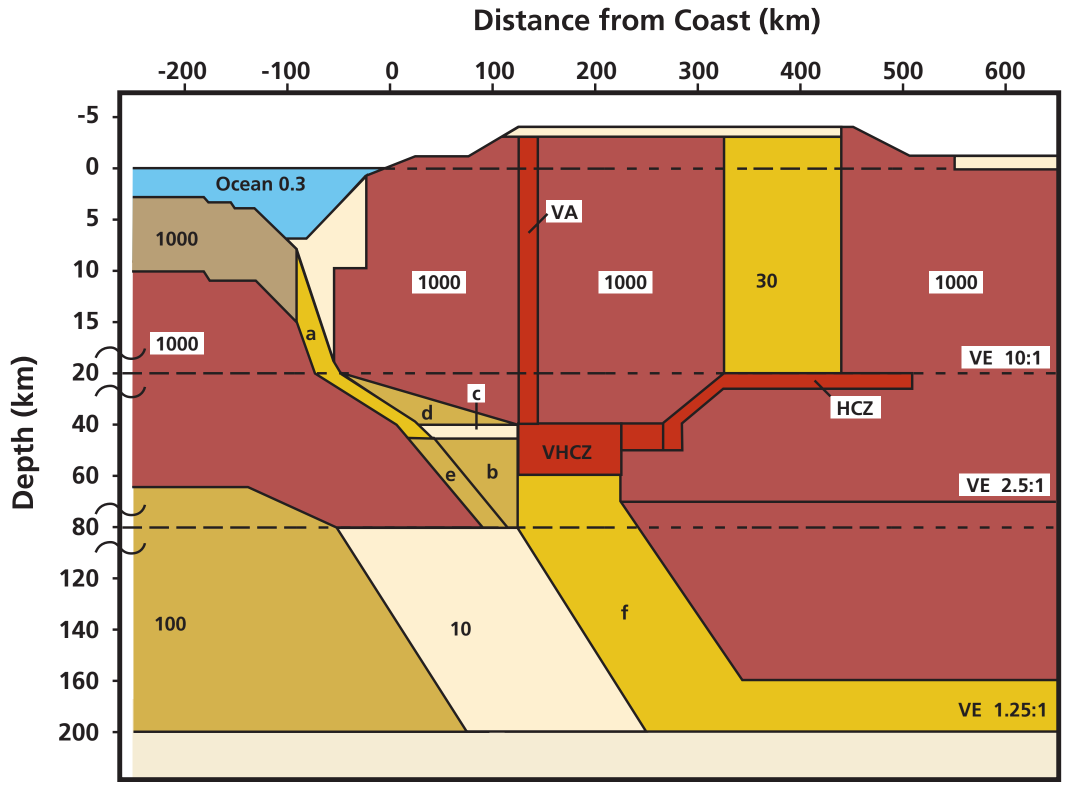
Region	0-100 km	100-200 km	200-300 km	> 300 km
Tonga-Kermadec	2.20	0.28	0.19	1.37
Marianas	0.44	0.12	0.05	0.10
Izu-Bonin	0.36	0.06	0.02	0.35
Japan	1.29	0.08	0.02	0.11
Aleutians-Alaska	0.62	0.04	0.01	0
Cascadia	0.07	0	0	0
Central America (Nic-CR)	0.84	0.04	0.02	0
Peru-Chile	0.48	0.22	0.06	0.08

Table 1. Events are those with seismic moment > 1024 dyne-cm, over the 20 years history of the Harvard CMT catalog.

Seismic imaging of the mantle wedge

4.3.3. Magnetotellurics

From magnetotelluric (MT) studies at Cascadia, we know that the uppermost part of the subducting plate is about ten times as electrically conductive as normal mantle. Enhanced electrical conductivity at subs-



Electrical conductivity

Figure 11: Electrical resistivity structure (in ohm-m) of a subduction zone, using the central Andes as an example. The volcanic axis (VA) and high and very high conductivity zones (HCZ and VHCZ) are regions of enhanced conductivity associated with the magmatic arc and back-arc regions. Region a is the 10 km thick upper part of the subducting plate to 40 km depth, while regions b, c, and d represent different parts of the mantle wedge, e is an extension of the upper subducting plate to 80 km depth, and f is the asthenospheric corner. If region a is ten times more conductive than its surrounding (as is observed in Cascadia), the offshore MT anomaly relative to a model without this feature is very large (about 20 times the standard error with which the MT response can be measured). The figure shows the differences between the phase of the two independent modes for a 2D structure at offshore distances of 70 and 140 km, straddling the trench at 100 km, as a function of period in seconds. The differences are relative to those for a model with enhanced conductivity in region a only. The solid line represents hydration (and hence ten times larger conductivity) in the entire mantle wedge (regions b-d), while the dot-dash line is for enhanced conductivity in region e extending to the putative asthenosphere at 80 km, and the dashed line is for enhanced conductivity only in the thin middle part of the wedge (region c).

olidus temperatures is principally caused by the presence of water; the addition of 0.1 wt% water to dry olivine enhances conductivity by nearly two orders of magnitude. Consequently, elucidating conductive pathways serves as a geophysical tracer of the flow of water into the mantle. Numerical 2D modeling shows that moderately good MT data has the potential to distinguish between hydration of the upper slab, hydration of the adjacent mantle wedge, and localized enhanced conductivity in the thin central part of the wedge (Figure 11).

4.3.4. Heatflow

High-quality heat flow data provide critical information on the thermal structure of a subduction zone, which forms the basis of seismological and petrological models. Surface heat flow data need to be collected on the incoming plate and in the forearc, arc, and backarc regions. For example, offshore and onshore heat flow data have been used to demonstrate that frictional heating is negligible in some subduction zones. In North-East Japan, comparison of seismic velocities derived from tomographic inversion with the sublithosphere temperatures derived from heat flow suggest that the forearc mantle is hydrated in this mature arc. Heat flow data can also constrain the geometry and magnitude of fluid flow through the forearc.

4.3.5. Submarine Sampling Strategies

ODP-IODP: The ODP-IODP Program has been, and will continue to be, essential for studies of the subduction factory. Much of what we know about the alteration of the incoming plate and the composition of its sedimentary veneer comes from ODP drilling. Recovery of the sedimentary section outboard of the trench will continue to be important. In addition, scientific and technical progress has changed the way in which the ODP-IODP Program can be used. Casing techniques can provide better hole stability for deeper penetration and core recovery in the compressive regime of the accretionary prism. Logging-while-drilling techniques provide high quality logs for density and porosity in fore-arc sites. Pore fluid sampling and analysis both outboard and inboard of the trench provide a very sensitive look at the diagenetic, hydrological and chemical changes in the earliest stages of subduction. Deep drilling with the ODP-IODP Program would allow penetration into the altered oceanic crust in the deep waters near trenches. In any study of the Subduction Factory, it is essential that a reference site be drilled outboard of the deformation front.

Riser Drilling: Aspects of the Subduction Factory Initiative that were discussed at the CONference on Cooperative Ocean Riser Drilling (CONCORD) include subduction zone earthquakes, the initiation of subduction, formation of juvenile arc crust, and mass fluxes at convergent margins. Riser drilling would ultimately allow deeper penetration, improved hole stability and better recovery under difficult drilling conditions typical of convergent margins. Drilling through the seismogenic zone will provide samples of aqueous fluids and of accreted and subducting sediments, necessary for understanding shallow subduction processes, and their effect on the slab delivered to depth. Riser drilling could provide improved access to deeper fore-arc serpentinites and associated pore-fluids. It could also provide a longer record of arc evolution through deep drilling in well-chosen locations in the arc edifice or in subsiding basins that receive volcanic sediments or ash.

Borehole Observatories: Increasingly, boreholes are used for hydrological or seismic experiments while the drill ship is on station, or as long-term observatories. CORK (Circulation Obviation Retrofit Kit) technology allows boreholes to be sealed and isolated from seawater. Perforated casing or screened intervals allow pore fluids from formation levels of interest to percolate into the borehole. The pressure and temperature is monitored, and borehole fluids and gases are sampled osmotically and stored for later chemical analysis. Tracer injection studies allow estimates of fluid flow rates. Filtered water samples can also be used to investigate the microbiology of the site. New de-

Drilling and borehole observatories

velopments are leading to a second generation CORK that will allow multiple levels in the borehole to be isolated from each other and from seawater, so that the hydrology, chemistry and microbiology can be investigated at different levels in the borehole. Such observatories would be particularly useful in the fore-arc of margins selected for focused study, with isolation of intervals above and below the décollement and in the basement of the subducting plate. In the often unstable hole conditions of convergent margins, it will be necessary to develop packer technology that will make effective seals against sometimes unstable formations.

CORK's and ROV's

To date, CORKs have only been used with ODP drill hole equipment. A mechanism whereby smaller CORKS (mini-CORKs) can be used in conjunction with gravity core or piston core equipment is currently under development. The corers and mini-CORKS can be used to study sites of fluid flow along fault zones or conduits in convergent margin settings. They can be deployed cheaply and in large numbers to effect "arrays" of seafloor monitoring sites. The mini-CORKs and down-hole monitoring devices are designed to be compatible with ODP dedicated borehole observatories and with JAMSTEC designed long-term monitoring devices. Thus, these mini-observatories could be linked with borehole observatories as arrays for the investigation of 3-D aspects of various phenomena associated with convergent margin processes, such as hydrologic processes, heat flow, seismicity, regional strain, geochemical variability, and biologic processes.

ROVs: One aspect of 3-D mini-CORK observatories in convergent margins is that deployment and servicing of these devices may be in water depths exceeding 6500 m. Thus some applications will require deep water ROVs (Remotely Operated Vehicles), control devices or AUVs (Automated Underwater Vehicles). In addition to servicing seafloor observatories, next generation ROV capability will allow investigating otherwise inaccessible parts of the submarine subduction zone. Ideally, new ROVs will combine the robustness necessary for operation in deep waters, maneuverability, video for high quality mapping and sample recovery (aqueous fluids, sediments, rocks).

4.3.6. Geodesy

GPS

GPS is currently the premier method for determining 3D displacements in a global reference frame. For the Subduction Factory, GPS will be important for several reasons. It will allow precise measurements of contemporary convergence rates, and how they vary along the margin. It can constrain intra-arc strain, deformation and crustal shortening in response to subduction of bathymetric features such as seamounts and volcanic ridges. GPS studies and associated modeling can also be used to investigate modes of back-arc spreading and rifting, constraining the role of actively driven (magmatic) rifting.

4.3.7. Studies of Magmatic Systems

Arc Magma Production Rates: It is essential to know not only what the Subduction Factory makes, but how fast it makes it. Magma production rates are necessary to assess the influence of the forcing functions, calculate volatile and other elemental fluxes, and constrain the rate of continental growth. Assessing magma production rates in arcs is more complicated than for mid-oceanic ridges, where crustal production is simply the product of crustal thickness and the full spreading rate. In contrast, arc crust may include pre-existing material and growth may be non-steady-state. Further complications arise because arcs grow vertically, arc magmas are fractionated, and the most productive arc volcanoes are explosive and subaerial. The arc environment is also conducive to mass losses through crustal delamination.

One method for estimating convergent margin crustal growth takes the total crustal volume for the magmatic arc and divides it by the age of the arc system. This results in an estimate around 1 km^3/yr globally. While this is probably sufficient for a global average (with a factor of 2 uncertainty), more precise regional rates are needed to address the central scientific issues.

Another approach for calculating magma production rates uses the arc eruption rate and the ratio of intrusives to extrusives. A ratio of 2:1 has been inferred for the Aleutian Arc, but this is poorly constrained. Further petrologic studies in addition to study of deep crustal exposures of plutonic arc sections should be pursued to aggressively address intrusive/extrusive partitioning. In addition to the petrological approaches, refraction studies of intra-oceanic arc systems, such as shown in Figure 9, may provide an independent means to estimate plutonic layer thicknesses, assuming that the velocity structure of arc crust can be interpreted as due to either intrusive or extrusive igneous rocks. This is another reason why deep geophysical sounding of intra-oceanic arc crust is a top priority of the MARGINS program.

Nor will it be easy to quantify arc eruption rates. The largest arc volcanoes generally have the best resolved chronologies, and conical stratovolcanoes are the simplest geometries for estimating eruptive volumes, both prerequisites for reliable eruption rate estimates. But a significant fraction of the volume of volcanoes has been lost as violently ejected ash or washed away by glaciers and streams. An alternative strategy is to estimate eruptive volumes over submarine arc volcanoes, where erosion is negligible and violent dispersal is minimized. This approach will require detailed marine reflection studies that can be tied to drill cores in order to reliably estimate volumes and establish chronologies.

The eruption rates and intrusive/extrusive ratio at different arcs will naturally vary due to different crustal structures and stress regimes. For example, low-density continental crust will retard rising of mafic magmas so that the ratios will be higher than for arcs built on high density oceanic crust. An important site selection consideration for at least one of the arcs to be studied is that it should be a good place to determine both intrusive to extrusive ratios and eruption rate.

Magma production rates

The Importance of Primitive Arc Melts: In order to understand how the Subduction Factory operates, we must know how one of its most important product - magmas - are produced. To do this, we first must know the composition of unfractionated, primitive melts. This knowledge is essential for calculating mass fluxes, which is itself a paramount goal of the Subduction Factory initiative, but many other benefits accrue. For example, if we know the composition of primitive arc melts, we can reproduce these experimentally to constrain temperatures, pressures, and volatile contents in the mantle at the point of melt generation, providing constraints for theoretical models of the mantle wedge that can be obtained no other way. Furthermore, this information will allow us to move from speculation to quantification of otherwise intractable problems such as formation of the lower crust and lower crustal delamination.

Deducing the composition of primitive arc melts is not simple, because although scientists agree that most arc magmas originate by melting of subduction-modified mantle peridotite, we rarely find the aphyric and unfractionated lavas that record this equilibrium. In contrast to basalts from other tectonic environments, arc lavas have lost nearly all of the volatiles bestowed at the time of melt generation. This is true for lavas erupted from submarine as well as subaerial arc volcanoes, and it is likely that degassing and melt fractionation are closely linked. Just adding water lowers mantle melting temperatures by several hundred degrees, and crystals will form rapidly as decompressing melts approach the surface. An important part of the Subduction Factory initiative must be learning to interpret magmatic evolution from degassed, porphyritic arc lavas.

Geochemical and Microbeam Approaches: One approach to reconstructing primitive arc melts is to use long-established geochemical and isotopic techniques. Some studies, principally isotopic investigations (Sr, Nd, Hf, Pb; Rare gases; U-Th disequilibrium; ^{10}Be), which provide essential information such as mantle or subducted slab isotopic signatures or melt generation and ascent timescales, may still be carried out to good effect on fractionated or accumulative lavas.

Geochemistry and isotope techinques

Timing of processes in subduction

Tremendous opportunities to surmount problems posed by porphyritic lavas are provided by recent technological advances in microsampling and microanalysis. Small melt samples (< 100 microns) are captured in phenocrysts and frozen as glass. These glass inclusions are extremely valuable because they are more easily reconstructed to pure melt compositions, sometimes more primitive, and much less degassed than erupted lavas. In fact, glass inclusions have provided the only direct means to determine magma volatile concentrations. Several established or developing microanalytical techniques have opened-up the study of melt inclusions: electron microprobe for major elements, ion probe for trace elements, Fourier transform-infrared spectroscopy for H_2O and CO_2 contents, and laser ablation-multiple-collector ICP-MS for isotopes. These microanalytical techniques can also permit study of individual crystals in mantle xenoliths and stratigraphically controlled tephra glasses.

It is essential that petrologic-geochemical-isotopic studies of the arc suites selected for study be coordinated among the various laboratories where this work can be carried out. Because of the wide range of lava types that can be encountered at a single arc and the many directions that studies of these rocks can take, it will be important to form a team committed to the complete range of studies on a sample suite.

Temporal Evolution of Arcs and Approach to Steady-State: We need to understand how the Subduction Factory has evolved through its life. This is needed to assess the extent to which the present operation of the factory reflects its past. Is the system in steady state? If so, how long did it take to attain this condition after subduction began? There are three ways to do this, each of which samples arc history differently. All three require drilling, but at different distances from the volcanic apex. Because sedimentation rates decrease over several orders of magnitude as distance from arc volcanoes increases, we can recover much longer histories more efficiently by drilling farther away from the arc. Drilling through the volcanic carapace yields a detailed history through the lifespan of a single edifice. Studying samples recovered by drilling through volcaniclastic (mass flow) deposits at some distance (10's of km) from the arc integrates the histories of several arc volcanoes through the life of the sedimentary basin. Studying samples drilled downwind 100's of km from the arc or in forearc basins reveals the history of subaerial, explosive volcanism in the arc system, provided contributions from other volcanoes can be resolved or neglected. The microanalytical techniques discussed above are increasingly important in moving through these three scales of dispersal, not only for the reasons outlined previously but also because the far-traveled tephra in particular is so fine that it cannot be analyzed any other way. Application of this technology to arc history has already contributed tremendously to our understanding of arc magmatic history of the Mariana-Izu Arc system.

Sedimentation and Arcs: Finally, the evolution of sedimentary basins built on the roof of the Subduction Factory - both forearc basin and back-arc basin - provide an easily accessible record of the past activity of the factory. In addition to chemical evolution of the arc preserved in these volcaniclastic sediments, the subsidence history of these basins and the diagenetic history of these sediments constrains the thermal evolution of the arc lithosphere. Assuming these deposits are submarine in the arc system being studied, it is essential that studies of forearc and back-arc basin sedimentary sequences be based on MCS and heatflow surveys leading to ODP drilling.

Rapid Response Plans: We need to be able to quickly reach places where earthquakes have just occurred or volcanic eruptions are in progress or about to happen. A framework for rapid responses to these or other phenomenon must be developed and implemented.

4.3.8. Experimental Studies

Seismic Calibration: Interpretation of the P and S-wave velocity requires calibration with measurements at relevant temperatures and pressures under laboratory conditions. These are difficult measurements, particularly with hydrous materials, but are critical for interpreting the seismic data.

Experimental Petrology: The following experimental goals are essential for constraining models of how matter is transferred from the subducting plate to the overriding plate, how different elements equilibrate with and migrate through the mantle wedge, how melts are generated in the mantle wedge, how they rise to the surface, and how they fractionate before they erupt:

1) In order to know at what temperature and pressure critical dehydration reactions occur, we need experimental studies of the subsolidus transformations of water and CO_2-bearing phases and rocks in the subducting slab. Emphasis will be placed on understanding the dehydration behavior of natural mixtures or analogs appropriate to the focus margins.
2) In order to reconstruct metamorphic reactions in the subducted slab, as well as melting in the slab and mantle, we need to understand the partitioning of specific tracers between melts, solids and aqueous fluids. Tracers chosen for focused study will reveal fundamental processes in the Subduction Factory, constrain development or testing of models, or are essential for mass balance. A list of such high priority tracers include species that illuminate sources in the subducted slab, (i.e., ^{10}Be, B, Li, Cl, Ar), elements that reveal transport timescales (i.e., the U-series nuclides: U, Th, Ra, Pa), species mostly derived from the mantle wedge (e.g., ^{3}He, Nb, Yb), elements that reveal mineralogy where melting occurs (REE, Sc, Y), radiogenic isotopes that reveal source histories (i.e., Sr, Nd, Hf, and Pb), and species comprising the fluid itself (H_2O and CO_2). There is also virtually no partitioning information for key minerals in the slab, including lawsonite, phengite, serpentine, and aragonite. Determining partition coef-

Sedimentation

Experimental petrology goals

ficients for these phases will allow us to estimate the composition of aqueous fluids or melts at the point where these leave the slab and enter the mantle wedge.

3) In order to understand how dense aqueous fluids and hydrous melts move through the mantle and interact, we need thermodynamic modeling and experimental investigations of the wetting and transport properties of dense aqueous fluids in slab and mantle lithologies. These constraints will help refine chromatographic and fluid migration models for the mantle wedge.

4) In order to understand how magmas are generated in the mantle wedge, we need experimental analogs for hydrous flux melting of peridotite, amphibole peridotite melting, and decompression melting of hydrous and amphibole-bearing peridotite, over a pressure range of 2-4 GPa. Experimental analogs are also needed for mafic melt crystallization during volatile loss in order to understand how arc magmas fractionate. Experimental constraints on the generation of felsic magmas are necessary to understand how continental crust forms.

Modeling parameters

4.3.9. Geodynamic Modeling

As outlined above, developing models for the Subduction Factory is integral to the strategy of the Initiative. A testable model must be able to describe the observable geochemical consequences of slab and mantle processes. Thus geodynamic, physical models for subduction and media flow must eventually incorporate chemical partitioning such that the chemistry of fluid and melt outputs can be used to constrain the models. The following aspects should be a part of any modeling effort:

1) Subduction of lithosphere and mantle convection beneath the arc and back-arc, if present.
2) Metamorphism, dehydration, and partial melting of subducted crust and sediments
3) Thermal structure in the convecting mantle wedge and the subducting plate.
4) Flow of aqueous fluids and melts from the subducting plate to the site of initial melt generation in the mantle wedge, including porous and channelized flow, the effect of the convecting mantle on the migration path and composition of aqueous fluids and melts, and fore-arc sites of aqueous fluid egress.
5) Ascent of melts through the mantle to the base of the crust, including diapiric ascent, porous flow, channelized flow, and melt-rock interactions.
6) Storage of melts in the crust and their subsequent fractionation, degassing and eruption

A focus for initial work should be the internal workings of the factory, the engine that transfers down-going material to up-going material. This includes wedge convection and melting. Melting in the mantle wedge probably results from adiabatic decompression as well as hydrous fluxing. To assess the significance of decompression melting requires tracking the movement of the solid, including the residue of melting. Existing kinematic models do not allow the thermal component of mantle buoyancy to be considered rigorously; hence dynamic models of subduction will be required. Observations that are needed to constrain dynamic models include slab shape, rollback rate, surface heat-flow, seismic imaging (velocity, attenuation and anisotropy), gravity field, surface stress state and surface subsidence history. To constrain the inputs to these models will require a better understanding of the density and rheology of hydrated, molten, fertile and residual mantle. Such dynamic thermal models will form the template on which models of melt and fluid migration and chemical interactions can be developed and tested with magma geochemistry.

4.3.10. Databases

Interdisciplinary studies and international cooperation require free and easy access to a wide array of data. Despite its importance to the broadest community of scientists, development of databases is a neglected effort. Different communities within the Earth Sciences have organized their data to varying degrees, from well-managed databanks (like seismic data through IRIS) to data that is scattered among individual scientists. Because of the multidisciplinary team approach of all MARGINS initiatives, it is essential to develop open databanks. For the same reason, samples collected under MARGINS aegis must be properly curated.

We envision two types of databases: one for each of the focus areas, and one for global data. The first database developed should be for the sites chosen for focused, interdisciplinary study. Much data is already organized through such organizations as ODP and IRIS, and MARGINS should not duplicate these efforts. Instead, emphasis will be on data not routinely curated, such as bathymetric and geologic data, seafloor imagery, seismic reflection data, measurements of potential fields and heatflow, and geochemical analyses. We envision an RFP for web-based or GIS-based database that takes advantage of experience gained from development of RIDGE databases. A link should be made to GERM (the Geochemical Earth Reference Model) which has a program already underway to develop geochemical databases for volcanic and sedimentary rocks.

Another vital aspect of the Subduction Factory Initiative is to develop global databases, such that comparative studies can be made using results coming out of the focus areas. An effort identified for initial work is development of geochemical databases for input and output products. The geochemical data for subduction-related igneous rocks is poorly organized and not currently available to a wide community of investigators. A modest investment of resources and effort could lead to potentially great gains in identifying relationships to geophysical measurements, or providing constraints on theoretical models. Also essential for SubFac-sponsored projects is sample curation and distribution. Although marine samples are generally well curated at the major marine institutions and ODP, with clear labeling and distribution protocols, the same is not always true of terrestrial samples. Samples collected from subaerial volcanoes are dispersed throughout the geology departments of the country, with non-standard numbering schemes, vulnerable to separation from their geographic location. At the minimum, organized and open sample collections should be developed for each of the focus sites.

Data management

5. Where Will We Study the Subduction Factory?

5.1. Focus Experiments

To sample the products of the Subduction Factory and to image its internal workings requires integrated interdisciplinary experiments that are focused on a small number of convergent margins. Subsets of the above studies used in different margins reveal the power of the approaches. However, the complexity of convergent margins, such as variations in slab temperature, water flux and slab and mantle chemistry, make it very difficult to understand the underlying processes except in the context of a focused experiment. The magnitude of the investment needed for a focused experiment requires guidance to margins where focused study promises scientific breakthroughs.

Selection of Focus Sites

Criteria for Selection of Focus Sites: The following are a refined set of guidelines developed at the various workshops for focusing discussion on the optimal margins for an integrated experiment:

- Must have an active volcanic arc. Sampling the volcanic output of the factory is clearly essential.Nankai, endorsed by SEIZE, does not have an active arc.
- Weather, local infrastructure and government regulations must not impede study of margin.
- Enough background information must be available to formulate a focused experiment.
- The subducting input must be accessible to sampling by existing drilling technology. Output (gases, aqueous fluids, volcanic sediments, volcanic rocks) must be available as needed to address the major questions.
- Seismic illumination of the subducting slab and overlying mantle wedge between 0 and 200 km depth must be feasible with on-land stations or in a realistic time frame for OBS deployment. Illumination to > 200 km is desirable. Both active and passive source methods are essential.
- An historical perspective is necessary to evaluate the question of whether steady-state conditions are an acceptable approximation for the subduction time of the margin (i.e., the time for trench input to be processed through the factory). For margins with relatively fast convergence rates, this characteristic time is about 2 Ma, and lengthens as the rate slows. Where the subduction time is greater than about 2.6 Ma, changes in sedimentation patterns, particularly at high latitudes, must be factored in.
- Margin(s) selected must show variation in forcing functions, either through variation along-strike in a single margin or through contrasting values between margins. Key parameters include convergence vectors, slab temperature, sediment transport to depth, and upper plate structure.
- At least one margin endorsed for focused study should allow a cross-arc perspective. Factory outputs (aqueous fluids, gases, magmas, volcanic sediments, hydrothermal deposits) should be recoverable across a wide swath from fore-arc to back-arc, in order to integrate the sum of factory processes.
- Continental contamination of ascending magmas must either be minimal or decipherable.
- The margin must be an optimal candidate for addressing one or more of the three science objectives highlighted previously: 1) Subduction parameters as forcing functions, 2) Volatile cycle, 3) Towards mass balance and crustal growth.

Assessment of Candidate Margins: Many candidate convergent margins fail to meet some of the above criteria. For example, weather conditions preclude extended access to the Scotia arc. Drillship access to Indonesian waters has been limited. Infrastructure in Kamchatka makes field work difficult and expensive. The slab beneath Cascadia is hot enough that little seismic energy is released, and seismic imaging would be difficult except by teleseismic methods. Crustal contamination of many lavas in the Lesser Antilles, Andes and New Zealand makes it difficult to invert magma composition for processes operating deeper in the factory. The tectonic complexity of the Philippine collision zone, Bismarck and Vanuatu makes it unlikely that these systems are in steady state. The splendid seismic imaging and groundbreaking petrologic work done in Japan makes it a natural candidate for further study; the large body of work currently underway, however, indicates that a focused experiment is, in fact, already being done. Unfortunately, the presence of continental crust and widespread occurrence of fractionated and contaminated magmas means that this is not the optimal place to study the subduction factory.

Central America as a High Priority Focus Area: Central America has emerged as an optimal margin for focused study for several reasons (Figure 12). Changing subduction dynamics result in sharply varying differences in the apparent sediment transport to depth. Seismic and geochemical imaging suggest that all incoming sediments are subducted to depth beneath Nicaragua, while much of the upper hemipelagic sediments are underplated off Costa Rica, leaving a largely carbonate section to subduct to depth. The relatively large proportion of carbonate subducted here sets the stage to begin investigating the carbon cycle through a subduction zone, a unique part of the volatile cycle. Melt inclusion studies of Nicaragua volcanics have revealed among the highest water contents in any basaltic liquid on the planet (up to 6 wt% H_2O).

Central American volcanoes are extremely active; several are erupting now. A modern eruption in Nicaragua, equivalent to the 2500 yr. bp Masaya eruption, will obliterate the capital, Managua, and completely disrupt the country. Most volcanoes erupt basalts free from obvious upper plate contamination.

Central America has geochemical characteristics like an island arc but has the continental advantage of easy access to all the volcanoes and on-land sites for seismic stations. Volcanoes in Nicaragua record the global maximum in recycled sediment signals, such as ^{10}Be and Ba/La. The uplifted Cordillera de Talamanca provides exposures of the deeper crustal section, allowing investigation of the plutonic arc crust. Due to arc migration, a long-term record of arc volcanism through the Tertiary is exposed for study. Serpentinites in the Guatemala forearc may provide samples of hydrated fore-arc mantle and intermediate aqueous fluids. Changes in forcing functions along-strike allow some parameters to be investigated while others are held constant. Convergence rates increase slightly southward from Nicaragua to Costa Rica (from 70 to 90 mm/yr), while slab dip shallows from 75° to 65° at relatively constant plate age (22- 23 Ma). Dramatic along-strike variations in sediment tracers in the volcanoes attest to dramatic changes in the sediment subducted to depth, despite a relatively constant thickness of pelagic sediments (400-500 m of hemipelagic ooze and carbonate). Crustal thickness increases from Nicaragua to Costa Rica (30-40 km), along with an apparent decrease in the extent of melting in the mantle.

In short, Central America provides the opportunity to investigate all three of the major themes highlighted earlier. Forcing functions vary smoothly but lead to dramatic regional variations in the volcanic output.

Candidate margins

Central America

Central America

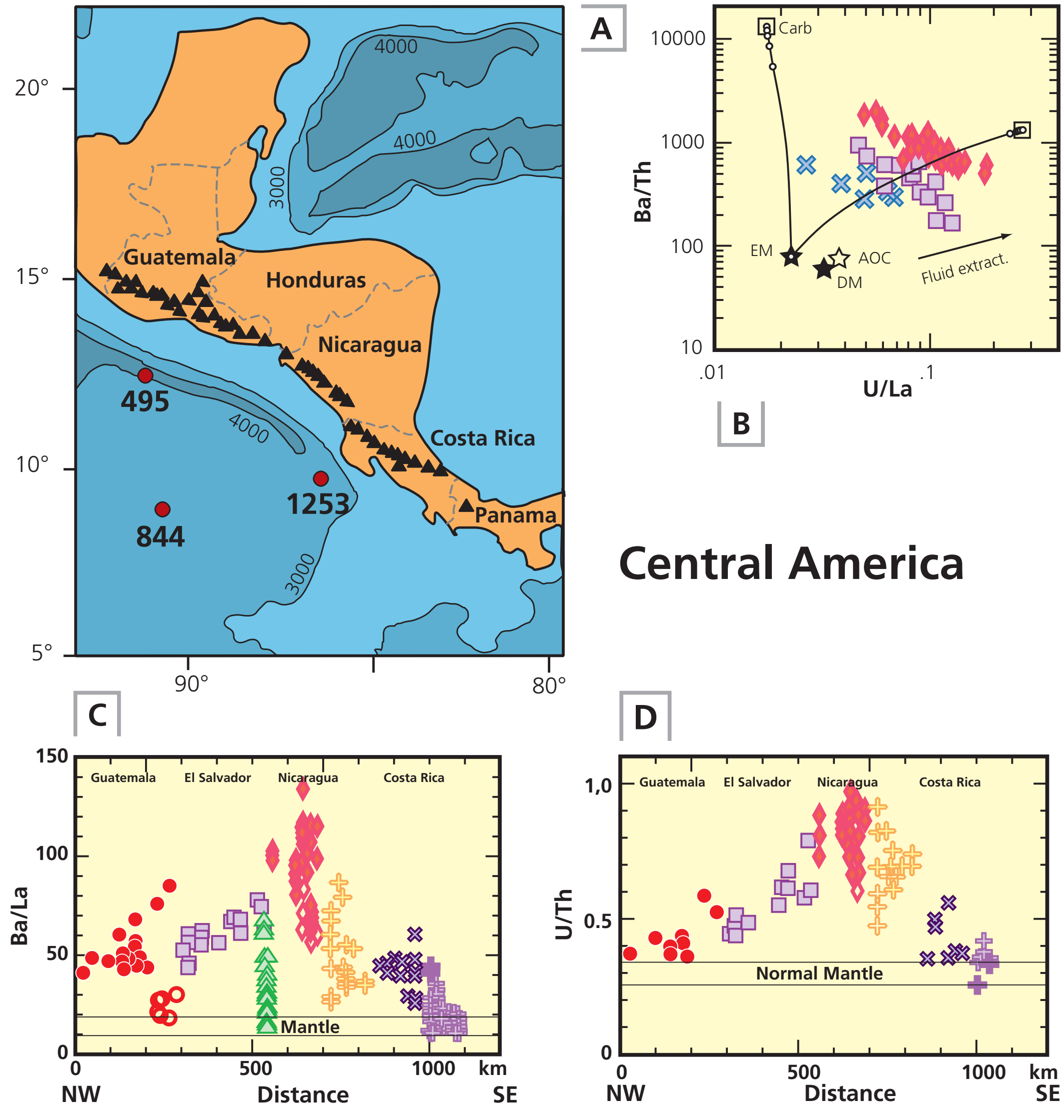


Figure 12 A: Map of the Central American convergent margin, showing the location of volcanoes and DSDP site 495 and ODP sites 844, 1039, and 1253. Subduction signal is maximum in Nicaragua. Open symbols are back-arc or back-arc like samples? See also Figure 4.

B: Variations of Ba/Th vs. U/La in lavas from the volcanic front of Central America. Lavas from Nicaragua (diamonds), El Salvador (squares), and western Costa Rica (crosses) define binary mixing arrays between carbonate-dominated and hemipelagic-dominated end members. Sources include the carbonate (Carb) and hemipelagic (Hemi) sediment sections on the Cocos Plate and three depleted sources, a depleted MORB source and an E-MORB source from Sun and McDonough (1989) and an altered oceanic crust (AOC) estimate. Any triangle, formed by mixingbetween the two sediments and any of the three depleted sources, includes most but not all the lavas. Fluid extracted from AOC and Hemi should have much higher U/La and thus may expand the triangle over the observed range.

C: Regional variation in Ba/La in lavas from along the Central American arc. Ba/La is another monitor for the subduction component. Filled symbols are samples from along the volcanic front.

Carbonate subduction, and actively venting water-rich volcanics all show promise for study of the volatile cycle. Lower crustal exposures and high-fidelity tracer studies will help to pave the way to mass balance. Many of the objectives link very naturally with those of the SEIZE science plan in Central America. Further value-added for Central America comes from the excellent marine geology and seismology work underway at German institutions. Other considerations are the strong field effort already underway and opportunities for determining gas flux.

Izu-Bonin Mariana as a High Priority Area in the Western Pacific: A second margin for focused study should ideally contrast Central America in terms of forcing functions. The slab subducting beneath Central America is relatively young and the margin is towards the warmer end of the arc spectrum. Central America has few back-arc volcanoes and hence offers a weak cross-arc perspective. Parts of the Central American fore-arc are sedimented. Natural counterpoints to Central America exist in the western Pacific arcs characterized by the subduction of old, cold slabs, back-arc spreading and sediment-barren forearcs: Tonga, Izu-Bonin, and Marianas.

It was difficult to choose one of the three Western Pacific margins for focused study: Tonga, Izu-Bonin, and Marianas. This is partly because each margin offers different opportunities and limitations. For example, Tonga has the fastest convergence rate in the world and is a natural end-member for investigating convergence rate as the forcing function that drives the factory (Figure 13). Confusingly, however, volcanic activity here is apparently rather low. Tonga also has a very depleted mantle and thus the slab and mantle signatures may be distinguished easily. Seismicity is deep enough and abundant enough to allow good seismic imaging with OBS deployments.

The Marianas offer a great opportunity to investigate the volatile cycle and its consequences across the entire factory from trench to back-arc (Figure 14). Serpentinite diapirs in the fore-arc actively vent aqueous fluids from the slab and transport metamorphic rocks (blueschists) from inside the factory to the surface. Ore-forming hydrothermal fluids at the arc and back-arc have slab signatures. Chemical variation along strike in the Marianas is pronounced and reflects either variation in the subducted input or in the mantle. Low seismicity, however, means that long OBS deployments would be necessary and resolution may be rather coarse.

Seismic imaging of the Izu-Bonin margin reveals the presence of the Vp=6 layer of middle and lower arc crust, with a few submarine locations where tonalite is exposed, making this an excellent candidate for investigating initial crust formation in a juvenile intra-oceanic arc. The Izu-Bonin margin is similar to Tonga in that the mantle here is depleted, making the slab signature easy to read. Serpentine diapirs are present in the fore-arc although no active venting has been reported.

Western Pacific

Izu-Bonin-Mariana

(Figure 12 continued)
Open symbols are back-arc samples. The back-arc samples in Honduras, furthest from the volcanic front (open triangles), have low Ba/La and are derived from depleted mantle and lack a subduction signature. Lavas from western Nicaragua (magenta diamonds) show the maximum slab signal (Ba/La up to 140 compared to normal mantle Ba/La =10-20).

D: Regional variation in U/Th along the volcanic front of the arc. This ratio is a useful tracer for sediment subduction in Central America because of the unusually high U content and U/Th of carbon-rich hemipelagic sediments near the top of the sediment section on the Cocos plate, as found at DSDP site 495.

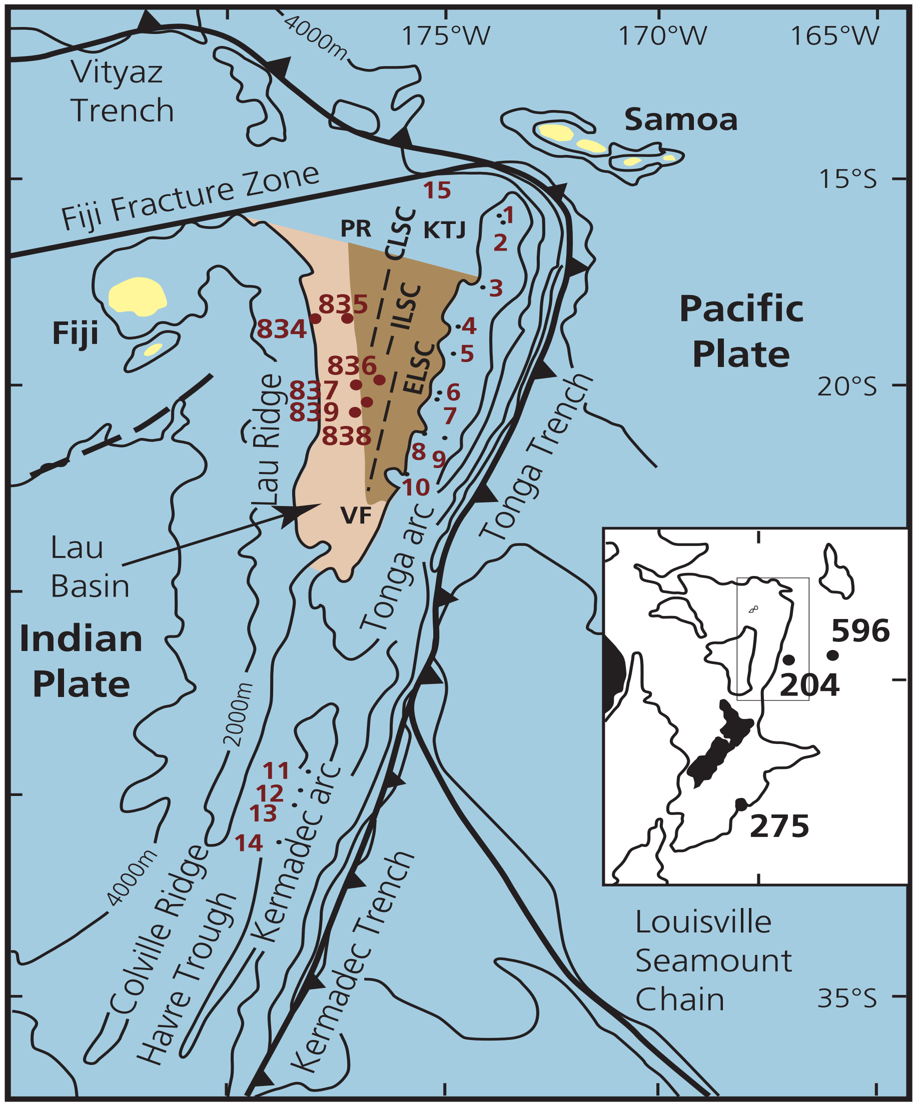


Figure 13: Tonga-Kermadec Arc and Lau Basin-Havre Trough, showing locations and major tectonic features. The numbers 834-839 refer to ODP sites (Leg 135). Tonga and Kermadec islands are numbered: 1, Tafahi; 2, Niuatoputapu; 3, Fonualei; 4, Late; 5, Metis; 6, Kao; 7, Tofua; 8, Hunga Ha'apai and Hunga Tonga; 9, Eua; 10, Ata; 11, Raoul Group; 12, Macauley; 13, Curtis; 14, L'Esperance; 15, Niua fo'ou. Other abbreviations: PR, Peggy Ridge; KTJ, Kings Triple Junction; CLSC, ILSC and ELSC, Central, Intermediate and East Lau Spreading Centres; VF, Valu Fa Ridge. Inset shows DSDP Sites 204 and 275, and ODP Site 596. Bathymetric contours in meters.

After extensive discussion, IBM was selected as the Western Pacific Focus Site. A one-day MARGINs sponsored workshop at the December 1998 AGU meeting was convened to select focus sites.

5.2. Allied Studies

In addition to the focus sites, allied studies at selected margins and paleosubduction zones are necessary to make global comparisons to models that will emerge from the focus areas and to provide valuable further insight into subduction factory processes. In some cases these may occur after initial studies in the focus areas.

Aleutians. The Aleutians show pronounced variation along-strike in plate age, convergence rate and obliquity, sediment thickness and composition, and upper plate thickness and structure (Figure 15). In addition, this margin subducts sediment that is unusually rich in silica due to high-latitude diatom productivity and thus provides a silica-rich endmember for forcing function considerations. With high magma production rates and volcanic hazards to US citizens and planes flying in US airspace, the Aleutians are a strategic region for focused study. At this stage, however, too little is known to frame such a study. Recommend studies in the Aleutians include: ODP-type drilling of the incoming plate, swath-mapping, MCS surveys, and sampling and analysis of volcanic and plutonic products of the lesser known parts of the arc.

Cascadia: Another US margin, the Cascades, is at the hottest end of the arc spectrum. Indeed, the slab beneath Cascadia is hot enough that little seismic energy is released and seismic imaging is made difficult. As a consequence of the higher slab temperature, however, many elements apparently leave the slab at shallower depths than elsewhere, resulting in a smaller slab signature in the arc, and possibly a lesser supply of water to depth. Recent studies of intrinsic water contents of primitive lavas from the Cascades show that some are relatively water rich while others are apparently dry. While Cascadia might not be the best place to study slab inputs (the incoming sediment section is very thick and complexly partitioned in the shallow part of the margin), it is a good place to study other inputs to the factory—the mantle wedge and upper plate lithosphere. Selected studies in Cascadia would also be useful in examining the relative roles of water fluxing, decompression and mantle temperature in mantle melting.

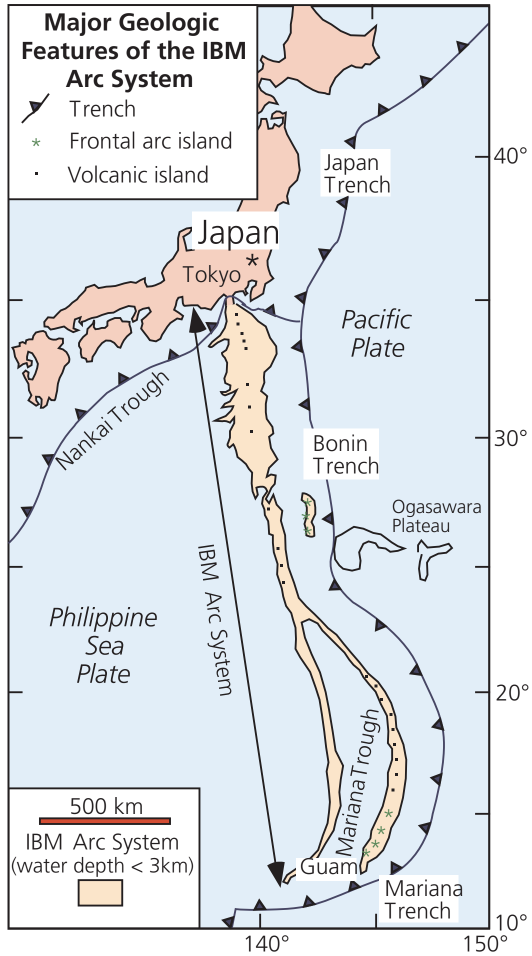


Figure 14: Locality map for the Izu-Bonin-Mariana arc system. The IBM arc system shows tremendous variations in tectonic style and morphologic expression, from collision with Japan in the north to the greatest deep in the world, the Challenger Deep, in the south. The Mariana Trough is an actively spreading backarc basin and the Mariana forearc contains the only sites of active serpentine diapirism and fluid egress through a forearc. The detailed crustal section shown in Figure 9 is from the northern part of this arc system.

Cascadia and Paleo-Subduction Allied Studies

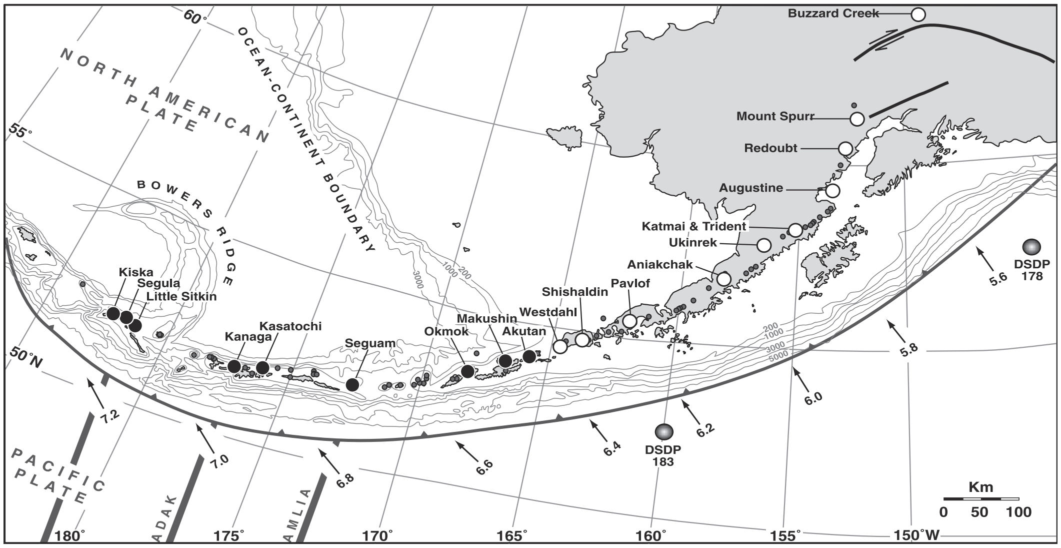


Figure 15. Location map of the Aleutian arc (see Nye et al., 1998). Historically active volcanoes are shown as shaded circles (Wood and Kienle, 1990), while the active volcanoes analyzed in this study are labeled. Volcanoes are subdivided on the basis of geographic position into intraoceanic (Aleutians sensu stricto) and continental (Alaskan). Convergence vectors and rates of subduction of the Pacific plate beneath the North American plate (DeMets et al., 1994) and the positions of the Rat, Adak, and Amlia fracture zones on the down-going plate are shown (Geist et al., 1988), along with the positions of DSDP sites 183 and 178 (Creager et al., 1973). Faults in mainland Alaska are shown as bold lines and contours are in meters below sea level.

SubFac workshops and theoretical institutes

Paleo-Subduction Zones: The chemical processing and P-T conditions of the slab between about 40 km and 100 km depth can be studied directly only in metamorphic assemblages from paleo-subduction zones. When exhumed and exposed subaerially, subduction assemblages such as the Catalina, Pelona, and Kodiak record the prograde metamorphism of the subduction zone. Petrological and chemical studies can illuminate the behavior of volatiles during metamorphism, the localized presence of melting, and the changing composition of the slab as dehydration and metamorphism distill elements out of the slab at increasing pressure and temperature. Allied studies in paleo-subduction zones will be an important part of understanding the subduction factory in the intermediate-depth interval.

5.3. Theoretical and Experimental Institute: "Inside the Subduction Factory"

An important component to the Subduction Factory Initiative is the periodic convening of theme institutes and results workshops. Such gatherings are necessary to educate, exchange ideas, and pose problems across the disciplines.

Subduction Factory Workshop participants in 1998 recognized the immediate value of convening a Theoretical and Experimental Institute to address the internal workings of the subduction factory. Many of the fundamental processes—melt generation, crustal recycling, slab-mantle interactions—occur within the most inaccessible reaches of the factory. How do forcing functions such as convergence rate, dip and slab temperature affect flow and temperature in the mantle wedge? Where does the slab dehydrate, and how does

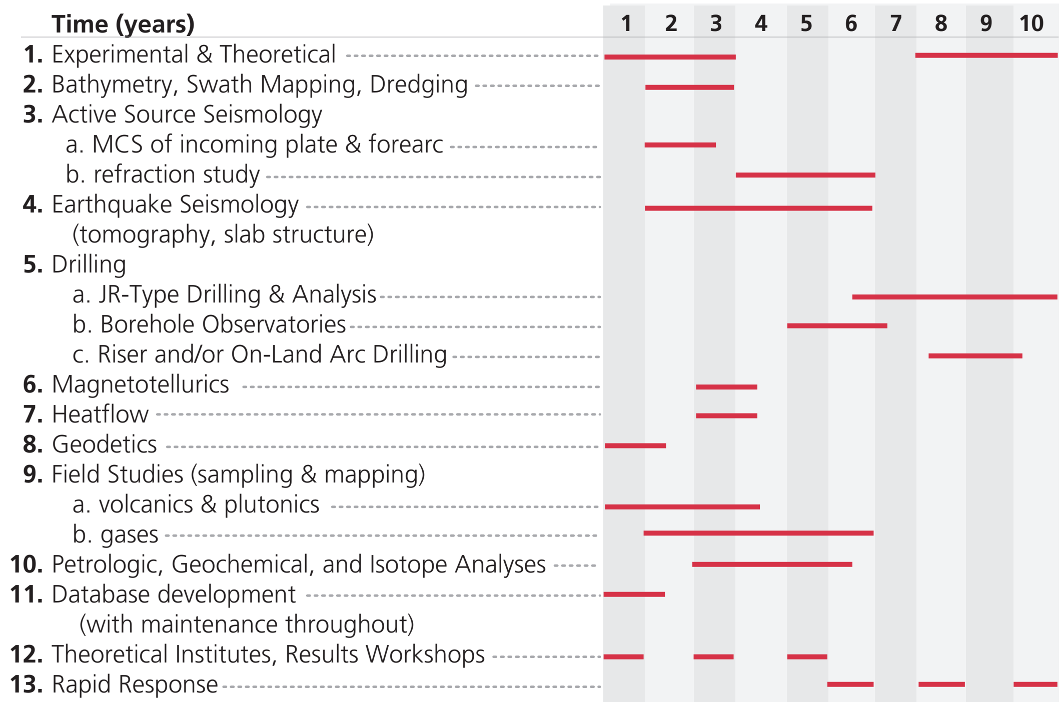


Table 2. Timeline for implementation of Subduction Factory research for a given convergent margin.

this release of fluid relate to the melting process in the mantle? Where does melting occur in the mantle wedge? These fundamental questions are still with us after 30 years of subduction studies. Quantum progress can be made only by combining seismic imaging, laboratory experiments, geodynamic modeling of solid and fluid flow, and petrological and geochemical constraints provided by input and output products. Successful institutes combining these elements have been held by RIDGE and have led to vigorous exchanges between modelers and petrologists and the recent MELT experiment. By comparison to ridges, the models for mantle flow and melting at subduction zones are crude, and the models are lagging behind the observations. A theoretical and experimental institute on the "Inside of the Subduction Factory" held in 2000 brought together geodynamicists,petrologists and seismologists to develop the models for the internal workings of the subduction factory and the ways to test them. Other institutes for future years will be proposed by the community.

6. How Long Will It Take to Study the SubFac?

A ten-year program is necessary for an integrated study of the Subduction Factory. The timeline in Table 2 follows the implementation strategy outlined in Section 3.

The first three years have focused on developing the geophysical and geological background (seafloor mapping, MCS, geodetics, dredging) to guide later large-scale efforts (drilling and seismic imaging). Other critical activities in these first years include developing databases for rapid dissemination of information, and establishing seismic stations for long-term monitoring of earthquakes to image the mantle wedge and slab. On-land mapping programs have begun, in order to provide samples for geochemical analysis, which will also help to focus future drilling and imaging programs. Modeling in the early stages of the program will help to guide data acquisition. Theoretical institutes have been and will be held in order to galvanize the diverse community and to provide models to be tested with the field experiments. In addition to the on-going modeling, geochemical analysis, and earthquake monitoring, included ODP drilling studies of submarine fluxes in the subduction factory: incoming materials and forearc output. Borehole monitoring began immediately following drilling. Also beginning in this time period are seismic refraction and magnetotelluric studies of upper plate structure, in order to guide future arc drilling. Results workshops will occur throughout the intermediate stages of the programs, to integrate results from the different disciplines and experiments.

The final observational phases of the subduction factory studies will include riser (or land) drilling in the arc, to test predictions from the refraction studies of arc structure and evolution, as well as riser drilling of holes in the fore-arc and back-arc. Modeling and laboratory experiments will be critical to interpreting results from the various observational phases.

Thus, throughout the ten-year initiative, the different major off-shore and on-land programs are staged in a natural progression of events, with early experiments paving the way for later ones. This timeline, however, is a generic one, and the details of the activities and the exact sequence of events will be dictated by the compelling proposals written. It may be that the full barrage of activities may not be necessary at the chosen focus areas.

7. How Much Will SubFac Cost?

Cost of SubFac

A comprehensive study of the subduction factory will cost 15 to 20 million dollars, exclusive of ship time and drilling costs. The probability of extensive international cooperation will distribute these costs over the scientific funding agencies of a number of nations. Less ambitious programs will provide valuable information on the selected subduction zones; however, the synergism of a comprehensive study should yield a greater benefit per dollar invested than the more limited approach.

8. How Will We Communicate Results and Opportunities for Cooperation?

Dissemination of SubFac results and information

A Subduction Factory web site is maintained as part of the MARGINS Office (currently at Washington University, St. Louis). The SubFac web site will provide the following: (1) information concerning upcoming field expeditions and experiments, (2) access to databases and data recently acquired by SubFac, and (3) a news bulletin board to foster communication across the different disciplines in the SubFac community.

By making information concerning upcoming cruises and field experiments available in a timely fashion, other researchers can capitalize on these opportunities and secure funds to participate in these projects or design piggy-back projects. In addition, recently acquired SubFac data and/or pathways to access the data will be available on the web site soon after acquisition. This time frame will vary for different data types.

Existing data acquired in the SubFac natural laboratory will also be compiled, catalogued, and entered into the data base. Rapid dissemination of data and new ideas will help focus the community, which, in turn will lead to a more interdisciplinary approach toward studying the subduction factory. For example, preliminary tomographic and seismic reflection images will be available on the web site soon after they are developed; geochemical data and phase diagrams will be posted on the web site so that geodynamic models can be tested. Data availability, together with the news bulletin board, will improve communication between observationalists, experimentalists and theoreticians. This enhanced communication will allow rapid determination of the critical observations and experiments necessary for constraining models of the subduction factory. In this way, first order model predictions can be immediately tested. Such an iterative approach between modeling and data analysis is the necessary first step towards developing realistic quantitative models of the subduction factory.

In addition to the web site, international meetings and publications will promptly communicate the results of SubFac. Workshops on the main scientific themes (volatile cycling, forcing functions and crustal growth) will also be an important component to focusing efforts within the broad community. These workshops will bring together the diverse community of researchers needed to cross-fertilize ideas and develop multidisciplinary approaches to make progress on the SubFac scientific objectives.

Finally, an important component of SubFac science communication will be sharing SubFac science objectives and results with professional educators, whose primary concern is the development of curriculum, teacher training, and textbook preparation for K-12 and undergraduate students.

9. How Will International Cooperation be Established?

A number of current and planned efforts in different countries address aspects of convergent margins complementary to those of the US Subduction Factory Initiative.

For example, the Japanese subduction factory efforts build on many decades of groundbreaking research in convergent margins and will focus on subduction initiation and birth of the continents. Methods will include field work and analytical studies, superb seismic imaging, and ultimately riser drilling through OD 21. A Japanese workshop on the Subduction Factory held in the fall of 1998, and organized by Gaku Kimura, led to a science plan for subduction factory research in and around Japan. MARGINS strongly endorse international cooperation to further Japanese objectives in studies of the Subduction Factory.

International collaboration

German activities along convergent margins are global but include much effort in the Middle America area. The R/V Sonne has geophysically mapped and sampled from the Cocos Ridge to central Nicaragua and south to Costa Rica on multiple cruises since 1992. The TICOSECT project has just been completed and included crustal transects from the Pacific to the Caribbean oceanic plates across Costa Rica and Nicaragua, studies of volcanoes, on-land geologic mapping and the geochemistry of on- and offshore samples. A project from the GEOMAR Research Institute for a long term research study of fluid in the subduction zone and cycling of subducted chemical components (e.g., methane) is now well established.

A French Margin Initiative—the *Group De Recherche MARGES* or GDR-MARGES, http://gdrmarges.lgs.jussieu.fr —has been established. Their convergent margin program builds on an extensive body of work studying great earthquakes and the seismogenic zone (Eastern Nankai, Northern Andes), aqueous fluids in accretionary wedges (Mediterranean Ridge, Barbados), accretion versus tectonic erosion (Peru, Chile, Hikurangi margin), oblique subduction, collision, and incipient subduction (South Philippines, South Ryuku and Taiwan, New-Hebrides, Puysegur); and back-arc opening (North Fiji Basin, Manus Basin, Okinawa Trough).

New Zealand efforts focus on a North Island transect, which is a natural follow on from the highly successful South Island Geophysical Transect (SIGHT). Funding from the New Zealand Science foundation has been approved and assigned to groups at the Institute of Geological and Nuclear Sciences (IGNS) and the School of Earth Sciences, Victoria University of Wellington. International collaborations are underway. Some of the principal issues to be explored include the origin of andesites, the link between Quaternary uplift and upper mantle processes, and the initiation of subduction.

A critical aspect of international collaboration will be interaction with scientists from those nations hosting the target margins, both onshore and offshore. This is particularly important in Central America, where volcanological and seismological teams in Costa Rica and Nicaragua have made great progress in research, cooperation and infrastructure: 1) planning workshops held in Costa Rica have facilitated close scientific and logistical ties, and; 2) collaborative work with Japanese scientists is well underway in the IBM system.

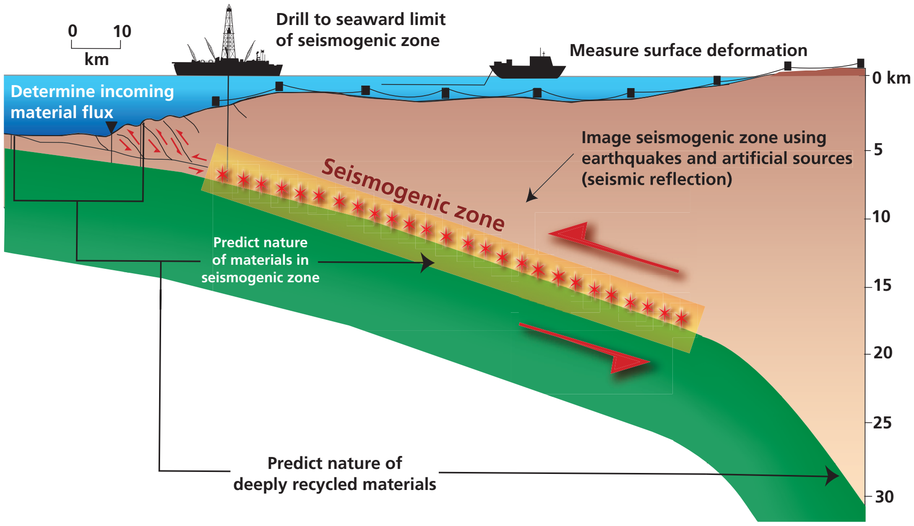
This range of studies provide cooperative ways to maximize scientific return. They also emphasize the need for continuing rapid development of the international aspects of the MARGINS.

10. How Will SubFac be Evaluated?

Evaluation of SubFac

We realized that the Subduction Factory will not be block funded but progress through a series of peer reviewed proposals/grants. This funding mechanism provides continual evaluation that functions every time a proposal is submitted and reviewed. In addition, the MARGINS Office will issue progress reports, and the SubFac initiative will be periodically reviewed. Such reviews should not only demonstrate the scientific progress that is resulting from individual proposals but should include evaluations of the effectiveness of interdisciplinary and international activities. After 5 and 10 years MARGINS should hold a progress meeting/workshop to evaluate the initiative and to refine/redefine directions. NSF program managers and our peers will also evaluate the initiative.

The Seismogenic Zone Experiment (SEIZE)



1. Introduction

Subduction zones generate the world's largest and most destructive earthquakes, most of the world's tsunamis, and most of the world's explosive volcanoes. They are also the sites where much of the world's population is concentrated (the coastal zones) and, over geologic time, where most of the earth's continental crust and mineral resources are generated. NSF's MARGINS program includes the Seismogenic Zone Experiment (SEIZE) to study the shallow subduction plate interface that is locked and accumulates elastic strain, periodically released in large or great earthquakes. The scientific rationale for these studies was originally outlined in the SEIZE science plan, based on a workshop held in Hawaii in 1997. The MARGINS program officially began in 1998, and has provided funding for US researchers for focused studies in the Nankai Trough and Central America, complementing research funded by Japan, Germany, Costa Rica, Nicaragua and other nations. It is appropriate to re-evaluate this plan based on these and other data as well as new laboratory and theoretical developments. The SEIZE Science Plan update was carried out in association with the SEIZE 2003 Theoretical Institute in Snowbird, UT, March 2003.

1.2 Questions Posed by SEIZE I

The science plan derived from the 1997 meeting focused on the following questions:

1. What is the physical nature of asperities?
2. What are the temporal relationships among stress, strain and pore fluid

composition throughout the earthquake cycle?

3. What controls the updip and downdip limits of the seismogenic zone of subduction thrusts?
4. What is the nature of tsunamigenic earthquake zones?
5. What is the role of large thrust earthquakes in mass flux?

Here we provide some additional scientific background to these questions and discuss the extent to which the MARGINS program has begun to address them (section II), pose some new questions (section III), and revise a plan for obtaining the requisite knowledge (section IV).

Scientific background

Asperities

2. Scientific Background: What is known and what remains to be learned

2.1 Physical Nature of Asperities

Understanding the factors leading to Earth's largest and most destructive earthquakes is obviously an important goal. While the rupture process as well as factors controlling strain accumulation could be different for smaller (M<6) vs. larger (M>8) events, simple earth-quake scaling relations suggest that, for similar types of focal mechanisms, earthquake moment scales with rupture area over a relatively large range of moment. To a first approximation, we understand why subduction zone earthquakes release the great majority of earth's seismic energy (they are capable of rupturing large areas) although we do not yet understand the factors that occasionally lead to extremely large rupture areas and truly great (M>9) subduction zone events. While some subduction thrusts produce M~9, others only produce M<7.5. Why? What are the relative roles of fault area, seismic coupling, seismic vs aseismic slip, asperities, type and thickness of subducted sediments, and fluid flow?

> "Understanding the factors leading to Earth's largest and most destructive earthquakes is obviously an important goal"

Lay and Kanamori (1981) described a model that relates the size of an earthquake to the characteristic size of asperities, defined by these authors as regions that slip by large amounts in an earthquake. In this model, events like the 1960 Chile earthquake rupture large asperities and are characterized by large displacements (maximum displacement in this event probably exceeded 20 m). Regions that typically have smaller earthquakes would be characterized by smaller slip on smaller asperities, limiting rupture area. Unfortunately it has proven difficult to relate asperities to physical features.

There is even some ambiguity in the literature on the use of the term. Do asperities represent regions of high strength (high friction) such that large amounts of locked slip accumulate in the interseismic period, to be released in a subsequent earthquake? Or are they regions of low dynamic friction that are therefore able to slip by larger amounts in an earthquake, promoting rupture over long distances. In this latter view, a high strength region may actually block further propagation of earthquake slip. Are asperities only the source regions for past earthquakes, or are they also regions that are currently locked, to rupture in the future? Are these two definitions in fact the same? In other words, do asperities have enduring significance? If so, are they controlled by specific fault properties or features on the subduction interface? Can these be measured

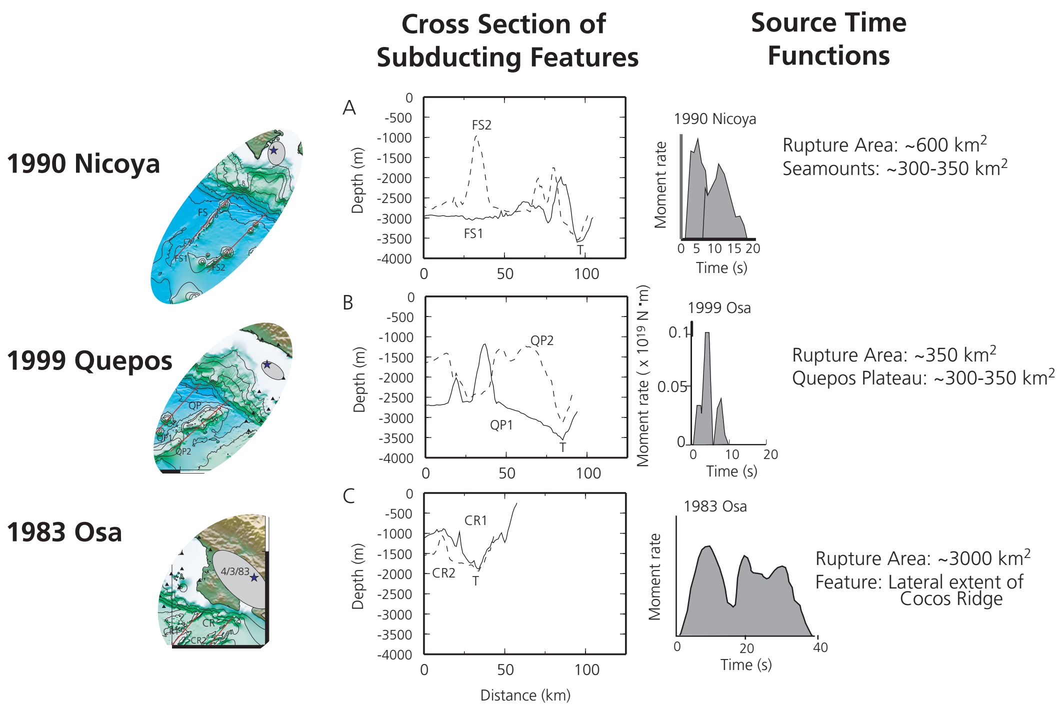


Figure 1. Large Costa Rica plate interface earthquakes and subducting topographic features that may have influenced these earthquakes. Left: Earthquake rupture area and bathymetry. Middle: Cross sections through the bathymetry data. Right: Source time functions for the 3 large earthquakes. Rupture areas and source time function complexity are related to the complexity of the subducting topographic features opposite the earthquake location, with the fairly simple 1990 and 1999 earthquakes related to the simpler Fisher Seamount Group and Quepos Plateau. The more complicated rupture of the 1983 earthquake broke the lateral extent of the Cocos Ridge. From Bilek and Lay (2002).

Earthquake size controls

directly or otherwise quantified in any way, e.g., by models? Ultimately, comparing the "patchiness" of locked slip on the subduction interface as measured by interseismic geodetic data to subsequent slip distribution in the next large earthquake (measured seismically or geodetically) may help resolve this problem. "Imaging" the fault surface with active source techniques may also reveal physical features or changes in reflective properties that are diagnostic.

In the ~20 years since the asperity model was first discussed, there has been surprisingly little progress in resolving these issues. Part of the philosophy of the MARGINS-SEIZE program is to accumulate a variety of key data sets in specific focus sites (Central America, Nankai Trough) to better attack such problems.

What controls maximum earthquake size in subduction zones? Why do subduction zones occasionally generate the largest known (M>9) events? A simple empirical model incorporating only plate convergence rate and lithospheric age has been proposed (Ruff and Kanamori, 1980). This model is plausible if one considers only the down-dip width of the seismogenic zone; since earthquake size scales with rupture area, faster convergence rates tend to depress the brittle-ductile transition depth, and young, buoyant lithosphere will tend to subduct at shallower angle, all promoting a larger plate contact area in the seismogenic regime and resulting

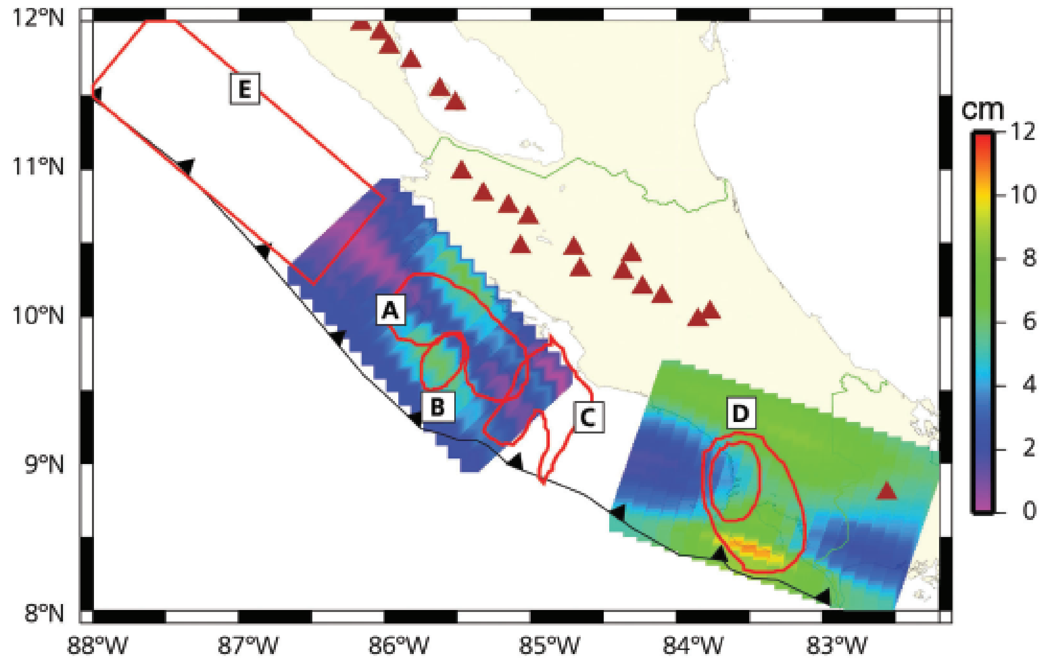


Figure 2. Estimated rupture areas of past large earthquakes in central America (red circles and rectangle) compared to estimated locked slip zones from GPS (full locking is approximately 9 cm, the plate motion in 1 year). A is 1950, B is 1978, C is 1983, D is 1990, E is the 1992Nicaragua tsunami earthquake, estimated from 30 days of aftershocks. Red triangles are Quaternary volcanoes. From Norabuena et al. *[2003].*

Longest recorded earthquake rupture length

in larger down-dip width. On the other hand, a key characteristic for the largest subduction zone earthquakes is the along-strike rupture length, and this does not relate in any simple way to plate subduction rate or age.

Once earthquakes are large enough to rupture down to their maximum depth, earthquake moment scales with the along-strike length of the rupture (e.g., Scholz, 1990). Thus, understanding variations in earthquake moment in the subduction environment requires that we understand variations in rupture length. The great 1960 Chile earthquake had the longest recorded rupture length, ~1000 km (Plafker, 1972). Shorter segment ruptures sometimes appear to correlate with certain sea floor bathymetric features such as seamounts or oceanic plateaus (Figure 1), but this does not explain why the rupture zones of rare great earthquakes pass through and connect several such features to achieve very long rupture lengths. At this point we have very little understanding of factors controlling rupture length, although the smoothness of the incoming oceanic plate may play a role, and this could be affected by incoming sediment (see later).

Another factor limiting the applicability of simple models such as those focusing only on plate rate and age is that the rupture length, slip and seismic moment may vary considerably from cycle to cycle along a given trench segment (Thatcher, 1990; Schwartz, 1999). This variability suggests that there may be temporal changes in key properties on the plate interface (Figure 2).

Many studies have compared seismic moment release to the full plate convergence rate, and report either "seismic coupling", the ratio of seismic slip to plate motion (Kanamori, 1977) or the amount of missing slip as the percentage of "aseismic" slip. Although these were initially assumed to reflect physical coupling on the plate interface and be consequences of convergence rate and age of the subducting plate, further study has suggested that such correlations are weak (Pacheco et al., 1993). While there are other difficulties and problems in estimating seismic coupling and locked slip from seismic data (McCaffrey, 1997; Norabuena et al., 1998), the large numbers of such studies that point out differences between the full plate rate and seismic rate, as well as newer geodetic studies suggesting that some seismogenic zones do not appear to be fully locked, requires explanation.

One difficulty is that there are significant trade-offs between geodetically determined "coupling" and a variety of other parameters, including the post-seismic response to past earthquakes, assumed down-dip width, dip, and curvature of the subduction zone, and these need to be fully investigated before we can obtain rigorous, quantitative estimates of the amount of locked slip on the plate interface. Accurate estimates of locked slip, how this varies with depth, along strike, and with time, are not yet available for most subduction zones. Geodetic studies can measure strain accumulation above the seismogenic zone, and have documented fully coupled (locked) seismogenic zones, freely slipping seismogenic zones, and perhaps partially coupled zones. What is not clear is whether partially coupled zones represent regions with uniform properties, or a spatially more heterogeneous plate interface characterized by small, fully locked patches intermixed with freely slipping zones, with the "mixture" poorly resolved by available data. It is also possible that the explanation for "partial coupling" reflects a temporally heterogeneous interface with time-varying properties that are "averaged out" in campaign-style geodetic measurements (this latter problem will presumably be resolved once continuous geodetic monitoring capability is well-established).

A series of seismic reflection studies offshore Costa Rica (von Huene et al., 2000; Ranero et al., 2001; McIntosh et al., 2000) have imaged the locations of subducting seamounts, and these are implicated as source regions for several M=6-7 earthquakes during the past decade (Protti et al., 1995; Bilek et al., 2003). These studies document our ability to tie physical features such as seamounts with earthquake sources, and potentially with geodetically determined locked patches. The regions where seamounts are clearly implicated as seismic sources are also those in which the earthquake magnitude is less than 7.5. Larger earthquakes (Mw>8.0), are often associated with regions of thick trench sediment (Ruff, 1992) and/or a strong forearc (McCaffrey, 1995).

Locked, partially coupled and freely slipping zones

2.2 Temporal Relationships among Stress, Strain, and Pore Fluid Pressure Throughout the Earthquake Cycle

Transient Strain. An important class of phenomenon that was not well understood at the time of the first SEIZE workshop in 1997, but is now becoming more widely appreciated, concerns transient strain events. Several of these events have been imaged with continuous GPS in Japan, Cascadia and other subduction zones in the last few years (the requisite network does not yet exist in Central America). Future SEIZE research will undoubtedly focus on the implications of these time-transient phenomena for seismogenic zone processes.

Slow transient deformation in subduction zones may be quite common, but until recently has been only rarely observed. Slow/silent earthquakes were initially postulated on the basis of borehole strainmeter data (Sacks et al., 1978; Linde et al., 1996), elevation data (e.g, Linde and Silver, 1989), and low frequency seismic observations (e.g., Beroza and Jordan, 1990). The advent of GPS, and reductions in the cost of receiver hardware and the complexity of data reduction, facilitate dense GPS networks and much better recording of this important class of geophysical phenomena, largely outside the frequency band of seismometers. Several transient events related to subduction have now been recorded in Japan (Heki et al., 1997; Hirose et al., 1999; Ozawa et al., 2001), Kamchatka (Burgmann et al., 2001), Mexico (Lowry et al., 2001) and Cascadia (Dragert et al., 2001).

Transient strain phenomena:

In fact, every subduction zone that has been instrumented with continuous GPS, even relatively sparse networks, have observed these phenomena, suggesting that they are quite common. Below we briefly discuss some of the classes of transient strain phenomena that have been described in the literature. With the exception of viscoelastic relaxation in the lower crust and upper mantle, these phenomena likely involve temporal variations in pore fluid pressure (either as cause, effect or both), reflecting either changes in fluid production (e.g., from metamorphic reactions) or changes in permeability. Variation in pore fluid pressure within or near the plate boundary is particularly relevant to the issue of strain accumulation and release because of its direct control of effective normal stress on the fault plane, as first pointed out by Hubbert and Rubey (1959). Observations of transient fluid flow in "CORKed" ODP holes are increasingly common, lending support to the idea that variations in fluid flow in the subduction environment play a key role in a variety of processes. Obara (2002) has recently reported nonvolcanic tredmor at the down-dip edge of the Japan seismogenic zone and noted its possible relationship to fluid migration in this critical region. Section 2.6 focuses on fluids specifically..

Fore slip

Precursory phenomena ("Fore slip"). A long-standing and controversial question deals with the presence or absence of observable phenomena precursory to seismic failure. Fore-slip, anomalous motion immediately before a major earthquake, has been recognized in a few cases, for example the great 1960 Chile earthquake (Linde and Silver,1989). However, well-documented foreslip observations are exceedingly rare, and obviously much more difficult to obtain than afterslip observations, since they generally require data collection protocols (e.g., a reliable continuous network) to be in place before the event. The great majority of earthquakes have no clear precursory signals (Geller et al., 1997), implying that such signals are either rare—consistent with the hypothesis that earthquakes are essentially unpredictable—or of low amplitude and/or so close in time to the main earthquake that they are difficult to observe with current geodetic techniques. Perhaps we are not monitoring with the right instruments and/or with the right frequency window.

Laboratory studies that take samples to frictional failure have documented precursory failure phenomena, perhaps related to exponential crack growth and precursor dilatation, i.e., crack opening prior to rupture. Better documentation of the laboratory conditions leading to such behavior may lead to improved understanding of when, where and why such behavior does (or does not) occur in subduction zones, and guide appropriate field measurements. Geodetic instrumentation capable of high precision continuous monitoring (e.g., borehole strain and tilt, continuous GPS) needs to be installed, and rigorous data analysis/interpretation protocols need to be in place.

After-slip, with periods of days to a year, may occur after major earthquakes, and may propagate down-dip or up-dip from the main thrust plane, or be confined largely to the location of the main shock. It decays logarithmically, with the majority of motion occurring within the first few hundred days after the main earthquake. Hutton et al., (2001) report measurable motion 3.5 years after the Mw 8.0 1995 Colima-Jalisco earthquake in Mexico. In some cases, cumulative moment from these events approaches or exceeds that released in the main earthquake (e.g., Heki et al., 1997; Burgmann et al., 2001). Consequently after-slip may in part explain the observation that seismic moment released at subduction plate boundaries is less than the total moment expected if all plate motion is accommodated seismically. The strain released as afterslip should be observable in geodetic fault locking studies prior to the earthquakes, along with the coseismic slip, and hence be distinguishable from steady aseismic interseismic slip.

Afterslip observations have a number of important applications, one major one being to test rate- and state-variable friction laws (Marone et al., 1991; Marone, 1998; Hutton et al., 2001). These are now widely believed to be the appropriate friction constitutive law governing the earthquake process. Accurate estimation of decay time, as well as rigorous numerical tests of whether observed decay is in fact logarithmic, and remains logarithmic over the entire observing period, would enable tests of rate/state friction laws with field observations.

Poroelastic deformation can be significant following a large earthquake, as demonstrated for the Landers earthquake (Masterlark and Wang, 2002; Peltzer et al., 1996). Masterlark et al., (2001) predict several centimeters of transient poroelastic deformation following the 1995 (Mw=8) Jalisco-Colima subduction zone earthquake. All too often, the poroelastic deformation is ignored and inadvertently lumped together with either afterslip or viscoelastic relaxation.

Slow slip events can occur on the subduction interface with no clear relation to major earthquakes. Dragert et al., (2001) document an event in the Cascadia subduction zone, where about 2 cm of slip on the plate interface propagated up-dip over a broad area over a period of several weeks, with moment equivalent to a M~6.7 earthquake. Similar events appear to have occurred in a quasi-periodic fashion in the past (Miller et al., 2002). Ozawa et al., (2001) describe an event where up to 20 cm of slip on the subduction interface in the Nankai Trough accumulated over a period of about 1 year. Lowry et al., (2001) document a similar event in southern Mexico on the Middle America trench. Observing more such events, understanding why they occur, and why they do not always lead to instabilities that lead to earthquakes, are critical research areas. To our knowledge, all subduction zones that are well instrumented with GPS have now observed such events, suggesting that they may in fact be quite common and may also contribute to the apparent discrepancy between total (plate motion-related) moment and seismic moment.

Earthquake-stimulated viscoelastic flow. For periods longer than about one year, it is generally believed that deviations from steady, interseismic strain accumulation reflect viscoelastic relaxation in the lower crust and upper mantle, stimulated by coseismic rupture, afterslip, and other stress transfer processes. Such deviations may persist for several years (perhaps several decades, de-

Transient strain phenomena:

After-slip

Poro-elastic deformation

Slow slip

Visco-elastic flow

Transient strain phenomena:

Combinations

—

Updip and downdip limits of the seismogenic zone

pending on viscosity) after the main earthquake. In theory, upper crustal flow due to viscous response of the lower crust could also be stimulated by the slow slip events described above, but the signal may be small. All such observations of surface deformation can in principle be inverted to obtain information on the rheology of this important region, otherwise inaccessible for study.

Combinations. Of course real earthquakes generate multiple deformational mechanisms, and increasingly our data are adequate to resolve two or three for a given event. Pollitz et al., (1998) and Azua et al., (2002) used a combination of viscoelastic and afterslip deformation mechanisms. Masterlark and Wang (2002) demonstrate that a combination of viscoelastic and poroelastic deformation is required to account for transient postseismic deformation.

2.3. Controls on the Updip and Downdip Limits of the Seismogenic Zone of Subduction Thrusts

One focus of the 1997 SEIZE workshop concerned the factors controlling the depth limits of the seismogenic zone. The up-dip and down-dip limits of rupture in great subduction-thrust earthquakes are important for assessing and understanding seismic and tsunami hazard, and more generally for understanding the physical processes involved in generating earthquakes. The down-dip limit determines the landward extent of the seismic source, important for assessing earthquake hazard at inland localities. An accurate "mapping" of this feature also helps us understand the physical processes that control locking on the plate interface. For example, does plate interaction change from locking to stable sliding at a thermal boundary, at a mineralogical boundary that is thermally controlled, or at a mineralogical boundary controlled by pressure (e.g., transition to phases with lower water content)?

> "The down-dip limit determines the landward extent of the seismic source, important for assessing earthquake hazard at inland localities"

Great earthquakes have variable maximum depth of rupture, ~10-50 km. Potential factors controlling this limit related to properties of the incoming plate include (a) composition; (b) temperature; (c) fault material state change; and (d) fault zone seismic "coupling". The elastic properties of the upper plate may also play a role, by increasing the total seismogenic contact area. As is the case in continental fault zones there appears to be a thermal limit of about 350°C (e.g., Hyndman and Wang, 1995), in agreement with laboratory data for the maximum temperature for velocity-weakening seismic behaviour in rocks of crustal composition (e.g., Tse and Rice, 1986; Blanpied et al., 1991; 1995). Detailed thermal models show that the downdip limit of great earthquakes and of the interseismic locked zone agrees well with this temperature for hot subduction zones, including SW Japan (Nankai), Cascadia, Mexico, and S. Chile (Hyndman et al., 1995; Hyndman and Wang, 1995; Oleskevich et al., 1999; Currie et al., 2002). However, for cold subduction zones this critical temperature is at great depth and another limit must apply. That second limit may be the forearc mantle, which is inferred to be serpentinized and aseismic (Hyndman et al., 1997). The forearc mantle is usually at 35-45 km depth for continental subduction zones and ~10 km for island arcs. Because of their structure, serpentine minerals are expected to be aseismic, but laboratory data do not yet give a clear story for their aseismic or seismic behaviour. Peacock and Hyndman (1999) argue that the forearc mantle in contact with the thrust should contain significant amounts of talc due to rising silica rich fluids. Talc is a very weak mineral and is unlikely to act seismically. The thrust intersection of the forearc mantle agrees with the downdip seismogenic limit in many subduction zones, but there are discrepancies, for example in N. Japan and the Aleutians, so questions remain.

"Drilling into the seismogenic zone will obviously be important to answering the question of which material (or materials) control onset of seismogenic behavior"

In a general way we understand the updip limit for subduction zone seismicity: porosity losses and mineral dehydration reactions in response to increasing pressure and temperature initially release large amounts of water from subducted sediment and oceanic crust, probably maintaining high pore fluid pressures on the fault interface and limiting frictional build-up of shear stress and strain. At some point, however, the rate of fluid loss decreases, increasing effective stress and potentially allowing build-up of elastic strain and seismogenic behavior (e.g., Moore and Saffer, 2001).

At the beginning of the SEIZE initiative in the mid-1990's there was considerable focus on the transition from smectite to illite clays as a possible control on the up-dip seismic limit. This transition is known to coincide with the 100°C-150°C isotherm, which in many subduction zones approximately marks the up-dip seismic limit. Further heat flow measurements at a number of subduction zones (including the Nankai Trough and Costa Rica margin) and modeling of the estimated temperatures as a function of landward distance and depth have led to a refined picture of thermal state of the seismogenic zone. While there are still large uncertainties in thrust temperatures and estimates of the updip limits, results are consistent with a thermal control of the updip limit at 100°-150°C. However, new laboratory data do not support a simple model of smectite-illite representing the transition between velocity strengthening and velocity weakening. Experimental work, in part funded by the MARGINS-SEIZE program, suggests that illite remains velocity strengthening and thus is unlikely to cause a transition to seismogenesis (Saffer and Marone, 2003). Some other at least partly temperature-controlled process downdip must be sought. One option is rising pore pressure downdip as a consequence of temperature-controlled diagenetic processes that reduce permeability.

Exhumed accretionary prisms clearly show a range of diagenetic-metamorphic processes above 150°C that could also trigger velocity weakening behavior. Most promising among these is quartz mobility expressed as pressure solution, cementation, veining, and coatings of shear surfaces (Fisher and Byrne, 1990; Moore and Saffer, 2001; Ujiie, 2002). Because quartz is velocity weakening (e.g., Blanpied, 1995), its introduction along shear surfaces could also induce seismic behavior (see Figure 3). Drilling into the seismogenic zone will obviously be important to answering the question of which material (or materials) control onset of seismogenic behavior.

Diagenetic-metamorphic processes

Smectite-illite transition

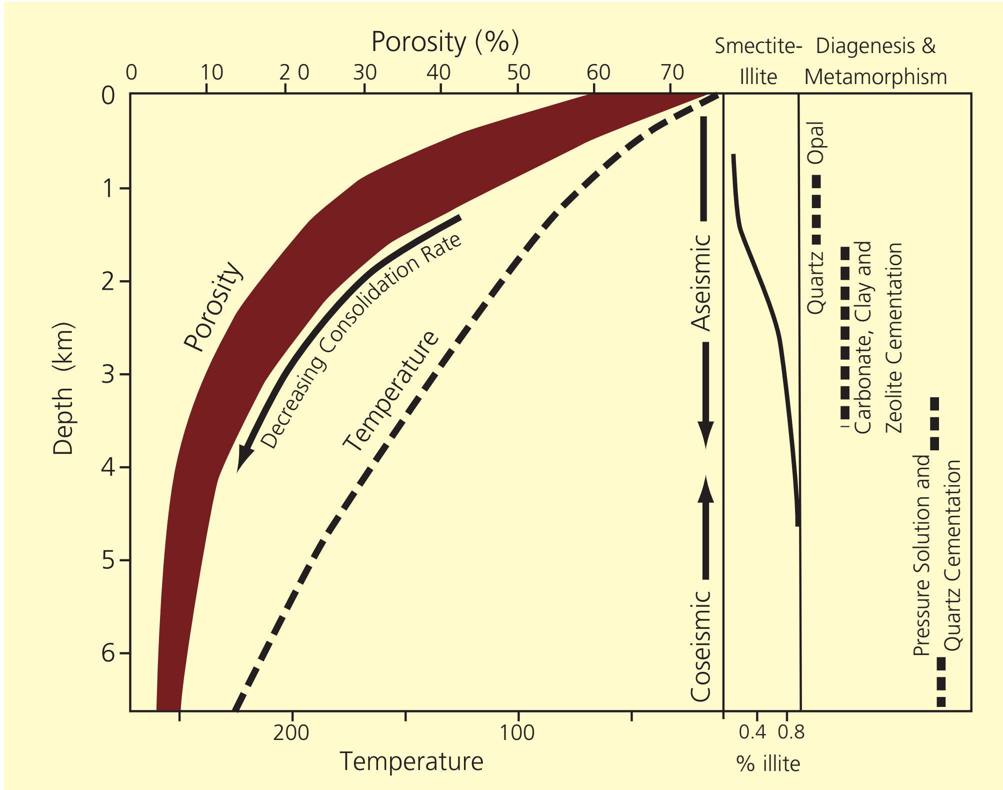


Figure 3. Depth distribution of temperature, porosity, temperature dependent diagenetic, metamorphic phenomena, and the upper coseismic limit of 1946 great earthquake estimated to occur along subduction thrust of central Nankai subduction zone. Note that pressure solution and quart-cementation correlates well with upper coseismic limit of 1946 great earthquake. Modified from Moore and Saffer, 2001. See also Figure 4.

"One SEIZE does not fit all"

It is also possible that individual subduction zones may have different dominant processes controlling this important transition, depending on the nature of subducted material and other specific properties (one SEIZE does not fit all)!. For example, the onset of seismogenic behavior could be both temperature-dependent (cementation/pressure solution) and stress-dependent (compaction). Both of these properties depend on the materials in the subduction interface plus fluid pressure distribution, and it seems likely that this could lead to a highly variable depth limit (Figure 4). Different regions may become "seismogenic" at different depths in the system and may do so in patches or more uniformly depending on the specific margin. It is also possible that topographic features on the down-going plate impart important perturbations to the local state of stress, permeability, and distribution of materials and fluid pressures within the subduction fault.

Accurate recording of the locations, sizes and other characteristics of moderate and smaller magnitude earthquakes that "illuminate" the plate interface between great events is another way to investigate up-and down-dip limits. Unfortunately, given subduction zone geometry, most such earthquakes tend to be poorly located, or their locations have systematic errors. This reflects the fact that most subduction zone earthquakes can only be characterized on the basis of teleseismic data. Even if local seismic arrays are available, they are usually "one-sided" (i.e., sited only landward of the trench). Improving the accuracy of event location requires simultaneous recording by seismometers on land, over the down-dip portion, as well as on the sea floor, around the up-dip portion, at an array of azimuths and distances. This is obviously a technical and logistical challenge, and until recently there have been few such measurements. Several observation programs relevant to this problem have now begun under the auspices of the MARGINS program, in both Central America and Japan. For example, seismometer deployments occurred near the Osa Peninsula in southern Costa Rica in November-December 1999, and off the Nicoya Peninsula in northern Costa Rica in January-June 2000, for comparison to geodetic results (Dixon et al., 2001; DeShon et al., 2003). Each experiment included simultaneous deployments of IRIS/PASCAL broadband seismometers on land, and state of the art ocean bottom seismographs (OBS) offshore. The Nicoya deployment involved 20 PASCAL stations deployed for 18 months, and 14 OBS for 6 overlapping months, with thousands of events recorded. Initial results from these deployments (Newman et al., 2002; DeShon et al., 2003) suggest spatial variability in the updip limit of this seismogenic zone.

Nankai has also had careful land and OBS deployments conducted. A key finding is that there is a very low background level of microseismicity on the plate interface. Why this region is so different compared to Central America, and whether it is a stable or time-transient feature, is not known.

In January-February 2000, a geodetic network in Central America that was first measured in 1994 (Lundgren et al., 1999) was resurveyed to improve the accuracy of the existing GPS site velocities, and new sites were installed in Costa Rica and Nicaragua. An accurate and well-sampled regional surface velocity field is being defined as these new sites are re-occupied, and interpreted in the context of the new earthquake data described above. Preliminary results suggest that a large patch beneath the Osa Peninsula is fully locked and accumulating strain at or near the plate convergence rate, and also experiences back-arc shortening on the Panama fold and thrust belt at rates of ~1-2 cm/yr. In the better sampled Nicoya region, patches of essentially fully locked areas alternate with

Earthquake location efforts within MARGINS

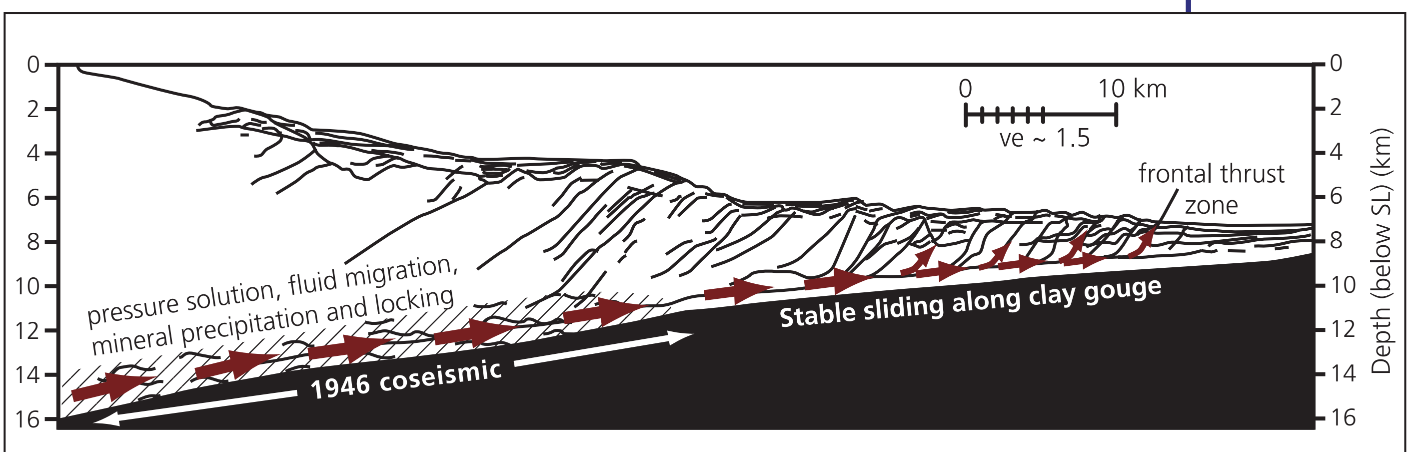


Figure 4. Cross Section of central Nankai Subduction Zone showing depths of diagenetic/metamorphic mineral precipitation along subduction thrust and probable correlation with 1946 coseismic rupture.

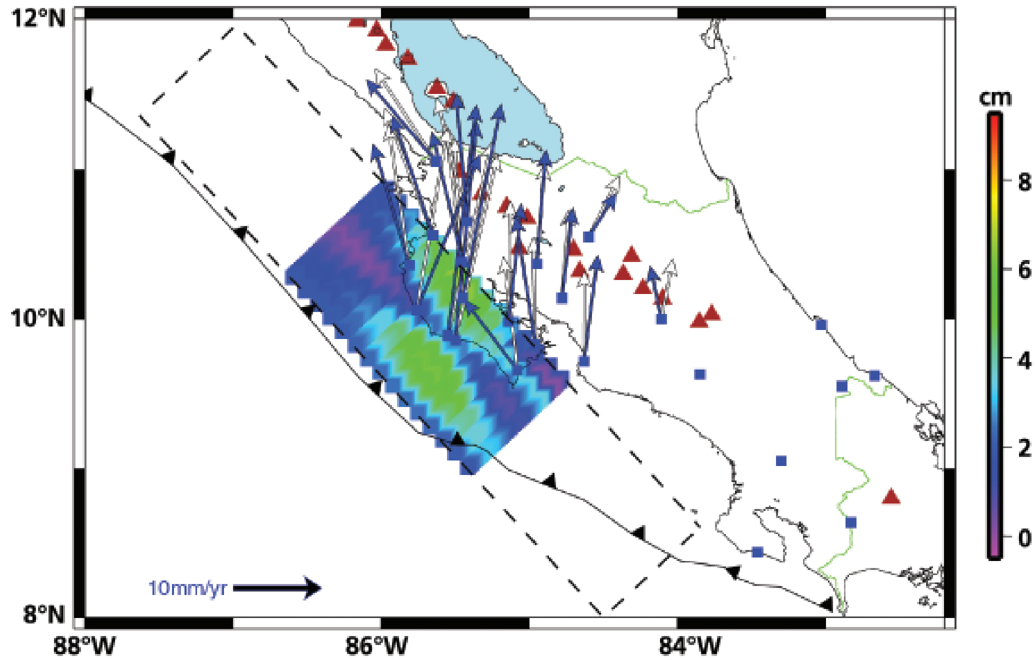


Figure 5. Results of inversion of GPS data for locked slip on subduction thrust beneath Nicoya. From Norabuena et al. [2003].

Nature of tsunamigenic earthquake zones

regions of lower coupling (Figure 5). However, the resolution of these data is not yet sufficient to determine if this "patchiness" in fact represents adjacent fully locked vs. freely slipping regions or true "partial coupling" and how these patches correlate with plate boundary microseismicity

Costa Rica is one of the few places where the land is close enough to the trench (Osa and Nicoya Peninsulas) that terrestrial geodetic data can provide constraints on the updip limit of the seismogenic zone. Generally geodetic data only constrain the downdip limit of the locked zone and great earthquake coseismic rupture zone. This is one of the reasons Costa Rica was chosen for focused MARGINS/SEIZE studies.

For the much better instrumented Japan subduction zone, a precise GPS interseismic velocity field has been available for several years, and indicates strain accumulation consistent with a fully locked seismogenic zone in most areas. The dense network of continuous GPS stations has also documented several transient strain events (e.g., Heki et al., 1997; Ozawa et al., 2001), and elucidated important tectonic aspects (Heki and Miyazaki, 2001; Miyazaki and Heki, 2001).

2.4 Nature of Tsunamigenic Earthquake Zones

Tsunami earthquakes are defined as events that because of their slow (possibly very slow) rupture speed, do not effectively radiate seismic energy, but do actively excite tsunami waves. At this point, not much is known about the mechanical processes that allow rupture to proceed at such slow speeds, however there is mounting evidence that there is a significant decrease in rigidity in and around the seismogenic updip limit (Bilek and Lay, 1999). Currently it is not understood if the decrease in rigidity is controlled by subducted sediments or if other factors, including fluid flow, play a significant role. Changes in the rupture mechanics of shallow earthquakes may also influence tsunami earthquake generation. For some of these earthquakes the rupture upward through the normally inactive up-dip limit, all the way to the sea floor, may contribute further to the generation of tsunami waves.

Understanding why some earthquakes occasionally rupture through this normally aseismic region is an important question and may relate to rate- and state-variable friction. Some models have proposed rupture propagating along splay faults in the accretionary wedge. Others have suggested that heterogeneous distribution of asperities and rate- and state friction variations may also be important for producing the large amounts of shallow slip observed during tsunami earthquakes (Bilek and Lay, 2002). Obviously, anything we learn about how tsunami earthquakes are generated and propagated would play an important role in mitigating tsunami hazards.

Some slip seems to be too slow even for tsunamis and is only detected in geodetic data. We can therefore consider three speed classes for slip on subduction thrust faults:

(a) Fast; generates seismic energy,
(b) Intermediate; generates large tsunamis but small or no earthquake (tsunami earthquake);
(c) Slow; only seen in geodetic data, often shallower or deeper than seismic zone; may be related to deep slow slip events.

Understanding controls on rupture speed, and understanding why some earthquakes and slow slip events apparently rupture through the normally aseismic up-dip and/or down-dip limits are important questions and may ultimately bear on our understanding of the physical processes on the plate interface.

Tsunamis and rupture speed controls

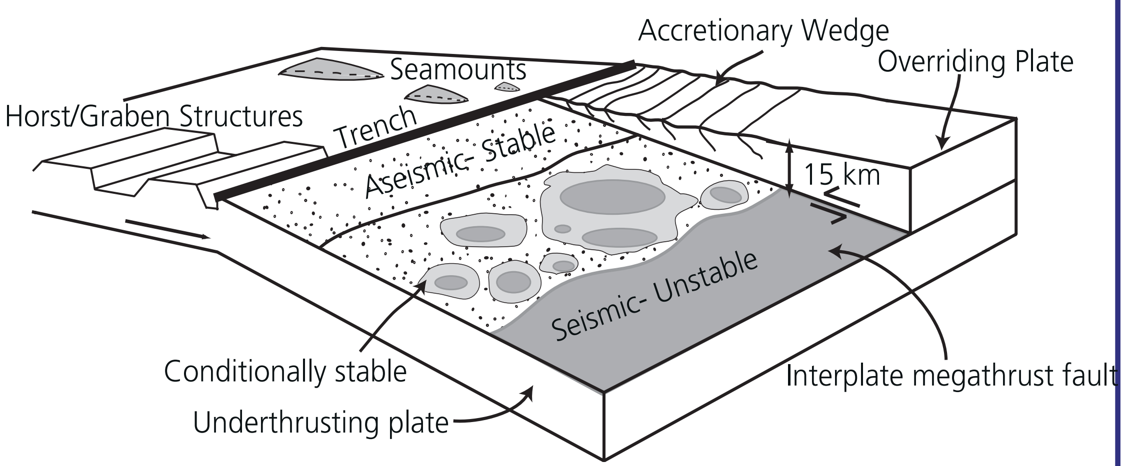


Figure 6. Schematic depicting possible frictional conditions of the subduction thrust fault plate. Unstable sliding contact areas (dark gray) allow earthquake nucleation in the shallow subduction zone, which is typically a stable (stippled) or conditionally stable (light gray) frictional region. A variety of features and mechanisms, such as subducted seamounts, ridges, horst and graben faults, and permeability variations, can produce isolated asperity-regions within the weaker sedimentary materials. From Bilek and Lay (2002).

2.5. Role of Large Thrust Earthquakes in Mass Flux; Nature of the Subduction Thrust

Role of subducted sediment. Regional stress and earthquake studies suggest that subduction thrust faults are weak. Sediment subduction may play an important role, providing a mechanism for bringing large amounts of water to the plate interface. However, there is little consensus on the nature of this role and even less hard data. For example, subduction of large amounts of sediment could generate a large, relatively uniform region of lowered effective friction coefficient, perhaps facilitating rupture over large areas (more sediment equals larger maximum magnitude earthquakes). On the other hand, very low effective friction coefficient could reduce the tendency for strain accumulation and seismic rupture (Pacheco et al., 1993) (more sediment equals less seismicity).

Nature of the subduction thrust

The stress drop in subduction earthquakes is inferred to be close to complete. This might reflect:

(a) high pore pressure that reduces normal stress;
(b) inherently weak fault gouge, or;
(c) something unique to the dynamic rupture process.

Mass Transfer. Transfer of mass in subduction zones can occur as solid mass or as dissolved mass carried by fluid flow. In the solid phase, transfer of material from one plate to the other is a fundamental part of the subduction process. In the upper part of subduction zones, including the seismogenic zone, this can take the form of the addition of material from the subducting plate to the base of the overriding plate by underplating, with consequent uplift. Alternatively, removal of material from the base of the overriding plate by a number of processes leads to tectonic erosion, manifested by subsidence. We do not know whether major thrust earthquakes are part of the mechanism of either of these processes, or whether earthquakes arise purely from slip between the two plates with no material transfer. The association of areas of rupture with regions of the forearc known to exhibit underplating or tectonic erosion suggest that large thrust earthquakes are involved in either one or perhaps both of these processes. This issue can be resolved by comparing:

1) seismic reflection images of the basal detachment;
2) the earthquake or microearthquake-determined locations of the detachment, and;
3) changes in shape of the sea floor above the zone of underplating or tectonic erosion.

Thermal Models. Numerical thermal models give us our best temperature estimates for the subduction thrust. New subduction zone specific thermal models using finite element methods have greatly improved our temperature estimates over older generic models using finite difference. However, many uncertainties remain, including (a) the isotherms intersect the thrust at a fairly shallow angle which limits thrust temperature resolution, (b) frictional heating, although concluded to be small, remains an uncertainty, (c) transient effects, (d) updip temperatures can still be improved by more detailed description of the thrust dip profile, including how much and where sediment is scraped off, and the seafloor profile at the model location (and how has this varied with time). Detailed heat flow measurements are needed, because comparison of predicted with observed surface heat flow is one of the more important tests of such models. Other parameters needed are the thermal properties of the forearc, its radioactive heat generation, and the thermal state of the incoming oceanic crust and overlying sediments.

Exhumed faults. Study of exhumed subduction thrusts should be a key aspect of the SEIZE program. They provide the requisite "ground truth" for many of the ideas discussed here, and are also a necessary first step for drilling because they provide information on the material properties likely to be encountered at depth.

Seismic reflection, downdip limit. The subduction thrust reflection image generally is thin and sharp where seismogenic, but becomes a thick reflection band deeper in areas of "slow slip"; the concept of a "plastic shear zone" has been proposed (e.g., Nedimovic and Hyndman, in press). This change in width from the shallow brittle part of the fault zone to a deeper wide shear zone where there is more plastic deformation is well recognized in exhumed continental fault zones. The change in subduction thrust reflection image may therefore provide an indicator of the seismic-aseismic boundary.

Seismic reflection, updip limit. The updip aseismic zone has been shown to have variable positive and negative polarity reflections. These have been interpreted in terms of variable pore pressure

2.6. Magnitude and Temporal Variation of Pore Fluid Pressure and Flow

Fluids play a key role in faulting and earthquake mechanics (e.g., Hickman et al., 1995; Raleigh et al., 1976) and in all five questions noted in Section 1.2. Fluid pressure likely controls a wide range of faulting characteristics, from fault strength to rupture propagation, in both subduction zones and continental settings (e.g., Rice, 1992; Johnson and McEvilly, 1995). In subduction zones, elevated pore pressures (approaching lithostatic values) result from a combination of rapid compaction and low permeability typical of marine sediments. Studies have shown that pore pressure affects decollement strength, structural development, and taper angle (e.g., Hubbert and Rubey, 1959; Davis et al., 1983) because it controls effective stress. In addition, pore pressure has been postulated to influence the position of the shallow limit of seismogenic faulting behavior, through its control on effective stress and consolidation state (e.g., Moore and Saffer, 2001; Scholz, 1998). Pore pressure is thought to affect earthquake source duration (e.g., Bilek and Lay, 1998) and the time-dependence of aftershock activity. The compaction state and fluid flow patterns associated with subsurface pore pressure are also important for interpretation of chemical data as a constraint on fluid mass fluxes (e.g., Bekins et al., 1995; Saffer and Bekins, 1998).

Pore fluid pressure and flow

Geologic observations of exhumed subduction zones document a close connection between fluid over-pressure and faulting (e.g., Sibson, 1990). Slow-slip events in the down-dip region of the Cascadia subduction zone may be related to cycling of metamorphic reactions (Dragert et al., 2002). These reactions release water, possibly in conjunction with low matrix permeability that limits drainage, resulting in elevated pore pressure and low effective stress, allowing fault slip and opening high-permeability pathways.

Direct measurement of fluid pressure and permeability within active fault zones is challenging, but important to the SEIZE initiative. We need to understand the distribution of pore pressure, dewatering from compaction and metamorphic dehydration reactions, permeability, and porosity—both along strike and down-dip—on subduction plate boundaries. Quantitative models linking transient changes in pore pressure, fluid production, permeability, and porosity to transient strain events are just beginning to be developed (e.g., Saffer and Bekins, 2002, Revil and Cathles 2002). A unique aspect of the MARGINS-SEIZE program is the ability to link such processes and models through a unified field program.

Some examples of key issues related to pore pressure and seismogenic faulting for the five original SEIZE questions are discussed below.

2.6.1. Fluid Pressure and the Nature of Asperities

Fluid pressure and asperities

Fluid pressure, through its influence on effective stress, is known to profoundly affect fault strength (e.g., Hubbert and Rubey, 1959) and the sliding stability of faults (e.g., Scholz, 1998). Fluid pressure distribution within fault zones is an important parameter controlling the rupture and aftershock sequence in some earthquakes (e.g., Bosl and Nur, 2002; Miller et al., 1996). Thus, the spatial variability of pore fluid pressure within fault zones is a potentially significant factor in controlling the distribution of fault strength and slip behavior.

2.6.2. Temporal Variation of Pore Pressure and Relationship to Strain

Pore pressure, fluid flow, and strain

Strain, pore pressure, and fluid flow are intimately related at subduction zones where hydrologic process are highly active (e.g., Sibson, 1990). Fluid pressure is thought to be related to earthquake triggering, post-faulting evolution of permeability and effective stress, and volumetric strain, in addition to the spectrum of transient strain behavior discussed above. One question that can be addressed at both the Nankai and Costa Rica margins is whether the physical properties, chemistry, and state of the fault zone change with time throughout the earthquake cycle (inter, co- and immediate post- seismic periods). To address this issue requires sampling and instrumentation of long-term chemical and hydrological sensors in boreholes and at the surface (Figure 7). Physical properties and state variables such as permeability, seismic velocity, fluid pressure, stress, temperature, and fluid chemistry and flow rates are important parameters.

Information gained from pore water chemistry, cementation, and pressure/temperature monitoring could have profound implications for our understanding of the temporal relationships of key parameters (stress, pore pressure and permeability) and mineral reactions that occur at depth and that affect fault mechanical behavior and the nature and magnitude of fluid/chemical fluxes through subduction systems. Two hydrologic hypotheses can be simultaneously addressed during long-term monitoring of the hydrogeological system along faults. These concern the depth from which hydrologically active faults have their fluids sourced and how the movement of these relate to the state of stress, fluid chemistry, and dynamics of faulting.

Hypothesis 1 suggests a deep connection with chemical dehydration reactions that effectively drives fluid pressure and fluid transmission up major faults. Such transmission may occur transiently and can be coupled to rupture. Fluids transmitted up the fault from depth will be progressively modified by shallow water sources and reactions.

In Hypothesis, 2 up-dip flow is limited and fluid pressures within the fault are set by local conditions. Under these conditions pore pressure in the fault can respond to stress changes and pore elastic effects imposed during the earthquake cycle, but fluid movement and fault dilation is limited and does not necessarily drive instabilities and rupture by a fault valving mechanism. Likewise, the importance of high-amplitude seis-

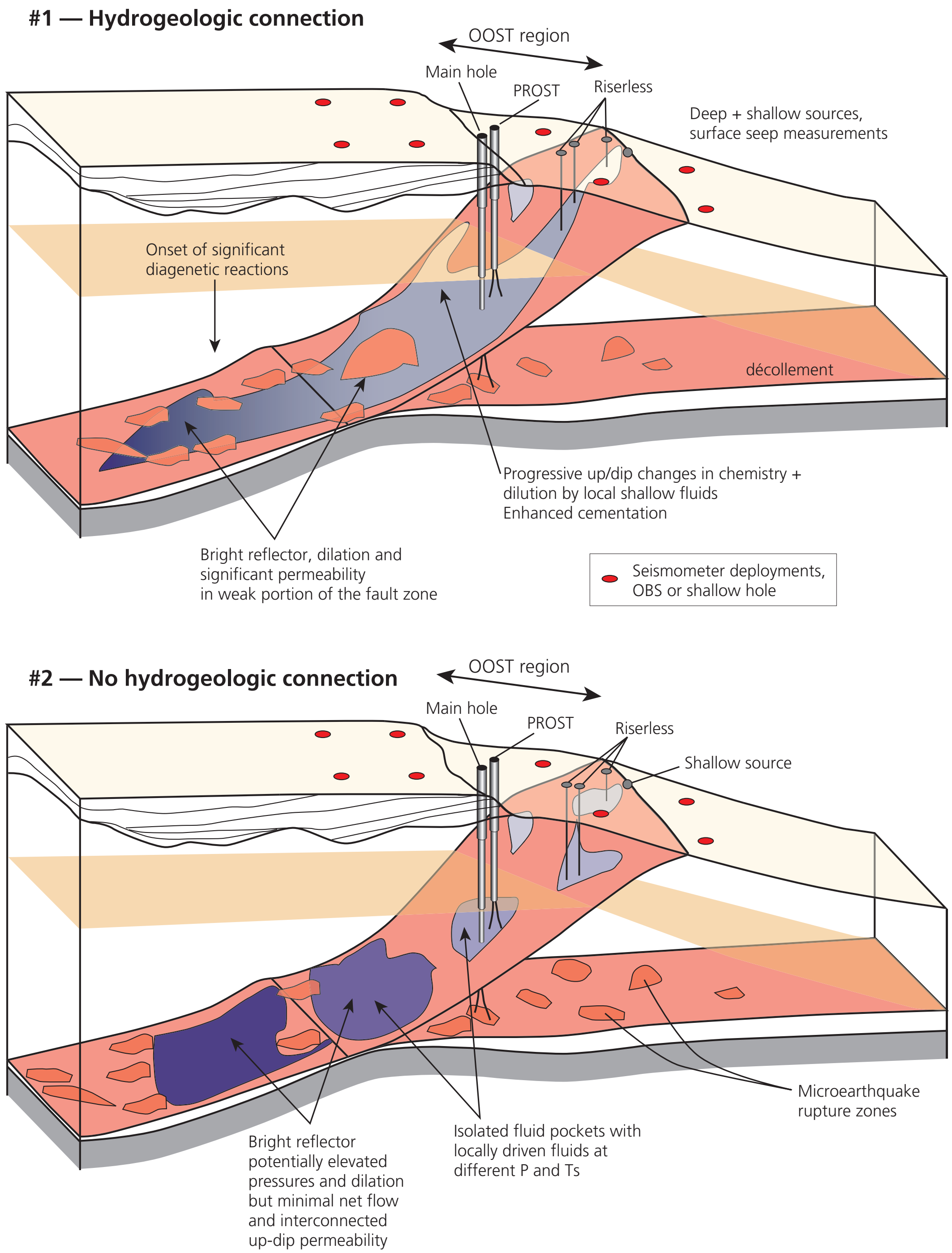


Figure 7. Two potential end-member hypotheses for the hydrogeologic environment along the out-of-sequence thrust (OOST).

mic "bright spots" that can occur along the faults and their relationship to fluid flow and fluid pressure are unknown but may provide a means to design experiment that will allow us to study along fault fluid transmission scenarios. In Figure 7, we show for Hypothesis 1 and 2 different types of patchiness that might indicate different types of fluid transmission indicators. There may also be little to no fluid concentration and dilation on the fault plane, in which case any geophysically observed patchiness may related to other factors such are the wall rock properties and lower velocity gouge distributions.

Out-of-sequence thrust fault and fluid pressure

2.6.2a. Fluid triggering of earthquakes

Fluid triggering of earthquakes

Direct observations (e.g., Raleigh et al., 1976; Bosl and Nur, 1992; Johnson and McEvilly, 1995), field study of exhumed faults, and theoretical models (e.g., Sleep and Blanpied, 1992) all indicate that fluid pressure affects earthquake nucleation. An additional complexity arises because both permeability and porosity are known to depend on effective stress, and thus vary as fluid pulses propagate (e.g., Rice, 1992). In subduction zones these types of behavior may provide destabilization and fault-triggering mechanisms, perhaps "powered" by nearby earthquakes that affect permeability (e.g., Miller et al., 1996) or by chemical reactions (in which case fluids could be characterized by distinct chemical and isotopic signals (Hypothesis 1 in Figure 7).

2.6.2b. Post-faulting responses

Fault movement itself may change the surrounding permeability structure, pore pressure distributions and thus flow rates and pressure distribution, giving rise to post-earthquake transients (e.g., Sibson, 1990) or triggering phenomena (e.g., Bosl and Nur, 1992). Regional changes in the permeability of shallow aquifer systems may be monitored in wells and fault controlled seeps on land, and with long-term pressure and temperature measurements in boreholes and surface flux meters offshore.

2.6.2c Volumetric strain

A number of recent studies have looked at the static stress changes associated with earthquakes and stress triggering of nearby faults. While syn-faulting stress transfer is often quite small, additional postseismic poroelastic and viscoelastic stress relaxation may enhance static stress and transient pore pressure effects far from the earthquake. The temporal distribution of Landers earthquake aftershocks suggest that a combination of coseismic strain and subsequent pore pressure decay (and resulting poro-elastic stress changes) resulted in significant stress change out to distances of ~50 km from the fault (Bosl and Nur, 2002). These should be measurable both in bore holes and potentially at the seabed.

2.6.3. Role of fluids in controlling the updip limit of the seismogenic zone

In the same manner that it may affect sliding stability of fault regions through its control on effective stress, pore pressure is thought to be one of several factors that mediate the upper transition from aseismic to seismic slip (termed the "Updip Limit" of the seismogenic zone) (e.g., Scholz, 1998; Moore and Saffer, 2001). Increased effective stress at the fault interface increases the tendency for unstable slip; systematically increasing effective stress with depth in subduction zones may result from a combination of increased overburden and declining fluid pressure or fluid production.

2.6.4. Role of Fluids in Tsunami Earthquakes

As noted above, the processes controlling tsunami earthquake rupture are not well understood. In particular, the properties and state of the plate interface which allow rupture to extend through the normally aseismic region above the updip limit of the seismogenic zone are unknown. Distinct patches of elevated pore fluid pressure, in conjunction with the complex frictional behavior of some clays, have been hypothesized to control this process, by allowing slip to propagate to the seafloor (e.g., Seno, 2002).

2.6.5. Role of Fluids in Mass Transfer

Transport of dissolved mass by fluid flow along faults from deep reaction zones has been observed in subduction zones worldwide (e.g., Kastner et al., 1991). Current monitoring studies are based on the hypotheses that pore fluid chemistry along shallow thrusts faults may be used to infer mineralogy, temperature, and reactions occurring at seismogenic depths (Hypothesis *1* in Figure 7). However, it is not always clear that such updip transport occurs in every environment (Hypothesis *2* in Figure 7) and there are important questions that have to be addressed concerning the widespread applicability of large scale updip fluid migration. Even if fluid migration is limited to local scales, the role of fluid mass transport in vein formation may also be important in changing the material properties of the fault. For example, vein formation occurs along faults as solutes are transported upward to lower temperature and pressures. Changes resulting from vein formation such as permeability decreases and increases in mechanical cohesion may be central to seismogenic processes.

2.6.6. Outstanding issues

Because sampling by drilling and direct measurement of fluid pressure and hydrologic properties is only plausible at shallow depths and over limited spatial extent, addressing these outstanding issues requires an integrated plan including the following:

Theoretical modeling provides a means to test hypotheses related to feedbacks between hydrologic and mechanical processes, identify and quantify important controlling processes, and direct future data collection efforts. Viable models for subduction zones are needed at multiple scales to (a) link fluid flow models with laboratory and field data, (b) extend results from areas that are well-constrained by direct monitoring to unmonitored regions, and (c) couple fluid flow and mechanical (deformation) models.

Fluid production from compaction, hydrocarbon generation, and metamorphic reactions are central aspects of existing hypotheses explaining earthquake and pore water geochemical observations. Better constraints on the distribution of fluid production, as well as any expected chemical and isotopic signatures, are therefore critical. These objectives can be realized through a combination of laboratory studies (e.g., deformation tests, experimental petrology) and theoretical modeling.

Permeability of both fault zones and country rock (matrix) strongly mediate the de-

Fluids in tsunami earthquakes

Fluids and mass transfer

Outstanding issues

velopment of elevated pore pressures. Thus, estimates of permeability at a range of scales–for both faults and matrix–are needed. These estimates can be obtained by direct measurement on core samples (cm scale), hydraulic testing in boreholes and between pairs of boreholes (10's-100's of m scale), and inverse modeling (several km scale).

Direct measurement, long-term monitoring. Direct measurement of pore fluid pressure, via long-term monitoring and downhole measurement in boreholes, is needed to evaluate the magnitude of pore pressure within fault zones and adjacent wall rocks, as a means to test hypotheses for fault weakness, and as a constraint on theoretical models. Long-term monitoring is an integral component of testing hypotheses discussed above relating temporal variation in pore pressure, permeability, and fault slip. Surface measurements of flow at fault-controlled cold seeps, associated with transient changes in fault permeability and pore pressure distribution, may also give further cost effective field indications of slip events (silent or otherwise) in regions away from boreholes (Tryon et al., 2001, 2002). Together with surface measurements of episodic flow that are associated with coseismic volumetric strain events, these may give us a geographically broader array of allied measurement opportunities to track the impact of rupture events over regional scales.

New questions for SEIZE

3. New Questions

Based on the presented discussion, a number of new questions can be posed, supplementing the questions posed at the beginning of the SEIZE initiative:

1) What controls the overall distribution of seismic energy release during a subduction zones earthquake (up, down, and sideways). Is there one P-T-X condition that defines the onset and down dip limit, or do they vary with the material properties fault geometry, pore pressure, and state of stress in the subduction system?
2) What controls the sometimes heterogeneous distribution of locking patterns on the plate interface and subsequent variations of energy release during earthquakes? Are such “asperities” linked by common physical processes within the fault region or governed by separate, unrelated phenomenon? Can such features be accurately mapped with microearthquakes? With space geodesy? What are the prediction errors associated with typical mechanical models for subduction zone strain accumulation? Do the patches vary in time, and if so, over what time scale? How do these heterogeneous features influence tsunami earthquake generation?
3) What controls the rate of propagation and slip rates of earthquakes and the distribution of fast, slow, tsunamigenic, and silent earthquakes in time and space?
4) What is the nature of temporal changes in strain, fluid pressure and stress during the seismic cycle? Do these change gradually during the seismic cycle or are there transient interseismic phenomena that lead to strain and energy release at various times during the seismic cycle?
5) What are the prediction errors associated with typical mechanical models? For example, Masterlark et al., (2001) demonstrate enormous prediction errors associated with the homogeneous material property assumption in both forward and inverse models of GPS displacements caused by dislocations along

a fault. The analysis was performed using finite element models (see attached figure from Masterlark et al., 2001).

4. Implementation Strategy of SEIZE

We are now four years into the SEIZE study, and significant data collection efforts have been made in Japan and Central America (see Appendix for discussion of focus site selection criteria). The updip limit of a 1999 rupture zone for a M=6.9 earthquake has been carefully mapped off southern Costa Rica. It appears to be limited to depths in excess of 13 km. There is some indication of a shallower limit farther south but that is outside the boundaries of the OBS experiment. Clearly more OBS experiments are needed to fully understand the up-dip limit of the seismogenic zone and to investigate its possible spatial and temporal variations (this may only be useful in Central America, as the rate of microseismicity is quite low in Nankai). One borehole seismometer has been installed offshore Japan, and the initial results are very promising. Similar instrumentation is necessary off Central America.

Much geodetic work has been carried out in both regions and we have significantly better understanding of locked vs. slipping zones. Excellent methodology for studying locked vs. slipping zones along the thrust interface has also been developed. Further geodetic data and modeling are necessary to establish detailed understanding, and to begin to investigate the difficult question of temporal variation. Continuous GPS in Japan has recorded a number of transient events on the plate interface, and these are revolutionizing our previous picture of a "static" (between major earthquakes) plate interface. A similar network is necessary in Costa Rica.

A great deal of seismic reflection data has been obtained, sufficient to image the entire seismogenic zone beneath Nicaragua, Costa Rica and Southeastern Japan. Two three-dimensional reflection surveys have been done off Japan, and one 3-D in Central America.

Based on these and other studies, some general characteristics for the two regions have emerged:

4.1 Central America (Osa to Nicaragua)

Temporal and spatially complex, with behavior that varies considerably along strike. In particular the basement topography and sediment thickness vary greatly, with "patchy" seamount distribution, possibly related to patchy locking. Characteristic earthquakes tend to be smaller in magnitude (M~7-7.5) with a limited slip distribution, possibly controlled by bathymetry; slow tsunamigenic earthquakes have occured off Nicaragua.

4.2 Nankai

Larger magnitude (M~8-8.5) earthquakes, with relatively uniform fault properties and only small lateral changes; large areas are fully locked most of the time; limited microseismicity.

What has not yet occurred in either region is direct sampling, e.g., by drilling or submersible vehicles. Drilling is planned in both regions, however a number of site characterization studies still need to be carried out. For example, no 3-D seismic reflection surveys exist in the most promising areas for riser drilling in either Japan or Central America. The general properties outlined above for each region will be used as a guide to picking appropriate drilling targets. Particularly for Central America, with its great spatial variability, several drilling targets

Time (2000 to 2014)	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14
1. Monitoring Earthquakes and Strain	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
2. Seismic Reflection Imaging	▬	▬	●	●	●	●	●	●	▬	▬	▬				
3. Studies of Paleoseismic Zones	●	●	●	●	●	●	●	●							
4. Determining Nature of Incoming Mtrl.	▬	▬	●	●	●	●	▬	▬							
5. Monitoring ODP and Riser Holes			●	●	●	●	●	●	●						
6. Experiments	●	●	●	●	●	●	●	●							
7. Modeling	●	●	●	●	●	●	●	●	●	●	●	●	●		
8. Deeo Riser Drilling						▬	●	●	●	●	●				

*Table 1. Schedule for Implementation of Research: * major activity, - rampup and rampdown. Monitoring earthquakes and strain (1) defines the seismogenic zone and locates targets for imaging and drilling (2). ODP drilling will determine the nature of incoming material near the deformation front (4). Images (waveforms) of the seismogenic zone plus experiments (6) on the incoming material will lead to model predictions (7) on the nature of the materials in the seismogenic zone that can be ultimately tested by deep drilling (8). Locating the deep drilling site will require extensive site surveys, including OBS, borehole strain/tilt, seismic reflection imaging and GPS (in Costa Rica, where land exposure enables strain measurements close to the seismogenic zone).*

Time frame of SEIZE

spanning both cross-strike and along strike directions are appropriate. The proximity of land to the trench in Costa Rica suggests the possibility of joint land-ocean drilling.

The new drilling program (IODP) is progressing well. The riser vessel has been built and an RFP has been submitted for a non-riser vessel, the latter to begin scientific drilling in 2005. Non-riser drilling has been done in both the Nankai Trough and offshore Costa Rica, the latter with two drilling legs off the Nicoya peninsula. Complex drilling proposals have been submitted for use of both riser and non-riser ships for drilling into the seismogenic zone off both Japan and Central America.

4.3. Duration of SEIZE

The original SEIZE Science Plan envisioned a 10 year program. However, because the funding level of the MARGINS Program has been less than anticipated and started somewhat later than anticipated, we now believe that achieving SEIZE objectives will require a 15 year program, 2000-2014.

The ordering of certain elements of the program is obvious, for example, extensive geophysical surveys (Table 1, item 2) are required prior to deep drilling (Table 1, item 5). Other aspects of the program are strongly interwoven, with results from one potentially triggering further studies in another. The first 5-6 years of SEIZE will focus on developing geological and geophysical background (Table 1, items 1-4) for the candidate seismogenic zones. Monitoring of seismicity, strain, and fluid flow, whether at the surface or in boreholes, is required for the full duration of SEIZE to document and understand the spectrum of transient phenomena (Table 1, items 1 & 5). Modeling and laboratory experiments will be necessary throughout, to guide data acquisition and evaluate results. Riser drilling, beginning in about 2007, will ultimately test predictions of the nature of the seismogenic zone.

Appendix: From the Original SEIZE Science Plan

The Location of SEIZE Focus Sites;
Selection Process

SEIZE must focus in a few locations to maximize the essential multidisciplinary interaction and integration. A major goal of the June 1997 SEIZE workshop was to select sites for intensive research. The criteria for selection of localities are as follows: 1) The region must include historic large thrust earthquakes. 2) The subduction thrust must be imageable by seismic reflection techniques over much of the seismogenic zone. 3) The subduction thrust must be drillable, both near its seaward terminus and into the seismogenic zone. 4) The availability of data from previous geological and geophysical surveys and ODP drilling as well as proximity to ports, logistical support, and favorable weather conditions should favor the candidate sites. 5) The geological and geophysical nature of subduction (e.g., convergence rate) is a consideration in site selection.

Selected Localities for Intensive Focus: Japan and Central America

Earthquake seismologists attending the June 1997 workshop proposed 14 seismologically compelling targets. Consideration of the criteria outlined above reduced the 14 to seven. The report of the June 97 workshop outlines the complete cases for each of the seven candidate localities. After much discussion the workshop participants agreed that SEIZE should be focused in Japan (Nankai Trough and Japan Trench) and Central America (Costa Rica and Nicaragua). Specifically, landward of the Nankai Trough, sediments underthrusting the prism can be traced into the seismogenic zone on existing 2D seismic reflection images; therefore, the material properties of the seismogenic zone are predictable. The seismogenic zone here lies within the planned capability of the OD 21 riser drilling ship. In the Central America region, the Nicoya Peninsula lies over the seismogenic zone and offers an exceptional opportunity for seismic recording and GPS monitoring. The seismogenic zone is located at 10 to 12 km beneath the Nicoya Peninsula, and lesser depths offshore.

The Japanese and Central American seismogenic zones have compelling contrasts and comparisons that behoove their investigation. The Costa Rica margin contrasts well with the Nankai seismogenic zone because the former is non-accretionary and the latter is accretionary. Pelagic sediment dominates underthrusting section of Costa Rica, whereas terrigenous deposits are dominant in Nankai. Costa Rica converges at a high rate whereas Nankai converges at a slow to moderate rate. Costa Rica has a low and Nankai a relatively high thermal gradient. Both the Japan Trench and the Nicaragua Trench have produced tsunamigenic earthquakes, with shallow seismogenic zones. As these tsunamigenic seismogenic zones are within the drilling capability of the JOIDES Resolution, they can be investigated soon. The Central American localities have potential to fulfill goals of MARGINS in crustal recycling and SEIZE. Logistical reasons all support focus of SEIZE in Japan and Central America. In the Japanese Islands the large number of seismic stations both on land and underwater, the extensive GPS network, and an abundance of other available data provides overwhelming scientific investment that a SEIZE program can build on. Both the Japanese and Central American regions have active scientific communities that can develop strong SEIZE efforts. Both are near major ports and easily accessible to study.

Methods and Approaches

Earthquake Seismology: Three methods can potentially characterize the seismogenic zone at subduction zones: 1) seismic tomography; 2) earthquake waveform inversion; and 3) active source imaging and velocity studies. Characterization of the seismogenic zone using earthquake waves as sources is the method that has yielded nearly all we now know about subducted slabs. Unfortunately, the location of shallow earthquake sources at subduction zones, and thus much of characterization, depends on teleseismic arrivals at distant stations and arrivals from stations on land, which are nearly always located on only the landward side of the trench. Such location estimates are likely to have systematic errors associated with them, which are difficult to detect and correct. To properly characterize this zone with earthquake arrivals, sensors are required close to the sources and at a variety of azimuths and distances. This requires that permanent ocean bottom seismic stations be established, some of which should be seaward of the trench axis. Technology exists to establish such stations, which can also double as tsunami detectors and monitors of other geophysical parameters. For many applications, data from these stations should be transmitted to shore in real-time. Seismologists can resolve focal mechanisms from teleseismic waves of earthquakes with a magnitude greater than 5.5 Ms (magnitude from surface waves). Broadband waveform inversion of earthquakes with magnitudes greater than 7 Ms and inversion of tsuna-

Appendix:
Excerpt from
original 1997
Science Plan

mis recorded at tide gauges can resolve information from source processes. Measurements should also include the recording of S-wave transmission through the seismogenic zone, including S-wave splitting, to estimate fracture orientation and to monitor changes in state of stress.

By extending seismic recording arrays offshore we can monitor the build-up of stress in the oceanic crust as the earthquake cycle progresses. In regions up-plate from an asperity, this stress buildup has caused intraplate focal mechanisms to take on a stronger compressional component than would otherwise be present. Although extraction of focal mechanisms using OBS data has been complicated by uncertain performance of horizontal components, focal mechanisms from intraplate earthquakes can be recovered using 3-4 instruments. Where earthquakes are monitored regionally with modern broadband instrumentation, source processes are routinely being determined to for events with magnitudes as small as 3.5. Although this can be done from shore to some extent, in a subduction zone, 3-component OBSs would greatly extend capabilities.

Recent observations in California have revealed the presence of seismic waves controlled by a low-velocity layer of fault gouge in a strike-slip fault zone. This waveguide supports dispersive wave propagation in the same fashion as does a low velocity crust overlying mantle. Very effective excitation of the waveguide occurs since the source is located within the waveguide. Simple modeling as a single layer between two half-spaces has allowed extraction of fault zone thickness and the shear velocity of the infilling material. In the California example, fault thicknesses of 120-170 meters and shear velocities of 0.7-0.85 km/sec have been observed from interface waves. Lower- resolution body-wave studies yield 1-2 km wide zones with shear velocities of 2-3 km/s and Vp/Vs ratios of 2-2.3.

We can expect similar physics to govern subduction fault zones. Broad-band seismometers located on islands have observed low-frequency guided waves traveling up slabs. On land, the trapped waves were recognized by their phase velocity, so use of this phenomenon will require a linear array of OBSs in the trench, and, as necessary, enough land and sea seismic stations to provide usable locations. Depending on the distribution of sources and receivers, the potential for two-dimensional tomography exists. If asperities (strong regions) have a velocity structure that is different from regions that are freely slipping (or nearly so), they should be imageable by two dimensional tomography, depending on the source-receiver distribution.

Reflection Seismology: Imaging of the seismogenic zone at depths of 10-20 km in subduction zones will require new experimental designs. In its simplest form, the imaging must define the top of the down-going slab and structures within the base of the overriding plate, from the deformation front, landward through the seismogenic zone. These will help define the geometry of the subduction zone, possible asperities, and erosion and accretion at the base of the overriding plate, and properties of the fault zone. We must be able to observe seamounts and thrust packages at vertical scales of ~500 m and lateral extent of ~1 km at depths of 10-20 km.

Seismic sources must be large to penetrate to the needed depths, yet contain a broad-band spectrum of energy to preserve resolution and allow waveform inversions of the seismic reflections. Seafloor swathmapping provides 3D information that greatly constrains interpretations and helps locate seismic lines in areas of minimal out-of-plane effects. Multichannel seismic (MCS) reflection methods, particularly 3D acquisition and processing can provide high-quality images of the décollement and structures above and below. Although there is always a desire for higher resolution and deeper penetration, depth is limited by attenuation and source strength, and resolution by frequency content of the source. The reflection and refraction techniques become more powerful when combined than when applied separately. Closely spaced ocean bottom seismographs/ hydrophones (OBS/H) along a modern normal incidence reflection line can extend structure to depth and can provide velocity data to aid processing. These data will also provide background velocities to combine with reflection waveform analysis. The few examples of such combined data suggest we can image to the depths where great earthquakes nucleate.

The best way to obtain high-quality images is by using 3D seismic reflection, particularly with enhanced processing such as 3D dip-moveout and 3D prestack migration. These techniques require high quality data as well as high-performance computing capability. Use of a high capacity, broad source, a ~6 km streamer, and OBS(H) at perhaps 500 m spacing would likely be necessary for adequate images. With extensive prestack processing, the 6 km streamer will provide adequate images of shallow structure, although velocity information will be limited. Where the structures above the seismogenic zone are more complex (probably the more common case), first order corrections for the overlying structure are essential. If the shallow structure is not properly accounted for, reflection amplitudes and waveforms of deeper events will be severely distorted. Short of a full 3D program, a swath 3D approach could correct for some of the structural complexities. A high capacity broad-bandwidth source, densely spaced OBHs along a dip line, and a multiple-streamer ship shooting a series of parallel lines (the number and spacing would have to be determined from modeling) would produce exceptional observations.

The use of multi-OBS/H enables us to get fine images of the seismogenic zone. Recent experiments suggest that, OBS/Hs spaced along a 2D line every 500 m with the combination of tomography might give a reasonable 2D image. This image will still suffer from the 3D effects. Such densely-spaced OBS/H provide the information to develop a proper velocity field for the entire margin. This is essential to the full characterization of the margin and is an important method to improve locations of microearthquakes.

Geodetic Methods: A fundamental measure of slip on the seismogenic zone is the deformation of the surface of the overriding plate from the trench to the backarc. Measurement of the surface deformation predicts, through appropriate models, maps of locked and slipping portions of the seismogenic zone. The geodetic measurements must be able to measure deformation rates that may approach a few cm/yr in both horizontal and vertical dimensions over 100-200 km range from the trench. Traditional methods such as leveling only measure the vertical component and must be carried out over long distances to tie into a stable plate interior. GPS is currently the premier method for determining 3D displacements in a global reference frame. Simple models of elastic, interseismic strain at seismogenic zones feature rapid subsidence nearest the front of it diminishing in rate inland and crossing over to uplift roughly above the deepest extent of the locked zone. The horizontal expressions of such elastic strain models predict a smoother transition, with the near trench portion of the overriding plate moving mostly with the downgoing plate velocity and decreasing towards the stable plate interior. The vertical component of motion can be highly diagnostic of the dip of the seismogenic zone; to be most effective, measurements must be made to ~100 km of the trench to define the down-dip extent and within a few tens of km to define the updip extent of the seismogenic zone. In the case of land-based GPS, choosing a location where the coastline extends as close to the trench as possible is a great advantage towards "imaging" the locked and slipping portions of the seismogenic zone. In the marine environment, underwater sound transmission can tie seafloor reference points to sea surface platforms whose positions are simultaneously determined with GPS. Results from initial tests imply that uncertainties in velocity vector estimation should be 5 mm/yr or less. Besides standard GPS campaigns carried out at year-scale separation, any geodetic monitoring of the seismogenic zone requires the incorporation of continuously operating GPS receivers both to more quickly recover the quasi-steady-state interseismic deformation and to provide the potential to measure any transient strains related to coor postseismic deformation.

ODP Penetrations: Although depth-limited, ODP penetrations must be an integral part of SEIZE. Subduction zones are conveyor belts, moving materials from the surface through the seismogenic zone to great depth. Therefore, ODP-style penetrations of about a km can sample the materials that ultimately become the fault rock of the seismogenic zone. A SEIZE program will require a series of holes to characterize the incoming sediments and rocks, and their associated fluids. It will be essential to characterize important geologic properties in three dimensions, so drilling strategies will have to expand beyond the typical 2-D transects.

The décollement zone is the shallow, seaward manifestation of the seismogenic zone megathrust. Fluids sampled from some décollement zones may have migrated from the seismogenic zone. Therefore, sampling and ultimately instrumentation of this structure, both down-dip and along strike, provides access to the pulse of the seismogenic zone.

In addition to sampling the incoming material and monitoring, relatively shallow ODP penetrations can opportunistically provide information on deeper levels of subduction zones related to the seismogenic zone. For example drilling into diapirs can sample material brought up from great depths, and constrain the pressure-temperature conditions in the forearc. Deeply sourced fluids sampled at shallow depths in monolithologic forearcs may provide unique information about processes at depth. Drilling into out-of-sequence thrusts in areas of slope erosion can access deeper levels of faults than normal accessible by ODP.

Borehole Observatories: SEIZE will benefit greatly from emplacement of permanent observatories including seafloor seismic and fluid flow, observatories and borehole monitoring devices. Technology for construction of such observatories at subduction zones exists, and can be accomplished with an electro-optical cable to provide power to experiments and communications to shore. Although initially expensive, savings in ship time, and the constant availability of real-time data make emplacement of observatories practical where cable lengths are relatively short.

Instrumented, hydraulically-sealed boreholes (CORKs) provide a real-time record of sub-surface transient events manifested by temperature, pressure, and porewater chemistry anomalies. At the very least, these records will establish the "steadystate" hydrologic conditions in various parts of the formations that host seismogenic zones, including the faults themselves. They may also define precursor, coseismic, or postseismic signals related to seismic events, since it is almost certain that hydrologic signals are sensitive to changes in stress, ground motion, and fault-zone slip.

During SEIZE, it will be essential to correlate CORK data with synoptic OBS or borehole seismometer results. In addition, other downhole sensors (which may require emplacement or periodic replacement) can be incorporated with a wireline-deployable CORK. These complementary sensors might include hydrophones, geophones, tiltmeters, strain gauges, or chemical sensors. Hydraulic access through the CORK accommodates a continuous osmotic fluid sampler or periodic borehole fluid extraction for time-series determinations of pore water chemistry.

Active hydrogeologic tests, conducted by submersible or ROV through the hydraulic port on the CORKs, provide in-situ determinations of formation transmissivity/ permeability and storativity. The duration of these tests can be extended to minimize effects of drilling and maximize the radius of investigation. Furthermore, the in-hole tidal signal variations can constrain the mechanical/hydrologic properties of the tested interval.

The existing CORKs seal the borehole as a single volume and allow conditions to be monitored in a single interval of open hole or perforated casing only. Monitoring and testing of multiple intervals (which require sophisticated casing strings and drillstring packers) is necessary if the variations with depth of the fluid regime is to be delineated in a single hole.

Riser-Type Deep Drilling: Drilling into a seismogenic zone or relevant deep objectives that are inaccessible by the current capability of JOIDES Resolution is one of the major goals of the SEIZE. Proposed Japanese riser drill ship (OD21 drilling vessel) provides an opportunity to achieve this goal. Experience gained through DSDP/ODP drilling indicates that convergent margin borehole conditions are generally quite hostile. Overpressured pore fluid, swelling clay, and stress-induced hole collapse often cause unstable hole conditions. Such instability has hindered core recovery, wireline logging, and longterm measurements. Deployment of a drilling-mud circulation system (riser system) can overcome such obstacles, especially in deep holes.

Current OD21 specifications call for implementation of a riser in two phases, initially at a 2500-2800 m length and later 4000 m length. The drill string will be 12000 m in length. A blowout prevention system at the seafloor will control hydrocarbon risk. The Conference on Cooperative Ocean Riser Drilling (CONCORD) set drilling into the seismogenic zone as the first priority of an international deep drilling program (OD21). The first phase of OD21 (2003-2008) would target a hole starting at about 2500-2800 m water depth with a 6000 m penetration to the seismogenic zone. To best locate optimal sites for an extraordinary scientific program like SEIZE, it is essential to conduct site survey and preparatory experiments, including conventional ODP drilling.

Field-Based Observations of Paleoseismogenic Zones: Field studies of onland analogues can provide critical information about rock properties and alteration products over the ranges of P-T conditions relevant to the seismogenic zone (~125°-400°C). On land observations, sampling and associated lab measurements will feed into conceptual models of the seismogenic zone that can be initially tested by seismic reflection techniques, and ultimately by drilling. Drilling results may be extended and better understood through firm knowledge of ancient analogues. Paleoseismogenic zones will be studied with the disciplines of structural geology, metamorphic petrology, geochemistry, and geochronology. Particular attention should be focused on structural packages that may represent the paleo-décollement and on out-of-sequence faults that display large amounts of vertical displacement of the paleotemperature structure. Analyses should focus on contrasts among hanging wall, footwall and associated shear zones. These contrasts may be defined by differences in deformation fabrics, vein mineral paragenesis, stable-isotope composition of vein minerals, fluid inclusion microthermometry, vein density and orientation, alteration of organic matter, and phyllosilicate diagenesis. Determination of the thickness of paleoseismogenic zones will provide constraints on waveform models from seismic reflection data. Timing of faulting can be established using such methods as fission track geochronology.

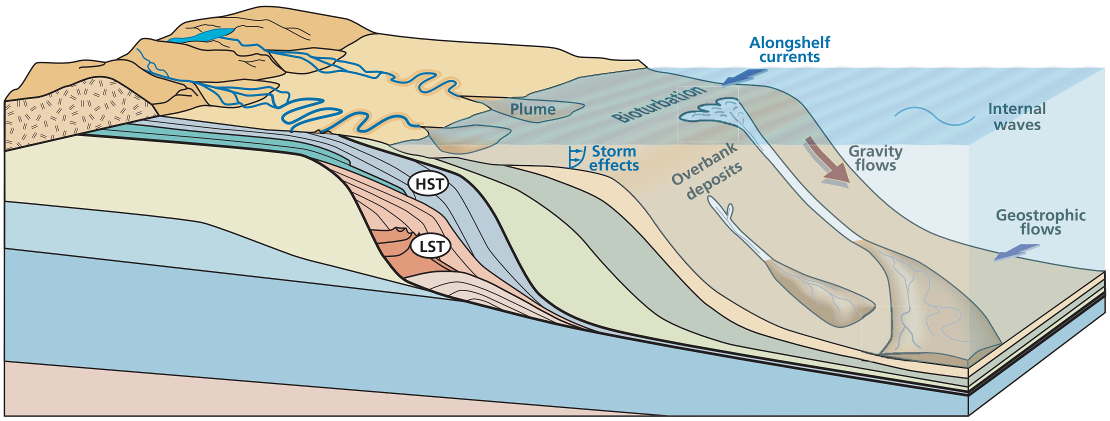
Laboratory Experiments: A laboratory-based program of controlled experiments is critical to the success of SEIZE to link the various indirect measurements to in situ conditions of the seismogenic zone. The composition, temperature, stress, and mechanical state of the rocks and fluids of the seismogenic zone will be inferred from remotely-sensed data, such as measurements of surface heat flux, seismic velocity and reflectivity, fluid fluxes, and geochemical signatures. The relationships among these proxies remain insufficiently known to extrapolate chemical and physical data collected at shallow levels to infer conditions existing at seismogenic depths. SEIZE must therefore include a comprehensive program of laboratory experiments documenting relevant physical-chemical processes and elastic and material properties, at in situ temperature, stress, and fluid pressure. These experiments should involve sediments and laboratory-generated analogs, altered oceanic basement, serpentinites and their exhumed equivalents, representative of the décollement zone and underthrust sequences. The experimental data will provide important input to hydrologic and mechanical modeling efforts, which will in turn help focus experimental investigations.

Laboratory experiments should address at least the following fundamental processes and rock features: 1)

Steady-state fluid-rock reactions and their kinetics, partition coefficients, and isotopic fractionation factors. 2) Thermally and physically activated mineral dehydration reactions and their impact on rheological boundaries. 3) The changes in relationships among seismic velocity (Vp and Vs), attenuation, density, fluid content and composition, and stress during compaction, diagenesis, metamorphism, and deformation, necessary to infer the physical meaning of seismic images and wave propagation. 4) The linkage of chemical and physical processes to changes in porosity, permeability, stress, and rheology, crucial to a complete understanding of the temporal and spatial changes in seismogenic behavior and interplate coupling (e.g., velocity strengthening/weakening relationships, seismic/aseismic stress release).

Modeling: Because access to the seismogenic zone is limited, numerical models will be essential for integrating the field observations and laboratory results. Initially the models will be important for guiding data collection needs and laboratory experiments. New observations and parameter values will refine the existing models and guide further sampling and experiments. For example existing tectonic models are often constrained only by onshore geodetic data. The addition of strain and tilt data from offshore observatories will improve our ability to use these models to understand the seismic deformation cycle. Another example concerns the need for refining existing models of fluid pressure. New laboratory results and drill core observations of the average composition of the oceanic crust will constrain the mass of fluids and rate of release over the seismogenic zone. As our level of knowledge about the important processes grows, it is anticipated that new models will be required that account for multiple coupled processes. These would include, for example, the coupling of pore pressure, stress, and temperature, or coupled fluid flow, chemical reactions, and transport. Moreover, some existing models will need to be extended from two to three dimensions to account for variations along strike of important controlling processes. Simulations will be required on a range of scales from the borehole to the entire subduction zone. Models of borehole hydrologic data provide needed input to larger scale hydrologic models of the entire margin. Smaller scale process models, involving such aspects as rupture dynamics or sediment consolidation, provide insights into the important controls on larger scale observations. The ultimate goal is to have models that test hypotheses about the nature and extent of the seismogenic zone. Models on such a large scale necessarily require many simplifications compared to the natural system. The insights needed to determine which simplifications are possible come from comparing smaller scale models with observations.

Source-to-Sink (S2S)



Introduction

S2S Questions

1. Executive Summary

Erosion sculpts the landscape, and redistribution of the sediment creates the alluvial plains, coasts, deltas, and continental shelves upon which most of the world's population lives and derives much of its energy and water. This transfer of sediment and solute mass from source to sink plays a key role in the cycling of elements such as carbon, in ecosystem change caused by global change and sea-level rise, and in resource management of soils, wetlands, groundwater, and hydrocarbons. Although the source to sink system has been studied in its isolated component parts for more than 100 years, significant advances in our predictive capability require physical and numerical modeling of fluxes and feedbacks based on data from integrated field studies. The Source-to-Sink Initiative is an attempt to quantify the mass fluxes of sediments and solutes across the Earth's continental margins by answering the following questions:

1) How do tectonics, climate, sea-level fluctuations, and other forcing parameters regulate the production, transfer, and storage of sediments and solutes from their sources to their sinks?
2) What processes initiate erosion and transfer, and how are these processes linked through feedbacks?
3) How do variations in sedimentary processes and fluxes and longer-term variations such as tectonics and sea level build the stratigraphic record to create a history of global change?

The Source-to-Sink Initiative will consist of focused investigations on active convergent continental margins that produce

Processes in the Source-to-Sink system

large amounts of sediment deposited in adjacent, closed basins. A suite of inter-connectable numerical and physical-process models with shifting boundaries will be used to test hypotheses concerning process connections and to predict the behavior of these source to sink systems on time scales ranging from individual events to millions of years. Forcing and boundary parameters measured in the field will drive the models, and observations of system variables will allow comparison with model predictions. In this way model results will help to interpret data and data will help test the conceptual understanding embedded within the models.

Rates and mechanisms of sediment production, transport, and accumulation will be monitored using high-resolution digital elevation models, new dating and tracer techniques using cosmogenic isotopes and optically stimulated luminescence, and field acoustic and optical velocimeters for measuring sediment velocity and concentration. High-resolution documentation of the spatial structure of the sedimentary record will be obtained through swath mapping and CHIRP, combined with sediment coring, which will involve new logging tools such as GRAPE and FMS. Experimental work in laboratory settings will allow for the testing of hypotheses under strictly controlled conditions, in which forcing and boundary parameters can be systematically varied.

> "The source to sink system contains most of our energy resources and potable water, and as a result most of Earth's human population lives along the source to sink path"

Following community-wide discussions, the Fly River and adjacent Gulf of Papua (Papua New Guinea) and the Waipaoa River System on the east coast of New Zealand's North Island were chosen for focused research. Selection was based on the ability of the various study areas to address primary scientific objectives, the presence of a strong forcing that produces strong signals, active sedimentation spanning the various source to sink environments, active sediment and solute transfer among environments, system closure to sediment transfer, a high-resolution stratigraphic record, advantageous background data and scientific infrastructure, manageable logistics, small anthropogenic influence, and societal relevance. After five years the two focus areas will be re-evaluated, at which time focus priorities may change.

Differences between the two focus areas are noteworthy. The Fly River and Gulf of Papua constitute one of the few modern examples of a developing foreland basin, and the Waipaoa drainage basin reflects growth of a terrain by volcanism and vertical uplift. The Fly/Gulf System experiences a tropical environment, whereas the Waipaoa is subtropical/temperate. Because of differences in oceanographic environments, the Gulf of Papua possesses both siliciclastic and carbonate sedimentary environments, whereas the Waipaoa margin contains only siliciclastic sediments. The Fly drainage basin (75,000 km^2) experiences relatively constant discharge, the main perturbations being linked to ENSO-related droughts, and it is practically unaffected by human activity, although recent mining on the Ok Tedi has provided a sediment spike that can be monitored farther downstream. In contrast, the Waipaoa system (2000 km^2) is strongly affected by seasonal variations in discharge and (particularly) by tropical cyclones; and for the past 100 years it has been affected by the impacts of European landuse and (to a lesser extent) by dam construction.

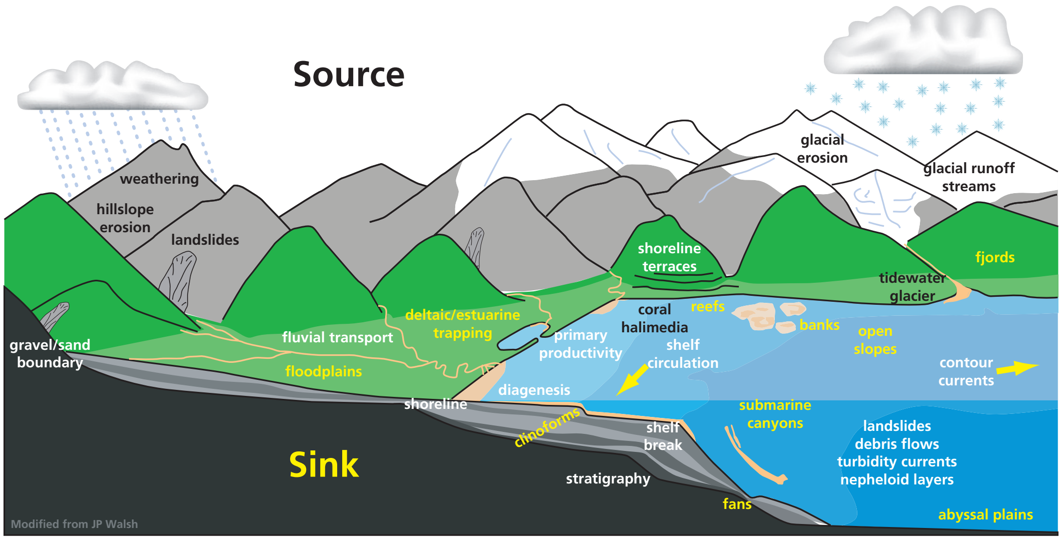


Figure 1. A simple schematic showing the dispersal system. The color of the lettering is coded: sources are indicated by black text, sinks are yellow, processes are shown in white italics, and locations in white regular typeface.

The Source-to-Sink Initiative will be a decadal effort, with initial studies focusing on delineating the sedimentary fluxes in the source areas and their near-term and long-term fates. International collaboration with scientists from New Guinea, Australia, and New Zealand will provide local expertise, access to local facilities (such as ships and on-land facilities), and help disperse research costs. Scientific results will be disseminated through workshops and the MARGINS website, as well as through more traditional scholarly venues.

The integrated approach fostered by this study should pave the way for greater coherence and direction in future studies in sedimentary geology that will go far beyond the scope of source to sink or MARGINS.

Scope of the Source-to-Sink Initiative

2. The Source-to-Sink System

When landscapes are eroded, the resulting sediment and dissolved constituents pass through a connected suite of geomorphic environments, ultimately to be deposited or precipitated on an adjacent flood plain, marine shelf or abyssal plain. This journey from source to sink represents the return limb of a mass flux loop that begins when rock is first exposed to subaerial erosion by tectonic processes such as crustal thickening or volcanic processes. The suite of connected environments through which the journey takes place is the source to sink system (Figure 1).

The connected environments of the source to sink system are separated by dynamic boundaries that shift in response to changes in sediment fluxes and accommodation (Table 1).

Unit:	Boundary:
Terrestrial upland	
	Transition from gravel-bed to sand-bed streams
Terrestrial lowland	
	Coast (shoreline, estuaries, and deltas)
Continental shelf	
	Shelf-slope break
Continental slope	
	Slope base
Continental rise and abyssal plain	

Table 1. The connected environment units and their dynamic boundaries in the source to sink system (cf. Figure 2).

Each environmental unit, which is inter-linked with other units by the flux of sediment through the boundaries, may produce sediment through erosion or act as a sediment sink through deposition, either temporarily or permanently (Figure 2). The erosion and deposition occur at spatial and temporal scales that vary over at least four orders of magnitude, making system behavior especially difficult to predict.

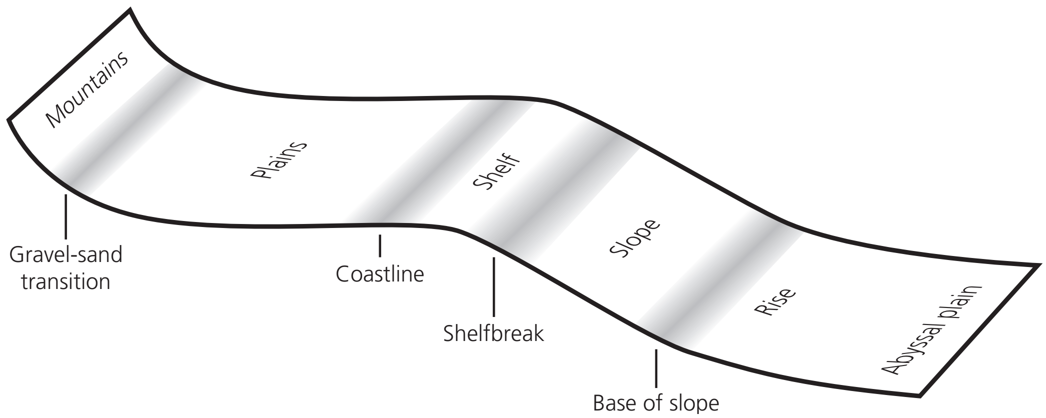


Figure 2. Hypsometric configuration of the various environmental units and boundaries in the source-to-sink concept

Societal relevance

Archive of global change

Predictability

The source to sink system is a particularly important historical archive of past and present global change. Yet, whether we look at landscape morphology or the stratigraphy that records its erosion, we see the integral effect of many events over time. Thus, our ability to tell the story of individual events from landscape morphology or from the stratigraphic record remains poor. We see the book of time, and perhaps chapters in the book, but we are only rarely able to read individual pages. Yet it is at the page level that the story truly unfolds. Sometimes an event is global and so large, such as the K-T impact event, that it leaves not only footprints, but also calling cards. But the stratigraphic record is more likely to be an unclear succession of event-related deposits that are recorded in ways we cannot yet read, because it is created by internal and external perturbations that constantly propagate through the system. Similarly, the inverse record, i.e. the eroded landscape, shows the same effects of events and their integral effects over time, and it too remains difficult to interpret.

An ability to predict the quantitative behavior of the source to sink system is important for a variety of societal reasons. The source to sink system contains most of our energy resources and potable water, and as a result most of Earth's human population lives along the source to sink path. Sediment eroded in uplands represents a significant loss of agricultural productivity even as it replenishes eroding coastlines. Yet we are presently unable to anticipate how perturbations in one part of the system will affect another. Would, for example, a 50% increase in sediment yield over the next century reverse coastal zone erosion, or would the sediment be sequestered on floodplains, leading to increased flood risk up river? Would the increased sediment yields from a large magnitude earthquake in the headwaters of a fluvial system disrupt shipping in its lower reaches, and if so, over what duration? Questions like these require accurate quantitative methods for predicting system behavior over an intimidating range of time and space scales. To better explore these questions, as well as to provide the page-by-page reading of the geologic record needed to predict future energy resources, we need improved quantitative methods for predicting bed characteristics and architecture that exist in the subsurface. Stratal patterns arising from the interplay of changing sea level, sediment supply, and accommodation can be crudely predicted from first-generation conceptual and numerical models, but more physically based, coupled landscape-seascape models are needed if we are to predict stratal geometries from reconstructed ancient landscapes and climates.

> "We see the book of time, and perhaps chapters in the book, but we are only rarely able to read individual pages. Yet it is at the page level that the story truly unfolds"

This problem is compounded by the historic disciplinary divisions between geomorphologists who examine erosion and production of sediment on land, the oceanographic community, which examines transport and deposition of marine sediments, the stratigraphic community, which examines the longer-term record, and the modeling community, which establishes the physical basis for construction of the sedimentary record. Some of these divisions, notably between oceanographers and geomorphologists, occur specifically at the environmental boundaries listed above, which remain grossly understudied.

The over-arching NSF-MARGINS approach is critical, for only by encouraging an interdisciplinary community to interact in solving broad problems at selected field sites can we develop quantitative, 3D, field-tested models that are able to predict the response of a sedimentary system and its deposits to perturbations of variable temporal and spatial scales, such as climatic and tectonic variability, and relative sea-level change.

3. What Do We Need to Know about the Source-to-Sink System?

The key scientific issues impeding better predictive capabilities for the source to sink system were identified at two MARGINS Source to Sink Workshops and a MARGINS Workshop to define the concept of a Community Sediment Modeling Environment. Similar issues also were identified by an NSF Geology/Paleontology Panel convened in 1999 to suggest key problems and major thrusts for the next decade. The scientific issues are contained within three questions:

Key scientific issues

Forcing parameters

Question 1: *How do tectonics, climate, sea level fluctuations, and other forcing parameters regulate the production, transfer, and storage of sediments and solutes from their sources to their sinks?*

To better manage the landscapes on which we live, we need to model linked continental margin systems so we can predict quantitatively the response of these systems to perturbations (both natural and anthropogenic). We need to decipher how input signals (e.g., individual storms, floods, or landslides) are filtered or amplified along a dispersal system.

For example, it is postulated that sediment delivery to the continental slope occurs primarily at low stands of sea level (Jervey, 1988; Posamentier et al., 1989; Lawrence, 1993) with a consequent order of magnitude increase in sedimentation rates compared to high stands. This increase also has been interpreted to result in frequent hyperpycnal flows that may feed deepwater submarine fans and slope aprons (Mulder and Syvitski, 1995). However, there is no dynamic model linking sediment delivery and storage in large rivers on the coastal plain to sediment delivery and storage in the sea. How exactly, for example, does the sediment transfer vary as a function of sea level? Rivers can erode and transport massive amounts of sediment from the montane system, independent of sea level, but the site of ultimate sediment accumulation (particularly on passive margins) depends on sea level. A definitive answer to this issue requires an improved understanding of the leads and lags in river response to perturbations, and further observations and models linking the coastal plain with the subaqueous margin. Monitoring of present-day sediment fluxes and comparison of accumulation rates over longer geologic time scales by examination of the stratigraphic record can address this question.

As another example, there are fundamental uncertainties as to how sediment is partitioned between the floodplain, shelf, and slope during major flood events. The bulk of sediment carried by most modern rivers is suspended mud (Milliman and Syvitski, 1992), yet the stratigraphic record abounds with examples of sand-dominated fluvial and shelf deposits, much presumably transported as bed load or bed-material load. Were these ancient dispersal systems fundamentally different from today, or is there a combination of forcing parameters that yields sandy deposits from otherwise mud-laden rivers? What controls the proportion of mud deposited in a floodplain versus carried through a river system and deposited on a muddy shelf? Synchronous monitoring of sediment transport in different parts of a source to sink system is required to address these questions.

Process initiation and linkage

Question 2*: What processes initiate erosion and sediment transfer, and how are these processes linked through feedbacks?*

Erosion and transport agents are well known, but processes that initiate erosional events are often less well understood, even though they can have significant scientific and societal impact. Moreover, feedback mechanisms can either increase or decrease the impact of a particular event.

> "Erosion and transport agents are well known, but processes that initiate erosional events are often less well understood, even though they can have significant scientific and societal impact"

To cite one example, terrestrial and submarine landslides, generated by both earthquakes and floods, are dominant agents of sediment transfer and morphological evolution, as well as constituting widespread hazards in mountains and in marine environments (the latter by generating tsunamis, rupturing pipelines, and disrupting communication cables). Presently, however, we have limited ability to anticipate landslides and predict their rate of occurrence. What, for example, is the relative importance of earthquake-driven landslides versus those triggered by floods? To help prepare for landslides and lessen their impacts, we need to understand more thoroughly the processes that cause slope failure and landslides, particularly distinguishing flood-caused versus earthquake caused. While the study of individual landslide genesis is crucial, it must be complemented by a more integrated approach of landsliding in the context of the margin system. This would allow for evaluation of how, for instance, incisional events that start at the shoreline propagate through the landscape (e.g., Westcott, 1993), triggering submarine landslides seaward, and fluvial rejuventation landward, as the perturbation is transmitted through the dispersal system. Incision at the shoreline may be initiated by migration of tidal inlets in a barrier system, by landward migration of a sediment failure at the continental shelf-slope break, by sea-level changes, and also potentially by storms and earthquakes. These processes operate at a variety of time-scales. Sediment failure in the shelf, for example, can be driven by sediment loading during progradation of an individual mouth bar, such as those that cause growth faults, and by movement of salt and overpressured shales (Bhattacharya and Davies, 2001). Collapse of sediment at the shelf edge can also generate tsunamis that may cause coastal erosion that can in turn affect associated rivers. A complete understanding of landslides, therefore, requires understanding how the dispersal system is linked to the source of sediment and specifically how depositional or erosional events in one part of the system may destabilize the landscape elsewhere by triggering waves of erosion or sedimentation.

Question 3: *How do variations in sediment processes and fluxes and longer term variations such as tectonics and sea level build the stratigraphic record to create a history of global change?*

The stratigraphic record is our main source of information about the history of the Earth's surface over geologic time, as well as the repository of major reserves of groundwater and hydrocarbons. If the record is deconvolved correctly, it allows us to reconstruct the history of sea level, climate, and tectonics and better predict the properties and occurrences of reservoirs in the subsurface. But the fidelity of the stratigraphic record is imperfect, often distorted and containing gaps over a wide spectrum of time scales (Barrell, 1917). Our reconstruction of past events is only as good as our understanding of the processes by which they are recorded in sediments. Moreover, recognizing that the modern depositional environment of the shelf reflects the recent past as well as the present, we need to know more about its evolution, particularly since the last glacial maximum (LGM). Our ability to find the next generation of sediment-hosted resources, for example, will be limited by our ability to predict the locations of potential reservoir bodies in the subsurface. Understanding the formation of the stratigraphic record is truly a source to sink problem, from the generation of the signal carrier (the sediment) to the partitioning of fluxes among the whole suite of margin environments. Integrated studies of sediment production and accumulation over a time interval for which key controls (e.g., sea level) are relatively well understood is a crucial step toward developing reliable interpretive and predictive stratigraphic tools.

Reconstructing the record of global change

In terms of global change, the various environments of the continental margin are also major reactors in many geochemical cycles, particularly those of Si, Ca, P, and C. Carbon (both organic and inorganic) cycling has important relevance to climate-change modeling. Margin environments are critical sites for CO_2 sequestration via weathering reactions in source areas as well as by carbonate deposition in the shallow and deep ocean environments. Quantification of weathering rates, organic carbon and inorganic carbonate production, reactive surface area, and particle fluxes will provide critical information for carbon-cycle models and evaluation of global-change scenarios. Carbonate reefs and platforms are particularly sensitive to environmental perturbations such as changes in sediment discharge, changes in salinity, sea-surface temperature, fertilization by nutrients (anthropogenic and weathering by-products), sea-level change, and topography (James and Kendall, 1992). The dynamics of many carbonate systems are fundamentally linked to input of sediment and nutrients from upstream terrestrial sources. By choosing a mixed clastic-carbonate system, it is possible to test hypotheses on the relative importance of the factors that control the stability of carbonate systems, such as investigating the relative importance of El Niño-type phenomenon versus changes in river-discharge.

The sedimentary wedge that characterizes many continental margins is built from depositional systems that relate to the specific environments that comprise source to sink. Localized delta depocenter progradation and along-shelf sediment transport turn sediment point sources into broad continental shelves and provide sediments to replenish coastlines. To understand how such processes affect margin architecture, we must acquire observations and develop stratigraphic models that combine knowledge about deltaic sedimentation, and shelf and slope depositional processes with tectonism and sea-level variation. River avulsions and delta lobe switching are linked processes, but there is significant debate as to the importance of allocyclic controls, such as sea level change, versus autocyclic controls, such as super-elevation of a channel above the floodplain (Blum and Tornqvist, 2000).

S2S and continental margins

The shoreline is a dynamic boundary that records the complex interplay between relative sea-level perturbations, physiography and sediment supply. As such, margin sediments often are contained within an expanded section from which both terrestrial and marine signals can be obtained. Qualitative models have predicted that the shoreline is farthest seaward when the rate of sea-level drop is a maximum (e.g., Posamentier et al., 1988). Recent morphodynamic experiments have suggested that this result may not always be the case. A combination of morphodynamic and numerical studies linking moving boundaries (e.g., the shoreline) will help direct future data acquisition to test model predictions, and will yield new insights to help mitigate future hazards in coastal environments in response to such events as rising sea level.

4. Methods of Investigation

To address these questions, Source-to -Sink will proceed as a focused modeling and field investigation of landscape and seascape evolution, and of sediment transport and accumulation in two primary field areas where the complete source to sink system can be analyzed. Deciphering the transfer of a signal of an event through a complete and natural source to sink dispersal system will require strong process-based analyses, predictive models, and examination of environmental linkages to other segments of the dispersal system. At present, for instance, we cannot quantitatively delineate how the segments respond to changes in water discharge or sediment loading. Answers to such questions require us to examine controls on the rates and processes of floodplain and clinoform sedimentation within a holistic modeling of the environment.

Signal transfer through a system can be investigated as a "forward" or an "inverse" problem, or both. The forward problem asks: what are the effects of variable sedimentary processes on the signal transferred between a succession of environments and on the signature imparted to the preserved strata? In contrast, the inverse problem asks: what signatures in the stratigraphic record can be used to interpret sediment source dynamics in order to deduce the role of climate, tectonics, and sea-level variation in its formation? The answer to the forward problem may range from significant transfer of a pulse through segments of the dispersal system (top option in Figure 3) to complete attenuation of the pulse along the dispersal system, such that locally generated signals (e.g., from sediment dynamics) are recorded in the lower segments of the system (middle option in Figure 3). The time scales for these two questions generally fall into one of three time categories: short term (present to 7 ka BP), medium term (7 to 18 ka BP), and long term (>18 ka BP), corresponding to sea-level conditions of highstand, transgression, and last glacial lowstand, respectively.

At present, we have little predictive ability to address the forward problem and thus limited criteria for the inverse problem be-

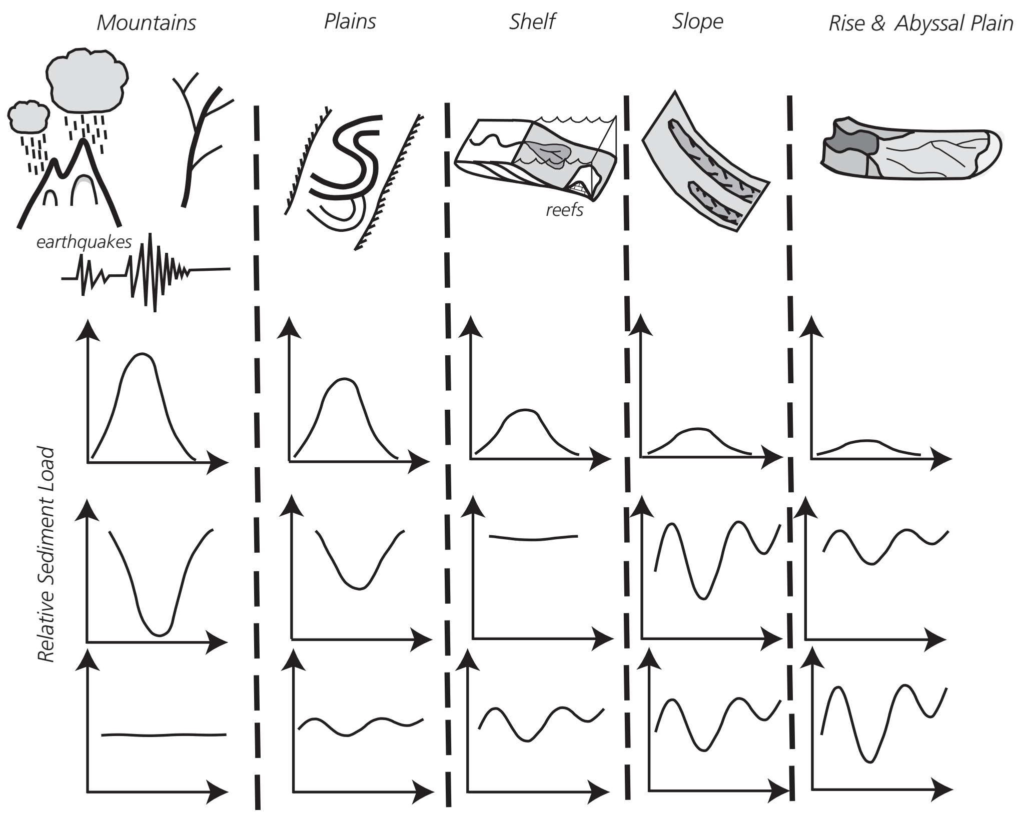


Figure 3. Several scenarios might explain how a sediment discharge "signal" varies through the morphodynamic segments of sediment dispersal systems. Three scenarios are displayed and can be viewed from a "forward" modeling perspective or an "inverse" modeling perspective, as discussed in the text. The time scale is shown as arbitrary, but needs to be defined in order to identify the processes responsible for impacts on the signal transitions. The first row of graphs shows a strong uplands input that progressively attenuates downstream, but is still visible in the marine record. This might be the case in the Waipaoa basin. The second row shows a negative signal (e.g. the El Nino signal in the Fly system) damping completely downstream and being replaced with a signature driven by tidal, shelf or deep-water transport dynamics. A third scenario shows that even without variations in source sediment (e.g., Fly during many years), local processes can lead to significant temporal variation in sediment flux. The two focus sites have strong signals generated, but little is known about how the signals are transferred.

Signal transfer in the S2S system

cause of the incomplete nature of the stratigraphic record. Progress can only be made through a well-structured, nested research plan involving collaborative efforts of individuals from disparate backgrounds integrating whole systems, and including all morphodynamic segments present in those systems. By selecting a well-chosen pair of focus sites we ensure that the potentially enormous scope of source to sink questions can be directed towards a tractable solution.

Model development within the S2S initiative

Developing quantitative and physical models for the source to sink System is integral to the strategy of the initiative. Models will be used to help define key questions and to test various hypotheses. Model predictions will help guide aspects of field programs and field observations will validate/verify model output. Finally, models will allow us to generalize our observations, and thus extend our understanding to other regions. A new generation of numerical modules predicting the transport and accumulation of sediment in landscapes and sedimentary basins over a broad range of time and space scales is a high priority of the Source-to-Sink Initiative. The models should be based on algorithms that mathematically describe the processes and conditions relevant to sediment transport and deposition in a complete suite of earth environments, and contain the optimum algorithms, input parameters, feedback loops, and processes to better predict behavior of the complete system (Syvitski et al., 2002). The general program of investigation for each selected site will include:

1) Assessment of available data and its appropriateness for building first-order computational and physical models;
2) field investigation of sediment production, transport and accumulation, and associated mechanics and rates;
3) second-order model building/testing to illuminate mechanisms of sediment transport and stratigraphy generation under various controls; and
4) stratigraphic documentation at appropriate spatial concentration to provide desired temporal resolution.

Monitoring and modeling of active processes are examples of work that should occur throughout the course of the proposed studies. This will include high-resolution digital elevation models (DEMs) and swath imaging of both landscapes and seascapes. Monitoring of the fluxes throughout the system, can be compared with measurements in the changes between surfaces surveyed before and after major events to determine system response. For example, successive high-resolution surveys of the seafloor before and after a major storm event can be used to determine how the shelf responds, where erosion occurs and where deposition occurs. This can be compared with rates and magnitude of changes in coeval landscape and seascapes. This can also be linked to the relative scale of changes in the floodplain. Documentation of the stratigraphy can proceed in phases by working through the different storage elements of the morphodynamic segments, and by investigating the temporal resolution initially from the finest-scale deposits of the past thousand years and later to longer, deeper records that extend back to millions of years. Both monitoring and modeling can be greatly enhanced by capitalizing on existing data and measurements taken in selected study sites.

5. New Technologies and Opportunities for Source-to-Sink Research

For each of the segments of the source to sink system, recently developed technology offers unprecedented opportunities for new insight. Several of these key innovative technologies are explained below in their relation to Source-to-Sink scientific objectives.

- High-resolution DEMs, radar interferometric DEMs (broad coverage, lower accuracy) and laser-altimetry (LIDAR, narrow coverage, high accuracy, very-high resolution) permit the finer-scale mapping of fluvial dispersal systems (flow routing), calibrating transport laws, and documenting surface evolution. Programs such as goCad and ARCVIEW can be used to measure volumetric differences in degrading landscapes and aggrading seascapes. These differences can be used to measure mass balances among linked systems.
- Precision positioning (e.g., DGPS) allows us not only to define our position within a few centimeters (Xu et al., 2000), but also permits the reoccupation of study sites, so that short- and medium-term changes can be studied.

Technology in the S2S initiative

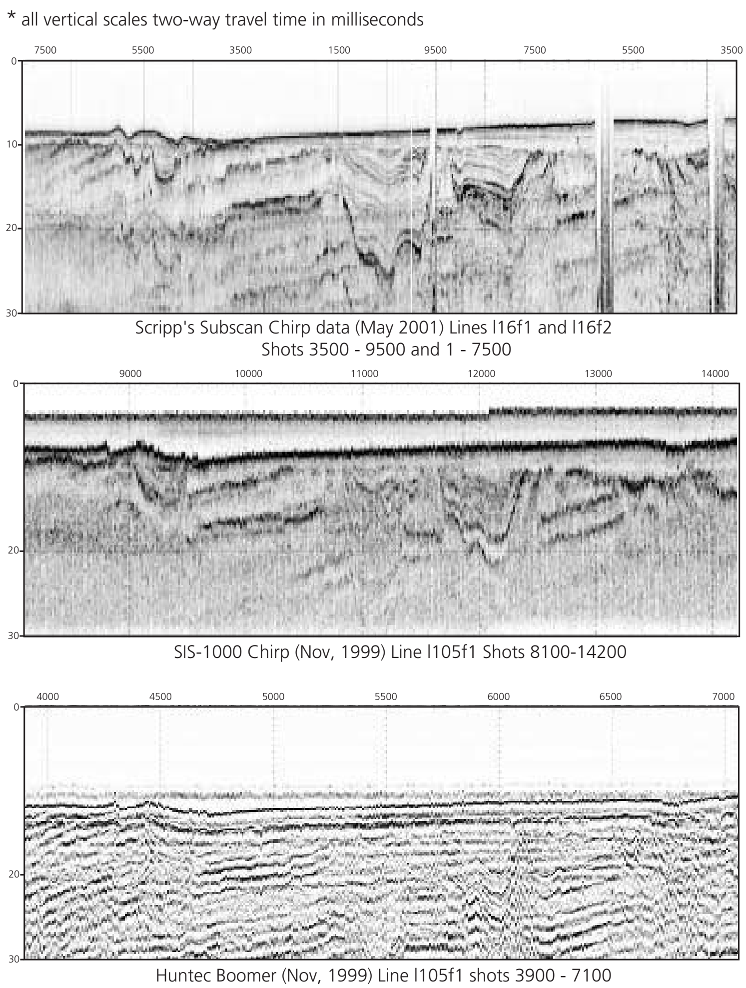


Figure 4. Geophysical images acquired offshore South Carolina's Grand Strand, illustrating the improved resolution and penetration of the Subscan CHIRP system (top), relative to standard CHIRP data (middle), and a Huntec boomer (bottom). Resolution increases from several meters in the Huntec record to considerably less than 1 meter in the Subscan record.

Figure courtesy of Neal Driscoll, Scripps Institution of Oceanography.

- Similarly, swath-mapping—particularly the new interferometric swath sonar system—and the CHIRP seismic profiler allow marine geologists and geophysicists to achieve horizontal and vertical resolutions of less than 15-20 cm, thus providing unprecedented ability to define fine-scale bathymetry and stratigraphy (Figure 3). Together with DGPS, these new technologies allow us to document the change in seafloor morphology and stratigraphy with time.
- Enhanced coring (e.g., wire-line coring that can be obtained through the Ocean Drilling Program) can continuously sample long sections of unconsolidated sediments in diverse environments. New and established logging tools and geophysical processing (e.g., GRAPE, FMS, magnetic susceptibility, and the multispectral scanner), moreover, allow continuous acquisition of downhole physical properties data.
- Acoustic, electromagnetic, and optical devices have been developed to measure velocity, concentration and grain size of sediment particles in transport, and high-speed video imaging, particle-image velocimetry used in monitoring physical experiments can provide valuable constraints on conceptual, analytical and numerical models.
- Laboratory experimental facilities, such as those recently developed for experimental stratigraphy, allow for the testing of hypotheses under strictly controlled conditions in which forcing and boundary parameters can be systematically varied.
- Recently developed experimental facilities (e.g., large-scale tanks and flumes, Paola et al., 2000) enable unprecedented physical modeling studies to be posed, especially if constrained by good field data, as is a central aim of Source to Sink (Figure 5). This is particularly important because most previous modeling studies have been purely 2D (e.g., Jervey, 1988; Lawrence, 1993; Wehr, 1993).

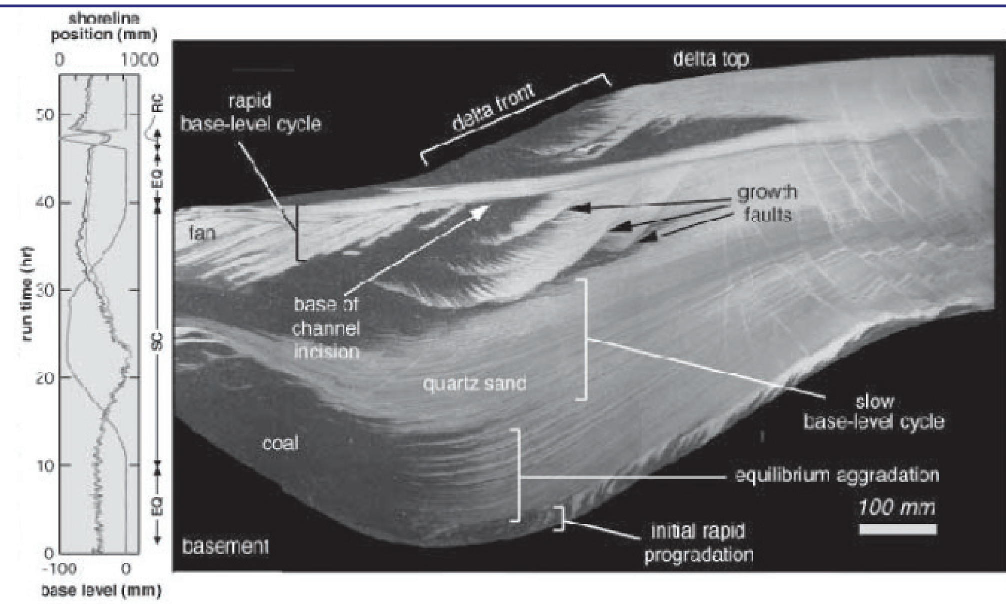


Figure 5. Experimental run illustrating the complex interplay between base level, shoreline position, and accomodation. Illustration courtesy of Chris Paola, University of Minnesota.

6. Selection of Focus Sites

Through discussion at various workshops and working groups, there was general agreement about the criteria considered essential in the selection of a Source-to-Sink study area. Other criteria were considered important, although perhaps not mandatory:

6.1 Critical Criteria

- Strong forcing that produces strong signals, some of which may be transferred between environments - Areas experiencing rapid uplift and vigorous atmospheric forcing (e.g., heavy rainfall, frequent storms) yield large amounts of sediment, often during catastrophic events. Because they tend to erode and store less sediment on their flood plains, smaller mountainous rivers tend to have particularly high sediment yields (Milliman and Syvitski, 1992). As a result, more than 65% of the sediment presently discharged to the global ocean comes from rivers draining southern Asia and the high-standing islands in Oceania. Rivers draining the high-standing islands in the East Indies and the Philippines alone are estimated to discharge about more than half of the southern Asian fluvial sediment load (Figure 6).
- Active transfer among environments within a generally closed system - Because larger watersheds tend to store more sediment and to modulate the effect of individual events, it is preferable to study systems in which the source drains moderate- to small-sized basins (e.g., 10^3-10^5 km in area). In this way the transfer and fate of sediment within the study area can be quantified, allowing a mass-balance calculation.
- High-resolution stratigraphic record — a long record better allows delineation of various-scale events as well as larger changes in climate and sea level. A high-resolution stratigraphic record extending back to glacial stage 5e (125 ka BP), for example, would allow us to delineate the stratigraphic response to glacial-interglacial cycles and eustatic sea-level fluctuations.
- Must have sufficient background data to allow the formulation of an optimal integrated systems study — quantitative data concerning rainfall, stream flow, sediment discharge, the oceanographic environment as well as a general understanding of the sedimentary sinks facilitate the formulation of an effective field study. Aerial photographs, digital models, and remotely sensed data also would be extremely helpful.
- Local scientific infrastructure — access to the entire study area, from source to sink, is necessary. Access to local ships and land support systems (e.g., shallow-water boats, field camps) would provide the opportunity to reach areas otherwise inaccessible and also allow us to study the impact of episodic events, such as floods and storms.

6.2 Other Important Criteria

* Analogs with ancient sedimentary environments - Sites whose environments and/or sedimentary deposits can be linked to geological formations clearly would enhance the uniformitarian aspects of the study.

* Presence of carbonate environments - By virtue of their usually forming within the environment in which they are deposited, carbonate sediments offer unique paleo-environmental and

Focus site selection criteria

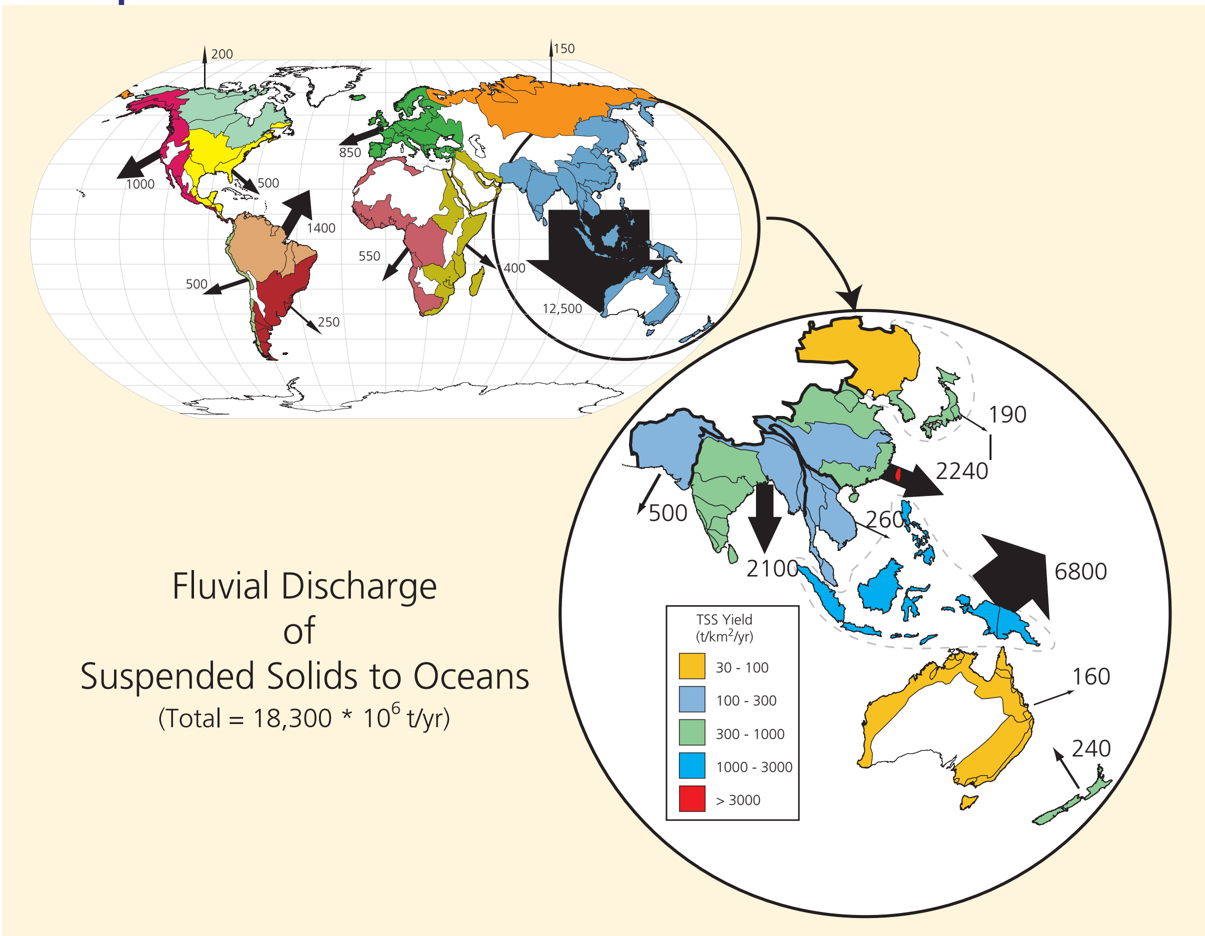


Figure 6. Calculated fluvial discharge of suspended solids to the global ocean (upper left). Of the approximately 2/3 of the global load emanating from southern Asia, more than half comes from high-standing islands in the East Indies and the Philippines. Illustration after Milliman and Farnsworth (in preparation).

geochronologic constraints as well as chemical signals, sea-level information, and other insights. While mixed siliciclastic-carbonate deposits are common in the geologic record, the factors that control the dominance of one system relative to the other are only qualitatively understood (James and Kendall 1992). By supporting a field focus site in which there are mixed siliciclastics and carbonates, this research will help bridge another gap between deep specialist divisions in our community. Bridging this division is particularly important in protecting and managing the world's carbonate reef communities, which are so strongly affected by changes in siliciclastic sedimentation.

- Societal relevance - The results of the investigations at the two study sites should help document the impact of anthropogenic activities on the environment. What is the effect on landscape evolution, for example, of deforestation or farming, or the effect on water quality or stream flow by dam construction? Landslides and tsunamis are perhaps two extreme examples of events that can have extreme impact on both the sedimentary environment and human communities inhabiting those environments.

- Significant differences between two sites - By choosing two sites with different climatic regimes, hydrography, sediment sources, oceanographic forcing and stratigraphic architectures, we can better differentiate the qualitative and quantitative impact of these different environmental controls. Where possible, drainage basins should have significant differences in land-use activities and histories. Where perturbations have occurred - and most drainage basins throughout the world have been affected by anthropogenic activities - it is preferable that the changes be quantifiable and should not overwhelm the natural processes.

6.3 Assessment of Candidate Sites

More than twenty sites were considered within the community as possible candidates for a source to sink study. Candidate areas ranged from Belize to Alaska and to Papua New Guinea. Nearly all candidates, however, failed to meet one or more of the critical criteria. The Mississippi River, for example, suffered both its very large size (which tends to dampen the down-basin effect of even very large events) as well as the fact that it contains more than 30,000 dams of various sizes, which collectively greatly control the fluvial regime. On the other hand, because of its arid and dammed drainage basin, the Brazos River presently supplies relatively small amounts of modern sediment to its dispersal system. Consequently there is little or no sediment transport to the more distal shelf and offshore segments of its system, despite an otherwise excellent offshore seismic and core subsurface data set that extends back to the Pleistocene.

Candidate sites

The two sites that appeared to satisfy all or at least the most critical criteria were the Fly River/Gulf of Papua in Papua New Guinea, and the Waiapoa dispersal system in New Zealand. Two adjacent areas (the Markham River in PNG and the South Island of New Zealand) were considered reasonable alternative sites that should be reevaluated after the first five years of the Source-to-Sink program have been completed.

6.4 Candidate Sites

6.4.1 Fly River/Gulf of Papua (New Guinea)

Papua New Guinea
Focus Site

The Gulf of Papua (GoP) and, in particular, the Fly River system provide a unique opportunity to study a major river system that remains in a nearly pristine condition (Figure 7). The Fly River (drainage basin area 75,000 km^2) rises in the fold and thrust belt of central New Guinea, where mountains locally reach elevations of 4000 m. The basin receives up to 10 m of rain in its headwaters and mean annual Fly River runoff approaches 2 m/yr. The two major tributaries to the Fly, the Ok Tedi and Strickland, join the Fly along a broad flood plain less than 20 m above sea level (Figure 8).

Most of the Fly's sediment load comes from the mountains, with natural loading dominated by landslides. The natural sediment load of the Fly River delta is estimated to be 85 x 10^6 t yr^{-1} (Pickup et al., 1981), 90% of which is fine-grained. Mass wasting and (to a lesser extent, ENSO variations) may cause significant fluctuations in this load. During El Niño periods, the normally high levels of Fly River discharges of water, solutes and particulates decrease to negligible levels, creating a decadal signal whose propagation can be studied through the diverse segments of the dispersal system.

Unlike most rivers, the Fly system has experienced little deforestation or agricultural development and has no dams or artificial levees. The one major anthropogenic perturbation to the system has been the Ok Tedi gold and copper mine, begun in 1985 and by 2010 predicted to have introduced 1.7 x 10^9 t to the watershed. The large influx of sediment in the Fly offers a unique opportunity to examine a large sediment signal, with a distinctive chemical composition, which can be exploited to document and model sediment transfer processes through the entire system. While the vast majority of the sediment thus far has remained within the Ok Tedi and upper Fly rivers (G. Parker and W.

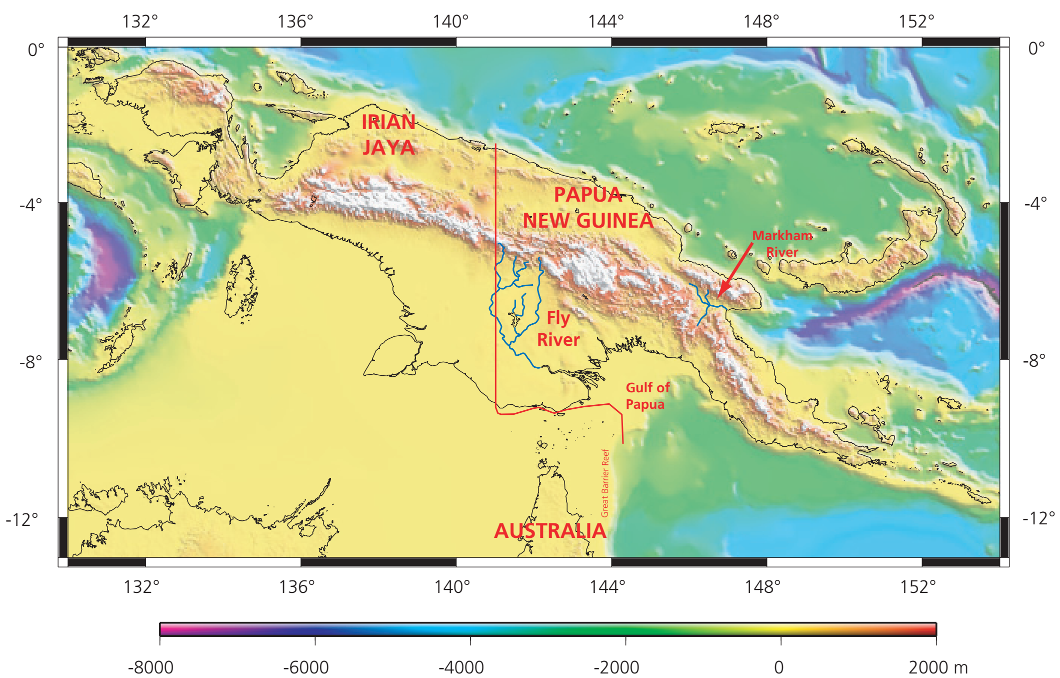


Figure 7. Location map showing the Fly River, Gulf of Papua, and Markham River in Papua New Guinea.

Dietrich, unpublished report), it will produce a strong, long-duration signal that differs from short-term stochastic introduction associated with natural loading events.

As a result of mining activities, there are currently nine flow and suspended-sediment gauging stations along the Ok Tedi-Fly system, some of which go back to the early 1980's. Detailed topographic maps using high-resolution aerial photographs and repeat infrared surveys also have documented changes in morphology and vegetation. Using differential GPS, a high-resolution network of benchmarks has been established on the Fly and Ok Tedi, resulting in a high-quality river profile in very flat terrain. Numerous cross-sections have been established for repeat surveys. The Ok Tedi and Fly floodplains have been topographically mapped through a combination of aerial photography, laser profiling and ground surveying. The extensive data already collected and the established precipitation and hydrologic program in the Fly greatly increase the opportunity and possibility of obtaining accurate sediment budgets through the system.

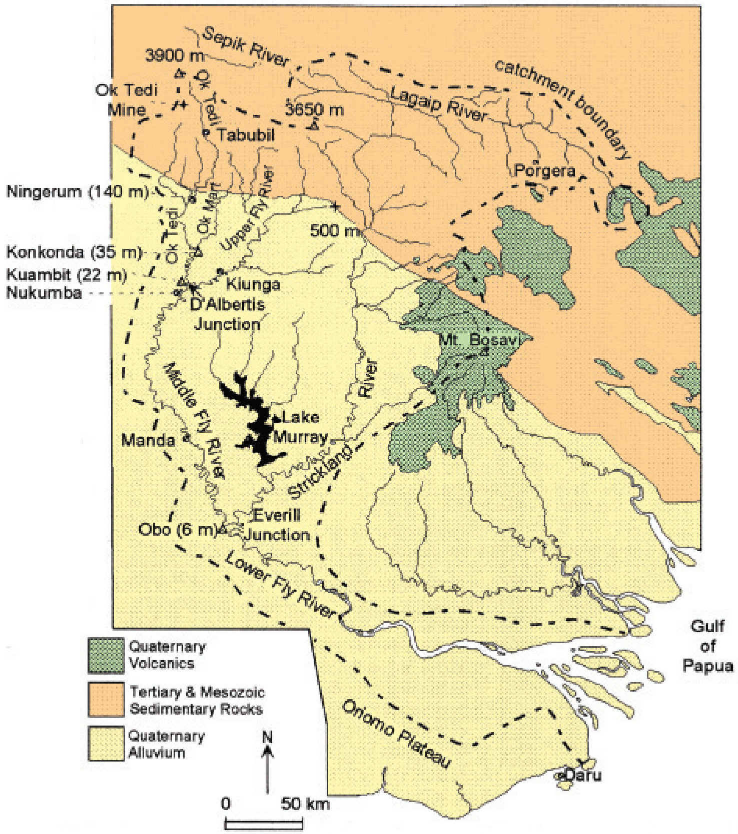


Figure 8. Fly River watershed, also showing Ok Tedi mine, Strickland River and present-day estuary, and adjacent Gulf of Papua. Modified from Dietrich et al (1999).

The Fly River delta has the classic funnel-shaped geometry of a tide-dominated system (Galloway, 1975), and has been used as the end-member example in delta classification, although in terms of our knowledge about the different delta types, we know the least about tide-influenced deltas (Bhattacharya and Walker, 1992). Local tides range from about 3.5 m at the mouth to 5 m at the apex (meso- to macro-tidal). Strong tidal currents cause fluid muds to be deposited on the floors of distributary channels, which are hypothesized to represent the staging area for distribution to the offshore shelf clinoform (Dalrymple et al., in press). The continental shelf contains an actively growing mud-dominated clinoform similar in scale to those associated with other major rivers (e.g., Amazon, Ganges- Brahmaputra, and Changjiang), and which represents the dominant stratigraphic unit of continental margin architecture around the world (Driscoll and Karner, 1999). Sediments become progressively finer in the offshore direction as wave and current velocities diminish. Simulta-

Fly River

Low human impact

neously, benthic organism abundance increases, and the interbedded physical structure is replaced by homogenous, bioturbated muds (Harris et al., 1996). A preliminary sediment budget over a ^{210}Pb timescale (100-yr) indicates that modern sediments are partitioned in the following fashion: Delta Front 24 ± 12x10^6 metric tons/yr, Prodelta 22 ± 6x10^6 metric tons/yr, Distal Delta 0.9 ± .2x10^6 metric tons/yr, which collectively represents about 55% of the Fly's average annual load (Figure 9). An additional 2% is estimated to be transported southward into the Torres Strait, and some may be sequestered in the extensive mangrove forests that line the GoP coastline. The "missing" Fly sediment is hypothesized to move northeastward along the GoP shelf (Harris et al., 1993), where it mixes with sediments supplied by the Kikori, Purari and other rivers and accumulates on the shelf, probably on clinoform deposits that extend along the 50-m isobath. High sediment accumulation rates (> 1 cm/yr) are known to occur in this region. Geochemical evidence also suggests some terrestrial sediment is escaping the shelf into Pandora Trough, but the magnitude of this loss is unknown. The GoP also provides an excellent locality for Source-to-Sink research, including its long marine sedimentary history of foreland-basin evolution (3000 m since the Jurassic).

Fly River sediment productivity

Finally, the Fly River-dominated GoP can be distinguished by its close proximity

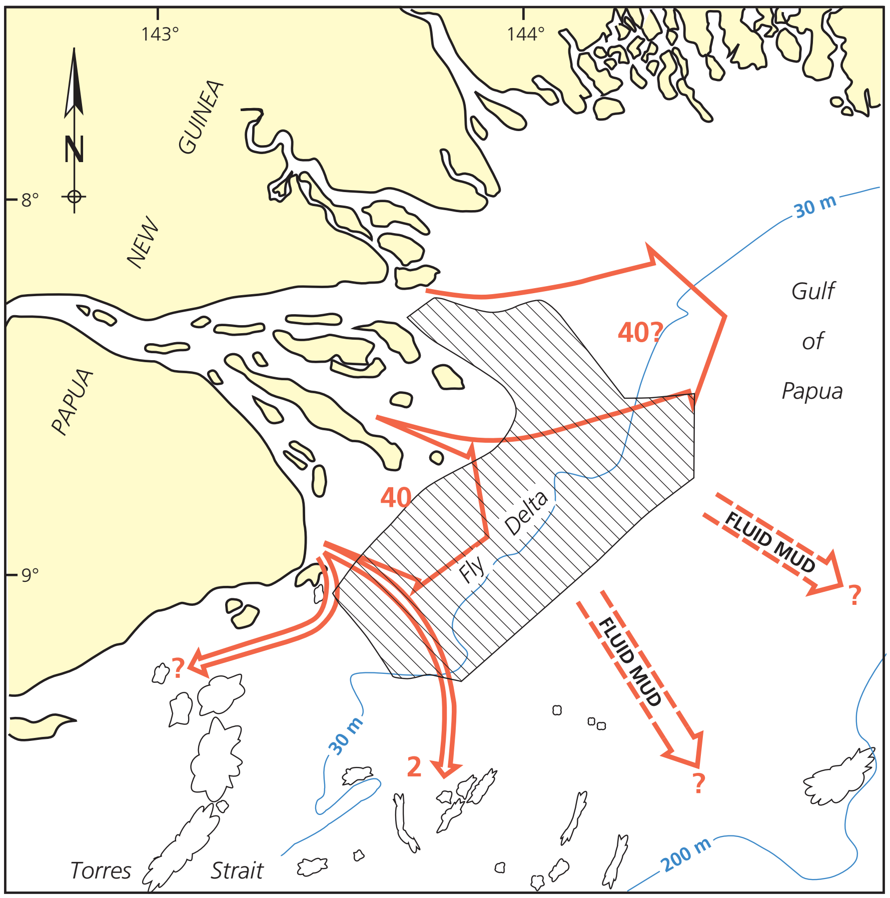


Figure 9. Schematic diagram showing transport pathways for Fly River sediment dispersal. According to this model, floodplain sedimentation is zero and nearly half of the annual load moves alongshore and offshore to the northeast. Modified from Harris et al. (1993).

to extensive coral reefs and Halimeda banks that extend northward from the Great Barrier Reef, thus providing a unique opportunity to study the carbonate- siliciclastic transition (Wolanski et al., 1984).

Scientists from Papua New Guinea and Australia have been investigating the terrestrial and marine portions of the dispersal system for more than 20 years. In particular, recent and ongoing flow and sediment monitoring on the Fly River (http://www.Ok-Tedi.com) provide essential flux data as well as (ultimately) insights as to the impact of a major anthropogenic activity (the Ok Tedi mine). Project TROPICS (Tropical River-Ocean Processes In Coastal Settings) has recently studied the fate of solutes and particulates entering the Gulf of Papua over Holocene time scales (http://www.aims. gov.au/pages/research/projects/ project05/tropics/tropics.html). The US-NSF RiOMar program is planning to collaborate with Source-to-Sink investigations in the examination of carbon pathways through this wet-tropical system.

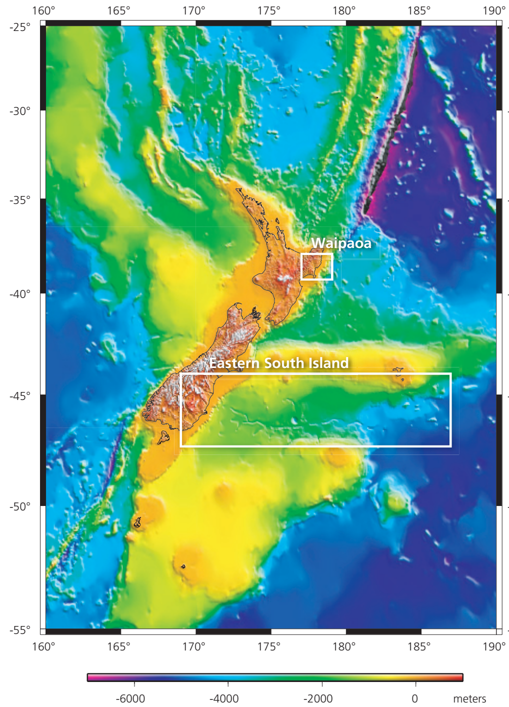


Figure 10. Location map showing the Waipaoa dispersal system and the eastern South Island dispersal system.

New Zealand Focus Site

6.4.2 Waipaoa Dispersal System (New Zealand)

The Waipaoa River margin provides an opportunity to investigate the signal transfer of high-magnitude perturbations during the late Quaternary (ENSO driven changes in precipitation, cyclonic storms, and large-scale destruction of forests from major volcanic eruptions and historical land-use practices) across a relatively closed, small-scale, sedimentary system. The system (Figure 10) is compact (~2570 km^2 source, ~900 km^2 sink), has a point-source discharge to the ocean, and is virtually closed under present highstand conditions (i.e. sediment budgets can be balanced from upland to shelf).

The setting is within the zone of active deformation associated with the Hikurangi subduction margin, and encompasses the 2200 km^2 Waipaoa and 370 km^2 Waimata river basins, which drain the eastern flanks of the Raukumara Range (Figures 10, 11). These drainage basins are positioned above a major tectonic plate boundary and are underlain by deformed Cretaceous and Early Tertiary mudstones and argillites, early Cretaceous greywacke, and a thick forearc sequence of Miocene-Pliocene mudstone and sandstone. Subduction has induced rapid uplift (~4 mm y^{-1}) in the ranges at the head of Waipaoa River (Berryman et al., 2000), where there has been 120 m of downcutting in the last 15 kyr, much of which was accomplished in the late Pleistocene and early Holocene. Rainfall across the basin is primarily controlled by topography, with a mean annual rainfall of 1470 mm from a gauging station 48 km upstream from the coast.

Waipaoa River

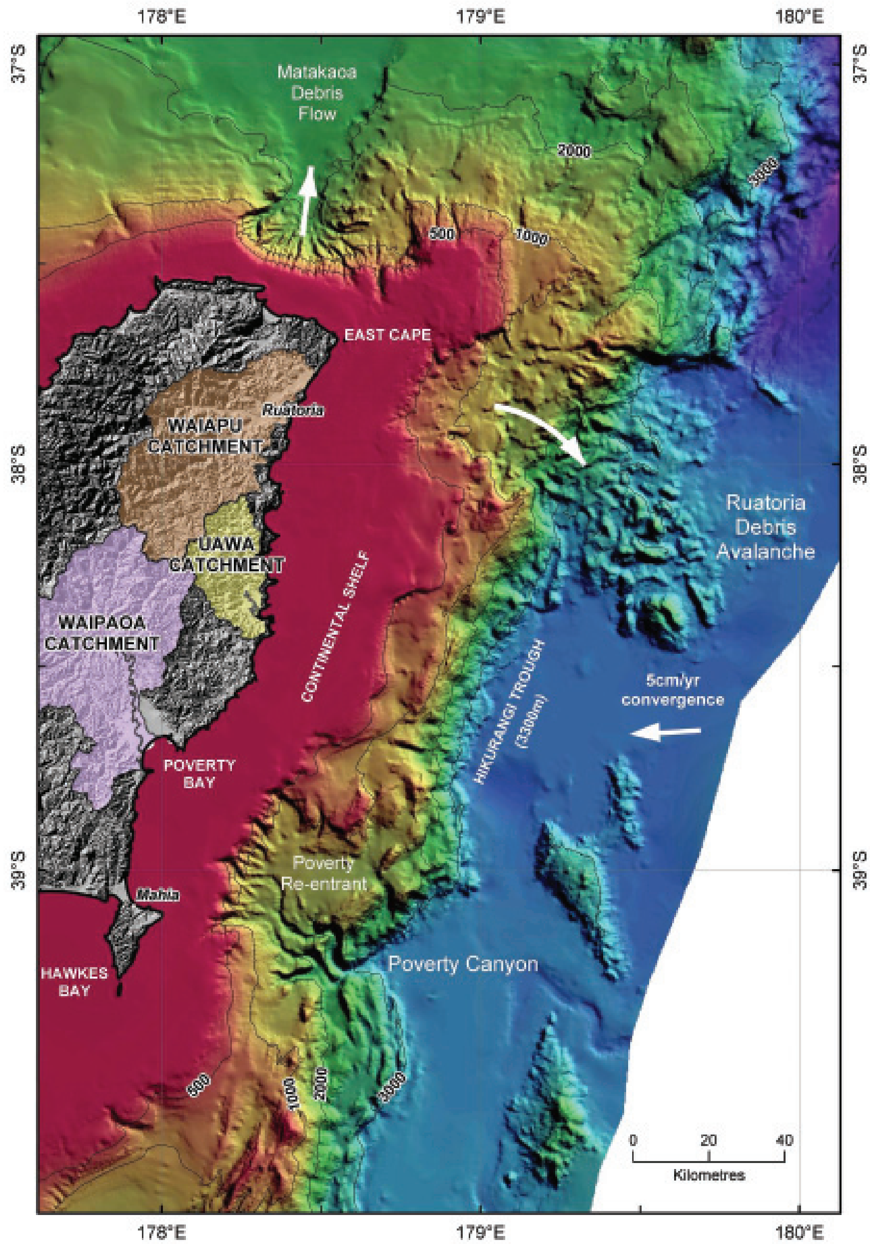


Figure 11. Topography and bathymetry of the Waipaoa, Waiapu, and Uawa Rivers in the eastern North Island of New Zealand, showing the onshore and offshore dispersal parts of the Waipaoa dispersal system. From Orpin et al., 2002.

A remarkable Holocene history of catchment erosion events (mainly storm-induced rainfall) during the past 2 ka has been documented for the east coast of New Zealand from Lake Tutira (Eden and Page, 1998), formed just south of the Waipaoa basin by a large landslide ~6500 ^{14}C years before present (Trustrum and Page, 1992). In the historical period these can be tied with recorded large storms (e.g., Cyclone Bola) that cause extensive landsliding. Periods of abundant storm layers are observed throughout the 2-ka record, which have been hypothesized to correspond with ENSO variations (Eden and Page, 1998), although neotectonic movements also could be important. New Zealand researchers are planning to extend the high-resolution storm record to the lake's origin by coring through the thickest part of the lake sediment in 2003. This 6-ky lake record of erosion events is an unique proxy for river discharge events, and can be used to drive quantitative models of river input to the coastal ocean.

Present-day sediment and nutrient fluxes in the Waipaoa system have been strongly influenced by anthropogenic activities. Although Maori settlers to the area had disrupted the natural vegetation, widespread clearing of the indigenous forest did not commence until after the arrival of European colonists in the late 1820's, and by 1920 the headwaters were cleared; today only ~3% of the basin remains under primary indigenous forest. The destabilized landscape consequently initiated severe hillslope erosion in the Waipaoa River Basin's headwaters, where amphitheater-like gully complexes (up to 0.2 km^2 in area) developed in the highly sheared rocks. Large volumes of fine sediment are delivered to stream channels by gully erosion and shallow landsliding, and the Waipaoa River has a mean sediment concentration of ~1700 mg l^{-1}. The annual average suspended-sediment load to Poverty Bay of 15 $x10^6$ t yr^{-1} (Hicks et al., 2000) ranks amongst the highest measured in New Zealand, and its sediment yield (5900 t km^{-2} yr^{-1}) is very high by global standards (Milliman and Syvitski, 1992). Moderate flows (less than the bank-full discharge of ~1800 m^3 s^{-1}) transport ~75% of the sediment load. As such the Waipaoa is an ideal system to study the effects of heavy landuse on the source to sink system, and may lead to a better ability to predict the longer term consequences of deforestation that is an epidemic land management problem globally. Furthermore, large sediment pulses may be mimicked by natural events common to the area, such as those thought to occur following a major volcanic eruption or neotectonic displacement.

Strong human impact on Waipaoa River system

Fine sediments discharged from the Waipaoa are distributed primarily as hypopycnal plumes and are carried out of Poverty Bay onto the shelf by the baroclinic circulation (which may be intensified during periods of high river discharge). Hyperpycnal flows are though to occur during high discharge events, such as those associated with cyclonic storms (Foster and Carter, 1998). The frequency of hyperpycnal flows during certain times in the past may have been considerably lower, as pre-deforestation discharge was reduced nearly an order of magnitude. Such changes should be reflected in distinct sediment dispersal patterns, offering the potential to examine the effect of changing river discharge on the development of shelf stratigraphy. Study of hyperpycnal flows is of particular economic interest because of their potential importance in delivering coarse sediment into deepwater environments. Much of the global energy exploration budget is focused on attempting to predict the distribution of potential hydrocarbon bearing sandstone reservoirs deposited in deep water environments.

The combination of a broad crescent coast and actively growing anticlines (Lachlan Ariel; Figure 11) on the outer shelf effectively captures sediment on the middle shelf. Post-glacial accumulation rates are high (~1.9m ka^{-1}). A 13 km-wide gap between Ariel and Lachlan anticlines provides an escape route for some sediment, but it is estimated that the off-shelf loss of modern mud is small. Sediment escaping onto the continental slope is likely to be retained within a

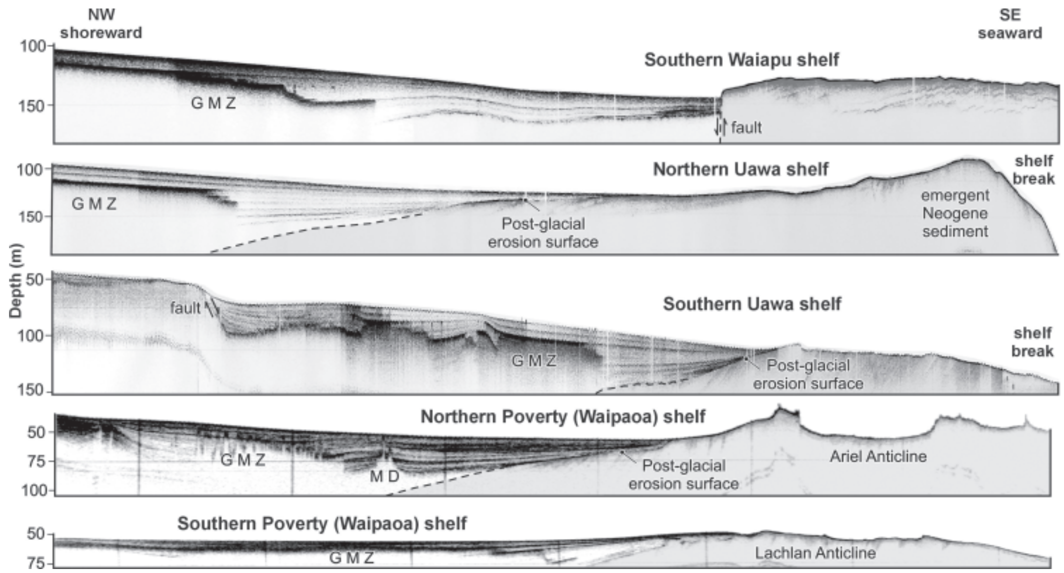


Figure 12. Seismic sections across the mid-shelf at the Waipaoa, Waiapu, and Uawa Rivers, showing mudstone structural highs on the seaward side, trapping Holocene sediments. From Orpin et al., 2002.

Sea level and sediment trapping on Waipaoa shelf

large amphitheater of a (Pliocene?) collapse structure formed by collision of the accretionary prism with a seamount on the subducting Pacific Plate. Given the shelf and slope entrapment of sediment, conditions must be considered favorable for closing the modern Waipaoa budget. The only uncertainty relates to sediment transported into the area by the prevailing along-margin circulation. On the shelf, transport is weak and ephemeral. However, on the outermost shelf and upper slope, sediments come into contact with the southwest-flowing East Cape Current. This flow mainly affects sediment escaping the shelf depocenter and transport rates have yet to be resolved.

During sea-level lowstands, the Waipaoa River presumably reached the shelf edge, although the exact point of discharge is not obvious as the course of the ancestral river has not been traced entirely across the shelf. If discharge was into Poverty Canyon, south of the Ariel-Lachlan gap, sediment within the canyon would be guided to a shallow basin at 3000-3200 m depth that has formed between the base of slope and the left bank levee of Hikurangi Channel. If the lowstand discharged at a gully near the central part of the gap, then sediment would accumulate mainly within the amphitheater of the collapse structure. Whichever is the case, the slope conduits lead into basins where there is a reasonable expectation of closing the budget.

6.5 Differences Between the Two Study Sites

One of the important criteria in study site selection were the differences between the two sites. At first it may appear that the Fly and Waipaoa sites are closely similar, and it is true that both study sites involve documenting the input and fate of sediment from relatively small mountainous rivers in the SW Pacific Ocean. A closer inspection, however, shows many fundamental differences. For example:

These and other contrasting sedimentary considerations provide a wide variety of processes and stratigraphic signatures that will help develop a global understanding for sedimentation, but also will allow greater fundamental insights through comparison of the mechanisms and patterns found in the two areas.

	Fly	Waipaoa
Drainage-basin size	(75,000 km^2), medium	(2000 km^2), small
Terrestrial and marine climates	tropical	sub-tropical
Fluvial database	small	substantial
Seasonal river discharge	steady	episodic
Anthropogenic impact	minimal	considerable
Sediment residence time in drainage basins	long	short
Dominant oceanographic variability	trade winds	cyclonic storms
Shelf sediments	siliciclastic, with reef-derived carbonate facies to the south	siliciclastic
Shelf stratigraphic architecture	clinoform progradation	basin infill

Table 2. Comparison between the two focus areas, Fly River in Papua New Guinea, and Waipaoa River in New Zealand.

understanding in a realistic time frame given the length of the Source-to-Sink Program.

Because both the Fly and Waipaoa rivers are subject to episodic events, the Fly to ENSO variations in precipitation and the Waipaoa to cyclone activity, it is critical that the dispersal system be monitored for the full duration of each study. Onshore and offshore imaging will help define the morphologic and stratigraphic framework and thereby locate targets for detailed imaging and sampling. Onshore sampling and dating would help provide constraints on age of surface exposure and material properties. Box, vibra-, and piston-coring of the preserved stratigraphy will provide age constraints required for sediment budgets as well as lithologic information for geophysical data. Where longer histories are needed, non-Riser drilling will determine the history and rates of incoming material to the sink; the location of these cores will depend greatly

7. Implementation Plan

Because the source to sink concept involves a wide range of terrestrial and marine studies, field work and modeling, the entire integrated effort will take at least a decade. The general outline for these various studies is given in Table 3, in which the timelines for various activities are indicated. The sequence of study and relative effort was designed to build on the strengths of each site to yield new

Time (years)	1	2	3	4	5	6	7	8	9	10
1. Monitoring Dispersal System	●	●	●	●	●	●	●	●	●	●
2. Onshore/Offshore Imaging	●	●	●	●	●					
3. Onshore Sampling and Dating		●	●	●	●	●				
4. Sediment Properties/Rates		●	●	●	●	●				
5. Offshore Non-Riser ODP Drilling						●	●	●		
6. Experimental Studies	●	●	●	●	●	●	●	●	●	●
7. Quantitative Modeling	●	●	●	●	●	●	●	●	●	●
8. Alternate Platforms/New Drilling								●	●	●

Table 3. Logical progression of studies within focus sites.

Implementation of the S2S Initiative

upon data acquired previously by both imaging and sediment sampling. Experimental studies and particularly quantitative modeling will provide insights and predictions about the dispersal system that can be tested; at the same time, modeling can provide directions for the acquisition of seismic and sedimentologic data. Particular attention is being devoted to development of the Community Sediment Model (CSM), whose goal is to produce a unified framework model, analogous on some levels to a Global Climate Model. Alternate platforms and new drilling technology presumably would be applied toward the end of the study, after all the data and model outputs have been evaluated; these final field operations can provide key samples from diverse environments to test model predictions.

CSM—Community Sediment Model

Communication and interaction will be cornerstones of the implementation policy, to provide opportunities for increased synergy through collaboration and piggyback research campaigns. A mid-program evaluation will occur in the fifth year to determine whether a course correction is required and, if so, how substantial.

Because, as pointed out earlier, there are considerable differences between the Fly/GOP and Waipaoa sites, actual implementation plans for the two sites will show some differences.

The Fly/GOP focus site is a complete, relatively pristine dispersal system, where we have the opportunity to address processes operating along all source to sink morphodynamic segments. Although sediment production rates in the highlands are large by world standards, the extensive floodplains of the lowland Fly and Strickland rivers appear to damp upland production variations, providing an opportunity to investigate damping mechanisms and the associated stratigraphic record. Because historic measurements along the river are relatively few, we need first to understand how changes in water discharge and sediment loading impact floodplain and shelf-clinoform sedimentary sinks, and how escaping sediments impact carbonate production by coral/algal communities on the shelf and in deeper water. On longer time scales, these sedimentary processes are modified by relative base-level changes (caused by tectonics and eustasy). We can address sediment production and sequestration questions in many of the morphodynamic segments of this system on short (0-7 ka BP), medium (7-18 ka BP), and long (>18 ka BP) time scales.

It is particularly important at the outset of the Fly/GOP research to engage both land and marine scientists. This can be accomplished best by focusing first on fundamental issues addressing sedimentary mechanisms on short time scales, which can be linked most strongly to stratigraphy. Of particular significance on short time scales is the high-amplitude sediment-transfer signal generated by the strong El Niño forcing. Based on this strategy, among the short time-scale problems that can be addressed are (in the downstream direction): siliciclastic sediment production in the uplands, sediment storage and transfer in the floodplain, lobe switching in the delta, clinoform development on the shelf, and carbonate production from the outer shelf to the deep sea. These require monitoring studies to be initiated first as well as collection of baseline morphometry of present landscapes and seascapes through high resolution DEM and seafloor mapping. We may also wish to re-map specific morphometric features following large events, particularly storms and floods, that may occur throughout the duration of the study. This places an even greater importance on the collection of baseline data (e.g., CHIRP data, High resolution DEM's) early in the individual studies.

On medium time scales, research should involve the paleoclimatic record in floodplains and lakes in response to sea-level rise. Shallow coring of the floodplain and lake sediments will accomplish this. Similarly, cores taken at selected sites within the shelf clinoforms can be compared with cores taken from the floodplain to examine the similarities and differences in how these changes are expressed. A significant seismic program also will be required to map subsurface deposits in 3D. Core data are also critical to calibrate lithology, thickness and age of the older strata imaged by these seismic data. These data will also help quantify the reciprocal carbonate and siliciclastic sedimentation offshore. The longer time-scale investigations should involve investigation of channel stacking in the flood plain, through collection of deep cores and possibly GPR or seismic data, as well as offshore seismic data, which will image channel incision of the shelf, and interaction of shelf-slope carbonate and siliciclastic sedimentation over glacial/interglacial cycles. Locations of deeper cores offshore will be selected after processing and preliminary interpretation of seismic data.

These will ultimately result in a complete characterization of a source to sink system in which short-term processes can be extrapolated back to a stratigraphic record of a few million years. Modeling work will be undertaken to simulate this system and test sensitivities to processes at a variety of scales, from short-term stochastic processes such as floods and storms to longer-term processes such as subsidence, tectonics, and sea level. This will allow us to perform a well-calibrated test of the relative importance of allogenic vs. authogenic processes in building the stratigraphic record.

This type of integrated modeling over orders-of-magnitude spatial and temporal scales has never been attempted before, partly because of a lack of well-constrained field examples against which to build the models, as is a key goal of the Source-to-Sink Initiative.

The specific sediment yield for the Waipaoa river ranks among the highest in the world, consequently, even small-scale perturbations in the terrestrial environment should create a strong depositional signal. Because of the small size of the drainage basin, the residence time of sedimentary material within the terrestrial environment is relatively small, and therefore changing discharge conditions should rapidly propagate to the shelf depocenter. As a result, the Waipaoa system represents a sedimentary end-member where the potential for preservation of climatic, geologic, and anthropogenic signals on the shelf is high. Despite this potential, we need to understand how operative marine processes filter the changing discharge conditions to determine the dominant control on the formation of shelf stratigraphy. Thus, a combination of terrestrial and marine observations and modeling should be undertaken to define the terrestrial signals, determine the dominant marine transport processes, and resolve the shelf stratigraphic record.

Differences in implementation between Focus Sites

Episodic and highly concentrated river outflow into an energetic coastal environment ultimately will allow the community to examine the role of marine transport processes in modulating strong signals emanating from the drainage basin. Monitoring and modeling studies will be required to understand the mechanisms of sediment dispersal from Poverty Bay to the open shelf, and the resulting depositional signatures. Near bottom observations are key to understanding present-day sediment dispersal patterns (e.g., instrumented tripods, swath mapping, high-resolution seismic) and will provide realistic constraints for sedimentary models which need to be developed in order to predict dispersal and accumulation patterns beyond the temporal range of these observations.

A large body of research already exists regarding the geologic framework and Ho-

International collaboration

NIWA-US

Ok Tedi Mine group

University of PNG

locene environmental conditions in the terrestrial part of the Waipaoa system (e.g., Foster and Carter, 1997; Eden and Page, 1998). Using these present data, process and sampling studies can begin in the uplands and floodplain regions. Information also exists for the offshore part of the Waipaoa system, but data are fewer. Waipaoa studies would build on past and continuing work of New Zealand scientists in three significant areas: 1) Holocene climate record and landscape evolution, as well as mechanisms and patterns of sediment production (Landcare Research; http://www.landcare.cri.nz); 2) flow and sediment discharge monitoring (Gisborne District Council and the National Institute of Water & Atmospheric Research, NIWA); 3) nature and amount of along-margin and off-shelf transport and sediment storage on the continental slope (NIWA; http://www.niwa.cri.nz). These studies represent a significant contribution from New Zealand partners and provide ample opportunities for collaborative efforts to make significant scientific advances toward the Source-to-Sink objectives.

A combination of methods will be needed to understand better the Waipaoa system. Shallow and deep coring of lacustrine and shelf environments along with chronostratigraphic analyses will be needed to define the inputs and sedimentary architecture. Numerous tephra layers and pronounced textural variations in marine cores off the Waipaoa will enhance our ability to constrain shelf stratigraphy. The erosion of regolith following large magnitude events that generate massive landsliding (e.g., 7.8 magnitude Napier earthquake of 1931) is characterized by an abundance of Tertiary pollen, which thus provides a means for identifying them in the shelf record (Wilmshurst and McGlone, 1996). The chronostratigraphic control afforded by tephrachronology, along with coring and high-resolution seismic studies, will facilitate construction of sediment budgets that can be used to constrain estimates of riverine inputs over the Holocene. Consequently, investigations should focus on the upland source regions, the floodplains, coast, and shelf. Ongoing studies of the continental slope by NIWA, in collaboration with US MARGINS scientists, will help to address the possibility of off-shelf transport, and to close the offshore portion of the dispersal system during the Holocene. Before process and sampling studies can begin, however, geophysical characterization of the shelf needs to be carried out, principally by swath bathymetry and high-resolution seismic profiling, with limited ground-truthing. This would be followed by more detailed sampling and observational studies. During this phase, it will be critical to coordinate closely the terrestrial and marine studies to address how changing terrestrial inputs and the dominant transport processes affect the segregation, dispersal and preservation of strata.

8. International Cooperation

The success of both focus studies will depend greatly on our foreign partners. Without their help in supplying previously acquired terrestrial and marine data, without their assistance in providing field support, such as boats and field camps, and without (particularly in the case of Papua New Guinea) permission to work in their territorial waters, these studies would be impossible.

In the Fly River study we rely on three prime groups for support. The Ok Tedi Mine group have been extremely forthcoming in sharing their hydrologic data from the Fly, and they also have given access to their river boats and even helicopters, the only practical ways in which field operations can be accomplished in the coastal lowlands. The Papua New Guineans themselves, particularly faculty at the University of Papua New Guinea, Port Moresby, have been helpful in obtaining permission to work in the country. Finally, the Australians have had a long-time interest in the Fly River, particularly as it stands at the northern end of the Great Barrier Reef; any change in the fluvial and/or dispersal paths of the Fly River system could have major impacts on the reefs to the south. As such, the Australians have conducted many research programs in the Gulf of Papua. Several Australian cruises, in fact, provided the first opportunities for American scientists to work in Papua New Guinean waters. These various links will be continued in future studies, particularly as the assistance of Ok Tedi and the Australians is critical for us to obtain small-draft boats that can work in river and coastal environments.

The success of any study of the Waipaoa River and adjacent offshore basin depends strongly upon New Zealand scientists. Fluvial data are available from Landcare, while access to New Zealand ships will come from close ties with NIWA (see previous section). The NIWA link to ships of opportunity is particularly critical, since it is our assumption that episodic events, most likely tied to cyclones, have a major effect on both the river and the transport of its sediment to the offshore basins. As US UNOLS ships are scheduled far ahead of any actual cruise, our only opportunity to study these major events and their effects on the dispersal and sedimentary systems most likely could come only from using New Zealand ships. As in the case of Australians, New Zealand scientists will be working as our research partners, and therefore ship costs should be less than if we were forced to lease a third-party ship.

9. Education and Communication

Educational opportunities should be vigorously incorporated within Source-to-Sink. Graduate students are expected to participate through the funded research activities. However, special attempts should be made to extend the terrestrial and marine research efforts to benefit younger and older scientists. Within NSF there are additional resources for undergraduate and post-graduate education. After an initial round of research is approved, plans will be developed for running undergraduate field camps for study of earth surface processes in conjunction with the research activities. Similarly, the opportunity will exist for professional field trips (~2 weeks) by interested scientists, especially university professors and secondary educators.

The MARGINS Office (currently at the Washington University in St. Louis) maintains an active website (www.margins.wustl.edu) that can provide information describing past, present, and future field programs and experiments as well as access to the existing databases. In this way both information of future opportunities and existing data can be accessed quickly, thus providing “instant” communication between geomorphologists, marine geologists, stratigraphers, and modelers.

An NSF-sponsored program entitled Digital Library for Earth Systems Education (DLESE) is a web-based operation that provides the basis by which many of the results by Source-to-Sink participants during the next 10 years. Unique opportunities would be dynamic figures, such as laboratory simulations of mass flows or time-series video observations of the seabed. This “text” would be used for the field camps and field trips, and would be available to anybody through the web. Other means for dissemination of results include Theoretical and Experimental Institutes (TEI), which are basically short courses. Regular sessions at national/international meetings should be planned. And the MARGINS web site will receive materials from Source-to-Sink studies.

Outreach

MARGINS Office and website

DLESE

Theoretical Institutes

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